

X. Zeng · Y. Li · D. Ruan
L. Koehl (Eds.)

Computational Textile

Xianyi Zeng, Yi Li, Da Ruan and Ludovic Koehl (Eds.)

Computational Textile

Studies in Computational Intelligence, Volume 55

Editor-in-chief

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Computational Textile, 2007

ISBN 978-3-540-70656-4

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Computational Textile

With 143 Figures and 24 Tables

 Springer

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Library of Congress Control Number: 2006940471

ISSN print edition: 1860-949X

ISSN electronic edition: 1860-9503

ISBN-10 3-540-70656-9 Springer Berlin Heidelberg New York

ISBN-13 978-3-540-70656-4 Springer Berlin Heidelberg New York

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Cover design: deblik, Berlin

Typesetting by the editors using a Springer L^AT_EX macro package

Printed on acid-free paper SPIN: 11598411 89/SPi 5 4 3 2 1 0

EDITORS' PREFACE

In advanced countries as well as developing countries, the textile and garment industry still plays an important role in economy, in terms of production and employment. However, there exist many barriers in this industrial field that are pressing companies to face the following competitive challenges:

- Shorter product life cycles: distributors and consumers are looking for more variety and personalization.
- Lack of flexibility in the supply chain.
- Cost reduction: retailers do not want to lose their sales margins which generates a pressure to compete for cheaper prices on products.
- Homogeneity need: the lack of integration, the heterogeneity and the lack of standards is a chronic weakness of the textile and garment industry.
- Consumers demand more comfortable textile and apparel products as casualization becomes a global trend over the decades.
- Biofunctional performance of textile devices and apparel products becomes critical area of concerns as more and more consumers pay attention to making healthy lifestyles.

Under this challenging economic pressure, there is a strong need to develop new methods in order to optimize the quality of textile products and textile management. Information technology, especially computational techniques can play an important role in this optimization.

Since 1950's, computational techniques have been widely applied in textile industry and garment industry for process and materials' structure modeling, simulation and control, optimization of product quality, product design, textile market forecasting, and production management. The related computational techniques include classical methods such as statistics, differential equations, classical signal and image processing (time series analysis and frequency analysis) and statistical pattern recognition, and intelligent techniques such as soft computing and data mining. Classical methods are essentially based on formalization of physical laws and analysis of measured numerical data while intelligent methods often deal with uncertainty and imprecision related to human knowledge on products and

processes and linguistic data analysis. The selection of specific computational techniques is strongly related to the nature of the problem of interest. In general, an optimal solution to a complex textile problem can be found by combining several complementary techniques in a suitable way.

This edited book reports recent research results and provides a state-of-the-art on computational techniques in textile and garment applications. The main objective of this book is to gather a peer-reviewed collection of high quality contributions in the relevant topic areas. Textile engineers in companies and technical centres as well as applied researchers and research students working on different textile topics can benefit from this book. The contributions of this book are mainly extracted from the special sessions on textile of the 17th IMACS Congress (IMACS'2005), held in Paris in July 2005. The following criteria have been used in screening the chapters:

- Quality and originality in methodology,
- Application oriented papers exhibiting originality with reasonable theory involved,
- Relevance to computational techniques and textile industrial/engineering applications.

This book collects a number of representative applications of computational techniques in textile and garment industry. These applications cover the following issues:

- 1) Textile quality assessment by image analysis,
- 2) Modeling and simulation of textile structures,
- 3) Computer aided garment design,
- 4) Computerized textile management and textile Supply Chain,
- 5) Textile quality subjective and objective evaluation;
- 6) Computational thermal bioengineering of textiles and clothing;
- 7) Computational biomechanical engineering of textiles and clothing.

The volume starts with an introduction chapter, entitled "*From biological macromolecules to drape of clothing: 50 years of computing for textiles*" and written by Prof. J.W.S. Hearle of University of Manchester. In this chapter, the author presented an overview of computing techniques (software and hardware) in various textile applications, including modelling of fibre, yarn and textile structure, modelling of textile mechanics, modelling of fabric drape, and textile and garment CAD.

The other chapters are divided into six logical parts each corresponding one category of applications.

Part 1 on *Textile Quality Assessment by Image Analysis* contains two chapters that apply techniques of image processing and analysis for extracting relevant features of textile surfaces and characterising the quality of related materials. In Chapter 2, the authors propose a new method of frequency domain image analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in sample images of knitted and nonwoven fabrics. Chapter 3 gives an objective evaluation method of seam pucker in textile samples compared to the existing references used by experts. This method is based on 3D image analysis, permitting to extract feature vectors from test samples and standards of seams using multi-scale wavelets analysis, spectral analysis, texture analysis and fractal analysis. The most relevant feature vectors are obtained using the criterion of sensitivity and conformity to expert knowledge on classification of seam specimens.

Part 2 on *Modeling and Simulation of Textile Structures* collects three chapters that apply mathematical and computer modeling and simulation techniques for predicting functional properties of textile materials from their structural parameters. Chapter 4 describes a method for characterizing yarn unevenness using the mass variation curve (MVC). Some statistical features of MVC (stationarity, independence, linearity etc.) are studied in order to identify long-range and short-range dependencies. The techniques of Fast Fourier Transform and estimation of Hurst exponent have been used in this approach. Chapter 5 presents a method of computer simulation of woven fabric structures using images of yarns taken along their lengths. The related fabric simulations are confined to single fabrics of plain, matt and twill weaves. This method permits to mathematically model yarn curves in the fabric structure and obtain projections of yarn images in the perpendicular direction to fabric surface. Chapter 6 gives a method for computing permeability of textiles using numerical simulations of fluid flow. The permeability is a key feature in the manufacturing of composite materials with textile reinforcement. The related simulations are performed by solving two different flow equations, i.e., the finite difference Navier-Stokes/Brinkman equation and the lattice Boltzmann equation. The obtained results have been validated with theory and experimental data.

Part 3 on *Computer Aided Garment Design* includes three chapters that describe several typical problems in garment and furniture design and give related solutions using computational techniques. Chapter 7 deals with the problem of 3D human body scanning for garment design. The authors propose a distributed collocation method for taking geodesic body measurements, which have been proved more efficient than classical linear measurements.

The geodesic measurements are obtained by solving the geodesics equations using the bicubic tensor product Bezier patches. Chapter 8 deals with the problem of rapid measurement of human body surface shape. A concept of isomorphic mesh (mesh of human body surface shape) has been proposed. It is generated from original data of human body measurements by applying geometrical rules related to some characteristic points on human body surface. Chapter 9 presents an adaptive CAD system for flexible design and manufacturing of sofas. This system permits to model current design and manufacturing processes and then improve these partially manual processes without customer's feedback. The improved system is highly adaptive and adjustable, which integrates adaptive virtual prototyping techniques and realistic pictures of products to be designed.

Part 4 on *Computerized Textile Management and Textile Supply Chain* contains two chapters dealing with optimization of planning and organization structure in textile supply chain. Chapter 10 discusses the problem of optimal purchasing policy, currently encountered in textile supply chain. The authors give an analysis on the limitation of the standard hypothesis of the knowledge of the uncertain demand modeled using exact probability distribution. Scarf's method has been proposed to study the optimal decision obtained from the defined family of demand models. Chapter 11 provides a simulation model linking manufacturer, retailer and customer in an apparel supply chain. This model generates a portfolio that satisfies the apparel retailer-defined customer service level. Fuzzy logic is integrated into the simulation model so as to investigate the different forecasting error degree between the sales forecasting and the customer demand in the apparel supply chain.

Part 5 on computational thermal bioengineering of textiles contains 6 chapters that describe the concept, models and computational systems with case studies. Chapter 12 introduces the concept of computational textile bioengineering and outlines the framework. Chapter 13 reports the development of a software package for computing simulation of dynamics of the human thermoregulatory responses when wearing clothing. Chapter 14 reports a computational model to simulate the temperature regulating effects of multi-layer textile assembly incorporated with phase change material (PCM) microcapsules. Chapter 15 discusses the numerical simulation of the coupled heat and moisture transfer processes in intelligent clothing incorporated with heating elements and PCM microcapsules. Chapter 16 deals with the modeling of the coupled heat and moisture transfer processes in the wall incorporated with textile materials and PCM microcapsules for studying the potential of energy saving efficiency during air conditioning process. Chapter 17 describes an mathematical simulation of the human psychological perception of moisture sensations.

Part 6 on computational biomechanical engineering of textiles consists of 5 chapters. Chapter 18 reports a CAD system for biomechanical engineering design of textiles and apparel products. This system allows computational engineering design of textile products by selection of fibers, yarns and fabrics with specification of their structural and mechanical properties, as well as patterns and human body., with which the dynamic interactions between human body and textile materials can be simulated and the results are visualized in 3D to show the skin pressure and stress distributions and the resulting discomfort sensations. Chapter 19 describes an application of moving mesh technique in simulation of human body deformation and garment pressure distribution. Chapter 20 reports a numerical simulation for predicting the skin pressure when wearing graduated compression stocking. Chapter 21 deals with computational modeling of the biomechanical behavior at the foot-sole interface. Chapter 22 reports computational simulation of the dynamic pressure distributions when wearing socks.

We would like to thank to all the contributors for their kind cooperation to this book; and to Dr Thomas Ditzinger and Heather King of Springer for their advice and help during the production phases of this book.

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October 2006

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From Biological Macromolecules to Drape of Clothing: 50 Years of Computing for Textiles

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Abstract

The development of computing of structural mechanics of fibres and textiles is linked to the advances in computer hardware and software. The examples cover wool and other fibres, continuous filament and other yarns, micromechanics of woven and other fabrics, and drape of fabrics. The tasks for the 21st century is to develop easy-to-use programs, which will generate a creative interchange between academics and industry, and to use the increased computing power to formulate individual fibre models.

1 Introduction

1.1 Historical

With a few years overlap at each end, the second half of the 20th Century has seen the rise of computing, as indicated below, and the study of the structural mechanics of fibres and fibre assemblies – as well as coinciding with the professional career of the author. An account of the history is instructive, but more attention will be paid to matters of current concern, particularly the *TechniTex* core research in the University of Manchester on the modelling of woven fabrics and the work with Canesis Network Ltd (formerly Wool Research Organisation of New Zealand) on wool and hair. The paper will progress from the nano-scale of molecular structures, through

the micromechanics of fibres, yarns and fabrics, to the macromechanics of overall performance of products. Almost all the references are to research in association with my colleagues and students. The level of computation in each study is indicated by comparison with the dates in the following list, for which some poetic licence has been taken in order to present a simple story.

- 1950: First programmable computer built by Williams and Kilburn in Manchester, using glass vacuum tubes and post-office relays. Major users only – programmed by changing switches.
- 1960: Batch processing by punched cards. Answers in hours to days. First languages: Mercury and Atlas auto-code in Manchester, Fortran by IBM, etc.
- 1970: Batch processing by teletype input.
- 1980: On-line from terminals to main-frame computer.
- 1990: Personal computers. Advanced languages. Powerful graphics.
- 2000: Global interaction by Internet and e-mail.

In reality, each development ranged over several years, with people and places being at different stages. For example, in July 1967, we made an on-line trans-Atlantic connection through the commercial telex network from Manchester to the textile information retrieval system on a computer at MIT, but it was many years later and with new technology before this became commonplace. Around this time, the Professor of Computing at UMIST saw no place for anything but batch processing on large main-frame computers, but the Professor of Control Engineering was pioneering on-line access to a PDP 10 mini-computer. Milos Konopasek (Hearle et al. 1972) used the PDP 10 for innovative computing techniques for textiles, but it is only now that there is a prospect of industrial usage.

1.2 Routes to Follow

In the beginning, we used computers as little more than powerful calculators to carry out the sums at the end of an investigation. Later it became common practice to carry out complex mathematical analyses and use computing routines for numerical evaluation at the end of the study. Alternatively attempts were made to apply techniques, such as finite element methods, that had been developed in other contexts. Because of the nonlinearity and complexity of textile systems, these academic routes seem doomed to failure as quantitative design tools. For software that will have industrial application, one should start by considering how computing

can best deal with the fundamental relations governing a fibre system and how, in a way that is easy to use, it can give useful answers. Getting the right software into industrial use is a necessity, in order to bring about the creative interchange between researchers and users, which has so far been lacking.

Prejudice has to be overcome. The textile industry has an amazing history of empirical development, but the triumph of the practical advances breeds a reluctance to embrace computer-aided design. There are two areas where there were great changes in the last quarter of the 20th Century. One was in computer control of machines, typified by electronic Jacquards and complete production of 3D garments by flat-bed knitting. The other is more relevant to this paper and can be illustrated by a Manchester story. In 1975, textile designers did not like the idea of using computers for the aesthetic design of fabrics by colour and pattern. An earlier grant application by UMIST and the Royal College of Art had failed because it was said that “why do designers need computers, they have pantographs?”. Peter Grigg was appointed a Lecturer in Textile Engineering. He obtained second-hand Elliot 903 computers, which were no longer needed by the Navy, and developed a textile CAD system. They were the size of upright pianos and thousands of times less powerful than a modern PC. In the 1980's, TCS Ltd was formed to exploit the system; in the 1990's, the company was bought by Ned Graphics, who now have large stands at textile machinery exhibitions. In this aspect of textile design, the use of CAD has become universal. The same is not true of the engineering design of fabrics. For technical textiles, qualitative trial-and-error, backed by experience, is the norm. One challenge for the 21st Century is to exploit the academic work of the last 50 years and bring in CAD; another is to advance the methodology, stimulated by a creative interchange between industry and academia.

1.3 Approaches to Mechanics

There is one more general point to make. The first approach to modelling textile mechanics has usually been to apply equilibrium of forces and moments. However, almost always, energy methods have proved more powerful. There are various reasons for this, but the most basic is that forces and moments are vector quantities, so that equations are needed for six components. Energy is a scalar quantity, so that there is one basic relation to satisfy. A practical advantage is that it is easier to make useful simplifying assumptions with energy methods. If there is a geometrical relation between macro- and micro-strains, e.g. affine deformation, conservation of energy can be used; if the deformation is undefined, as in

buckling, minimum energy or the principle of virtual work is used. Another practical point is that it is usually better to work with mass units (specific stresses in Newton/tex, where tex = g/km, and energies in J/g) than in conventional stress units (Pascals).

2. Molecules to Fibres

2.1 Wool and Hair

Wool and hair have the most complex of fibre structures, Fig. 1, with 10 levels from atoms through a collection of proteins to the form of the whole fibre, as shown in Fig. 2. The explanation of the unusual tensile properties of wool is summarized in Fig. 3 (Chapman 1969, Hearle 2000). The stress-strain curve has Hookean, yield and post-yield regions and, surprisingly, full recovery from large strains, but along a different curve. The structure is a composite of a rubbery matrix around intermediate filaments, which are helically crystalline and characterized by critical and equilibrium stresses for a phase transition to extended chains with 80% extension. This model is so simple as not to need computation. Fortran programs covered more detail of filament/matrix interactions (Hearle et al. 1971). Later, a BBC Acorn microcomputer was used to add time dependence to the model (Hearle & Susitoglu 1985). Other properties are explained by structures at a

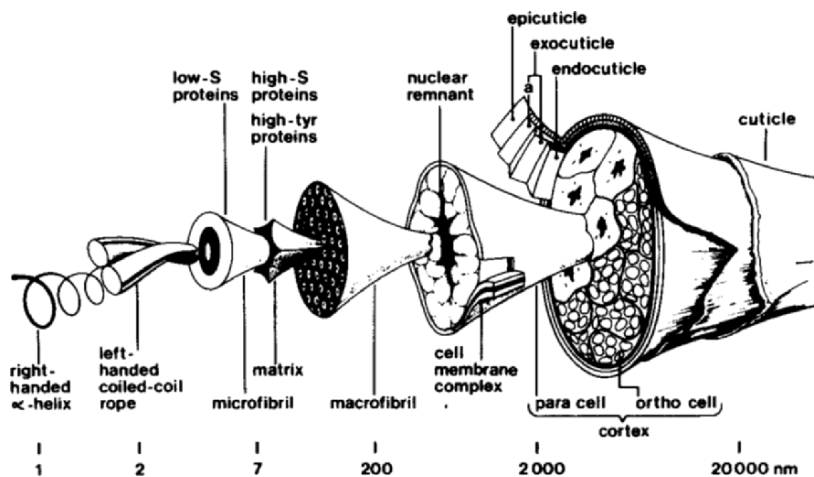


Fig. 1. A view of the structure of a wool fibre, as drawn by Robert Marshall, CSIRO.

coarser level. An important feature is that in the ortho-cortex the macrofibrils are helical assemblies of microfibrils, but in the para-cortex the microfibrils are all parallel to the fibre axis. The basic cause of wool buckling into crimped forms had been known since the 1950s, but it was not until it was programmed by a model involving differential contraction of para- and ortho-cortex that there were quantitative graphical predictions (Munro & Carnaby 1999, Munro 2001). A three-component model of stiffness has been modelled (Liu & Bryson, 2002).

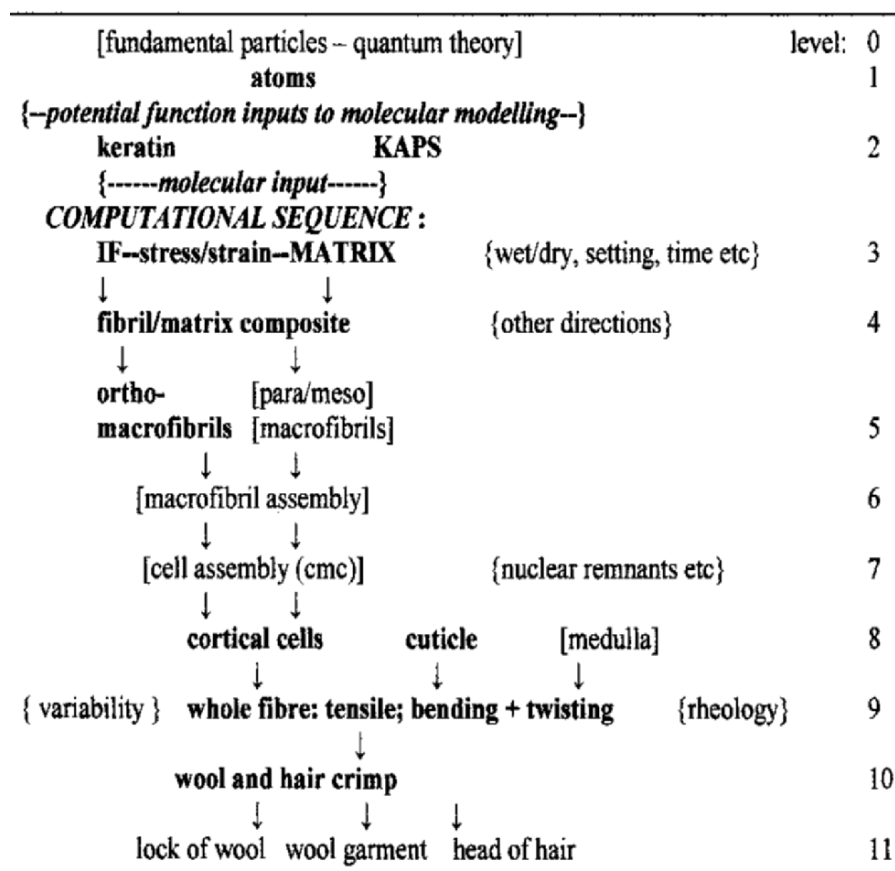


Fig. 2. Levels of structure in wool and hair, with indication of computational scheme for total modelling. Based on (Hearle 2003).

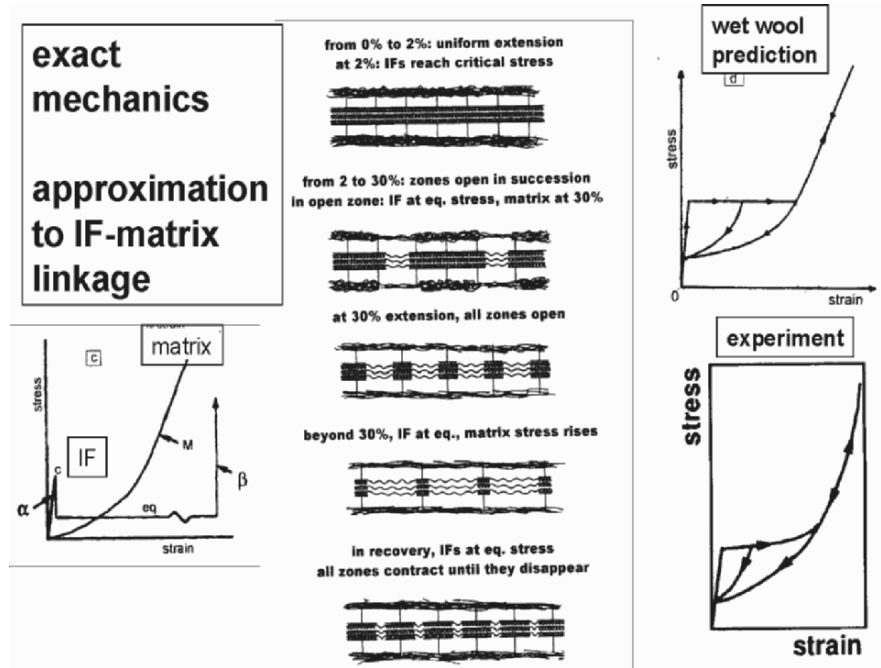


Fig. 3. Mechanics of the wool fibre at level 3 (Chapman 1969, Hearle 2000).

The work to date has been simplified and generic. It gives scientific understanding, but programs should explore the differences between wools, particularly if genetic engineering is used to modify structures. Several computational advances are now needed. A framework program is needed to take outputs from one level as inputs to the next level (Hearle 2003). Some parts of the total model, e.g. a simple dependence on mixture laws, are easy to program. Others are more challenging. At the nano-scale level, computational molecular modelling should be used to determine the full mechanical response of the complex protein assembly in intermediate filaments. Although such modelling has been used to determine protein conformations, the force options, which are in commercial programs, have not been applied to a system of this complexity. The full repeat length is too large to compute, but it should be possible to model separate simpler segments and then link them in a series model. The matrix presents a greater problem, because, although it is critical in determining mechanical properties, its structure is less well known. The development of computational modelling would stimulate an interchange with

molecular biologists and applications over a wide field. For the ortho-cortex, the methodology of twisted yarn mechanics needs to be extended to a system in which the matrix contracts on drying, with a consequent shortening of the macrofibrils. At the fibre level, the different properties of para-cortex, ortho-cortex and cuticle (sometimes also meso-cortex and medulla) need to be combined to predict bending, twisting and crimping modes. Another challenge is to model the formation of the structure.

2.2 Other Fibres

Computational modelling is a necessary tool to explain fibre properties. For cotton and other plant fibres with structures determined by nature, a sequence through structural features, summarised in Fig. 4, has been modelled (Hearle & Sparrow 1979). Once again this is a simplified generic treatment and more explicit modelling is needed to predict properties of different cottons. For manufactured fibres, the fine structure has a major role in determining properties, but it has never been engineered deterministically, in the way that both molecules and macroscopic structures are engineered. In the production of melt-spun fibres, fluid and heat flows are computed, but changes in structure result from “twiddling the knobs”. Figure 4 includes a view of the possible structure of a nylon fibre. This has been modelled by a network analysis based on energy minimisation. This has been briefly described (Hearle 1991) but not published in detail. The model includes two useful features: the fine structure was treated as a collection of chains emerging from a crystallite; the energy was due to two effects, extension of tie-molecules and change of volume. There is a need and an opportunity for advances in computational modelling of fibre formation, structural forms and prediction of properties.

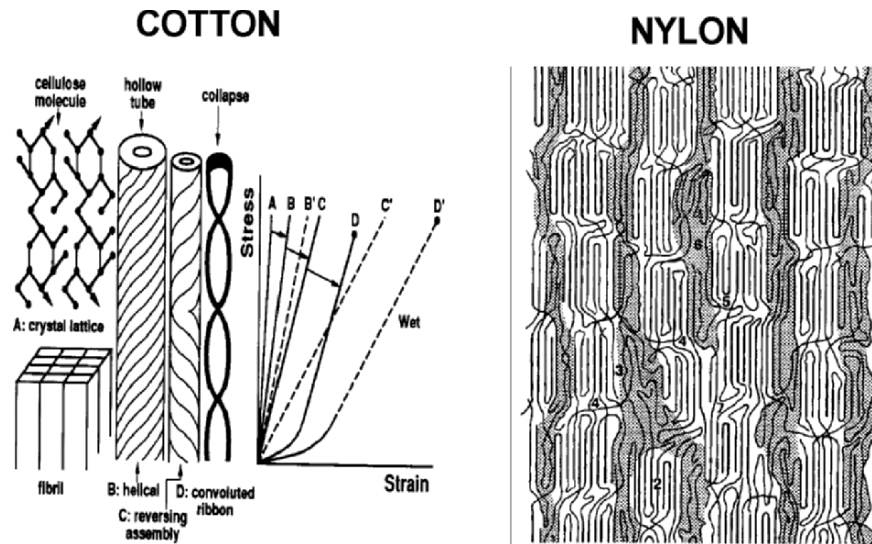


Fig. 4. Models for cotton and nylon. The cotton model is from Hearle (1991); the view of nylon is from (Murthy et al. 1990).

3 Yarns

3.1 Twisted Continuous Filament Assemblies

Twisted continuous filament yarns have a well-defined geometry. Affine deformation relates yarn strain to fibre strain through helix angles. In the 1960's, the force-equilibrium analyses, which were limited to small strains and linear elasticity, were overtaken by large-strain, nonlinear energy methods introduced by Treloar and Riding. This gave a few easily programmed equations (Hearle 1969). Torsion and plied yarns were later included (Hearle & Konopasek 1976).

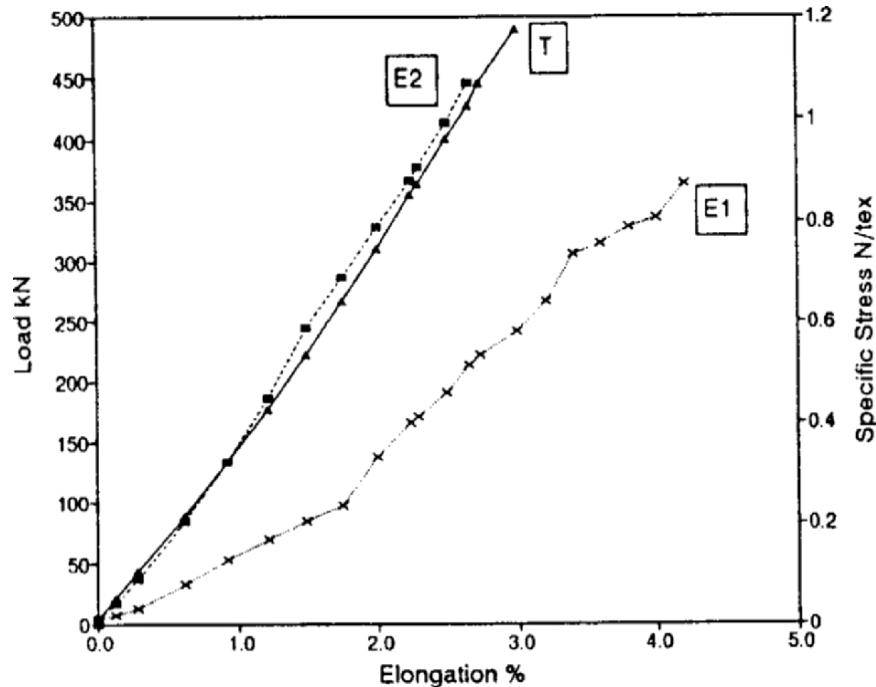


Fig. 5. Use of fibre rope modeller. T was the predicted response for a seven-strand aramid rope. Testing gave E1, but, when the rope was examined, it was found that it had not been made to the correct specification. A correctly made rope gave E2.

Application of the methodology to ropes led to a first use in engineering design by a manufacturer. Fibre Rope Modeller (FRM), developed by Tension Technology International Ltd (TTI) takes account of the multi-level structure of ropes. An earlier DOS version for the US Navy has been converted to Windows. The basic yarn stress-strain curve is input through a set of polynomial coefficients. The program runs through the multiple twist levels in ropes. The output includes details of rope structure, load-elongation curves to break and responses in cyclic loading. In order to determine internal forces, which cause fibre fatigue, the principle of virtual work was used. There are modules for creep failure, hysteresis heating, internal abrasion, and axial compression fatigue. An interesting example of the use of FRM, Fig. 5, shows the good agreement between predicted and tested load-elongation curves (Leech et al. 1993). Strength predictions are

typically about 10% higher than observed values due to effects of variability.

3.2 Other Yarns

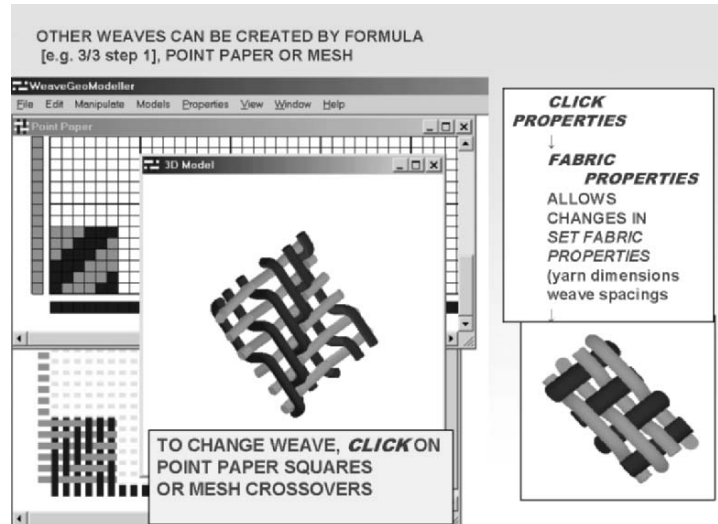
For the simplest staple fibre yarns, the effect of slippage at fibre ends is included (Hearle 1965, Hearle & El-Sheikh 1969). Bulky staple fibre yarns have been much studied from mathematical analysis (Carnaby & Grosberg 1977) to graphical computation (Cassidy 2000), but serious difficulties remain. The underlying problem is that, for quantitative predictions, computational modelling of yarn formation is needed. An open question is whether a global treatment is possible or whether to follow the detail of individual fibre segments.

For false-twist textured yarns, minimum energy computations of the various forms of alternating helices and pig-tail snarls have been carried out (Yegin 1969). For air-jet textured yarns, the entanglements and loops were modelled (Kollu 1985). These academic studies provide a basis for further work, but more is needed for realistic predictions.

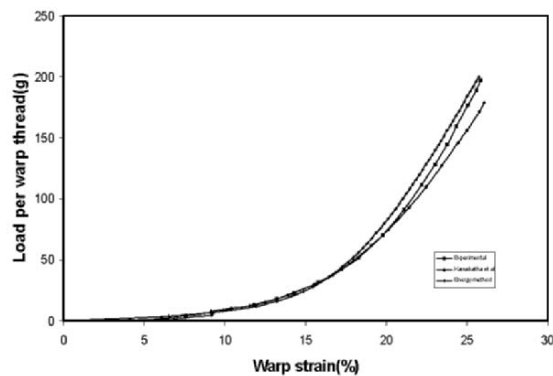
4 Fabric Constitutive Relations

4.1 Woven Fabrics

Almost all the many papers on the mechanics of woven fabrics have used force-and-moment equilibrium, with a saw-tooth model (Kawabata et al. 1973) being the most successful. However, this again seems to be a cul-de-sac, with no outlet to more realistic geometries, large deformations, and nonlinearities. An energy method (Hearle & Shanahan 1978) is the way forward. Through UK DTI-supported technology transfer, this was converted into WINDOWS-based software, *TechText CAD*, in a form for industrial use. Figure 6(a) shows a montage from screens for the input and display of fabric structures, which can be manipulated in various ways. Figure 6(b) shows a comparison of the predicted fabric stress-strain curve with experimental data.



(a)



(b)

Fig. 6. (a) Montage of screens from TechText CAD. (b) Comparison of theoretical predictions with experimental data for cotton fabrics from (Kawabata et al. 1973).

Another program developed by Chen and Porat at UMIST is *Weave Engineer* (TexEng Software Ltd 2005). This covers the basic structure of both hollow and solid 3D weaves, with single layer weaves as a special case, and provides a link to weaving machine settings. These two programs are now being integrated in *TexEng*, which is being developed and marketed by TexEng Software Ltd. Another module provides for easy

interchange between the many parameters used to describe fibre, yarn and fabric parameters, including other features such as costings. The intention is to expand *TexEng* to cover a greater range of applications, including knit structures, composites and flow properties.

Computational representation of structural geometry and energy-minimisation for structural mechanics have been advanced in the *TechniTex Faraday Partnership* core research in the University of Manchester to deal with more difficult aspects of woven fabric mechanics (Jiang & Chen 2005, Hearle et al. 2006). The aim is to determine constitutive relations, for a fabric subject to uniform strain. An important feature is the concept of control points. The biaxial deformation of the repeat unit of a fabric is defined by two axial displacements and one transverse displacement, which link an origin to two other primary control points. Additional primary control points are needed to cover the angular change in shear and the curvature in bending and twisting. Secondary control points within the repeat unit are needed to deal with mechanical deformation. Algorithms show up symmetries, which determine the smallest element of a structure to be included in energy minimisation.

Having defined the geometry, the next step is to minimise the sum of extension, bending and flattening yarn energies. Yarn lengths between control points are computed along bent yarn paths. The initial approximation is by B-spline interpolation, which defines curvatures between secondary control points, as illustrated in Fig. 7(a). Twisting would need to be taken into account when yarns follow 3D paths. Yarn flattening has been neglected in the past. Previous studies used symmetrical, circular, race-track or lenticular geometries. Real fabrics show other asymmetrical shapes. A general form is introduced, in which the shape is defined by the radial lengths at a series of angles round the yarn circumference, Fig. 7(b).

Unless the fabric has been totally relaxed, the initial specification of a fabric will not be the minimum energy state under zero applied forces. The first step is thus to minimise the yarn energies to determine this state.

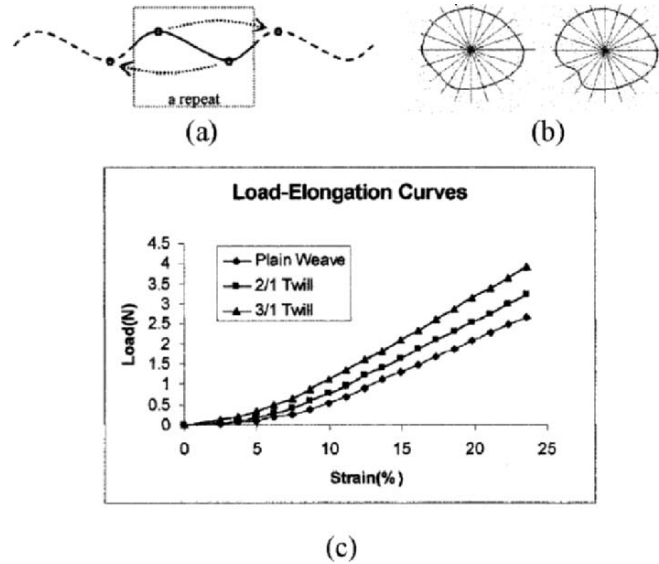


Fig. 7. (a) Curved yarn paths. (b) General specification of yarn shape (Jiang and Chen, 2005). (c) Prediction by Ramgulam of uniaxial load-elongation curve for similar plain, twill 2/1 and twill 3/1 fabrics.

There is a paradox here. The state under zero forces, although attractive as a mathematical origin, is poorly defined. It is easily shifted due to hysteresis or friction. It may be better to define a fabric reference state under small biaxial forces. For the determination of biaxial deformation, the potential energies of applied forces, given by products of force or moment and displacement, must be included. Instead of direct minimisation, it is better to determine the state of internal minimum energy at two closely spaced deformations, and then to equate the energy difference to the work done by the applied force. There are still difficult questions for energy minimisation. Yarn extension energy is known from experiment or yarn modelling. In principle, yarn bending is well understood and bending energy is given by the product of bending moment and curvature. However, the bending stiffness changes from a high to a low value when the fibres start to slip past one another. There will be a different response in free lengths between crossovers and contact regions where there is inter-yarn pressure. Furthermore, in the contact regions, curvature is determined by a combination of bending energy and the less well understood energy associated with change of yarn shape. Flattening energy depends on shear deformations of the cross-section and volume change, and its specification needs new experimental or theoretical methods. Yarn shape may change

from contact to free zones. Progress is being made by simplifying in two ways. The first is to carry out energy minimisation with simplified geometries for yarn paths and yarn shapes, so that the minimisation involves fewer terms. Having obtained an approximate solution, the minimisation can be refined by fitting more points along yarn paths and yarn radii. The second is to solve two extreme cases. For monofilaments and hard twisted yarns, we assume that there is negligible change of yarn shape, except through Poisson's ratio due to length change. The curvature in contact zones is then geometrically defined and only the shape in free zones results from the energy szation. Figure 7(c) shows predictions for similar fabrics in three weaves. Very soft yarns deform until the free zone has disappeared, so that it is only necessary to consider the combined bending and flattening energy in contact zones. Further research will lead to ways of treating the following problems: structures between the two extremes; shear and bending deformations; and non-plain weaves, in which side-by-side flattening as well as crossover flattening will occur.

The development of useable computer programs is not a simple matter. Most real needs for structure/property predictions for technical-textile CAD are complicated in yarn and fabric structures and in material responses. Although, in principle, the methodology would cover these complications, in practice, the demands in computer power and time may be too great even for one-off academic demonstrations and certainly for routine industrial use. Clever developments are needed to provide useable programs. The "tricks" should cover:

- efficient programming;
- identification of generally applicable simplifications of geometry and mechanics;
- identification of special cases with particular simplifications;
- recognition of the degree of accuracy required.

4.2 Other Fabrics

Plain knit fabric was modelled using a powerful bending curve program (Konopasek 1970). However, this approach has the same fundamental problem as for woven fabrics, and analogous energy methods need to be developed. Bonded nonwovens were modelled by energy methods based on the orientation and curvature of a representative set of fibre elements (Hearle & Newton 1967; Hearle & Oszanlav 1982), but agreement with experiment was only achieved by the input of measured values of lateral contraction and empirical rules for bond breakage. For needled fabrics, the

model added in friction and fibre paths round transverse tufts (Hearle & Purdy 1978). Individual fibre computation will be needed for advances in modelling of nonwovens.

5 Fabric Drape

Early modelling of fabric drape showed its dependence on both bending and shear properties (Cusick 1962). It is the low resistance to shear and area change, that gives weaves and knits their conformability. Computational modelling is needed to achieve a goal of the IT Age, the virtual catwalk. The aim is to enable someone buying an article of clothing on-line to view on a screen how they would really look when moving around in the garment. There are three levels of reality in such simulations. In cartoons, unrealistic distortion is preferred. For realistic animation, in which film-makers have achieved great success, it is only necessary that the image should look right to the viewer. The third level, which is our concern, is to relate the fabric forms to the actual fabric properties and applied forces. This is much more difficult and some IT specialists who came optimistically to the problem have retreated. Leaving on one side the dynamic problem, the first step is to model the quasi-static buckling of textile fabrics in complex situations. Most researchers have attempted to solve the total problem by the use of finite-element or similar methods. However, such programs have not tackled the full anisotropy, which involves three in-plane and three out-of-plane modes of deformation, and the nonlinearity of textile fabrics. The models are limited in their validity, and are horrendously expensive in computer power and time.

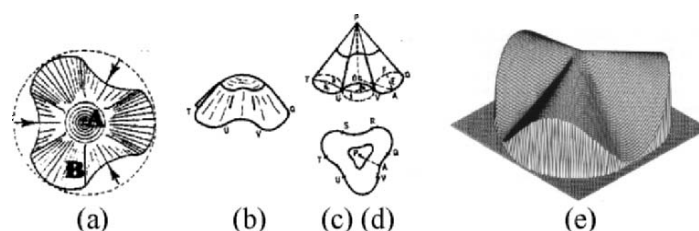


Fig. 8. Threefold buckling. (a) Circle of fabric pushed in from three directions. (b) Upper dome and lower folds. (c) Lower folds modeled as parts of cones. (d) Plan view. (e) Computed prediction of form. From (Amirbayat and Hearle 1986).

A more fundamental approach is needed. Research should elucidate the basics of how fabrics buckle in three dimensions, and find clever ways, which are right for textile fabrics, to build up to the more difficult problems. Threefold buckling of an isotropic, Hookean circular specimen has been modelled by a central dome of double curvature and an outer zone of alternating folds of single curvature as shown in Fig. 8 (Amirbayat & Hearle 1986). The sum of in-plane and out-of-plane strain energies and gravitational energy is minimised, using many simplifications. The approach needs to be improved and extended to remove mathematical infelicities and deal with multiple buckling of real fabrics, but it should show the way forward.

6 Conclusion

At the operational level, the urgent need is for industrial application of the computational techniques developed for fabric structure and mechanics in the last 50 years – to match the advance of CAD for aesthetic design in the last 25 years. It is important that programs should be easy to use and provide the information that is needed in daily operations. Another Manchester development will help this. Many textile problems, notably the way of specifying a woven fabric structure, involve the selection of a small set of independent parameters from a large number of possible parameters that may be used. In order to avoid the need for separate programs for each independent set, *QAS* was programmed to run round a network of equations (Konopasek & Hearle 1972). This later led to the commercial program *TK Solver*. A version of this network facility is included in *TexEng* (TexEng Software Ltd 2005).

At the academic level, the need is for research on treating the more difficult problems in clever ways, which are well adapted to the special features of fibre assemblies. Here the advance in computer power will help. In the 20th Century, we were constrained to treat problems in terms of small repetitive structural units or by statistical distributions of representative elements. In the 21st Century, there is the power to model the behaviour of large numbers of individual fibres or fibre elements. An example is the pioneering study of the compression of a random fibre assembly (Beil & Roberts 2002). Other examples are carpet wear (Hearle et al. 2005) and fabric pilling (Hearle & Wilkins 2006).

Acknowledgments

I acknowledge the contributions of many colleagues and students, in particular the recent input of Xiaogang Chen, Prasad Potluri, Raj Ramgulum and Yong Jiang of the Textiles and Paper group of the School of Materials, University of Manchester.

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Part I

Textile Quality Assessment from Image Analysis

Objective Assessment of Pilling of Knitted and Nonwoven Fabrics Using the Two Dimensional Discrete Wavelet Transform

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1 Introduction

Pilling is the formation of small tangles of fibers or balls on the surface of a fabric during washing, testing or in wear. The ‘pills’ on a fabric surface make the fabric very unsightly and such fabrics are rejected by discerning consumers. Fabric pilling is a serious problem for the apparel industry, causing an unsightly appearance and premature wear (Ramgulam et al. 1993). Resistance to pilling is normally tested by simulated accelerated wear, followed by a manual assessment of the degree of pilling based on a visual comparison of the sample to a set of test images (Abril et al. 1998). To bring more objectivity into the pilling rating process, a number of automated systems based on image analysis have been developed (Xu 1997, Abril et al. 1998, Sirikasemleert & Tao 2000). Existing methods either employ expensive and complicated equipment (Ramgulam et al. 1993, Sirikasemleert & Tao 2000) and/or employ complex image processing algorithms that involve multiple stages (Xu 1997, Abril et al. 1998).

A number of sources in the literature note the use of frequency domain image processing (Xu 1996, Campbell et al. 1997, Abril et al. 1998). These sources describe variations in the use of the two-dimensional discrete Fourier transform (2DDFT) to separate periodic structures in the image (the fabric weave/knit pattern) from non-periodic structures in the image (the pills). The 2DDFT can only provide gross summary spatial frequency in-

formation about the entire image, it cannot provide location information. Fabric defects such as pills are localized in nature and cannot easily be identified directly by the Fourier transform (Chan & Pang 2000). For this reason, many of the existing techniques described in the literature employ a complex mixture of spatial domain and frequency domain processing stages to characterize image elements in both location and frequency.

The authors have proposed a new method of frequency domain image analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in sample images. Detailed mathematical treatments of the wavelet transform are available elsewhere (Mallat 1998), but, in principle, the one-dimensional continuous wavelet transform (1DCWT) involves the comparison of a small waveform (wavelet – a time-limited waveform with special mathematical properties) with a section of the data under test. The process produces a coefficient that represents the ‘match’ between the data and the wavelet. The wavelet is translated by a small distance, and the comparison is repeated, in this way, the 1DCWT provides characteristic information about the data that is localized in position. Then, the wavelet is dilated (scaled up) and the process is repeated over a range of scales. Each different scale produces characteristic information about the image localized in scale (which can be related to frequency).

Rather than calculating the 1DCWT at every possible scale and position, if we choose scales and positions based on powers of two, (and satisfy some additional mathematical criteria) we have the orthogonal form of the discrete wavelet transform (DWT). At each analysis scale the DWT yields ‘approximation’ coefficients that represent low frequency (high scale) components of the data/signal, as well as ‘detail’ coefficients that represent high frequency components of the signal. The approximation forms the input to the analysis for the next successive scale decomposition, and the detail is a measure of the match between the signal and the wavelet at the current analysis scale. The multi-scale decomposition of the source data by iterative DWT analysis is known as ‘multiresolution analysis’. The DWT can be extended into two dimensions for image analysis. Here the analysis at each scale yields an approximation of the original image and three sets of details that represent the horizontal, vertical and diagonal details in the original image. This is the 2DDWT.

At each analysis scale, there will be a distribution of detail coefficients (distribution of cD_n^o ; where n is the analysis scale and o is the orientation – horizontal, vertical or diagonal); if the distribution is narrow, then the wavelet matches well with the image data in the current direction at the current scale; if the distribution is wide, then the wavelet matches less well

with the image data. The authors propose that for 2DDWT analysis of unpilled woven fabric images, where the wavelet scale is close to the fabric inter-yarn pitch, the distribution of cD_n^o will have a relatively small standard deviation ($SDcD_n^o$), and, as the amount of pilling increases, $SDcD_n^o$ will increase as the pills introduce variations into the image that disrupt the underlying pattern of the fabric structure. It is further proposed that it is possible to apply this image analysis method to a set of reference fabric pilling samples to develop a calibrated characteristic curve that relates pilling intensity to $SDcD_n^o$ obtained by analysis of a fabric test sample. In this way it is possible to perform an evaluation of pilling intensity that is analogous to the visual comparison method, but, once calibrated for a given fabric type and test environment, will yield an objective measure without human interpretation. Compared to previous image analysis techniques described in the literature, the proposed method has the advantage that it requires only a single-stage of analysis to produce a quantitative measure of pilling intensity.

2 Objective Assessment of Pilling of Knitted Fabrics

To evaluate the proposed method of pilling analysis a series of standard pilling evaluation test images were subjected to 2DDWT analysis and the standard deviation of the horizontal detail coefficients ($SDcD_n^h$) at the first five scales of analysis were recorded. The standard pilling test series used was the 1840 double jersey series from James H. Heal & Company Limited. This series contains five images – the supplier rated pilling intensities are 5 (un-pilled) to 1 (heavy pilling). Figure 1 shows the pilling intensity 1, 3 and 5 images.

There exist a large number of possible wavelets with varying mathematical properties that make them suited to particular analysis applications (Hubbard 1996). There are no clear rules for selecting the ‘best’ wavelet for a particular analysis application (Hubbard 1996, Percival & Walden 2000). Shape similarity between the wavelet function and the features in the data to be analyzed is one of the selection criteria noted in the literature (Farge 1992). The simplest wavelet is the Haar wavelet (Aboufadel & Schlicker 1999), which has the general appearance of a square wave, and it is suggested as an analysis basis for data with ‘jump’ or ‘step’ features

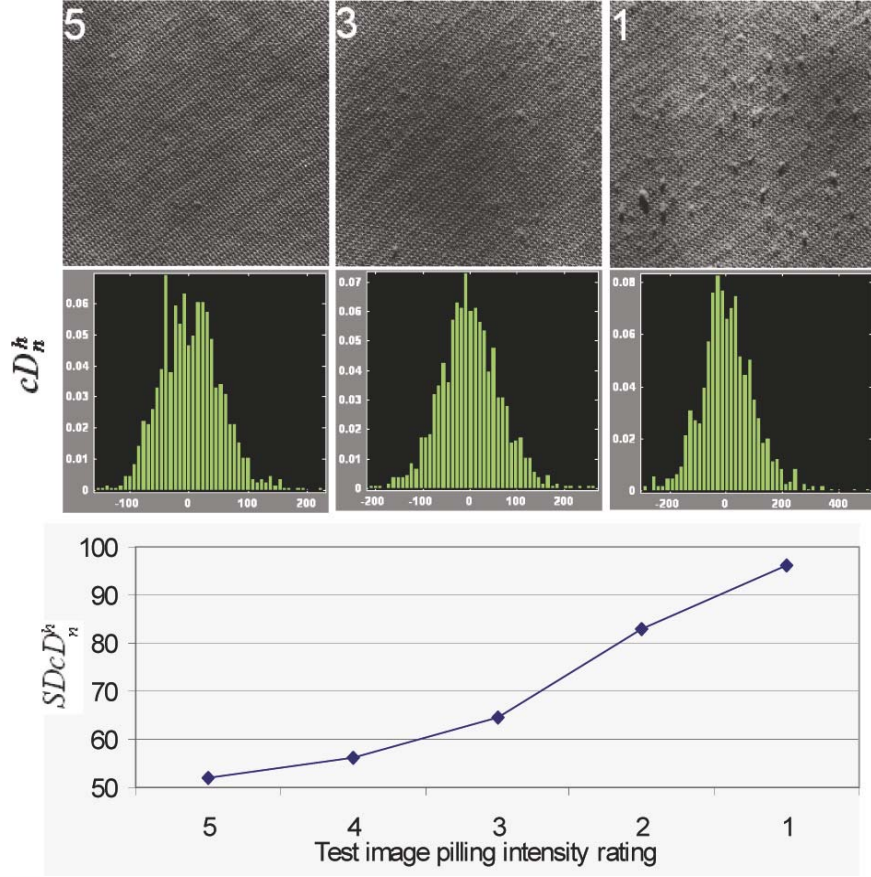


Fig. 1. James H. Heal ‘1840 double jersey’ fabric test images (top), distribution of 2DDWT detail coefficients (centre), and standard deviation of wavelet detail coefficients (bottom)

(Torrence & Compo 1998), as would be expected to be found in the image data from the repeating pattern of a fabric. Analysis using the Haar wavelet is also computationally simpler than many other wavelets (Percival & Walden 2000). On these bases, the Haar wavelet was chosen for the initial analysis trials.

The wavelet analysis was performed using the Matlab Wavelet Toolbox (The MathWorks Inc. 2004). Initial trials examined the horizontal detail coefficients (cD_n^h), as the image properties in the horizontal direction are representative of the entire image. For the 1840 double jersey series the horizontal fabric structure pattern was found to repeat approximately every 8 pixels. It was found that scale 3, scale 4 and scale 5 analyses produced a

monotonic, but non-linear increase in $SDcD_n^h$ with increasing pilling intensity. Figure 1 shows: a) three of the five standard pilling evaluation test images from the James H. Heal & Company Limited '1840 double jersey' set, including the supplier rated intensity of pilling (5 = unpilled, 3 = moderately pilled, 1 = heavily pilled); b) the distribution of the 2DDWT horizontal detail coefficients at four levels of analysis using the Haar wavelet; and c) the plot of test image pilling intensity versus the standard deviation of the distribution of the 2DDWT level four detail coefficients.

At each scale of wavelet analysis, the new approximation of the original image is developed by performing the analysis on the current approximation of the image and then decimating the computed wavelet coefficients in both dimensions by half, reducing the linear dimensions of the image by half and the image area by three quarters for each analysis level. Hence, the 'resolution' of the analysis (related to the original image dimensions) at 'analysis scale n ' is 2^{n-1} pixels. At low analysis scales the analysis resolution is small (at scale 1 the resolution is 1 pixel; at scale 3 the resolution is 4 pixels), and for the test samples used here, this is a fraction of the repeating horizontal fabric structure pattern in the image, and likely to produce irregular results. As the analysis scale approaches the fabric inter-yarn pitch, it is expected that the wavelet analysis should be able to best discriminate between an un-pilled image of the fabric and a pilled image. The results for the test image series presented here suggest that analysis scales related to integer multiples of the fabric inter-yarn pitch yield the best discrimination between pilling levels. Subsequent work by the authors investigating the relationship between inter-yarn pitch and analysis scale has confirmed this (Palmer et al. 2005).

The authors have developed a heuristic method for selecting the optimal wavelet analysis parameters (Palmer & Wang 2003), and established that the method is robust to translation of the sample under test (see Fig. 2) and to variations in the illumination of the sample under test (see Fig. 3) (Palmer & Wang 2004). The application of wavelet analysis to the automated detection of woven fabric flaws is an emerging field (Sari-Sarraf & Goddard 1999, Hu & Tsai 2000, Latif-Amet et al. 2001, Wen et al. 2001, Li & Huang 2002), however, the application of wavelet analysis to the problem of objective rating of pilling intensity is new. The underlying technique, wavelet analysis, offers novel approaches for tackling the objective assessment of pilling using image analysis for nonwovens as well.

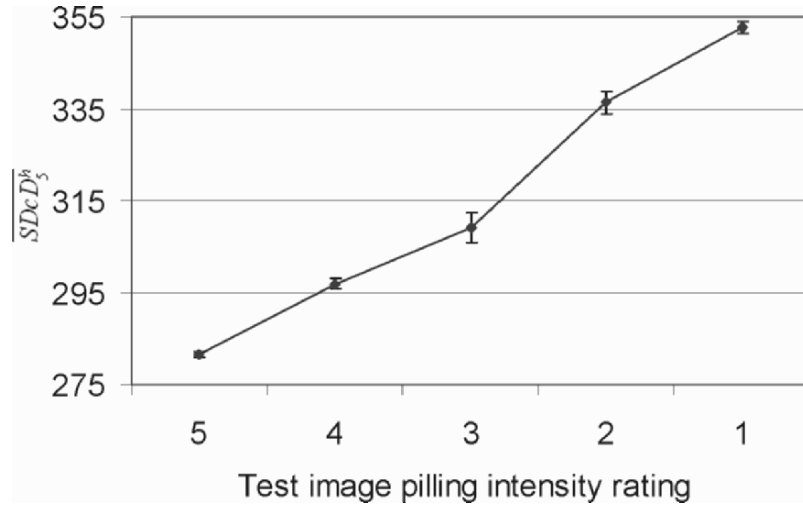


Fig. 2. Mean of standard deviation of wavelet detail coefficients and 90 % confidence intervals for image translations based on 1840 test images

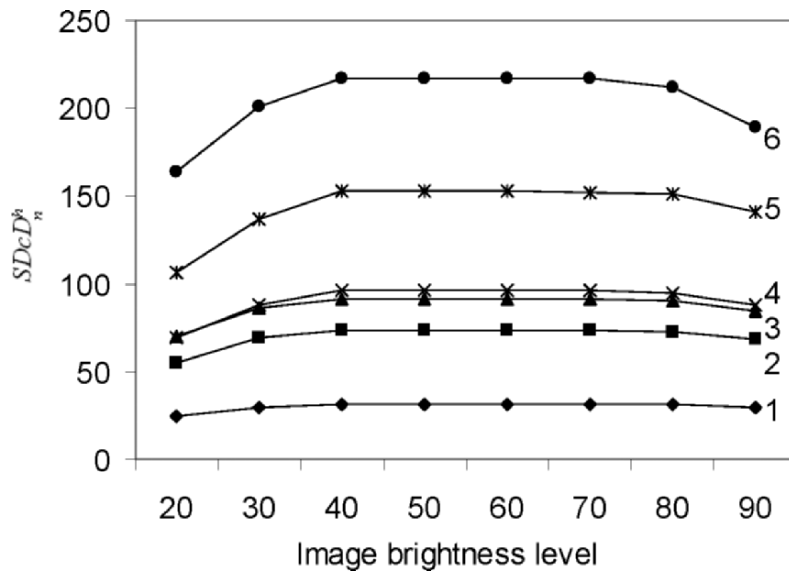


Fig. 3. Standard deviation of wavelet detail coefficients at first six analysis levels for variation in image brightness of 1840 test image pilling intensity level 1

3 Objective Assessment of Pilling of Nonwoven Fabrics

Pilling has been a serious problem for the apparel industry, which has traditionally been dominated by knitted and woven fabrics. The rapid development of nonwoven apparels in recent years has added a new dimension to the perennial problem of fabric pilling, and only limited fundamental research has been carried out on the pilling of nonwoven fibrous materials. A nonwoven fabric is a consolidated thin web of fibers. The nonwoven process is a relatively simple fiber-to-fabric process, compared to the lengthy and expensive fiber-yarn-fabric process used for producing traditional woven and knitted fabrics. Nonwoven materials differ from woven and knitted materials in structure and performance, and, they have many important applications, including hygiene absorbents, medical textiles, filters, geotextiles, natural fiber products, composite materials, automotive textiles, building materials, cushioning, carpet and insulation. These applications are predominately technical textiles manufactured from synthetic fibers (David Rigby Associates 2003).

Australia produces the best quality wool: merino wool. In 2004, Australian wool accounted for 51% of the total used in global wool apparel. In 2004/2005, wool exports were valued at \$A2.5 billion, accounting for 8.3% of Australia's total agricultural exports (Australian Wool Innovation Limited 2005). However, conventional wool fabrics have a relatively high tendency to pill, which has contributed to the declining share of wool in the world fiber market (Australian Wool Innovation Limited 2003a). Recently, a process for the production of woollen nonwoven apparel fabrics has been commercialized in Australia. The nonwoven process is 30 percent cheaper and 30 times faster than traditional wool fabrics by eliminating the conventional spinning and weaving (or knitting) stages (Australian Wool Innovation Limited 2003b). The entry of wool into nonwoven applications will create new markets for Australian wool. However, the success of such nonwoven apparels will, to a certain extent, depend upon their pilling propensity. To date, virtually no research has been published on the mechanism, measurement, prediction and control of pilling in nonwoven wool or wool blend fabrics, and this issue will be crucial in the success of wool in many nonwoven applications.

The development of practical and commercial nonwoven woollen textiles is a significant innovation, creating "fabrics with unique properties that cannot be achieved by traditional knitting or weaving, opening up a whole new range of market opportunities for Merino wool" (Wool Research Organisation of New Zealand 2003). The ultimate market for Australian nonwoven woollen products is international, and the commercial export of

these products is a key strategy in their development (Dockery 2003). For the potential of nonwoven woolen fabrics, and apparels in particular, to be realized, the perennial problem of pilling will need to be overcome (The Woolmark Company 2000). Australian Wool Innovation (AWI) has identified that removal of pilling is a key message from consumers, retailers and designers (Australian Wool Innovation Limited 2002). Reduction of pilling is also listed as its top priority (Australian Wool Innovation Limited 2003a).

Resistance to pilling is normally tested by simulated accelerated wear, followed by a manual assessment of the degree of pilling based on a visual comparison of the sample to a set of test images. There exists one set of international standard test images based on nonwoven wool fabric, the Woolmark 'SM50 Blanket' set. This image set provides four representative samples for each of five levels of pilling intensity. Figure 4 shows one of the representative samples for three of the five standard pilling evaluation test images from the Woolmark 'SM50 Blanket' set, including the supplier rated intensity of pilling (5 = un-pilled, 3 = moderately pilled, 1 = heavily pilled). This test image set was used as the basis for developing a wavelet-based image analysis technique for objectively assessing pilling intensity for nonwoven wool fabrics.

The two-dimensional discrete wavelet transform process produces two complimentary analysis components – detail coefficients and approximation coefficients. The detail coefficients represent the high spatial frequency components of the image, and are the basis used previously to characterize the impact of pilling on the periodic structure present in knitted and woven fabrics. For nonwoven fabrics, the authors propose that the random/apperiodic structure of the fabric can be characterized by the wavelet approximation coefficients, which represent the low spatial frequency components of the image. The authors propose that there will be a wavelet analysis scale that will distinguish between the underlying random nonwoven structure and the presence of larger pill structures on the fabric sample, and, that the distribution of wavelet approximation coefficients at that analysis scale will provide a quantitative measure of pilling intensity. This proposition was verified experimentally.

As indicated earlier, the Woolmark 'SM50 Blanket' set of standard pilling images presents four examples of each of the five levels of pilling intensity. These 20 images were scanned at 600 dots per inch and cropped of edge markings. While the authors' previous work with image analysis of knitted fabrics based on wavelet detail coefficients has been shown to be robust to variations in image brightness, there are many image processing applications that are sensitive to image brightness variations (Ghassemieh et al. 2002).

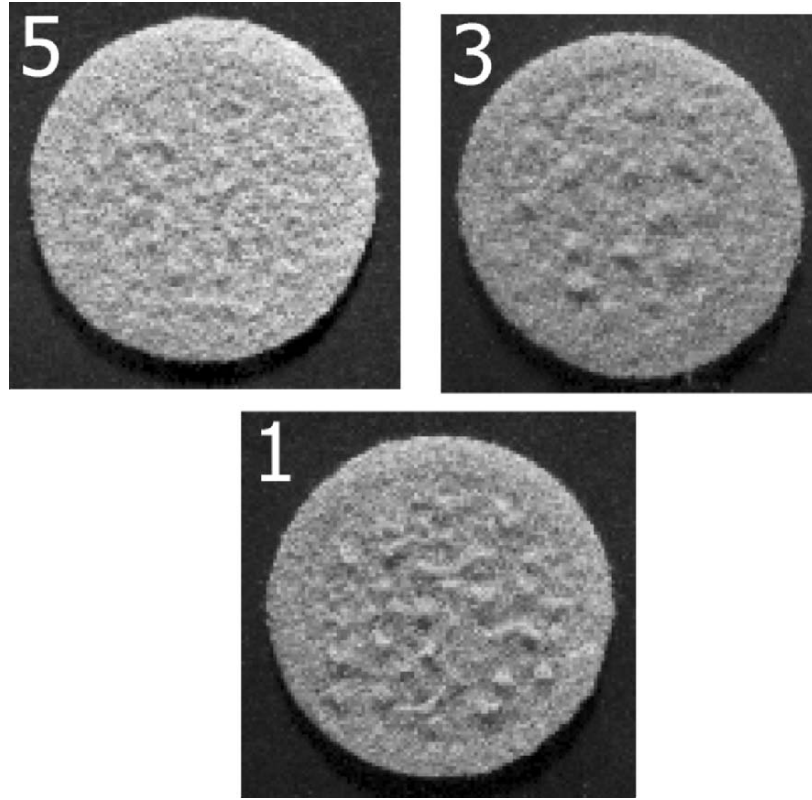


Fig. 4. Representative samples of The Woolmark Corporation ‘SM50 Blanket’ fabric pilling test images with supplier rated pilling intensity

Here, we propose to use the wavelet approximation coefficients as the basis for analysis, however, as the approximation coefficients represent low frequency information in the image, they will be sensitive to variations in image brightness (Mandal et al. 1999). Image pixel value histogram equalization is a useful method for putting images in a consistent format prior to comparison (Castleman 1996), and is reported in wavelet (Mojsilovic et al. 1997) and other (Srisuk et al. 2001) image analysis applications as a technique for dealing with variations in image brightness. The 20 images were pixel value histogram equalized.

For each of these 20 standard images, four additional images were synthesized by cropping one edge of the standard image by approximately 15 percent; producing 100 images in total; 20 for each pilling intensity. For each of the 100 images, the standard deviation of the distribution of the approximation coefficients ($SDcA_n$) at various analysis scales, based on

analysis using the Haar wavelet, was computed using the Matlab Wavelet Toolbox (The MathWorks Inc. 2004). Using the mean value of $SDcA_n$ obtained for the 20 test images at each level of pilling intensity, it was found that 2DDWT analysis at scale five produced a monotonic relationship between pilling intensity and $SDcA_5$. Figure 5 presents the mean value and 90 percent confidence intervals for $SDcA_5$ (standard deviation of the distribution of wavelet approximation coefficients for level 5 analysis) for each pilling intensity. It is proposed that it is possible to apply this image analysis method to a set of reference fabric pilling samples to develop a calibrated characteristic curve that relates pilling intensity to $SDcA_n$ obtained by analysis of a fabric test sample. In this way it is possible to perform an evaluation of pilling intensity that is analogous to the visual comparison method but, once calibrated for a given nonwoven fabric type and test environment, will yield an objective measure without human interpretation.

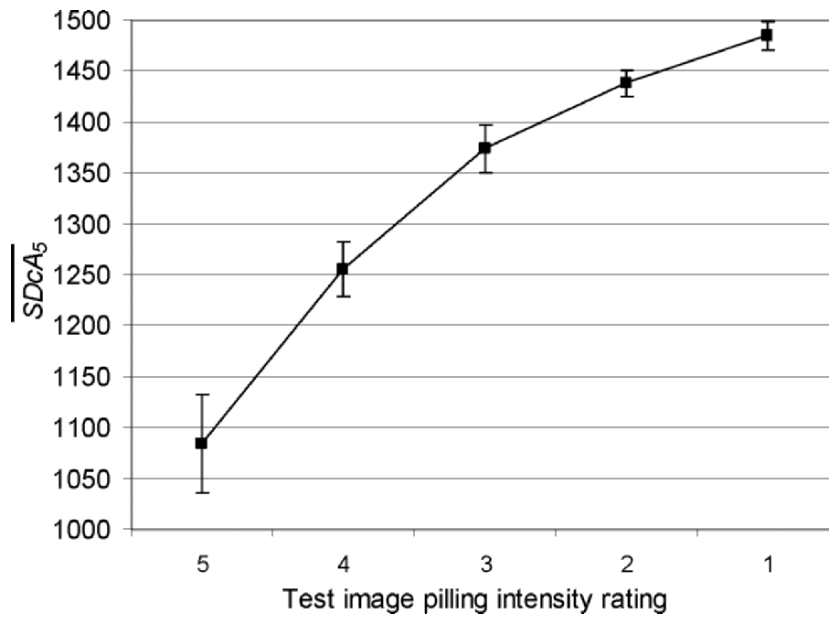


Fig. 5. Mean of standard deviation of level 5 wavelet approximation coefficients and 90 % confidence intervals for image translations based on SM50 Blanket images

4 Sample Image Preparation

For many image processing applications, sample image preparation is a crucial aspect for success. Factors such as illumination and scanning resolution can have a large impact on the results obtained. The two cases presented here were based on analyzing standard photographic test images, so, many of the imaging parameters were fixed. The photographic images were scanned at 600 dots per inch. The use of a flatbed scanner provided fixed illumination and position for the test images. Mounting samples on a flat, recessed sample holder (to avoid compressing pills and other fabric texture features) and using a high-quality flatbed scanner provides the same consistency of imaging conditions for real fabric samples. In most cases, a scanning resolution of 600 dpi is likely to be more than adequate. In the two cases presented here, the linear dimensions of the scanned images were reduced by a factor of four prior to analysis without impacting on the results. As long as the feature(s) of interest (inter-yarn pitch, pill size, etc.) do not become degraded in the process, image size reduction reduces the analysis time required by the square of the image linear dimension reduction factor.

As noted previously, the wavelet analysis process for knitted fabrics, based on wavelet detail coefficients, is inherently robust to a wide variation in sample illumination. It was also found to be robust to horizontal and vertical translations of the sample. As expected, it was sensitive to sample rotation and dilation. The sample holder/flatbed scanner setup reduces the influences of these two factors. For a nonwoven fabric with randomly oriented fibers, the wavelet analysis process based on wavelet approximation coefficients should be robust to sample rotation and translation. However, as the wavelet approximation coefficients represent the low frequency information in the image, analysis results will be sensitive to variations in sample illumination. Pixel value histogram equalization was employed to combat this problem for the sample images used here. Sample dilation will cause the apparent size of image features to vary, but, except for extreme dilation, the main impact should be to change the wavelet analysis scale that distinguishes between the fabric random structure and the presence of pills. The use of a sample holder/flatbed scanner setup will help to standardize sample illumination and provide constant apparent image dilation.

5 Conclusions

Fabric pilling is a serious problem for the apparel industry, and, the traditional process of subjective visual assessment of pilling intensity is prone to repeatability problems. Many systems of objective assessment of pilling intensity based on computer image analysis have been proposed. The periodic structure of woven and knitted fabrics makes them suitable candidates for frequency domain image analysis. The authors propose a new method of frequency domain analysis based on the two-dimensional discrete wavelet transform (2DDWT) to objectively measure the pilling intensity in knitted sample images. A similar approach should also apply to woven structures.

The rapid development of nonwoven apparels in recent years has added a new dimension to the perennial problem of fabric pilling. The aperiodic structure of nonwoven fabrics limits traditional frequency domain analysis approaches. However, the scale-based approach inherent in wavelet analysis offers approaches for the objective measurement of pilling intensity in nonwoven sample images that are analogous to those proposed for knitted fabrics.

The two wavelet-based analysis methods described here employ different, but complementary, aspects of the discrete wavelet transform - the detail coefficients for knitted fabrics, and, the approximation coefficients for nonwoven fabrics. Current research is leading toward a more sophisticated analysis that combines wavelet data from multiple scales and orientations (possibly with other image data), such as wavelet texture analysis. This approach has been reported in metal surface finish applications (Bharati & MacGregor 2004) and textile seam pucker applications (Miou Chraïbi et al. 2005). Preliminary work by the authors indicates that this approach may provide a unified analysis approach for both woven and nonwoven fabrics.

Acknowledgements

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Selecting Relevant Features from Fabric Images for Automated Quality Control of Seam Pucker Using Data Analysis and Human Experts Grading

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Abstract

Quality control of products is an important element required in textile industry. Nowadays, a great number of quality features are judged by human experts. Their scores, which represent a relative numerical score or a granular linguistic expression given by an expert for evaluating the sample on a particular aspect, are expressed using a common scale by a classification procedure. The scale includes several modalities which correspond to a template. By comparison, the appraiser chooses the most suitable modality that is the closest to the sample to be assessed. This procedure is based on normative references which take into account different parameters such as conditioning, lighting, and so on. In this chapter, we try to give a better understanding of the objective features which are involved in the experts' judgment of seam pucker. In the case of seam pucker, there are two categories: samples with simple needle seams and samples with double needle seams. Here we try to define a new objective evaluation method of seam pucker in textile samples compared to five references used by experts. This method is based on 3D image analysis. First, we explain the 3D digitizing system used to create 3D models of samples. After converting 3D models into 2D images and normalizing them, we extract feature vectors from test samples and standards of seams. The feature extraction is based on multi-scale wavelets analysis, spectral analysis, texture analysis and fractal analysis. Next, we decrease slightly the number of features by using the Principal Component Analysis. Finally, we select relevant feature vectors based on the criterion of sensitivity and conformity to expert knowledge on classification of seam specimens.

Keywords

Seam Pucker, Image Processing, Principal Component Analysis (PCA), Multi-Scale Analysis, Fractal, Wavelet, Classification

L. Koehl et al.: *Selecting Relevant Features from Fabric Images for Automated Quality Control of Seam Pucker Using Data Analysis and Human Experts Grading*, Studies in Computational Intelligence (SCI) **55**, 39–54 (2007)
www.springerlink.com

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1 Introduction

The quality control of textile products is an important research area in which many researchers have been involved for many years not only for designing international norms but also for testing in an accurate and objective way textiles quality. Since the quality evaluation is performed by human experts, the results can be slightly or quite significantly different from panelist to another. The sensitivity of each individual for the samples to be evaluated is strongly related to his personal experience and the corresponding experimental conditions. This research work aims at developing reliable methods for automated textile quality control of some aspects related to appearance, including pilling (Xin 2002) and seam puckering (Bahlmann 1999, Kang 2000). The quality control of these aspects accomplished by human experts is time consuming and quite fuzzy due to human subjectivity. In this paper, we focus on seam puckering in which human experts use normative references to evaluate quality of textile products. This evaluation consists of assigning scores to the test specimens by comparing them to normative standards, which may be either photographic (2D) or three dimensional plastic templates (see Fig. 1).

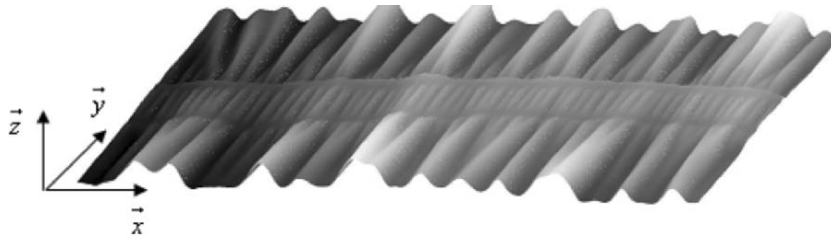


Fig. 1. 3D-picture of double needle seam plastic replica - grade 1 (the worst)

In this contribution, we present a system for judging seam quality from 3D objects. The process of automated evaluation of specimen rating is described below (see Fig. 2). First, we use a 3D digitizing system, which consists of a light projector, a CCD camera sensor and software permitting to merge different views of the object to be digitalized. The missing points in the 3D-image are replaced using a linear interpolation. Then, we convert our 3D models into 2D grey value images and normalize them so as to assign a grey value to the same depth value in the z-direction. The third step is to extract feature vectors from grey value images. The last step is to use classifiers for scoring each test specimen (see Fig. 2).

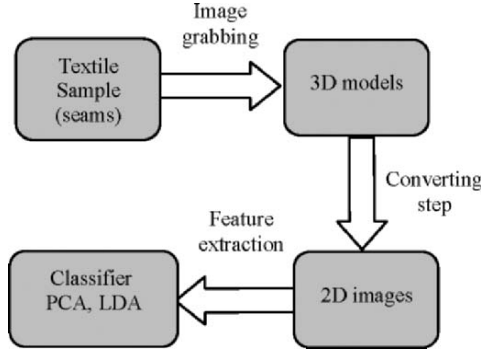


Fig. 2. Different steps of the classification system

2 Digitizing System OPTOCAT®

In our project, we use the system named OPTOCAT® to obtain images of the seam specimens. This system permits to perform several pre-processing steps on images of samples before the procedure of feature extraction. These steps include digitalizing, plane fitting and holes filling (for missing points). Some technical details on this system are illustrated below.

2.1 Structured Light Projection and Photogrammetry

Structured light consists of projecting light through a network of lines so as to create patterns on the object and to digitize it by a CCD camera (see Fig. 3), except the fact that acquisition of object is made through another set of patterns different from the first one, which produces the Moiré effect (CRE, 92). It allows us to obtain information about the depth information in the z-direction. Since camera settings are known, we can calculate distance between point to be digitized and sensor. The acquisition rate is about 105 points per second, with accuracy from 10^{-2} to 10^{-1} mm.

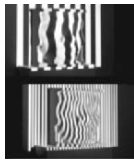


Fig. 3. Pattern projection of structured light

The sensor consists of a projector with a 128 sinus pattern, a halogen illumination and a high resolution camera. The control unit is connected with the host computer by image processing board. The resolution of digitization is 1300x1024 pixels in the x-y plan. To digitize an object, it is necessary to take measurements from different viewing directions and to combine them into a unique oriented 3D-picture. Projector and camera can be fixed together in different configurations, depending on the volume of the object to digitize. Resolution is a decreasing function of object volume. Since we are interested in the metrology aspect of seam pucker, we digitized all standard replicas using the same settings: resolution step in z (20 μm), digitizing step in x and y (0.15 mm) and the sample volume ($16 \times 12.5 \times 10 \text{ cm}^3$).

2.2 Aligning Views, Merging and Filling Holes of 3D Models of Seam Pucker

After we have digitized all 3D seam pucker replicas, we perform an operation of alignment for each of them. It consists of placing different views of one object in the same coordinate system. For doing this, we use a 3D modeling software. In this step, we align all 3D models in the same coordinate system.

2.3 Filling Holes

Having finished the step of alignment and merge of different views of standards replicas, we perform a hole filling procedure in the created 3D polygonal model, because there are some missing points or areas of the surface of the object that were not digitized. This step consists of an automatic algorithm that detects small holes and fills them by triangulating their surrounding vertices.

2.4 Seam Puckers

In textile industry, quality evaluation on appearance is a task generally done by human experts. They use a common standard procedure for visually examining surfaces of seam specimens ISO 105-A03. This procedure considers five different grades of quality, from grade 5 (best) to grade 1 (worst). The experts score seam quality by comparing seam specimens with these five references. For each test specimen, its evaluation result is the grade of the standard reference which is the closest (see Fig. 4).

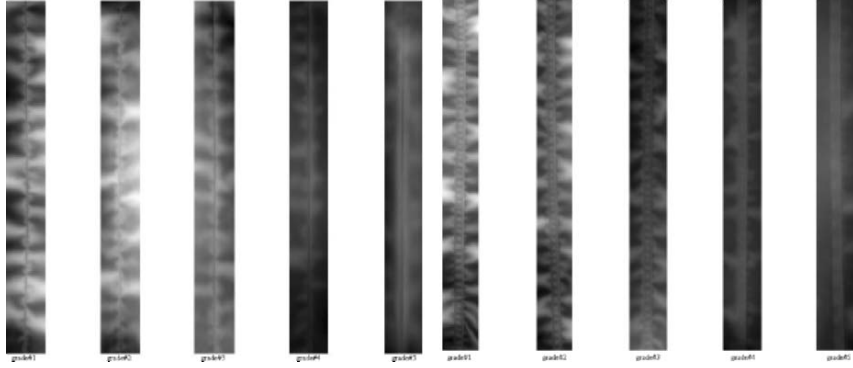


Fig. 4. left: 2D images of standard specimens of simple needle seams. Right: double needle seams

2D images are the result of converting 3D objects of seams. We perform a plane-fitting step and then convert the depth into a grey level scale. Figure 4 shows top views of different grades. The brightest pixels correspond to the highest peaks. Those 3D objects themselves result from the digitization of JIS-3D standards, since they contain relevant information about depth z , and allow the discrimination of different grades.

Sometimes, it often occurs that some points are not digitized: shadow, light saturation. For solving this problem, we interpolate 2D images so as to fill holes. In general, we use a cubic interpolation, leading to efficient results.

After that, in order to have the same grey value for the same depth altitude, whatever is the specimen, we have to normalize test specimens by comparing them with standards.

Given five 3D objects of standard replicas, for each specimen we have depth interval $[z_{\min}, z_{\max}]$. Since the depth interval differs from one sample to another one, we assume that the minimal depth of all the templates will be zero. And then, we resize the depth interval in order to cover all the grey values scale (see Fig. 5). For each test specimen, we repeat the same procedure by comparing it with standard references. It allows us to extract image features for all the samples using the same settings. It appears that for the best grade, the image is almost black which it is not surprising since the standard is very smooth.

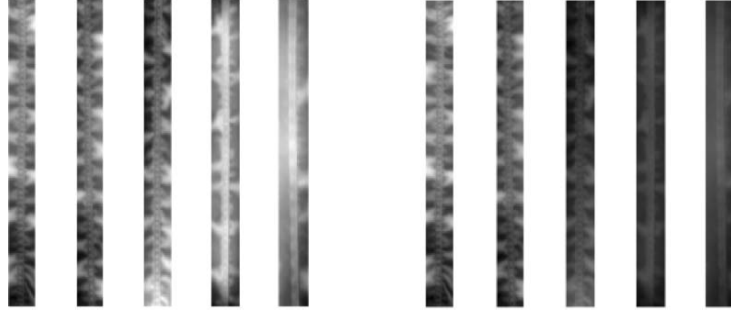


Fig. 5. Left: double needle seam references before normalisation, right: after normalisation

2.5 Extraction of Features Vector

Different parameters are extracted from the images of seam specimens using the following methods below. Since seam pucker deals with peaks and valleys, all image features are related to altitude, texture and roughness degrees at multi-scale.

2.5.1 Parameters related to altitude

Common estimators of image peaks analysis are related to the parameters of altitude and especially those related to the roughness. All the roughness parameters are standardized in the standard ISO 4287 and are defined compared to an average plan obtained by the plan of least squares of measured surface. For an image size of $N \times M$ pixels in the x-y plan, the different roughness degrees are the following:

$$\begin{aligned}
 R_a &= \frac{1}{N \times M} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} |z(i, j)| \\
 R_q &= \sqrt{\frac{1}{N \times M} \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} z^2(i, j)}
 \end{aligned} \tag{1}$$

$z(i, j)$ denotes the distance between the pixel depth and the average plan. These measures are strongly spatial resolution dependant.

2.5.2 Parameters of 2nd order

Texture analysis is an important and useful tool in artificial vision. Most of natural surfaces exhibit texture. It is related to the concepts of first and second order spatial statistics (Linka 2002). First order statistics measures the likelihood of observing a grey value at a randomly chosen location of the image (e.g. histogram). The second order statistics are defined as the likelihood of observing a pair of grey values occurring at the endpoints of a dipole of random length, placed at a random location and a random orientation. The use of grey-level co-occurrence matrices have become one of the most well-known and widely used texture features. In our study, we are interested in the second order statistics. For this purpose, we need to calculate the co-occurrence matrix. Each component $p(i, j)$ of this matrix represents the co-occurrence probability to displace from the grey value i to the grey value j , for a given length and a given angle of displacement. There is no well established method for selecting the most appropriate displacement length or angle. This means that a feature selection method must be used to select the most relevant feature. For seam specimens, we choose 5 displacement lengths: 1, 10, 30, 50 and 100 pixels. For the angle, we choose 0° , 45° and 90° . These values do represent the correct resolution and observation angle, since the seam orientation is about 0° and 90° and the distance between two seam peaks is nearly 50 pixels. The corresponding measured parameters are Energy or 2nd order angular moment:

$$\begin{aligned}
 \text{Energy} &= \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} p(i, j)^2 \\
 \text{Contrast} &= \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (i - j)^2 p(i, j) \\
 \text{Homogeneity} &= \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} \frac{1}{1 + (i - j)} p(i, j) \\
 \text{Entropy} &= - \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} p(i, j) \cdot \log(p(i, j)) \\
 \text{Correlation} &= \frac{\sum_{i=0}^{N-1} \sum_{j=0}^{M-1} i \times j \times p(i, j) - \mu_x \mu_y}{\sigma_x \sigma_y}
 \end{aligned} \tag{2}$$

The image boundaries have to be handled with care. Here μ_x and μ_y are the means and σ_x and σ_y are the standard deviation of $p(x)$ and $p(y)$, respectively, where $p(x) = \sum_{j=0}^{M-1} p(x, j)$ and $p(y) = \sum_{i=0}^{N-1} p(i, y)$.

All those image features are used in texture classification tasks. They all deal with the image contrast for determining the uniformity of spatial distribution.

2.5.3 Multi-scale analysis: fractal dimension and wavelets

The study of fractal geometry leads us to a better comprehension of complex systems in the nature which show fractal characteristics. These characteristics are the phenomena of auto-similarity or auto-affinity. Since the publication of Mandelbrot's book (Mandelbrot 1983) on fractal geometry, this concept has been widely used to characterize the behaviour of chaotic systems (Parker 1989), to define models of natural objects (Mandelbrot 1983). It has also been applied to the general area of image analysis as means for compressing images (Barnsley 1988), as a vehicle for segmenting images (Pentland 1984) and also for classifying seam pucker (Kang 2000). Fractal geometry is the most popular parameter for explaining and describing natural textures. A great number of estimators, such as the box counting method have been proposed (Chen 1993). According to the experimental results reported in the literature, the accuracy of these estimators is significantly affected by resolution, quantization effects or/and trend of surface. In this paper, the fractal dimension is based on the box counting method.

The wavelets offer a mathematical approach of hierarchical decomposition of functions. Applying some transformations in a function allow us to determine relevant information contained at different scales. The basic idea of wavelet analysis is to describe a function by series of approximation functions and detail functions (Mallat 1989).

The approximation and detail functions can be calculated by projecting the signal on the appropriate space. In practical, approximation and detail coefficients at one scale level j are calculated from those at its previous scale level $j-1$.

We apply wavelets to the decomposition of 2D images of seam pucker specimens and standard references. The choice of the wavelets is conditioned by the nature of the relevant information to be extracted. When observing images of seam puckers, we can find waviness appearance of specimens. In this study, we carry out multi-scale analysis using 5 kinds of

wavelets: Haar wavelet, Daubechies wavelet of order 2 (db2), bi-orthogonal wavelet of order 2.4 (bior2.4), Coiflets wavelet of order 3 (coif3) and discrete Meyer wavelet (dmey) (see Fig. 6)

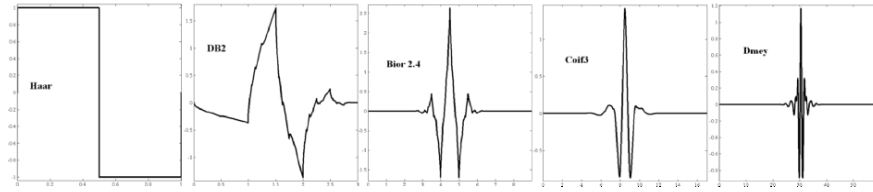


Fig. 6. Overview of the used primary wavelets set

For each decomposition image, we extract associated coefficients and then we calculate level of energy of each decomposition coefficient, at each resolution level (1 to 4) (Karras 1998). The feature vector result constitutes a raw matrix containing 65 variables. Those variables consist of approximation energy and detail energy (horizontal, vertical and diagonal) from level of resolution 1 to level 4. It implies 13 variables (features) per primary wavelet.

2.5.4 Spectral analysis

As we discussed above, seam pucker specimens present waviness appearance (Xin 2002), whose amplitude differs from one grade to another. Then, a Discrete Fourier Transform (DFT) is performed to each image of seam specimen for converting it into a polar diagram (see Fig. 7). The frequency represents the sum of DTF coefficients by number of pixels displacement, for a given angle. We also integrate other parameters such as maximum of the DTF, the mean, the standard deviation and the ratio between the mean and the standard deviation extracted from the polar diagram.

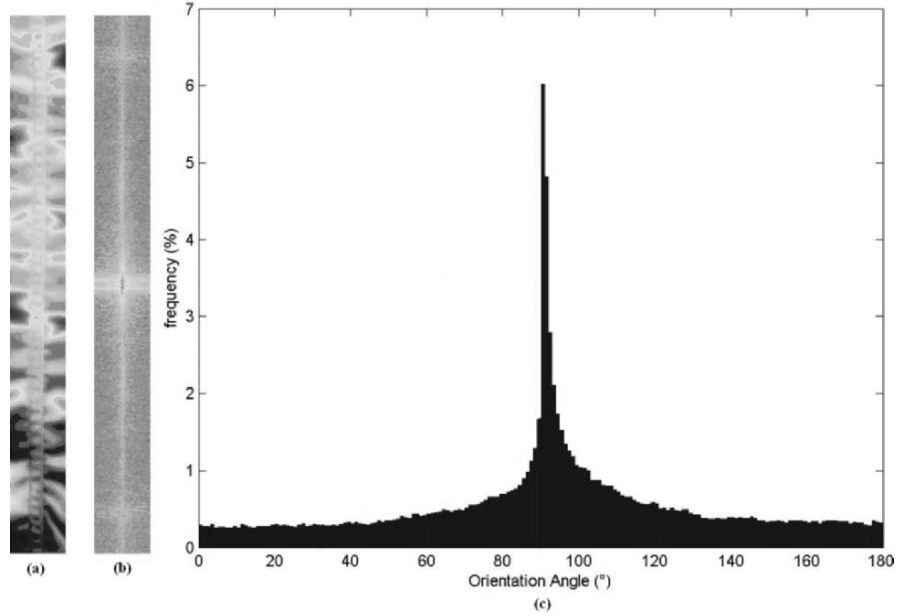


Fig. 7. (a) 3D picture of grade 1 specimen (false colors) – (b) power spectrum of Fig. 7(a) – (c) polar diagram of Fig. 7(b)

2.5.5 Principal Component Analysis (PCA)

In this chapter, we want to retrieve the most interesting image features which can explain the seam pucker classification. The process consists in exploring a large number of image features and then to keep only the most relevant ones. For performing this, we use two methods: a statistics based method, named PCA and a distance based method. PCA is a multivariate statistical method to reduce the dimension of a space of variables by projecting observed data on the original feature space onto a subspace with minimal information lost (Martinez 2001). The basic idea is to find principal components ($pc_1, pc_2, \dots, pc_p$) that can explain the maximum amount of variance possible by p linearly transformed components from a data vector with q dimensions ($p < q$). In our application, the feature vectors of all standard references and all specimens, extracted from images using the methods presented in Section ‘Extraction of Features Vector’ are reduced to a smaller set of 118 variables ($p, q = (118, 148)$). The exhaustive research of relevant image features generates a vector with 148 components. The results of applying PCA analysis on simple needle seams are done below (Fig. 8).

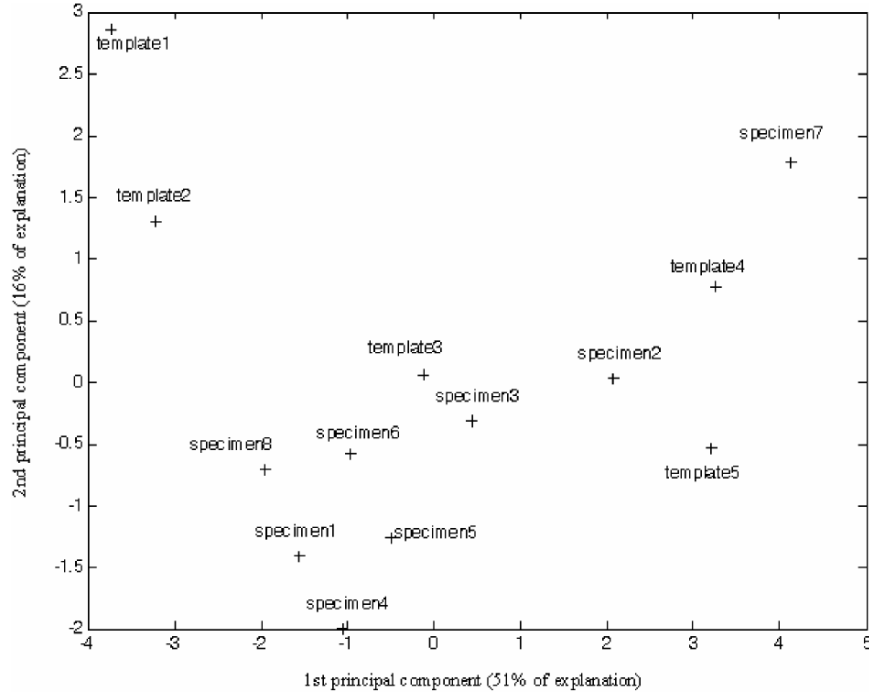


Fig. 8. Representation of samples cloud in the space of the two first principal components

Using PCA, we can decrease significantly the number of variables by checking the strong linear correlation between them. Moreover, Fig. 8 shows that the five templates are well spread in the samples cloud space. It implies that the remaining variables are relevant to distinguish the replicas and thus, well adapted for classifying seam puckers. The two first components are able to explain more than 66% of variance.

3 Selection of Relevant Features

After the removal of the image features with a strong linear relationship, in order to reduce more significantly the great number of remaining feature variables extracted from images of seam specimens and then simplify the classification complexity, we develop a new method for selecting the most relevant variables (Escofier 1982). All extracted features can be ranked using this method. This method is based on the sensitivity and the conformity of feature variables to the expert knowledge on classification of test

specimens into 5 quality grades. For this purpose, we have to maximize the following criterion: $D=BD/WD$

BD characterizes the sensitivity of feature variables to the expert knowledge by calculating the distances between all five standard references. For relevant feature variables, we obtain big values of BD, permitting to clearly separate measured data of these five standard references. Otherwise, we obtain small values of BD for irrelevant feature variables. Formally, it is defined by

$$BD = \sum_{1 \leq i \leq j \leq 5} d(sr_i, sr_j) \quad (3)$$

where sr_i represents the standard reference whose grade is i and $d(x, y)$ is the Euclidean distance between x and y in the space $\mathcal{R}^n$ ($n \in \{1, \dots, p\}$) when we are searching for the best n^{th} -tuple of relevant variables.

WD characterizes the conformity of feature variables to the expert knowledge on classification of seam specimens. It permits to calculate the average of the distances from all test specimens to the corresponding standard references classified by experts. For relevant variables, we obtain small values of WD because the classification result given by these variables is in adequacy with experts. Otherwise, for irrelevant variables, we obtain big values of WD. The definition of WD is given as follows.

$$WD = \sum_{1 \leq i \leq 5} \frac{1}{n_i} \sum_{x \in C_i} d(x, sr_i) \quad (4)$$

where C_i is the set of all test specimens whose grades are i according to human experts, x is one test specimen of C_i and n_i is the number of elements in C_i .

This criterion permits to test the relevancy of all groups of feature variables from the measured data of standard references and test specimens in a sub-space $\mathcal{R}^n \subset \mathcal{R}^p$. For example, we compare values of this criterion by taking in consideration only one variable ($n=1$), and take the feature variable maximizing the criteria D as the most relevant variable. The same principle can be applied to groups of two variables ($n=2$), three variables ($n=3$) and so on. In general, more feature variables we select for each group, more precise result the criterion D can lead. This is because there exists often correlation between variables and a small number of variables in a group risks to skip this correlation and then lead to information lost. However, the number of variables in a group can not be too big because

the corresponding complexity also increases. This criterion is able to take into account either linear or non-linear relationships.

We have tested the criterion on simple needle seams. The expert classification is done according to the AATCC normative reference, which implies a controlled environment. The results are presented as follows in the table 1, which shows the value of D increases as the number of kept variables increases.

Table 1. Criterion variation vs. the number of kept variables

Number of relevant variables	Criterion D
N=1	2.2533
N=2	2.5700
N=3	2.7893

- When searching for the most relevant variable, the diagonal detail coefficient of biorthogonal wavelet decomposition is considered as the most relevant variable of all features extracted from images of seam specimens (see Fig. 9&10). Fig. 9 shows clearly that the decomposition of the best grade is smoother than for the worst grade. Figure 10 represents the wavelet family used for the decomposition quite similar to a fabric wrinkle.
- When forming 2 variables in a group, the vertical detail coefficient of Haar wavelet decomposition at level 2 and the homogeneity with a radius of 30 pixels and an angle of 45° are considered as the most relevant variables. As we discussed previously in section ‘Principal Component Analysis (PCA)’, this method allows us to find an appropriate length and angle of displacement for the co-occurrence matrix.
- When searching for the subset of the top 3 variables in a t-uple, the energy of the vertical Haar wavelet, the energy of the vertical coif3 wavelet and the homogeneity are considered as the most relevant variables.

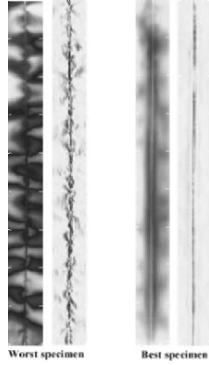


Fig. 9. Specimen and their decomposition with the bi-orthogonal wavelet (energy)

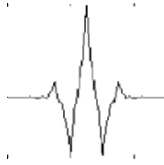


Fig. 10. Bi-orthogonal wavelet form (mother function)

When we want to rank the variable by descending order of relevancy, it appears that the features related to the texture and to the multi-scale analysis are significant, in particular those related to the wavelet analysis. As shown in Fig. 9, it is clear that the homogeneity varies a lot from the best to the worst specimens. But, since the seam puckers consist of peaks and valleys, the application of a wavelet analysis with an adapted waveform in the vertical direction provides relevant information. Moreover, multi-scale analysis is invariant to magnification effect. Thus, wavelet analysis combined with texture features offer appropriate tools for distinguishing the different grades of seam pucker. It shows experts' eyes use at the same time multi-scale and texture analysis for ranking samples by descending order of seam pucker quality.

4 Conclusion

In this paper, we are interested in the development of new automatic quality control methods for textile appearance, which respond to the consumers' expectations. Thus, it is necessary to find methods which are consistent with the expert's judgement. For this purpose, a digitisation process of

standard references of seams and test specimens is done, so as to extract 3D objects. Then, we extract feature vectors from 3D objects and 2D grey value images after normalization of data, so as to have the same depth value associated with the same grey value, for any test specimen and standard reference. Next, we apply PCA analysis to decrease the dimension complexity by removing linear correlation between image features and to improve the efficiency of the distance based method. Then, we applied a criterion for finding the best n^{th} -tuple of relevant variables which explain human expertise in the area of seam pucker. According to the literature, some research works showed the interest of the texture analysis or of the fractal analysis to explain the human expertise in this field. When applying our searching method, it appears that promising results for classifying seam quality can be achieved by using the combination of texture features and multi-scale analysis. The finding of relevant image features is crucial for putting into place a seam pucker classifier. This algorithm can potentially be adapted to form the basis of finding key parameters in appraisers' judgment. Such work would enable researchers to study how experts evaluate textile quality and gain understanding. It would also improve accuracy and productivity of evaluation sessions. Such method is efficient also for decreasing the classification model complexity and for handling non-linear relationships between variables. This ranking procedure is more reliable than the widely used statistics based methods, such as PCA, which need a great number of data and deal only with linear relationships.

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Part II

Modelling and Simulation of Textile Structures

Complex Characterization of Yarn Unevenness

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Abstract

Traditional approach to unevenness characterization of yarn is based on the CV i.e. coefficient of variation of mass between defined portions of yarn measured by USTER evenness tester. New generations of this device has provision to provide raw data about the whole mass variation curve (MVC). These data may be used to evaluate more deeply the unevenness characteristics in time (length) and frequency domains. This chapter mainly focusses in describing some tools for characterizing yarn unevenness. Here, simple methods for complex characterization of statistical behavior of MVC (stationarity, independence, linearity etc.) are presented along with methods to identify long-range and short-range dependencies. Processing of MVC is divided into the two phases. Core of the first phase is pretreatment of data and creation of power spectral density (PSD) curve. In this phase, the rough PSD estimator is based on a periodogram or, FFT. The mass variation curves are classified according to their slopes, S , that exhibit dependence of $\log(\text{PSD})$ on $\log(\text{frequency})$. Special techniques for estimation of Hurst exponent, related to the present context, are also included. The selected methods are core of UNYARN program in MATLAB. Applications of this program for deeper characterization of cotton type yarn are also provided.

Keywords: yarn unevenness, coefficient of variation, spectral analysis, long and short-range dependencies, Hurst exponent

1 Introduction

Traditional approach to yarn unevenness characterization is based on coefficient of variation (CV) of mass between short portions of yarn, Modern USTER evenness tester is equipped to give raw data of the whole mass variation curve (MVC). These data may be employed for more complex evaluation of unevenness characteristics in time and frequency domains. This chapter aims at describing some tools for characterization of yarn unevenness from the following standpoints:

random variation (structural unevenness);
periodic components (spectral analysis); and
chaotic behavior (complexity)

For accomplishing the above goals it is necessary to use system based on the characterization of long range and short-range dependence of variance. The Hurst exponent can, describe the long-range dependence. The entire processing of MVC comprises two phases. The first phase essentially refers to pretreatment of data and creation of power spectral density (PSD) curve. In the second phase, the mass variation curves are classified according to their slopes, S , that are derived from dependence of $\log(\text{PSD})$ on $\log(\text{frequency})$ (Eke A. et al. 2000 & Sacerdotti F. et al. 2000). The selected methods form the core of UNYARN program, coded in MATLAB.

2 Experimental Observations

A modified rotor spinning frame, running at about 80 000 rpm, was used to produce cotton carded yarn of 20 tex. Raw data of yarn mass variation were obtained from the evenness tester, ‘Uster tester 4.

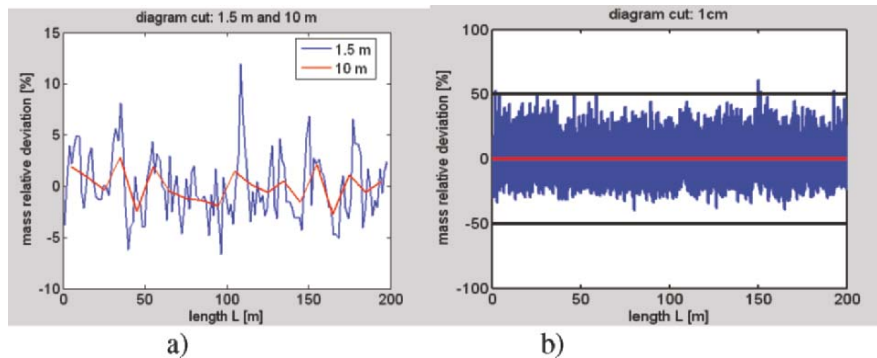


Fig. 1. Mass deviation diagrams: a) for cut lengths 1.5 and 10 m. b) for cut length 1 cm

The parameters of this diagram are: the number of measured points, N ($= 18458$), distance between points, δ ($= 0.010836m$), and the total measured length, H ($= 200m$). The mass variation diagram (MVC) for cut length of 1 cm is shown in Fig. 1(b). Figure 1(a) shows similar diagrams for cut lengths, L of 1.5m and 10m. The diagrams for higher cut lengths, L , represent short-range dependence, approaching to the white noise (random independent identically distributed series).

2.1 Basic Relations

The mass variation measurements by using evenness tester, like that of Uster's, are based on change of capacitance values, related directly to mass variation of yarn..

The set of the raw output signal from the capacitance measurement $S(i) = S(d_i)$, $d_i = (i-1) * \delta$, $i = 1..N$ at distances, d_i , is due to finite length of electrodes, sampled at intervals δ (1cm). This signal is converted to the mass variation diagram (MVC) expressed as relative deviation from the mean value.

$$y(i) = 100 * \frac{[S(i) - \text{mean}(S(i))]}{\text{mean}(S(i))} \quad (1)$$

The mass per unit length is directly proportional to the signal values $S(i)$. The unevenness (strictly speaking, quadratic mass unevenness) is, in fact, the coefficient of variation (CV) of mass per unit length. Let $CV(x,y)$ be the coefficient of variation between lengths x within length y . Standard output from Uster apparatus is called as *external quadratic irregularity* $CV(\delta, H)$ between lengths, δ . Evaluation of quadratic irregularity between lengths, L , within total sample length, H , i.e., quadratic irregularity for cut length L . is computed from the following relation

$$CV^2(\delta, H) = CV^2(L, H) + CV^2(\delta, L) \quad (2)$$

In the above expression, the symbol $CV^2(L, H)$ denotes the *external standardized variance* between lengths, L , within length, H , and $CV^2(\delta, L)$ is the *internal standardized variance* between small lengths, δ , within the cut length, L . The symbol $CV^2(\delta, H)$ refers to the *overall standardized variance* between smallest cut lengths, δ , within the sample length H .

3. Unevenness as Stochastic Process

Analysis, based on gradients, is used for characterizing structural unevenness. It is quite useful to relate the described variance analysis, based on cut lengths, L , with aggregation of random series. The objective is to characterize the types of random nature of relative deviations $y(i)$ or, directly the local masses $S(i)$, where $i = 0 \dots N-1$. Let these variables be stationary of second order. It is well known that statistical behaviour of a random process can be described by autocovariance function (Maisel L 1971).

$$c(i, h) = c(h) = \text{cov}(y(i) * y(i - h)) = E(y(0) * y(h)) \quad (3)$$

The second equality is valid if $E(y) = 0$ i.e., when data are centered. For a lag $h = 0$ the resultant variance $v = c(0)$. The autocorrelation function $R(h)$ is then simply defined as (Maisel L 1971).

$$R(h) = \frac{\text{cov}(y(0) * y(h))}{v} = \frac{c(h)}{c(0)} \quad (4)$$

In reality, the application of principle of cut length is same as that of aggregation of original data $y(i)$ into non overlapping blocks or, application of window of length L . Aggregated series, $y^{(L)}(i)$, are created by the averaging the values $y(i)$ in blocks having values of L i.e., characterization of blocks by their mean value

$$y^{(L)}(i) = \frac{1}{L} (y(i * L - L + 1 + \dots y(i * L)) \quad L = 1, 2, 3.. \quad (5)$$

The new series is still stationary of second order, with autocovariance function $c^{(L)}(h)$ and variance $v^{(L)}$. It is well known (Cox D.R. 1984 & Cox D.R., Townsend M. W. H 1948) that variance of an aggregated series is connected with autocorrelation structure of the original series

$$v^{(L)} = \frac{v}{L} + \frac{2}{L^2} \sum_{s=1}^{L-1} \sum_{h=1}^s c(h) \quad (6)$$

On the other hand, autocovariance of the original series is connected to variances of the aggregated series through the following relation:

$$c(h) = \frac{1}{2} \Delta^2 (h^2 * v^{(h)}) \quad h = 1, 2, 3.. \quad (7)$$

The above symbol $\Delta^{(2)}(x(j)) = x(j+1) - 2 * x(j) + x(j-1)$ denotes the central second order difference operator. The autocovariance function for an aggregated series $y^{(L)}(i)$ has the form

$$c^{(L)}(h) = \frac{1}{2} \Delta^2(h^2 * v^{(h*L)}) \quad h = 1, 2, 3... \quad (8)$$

The autocorrelation function of aggregated series, corresponding to a lag one, is given by:

$$R^{(L)}(1) = 2 * \frac{v^{(2*L)}}{v^{(L)}} - 1 \quad (9)$$

The nature of an original random series can be explained by using characteristics of the aggregated series. There are three main groups of series:

1. **Series of random independent identically distributed (*i.i.d*) variables:** In this case all $c(h) = 0$, for lags $h = 1, 2$, and data are uncorrelated. The case is ideal for unevenness analysis and assumed implicitly to be valid in majority of methods used in practice.
2. **Short-range dependent stationary processes:** In this case the sum of all $c(h) \quad h = 1, 2, \dots$ is convergent
3. **Long-range dependent stationary processes:** In this case the sum of all $c(h) \quad h = 1, 2, \dots$ is divergent

For *short-range dependent stationary* processes, the first order autocorrelation is $R^{(L)}(1) = 0$ for $L \rightarrow \infty$. The same is valid for autocorrelation of all lags, h . Therefore, the aggregated series, $y^{(L)}(i)$, tends to be of pure noise of second order as $L \rightarrow \infty$. For large L , variance is given by $v^{(L)} = v / L$. The autocorrelation structure of aggregated decreases until limit of no correlation is achieved. Typical model of short-range processes are autoregressive moving average processes (ARMA) of finite order. For the higher cut lengths, data approach the *i.i.d* case.

For *long-range dependent* processes, variance may be written down as $L * v^{(L)} \rightarrow \infty$ as $L \rightarrow \infty$. In this case, the autocorrelation structure does not vanish. Validity of these processes necessitates sufficiently large value of L .

$$c(h) \approx h^{-\beta} \quad \text{and} \quad v^{(L)} \approx L^{-\beta} \quad (10)$$

where, $0 < \beta < 1$ is the condition for feasibility of the stationary series, as no stationary case, β lies outside this interval.

A strictly second order self-similar process has $R(h) = \frac{1}{2} \Delta^2 (h^{2-\beta})$ and consequently, $R^{(L)}(h) = R(h)$ and $v^{(L)} = v * L^{-\beta}$. Therefore, for the long-range processes correlation structures of original and aggregate series are identical to each other. Moreover, for purely second order self-similar processes, $c(h) \approx \frac{v}{2} (1 - \beta) * (2 - \beta) * h^{-\beta}$. For the higher cut lengths, the correlation structure remains the same and the assumption of *i.i.d* cannot be used. For this case, Hurst exponent $H = 1 - 0.5 * \beta$ is frequently used (Mandelbrot B.B., Van Ness J.W. (1968) instead of β . When $H = 0$, the series is of extreme irregularity and when $H = 1$, the series is a smooth one. Exponent H is directly related to fractal dimension, D_F , since $D_F = 2 - H$ (Sacerdotti F., et al. 2000 & Takens F. (1981). The plots of variance $v^{(L)}$ on L in logarithmic scales is shown in the Fig. 2(a) for tested yarn and the dependence of

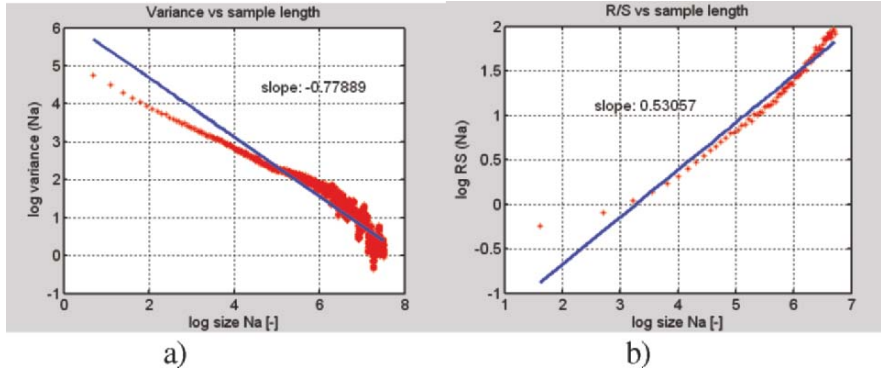


Fig. 2. a): Dependence of $\log v(L)$ on $\log L$ and **b) Dependence of $\log R/S$ and $\log L$**

$\log R/S$ on $\log L$ is shown in Fig. 2(b). R/S is the scaled range of series $y^{(L)}(i)$ (Mandelbrot B.B., Van Ness J.W. 1968). The slope of $\log R/S$ vs $\log L$ plot determines H . Generally, the i -th central moment of aggregated long range dependent series is defined by

$$M_i^{(L)} = \frac{1}{N/L} \sum_{k=1}^{N/L} \text{abs}(y^{(L)}(k) - \bar{y})^i \quad (11)$$

The function $M_l^{(L)}$ behaves asymptotically like power function $M_l^{(L)} \approx L^{l(H-1)}$. When the series has a finite variance and no long-range dependence, then $H = 0.5$ and the slope of the fitted line in log-log plot of $M_l^{(L)}$ on L is $-l/2$. If N and N/L are assumed to be large enough, then both the length of each block and number of blocks are large too. In practice, the points at very low and high ends of the plot are not used for fitting the least squares line. It has been observed that short-range effects are able to distort estimation of H if the low end of the plot is used (Constantine A. G., Hall P. 1994 & Davies S., Hall P., 1999). One of the best methods to evaluate β or, H is based on the power spectral density

$$g(\omega) = \frac{1}{2\pi} \int_{h=-\infty}^{\infty} c(h) * \exp(-i * h * \omega) d\omega \quad -\pi < \omega < \pi \quad (12)$$

For small frequency range the following relation is valid

$$g(\omega) \approx \omega^{-(1-\beta)} \quad \omega \rightarrow 0 \quad (13)$$

The parameter β is often evaluated from empirical representation of log of power spectral density

$$\log(g(\omega)) = -(1-\beta) * \log(\omega) + a_0 + a_1 * \omega + \dots + a_p * \omega^p \quad (14)$$

For long range processes it is ideal to have all $a_j = 0$, except the term for $j = 0$.

It is quite popular to use variogram (called often as structure function), which is defined as half the variance of differences $(y(i) - y(i+h))$ (Gressie N. A., Hawkins D.M 1980 & Quinn B.G., Hannan E. J. 2001)

$$\Gamma(h) = 0.5 * D[y(i) - y(i+h)] \quad (15)$$

For second order stationarity, variogram may be directly related to covariance as:

$$\Gamma(h) = C(0) - C(h) \quad (16)$$

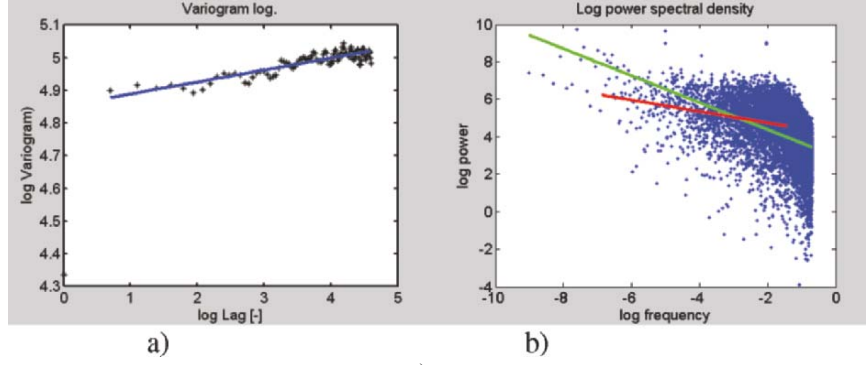


Fig. 3. a) Dependence of $\log \Gamma(h)$ on $\log h$ b) Dependence of $\log g(\omega)$ on $\log \omega$

It is much simpler to calculate a variogram as it assumes a weaker model of statistical stationarity, than the power spectrum. For long-range processes, variogram is given by $\Gamma(h) \approx |h|^{2H}$.

The plot of variogram versus lag h in logarithmic scales is shown in Fig. 3a for tested yarn and the dependence of $\log g(\omega)$ on $\log \omega$ is shown in Fig. 3b. Referring to Fig. 3b, the tested yarn has parameter β of values of 0.304 ($H = 0.652$) from final points and 0.718 ($H=0.859$) from all points. The series $y(i)$ is then classified as persistently weak and the process is stationary. From the slope of the log variogram line in Figure 3a, fractal dimension found to be as $D_F = 1.93$.

For estimation of H , many other ideas, dealing with series aggregation, can be used. *Dispersion analysis* is based on standard deviation of the local averages, $SD(L)$, of non overlapped blocks of length L of the series $y(i)$. This quantity is equal to $\bar{y} * CV_B(L)$ and dependence of $\log(SD(L))$ on $\log(L)$ has the same slope as that of $\log(\bar{y} * CV_B(L))$ on $\log(L)$. The slopes of these dependences are separately equal to $H-1$.

The *scaled windowed variance* method is based on averaging of standard deviations, $SW(L)$, of non overlapped blocks of length L of the original series $y(i)$. This is because, a direct relation between $SW(L)$ and $CV_B(L)$ does exist. Evidently, long-range dependence of yarn unevenness being computed by cutting and weighting methods is found (Cox D. R., Townsend M. W. H. 1948). Consequently it becomes apparent that dependence of quadratic unevenness on the cut length L in logarithmic scale can be used for indication of stochastic nature of $y(i)$.

Moreover, knowledge of β or, $S = 1 - \beta$ helps to characterise the series $y(i)$. The following cases, relevant in the present context, can be identified:

$S > 1$ indicates strong persistency and non stationarity

$0 < S < 1$ indicates weak persistency stationarity

$S = 0$ indicates uncorrelated case and stationarity

$S < 0$ indicates anti-persistency and stationarity.

$S < 0$ The mass variation curve will be classified according to the slope S of $\log(g(T))$ versus $\log(T)$ characteristic (Eke A. et al. 2000 & Sacerdotti F. et al. 2000):

For fractional Gaussian noise, fG , in the range $-1 < S < 0.38$, the fractal dimension from power spectrum can be used but variogram is not suitable.

In the case of fractional Brownian motion, fB , for $1.04 < S < 3$, variogram may be employed to estimate fractal dimension as well.

A transition for $0.38 < S < 1.04$ necessitates creation of cumulative sum of SHV (transformation to the case b)

No fractal behaviour is observed, when the power law model is invalid (in two decade range). For such cases, the chaotic models (broad bands on PSD) or, ARIMA models (narrow peaks on PSD) are to be used.

Correlation between elements of series, $y(i)$, has influence on the variance of mean, $D(\bar{y})$. For the case of short range dependence, variance of mean equals to

$$D(\bar{y}) = \frac{v}{N} * \left[1 + 2 * \sum_{k=1}^{N-1} (1 - k / N) * R(k) \right] = \frac{v}{N} G(R) \quad (17)$$

where, $v (= D(y))$ is the variance of data. If series $y(i)$ is random and independent then, identically distributed variable, $G(R) = 1$. Long-range dependence causes the variance $D(\bar{y})$ to decay more slowly

$$D(\bar{y}) = \frac{v}{N^\beta} G(R) \quad (18)$$

An additional complication for correlated data is that s^2 is biased estimator. For the short range dependence, the following relation is valid

$$E(s^2) = v * \left[1 - \frac{2}{N-1} \sum_{k=1}^{N-1} (1 - k / N) * R(k) \right] \quad (19)$$

3.1 Analysis of Unevenness Data

Considering a series $y(i)$, which is a “spatial” realization of random process $y = y(d_i)$, it is necessary to know if some basic assumptions about behaviour of underlying random process are to be accepted or not. These basic assumptions are (Maisel L. 1971):

Stationarity, ergodicity, and independency. Random processes are realised as $y_j(i)$, where index j correspond to individual realisations and index i corresponds to the distance d_i . For ensemble samples, there are values $y_j(i)$ for $i = \text{const.}$ and $j = 1 \dots M$. For these data, standard statistical analysis of univariate samples may be used for creation of distribution of data e.g. probability density function $p(y(i))$ or computation of statistical characteristics as mean value $E(y(i))$ or variance $D(y(i))$. In majority of applications the ensemble samples are not available and statistical analysis is based on the one spatial realisation $y_j(i)$ for $j = 1$ and $i = 1 \dots N$. For creation of data distribution and computation of moments, some additional assumptions are necessary. *The basic assumption is stationarity.* The random process is **essentially stationary** if the all statistical characteristics and distributions are independent on ensemble location. The **wide sense of stationarity** of g -th order implies independence of first g moments on ensemble location. The second order stationarity implies that:

Mean value $E(y(i)) = E(y) = \text{constant}$ (not dependent on the location d_i).

Variance $D(y(i)) = D(y) = \text{constant}$ (not dependent on the location d_i).

Auto-covariance, autocorrelation and variogram, which are functions of d_i and d_j , are not dependent on the locations but, only on the lag $h = |d_i - d_j|$.

The covariance $c(y(d_i) * y(d_{i+h})) = c(h)$ may be considered as an example. For process to be *ergodic*, the “ensemble” mean can be replaceable by average across distance (from one spatial realisation) and autocorrelation $R(h) = 0$ for all sufficiently high values of h .

Ergodicity is a significant issue, as statistical characteristics can be calculated from one single series $y(i)$ instead of ensembles, which are often difficult to be obtained. For a given a $y(i)$ series, selection of the appropriate

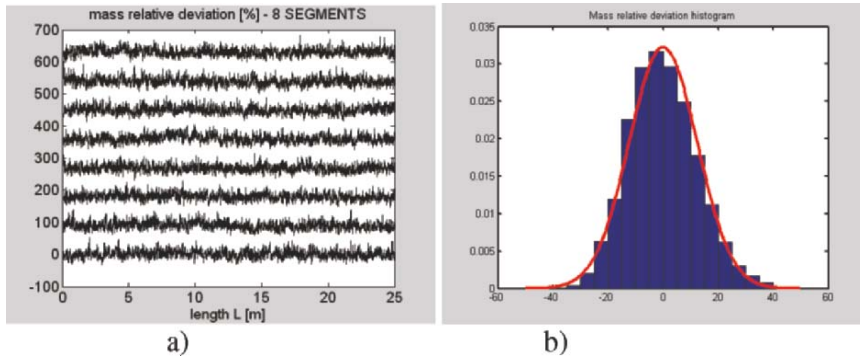


Fig. 4. a) Eight sub series of $y(i)$

b) Histogram of series $y(i)$

approach for its analysis is not a trivial task since the mathematical background of the underlying process is unknown.

Moreover, the $y(i)$ are generally corrupted by noise and consist of finite number of sample values. The task to analyse real data often means resolving the so-called inverse problem, i.e., to discover the characteristics of the underlying process for a given a series $y(i)$. Following three approaches are mainly applied:

First based on random stationary processes;

Second based on the self affine processes with multi-scale nature;

Third based on the theory of chaotic dynamics.

In reality, multi-periodic components are often mixed with random noise.

Before choosing an approach, some preliminary analysis is necessary to be undertaken to test the stationarity and linearity. This is vital as some kind of stochastic (self affine) processes, with power-law shape of their spectrum, may erroneously be classified as chaotic processes on basis of some properties of their non-linear characteristics, e.g., correlation dimension and Kolmogorov entropy. From this point of view, the tests for stationarity and linearity may be regarded as necessary preprocessings for choosing an appropriate approach for further analysis. Before selecting any method for data analysis, some simple tests may conveniently be applied on the series $y(i)$. The first one might be observing the $y(i)$ distribution through histogram. The histogram of series $y(i)$ for tested yarn is shown in the Fig. 4(b) and shape of eight sub series of $y(i)$ is in the Fig. 4(a).

In most of the methods of data processing that are based on stochastic models, normal distribution is assumed. If the distribution is proved to be non-normal (according to some test or inspection), there are three possibilities:

The process is linear but non-Gaussian; the process has linear dynamics, but the observations are as a result of non-linear "static" transformation (e.g., square root of the current values); the process has non-linear dynamics. It is suitable to construct the histograms for some cases like, four quarters of data separately and inspect non-normality or asymmetry of their distribution. The statistical characteristics (mean and variances) of these sub series can support wider sense of assumption of stationarity (when their values are statistically indistinguishable). The histograms of four sub series of $y(i)$ for tested yarn are shown in Fig. 5(b). Ensemble means and variance, computed from eight sub series, are shown in the Fig. 5(a).

For tested yarn, the t-test statistics for comparing two most distant means from four sub series is 4.538. This value is out of $P=95\%$ limits

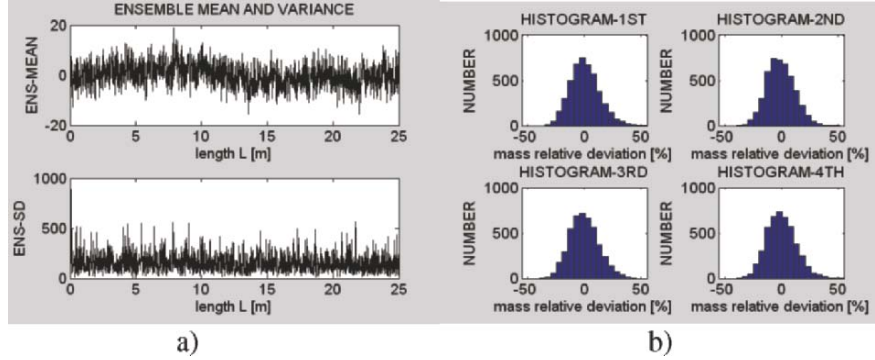


Fig. 5. a) Ensemble means and variances, b) Histograms of four sub-series of $y(i)$

$[-1.96, 1.96]$ and, therefore, stationarity is not accepted. The F ratio statistics for comparing two most distant variances from four sub series is 1.13. This value is out of $P = 95\%$ limits $[0.944, 1.06]$ and so, the stationarity is not accepted as well. The simple check of presence of first order autocorrelation requires zero order variability diagram, which is a plot of $y(i+1)$ on $y(i)$. For independent values, random cloud of points appears on this graph. Autocorrelation of first order is indicated by a linear trend. A first order variability diagram is constructed taking the first difference $d1(i) = y(i) - y(i-1)$ as a new set of data. Thus, the first order

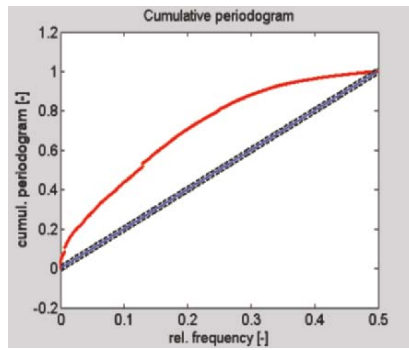


Fig. 6. Cumulative periodogram

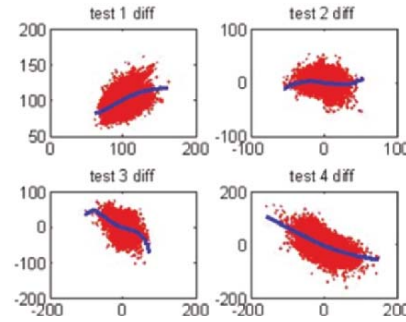


Fig. 7. Variability diagrams of first four orders

variability diagram shows the dependence of $d1(i+1)$ on $d1(i)$. The diagram “correlates” three successive elements of series $y(i)$. Similarly, the second order variability diagram for the second differences $d2(i) = d1(i) - d1(i-1)$ and subsequently, the third order variability diagram for the third order differences $d3(i) = d2(i) - d2(i-1)$ are created in Fig.7. As the order of variability diagram increases, the domain of correlations increases as well.

A simple nonparametric test of stationarity involves evaluation of reverse arrangement. The test is based on computation of all the instances for which $y(i) > y(j)$ with $i < j$ for all i . If the sequences of $y(i)$ are independent and consist of identically distributed (*i.i.d*) random variables, the number of reverse arrangements, NR , is a random variable with mean $E(N_R) = N(N-1)/4$, and variance $D(N_R) = N(2N+5)(N+1)/72$. If the observed number, N_R , is significantly different from $E(N_R)$, the nonstationarity (trend) is indicated. For the present purpose, the reverse test is statistic at $N_T = 52.4$ and upper limit for $P = 95\%$ is 1.96 only. The stationarity is not acceptable.

For characterization of hypothesis of independence against periodicity, a cumulative periodogram can be constructed. Cumulative periodogram is an unbiased estimate of the integrated spectrum.

$$CU(f_i) = \frac{\sum_{j=1}^i I(f_j)}{N * s^2} \quad (20)$$

The function $CU(f_i)$ is called the normalized cumulative periodogram. For white noise series (*i.i.d* normally distributed data), the plot of $C(fi)$ against fi would be scattered about a straight line, joining the points (0,0) and (0.5,1). Periodicities would tend to produce a series of neighbouring values of $I(fi)$, which are large. The result of periodicities, therefore, bumps on the expected line. The limit lines for 95% confidence limit of $C(fi)$ are drawn at distances $\pm 1.36 / \sqrt{(N-2)/2}$

If $y(i)$ corresponds to a dynamical system, it is often convenient to describe the “system” state in phase space. The phase space is defined as a multidimensional space, whose axes consist of variables of a dynamic system. Embedded dimension is a measure of minimum number of independent variables that describe the dynamic system (Takens F. 1981). The principle involved refers to embedding of data in $K = N - (D-1)$ dimensional Euclidean space. Data $y(i)$ for $i = 0 \dots N-1$ are lagged by lag τ , where τ corresponds to the first zero of autocorrelation function. These data are embedded through an Embedded Dimension D (usually $D \sim 15$) in an embedding matrix $\mathbf{G}$

$$\mathbf{G} = \begin{bmatrix} y(0) & y(\tau) & .. & y((D-1)*\tau) \\ y(1) & y(\tau+1) & .. & y((D-1)*\tau+1) \\ . & . & .. & . \\ y(K-1) & . & .. & y(N-1) \end{bmatrix} \quad (21)$$

Thus, the matrix of Euclidean norms E between rows $G(i)$ of matrix G is created. The element of this matrix has the form

$$E(i, j) = \sqrt{(G(i) - G(j))^T (G(i) - G(j))} \quad (22)$$

The recurrence plot makes $K \times K$ array of values, expressed in gray scale. Alternative way is transformation of matrix E to a matrix of zeros and ones by applying a suitable threshold and plot $K \times K$ array of values expressed in black and white scale. The threshold is often selected as $0.1*s$, where s is the standard deviation of series $y(i)$.

4. Program UNYARN

The program **UNYARN** in Matlab is a complex system for evaluation of mass and geometric unevenness of linear structures and for comparison of various methods in real or simulated series. The program is divided into logical blocks, which can be used as stand alone routines for data analysis. The basic building blocks of **UNYARN** are briefly described in this chapter.

4.1 Data Input

The data input block is fed from the signal $S(i)$ from USTER Tester in the form of external data file (ASCII and XLS format) or internal MATLAB file (MAT format). The following types of artificial signals with prescribed properties can be simulated:

White noise (Gaussian *i.i.d* random variables with selected values of variance and zero mean),

Autoregressive processes of first and second order, corrupted by white noise,

Harmonic waves, embedded in white or red noise,

Fractional fractal processes for selected Hurst exponents with or without additive white noise.

The length of simulated series is selected to be 200m and sampling interval is 0.01m.

4.2 Basic Graphs

The mass diagrams for cut lengths 0.01, 1.5 and 10m are presented. Thick and thin places are visible from the special bar plots.

4.3 Testing of Basic Assumptions

These procedures are meant for informal and formal testing of stationarity or ergodicity, independence and linearity.

The histogram of $y(i)$ series is used for informal testing of peculiarities of data distribution. The normal probability density function is superimposed for the purpose of interpretation.

Independence testing by using of reversing and run tests:

Data are divided into 8 sub series $y_j(i)$. Each i ($i=1...2200$) creates an ensemble, characterised by mean value $\bar{y}(i)$ and variance $s^2(i)$. The index graph of $\bar{y}(i)$ and $s^2(i)$ are created for inspection of stationarity and approximate ergodicity.

Creation of 4 sub series $y_j(i)$ and comparison of data distribution for $j = 1, \dots, 4$:

Histograms and cumulative density function are created. The stationarity is tested by t-test of maximal differences between population mean and F-test of maximal differences between population variances.

Creation of cumulative periodogram graph with confidence lines for the case of *i.i.d* data:

A recurrence plot and variability diagram for investigation of local correlation and chaotic behavior is created.

4.4 Structural Unevenness

Two types of methods for overall unevenness characterization are used. Basic components are variance length curves for $CV_B(L)$ and $CV_N(L)$ in various variants (index plot, semi logarithmic plot). The deviation rate DR and integral deviation rate IDR are computed and graphically presented in the form of DR - mass variation curve and index plots.

Nonlinearity checking is carried out through inspection of differences between $ACF(y^2)$ and $[ACF(y)]^2$ graphs.

4.5 Spectral and Harmonic Analysis

The general spectral moments and central spectral moments are computed. Spectrogram plot is also available as an option. The core is computation of periodogram from autocorrelation coefficients. The power spectral density estimator is based on discrete Fourier transformation (Welch method). From corresponding graphs in frequency and time (length) domain, the major peaks (periodic sources of variability) are identified. The harmonic regression models are associated with Fourier frequencies (linear least squares) and optimized frequencies (nonlinear least squares)

5. Conclusions

The complex analysis of mass variation curve (MVC) from Uster apparatus enables a deeper investigation of many phenomena connected to yarn unevenness and related problems. The models for short-range dependence or long-range dependence can be used for predictive purposes as well. In future it may be necessary to compute proposed characteristics for various yarns and typical faults. From these results it will be possible to select optimal one for description of typical phenomena connected to practical description of yarn quality and possible sources of errors in yarn production.

Acknowledgment

This work was supported by the research project “Textile center” of Czech Ministry of Education LN00B090 and 1M4674788501.

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Computer Simulation of Woven Structures Based On Actual Yarn Photographs

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Abstract

A method has been developed to obtain computer simulations of woven fabric structures based on photographs taken from actual yarns along their lengths. Yarn images are obtained using a digital video camera taking snapshots along the length of an actual yarn drawn intermittently by a yarn drawing arrangement designed. The fabric simulations are confined to single fabrics of plain, matt and twill weaves. Yarn curves in the fabric structure are modelled mathematically and projections of yarn images in the perpendicular direction to fabric surface are obtained by suitable software developed.

1 Introduction

In design work, it is important to visualize aesthetic appearance of the product as well as to estimate its performance characteristics. Both the appearance and performance properties of the product depend largely on raw materials used and the structure created; thus design work is simply planning the construction of a structure. This means defining the structural components. Mathematically speaking, it is a process of assigning suitable values to design variables which define the structure.

Many computer software exist in the market to design woven fabrics of simple and complex structures which enable the designer to create a fabric, guiding the designer in the selection of numerous design parameters, and also showing the fabric appearance simulated on the computer screen. To mention a few, there are software of Fashion Studio, Nedgraphics, Point-carré and Wonder Weaves Systems which provide fabric simulations from simulated yarn images. Uster Zellweger, Zweigle and Loepfe on the other hand, provide fabric simulation software to examine probable fabric faults due to defective yarns to evaluate fabric quality. Pascal, Giralt and Brunet developed an iterative package, which allowed the hierarchical specification of three kinds of yarn (Pascal et al. 2003). It also contains simple tools for the modification of the colours thorough the definition of colour maps. Adanur and Vakalapudi developed an image recognition program of spun yarns (Adanur & Vakalapudi 2003). A number of fibre parameters and yarn structural and processing specifications were inputs of program. Jasper, Suh, Woo and Cherkassky developed a simultaneous yarn measurement system and they analyzed and compared density profiles obtained from several spun yarns. By this system and 3-D prediction models, they predicted fabric appearance and other quality attributes (Jasper et al. 2000, Suh et al. 2003). Moussa, Dupont, Steen and Zeng applied the 2-Dimensional FFT (Fast Fourier Transform) to the woven fabric, which linked the topology of the obtained spectrum to fabric characteristics such as pattern and yarn densities. They made fabric simulations using the Inverse Fourier Transform with a simple change of dominant elements of the spectrum (Moussa et al. 2004). Adabala, Thalmann and Fei developed a technique for visualizing woven textiles in real time, while optimising a realistic fabric appearance. The proposed approach supports rendering of complex weave patterns by adopting Weaving Information File (WIF), a standard used in Computer Aided Design (CAD) of textile for representing the grammar of weaving (Adabala et al. 1995). Křemenáková, Sirková and Garg developed a textile design system which focused on the prediction of the structure as well as properties of the fibres, of the yarns and of the fabric. The principal aim of the system is to obtain fabric design optimisation on the basis of virtually created fabrics (Křemenáková et al. 2004). Keefe proposed a methodology to take into account potential effects of compressibility on a twisted assembly. His approach assumes that an individual yarn in compression could be approximated by a single element with an elliptical cross-section (Keefe 1994a). He used elliptical cross sectional yarns in the basic plain weave pattern (Keefe 1994b).

The yarn images used in the above mentioned fabric simulations are generally images simulated from given or measured yarn parameters by some mathematical algorithm developed. It has been, however, the aim of the work reported here to develop a method to create fabric simulations based on actual yarn photographs taken by both a stationary camera and a digital video camera (Özdemir 2005).

2 Related Theory

The actual yarn image taken on the photographic film transferred later to computer screen is considered to be the projection of a cylindrical surface on a plane perpendicular to yarn axis.

The yarns which form the woven fabric structure follow planar curves showing a crimped shape lying in planes parallel to yarn axes and perpendicular to fabric plane. They are also flattened in the cross section in perpendicular direction. Crimped shape of yarns is due to intersection of crossing yarns resulting in bending deformation and the flattened shape of yarn cross section is due to pressure acting between them. Thus it can be assumed that the circular yarn cross section is transformed into an elliptic one and crimped yarn shape can be represented by an elastica.

To create the yarn images in fabric structure from the actual yarn photographs, it is necessary, first, to obtain the surface development of yarn cylinder from its planar projection (Fig. 1a), then, as the second step, to deform this surface into a flattened elliptical one (Fig. 1b). This can be done mathematically by the following transformations:

If a length along the yarn diameter in the projected image is Δx , the corresponding arc length ΔS_i will be given by the equations

$$\Delta S_i = r \int_{x_{i-1}}^{x_i} \frac{dx}{\sqrt{r^2 - x^2}}, \quad i=1,2,\dots,n_f$$

$$x_i = x_{i-1} + \Delta x, \quad \Delta x = 2r/n_f \quad (1)$$

where r is the radius of yarn and n_f is a whole even number. Then, ΔS_i can be found by integrating equation (1) within definite limits

$$\Delta S_i = r \left| \arcsin \frac{x_i}{r} \right|_{2(i-1)r/n_f}^{2ir/n_f} \quad (2)$$

Using the equation of ellipse in the parametric form as

$$x = \frac{a}{2} \sin \theta, \quad y = \frac{b}{2} \cos \theta \quad (3)$$

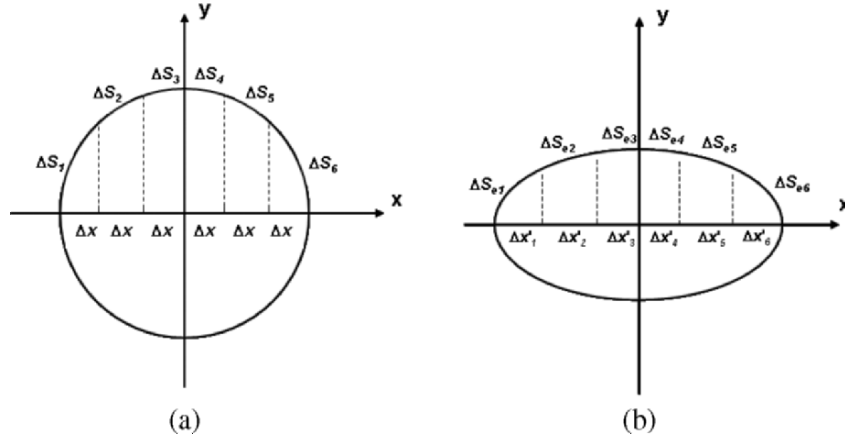


Fig. 1. Creating the yarn images in fabric structure

where a and b are the major and minor diameters of the flattened yarn cross section, the same arc length may be given by equation

$$\Delta S_{ei} = \frac{a}{2} \int_{\theta_{i-1}}^{\theta_i} \sqrt{1 - k^2 \sin^2 \theta} d\theta, \quad i=1,2,\dots,n_s \quad (4)$$

where $k^2 = 1 - b^2/a^2$ and n_s is a whole even number showing the total number of arc segments. This equation can be expressed in terms of incomplete elliptic integrals of the second kind as

$$\Delta S_{ei} = \frac{a}{2} [E(k, \theta_i) - E(k, \theta_{i-1})] \quad (5)$$

Based on assumption that the circular yarn cross section is deformed, in fabric structure, to the shape of an ellipse of the same perimeter, which is a more realistic assumption than that of the same area (Başer 1965), the arc segments ΔS_{ei} will be equal to those on the circular section.

The second kind of elliptic integral may be solved numerically by Simpson's Rule as follows:

$$\begin{aligned}
E(k, \theta_i) - E(k, \theta_{i-1}) &= \int_{\theta_{i-1}}^{\theta_i} f(\theta) d\theta \\
&= \frac{h}{3} [y_0 + 4(y_1 + y_3 + \dots y_{n_s-1}) + 2(y_2 + y_4 + \dots + y_{n_s-2}) + y_{n_s}]
\end{aligned} \tag{6}$$

where

$$h = \frac{\theta_i - \theta_{i-1}}{n_s}, \quad y = f(\theta) = \sqrt{1 - k^2 \sin^2 \theta} \tag{7}$$

When $\theta_{i-1} = 0$ and $\theta_i = \pi/2$ in equation (6) the circumference of the ellipse (S_e) can be expressed by the complete elliptic integral of the second kind $E(k, \pi/2)$ as

$$S_e = 2aE(k, \pi/2) \tag{8}$$

By equalizing the circumferences of circle to that of ellipse, the major diameter of the flattened yarn, a , will be given by

$$a = \frac{\pi d}{2E(k, \pi/2)} \tag{9}$$

where d is the yarn diameter as measured on the projected image in the yarn photograph. In calculations an assumed value for the eccentricity of ellipse, $e = b/a$, is employed.

The values of θ which give values of arc length (ΔS_{ei}) equal to that calculated from yarn image (ΔS_i) are determined by iteration and the corresponding values of $\Delta x_i'$ are found later from the parametric equation of ellipse given in the equation (3).

The value $\Delta x_i' / \Delta x$ will be a factor to resize the yarn image on the actual photograph to that in fabric simulation in the vertical direction.

The crimped shape of the yarn in weave structure is modelled by a curve known as elastica which lies on a plane perpendicular to fabric surface. In fabric simulation the straight yarn image deformed to a crimped shape is, also, to be projected on a plane parallel to fabric surface.

The parametric equation of elastica representing the yarn curve in a plain woven fabric is given in terms of its arc length (Pierce 1937) by the equation

$$\frac{1}{2}RS = \int_{\psi=0}^{\psi=\theta} \frac{d\phi}{\sqrt{1-k^2 \sin^2 \phi}} \quad (10)$$

where

$$\phi = \arcsin \left[\frac{1}{k} \sin \left(\frac{\psi}{2} + \frac{\pi}{4} \right) \right] \quad (11)$$

$$k = \sin \left(\frac{\theta}{2} + \frac{\pi}{4} \right) \quad (12)$$

$$R = \sqrt{V/B} \quad (13)$$

Here V is the shear force at cross over point, B is the flexural rigidity of the yarn and θ is the weave angle (Fig. 2a).

By applying boundary conditions to equation (11), the lower limit of ϕ for $\psi = 0$ is obtained as

$$\phi_0 = \frac{1}{k\sqrt{2}} \quad (14)$$

and the upper limit for $\psi = \theta$ as $\phi = \frac{\pi}{2}$.

Substituting these new integral limits, equation (10) becomes

$$\frac{1}{2}RS = \int_{\phi_0}^{\pi/2} \frac{d\phi}{\sqrt{1-k^2 \sin^2 \phi}} \quad (15)$$

This equation can be expressed in terms of elliptic integrals in the form

$$\frac{1}{2}RS = F(k, \frac{\pi}{2}) - F(k, \phi_0) = \bar{F}(k, \phi_0) \quad (16)$$

where $F(k, \pi/2)$ and $F(k, \phi_0)$ are complete and incomplete elliptic integrals of the first kind respectively.

The weave angle is calculated from an assumed crimp ratio (c) according to Pierce Geometry of plain woven fabric (Pierce 1937), as defined by

$$\theta = \sqrt{2c}, \quad c = \frac{S-p}{p} \quad (17)$$

The unit length in the direction of yarn axis, p , is expressed as

$$\frac{1}{2}Rp = 2k \cos \phi_0 \quad (18)$$

Eliminating R between equations (16) and (18), the arc length S , which is the length of the crimped yarn between two cross over points can be calculated from the equation

$$S = \frac{\bar{F}(k, \phi_0)p}{2k \cos \phi_0} \quad (19)$$

The arc length (ΔS) which is projected is found by

$$\Delta S = S/n_c \quad (20)$$

where n_c is a whole number (Fig. 2b).

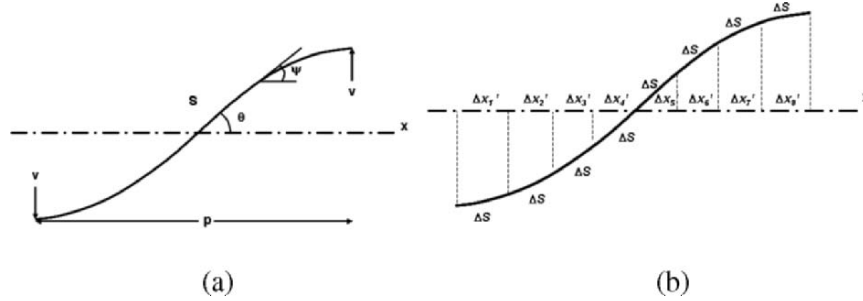


Fig. 2. Straight yarn deformed to a crimped shape

To find the projection $\Delta x_i'$ of a fixed length Δx on yarn image which is equal to the arc length ΔS on the crimped yarn, an iterative process similar to the one carried out for yarn flattening is applied by the following equations:

$$\Delta S_i = \frac{\bar{F}(k, \phi_i) - \bar{F}(k, \phi_{i-1})}{R}, \quad i=1, 2, \dots, n_c \quad (21)$$

$$\Delta x_i' = \frac{-2k(\cos \phi_i - \cos \phi_{i-1})}{R} \quad (22)$$

where R can be calculated for given values of θ and p by the equation

$$R = \frac{\sqrt{8 \sin \theta}}{p} \quad (23)$$

which is equivalent to equation (13) not involving the shear force and flexural rigidity parameters that are difficult to define or measure. It will, however, be necessary to assign an assumed value for θ to solve equations.

From the ϕ_i values attained when ΔS_i approaches ΔS , the $\Delta x_i'$ values are calculated by using equations (22) and (23).

When we look at the fabric from the top the projected image of the yarn is actually is that of its upper surface and not that of its central line as shown in Fig. 3. It may be important to base calculations on the shape of the upper curve when θ is quite large. The differentials of the x and y coordinates of the elastica are given by equations

$$Rdy = \frac{d\phi}{\sqrt{1 - k^2 \sin^2 \phi}} - 2\sqrt{1 - k^2 \sin^2 \phi} d\phi \quad (24)$$

$$Rdx = 2k \sin \phi d\phi \quad (25)$$

Since the surface curve are those at equal distance to the central curve at all points, their tangents will be parallel to those of the central curve. Consequently, the angle γ which a tangent on the surface curve makes with the x axis may be obtained by dividing equation (24) by equation (25) giving

$$\tan \gamma = \frac{2k^2 \sin^2 \phi - 1}{\sin \phi \sqrt{1 - k^2 \sin^2 \phi}} \quad (26)$$

The increments of $\Delta x_i''$ can be calculated from the increments of $\Delta x_i'$ which are found before from the central curve by the equations

$$x_i' = x_i - r \sin \gamma_i \quad (27)$$

$$x_{i-1}' = x_{i-1} - r \sin \gamma_{i-1} \quad (28)$$

$$\Delta x_i'' = x_i' - x_{i-1}' \quad (29)$$

$$\Delta x_i'' = \Delta x_i' - r(\sin \gamma_i - \sin \gamma_{i-1}) \quad (30)$$

where r is the flattened yarn radius, namely its minor diameter.

The increments of ΔS in the yarn image are, then, resized to the increments of $\Delta x_i''$ instead of $\Delta x_i'$.

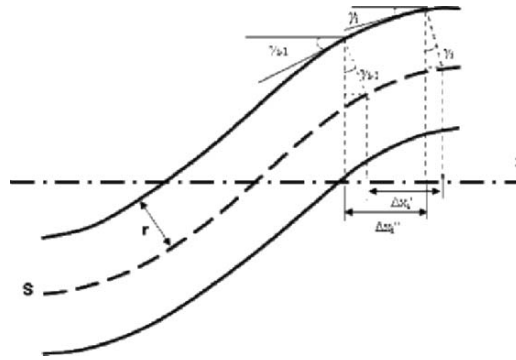


Fig. 3. Upper surface of the yarn

3. Experiments

Yarns with different structural properties and appearance such as carded and combed cotton yarns, worsted yarns and fancy yarns were used to generate fabric simulations. Yarn counts used ranged between from 6 to 60 metric counts.

As a preliminary experiment, photographs of yarns in stationary state were taken by a Canon EOS 50 model camera on both 100 ASA negative and chrome film. Macro and close up lenses to increase resolution and a UV filter to eliminate irregularity and cloudiness were used. Yarns were illuminated from the ceiling with two fluorescent lights of 40W during

taking photographs in daylight. Similar photographs were also taken by a Canon Powershot G5 digital camera.

In taking yarn photographs, yarn sections of approximately 10cm length were fixed on a flat hard paper of appropriate colour together with a scale in cm and mm divisions placed in the direction of yarn.

For the main experiment snapshot photographs of yarn were taken in succession along the yarn by a Sony TRV 40E digital video camera with a resolution of 1,39 mega pixel. Both digital video cassette and memory stick were used to store the images obtained. A special yarn drawing device was used to pull the yarn intermittently in front of the camera.

Yarn photographs were transferred to the computer as BMP, Photoshop PSD and TIFF formats. Then each picture file was converted to PPM file to be able to be processed with C programming codes by means of Irfan-View 3.95. The ground colour was erased and the images were cropped in pixel values related to the thread spacing by both Photoshop 6.0 and Matlab 5.3. In Photoshop, these processes are saved as action and applied to the directory selected. In Matlab, these processes are performed by converting RGB image to binary image by `im2bw` function, one of whose parameters was threshold value. The binary images which quite resemble to the actual RGB images were selected. While RGB values of colour image are stored in 3D arrays, values of binary image are stored in 2D arrays in Matlab. In addition to this, images are processed with program codes in C by dynamic memory management functions which allocate a memory (RAM) for arrays. RGB and binary image values are transferred to arrays by C codes. While elements of arrays of RGB image are struck with 3 elements, elements of binary image are unsigned char. Programs both in Matlab and in C perform processes by applying matrix operations on the yarn images on pixel level. Coordinates of elements of array are determined by controlling yarn colour in binary image. If yarn colour is light, binary value of yarn image value will be 1, if yarn colour is dark, binary value of yarn image value will be 0. So, processes required are performed at elements of RGB image arrays as parallel in elements of binary image arrays.

The problems of defining yarn outlines and of aligning yarn segments appearing in separate yarn photographs which have to be joined, later, especially in video snapshots, are to be solved.

With programs written in Matlab and C, bottom and top boundaries of yarns in images are found by controlling yarn colour, areas of yarn images are calculated from zeroth-order moment given by equation (Jain et al. 1995, Pitas 1993)

$$A = \sum_{i=1}^n \sum_{j=1}^m B[i, j] \quad (31)$$

where i is row index, j is column index and $B[i, j]$ is binary image. Centres of gravities of yarn image are calculated from first-order moments given by equations

$$\bar{x} = \frac{\sum_{i=1}^n \sum_{j=1}^m jB[i, j]}{A} \quad (32)$$

$$\bar{y} = \frac{\sum_{i=1}^n \sum_{j=1}^m iB[i, j]}{A} \quad (33)$$

where $\bar{x}$ and $\bar{y}$ are coordinates of centre of gravity, which are not to be integers. Yarn diameters were first measured against a scale with which the yarn photographs were taken and the pixel equivalent of yarn diameter in millimetres was calculated to obtain a conversion factor. Later average vertical lengths (yarn diameters) are calculated in pixel units by equations

$$V[j] = \sum_{i=1}^n B[i, j] \quad (34)$$

$$\bar{V}[j] = \frac{V[j]}{A} \quad (35)$$

where $V[j]$ is vertical length, $\bar{V}[j]$ is average vertical length. Orientations of yarn images are calculated by equations

$$a = \sum_{i=1}^n \sum_{j=1}^m (x'_{ij})^2 B[i, j] \quad (36)$$

$$b = 2 \sum_{i=1}^n \sum_{j=1}^m x'_{ij} y'_{ij} B[i, j] \quad (37)$$

$$c = \sum_{i=1}^n \sum_{j=1}^m (y'_{ij})^2 B[i, j] \quad (38)$$

$$\theta = \frac{1}{2} \arctan\left(\frac{b}{a-c}\right) \quad (39)$$

where a , b and c are parameters, θ is the orientation angle in radians. Then, each image is merged and cropped according to boundaries and average vertical length. Images whose gradients are bigger than 0.5° are rotated in opposite direction and cropped again. If x' and y' are coordinates of mid-points of the image, x'_2 and y'_2 are coordinates of mid-points of the rotated image, rotation being performed as follows:

$$\begin{aligned} x' &= n / 2 \\ y' &= m / 2 \\ x'_2 &= n_2 / 2 \\ y'_2 &= m_2 / 2 \\ n_2 &= n * \cos(\theta) + m * \sin(\theta) \\ m_2 &= n * \sin(\theta) + m * \cos(\theta) \\ B_2[i, j] &= [0.5 + \cos(\theta) * (i - x'_2) - \sin(\theta) * (j - y'_2) + x_1, \\ &\quad 0.5 + \sin(\theta) * (i - x'_2) - \cos(\theta) * (j - y'_2) + y_1] \end{aligned} \quad (40)$$

where n is number of rows of image in pixel, m is number of columns of image in pixel, n_2 is number of rows of rotated image in pixel, m_2 is number of columns of rotated image in pixel and $B_2[i, j]$ is pixel value of rotated image.

As a result of image processing techniques such as rotating, y values of centre of gravity of images may be changed. So, attributes of image mentioned above are calculated again. If y values of centre of gravity of images are different from y value of centre of the crop, pixel values of images will be transferred to crop array so that images are centred in vertical direction along the crop. Rotated and nonrotated images are joined end to end to become one of the horizontal yarn image. Ground colour value is appointed for horizontal yarn image by either directly C codes or keyboard. A computer program in C was written to calculate the resizing values, to resize these cropped yarn images in vertical and horizontal directions and to lay these resized yarn images side by side in vertical and horizontal directions to align intersecting yarn sections.

An example of resizing an image with 5 pixels to one with 4 pixels is shown in Fig. 4.

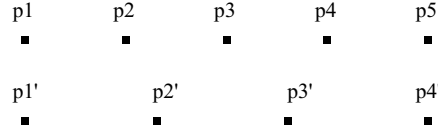


Fig. 4. Resizing an image with 5 pixels to one with 4 pixels

Here, p_1, p_2, p_3, p_4 and p_5 are RGB values of previous pixels, p_1', p_2', p_3' and p_4' are RGB values of new pixels.

Pixel values of new image are calculated by gravity factors which are inversely proportional to distance from neighbouring pixels as follows:

$$\begin{aligned}
 p_1' &= p_1 \\
 p_2' &= p_2 \times 0,67 + p_3 \times 0,33 \\
 p_3' &= p_3 \times 0,33 + p_4 \times 0,67 \\
 p_4' &= p_5
 \end{aligned} \tag{41}$$

Space for an array of fabric simulation whose number of rows and columns are equal to the number of columns of resized horizontal image in pixel is allocated. To obtain vertical yarn images, horizontal yarn images are rotated 90° clockwise. Procedures were built in the program to simulate weave structures by transferring pixel values of horizontal or vertical image arrays of fabric simulation according to the particular weave structure required, by controlling ground colour and by transferring pixel values of crossing yarn image. Array of fabric simulation is recorded as PPM file. Space assigned in memory for all images are set free.

In the application of the theory developed to calculate resizing factors, a reasonable value of the eccentricity of elliptic yarn cross section, $e = 0.6$, was assumed. As for the calculation of resizing factors to be applied to the yarn photographs in the direction of yarn axis, a weave angle of $\theta = 40^\circ$ was assumed, which gave a crimp factor, S/p , equal to 1.27. This represents a medium sett fabric.

This has been the applied procedure to simulate fabric appearance from yarn photographs. In simulating various woven structures other than plain weave such as 2/2 twill or matt, the assumption was made that the yarn path followed the elastica curve in intersecting parts whereas it remained

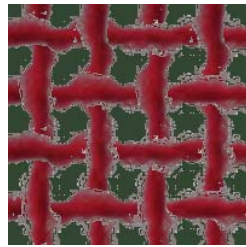
straight in flat portions, namely floats. Then the projections of the floats were images resized in diametrical direction only.

To take snapshots of yarn continuously along the yarn axis a yarn drawing device was designed and constructed. Drawing the yarn in equal lengths of approximately 1.75mm was achieved by a winding drum of approximately 10cm diameter driven by a stepper motor of 1 A. This was achieved by the revolution of the stepper motor for an adjustable period of time for each step controlled by computer using a program written in Visual Basic 6.0. A spring tension device was used to keep yarn under a constant tension in winding on the drum.

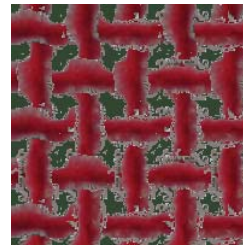
As for video camera recordings, the problem is to join snapshot photographs to obtain a continuous image of a longer length of yarn. This is achieved by separating each snapshot to frames obtained for a small section of the yarn corresponding to an exposure time of 1/24 second by Irfan View 3.95 as BMP format or by MPlayer in command line as PNG format. Each frame had to be converted to ppm format to enable it to be processed with C programming codes by IrfanView 3.95. Examples of fabric simulations achieved are shown in Fig. 5 and Fig. 6.



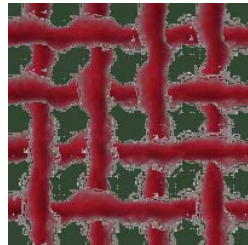
Yarn separated from background by filtering



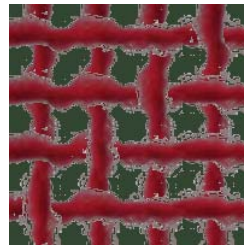
Plain weave
(Circular cross section)



Plain weave
(Resized according to Elastica,
elliptic cross section)



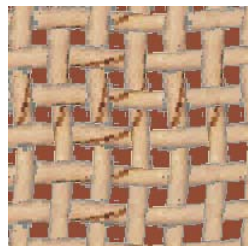
2/2 twill weave



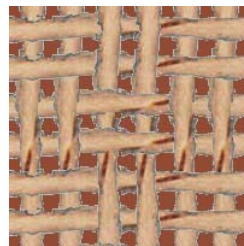
1/3 twill weave

Fig. 5. Simulation results I

Yarn separated from background by filtering



Plain weave



2 / 2 matt weave

Fig. 6. Simulation results II

6. Conclusions

As a result of the work done it seems possible to make a fabric simulation from actual yarn photographs using the available technology.

It seems that fabric simulation from photographs taken by stationary camera may give better results due to its more distinct image, whereas it may not be possible to attain the same quality with video recordings. Furthermore in video recordings a certain number of frames -which correspond to a single snapshot in a stationary yarn photograph- has to be taken per second and this increases the number of ppm files to be processed enormously.

There occurs some unavoidable loss of information in yarn outline due to the impossibility of displaying surface hair in the processed yarn image, as it actually appears to human eye, which may however be obscured partly, by compression, in certain regions of the real fabric structure. Improved image processing techniques will probably overcome such present difficulties in future works.

It is also worth mentioning, here, that while quality control firms obtain fabric simulation by measuring yarn diameter and density by means of optical and capacitive sensors, manufacturers of fabric design software rather tend to use vector graphics, employing yarn diameter values calculated somehow. Such software do not take into account the changes imparted to yarn appearance due to flattening. There are also quite important problems involved in selecting crop widths appropriate to yarn settings to take into account yarn flattening. Moreover, improved fabric simulation algorithms and crop width selection schemes may have to be developed for certain complex weave structures showing special surface features, such as fancy twills and cellular structures.

Depending on the duration of video recording and computer time, a very long length of yarn can be photographed and different sections of yarns can be used as individual warp and weft yarns to form the fabric as done in the actual weaving process. There may, however, be limitations, here also, involved with computer time and memory needed for fabric simulation process. These are the problems pending ingenious solutions in computer simulation of fabrics.

Acknowledgements

The authors wish to acknowledge the financial support of Dokuz Eylul University Research Fund. Thanks are also due to Dr. S. GUMUSTEKIN, Dr. M. CINSDIKICI, L. CETIN, MSc. and F. C. CAN, MSc for their help and valuable discussions.

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Computation of the Permeability of Textiles with Experimental Validation for Monofilament and Non Crimp Fabrics

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Summary. For the manufacturing of composite materials with textile reinforcement, the permeability of the textile is a key characteristic. Using Darcy's law the permeability can be derived from a numerical simulation of the fluid flow, i.e. by solving the Navier-Stokes or Navier-Stokes/Brinkman equations for a unit cell problem. In this paper we present the results of simulations with two different flow solvers: a finite difference Navier-Stokes/Brinkman solver and a lattice Boltzmann solver. The results are validated with theory and experimental data.

1 Introduction

For the manufacturing of composites with textile reinforcements, the permeability of the textiles is a key characteristic. It is of particular importance for the simulation of the injection stage of Liquid Composite Molding, since the permeability has to be assigned to different positions in the preform model, when simulating the impregnation process using tools like PAM-RTM or LIMS (Simacek and Advani, 2004; Trochu et al., 2006). The permeability is a geometric characteristic related to the structural features of the textile at several length scales. Textiles are porous media and the permeability tensor is defined by Darcy's law

$$\langle \mathbf{u} \rangle = -\frac{1}{\nu\rho} \mathbf{K} \cdot \langle \nabla p \rangle \quad (1)$$

with $\mathbf{u} = \mathbf{u}(x, y, z)$ the fluid velocity, ν and ρ the fluid viscosity and density, $p = p(x, y, z)$ the pressure, $\langle \rangle$ volume averaging and $\mathbf{K}$ the permeability tensor of the porous medium. Equation (1) is a homogenised equation, and the information of the internal geometry of the reinforcement is taken into

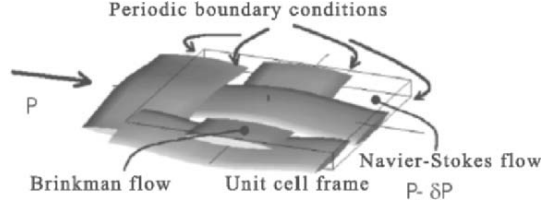


Fig. 1. A unit cell setup

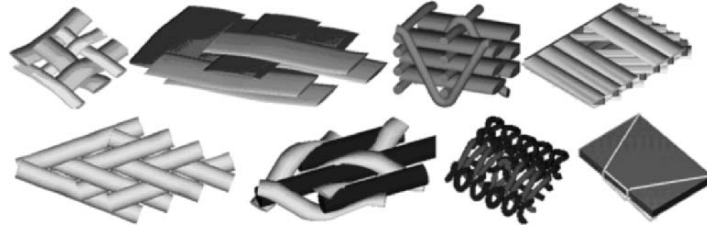


Fig. 2. Examples of models of textile reinforcements: 2D woven; 2D woven laminate; 3D woven; UD laminate; 2-axial braid; 3-axial braid; weft-knitted; Non Crimp Fabric

account in $\mathbf{K}$. Finite element or finite difference Darcy solvers require $\mathbf{K}$ as input. Unfortunately, the measurement of textile permeability is time and resource consuming (Hoes et al., 2001), hence reliable numerical prediction of $\mathbf{K}$ is required.

For the computation of $\mathbf{K}$, we can determine the flow in a unit cell, since textile has a periodic pattern (Fig. 1). As textiles are also hierarchically structured materials, our model for fluid flow must take into consideration the possible porosity of the material's yarns. Hence in the following, if the yarns are porous, we will distinguish between inter-yarn flow and intra-yarn flow. The porosity is accounted for by the local permeability tensor $\mathbf{K}_{tow}$. In both cases we aim at the computation of the mean fluid velocity $\langle \mathbf{u} \rangle$ and the mean pressure gradient $\langle \nabla p \rangle$ in order to solve Darcy's law (1) for $\mathbf{K}$. For the computation of the components of $\mathbf{K}$ we refer to (Verleye et al., 2006). More details on the applied mathematical model can be found in section 2.

A key task in permeability modelling is the characterisation of the reinforcement. For the creation of a single layer model of the reinforcement, we use the WiseTex software (Verpoest and Lomov, 2005). In practise however, often the permeability of a multi-layered reinforcement is required. Building the geometry model of a multi-layered reinforcement is a complex additional step, for which the LamTex software has been developed. The results of WiseTex and LamTex provide the input for the flow simulation tool. The software package WiseTex implements a generalised description of internal structure

of textile reinforcements on the unit cell level. The description integrates mechanical models of the relaxed and deformed state of 2D and 3D woven (Lomov et al., 2003, 2000, 2001), two- and three-axial braided (Lomov et al., 2002b), weft-knitted (Moesen et al., 2003) and non-crimp warp-knit stitched (Lomov et al., 2002a) fabrics (NCF) and laminates (Lomov et al., 2002c) (Fig. 2). All these models, including the models of deformed fabrics, use a unified description format of the geometry of the reinforcement unit cell. This format allows the calculation of physical and mechanical parameters of the fibres near an arbitrary point in the unit cell, as well as their fibre volume fraction (V_f) and their direction. The reader is referred to (Verpoest and Lomov, 2005) for more details. The models calculate the change of the internal geometry of the reinforcement in shear, tension and compression, accounting for local variations of the preform in the mould. It is also possible to assess the non-uniformity of the textile structure, creating a sampling of models with randomly perturbed parameters (Desplentere et al., 2004, 2005). In this paper we show computational results for woven and NCF fabrics, but the method can be applied to any of the abovementioned types of reinforcements.

We develop a software package, FlowTex, for the computation of the permeability tensor of textiles. A first version of FlowTex, based on a lattice Boltzmann model for fluid flow, has been tested and validated (Belov et al., 2004). In sections 2 and 3 we discuss our new module for FlowTex, based on a finite difference approximation of the Navier-Stokes and Navier-Stokes/Brinkman equations. Furthermore, we briefly explain the lattice Boltzmann model. Results of the permeability predictions with both models are compared and validated with analytical results for a model problem and with experimental data (section 4). Note that experimental validation is often missing in papers describing other software for permeability prediction.

2 Mathematical model

In case the model is limited to creeping, single-phase, isothermal, unidirectional saturated flow of a Newtonian fluid, the inter-yarn flow is described by the incompressible Navier-Stokes equations,

$$\begin{cases} \frac{D\mathbf{u}}{Dt} = \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\mathbf{u} \\ \nabla \cdot \mathbf{u} = 0. \end{cases} \quad (2)$$

The first equation states the conservation of momentum (momentum equation), the second equation states the conservation of mass (continuity equation). Intra-yarn flow depends on the local permeability tensor of the tow $\mathbf{K}_{tow}$, and is described by the Navier-Stokes/Brinkman equations which are the Brinkman equations (Slattery, 1972) without neglecting the convection

$$\begin{cases} \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} + \nu\mathbf{K}_{tow}^{-1} \cdot \mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\Delta\mathbf{u} \\ \nabla \cdot \mathbf{u} = 0, \end{cases} \quad (3)$$

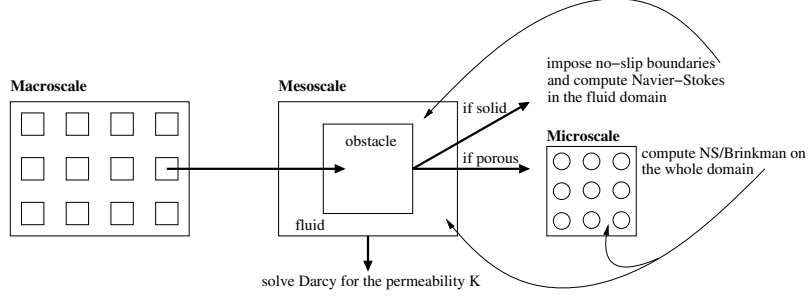


Fig. 3. The different scales and mathematical equations

where $\mathbf{u} = \mathbf{u}(x, y, z, t)$ and $p = p(x, y, z, t)$ for both the Brinkman and the Navier-Stokes equations. We assume ν and ρ to be constant when describing an incompressible Newtonian fluid and thus also in Darcy's law (1) for the computation of $\mathbf{K}$.

Homogenisation of the Stokes equations in a porous medium yields Darcy's law (1) on macro level and can be applied within the periodic domain of a textile (Fig. 3). In (Verleye et al., 2006) we show that solving equations (2) to simulate the fluid flow and then using Darcy's law to calculate the permeability, results in the same numerical value as using the definition of $\mathbf{K}$ arising from homogenisation theory.

The Navier-Stokes/Brinkman equations are seen as an extension of Darcy's law and as a practical way to deal with the coupled problem of flow in a porous medium and flow in the free fluid domain. Angot (Angot, 1999; Angot et al., 1999) showed that the Navier-Stokes/Brinkman model can be used for such situations with no explicit interface conditions. Thus, in (3) the additional term $\nu \mathbf{K}_{tow}^{-1} \mathbf{u}$ can be seen as a penalisation of (2). Equation (3) converges to equation (2) for large $\|\mathbf{K}_{tow}\|$. To compute the local permeability tensor $\mathbf{K}_{tow}$, the fibres of the yarns are locally approximated as a regular array of cylinders. The components of $\mathbf{K}_{tow}$ can then be calculated according to the formulas of Berdichevski (Berdichevski and Cai, 1993) and Phelan (Phelan and Wise, 1996):

$$K_l = \frac{d^2}{32V_f} \left(\ln \frac{1}{V_f^2} - (3 - V_f)(1 - V_f) \right); K_t = \frac{4d^2}{9\pi\sqrt{2}} \left(\sqrt{\frac{\pi}{4V_f}} - 1 \right)^{\frac{5}{2}}. \quad (4)$$

For yarns $\|\mathbf{K}_{tow}\|$ is typically $10^{-4} \leq \|\mathbf{K}_{tow}\| \leq 10^{-7}$. For such small $\|\mathbf{K}_{tow}\|$ we can expect that the term $\nu \mathbf{K}_{tow}^{-1} \mathbf{u}$ dominates over the viscous and convective terms in the internal part of the textile, and then Brinkman approximates Darcy.

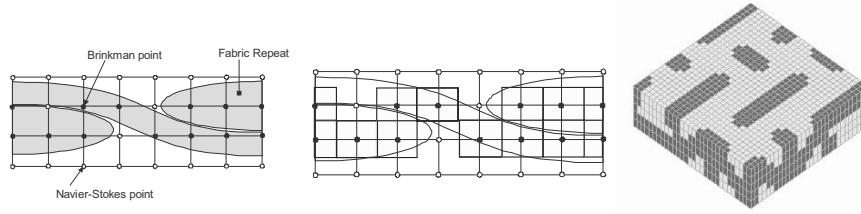


Fig. 4. A 2D-textile model (left) and its first order approximation on the grid (middle); 3D voxel geometry(right)

3 Numerical approach

3.1 Finite difference discretisation

Solution of the Navier-Stokes equations

For flow simulations in the irregular geometry of a textile, we have chosen to solve equations (2) numerically on a regular staggered grid with a finite difference discretisation. An example of a textile geometry and its discretisation on a regular grid is shown in Figure 4. In the staggered grid approach, the pressure is discretised at the center of the cells, while the velocities are discretised on the edges. This discretisation leads to a strong coupling between pressure and velocities, and therefore avoids the occurrence of unphysical oscillations in the pressure. One could also use an irregular (unstructured) grid and a finite element or finite volume discretisation. However, generating the appropriate 3D meshes for complex textile geometries is difficult and time consuming for these methods.

Geometry issues and boundary conditions

If we neglect the intra-yarn flow, the yarns are treated as impermeable. Each grid point is either located in the fluid domain ('fluid points') or in the solid yarn domain ('solid points'). At the boundaries between the fluid and the solid, no-slip boundary conditions are set. We have chosen a linear approximation of the solution at the boundaries:

$$V_{i,j,k} = -V_{i+1,j,k},$$

where (i, j, k) denotes a solid point, and $(i + 1, j, k)$ denotes a fluid point. We use a second order discretisation of the Navier-Stokes equations, but since the geometry is approximated to first order, we cannot expect second order accuracy near boundaries. Including a second order description of the geometry would not only lead to the geometry modelling problems that we avoid by using the finite difference method, but a second order approximation of

the boundary imposes additional numerical stability problems. Using a first order approximation of the yarns means that fine meshes are required to obtain an accurate result. Thus, for highly complex geometries we can distribute the according fine grids on parallel computers to speed up our permeability computations.

Solution of the Brinkman equations

The Navier-Stokes/Brinkman equations (3) are similar to equations (2), and the same discretisation methods are used. They have to be solved in the yarn points if we take intra-yarn flow into account. Therefore the local permeability tensor $\mathbf{K}_{tow}$ is first calculated by the formulas (4). The diameter d and the local fibre volume fraction V_f in the vicinity of the point, are provided by the WiseTex software. K_l is the permeability along the fibre, K_t stands for the permeability across the fibre. WiseTex also provides the direction of the fibres. K_l and K_t are projected onto the main directions X, Y, Z of the unit cell and those projections form the entries of the tensor $\mathbf{K}_{tow}$.

We now solve the Brinkman equations on the whole domain with $\|\mathbf{K}_{tow}\| = \infty$ at fluid points while for yarns $\|\mathbf{K}_{tow}\|$ is typically $10^{-4} \leq \|\mathbf{K}_{tow}\| \leq 10^{-7}$.

Implementation

A finite difference Navier-Stokes solver, NaSt3DGP, was developed by the research group of Prof. Michael Griebel at the Institute for Numerical Simulation at the University of Bonn (Griebel, 2004; Griebel et al., 1998). The flow solver employs a Chorin projection for the solution of the Navier-Stokes equations (2). In time-discrete notation the projection method is given by:

Step 1: Solve the momentum equations for an intermediate velocity field $\mathbf{u}^*$:

$$\frac{\mathbf{u}^* - \mathbf{u}^n}{\Delta t} + [\mathbf{u} \cdot \nabla \mathbf{u}]^n = \nu \Delta \mathbf{u}^n \quad (5)$$

Step 2: Project the vector field $\mathbf{u}^*$ on a divergence-free vector field $\mathbf{u}^{n+1}$:

$$\begin{cases} \mathbf{u}^* = \mathbf{u}^{n+1} + \Delta t \nabla p \\ \nabla \cdot \mathbf{u}^{n+1} = 0 \end{cases} \quad (6)$$

Applying the divergence operator to the first part of (6) results in a Poisson equation for the pressure which has to be solved in every time-step Δt . For the solution of the Poisson equation NaSt3DGP offers several iterative solvers like SOR, Red-Black Gauss-Seidel or BiCGStab. For the approximation of (5-6), the code provides several second order TVD upwind schemes for space discretisation and an explicit Euler as well as a second order Adams-Bashfort scheme for time discretisation. Furthermore, the code works completely in parallel on MPI (MPI, 1994) platforms.

Explicit treatment of the time-advancement of the momentum equations (5) yields a Courant-Friedrich-Levy (CFL) stability constraint for the convective terms, as well as a stability constraint for the diffusive terms depending strongly on the magnitude of the viscosity

$$\Delta t \leq \frac{1}{2\nu\Delta x^2}, \quad (7)$$

where Δx denotes the smallest grid resolution. This is a strong restriction on the time-step size, as in permeability computations we deal with Reynolds number $\text{Re} = \frac{1}{\nu} \approx 1$. In this low Reynolds number regime the CFL condition for the convective terms usually allows for a much larger time-step than (7). Therefore, it is desirable to treat the diffusive terms implicitly.

Semi-implicit solution of the Navier-Stokes equations

We opted for a second-order semi-implicit discretisation of the Navier-Stokes equations (2) given by

$$\begin{cases} \frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} + [\mathbf{u} \cdot \nabla \mathbf{u}]^{n+\frac{1}{2}} + \nabla p^{n+\frac{1}{2}} = \frac{\nu}{2} \Delta (\mathbf{u}^{n+1} + \mathbf{u}^n) \\ \nabla \cdot \mathbf{u}^{n+1} = 0. \end{cases} \quad (8)$$

In this representation

$$[\mathbf{u} \cdot \nabla \mathbf{u}]^{n+\frac{1}{2}} = \frac{3}{2} \mathbf{u}^n \cdot \nabla \mathbf{u}^n - \frac{1}{2} \mathbf{u}^{n-1} \cdot \nabla \mathbf{u}^{n-1}$$

denotes an explicit, second order Adams-Bashforth approximation of the convective term, while the diffusive terms are discretised with the Crank-Nicolson scheme and are treated implicitly. With this scheme we avoid the restriction of the time step (7) as well as the solution of a nonlinear system of equations. Again, we use a fractional step method to solve (8). In order for $\mathbf{u}^*$ to be a good approximation of the divergence-free velocity field $\mathbf{u}^{n+1}$, the pressure gradient is included in the momentum equations resulting in the following pressure-correction scheme as proposed by Bell et al. (Bell et al., 1989):

Step 1: Solve the momentum equations for the intermediate velocity field $\mathbf{u}^*$:

$$(I - \frac{\nu \Delta t}{2} \Delta) \mathbf{u}^* = \mathbf{u}^n - \Delta t \cdot \{ [\mathbf{u} \cdot \nabla \mathbf{u}]^{n+\frac{1}{2}} + \nabla p^{n-\frac{1}{2}} - \frac{\nu \Delta t}{2} \Delta \mathbf{u}^n \} \quad (9)$$

Step 2: Recover $\mathbf{u}^{n+1}$ from the projection of $\mathbf{u}^*$ by solving

$$\begin{cases} \mathbf{u}^* = \mathbf{u}^{n+1} + \Delta t \nabla \phi^{n+1} \\ \nabla \cdot \mathbf{u}^{n+1} = 0 \end{cases} \quad (10)$$

Step 3: The new pressure is now found by computing

$$p^{n+\frac{1}{2}} = p^{n-\frac{1}{2}} + \phi^{n+1} - \frac{\nu \Delta t}{2} \Delta \phi^{n+1} \quad (11)$$

The last term in this equation was introduced by Brown et al. (Brown et al., 2001) in order to be consistent with a second-order accurate discretisation of the Navier-Stokes equations.

Altogether, this kind of implicit treatment of the Navier-Stokes equations yields three modified Helmholtz equations (9) for the velocities in addition to the Poisson equation for the pressure. For the solution of these equations we employ an SSOR Preconditioned Conjugate Gradient Method. The step size is now only limited by the CFL condition and by accuracy considerations. Compared to the explicit solver, the extra computational costs per iteration for the semi-implicit solver do not outrun the gain due to the larger time steps: computations of the permeability can be obtained much faster with this method as will be shown in the next section.

Further Improvements

In order to perform permeability calculations, we have made several further extensions to the NaSt3DGP code. For the unit cell setup, we implemented periodic boundary conditions in three directions for the velocity, and periodic boundary conditions up to a constant gradient for the pressure (Fig. 1). Discretisation of the Brinkman equations leads to a straightforward implicit implementation of the additional term $\nu \mathbf{K}_{tow}^{-1} \mathbf{u}$ in the momentum equations (5).

Using the computed average velocity over the whole domain at steady state, the permeability $\mathbf{K}$ is derived from Darcy's law (1). As a stopping criterion we use convergence of the permeability $\mathbf{K}$ up to a predefined threshold ε . Furthermore, for the input of the geometry, an interface between WiseTex and the Navier-Stokes and Brinkman code has been developed.

3.2 Lattice Boltzmann Method

The lattice Boltzmann model (LBM) is a mesoscopic approach to fluid dynamics and is based on the solution of a Boltzmann equation on a regular grid. The LBM applies for a large scale of macroscopic equations. It has been shown that the LBM can be used to simultaneously solve equations (2) and (3) (Spaid and Phelan, 1997). For our purpose, we have chosen to implement the permeability model based on the LBM D3Q19. Here, "Q19" describes the connectivity pattern of the 3D lattice: every cell is connected with its neighbour and its next-nearest neighbours.

A disadvantage of the LBM is the prescribed constant lattice step in all directions, which may result in unnecessary large lattice sizes. Note that this is not the case with the finite difference discretisation. The lattice of the LBM also contains three kinds of cells: fluid cells, solid cells and Brinkman cells. For

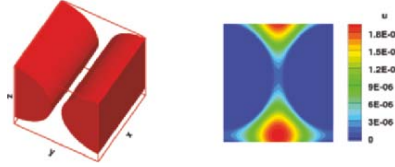


Fig. 5. Unit cell of the impermeable parallel square array with 62% volume fraction (left), 2D cut of the computed velocity field (right) $\Delta x = 0.025$

the implementation of the non-slip boundary condition, the bounce-back rule is used. For the prediction of the flow in Brinkman cells, the local permeability is calculated as described in section 3.1 and then included in the LBM.

The described LBM has been implemented as a module for the FlowTex software at the K.U.Leuven. For more details on this module, we refer to (Belov et al., 2004).

4 Results and Validation

Validation tests with the lattice Boltzmann module and the finite difference module show good results. As described in the introduction, our software can be used to calculate the permeability of all textile models produced with WiseTex. We present the results of the simulation of a flow through a parallel array of cylinders, and of two realistic reinforcements for which we have experimental verification. Forward Euler time-integration, and the VONOS (Varonos and Bergeles, 1998) scheme for spatial discretisation were used in the finite difference method and its performance and accuracy will be compared to semi-implicit (Crank-Nicolson) time-integration. In both cases the BiCGStab (van der Vorst, 1992) method with Jacobi preconditioning was used to solve the pressure Poisson equation.

4.1 Parallel Square Array

Impermeable Array

For the flow through a parallel array of impermeable tows (Fig. 5), theoretical, numerical and experimental data are available (Gebart, 1992; Westhuizen and Plessis, 1994). Results can be found for different fibre volume fractions, i.e. different radii (R) of the cylinders. Figure 6 shows the theoretical permeability, together with the calculated permeability, both for flow along the cylinders and for transversal flow. The graph also shows a comparison between the permeabilities obtained with the finite difference Navier-Stokes solver and the lattice Boltzmann method. For the example of two volume fractions, Table 1

Vf	Δx	#gridpoints	#iterations	K_{along}
20	0.1	1000	1200	0.05876
	0.05	8000	3900	0.04881
	0.03	35937	10100	0.04626
	0.025	64000	19100	0.04537
62	0.1	729	350	0.004906
	0.05	5832	850	0.003374
	0.03	27000	2100	0.003337
	0.025	46656	2950	0.003178

Table 1. Finite difference Navier-Stokes solver: results for the parallel square array setup: number of required iterations for the Poisson solver and computed permeability for different fibre volume fractions and mesh sizes

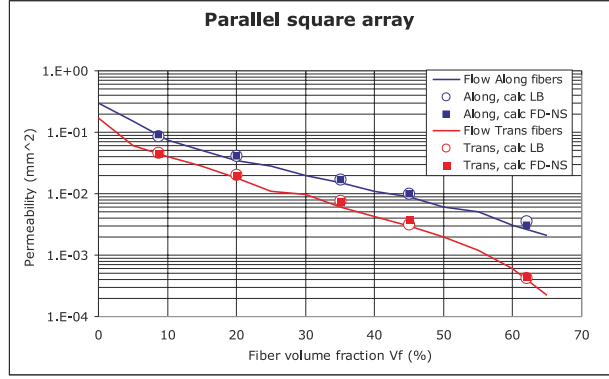


Fig. 6. Permeability for the parallel square array setup with different fibre volume fractions. Full lines: theoretical permeability; circles: lattice Boltzmann results; squares: finite difference Navier-Stokes results

shows the calculated permeabilities for different grid spacings: the permeability converges to the analytical value, as Δx decreases.

On a finer mesh more iterations for the Poisson solver are required (Table 1) because of two reasons. First, a finer mesh requires a smaller time-step, and therefore, more time-steps have to be taken. In the semi-implicit case the time-step may not be chosen much larger than the local mesh size, in order to obtain accurate results and in the explicit case it has to satisfy the even stronger restriction (7). Second, the preconditioned BiCGStab scheme for the Poisson equation converges more slowly to a solution on a finer mesh (Briggs et al., 2000), so in each time-step more iterations are required.

	Explicit	Semi-Implicit
#iter. Poisson	187713	14309
#iter. Helmholtz	0	893
Δt	$3.12 \cdot 10^{-5}$	$9.37 \cdot 10^{-4}$
$K_x (mm^2)$	$3.784 \cdot 10^{-3}$	$3.774 \cdot 10^{-3}$
Comp. Time	50m23s	03m37s

Table 2. Computational results of the semi-implicit Adams-Bashforth-Crank-Nicolson vs. the explicit Forward Euler method

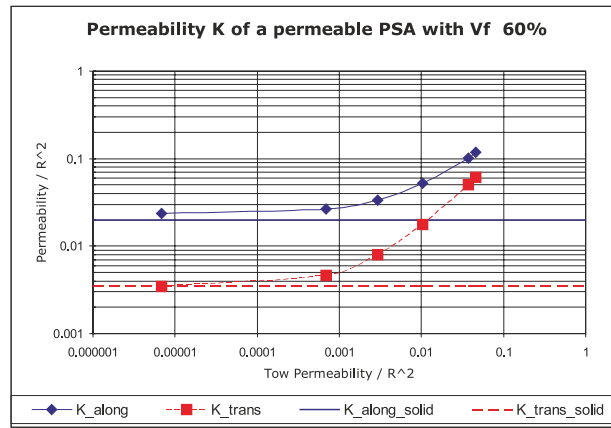


Fig. 7. Permeability of a Parallel Square Array with different local permeabilities

Semi-implicit calculations

Semi-implicit and explicit time-stepping are compared for an impermeable array of cylinders with a fixed volume fraction of 60% (Table 2). Permeability calculations are carried out on a (40^3) grid. Stopping criterion is convergence of the permeability. Both calculations are performed on an Intel(R) Xeon(TM) CPU, 3.20GHz.

The time-step size for the semi-implicit calculations is 30 times larger than for the explicit case. This does not result in a speed up in computational time of the same factor because of the extra costs of solving three Helmholtz equations per time-step. Still, in this case, the implicit solver is about 14 times faster than the explicit solver. Both methods result in accurate permeability values.

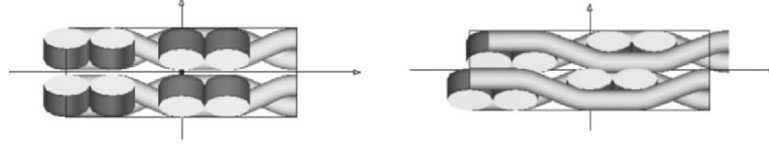


Fig. 8. Two layer model of the monofilament fabric; left: no nesting, right: maximum nesting

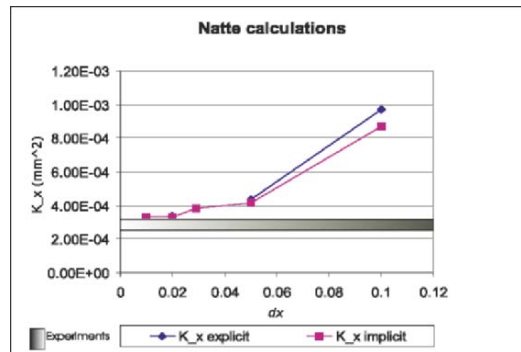


Fig. 9. Permeability K_x of the Natte textile as a function of the grid spacing Δx

Permeable array

Figure 7 shows the results of permeability predictions with the Navier-Stokes/Brinkman solver. For a fixed volume fraction (60%), the permeability is calculated for different cylinder permeabilities $\mathbf{K}_{tow}$. For large $\|\mathbf{K}_{tow}\|$, the permeability of the unit cell increases to the permeability of an empty cell. As $\|\mathbf{K}_{tow}\|$ decreases, the cylinders become more and more solid and the unit cell permeability converges to the permeability of an impermeable array.

4.2 Monofilament fabric

The Monofilament fabric Natte 2115 is a more realistic structure which is close to actual textile reinforcements, and for which permeability is experimentally validated. The full description of the Monofilament Fabric Natte 2115 test-fabric can be found in (Hoes, 2003; Hoes et al., 2001). The yarns are impermeable, so the Navier-Stokes equations are solved. Figure 8 shows two layers of the WiseTex model of the textile with no nesting, and on the right the output of the LamTex software, with the two layers maximally nested. Table 3 compares the results of calculations on the single layer model, the two layer model with maximum and random nesting with the experimental

Model	Permeability (mm^2)
Single layer	3.44 E-04
Random nesting	$3.24 \text{ E-04} \pm 1.03 \text{ E-04}$
Maximum nesting	1.54 E-04
Experimental	$2.7 \text{ E-04} \pm 10\%$

Table 3. Results for the Monofilament Fabric with different nesting

result. The permeability of the model with random nesting is the average of 15 calculations on models with different random nesting. The experiments were performed with several layers of Natte to fit into the experimental setup. The layers are compressed in the mould cavity, which leads to a random nesting. The random nesting parameters of LamTex are however not fitted to the laying up process. In table 3 we see that the experimental value is in between the single layer and the maximum nesting value, which is an acceptable result. Calculations are carried out with semi-implicit as well as explicit time-integration. Figure 9 shows, for the single layer model, that the predicted permeability depends strongly on the grid spacing. The first order discretisation of the geometry leads to a slightly different actual geometry. Hence on a coarse grid, we actually solve a different problem, which leads to a higher permeability. Furthermore, with semi-implicit time-stepping the calculated permeability is smaller than in the explicit case, but for a finer mesh this difference tends to zero.

4.3 Non crimp carbon fabric

Figure 2 shows -among others- a model of a non crimp fabric. We present experimental verification for two different non crimp carbon fabrics: a biaxial and a quadriaxial carbon fabric. Table 4 shows the most important parameters to describe the fabrics; for a more detailed description we refer to (Lomov et al., 2002a). On the biaxial structure, three institutes performed the experiments: MTM (K.U.Leuven), EPFL (Lausanne) and Ecole des Mines (Douai). The experimental results are shown in Figure 10, together with the permeabilities computed by solving the Navier-Stokes/Brinkman equations (3). The parameters of the computational unit cells are summarized in table 5. The table also shows a comparison between the permeabilities computed in the case that intra-yarn flow is taken into account and in the case that the yarns are treated as impermeable. Note that the resolution in z -direction is higher than the resolution in x, y -direction, which is not possible if we use the lattice Boltzmann solver (see 3.2).

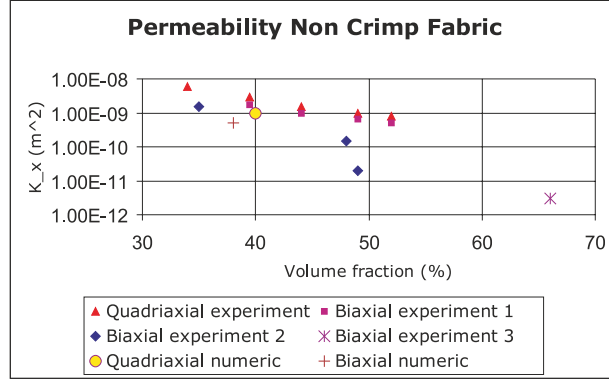


Fig. 10. Permeabilities of the non crimp fabric: two numerical values and the results of experiments

Fabric name	Number of plies	Orientation of plies (degrees)	Mass of the fabric (g/m^2)	Stitching pattern
Biaxial	2	+45;-45	322 ± 16	Tricot
Quadriaxial	4	0;-45;90;-45	629 ± 31	Tricot-warp

Table 4. Parameters of the non crimp carbon fabrics

Preform name	Δx	Δy	Δz	x	y	z	$K_{xx}NS$	$K_{xx}NS/B$
Biaxial	0.04	0.04	0.03	3.4	4.92	0.45	2.78E-04	5.04E-04
Quadriaxial	0.055	0.055	0.045	8.195	5.06	0.945	5.27E-04	9.44E-04

Table 5. Parameters of the non crimp fabrics unit cells and computational results with the Navier-Stokes (NS) and Navier-Stokes/Brinkman (NS/B) equations. Units are mm and mm^2

5 Conclusions

We presented a software package for the computation of the permeability of textile reinforcements.

First a textile model is designed with the WiseTex or LamTex software. An accurate model is required as slight differences in the model lead to different permeabilities. Using the model resulting from WiseTex or LamTex, flow simulations are performed to predict the permeability. We have chosen to solve the Navier-Stokes and Navier-Stokes/Brinkman equations with the finite difference method and we compare the results with those obtained with a lattice Boltzmann method.

Both methods were validated on a parallel array of cylinders. For impermeable arrays, the calculated permeability can be compared with theoretical results. Both the finite difference Navier-Stokes and the lattice Boltzmann solver give accurate results for such setup. For permeable arrays theoretical results are not available, but the predictions of the Navier-Stokes/Brinkman solver, including the intra-yarn flow, show good convergence to the results of the Navier-Stokes solver in case the permeability of the array tends to zero. To evaluate permeability calculations for real textiles, we presented validation results for a monofilament fabric Natte and a Non Crimp Fabric fabric, for which experimental data are available.

In order to speed up permeability computations we implemented a semi-implicit pressure-correction method for the finite difference Navier-Stokes (/Brinkman) solver. With this numerical method a substantial reduction of computation time has been observed in all calculations.

6 Further research

Further validation of the software is necessary. Textile design engineers not only need correct permeability results, they also need them fast during the design process. Although the software is already useful for designing purposes, we will include more numerical improvements to speed up the calculations.

The presented results are accurate. However, permeability is sometimes slightly overestimated. This may be due to the models used, which ignore physical phenomena (e.g. moving textile boundaries) as well as to the first order discretisation of the boundaries. The improvement and extension of these models towards e.g. higher order boundary conditions is part of our ongoing research.

Acknowledgements

This research is part of the IWT-GBOU-project (Flemish government, Belgium): *Predictive tools for permeability, mechanical and electro-magnetic properties of fibrous assemblies: modeling, simulations and experimental verification*.

Roberto Croce and Margrit Klitz were supported in part by the Sonderforschungsbereich 611 *Singuläre Phänomene und Skalierung in Mathematischen Modellen* sponsored by the *Deutsche Forschungsgemeinschaft*.

The authors thank V. Michaud from EPFL, Lausanne, for the permission to use the data from figure 10.

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Part III

Computer Aided Garment Design

Measuring Geodesic Body Measurements with Distributed Collocation Method

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Abstract

For the application of 3D body scanning in the apparel industry, measurements extraction is a minimal feature of the system. Standard commercial 3D garment CAD systems offer only linear measurements, such as height and width, and cross-sectional measurements, such as girth. However, much useful information in apparel design requires arc length distance along the body surface. These geodesics are not available, because the calculation of geodesics is nontrivial, and can only be approximated for free-form surfaces. This is because the computation of geodesics requires solving a set of ordinary differential equations (ODE), which do not have any closed form general solution for free-form surfaces. In this article, distributed collocation method is used in solving the geodesics equations based on the bicubic tensor product Bezier patches.

1 Introduction

A Geodesic is the locally minimal arc between two points on a surface. From the theory of Differential Geometry, a local geodesic satisfies a pair of ODEs, (1) and (2), defined using the Christoffel symbols, Γ_{jk}^i . The complexity of solving the geodesic equations depends on the complexity of the surface. Typically, the solutions of geodesics on free-form surfaces do not exhibit any closed form. For this reason, numerical method must be used to approximate the value.

$$GE_1(u, v) = u'' + \Gamma_{11}^1(u')^2 + 2\Gamma_{12}^1u'v' + \Gamma_{22}^1(v')^2 = 0 \quad (1)$$

$$GE_2(u, v) = v'' + \Gamma_{11}^2(u')^2 + 2\Gamma_{12}^2u'v' + \Gamma_{22}^2(v')^2 = 0 \quad (2)$$

The numerical methods being used can be typically classified into two classes according to whether the surface is continuous or discrete. In solving the geodesics on continuous surfaces, one usually solves the differential numerically. Gray (1993) presented a numerical scheme of solving the geodesic equation (1) and (2) with uv -parametrization using the MathematicaTM software. Maekawa (1996) presented another numerical scheme based on finite difference method. A survey of numerical schemes for solving differential equations and integral equations is available in Cheney (2001).

On the other hand, another class of techniques is used for discrete surfaces, such as polyhedral surfaces. Polthier and Schmies (1998) derived the light ray tracing method of shooting the end point of the geodesics along the polyhedral surface. Pham-Trong, Szafran and Biard (2001) presented their work on finding the discrete geodesics using the subdivision of patches with unfolding, so that the beam propagation can

reach the destination point on the other end of the geodesics. Ravi Kumar, Srinivasan, Devaraja Holla, Shastry, and Prakash (2003) introduced modified version of Polither and Schmies' work, by considering the normal information of the surface. They demonstrated on the NURBS (Non-Uniform Rational B-Spline) and compared to the numerical solutions. Kimmel and Sethian (1998) demonstrated the application of the Fast Matching Method in finding the geodesic paths on a triangularly meshed surface.

In the current study, the distributed version of collocation method is used to solve the geodesic equations on a family of bicubic tensor product Bezier surface patches under uv -parametrization.

The application of geodesic is popular in physics and engineering. In the 3D garment pattern design, a surface mapping technique, Bijective Pattern Map (1996), unfolds the 3D surface patches into 2D enclosed areas using the geodesic information on the 3D mannequin. Manually, the body measurement can be measured by using a tensioned measuring tape. In a virtual world, as a free-form surface, the 3D virtual mannequin can be represented as an atlas of tensor product Bezier or B-Spline or NURBS surface patches. In this case, the body measurement, such as the armhole circumference, Fig. 1, can only be calculated using the geodesic arc length.

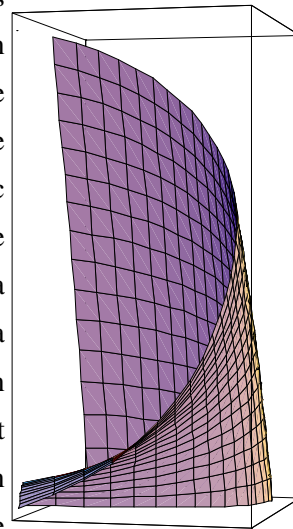


Fig. 1. Armhole Curve

In this article, the calculation of the geodesic will focus on a class of non-self-intersecting surface patches, defined using the bicubic tensor product Bezier form. With the scalable properties, it is possible to reduce the problem by considering only the normalized patches, lying within the unit cube. The numerical algorithm is based on the collocation method (Cap 2003). The choice of the collation points and trial functions will be presented. The computational experiment will be introduced and the result will be compared to the physical data measured from the mannequin. Finally, to speed up the performance of the calculation, the author has enhanced the algorithm into parallel codes. All the programs are written using Mathematica™ version 5.0.

2 Preparation of Surface Patches

A family of normalized bicubic tensor product Bezier surface patches is defined over the unit cube with the longest side of the patch aligned with the line segment of $[0,1]$ along the x -axis. As the bicubic tensor product patch representation is fully scalable, this representation can cover the whole family of bicubic tensor product Bezier surface patches, since any finite bicubic tensor product Bezier surface can be enclosed by a cubic of size equals to the longest straight line distance between any pair of control vertices.

The normalization process can be achieved by these transformations:

Stage 1: /* set origin, force all points into positive zone */

$$P_i = p_i - \text{Min}(p_i) \quad (3)$$

Stage 2: /* scale to fit the unit cube */

$$P'_i = P_i / \text{Max}(P_i) \quad (4)$$

where p_i are the initial data points, P_i are the translated points, and P'_i are the normalized points with $\text{Min}()$ and $\text{Max}()$ to be the minimum and maximum function respectively. It should be noted that when the $\text{Min}()$ is taken over the ordinates individually, the data points are guaranteed to be translated into the positive zone of $\{x, y, z : x \geq 0; y \geq 0; z \geq 0\}$. However, any of the data points may not be located at the origin. Yet, at least one of the data points can be found on the surface of the unit cube.

3 Preparation of Collocation Points

The geodesic from a point c_0 to another point c_1 along the bicubic tensor product Bezier surface patch $S(u, v)$ is intended to be written in the form of a parametric curve $a(t)$ with the end points matching the boundary condition of $a(0) = c_0$ and $a(1) = c_1$. The collocation points are thus defined as the set of N chosen points $\{a(t_i)$ where $i = 1 \dots N$, and each t_i lies in the range of $(0, 1)$. In this study, the collocation points are evenly distributed along $(0, 1)$. Based on the experience with using collocation method, the collocation points must be chosen in a way to ensure the non-degenerate determinant of the matrix derived by submitting the trial functions and combining the matching requirement at the collocation points.

4 Selection of Trial Function

The trial functions $geo_1(t)$ and $geo_2(t)$ are both selected to be a polynomial with coefficients $\{a_i\}$ and $\{b_i\}$ respectively, on t of order matching the conditions available, including the pair of geodesic ODEs, the boundary conditions and the matching at the collocation points. The $geo_1(t)$ corresponds to the u -parameter while the $geo_2(t)$ corresponds to the v -parameter. Since the surface is represented in the form of $S(u, v)$, the

$GE_1(u, v)$ and $GE_2(u, v)$ can in fact be written as $GE_1(t) = GE_1(u(t), v(t))$ and $GE_2(t) = GE_2(u(t), v(t))$ respectively by substituting:

$$geo_1(t) = u(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \dots \quad (5)$$

$$geo_2(t) = v(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + \dots \quad (6)$$

5 Preparation of Matrix Equation

In this study, the scope is limited to the geodesics across the diagonal of the surface patch, because such measurements are most commonly used in the Bijective Pattern Map. By substituting the definition of $S(u, v)$, the $geo_1(t)$ and $geo_2(t)$ into the pair of geodesics equations, two equations are found, $GE_1(t)$ and $GE_2(t)$. [Note that these two equations with the unknown coefficients are very long and are omitted.] By matching the boundary conditions, four more equations are found, (7) to (10). Finally, requiring a perfect match of the estimation by $geo_1(t)$ and $geo_2(t)$ at the collocation points t_i , $2N$ equations are found, (11) and (12). These equations can be written in the matrix form.

$$u(0) = 0 = a_0 \quad /* u(0) */ \quad (7)$$

$$v(0) = 0 = b_0 \quad /* v(0) */ \quad (8)$$

$$u(1) = 1 = a_0 + a_1 + a_2 + a_3 + \dots \quad /* u(1) */ \quad (9)$$

$$v(1) = 1 = b_0 + b_1 + b_2 + b_3 + \dots \quad /* v(1) */ \quad (10)$$

/* perfect match at collocation points */

$$GE_1(t_i) = 0, i = 1 \dots N \quad (11)$$

$$GE_2(t_i) = 0, i = 1 \dots N \quad (12)$$

After the substitution process is completed, they form a matrix equation. It is important to check and ensure the determinant of this matrix equation to be non-zero, so that solution can be guaranteed. In case, the determinant is zero, the choice of collocation points must be revised.

As an example, from the experience of calculating the geodesics on the bicubic tensor product Bezier surface patches when developing the Bijective Pattern Map, quadratic polynomial could be sufficient for patches with small Gaussian curvature. In that case, six equations (two from (1) and (2) and four from (5) and (6)) will be derived with two boundary points and one collocation point. When higher order trial function is used, more collocation points are needed to solve the extra coefficients. If the determinant of the matrix of the equation is zero, another set of collocation points falling in between the existing collocation points can be chosen or the degree of trial function can be elevated.

6 Data Preparation

6.1 Testing Data

The testing is prepared based on the following criteria:

- i. One corner point is now fixed at $(0, 0, 0.5)$.
- ii. The boundary line containing this corner is positioned along the line $\{(0, y, 0.5), y \text{ belongs to } [0,1]\}$.
- iii. All other corresponding control vertices are positioned at $\{(x, y, z), x \text{ belongs to } \{0.35, 0.65, 1\}, y \text{ belongs to } \{0.35, 0.65, 1\}, z \text{ belongs to } \{0, 0.25, 0.5, 0.75, 1\}\}$.

The total sample size is thus 12 points at 6 possible heights = 72 choices. Then, the control vertices can randomly move within a radius of 0.175, while a total 1000 samples are selected. The samples are divided into four groups of data. In this configuration, some of the patches can have local optimal values but uniqueness of the geodesics is not guaranteed, as conjugate points may exist. Yet, as long as the control points do not intersect each other, the surface patch does not intersect itself. The surface is also ensured to be compact and continuous.

6.2 Evaluation Data Based on Ritz's Method

The full set of testing normalized bicubic tensor product Bezier surface patches was run again using another numerical method. Among many choices, the Ritz's method was chosen because it is a popular numerical technique for Calculus of Variation (1963). The basis function for the Ritz's method was chosen to be polynomial in the form of (13) and (14). In this case, the v -parameter becomes a function of u -parameter. The values of geodesic distances were compared to those of the collocation method.

$$u(t) = t \quad (13)$$

$$v(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 + \dots + c_n t^n \quad (14)$$

6.3 Evaluation Data From Physical Objects

One more set of physical data measured directly from a mannequin was prepared for comparison. In previous study, the modeling of human mannequin using bicubic tensor product Bezier patches had been demonstrated with reasonable accuracy if the patches were properly defined (Ng 1998).

The mannequin was digitized by a 3D body scanner and stored in the form of a bicubic tensor product Bezier surface atlas. The lengths of the boundary curves of each patch were ensured to be equal to the physical value. Then, both of the diagonal lengths were measured and used as the reference physical data, and compared to the computer-calculated values.

7 Solving Matrix Equation

The matrix equation derived according to section 5 was solved using the built-in equation solver of Mathematica™ 5.0. However, an adaptive scheme must be used to select different collocation points because it is possible that some pairs of collocation points do share some kind of symmetry, meaning that the rank of the matrix equation may be reduced. In these cases, other collocation points must be used. For example, $\{0.35, 0.65\}$ can be replaced by $\{0.2, 0.8\}$ or $\{0.4 \text{ and } 0.6\}$.

It should be noted that the matrix equation is nonlinear with respect to the coefficients a_i and b_r , as the surface patches are in the bicubic tensor product form. Therefore, there can be one or more real solutions even for the quadratic trial functions. Each solution set in the coefficient must be testified and compared to determine the global optimal solution set. During the calculation by Mathematica™, the response was very slow when cubic polynomial trial functions were used. So, in this study, the results are based on the quadratic polynomial trial functions.

8 Evaluation of Result

The computation speeds of both methods were measured using the TIMING command of the Mathematica™. Since there are many common

codes shared by both methods, the timing of the collocation method included the execution of the following lines in pseudo MathematicaTM code, Table 1, while the counter part for the Ritz's Method is listed in Table 2. The parallel pseudo code of collocation method is listed in Table 3.

Table 1. Kernel of sequential collocation method

```

Generate_Equation_Time =
  Timing[Generate_Equations_of_Collocation_Points;
  Repeat[Equation_Degenerate,
  Use_Other_Collocation_Points;
  Generate_Equations_of_Collocation_Points;];
  Answer = Solve_Matrix_Equation;
  Return[Answer];];];
Generate_Arc_Length_Time =
  Timing[Mini_Arc_Length = Infinity;
  For[i = 1; i<Number_of_Answer,
    Arc_Length = Calculate_Arc_Length[Answer[[I]]];
    Mini_Arc_Length = Min[
    Mini_Arc_Length, Arc_Length]; I++];];
(* i is the counter *)
Total_Time = Generate_Equation_Time +
  Generate_Arc_Length_Tim;

```

The sample report of the result is listed in Table 4. The comparative result between collocation method and Ritz's method is summarized in Table 5. The Relative Root-Mean-Square Error (RMS), (15), is used to indicate the differences in the accuracy of the geodesic distance from collocation method, gC , and the geodesic distance from Ritz's Method, gR ,

while a relative ratio (16) is used for the improvement of the computation time, tR for Ritz method and tC for collocation method. The result is presented in six significant figures in the normalized unit.

$$\text{Sign}(gC - gR) * \text{Sqrt}(\bullet(((gR - gC) / gR)^2)) \quad (15)$$

$$(tR - tC) / tR \quad (16)$$

[Note: Sqrt is the square root function.]

Table 2. Kernel of ritz's method

```
Total_Time =
Timing[Initialize_Variation_Parameter;
  Initialize_Max_Iteration;
  Error = Infinity;
  Geodesic = Infinity;
  Repeat[Error > Error_Bound
    && J < Max_Iteration,
    Increase_Order_of_Basis_Function;
    Substitute_Differential_Equation;
    Prepare_Matrix_Equation;
    Solve_Variation_Parameter;
    Arc_Length = Verify_Variation_Parameter;
    Error = Abs[Geodesic — Arc_Length];
    Geodesic = Min[Geodesic, Arc_Length];
    J++; ]; (* J is the iteration counter *)
```

Table 3. Distributed collocation method in parallel

```

Inititalize_Fundamental_Form_Table;
Selection_of_Collocation_Point;
Remote_Evaluate[
  Repeat[Equation_Degenerate,
    Update_Collocation_Points;
    Generate_Equations_of_Collocation_Points;]; ];
Collect[Equations];
Answer = Solve_Matrix_Equation;
Mini_Arc_Length = Infinity;
Remote_Evaluate[For[i = 1; I < Number_of_Answer,
  Arc_Length = Calculate_Arc_Length[Answer[[I]]];
  Mini_Arc_Length = Min[
    Mini_Arc_Length, Arc_Length]; I++];];
Return[Mini_Arc_Length];

```

Table 4. Sample data output table

Distributed Collocation Method		Ritz's Method	
Normalized Unit	Second	Normalized Unit	Second
1.79237	0.047	1.79179	0.141
1.86393	0.031	1.85298	0.125
1.79204	0.016	1.7876	0.125

Table 5. Comparison of collocation method and Ritz method

Set	Mean Accuracy Loss	Mean Time Improved
1	-0.19%	358%
2	-0.26%	355%
3	-0.23%	337%
4	-0.21%	337%

Finally, a set of sample geodesic distances calculated using the collocation method according to a scanned image was compared to the geodesic distances measured physically. Since the measuring tape has an accuracy marking of 0.1 cm, the calculated geodesic distances are rounded up to two decimal places. The relative error was measured according to (17), with gP representing physical geodesic. The result is shown in Table 6.

$$\text{Sign}(gC - gP) * \text{Sqrt}((gP - gC)/gP)^2 \quad (17)$$

9 Comments on Collocation Method

According to the current pilot study, the advantages of using the distributed collocation method include:

- i. Efficient method with reasonably accuracy even when low order of trial function to be used,
- ii. Ease of software implementation.

Yet, this method has the following disadvantages:

- i. Efficiency drops when more collocation points are used;
- ii. The convergence of the matrix equation solving may take much longer time when higher order trial function is used.

Table 6. Comparison of calculation by collocation method and physical data

Data	Calculated by Collocation Method	Physical Data (cm)	Relative Error (%)
1	15.53	15.3	1.50
2	15.39	15.3	0.59
3	16.87	16.6	1.63
4	17.37	17.4	-0.17
5	34.02	33.7	0.95
6	31.62	31.6	0.06

The typical computation of sequential collocation method based on quadratic polynomial trial functions, implemented on a dual Xeon™ 1.8 GHz personal computer under Mathematica™ Version 5.0, takes 20 seconds to generate 100 geodesic distances. This method can be very time consuming as the degree of the basis function increases.

Therefore, the canonical strategy to speed up the computation is to increase the CPUs in the distributed version. As the collocation points are independent to each other when computing the geodesic equations, the Parallel Computing Toolkit, an application package of Mathematica™, can reduce the aggregate computing time. In the parallel computing toolkit environment, more CPU can be accessed via the network connection. After the connection has been established between the master node and the slave nodes, the definitions can be exported to the slave nodes. The computational assignments can then be distributed to the slave nodes. In the current project, since the computer is equipped with dual Xeon CPU, one of them acts as the master and the other as a slave.

10 Conclusion

In the pilot study, the geodesic equations on the subset of bicubic tensor product Bezier have been solved numerically by using the distributed collocation method. The results of computing the geodesics by distributed collocation method are compared to that by the Ritz's method. The agreement between these two methods is acceptable, while the computation efficiency of collocation method is higher. Moreover, the accuracy of computing geodesics on the virtual mannequin is found satisfactory (similar error level of taking the manual measurements) when compared with the physical measurements on the physical counterpart. The future work is to extend the study to at the full scale and proceed with the theoretical analysis.

Acknowledgment

This project is financially supported by the Polytechnic University Research Grant, A/C PE04. The authors would like to express their gratitude to the funding body. Special thank to Mr C.F. Li, who prepared the physical body measurements.

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Isomorphic Mesh of Human Body Surface for Computerized Apparel Design

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Abstract

Recently, rapid measurement of human body surface shape has become general. A problem in utilizing this measured data of is expression of the data. For this purpose, a concept of isomorphic mesh was presented. An isomorphic mesh is a mesh of human body surface shape generated applying geometrical rules based on some landmarks on human body surface. A program was constructed to generate an isomorphic mesh from measured human body surface shape. This program consists of two parts, a part that generates a fine mesh from a measured data cloud and a part that generates an isomorphic mesh from the fine mesh and coordinates of landmarks. The isomorphic mesh of three mannequins at the age of twenties, forties and seventies were generated for trial.

Keywords: 3-D measurement, static body model, isomorphic meshes, human body surface shape

1 Introduction

Clothes have a wide variety from those produced with mass production system at a low cost to those produced with order made at a high cost. Recently, a concept of “mass customization” (Certain and Stuetzle 1999) has been presented. The concept of mass customization means that consumers can obtain

nicely fit clothes at a low cost. To make the cost of mass customization lower, 3-D measurement and computer technology should be utilized.

For an application of computer technology to apparel field, we have developed a simulation technique for clothes (Okabe et al., 1992), and a technique to develop human body surface shape to paper pattern (Okabe et al., 2000). Using this simulation technique, we can predict a shape of clothes put on a dummy body. The mechanical calculation for the prediction is executed with information of pattern shape, mechanical properties of fabrics and human body shape. The technique to develop body shape to paper pattern was formalized as an inverse problem of the prediction of clothes shape.

Another technical element for mass customization is acquisition of human body shape. With development of measurement instruments for 3-D scan, it becomes possible to measure human body surface shape quickly and precisely. Data cloud of human body surface shape can be obtained with 3-D scanner. Human body data should be reconstructed, because the data cloud has no structure and its data amount is huge. For our purpose of apparel design, static human body model correctly reconstructed its shape is required.

To this purpose, we introduced a concept of isomorphic mesh. An isomorphic mesh is a mesh with a pre-designed structure. An isomorphic mesh is obtained by applying the mesh structure to human body shape measured with 3-D scanner. Although human body shape differs person to person, the structure of the isomorphic mesh is always identical.

In the Following sections, we present the procedure generating an isomorphic mesh. First, landmarks and borderlines of human body segments are marked on human body surface before measurement. A human body surface is scanned and then a data cloud of surface shape and images are obtained. A structured fine mesh is generated using the data cloud, and coordinates of the landmarks are extracted from the data and the images. Positions of the landmarks can be edited if it is necessary. The mesh is divided into segments with the borderlines of body segments. An isomorphic mesh is generated applying rules to the mesh based on the landmarks.

2 Previous Works

There are two main aspects about researches or projects of human body surface shape. One is 3-D measurement and the other is animation. About 3-D measurement, landmarks, precision of measurement and representation

of surface shape have been studied. Skeletal models to animate face or body, and methods to move face or body surface according to movements of skeletal models have been studied. To determine surface shape of face or body, at first sizes or photographs were utilized and now 3-D scanned data.

In some countries, there used to be national projects to measure many human body surface shapes. More than ten years ago, this kind of project started in Japan (HQL). There were the same kind of projects, size US (sizeUS), size US (sizeUK) and size KOREA (sizeKOREA). In CAESAR project (CAESAR), measurements were done both in US and Europe. All the projects have finished and the results are published now. Now in Japan, 2nd round measurement is now under progress after an interval of more than ten years. In Europe, there used to be another kind of project “e-Taylor” (e-Taylor). This project was aiming at an innovation of clothing industries.

Followings have been studied about human body data obtained with 3-D scanner. Nurr and Lewark (Nurre 1997; Lewark and Nurre 1998) presented software for locating or labeling anthropometric landmarks from a 3-D data cloud of human body shape. We also located landmarks on which markers were pasted for measurement with software, and software for editing landmarks was added.

Mckinnon and Istook (Mckinnon and Istook 2000) discussed precision of human body shape data obtained 3-D scanner and effect of aspiration to the data. Bougourd et al., (Bougourd et al., 2000) compared results of anthropometric measurements by traditional hand methods and 3-D scanner. Good correspondence was obtained on many measurements, but posture or location of landmarks affected on some measurements. This was a preparatory study for size UK. Robinette and Daanen (Robinette and Daanen 2006) analyzed precision of data obtained in CAESAR project.

Li and Jones (Li and Jones 1997) presented a method to segment 3-D human body surface scan data based on 2-D projection. Nurr et al. (Nurre et al., 2000) developed software to categorize a cloud of human surface shape data points to segments. Discrete point cusp detector is a main algorithm adapted to the software. Zhong and Xu (Zhong and Xu 2006) segmented scanned 3-D human body shape using three different methods. We avoided complexity of segmentation by marking borderlines of human body parts.

On the other hand, facial or body animation has been studied (Parke 1982; Lee et al., 1995; Magnenat-Thalmann and Thalmann 1987). In those studies, skeletal models for human face or body were built and surface shape was changed owing to the movement of the models. At first, the surface

shape was given from anthropometric measurement or photographs, then Lee et al., (Lee et al., 1993) discussed a method to reduce range data of human face to a generic mesh structure. Starck et al. (Starck et al., 2003) utilized a 3-D scanned human body shape for surface shape of an animatable human model. 3-D scan data was fit to a template of surface shape of the model by minimizing an energy function including an annealing term. In e-Taylor project (Kartsounis et al., 2002), 3-D scan data was utilized for surface shape of a human model simplifying with curvature-adaptive mesh decimation technique.

Li et al. (Li et al., 2000) obtained a static body model by approximating 3-D scan data with B-spline curve. Kim and Kang (Kim and Kang 2003) described garment pattern generation by development of human body surface. For this purpose, they utilized a static body model transforming 3-D scan data into a set of cross sections approximated with Fourier transformation.

Our purpose is to generate an isomorphic mesh as a static human body model for apparel design from 3-D scanned data, because amount of scanned data was huge and it is not convenient to handle. For generation of an isomorphic mesh, we did not adopt curve fitting nor data fitting to a template mesh, but geometrical rules were applied to the data cloud. Coordinates of 3-D scan data were utilized for vertices of an isomorphic mesh. If more fine shape is needed, it can be generated easily from the isomorphic mesh.

3 Isomorphic Mesh

An isomorphic mesh is generated applying a pre-designed mesh structure to a measured 3-D data cloud of human body surface. Amount of data obtained with a 3-D scanner is too large to utilize in virtual environments. The data can be simplified to a proper amount with the concept of isomorphic mesh. Topological structure of isomorphic mesh is identical for any human body shape while topological structures of meshes generated with an ordinal mesh generator are different according to human body shape.

The concept of isomorphic mesh has following merits.

1. By pointing a triangular element and its areal coordinates, an arbitrary point on a human body surface can be indicated.
2. A sufficient amount of data can be held to reproduce the whole human body surface shape.
3. Every vertex described with this method has certain meaning and is common to every human body shape.

4. Every triangular element of the mesh can be properly designed its dimension or shape.
5. 3-D body shape represented with isomorphic mesh can be compared or processed statistically, because differences among human body shapes are condensed to space coordinates of vertices.

Main purpose of isomorphic mesh is to provide human body shape for apparel design. There are some fitting simulators for clothes. Only a few specific human body models are prepared for the simulators. But personal body model is desired for the simulators to realize customization of clothes. Personal body model also required for development of advanced pattern making expanding 3-D body shape or automatic precise pattern grading. Isomorphic mesh can comply with the demand of the personal body model. Isomorphic mesh can be applied to qualitative or statistical studies of characteristics of human body shape, standardization of 3-D human body data format and construction of a parametric human body surface.

Following is a procedure to generate an isomorphic mesh. 3-D human body shape can be measured with body scanner. Before measurement, markers are pasted on landmarks of human body surface. Marker lines are also pasted as borderlines that segment human body parts. As results of a measurement, a cloud of 3-D human body surface shape data and human body images with landmarks and marker lines can be obtained. A fine mesh is generated using all the points of the data cloud, and 3-D coordinates of landmarks and points on the marker lines are detected comparing those locations on the image with the data cloud.

An isomorphic mesh structure was pre-designed and a set of geometrical rules to define vertices of triangular elements of the mesh was determined. This set of geometrical rules is applied to every human body shape data to generate an isomorphic mesh. Landmarks are utilized as vertices of the isomorphic mesh. Another vertices of the isomorphic mesh are generated one after another applying the geometrical rules to the fine mesh successively. Then we can construct an isomorphic mesh from every human body surface shape.

We have developed a program to generate an isomorphic mesh. Fig. 1 shows the process flow of the program. The program consists of two parts. Former part is for making a fine mesh of human body surface from a measured data cloud of human body surface. This part depends on a measurement instrument, and triangular elements of this fine mesh amount to about 300,000. Latter part is for making an isomorphic mesh from the fine mesh. This part is independent to measurement instrument.

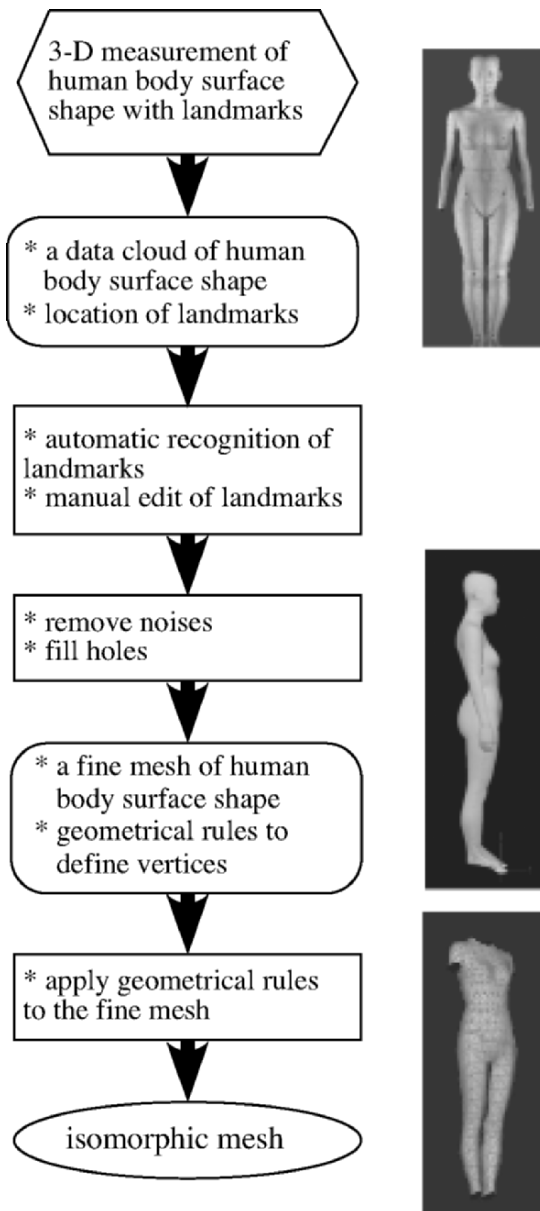


Fig. 1. Process flow for generation of an isomorphic mesh.

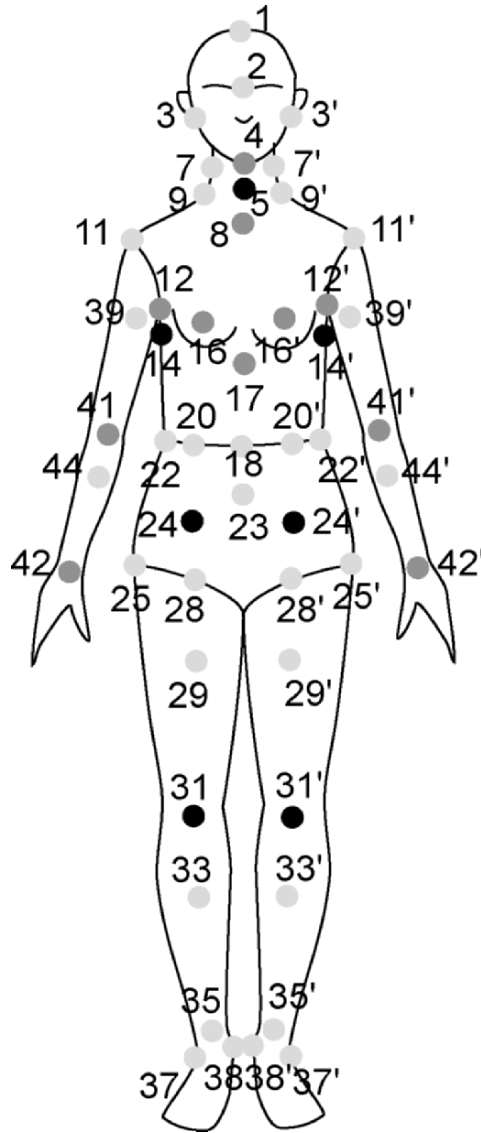


Fig. 2. Landmarks on human body surface.

3.1 Generation of a Fine Mesh

About 50 landmarks on human body surface for the isomorphic mesh were defined as shown in Fig. 2. In the figure, for example, point 24 is Navel point and its definition is the point of navel center. Before measurement,

markers are pasted at the landmarks. Tapes are also pasted at a waist, groins and shoulders to detect borders of body parts. The markers or the lines can be detected from an image of a body captured at measurement with the differences of brightness or color.

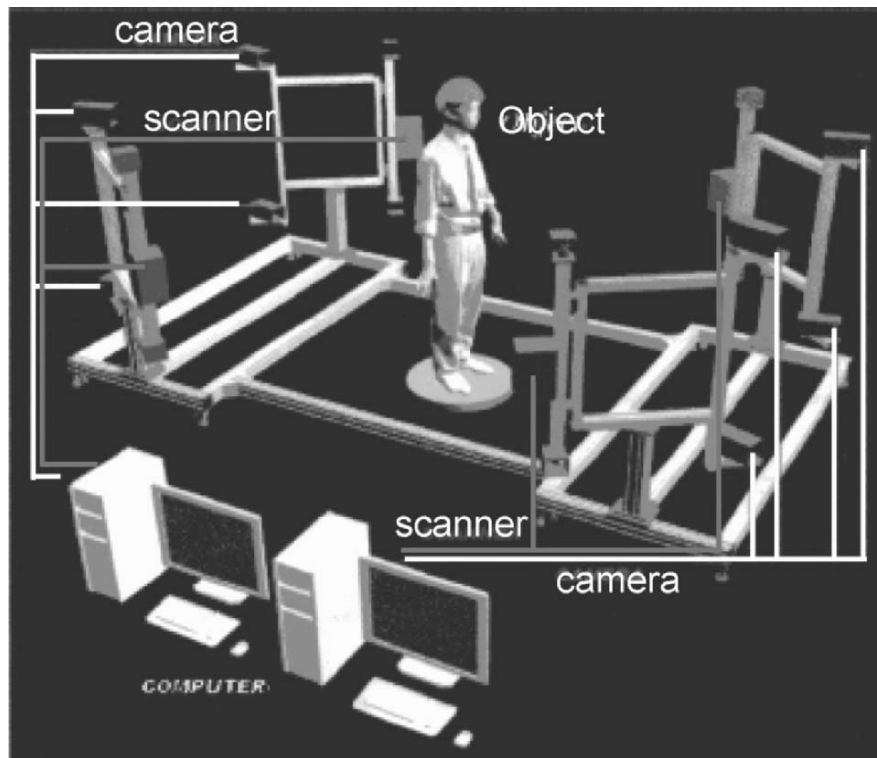


Fig. 3. Image of measurement instrument.

An instrument for measurement of human body surface shapes was VOXELAN LPW-2000FW (VOX). Principal of the measurement is based on an image encoding method of optical cutting. Images and 3-D coordinates of about 300,000 points of front and backside surfaces of human body can be obtained with the instrument. Range of the measurement is 2000mm(H) $\times$ 850mm(W) $\times$ 600mm(D), time for the measurement is about 8 seconds, pitch of measurement points is 1.9mm and the accuracy of the measurement is said to be ± 0.1 mm. An image and the specifications of the instrument are shown in Fig. 3.

Images of front and backside of a mannequin obtained with the instrument. The mannequin was specially manufactured based on averaged

anthropometric sizes of human body data measured from 4,000 women at age of twenties (NAN). Four units consist of a laser beam scanner and a CCD image sensor are equipped for measurement of front side of a body, and the same units are for backside. Front and backside of a human body are measured separately with the instrument.

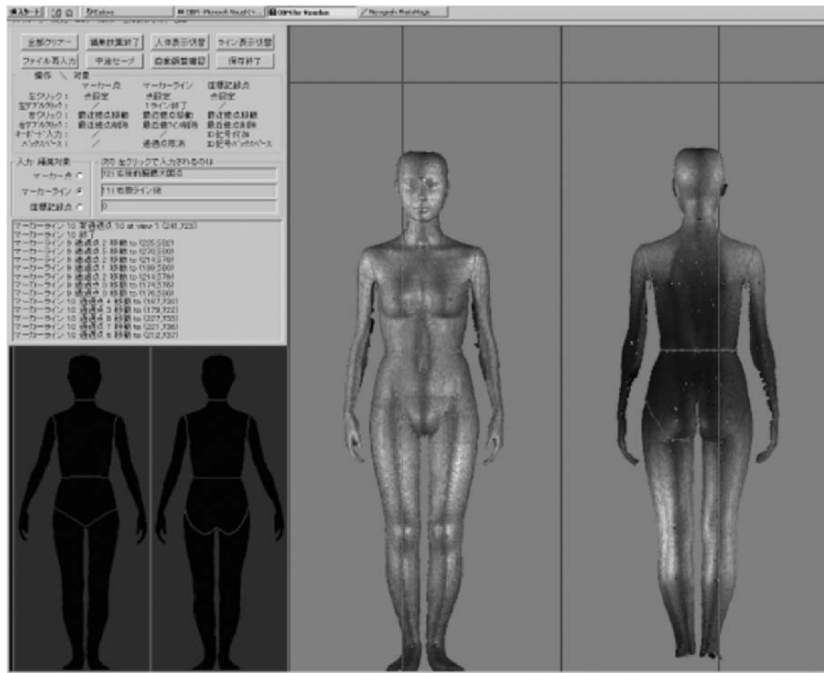


Fig. 4. Screen shot of manual marker editor.

Coordinate of the landmarks are automatically extracted from the images and the data cloud. The landmarks can be manually edited with the program because automatic extraction is not perfect and sometimes some modifications are needed. A display of the editing program is shown in Fig. 4. Then the program starts to generate a fine mesh from the data cloud of measured body shape. Noises are removed and holes are filled on the way to generate a mesh. In some cases, armpit or groin is modified. After modification of data, fine body surface meshes of front and backside are generated separately. Lateral part of a body could not be measured because the part is dead angle of the instrument. Then, the program fills up the gap of the lateral part of a body, and a finished fine mesh is shown in Fig. 5. Vertices of the fine mesh are segmented to body parts from the data of borderlines and then the vertices are labeled according to parts included in.

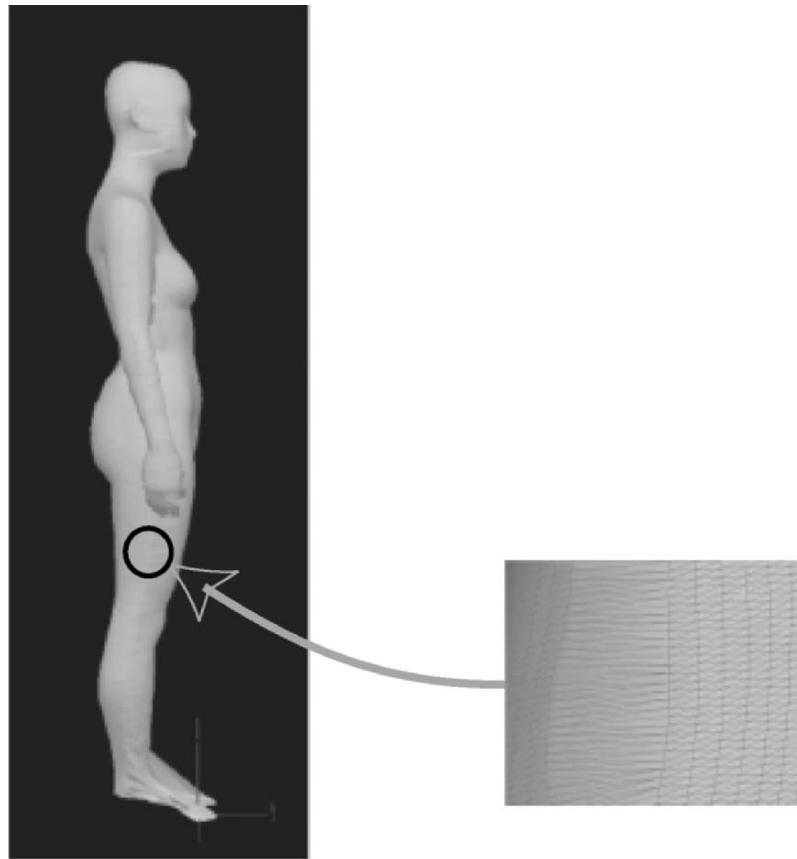


Fig. 5. Whole human body surface shape mesh pasted front and backside together.

3.2 Generation of an Isomorphic Mesh

Structure of isomorphic mesh is pre-designed. It was designed as a drawing of an extend elevation of each body part, trunk, waist, right and left arms and right and left legs, with triangular elements of meshes. Fig. 6 shows a mesh structure of front side trunk.

An isomorphic mesh consists of coordinates of vertices and a topological structure of triangular elements. Some of the vertices are given as landmarks anatomically predefined on a human body surface. Another vertices are generated from geometrical rules applied to a fine mesh of human body surface shape.

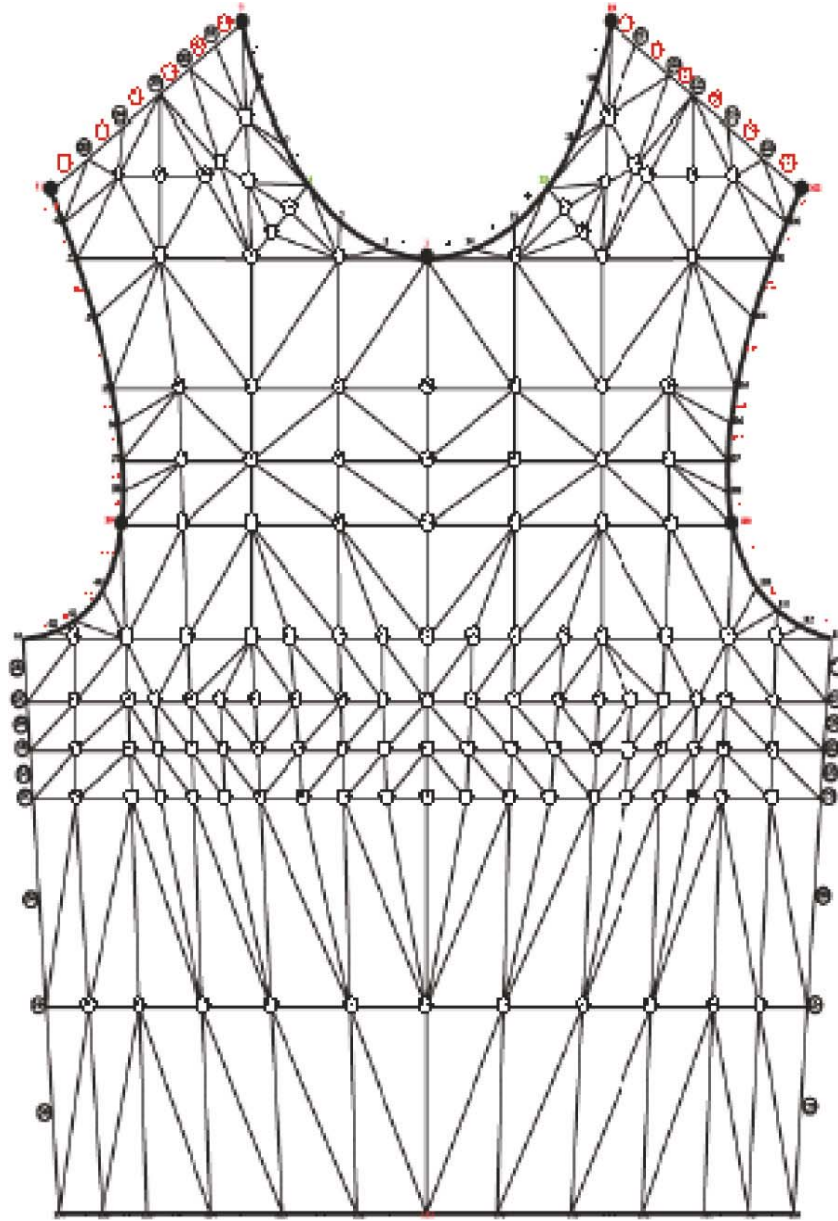


Fig. 6. Drawing of mesh structure of front side of trunk.

A set of geometrical rules to generate vertices of an isomorphic mesh consists of commands for definition of a plane, a line and a point or points. Following is an example of commands.

LegLine		209	1503	1867	
DividedPoint	206	4	2060	2061	2062
GeodesicLine	211	1817	1867		
Plane	100	Z	1	1817	



Fig. 7.1. An intersecting line of a plane and human body surface.

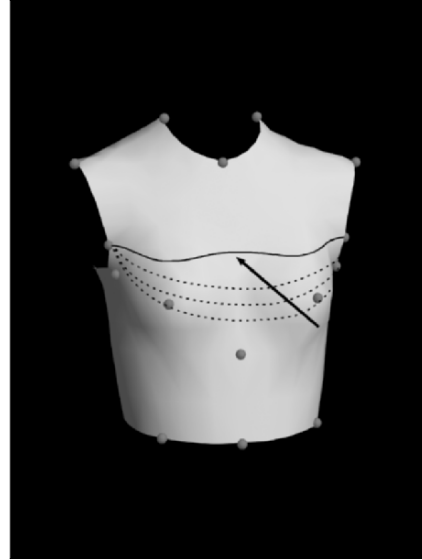


Fig. 7.2. A geodesic line on measured human body surface.

Geometrical rules are made up with three categories of commands for planes, lines and vertices.

“Plane 100 Z 1 1817” is an example of a command to define a plane. Each argument of the command is plane number, coordinate axis perpendicular to the plane, number of points on the plane and those numbers.

Five commands were defined to generate a line.

1. an intersecting line between a plane and measured human body surface (Fig. 7.1.).
2. an intersecting line between measured human body surface and a curved surface.
3. an geodesic line on measured human body surface (Fig. 7.2.).
4. a catenary on measured human body surface.
5. marked lines such as arms, waist and groins.



Fig. 7.3. An intersection line of a measured human body surface and a plane or a curved surface.



Fig. 7.4. An intersection of two lines on measured human body surface.



Fig. 7.5. Interior division points of a line on measured human body surface.

Geodesic line is obtained by a mechanical method. An arc is generated as initial state of mechanical calculation for geodesic line. Two end points of the arc are the same as those of geodesic line, but the arc locates above body surface except the two end points. The arc divided into many segments, and they are assumed to be springs. After calculation starts, the arc shrinks to decrease potential energy of springs and when they get near body surface, they are exerted repulsive force from the surface. Geodesic line is finally obtained as equilibrium of the springs.

Three commands were defined to generate a point or points

1. an intersection line of a measured human body surface and a plane or a curved surface (Fig. 7.3.).
2. an intersection of two lines on measured human body surface (Fig 7.4.).
3. interior division points of a line on measured human body surface (Fig 7.5.).

Vertices except those originated from landmarks are defined by geometrical rules as follows. At first, planes are defined by a rule for plane with landmarks, lines are defined by rules 1 to 5 for line with planes defined or landmarks. Vertices are defined by rules 1 to 3 for vertices with lines already defined. Then, other lines are defined with the newly defined vertices, and remaining vertices are finally defined with the other lines.

We have developed a program that generates vertices of an isomorphic mesh interpreting and applying the geometrical rules to a fine mesh of measured human body surface shape. Fig. 8 shows drawn lines applying the rules on the trunk part of the surface data. Fig. 9 shows generated isomorphic meshes. Left one is a mesh of mannequin of age of twenties, middle one is that of forties and right one is that of seventies. Fairly well shaped meshes were obtained with this method except on breast or abdomen part, some long and narrow triangle elements can be observed.

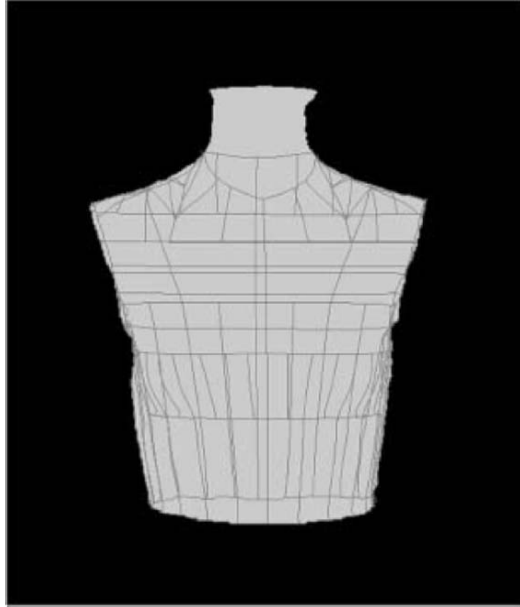


Fig. 8. Lines generated by geometrical rules on a body surface.

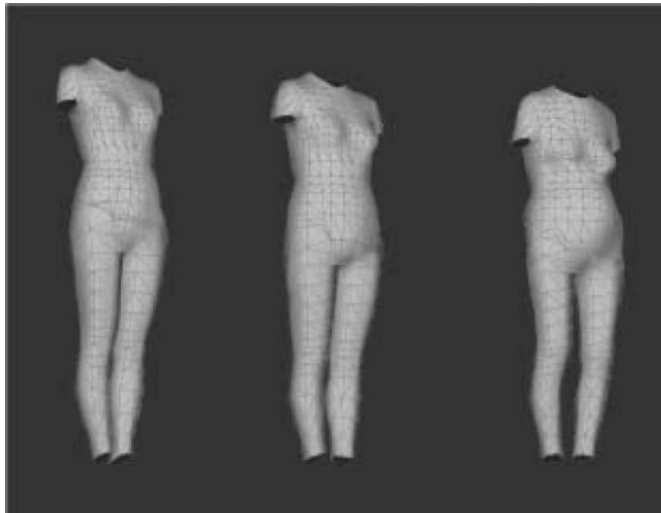


Fig. 9. Isomorphic meshes of mannequins of the age twenties, forties and seventies.

Almost all the vertices of isomorphic mesh are, as described below, measured data point of human body surface shape. Few vertices of an isomorphic mesh derived from landmarks are moved to let a mesh symmetric,

because a body for apparel design should be symmetric. Coordinates of those vertices come off 2,3 mm from coordinates of landmarks. In principle the vertices generated from geometrical rules are almost on surface. Distances from the vertices to the nearest data point were calculated. About 78% of them were less than 1mm, 21% are from 1mm to 2mm and 0.7% are more than 2mm. All the vertices of an isomorphic mesh are on a body surface because pitch of measurement data is about 2mm. Human body surface shape is not approximated by some curves, but approximated as polyhedron of triangle elements. If more fine mesh is needed, a mesh four times as fine as ordinal one can be obtained by adding rules to divide every side of triangular element of isomorphic mesh.

Surface shape of arms could not be measured correctly with the instrument, because laser beam emitted from the instrument was shadowed at the trunk side of the arms. It was impossible to reconstruct arm meshes from measured data. Arms should be provided for a body model of apparel design, but those accurate shapes are not necessarily reproduced. Arm meshes were substituted for those generated from measured data of a mannequin. Some landmarks on real human arms can be extracted from data measured with the instrument, and some circumferences of arms can be obtained with manual measurement. Isomorphic meshes of arms generated from the mannequin data was deformed so that coordinates of landmarks and the circumferences agree with those of a measured human body. Then the arm meshes were connected to trunk part of an isomorphic mesh.

4 Conclusion

We have constructed a system that is able to convert measured data of human body surface to an isomorphic mesh. To make the most use of the merits of the isomorphic mesh, various improvements are required for the measurement system, the mesh generation system and the definition of the characteristic points on human body surface. Those improvements should be based on the feedback from the utilization experiences of the system, and for this purpose, the mesh generation system was designed as a rule base.

The measurement of many human body shapes are required to confirm that the method of the isomorphic mesh can be applied properly, because there is a wide variety of the human body shapes. When a contradiction is observed in the generation processes of the isomorphic mesh, the structure of the isomorphic mesh, the definition of the marker points and the geo-

metrical rules should be reexamined. It is planned to measure several tens human body shapes of ages and to generate isomorphic mesh for those shapes.

Acknowledgment

This research was supported by Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science. The number of grant is B-16300231.

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Integration of an Adaptive CAD System for Flexible Furniture Industry

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Abstract

The furniture industry is a very competitive market. Consequently, the companies continuously have to improve their creation, production and distribution processes. In order to respond to the consumer demand, one solution consists of increasing the reactivity, the flexibility of the creation process and the product variety. For this, new technologies such as CAD, virtual prototyping, ..., have demonstrated their efficiency in other industrial sectors, for instance automobile. This paper describes the current methodology of creation for sofas and proposes the integration of these digital technologies. The short-term benefits mainly concern the reduction of the lead time and the costs of creation. In mid-term, this new strategy should involve the possibility to integrate the notion of mass customization in the furniture industry.

1. Introduction

Currently the furniture market is in complete reorganization. Indeed, as in many others industries, furniture companies have to be responsive enough to meet the rapidly changing customer demand and much shorter product life cycle (Chen, 2003). The emergence of new technology such as CAD and 3D virtual prototyping strongly interests the companies of this sector (Balasubramanian, 2000) (Oh, 2004). The main aim is to drastically reduce the manufacture costs of prototypes and also the production lead time of items of the same range (Baes, 2005). A 3D virtual prototype

enables the visualization of a fixed item with various variants of fabrics without needing to carry out a new real prototype. The second purpose is to quickly adapt the items to the customer's demand. Thus, an interactive modification of the design in a 2D visualization, which enables an automatic update of the 3D virtual prototype, should offer a new process of creativity. Furthermore, the digital relationship between the virtual prototype and the production processes enable the designers to visualize and to check their creativity. For this, the 3D prototype requires the integration of both conception and production data. This integration should enable, for example, the automatic extraction of global, visual and dimensional information for the various technical files of production. Additionally, the high quality of the techniques of realistic rendering enables the direct integration of virtual collection resulting from CAD into catalogue or E-stores web sites (Oh, 2004). This strategy also involves an optimized management of conception and manufacturing data flow which implies a global improvement of the logistic process (Tseng, 1998) (Loker, 2002).

This paper describes an original conception method of prototype of sofa adapted to the new requirement of the furniture industry. The first stage consists of the modeling of the current creation and manufacturing processes. The obtained model, described in section 2, shows the numerous manual procedures which require experience and are time-consuming. Furthermore, this model does not allow any customer feedback. Only some privileged customer can customize their demand. However, this requires the revision of each steps of the conception which involves an unreasonable increase of lead time and cost. These different drawbacks penalize the current manufacturing process.

The proposed conception and production model, presented in section 3, is highly adaptive and adjustable. The basic idea seems close to the current procedure; however the contribution of the virtual prototyping associate with an adapted methodology revolutionizes the production process. The use of realistic pictures enables the management of various products but also allows (requires) an inversion of the creation process.

Different aims emerge in this new procedure (section 4). The first one consists in establishing a working and organizing method related to the creation, the production and the CAD areas. In medium term, these methods should reduce costs. The second purpose is to generate associative links between each elementary entities of the product to produce in order to carry out an automatic creation process. Thus, this notion of associability has to

be integrated in the CAD. The performed links significantly decrease the lead time and involve a quick response to the customer's demand.

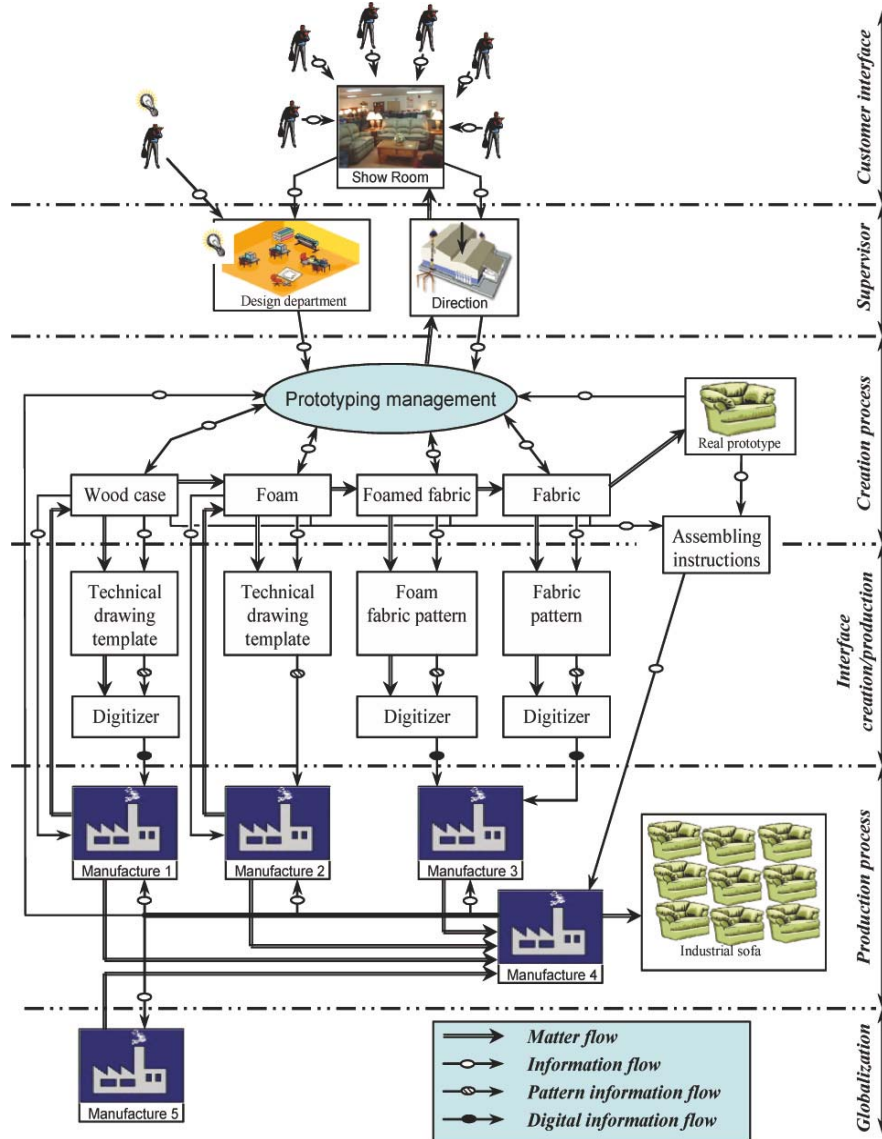


Fig. 1. Current creation and production processes of sofas

2. Current Creation Method

The modeling of the current method reveals that the industrial manufacture of the product should completely associate the conception process. An optimized management of the material and information flows has to take into account these procedures. The traditional model must reveal the different levels of the creation and production processes and describe the paths of the physical and numerical data flows. Fig. 1 shows the structure of the current creation and production model of a sofa. The different levels are detailed below.

2.1 Customer Interface and Supervisor

This upstream process enables the estimation of the feeling of the customers, the definition of the trends and also the sales interface with show rooms for prototypes of sofas and stores for the current collection of sofas.

The first step of the creation of a new sofa range is always performed by the designer. To begin, the designer creates the style of sofa according to the fashion trends. This crucial work determines the sofa design of the future years. It is also necessary to frequently update the sofa ranges according to the life time of the products. Indeed, the average life time of a sofa can fluctuate between 1 to 5 years according to its style. Thus, the choice of the design still remains an essential stage in the creation process of a sofa (Aussel, 1985).

Two possibilities can be envisaged to achieve this stage:

- the drafts of the collection are done by a designer of the company (design department),
- a customer orders a customized design which is not included in the collection.

This alternative involves two different information flows:

- the drafts included in the collection are proposed for validation to the design manager and then are sent to the prototyping department.

- the customized designs are directly sent to the prototyping department via the design department.

Lastly, the head of department checks the new collection of the sofa and exhibits it in showrooms.

2.2 Creation Process

From the design achieved previously, the prototyping manager carries out a business plan of the manufacture of the product. The purposes are the cost reduction of the different sofa units and the lead time optimization of the creation and production processes in accordance with technical and comfort features.

After a detailed analysis of the creation process of a sofa, mainly three steps emerge (Maubert, 2003):

- *construction of the wood case*: the wood frame supports the whole unit of the final product. Different wood materials can be used according to the expected price and solidity and also the manufacturing time. The manufacturing instruction and the sofa cardboard pattern are sent to the department in charge of the creation/production interface to be digitalized. Manufacture 1 send back the corresponding wood units which will be joined together from the instructions of the prototyping department.
- *cut and installation of the foam*: the desired comfort for the different place of the foam on the wood structure are defined by the choice in the density of foams (Dillard, 2004). Manufacture 2 sends the foam in the chosen densities which are cut according to the sofa cardboard pattern. The prototyping department then fastens the foam onto the wood structure.
- *cut of the foam and furniture fabrics*: this step consists of the cut, the assembly and the pose of the foam and furniture fabrics. The designer drapes the foam fabric on the basic structure to carry out each unit patterns. The units are then cut and joined together to produce the foam and fabric covers. The same process is used to pose the furniture fabric (edging, contact,...). This fabric generates the design and the comfort of the final product from sensorial aspect. Thus a crucial information flow is required between the design department and the model maker for the choice of the style and raw material and between the model maker and the dressmaker for the assembly instructions. The production department is

not involved in this step because the prototyping department has got its own inventory of fabrics.

These steps result in a real sized prototype of the sofa. The prototyping department checks the esthetics and the feasibility of this final prototype and could eventually adjust some components or completely modify the sofa from the first step. These adjustments imply in the creation process significant increase of costs and lead time. Finally, the features of the final prototype have also to be validated by the head of department.

2.3 Creation/Production Interface

This stage enables the preparation of the industrial production from the pattern previously carried out by the prototyping department. Except for the foam which is manually cut, all other patterns are digitized before they are sent to the manufactures 1, 2 and 3.

Thus, these data are saved and should be used to produce all the sofas of the same range. For the single customized sofas, this digital step can be cancel because of excessive cost.

The assembling instructions are also sent to the manufacture 4.

2.4 Production Process

The four steps of the production process of the sofa are carried out by a particular manufacture:

- the first manufacture cuts the wood items and assembles the wood case from the digitized pattern and the technical instructions
- the second manufacture cuts the foam according to the shape defined during the creation process.
- the third manufacture performs the cut of the covers of sofas. Two types of covers are cut: the foam cover and the fabric cover. These covers are carried out from the patterns defined in the creation process.

Finally, the components, produced by these 3 manufactures, are sent to a fourth manufacture for the last step: the assembly process.

2.5 Globalization

As in many industries, in order to reduce costs, the production of standard sofas in large quantities is usually globalized. The procedures should be globalized (manufacture 5) as previously described. However, this strategy implies some difficulties with the digital step (low cost manufactures generally do not have technology and human resources). Furthermore it will significantly increase the lead time of the product. Thus, the globalization does not enable the customization of the production.

3. Interactive and Adaptive Model

In order to increase and to adapt the production, the current creation process should be improved. New technologies such as associative CAD, the different flows in the creation process have completely been modified to improve the ability of the company. An original strategy, based on digital technology, is proposed (Fig. 2). This strategy seems globally similar to the current ones, but in fact it completely transforms the working methodology. Indeed, this enables a digital safeguard of the “know-how” and optimizes informational and material flows, digitalized or not. Furthermore, the virtual creation is suitable for the use of the Internet as an optimized communicative and safety tool.

3.1 Customer Interface and Supervision

At this level, the process is quite similar to the traditional model.

The main distinction concerns a better open to the customized demand. Indeed, the digital creation process improves the flexibility of the conception of prototypes (virtual and real).

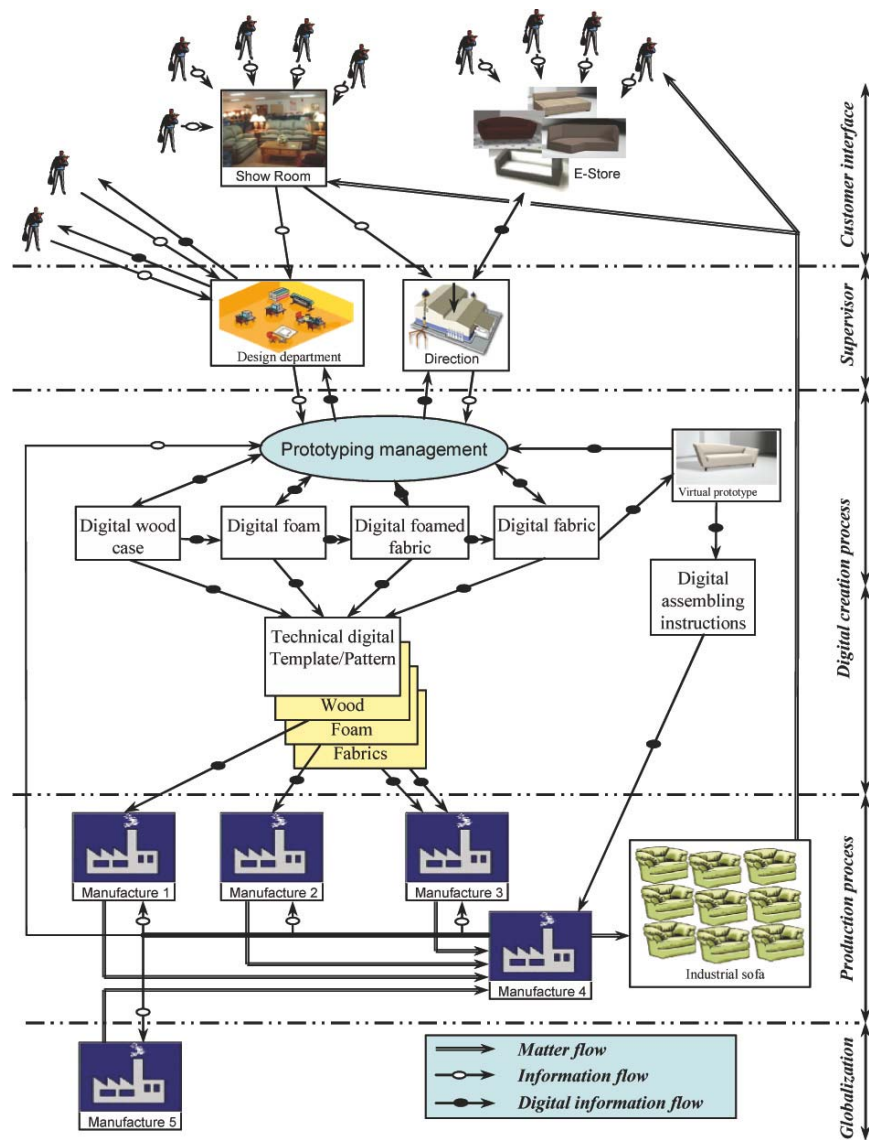


Fig. 2. Digital model

3.2 Digital Creation Process

The prototyping department performs the three steps defined previously (section 2) of the creation process. However, these steps are adapted to digital technology. The different types of material (wood, foam, fabric) have to be previously analyzed and modeled with the CAD (Shao, 1992). The three steps of the digital creation process consist of:

- *creation of the wood case*: the creation process is directly achieved with a associative CAD. The main design lines are also digitalized to obtain the wood case in a 3D space. All the components are made and assembled with the CAD tools.
- *creation of the foam*: the shapes of the foam are defined from the 3D structure of the wood case. The digital process ensures the design management and the feasibility of the step.
- *creation of the cover*: in order to define the surface (mesh surface) of the fabric cover, the seam lines are directly placed on the 3D structure (wood case + foam). The new generation CAD software is able to identify the surface delimited by the seams and to flatten the pattern (Fig. 4). The placement of the seam lines is crucial because imprecise seam lines would achieve an inaccurate pattern which will be unsuitable for the real structure. At the end of this step, digital patterns are completed.

These steps result in virtual prototype close to a real picture (Arquès, 1990). Some steps should be adapted according to the needs and demands. However, the creation method based on digital associative concept, enables an automatic modification of the parameters of the 3D prototype. The reactivity for the adjustments of the prototype is then optimum.

The design department checks the final virtual prototype and launches the industrial process. In the framework of the new B2B concept, these virtual prototypes (Fig. 3) should also be exhibited in E-stores (Lourdeaux, 2001).

In order to achieve the real prototype, the virtual creation also enables the direct compatibility of the digital data with the downstream industrial steps. Indeed, digital method of translation from 3D to 2D are automatically computed (Fig. 4): 2D drawing process for solid structures (wood case, foam) and flatten process for flexible structure (foam and

fabric covers). Furthermore, the assemblage instructions of the sofa can be directly extract from its digital representation. Thus, some crucial details should be highlighted with the CAD flexibility.



Fig. 3. Example of a real sofa and its virtual prototype

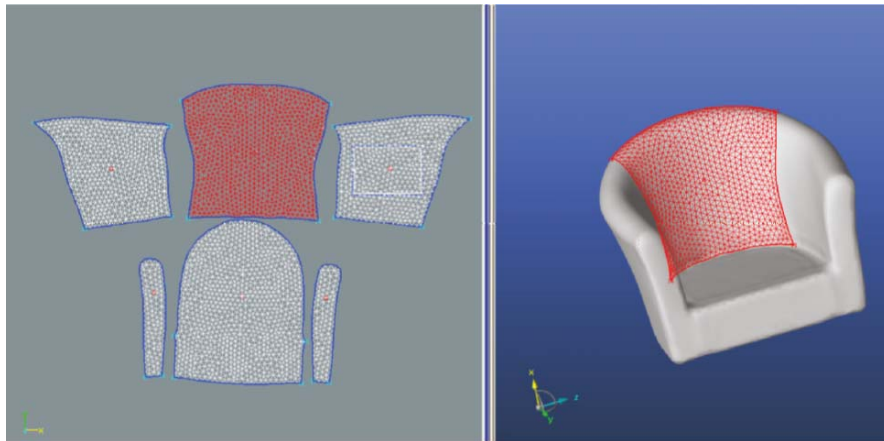


Fig. 4. Example of flatten process for fabric covers

3.3. Production Process

The industrial process is also relatively similar to the traditional model. The main specificity resides in the digitalized data which are suitable automatic cutting systems. Currently, these data are sent via email. However, it should be envisaged to use more efficient and safety transfer techniques such as EDI, XML,...

This strategy enables a mass production or prototype manufacture, and also customized prototypes. Real prototypes are then exhibited to customers in show rooms.

For this strategy, the globalization is not suitable since this will lose the benefit of reactivity and flexibility of the digital creation (Bae, 2005).

4. Benefits of the New Interactive Method of Creation

4.1 Industrial Production

The proposed interactive and adaptive method simplifies the creation process. Indeed, the associative CAD enables the prototyping management to substitute fusion and cancel some expensive and time consuming steps.

In practice, the manual method requires the manufacture of the different components to start the next step of the prototyping process: the cut of the foam involves the complete wood case, the manufacture of fabric requires the assembly of the foam and the wood case,... . For instance, with neighboring suppliers (delivery time less than half a day), this manual process which is long and fastidious requires at least 5 days (study and creation of patterns, wood cases, foam, foam covers, fabric covers, assembly process) to obtain one type of real prototype.

For the digitalized method, the different steps of the creation process can be achieved without needing any manufacture of components. For each step, the resulting digital data can be directly sent to the production departments. Thus, the reception of all the components should be synchronized for the assembly process of the eventual real prototype. This

method should be carried out in 2 days: one day to complete the virtual prototype and one day to make the real prototype.

4.2 Added Value to the Product

In the case of the manual prototyping process, the smallest modification requires the revision of all the creation steps. This involves to trace and to cut again the various patterns, to manufacture and to assemble the new components. Consequently, the lead time for the prototype creation significantly increases.

The digital method, based on the associative concept, easily enables the modification of the size and the design since the features of the virtual sofa and its associated patterns are automatically computed. Thus, from a virtual prototype, all the diversities of sofas of the same range are automatically generated without manufacturing any real prototype.

This substantially decreases again the lead time of creation. For instance, to produce a range of 10 sofas, the digital method requires 2 days (see previous section) to carry out the prototypes whereas the current method necessitates 5 days per prototype, i.e. 50 days.

This process provides an optimal reactivity to supplement the range of sofas, to attract new customers or to answer to customized demand.

Another benefit aspect of the creation of virtual sofas is the possibility the product should be directly exhibited on the Internet via E-stores. The customer should then choose its customized sofa (design, color, size,...) in a customized environment at home.

5. Tools Allowing the Evolution of the Process

5.1 The Associative Mode

This mode enables the creation of a “genealogical” tree during the design of a product with family links between each basic object. The objects in the associative model form a hierarchical structure with parent/child

relations. This process is very effective, but the users must be careful to not remove elements having children. This suppression would cause a break in the chain of elements parent/child. The parent/child relationship is a very powerful structure which makes it possible to modify an object easily. The example in Fig. 5 shows a simple genealogy defining a 3D surface. The relative points (@26-@27 -... -@34) to an absolute reference enables the creation of a generating curve (or profile) (@28) which is extruded over a length of 850mm that creates the desired surface (or part) (@36). By genealogy, the points are the parents of the curve, the curve is the parent of the surface and the points are the grandparent of surface. If a point is moved, then the genealogy causes a modification of the curve and the surface.

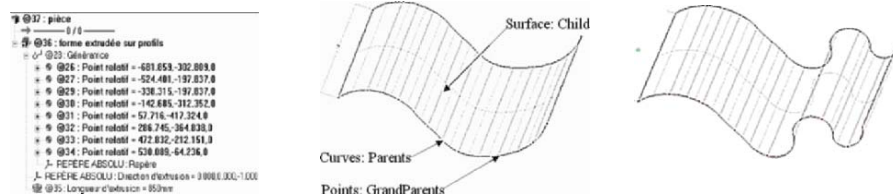


Fig. 5. Example of genealogy defining a 3D surface

5.2 Layer Based Management of Sub Process

The complexity of the design of a virtual 3D object requires a method of very rational organization. Also, it is very important to manage the various processes of design based on layers. Let us note that this management conserves the associative links between objects. This process allows us to visualize separately different phases of design. Thus it is possible to show or hide parts of a model according to the desired process of creation. If the designer wishes to modify the style of the sofa, the visualization of the wood case is enough for him to modify the lines of style of this one. The selection of the layer “wood case” enables the visualisation of the unique component; the others components (foam, fabric,...) are hidden. Figure 6 is an example of the evolution of a sofa using the layer based management.



Fig. 6. Example of the layer based management

5.3 Mechanical and Dimensional Constraints

The mechanical constraints can be applied automatically to the creation of an object. They are used to impose strict geometrical conditions on the positioning of the objects such as parallelism, perpendicularity, and the alignment between two lines. For the dimensional constraints, driving entities are defined. These driving entities associated with driving dimensions manage a distance, an angle, a ray... and control a virtual object in 2D or 3D. Furthermore, they can instantaneously adjust the dimensions and the shape of the object. When a driving line is created between two entities, a parameter is associated with it to control the entities instantaneously. The mechanical constraints can be associated with the dimensional constraints to preserve the symmetry of an object.

The table below shows the whole control parameters required for a wood case of a fixed design of sofa. Figure 7 illustrates the different profiles and measurement associated with these parameters. The basis contours use these profiles to define the volume of the sofa. The associative mode enables the virtual prototype to adjust all the components of the sofa

(foam, foamed fabric, fabric) from the smallest modification of the wood case. Each parameter of the wood case is completely independent.

Frame Width	LargC
Armrest Width	LargM
Front Height	HtFS
Armrest Height	HtM
Back Height	HtD
Case Depth	ProfC
Back Difference Width	Largdec D
Back Difference Height	HtdecD
Armrest Difference Height	htdecM
Armrest to Top Width	LargMH
Back inclination	AngD
Thickness material 1	EpTri
Thickness material 2	EpAgglo
Thickness material 3	EpIso
Armrest Differnce Height	DecM

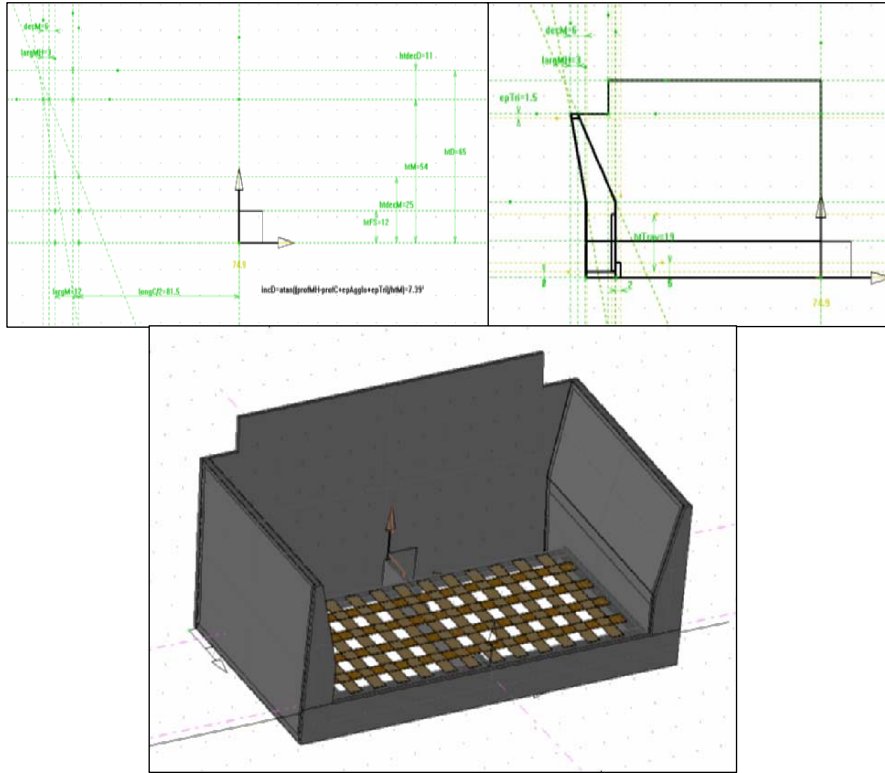


Fig. 7. Control profile, basis contours and wood case of a standard sofa

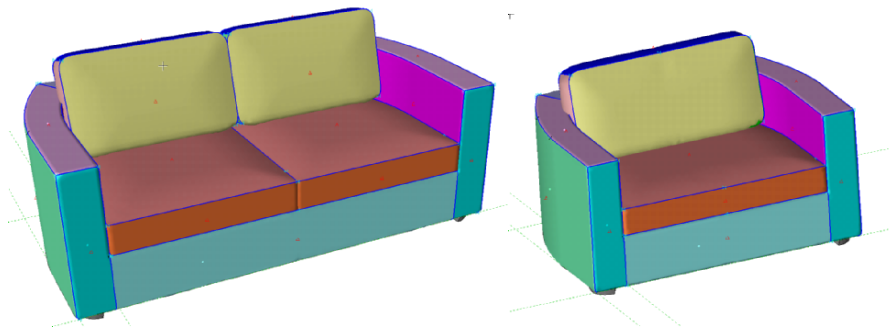


Fig. 8. Example of the layer based management

Figure 8 shows an example of dimensional based management in the longitudinal direction by an intermediary parameter. It is possible in the same range to obtain very easily one place sofa from two place sofa and conversely.

5.4 Assemblage and standardization:

In order to follow the associative concept, it is important to define standard pieces, used for all ranges of production. The standard objects such as back, cuff, face, base, tallies strap... are generally parameterized and are included in a library of components. The other personalized objects which correspond to the tendencies of designers, are not parameterized.

This concept is illustrated in Fig. 9. The assembly of the standard parts is carried out on a definite skeleton parameterized by the insertion points of each part. A principal part manages the positioning of the others which is carried out by translations, rotations or the arrangement of these two movements.

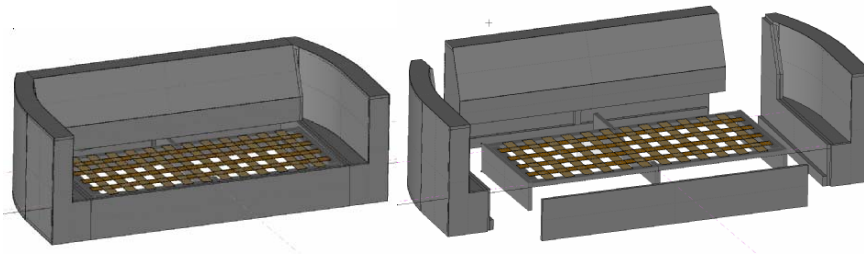


Fig. 9. Example of assembly process

Conclusion

The use of interactive and adaptive methods revolutionizes the prototyping of sofas. An optimized management of digital tools for the modeling of 3D sofa generates numerous advantages. The direct benefits of this original concept are the significant reduction of creation lead time from 5 to 2 days. Furthermore, from the first virtual prototype of a range, each sofa of this same range can be extremely easily and quickly created. Thus, the

conception and prototyping costs are also reduced. These financial and time gains increase the creation potential and variety of products.

In mid-term, indirect benefits should emerge in the specific modification of sofa. The CAD produces a high flexibility and efficiency for the modification of sofa. The smallest adjustment is automatically transmitted in whole the creation processes from the prototyping until the manufacturing during the flatten process of the pattern. The digitalization of the products enables the company to save its knowledge, and also to show and adapt the design sofa to its customers. This advanced technology contributes to show the dynamism of the company and to establish its customer loyalty.

In long-term the expected advantage is the increase of the mass of customers by using the sales by the Internet. The integration of digitalized sofas in a virtual store is currently possible. The 3D conception enables the complete observation of the sofa via a web site. Furthermore, it will be possible to interactively choose the fabric and the design. This process leads us to the mass customization.

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Part IV

Computerized Textile Management and Textile Supply Chain

Stochastic Planning in the Textile Supply Chain: How Robust is a Newsboy Model?

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Summary. One of the challenging problem in the area of the textile supply chain management is the identification of the best decision a retailer can make when he has to buy a certain quantity of a given good for the future sales season. Obviously, the answer depends on the knowledge available upon the future trends of the market. When expressing this knowledge by a probability distribution, many assumptions are often introduced that are not founded on an actual knowledge, but most of the time on computational ease.

In fact, the knowledge one ever can have upon the probability distribution of the future demand is far lower than the limited knowledge he can have over the future demand itself. Despite the impossibility of an exact knowledge on this future demand, the sourcing decision (here: the order quantity), may be the good one in the sense that its optimality is preserved from any possible demand model errors. It should then depend only on exact and verifiable information over the future demand. Therefore it is interesting to investigate how robust are the hints for an optimal order quantity that can be extracted from what is really known upon this future demand. This robustness will be studied by extending the well known newsboy problem to a family of demand models.

1 Introduction

The whole textile-apparel and retailing system is one of the domains which undergo great economical and market pressures. In such a fast changing environment, the skill of the manager at any stage of the supply chain is greatly solicited in order to make the best, or more likely, the least bad decisions.

Some of these decisions may be of strategical nature, for example dealing with long term investment on warehouse facilities, or choice of strategic partners, manufacturers or third-party logistic providers, with the objectives of unifying some common processes. Other decisions are for very short term, if

not in real time, such as those taken at the workshop level: scheduling problems, production decisions etc. The last type of decisions is intermediate of the previous, at the tactical planning level and covers few months of time horizon, e.g. one year budget decisions, or products purchasing policy for the next sales season. All of these decisions are interconnected, and involve a mix of exact data or knowledge and a greater or lesser amount of uncertainties. As obtaining extra information on these uncertainties may be expensive in terms of workload and information system investment, the main objective of this work is to identify the optimization methods and the minimal required information for these decision-making problems, based on the assessment of the value of information.

This chapter, which is an extended version of (Douillet and Rabenasolo, 2005), is focused on the quality and the robustness of a purchasing policy, especially the optimal order quantity. The purchasing problem is stated as follows: assuming a given knowledge of the future demand, the decision maker has to buy now a certain quantity of products in order to maximize his revenue during a future sales period.

In the textile-apparel context, the demand is hardly identified because of many factors typical to textile items: high competition between companies, consumer volatility, unpredictable fashion trends, high degree of diversity, and short product life cycle. The short life-cycle of most of the textile-apparel products implies that there is no opportunity to correct any error that the retailer may have made on this order quantity. The catalog of products is generally organized in two or four seasons of three months sales (spring, summer, autumn and winter seasons). Because of the specialization to one of these seasons, the product life-cycle rarely spans over two consecutive sales periods, for example summer-autumns. Moreover, the procurement delay for a fabric may be about three months, while the logistic and transportation delay may range from one to three weeks or more for delocalized industries. In the case of make-to-stock systems, the purchase decision should be taken about four months before any sale occurs. Any error cannot be corrected if this sales period is of three months. The best decision is a trade-off between the risk that the retailer can miss sales opportunity if he does not buy enough products (costs due to stock-out phenomena), and the risk that he may lose some revenue if the purchased quantity is greater than necessary (costs due to excess of inventory). The main problem is then, from the actual knowledge on the future demand, to define as precisely as possible these two risks and to solve the trade-off decision problem in a realistic context, without the bias of any extra information that is impossible to prove or to verify at the time of this decision.

In order to get a higher comprehension of the phenomena, the problem will be simplified and illustrated by the well known newsboy paradigm which is still largely used, with various extensions such as multi products environment with multiple discounts (Khouja, 1995), multi period sales and ordering, capacity constraints (Voros and Szidarovszky, 2001), or random procurement delays.

While in many real life cases, the only available knowledge is an expectation of the mean demand μ , the newsboy paradigm proposes an advanced model where the distribution of probability of the demand is exactly known. This assumption is a strong limitation because in reality, the knowledge we can ever have upon the probability distribution function (pdf) of the future demand is far lower than the limited knowledge we can have over the future demand itself. For example, it is *impossible* to prove, even after the sales season, that the future demand will exactly follow the normal Gaussian or any pdf. Therefore the best order decision must be analyzed under various weaker hypotheses. The main assumption of this work is that, instead of propositions similar to ‘the total demand for the next 4 weeks has a Poisson distribution of mean 52500 units’, we suppose that the retailer can reasonably make assertions like ‘we expect to sell in average 52500 units within an interval of $\pm 30\%$ ’.

In all the studied cases, it will be assumed that the mean demand μ is identifiable with enough precision through various statistical techniques, and that, additionally, some second-order characteristic of the demand is also identifiable. For example, the Scarf’s (1958) founding result addresses the case where the mean μ and the standard deviation σ of the future demand are known. In (Douillet and Rabenasolo, 2005), we have investigated for another second-order characteristic namely $\delta \doteq \theta(1 - \theta)(\xi^a - \xi^b)$, using notations of Section 2 that appears to be interesting.

In such a condition, various families of demand pdfs $\mathcal{F}(\mu, \sigma)$ or $\mathcal{F}(\mu, \delta)$ need to be investigated. The determination of the optimal decision is then a max-min problem, where the objective is to optimize the gain for the worst case over a family of demand models, in order to guarantee a lower bound for the expected performance.

The present chapter is organized as follows. In Section 2, we restate the hypotheses, fix the notations and recall the formulae for the optimal order quantity and the associated gain are recalled. Thereafter, in Section 3, we compare the results obtained when using different families of models: normal, lognormal, triangular and the “two Diracs” model.

In Section 4, we discuss the hypotheses that were at the basis of these results. The fact is highlighted that actual measures can hardly provide sufficient knowledge to allow a direct application of these formulae, requiring a carefull evaluation of the robustness of the purchase decision obtained from what we really know upon the future demand.

In Section 5, we address this question by the usual max-min method: for each order quantity y , the worst-case demand probability distribution function among a given family of models is determined, and thereafter the value of y that maximize the “gain in the worst case” is determined. The case of the triangular models with given μ and σ is examined, and compared with the general Scarf’s solution (that uses “two Diracs” models).

The chapter ends by some concluding remarks and a bibliography.

2 The newsboy paradigm

2.1 Description of the problem

The paradigm known as “the newsboy problem” involves two time periods: a time t_0 for product purchasing decision, and a time $t_1 > t_0$ for the future sales when the result of the previous decision can be established. Let us suppose that we have the opportunity of ordering now a quantity $y \geq 0$ of some good at unitary cost c . Let us additionally suppose that we know what is the probability distribution of the future demand ξ , as well as the exact unitary price r at which the sales will occur. At the end of the sales period, non sold products are supposed to be discarded. Without loss of generality, the common case of non zero discount price for sales occurring at $t > t_1$ will not be studied. We also suppose that no additional quantity can be purchased later than t_0 . Then, we have no opportunity to correct any forecasting error.

As usual, we denote f the probability density, and $\Phi(y) = \int_0^y f(\xi) d\xi$ the cumulative distribution. The satisfied demand ξ^+ will be ξ if it happens that the available products exceed the demand quantity $\xi < y$ and y otherwise, leading to the gain $G(y, \xi) = \xi^+ r - y c$ where $\xi^+ \doteq \min(y, \xi)$. The usual criterion for the identification of the optimal value y^* of the ordered quantity y is maximizing the expected value of this gain. Denoting this quantity by $G(y, \Phi)$, we have:

$$\begin{aligned} G(y, \Phi) &\doteq \mathbb{E}(G(y, \xi) \mid y) = \int_0^\infty (r\xi^+ - cy) d\Phi(\xi) \\ &= r \int_0^y \xi d\Phi(\xi) + ry \int_y^\infty d\Phi(\xi) - cy \end{aligned} \quad (1)$$

The derivation of (1) leads to the condition $\frac{dG(y, \Phi)}{dy} = r \int_y^\infty d\Phi(\xi) - c = 0$, i.e.

$$\Phi(y^*) = 1 - \frac{c}{r} \quad (2)$$

The best order quantity is associated with the critical fractile $(r - c)/r$ and therefore usually differs from the expectation of the demand $\mu = \mathbb{E}(\xi)$. The value y^* is smaller when the cost ratio c/r is higher: cheap and profitable products can be purchased at greater quantity without increasing the financial risk whereas the risk is obviously greater on expensive products. Moreover, it is clear that $y^* = 0$ when assuming $r < c$.

2.2 The cost of uncertainty

The uncertainty on the demand introduces a diminution of the expected revenue that can be defined as the cost of uncertainty: a loss of profit due to stock-out or an extra cost due to discarded inventory. Let us compare the eventual gain $G(y, \xi)$ with the naive value $\widehat{G} \doteq G(\mu, \mu)$, i.e. with the gain that will occur if the retailer purchases the expectation $y = \mu \doteq \mathbb{E}(\xi)$ of

the future demand and if, by chance, it happens that we effectively sell these μ units. Defining θ as the probability that $\xi \geq y$ and ξ^a (above) —resp. ξ^b (below)— as the expected value of the demand knowing that $\xi \geq y$ —resp. knowing that $\xi \leq y$ —, we have :

$$\begin{aligned}\theta &\doteq \int_y^\infty d\Phi(\xi) \\ \xi^a &\doteq \frac{1}{\theta} \int_y^\infty \xi d\Phi(\xi) \quad ; \quad \xi^b \doteq \frac{1}{1-\theta} \int_0^y \xi d\Phi(\xi)\end{aligned}$$

A straightforward computation leads to:

$$\widehat{G} - G(y, \Phi) = (1 - \theta) (y - \xi^b) c + \theta (\xi^a - y) (r - c) \quad (3)$$

Since the right hand side is obviously positive, $\widehat{G}$ is the Holy Grail of the problem, the maximum gain in the ideal case. Without uncertainties, the value of y can be chosen in order to obtain $\widehat{G}$ for the maximized gain (the solution being $y^* = \mu$). But in presence of uncertainties, the value $\widehat{G}$ becomes unreachable.

Moreover, the difference $\widehat{G} - G(y, \Phi)$ has a clear meaning in terms of risks evaluation. A retailer has a risk θ that the demand ξ overflows his inventory y . And in this case, his score is burdened by the fact that he misses the opportunity to sell $(\xi - y)$ units, leading to an average loss of earnings of $(\xi^a - y) (r - c)$. On the other hand, the retailer has a risk $(1 - \theta)$ that his inventory exceeds the actual demand. And in that case, his score is burdened by the resulting $(y - \xi)$ leftover units, leading to an average extra cost of $(y - \xi^b) c$.

Therefore, the right hand side of (3) is the cost of uncertainty. A better choice for y can decrease this cost, but it never vanishes. Equation (3) can also be used to investigate the gain obtained from reducing uncertainties, as illustrated in FIG.1, 2, 3 and 4.

3 Behavior of various families of distribution functions

As already stated in the introductory Section, assuming the knowledge of the probability distribution function Φ of the future demand may assume more knowledge than one can ever hope to obtain. Therefore, it must be carefully checked if conclusions obtained using a given model are robust relative to a change towards another model that remains compatible with our actual knowledge. These questions will be more precisely examined in the later Section 4.

In the present Section, we will assume that the mean of the demand has been identified and we shall examine how the optimal order decision changes when the variance of the demand or the assumed shape of the pdf are changing. We will consider the usually used normal model, as well as the lognormal,

triangular and Scarf's "two Diracs" models. In order to illustrate phenomena resulting from the increase of demand variance, we will consider the numerical values $\sigma/\mu = 0.1, 0.2, 0.4$.

3.1 Normal model

To illustrate the various topics related to inventory problems, let us start with the normal probability law since this distribution is widely used. Using this Gaussian model for the demand process would be unquestionable if consumers were (additive) processes having independent behaviors. But in the context of textile-apparel or more generally for many consumer goods, this is quite never the case since many buying decision criteria are the same for everybody (current fashion trends, common factors from national or global events, the welfare of the general economy ...), so that buying decisions are likely to be correlated, invalidating the Gaussian central limit theorem hypotheses.

Moreover, this model allows negative values for the demand ξ , an assumption that is unrealistic except for rare cases. Eliminating the negative values through a sufficiently small probability threshold $Pr(x < 0) = \alpha \approx 0$ requires that σ/μ remains small. For example, $Pr(x < 0) < 1\%$ requires that $\sigma/\mu < 0.43$. In FIG.1(a), this limitation is apparent for the lower larger curve ($\sigma/\mu = 0.4$): using greater values for σ/μ would usually be unrealistic.

In the two other pictures of FIG.1, we plot the values of the expected gain $G(y) = G(y, \Phi)$ versus the corresponding decision y for various uncertainty level. With the same average demand μ , a greater uncertainty modeled by a greater σ leads to a lower expected gain. More precisely, FIG.1(b) shows what happens when $c/r = 5/9 > 50\%$ and FIG.1(c) is related to $c/r = 4/9 < 50\%$. In both cases, we have a $\wedge$ -shaped broken line corresponding to $\sigma = 0$, and three curves, the lowest being relative to the greatest σ/μ .

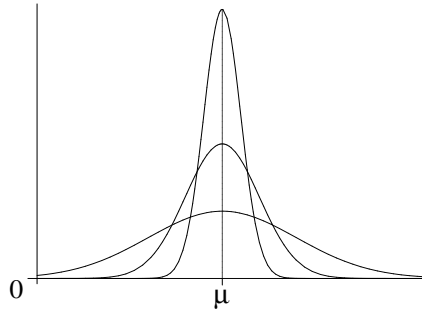
The small line starting from $(\mu, \hat{G} = \mu(r - c))$ is the locus of the extremal points (y^*, G^*) . Let us denote gau and Gau for the pdf and the cdf of the reduced normal law, and define Z by $Gau(Z) = 1 - c/r$. Then elementary computations based on (1) and (2) lead to:

$$\begin{cases} y^* = \mu + \sigma Z \\ G(y^*, \Phi) = (r - c) \mu - \sigma r gau(Z) \end{cases}$$

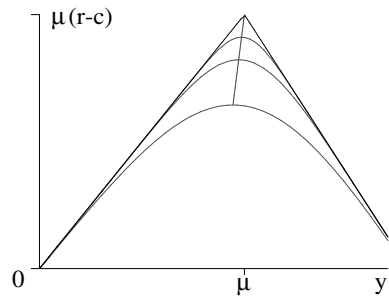
Therefore, when the distribution is normal with a given mean μ , the locus of the extremal points is a line segment which tends to the left, $y^* < \mu$ (resp. to the right, $y^* > \mu$) when the cost ratio verifies $\frac{c}{r} < 50\%$ (resp. $\frac{c}{r} > 50\%$).

3.2 Lognormal model

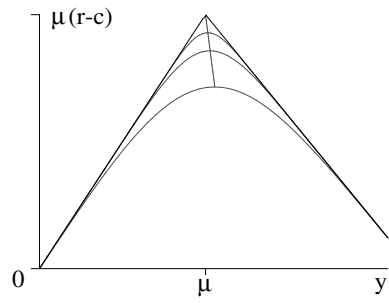
When modeling a positive quantity, the lognormal law is obviously a better candidate than the normal law since the lognormal distribution does not introduce artificial negative values. Nevertheless, it should be kept in mind that



(a) Pdfs, while $\sigma/\mu = 0.1, 0.2, 0.4$.

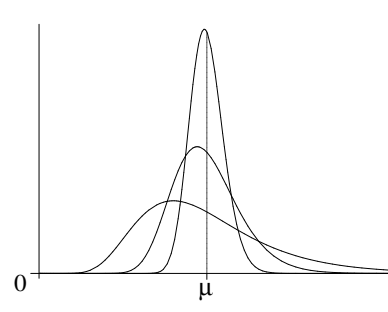


(b) Plotting $G(y)$ when $c/r = 5/9$.

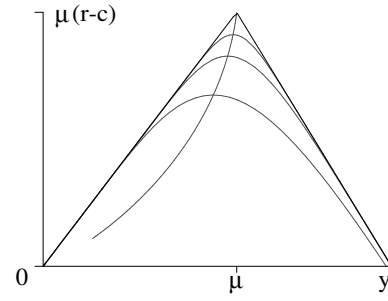


(c) Plotting $G(y)$ when $c/r = 4/9$.

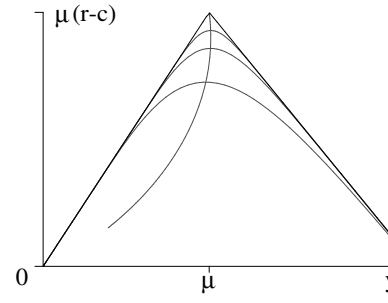
FIG. 1. Normal models.



(a) Pdfs, while $\sigma/\mu = 0.1, 0.2, 0.4$.



(b) Plotting $G(y)$ when $c/r = 5/9$.



(c) Plotting $G(y)$ when $c/r = 4/9$.

FIG. 2. Lognormal models.

using this model is roughly equivalent to assuming that the solvable demand is the product of many independent random positive factors, like the size of the population, the welfare of the economy, etc. Clearly, this is hardly the case.

FIG.2 describes what happens when using this model. FIG.2(a) shows the pdf's corresponding to $\sigma/\mu = 0.1, 0.2, 0.4$, while the other two figures are plotting the expected gain $G(y)$ versus the corresponding decision y in the four cases $\sigma/\mu = 0, 0.1, 0.2, 0.4$. As before, FIG.2(b) assumes $c/r = 5/9$ and FIG.2(c) assumes $c/r = 4/9$.

Now, the standard deviation σ can grow to infinity, inducing the existence of a “fat tail” for the distribution. Thus, as shown in FIG.2(a), most of the mass should concentrate towards 0 in order to equilibrate the “fat tail” since the mean μ has to remain constant. For this reason, we have $y^* \rightarrow 0$ when $\sigma \rightarrow \infty$, as it can be seen on both other graphs. But while, in FIG.2(b) where $c/r > 1/2$, the value of y^* always decreases when σ increases, we can see in FIG.2(c) that increasing σ from 0 induces in a first time an increase of y^* from μ (due to the value of $c/r < 1/2$) followed by a decrease towards zero when σ becomes bigger and bigger.

3.3 Triangular model

As said before, it is not realistic to assume that the distribution of the demand is exactly known. This will be further discussed in Section 4. We can at best extract some knowledge from the collected historical data so that actual problems are rather “fuzzy problems”. When using one of the former models, the parameters μ and σ are the only available degrees of freedom.

Therefore it is of interest to use a simple model, but nevertheless depending on at least three parameters, to test how robust are the conclusions drawn from our limited knowledge. Let us call *triangular distribution* a model whose pdf looks like FIG.3(a). If we note by α, β and γ , respectively, the min, mode and max of the distribution, the function Φ is given by:

$$\Phi(\xi) = \begin{cases} \frac{(\xi - \alpha)^2}{(\gamma - \alpha)(\beta - \alpha)}, & \text{when } \xi \leq \beta \\ 1 - \frac{(\gamma - \xi)^2}{(\gamma - \alpha)(\gamma - \beta)}, & \text{when } \xi \geq \beta \end{cases}$$

while mean and variance are:

$$\begin{aligned} \mu &= \frac{1}{3}(\alpha + \beta + \gamma) \\ \sigma^2 &= \frac{1}{36}((\gamma - \beta)^2 + (\beta - \alpha)^2 + (\alpha - \gamma)^2) \end{aligned} \quad (4)$$

These formulae show that the upper limit of the coefficient of variation σ/μ of a triangular distribution is $\sqrt{1/2} \approx 0.7$. In comparison, it has been seen

that $\sigma/\mu < 0.4$ is an acceptable limit for the normal distribution, while the lognormal model allows $\sigma \rightarrow +\infty$.

The triangular model is a simple way to deal with the fact that often the demand probability function is not symmetrical around its mean. This lack of symmetry is usually measured by the *skewness* $= M_3/\sigma^3$, where M_3 is the third centered moment. This moment has a nice expression over α, β, γ :

$$M_3 = \frac{1}{270} (2\beta - \gamma - \alpha) (2\gamma - \alpha - \beta) (2\alpha - \beta - \gamma)$$

But we can obtain a more compact expression to characterize the distribution by using μ : the mean, $\delta \doteq \gamma - \alpha$: the width, and $\tau = -1 + 2(\beta - \alpha)/(\gamma - \alpha)$: the barycentric position of β in $[\alpha, \gamma]$, with $-1 \leq \tau \leq +1$. We obtain:

$$\sigma = \delta \frac{\sqrt{2}}{12} \sqrt{3 + \tau^2} \quad ; \quad M_3 = -\frac{1}{1080} \delta^3 \tau (9 - \tau^2)$$

and therefore the skewness depends only on τ . Conversely, the skewness gives the shape (i.e. τ), then σ gives the size (i.e. δ) and finally μ fixes the position of the triangle along the horizontal axis. With this method, one can deal with skewness up to $2\sqrt{2}/5 \approx 0.56$ (value obtained when $\tau = -1$).

FIG.3 has been drawn using $\tau = -0.4$ (i.e. assuming that Φ is exactly known). In FIG.3(b), the skewness of the distribution and the cost to price ratio $\frac{c}{r}$ are acting in conjunction, and the locus of the extremal points shifts clearly to the origin $y^* = 0$. In FIG.3(c), these two factors are acting in opposition, and the shift to the right of the corresponding locus is not so strong.

3.4 Two Diracs model

Another model with three parameters is the “two Diracs” model that has been introduced by Scarf (1958) to obtain his max-min formula. In this model, the pdf is reduced to only two possible demand quantities $\xi = \alpha$ or $\xi = \gamma$. The parameters α, γ, θ are defined by:

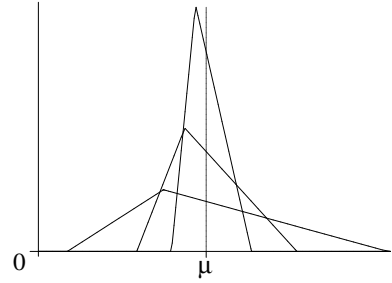
$$\alpha < \gamma \quad ; \quad Pr(\alpha) = 1 - \theta, Pr(\gamma) = \theta$$

while straightforward computation gives :

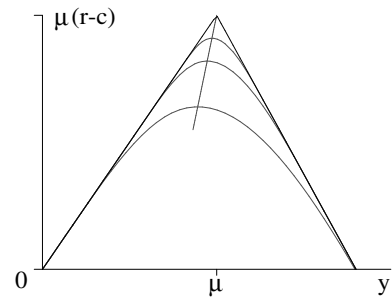
$$\begin{aligned} \mu &= \alpha(1 - \theta) + \gamma\theta \quad ; \quad \sigma = (\gamma - \alpha) \sqrt{\theta(1 - \theta)} \\ \alpha &= \mu - \sigma \sqrt{\theta/(1 - \theta)} \quad ; \quad \gamma = \mu + \sigma \sqrt{(1 - \theta)/\theta} \end{aligned}$$

Obviously, α should remain positive and, as σ/μ increases, the range $[0, \theta_0]$ of the allowed values for θ shortens.

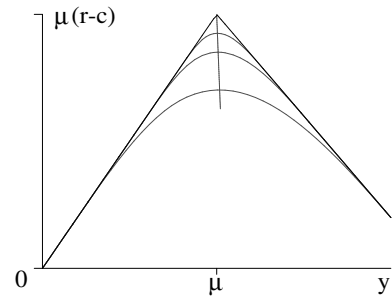
With some computations, we obtain FIG.4. The locus of the optimal order quantity y^* is on the envelop of the maximal gain $G(y)$ when $\frac{c}{\mu}$ varies, while y^* is either α (when $\theta < c/r$) or γ (when $c/r < \theta$).



(a) Pdfs, while $\sigma/\mu = 0.1, 0.2, 0.4$.

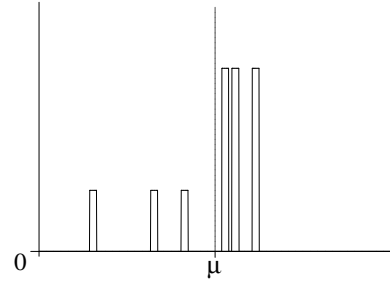


(b) Plotting $G(y)$ when $c/r = 5/9$.

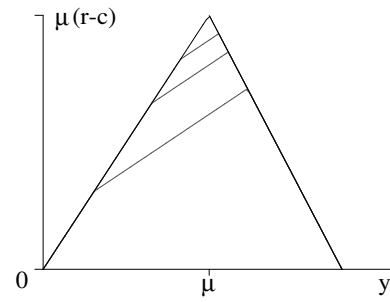


(c) Plotting $G(y)$ when $c/r = 4/9$.

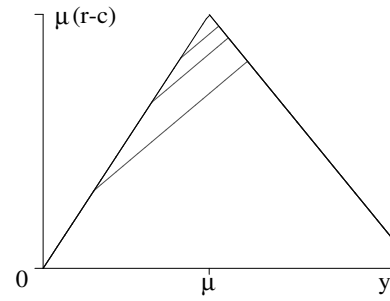
FIG. 3. Triangular models ($\tau = -0.4$).



(a) Pdfs, while $\sigma/\mu = 0.1, 0.2, 0.4$.



(b) Plotting $G(y)$ when $c/r = 5/9$.



(c) Plotting $G(y)$ when $c/r = 4/9$.

FIG. 4. Two Diracs models ($\theta = 0.75$).

4 Discussion about hypotheses

Assuming a low value of uncertainty σ obviously leads to an order quantity near the identified mean demand. On the contrary, the preceding section has shown that the optimal order quantity may vary to a great extent for different demand models even when assuming the same characteristics (μ, σ) , especially for high value of $\frac{\sigma}{\mu}$. Let us now discuss the meaning and the potential validity of the hypotheses that were assumed to obtain these results.

The first point to be mentioned concerns what is modeled. A probability function like $\Phi(\xi)$ can model our lack of actual knowledge concerning the future demand. We may for example think that a better knowledge (at ordering time) can be reached but that its cost would stay beyond the additional benefits resulting from this additional knowledge. A discussion of such cost balancing is undertaken in (Eeckhoudt and Godfroid, 2000). Another point of view is that markets are intrinsically wild and turbulent so that the probability function models the very nature of market, and not only a lack of knowledge.

The second point concerns what experimental procedure can be used to determine $\Phi(\xi)$. A “gedachte Experiment” is as follows: starting with a great number of exact copies of the actual world, put different order quantities in these worlds, inducing them to evolve (independently) in different manners and observe what happens at selling time. This experiment is obviously impossible to carry out. One cannot escape this point of view by considering approximations obtained from times series, since only ergodicity can justify such approximations, without mentioning the fact that actual times series are quite ever too short to conclude, even assuming ergodicity.

A third point is that the actual demand cannot be measured, even afterwards when the demand overflows the inventory. In such a case, the only actual knowledge is the observation of the stock-out $\xi > y$, not the exact value of ξ^1 . Therefore, a slight shift towards over-sizing the inventory could be a good policy since it results into a better knowledge for a slight cost (Tang and Grubbstrom, 2002).

From these considerations, a more realistic point of view is to consider the optimization of the purchase decision against a family of demand models with common practically identifiable characteristics. Examining this situation with the max-min method when assuming that the usual dispersion parameters are identifiable is the aim of the following Section.

5 Max-min problems

5.1 General statement

Let us assume now that only μ and σ are known and examine what can be said when Φ ranges over all the elements of a family of models that all fit

¹ In some cases, the unsatisfied demand ξ can be identified when the unsatisfied customer asked for the products through a formal ordering form.

these characteristics. In such a case, we can determine a robust value y_{robust} for the order quantity by the following algorithm : for each value of y , we determine the worst distribution of the family, i.e. the Φ that minimize the expected gain. And we choose the order quantity y that optimize the worst case. In other words, we solve:

$$G_{robust} = \max_y \min_{\Phi | \mu, \sigma} G(y, \Phi)$$

The quantity $\min_{\Phi | \mu, \sigma} G(y, \Phi)$ is the worst possible expected revenue induced by any pdf having the given characteristics (μ, σ) . The obtained order decision is robust in the sense that any possible pdf in the family $\mathcal{F} = \{\Phi | \mu, \sigma\}$ will give at least the gain G_{robust} , representing the guaranteed expected performance. For normal or lognormal family, $\mathcal{F} = \{\Phi | \mu, \sigma\}$ reduces to only one possibility, leading to the same result as in Section 3. It is of interest to study various families of models Φ with a third or more free parameters. This is the case for triangular models.

5.2 Max-min, using triangular models

When the family of models is the set of all triangular distribution having given values for μ, σ , one degree of freedom remains : the shape τ . When μ, σ, τ are known, the values of α, β, γ (resp. the minimum possible, the most probable and the maximum possible demand) are given by:

$$\mu - \frac{(3 + \tau) \sqrt{2}}{\sqrt{\tau^2 + 3}} \sigma, \mu + \frac{2\tau \sqrt{2}}{\sqrt{\tau^2 + 3}} \sigma, \mu + \frac{(3 - \tau) \sqrt{2}}{\sqrt{\tau^2 + 3}} \sigma$$

Obviously, α should be positive. It can be seen that if $\sigma/\mu < \sqrt{2}/4 \approx 0.35$, then all values of $\tau \in [-1, +1]$ are allowed, while $0.35 < \sigma/\mu < \sqrt{2}/2$ allows only $\tau \in [-1, \tau_0]$ where τ_0 is the useful solution of an equation of second degree. As a result, the set of the effective values for the couple $(\sigma/\mu, \tau)$ is the grayed zone in FIG.5(a).

In this new situation, the method to find the best decision is exemplified in the rest of FIG.5, where we have taken $\mu = 1000, \sigma/\mu = 0.35$ and $(r - c) = 10$ (leading to $\hat{G} = 10\,000$). In each sub-figure, there are several curves, each one labeled with a value of y . For example, the curve labeled “1100” describes what is the expectation of the gain, knowing that $y = 1100$, but depending on the value of τ . In other words, this curve is the graph of the function $\tau \mapsto G(1100, \Phi_\tau)$.

For each curve, the worst case is marked by a circle. It can be seen, in FIG.5(b) and FIG.5(c), i.e. for $c/r = 5/9$ and $c/r = 4/9$, that the worst case ever occurs when $\tau = \pm 1$. This can be confirmed by formal computation. A more precise result is:

Theorem 1. *Assuming that $\tau = 1$ is allowed (i.e. $\sigma/\mu < \sqrt{2}/4 \approx 0.35$) then, against all stochastic demand models with triangular probability density functions and given characteristics μ, σ , the robust order quantity is given by:*

$$\text{case } \frac{c}{r} \text{ in } \begin{cases} [0, 4/9] & y_{\text{robust}} = \mu + (2 - 3\sqrt{\frac{c}{r}}) \sigma \sqrt{2} > \mu \\ [4/9, 5/9] & y_{\text{robust}} = \mu \\ [5/9, 0] & y_{\text{robust}} = \mu - \left(2 - 3\sqrt{\frac{(r-c)}{r}}\right) \sigma \sqrt{2} < \mu \end{cases} \quad (5)$$

Moreover, in the central case, we have:

$$G_{\text{robust}} = (r - c) \mu - \left(8\sqrt{2}/27\right) \sigma r$$

5.3 Comparison with the Scarf's result

This result is to be compared with the following : in 1958, H. Scarf has proven that, over all distributions Φ having the given characteristics μ, σ , the worst case for a given y is attained by a "two Diracs" model. Therefore the solution of the problem

$$G_{\text{robust}} = \max_y \min_{\Phi | \mu, \sigma} G(y, \Phi)$$

can be obtained by taking into account only these "two Diracs" distributions, and the solution is, as published in (Scarf, 1958), given by:

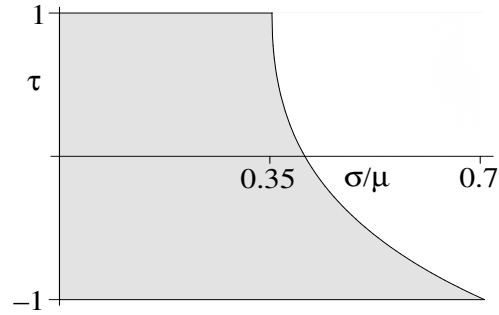
$$\begin{cases} \text{if } 1 < \frac{c}{r} \left(1 + \frac{\sigma^2}{\mu^2}\right) & \text{do nothing : } y_{\text{scarf}} = 0 \\ \text{if } \frac{c}{r} \left(1 + \frac{\sigma^2}{\mu^2}\right) < 1 & y_{\text{scarf}} = \mu + \sigma \frac{r/2 - c}{\sqrt{c(r-c)}} \end{cases} \quad (6)$$

This result holds for any possible form of the pdf Φ . Notice that in this case the robust solution y_{scarf} is not equal to μ unless $c = \frac{r}{2}$ or $\sigma = 0$. As expected, the value of G_{robust} obtained by (6) is less than the G_{robust} obtained when considering only a smaller family of models. The solution y_{scarf} is then a conservative result.

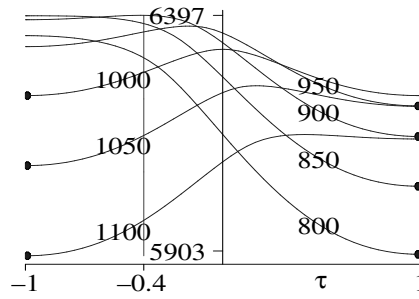
6 Conclusion

We have discussed about the limitation of the standard hypothesis of the knowledge of the uncertain demand modeled in the form of an exact probability distribution function. Such a model has been largely used in the literature to solve the problem of the optimal purchasing policy, a decision problem which is currently met in the supply chain. We propose to identify some characteristics of the future demand which are practically determinable, and following Scarf's method, to analyze the optimal decision obtained from the defined family of demand models.

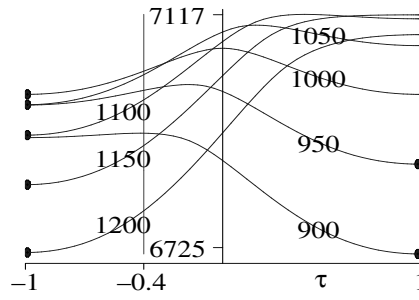
- With the knowledge of the only mean demand μ , the order quantity is obviously $y = \mu$. The model is limited since there is no possibility to analyze any uncertainties. The risk for the company manager is, in that case, to rely on a fictitious ideal revenue which does not take into account the cost of uncertainties.



(a) Possible associations for $(\sigma/\mu, \tau)$.



(b) Assuming $c/r = 5/9$.



(c) Assuming $c/r = 4/9$.

FIG. 5. Maximin problem (triangular model).

- With a knowledge on μ and σ or the coefficient of variation $\frac{\sigma}{\mu}$, the robust decision is y_{scarf} . This decision takes into account any general form of the demand probability function, leading to a conservative result. The gain correspond to the knowledge of the expected (minimal) guaranteed revenue. Any additional knowledge can improve this decision since the set of demand models is reduced.
- We have investigated the triangular models which have three parameters for the probability function : the minimum possible demand, the maximum possible, and the most probable demand. These parameters can certainly be identified without too much imprecision by sales managers.

The immediate perspective is to extend this result to the case of more variable demand $\frac{\sigma}{\mu} > 0.35$. Another perspective is the extension of these results to the multi-period purchasing strategy where the next order quantities can make some corrections on the previous decisions by observing the inventory at hand. This discussion can also be used to investigate how prices are fixed by the market for risky products: in the long run, the sellers will reorient their activity if they don't obtain in the average at least the average remuneration for their capital. Thus the final price must contain not only the costs and the usual remuneration, but also (at least) an insurance for the risks.

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Developing an Apparel Supply Chain Simulation System with the Application of Fuzzy Logic

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Abstract

In this paper, a simulation model linking manufacturer, retailer and customer in an apparel supply chain is presented. The purpose of the model is to generate a portfolio that satisfies the apparel retailer-defined customer service level. The portfolio consists of replenishment strategy and performance index under different degrees of forecasting errors in sales. Fuzzy logic is integrated into the simulation model so as to investigate the different forecasting error degree between the sales forecasting and the customer demand in the apparel supply chain. Experimental results based on a case study are discussed and the simulation model is validated. The results show that the proposed apparel supply chain simulation model is an effective tool of investigating relationship between forecasting error, replenishment strategy and performance for apparel retailers and manufacturers.

1 Introduction

Today apparel enterprises are facing an environment featured with fierce market competition, customer demand uncertainty, short product life cycle, sophisticated product features, heavy burden of information explosion, short lead-time and frequent style changes while increasing use of information technology has changed the traditional practice of doing business in the apparel industry. The development of an efficient apparel supply chain becomes the focus of many researchers.

In apparel supply chain, customer service level (CSL) is one of important objectives to achieve. It represents the percentage of customer's demand

being satisfied during the whole sales season. There are two methods to calculate the CSL. One is to calculate the in-stock of SKU (Stock Keeping Unit) percentage, and the other is to calculate the out-of-stock of SKU percentage. In-stock means a certain SKU that customer wants to buy is available when he/she comes to the shop while out-of-stock means the particular SKU is not available. In this chapter, the out-of-stock situation is employed to measure the CSL. Equation 1 shows the definition of the CSL.

$$CSL = (1 - \frac{\text{sum of out of stock}}{\text{sum of actual demand of customer}}) * 100\% \quad (1)$$

The CSL is affected by combinations of various parameters such as lead time, replenishment cycle, and replenishment quantity. Among the factors influencing the CSL, forecasting error, which is caused by demand uncertainty in apparel industry, is one of the most critical ones affecting the performance of the apparel supply chain. The forecasting error is the discrepancy between the actual customer demand and forecasting demand. The forecasting error greatly influences the performance of the apparel supply chain in terms of the CSL, inventory turnover, etc. If the retailer's prediction exactly equals to what customers want, there will be neither inventory nor stock out at the retailer. On the other hand, if the forecasting error is large, the retailer has to keep more stocks to maintain the required CSL which in turn increase the inventory.

In apparel supply chain, forecasting error is only approximately estimated by retailers using their experience and historical data. In these situations, uncertainties of forecasting error may be expressed using imprecise linguistic expressions; for example, the volume error is about eqm, but definitely not less than eql and not greater than equ, the forecasting error on size mix is about 10%, etc. Fuzzy sets are found to be useful in representing the approximate qualifiers of forecasting error between the predicted sales of retailer and the actual demand (Zimmermann 1996).

To maintain the expected CSL under different forecasting error, decision on replenishment strategies including lead time, replenishment cycle, replenishment quantity between the retailer and manufacturer is critical. This decision-making process is inherently complex. One feasible solution is to investigate the apparel supply chain using simulation technique.

In this paper, CSL is targeted by retailer as the constraint in the apparel supply chain. With different degree of forecasting errors, a proposed simulation model integrating with fuzzy logic will generate a

portfolio set including lead-time, replenishment cycle and replenishment quantities. The operation of apparel supply chain will be simulated under different sets of portfolio. Performance index, such as inventory turnover, predicted CSL in each portfolio, are then calculated. The proposed portfolio simulation model provides a tool for apparel retailers and manufacturers to identify the appropriate replenishment strategy so as to achieve the required CSL under different degree of forecasting error.

2 Previous Research

2.1 Apparel Supply Chain and Simulation Model

Researchers studied supply chain management significantly in the last two decades. Some of the literatures on apparel supply chain employed interviews and mail surveys to analyze the performance of the supply chain (Abernathy 2000, Kincade 2001). There are some literatures relevant to the simulation model in the apparel supply chain. Reference (Nuttle 1991) was one of the pilot reports on apparel supply chain simulation. The authors developed the simulation technique to evaluate a sourcing strategy for a retailer for a given set of input. A novel apparel-supply model was then studied which was compatible with quick response retailing of apparel within a finite shelf life (Hunter 1992). In a subsequent research (Hunter 1996), they used a stochastic computer-simulation model to quantify the underlying differences. The work done on simulation of apparel product's supply chain has focused on the effects of new technology such as QR usage on consumer perception, who implements the technology (Hunter 1992, 1996, 2002). They showed the difference between the apparel supply chains adopting the QR strategy and the traditional ones. In (Joines 2002) optimizing the sourcing decisions in the apparel supply chain and determining robust solutions were addressed. Little has done to generate the appropriate replenishment strategy between the retailer and manufacturer to satisfy the CSL.

2.2 Fuzzy Logic in Supply Chain Modeling

Managing uncertainty is an important issue in supply chain modeling. To study the uncertainties systematically, two methodologies are applied to

supply chain system. Some researchers addressed the uncertainty using stochastic models (Federgruen 1993, Porteus 2002). In these models, uncertain demand was incorporated with normal probability function based on past records. Another method was to utilize the fuzzy logic to describe the imprecise parameter under uncertainty. Some prior research have developed fuzzy supply chain model. In (Petrovic 1999), the researcher illustrated a supply chain fuzzy model to determine the order quantities for each inventory in the presence of uncertainties. The input of uncertainty of the supply chain was assessed by various simulation tests. In a subsequent publication (Petrovic 2001), the author described uncertainty data perceived in the supply chain by imprecise natural language expressions and modeled in a special purpose simulation tool by fuzzy sets. In (Dong 2006), a fuzzy decision methodology was developed to provide an alternative framework in order to handle supply chain uncertainties.

3. Development of the Simulation Model

3.1 Structure of the Simulation Model

The objective of the proposed simulation model is to generate a feasible replenishment strategy which recommending lead time, replenishment cycle, and replenishment quantity based on the CSL targeted by the retailer, and other pre-defined parameters, such as length of sales season, sales forecast and the pre-defined forecasting error. The performance of each replenishment strategy is reflected by the predicted value of inventory turnover and CSL. Figure 1 depicts the structure of the simulation model. Figure 2 illustrates the process of generating the replenishment strategy. The detailed procedure of the simulation model is explained as follows:

Step 1: Set the CSL targeted by the retailer as the constraint.

Step 2: Forecast sales, including the total quantity of garments, seasonal distribution pattern of the sales and the mixed proportion of the garments in terms of style, color and size based on the retailer's historical data. Approximate forecasting error in linguistic terms at different degrees is also estimated by the retailer based on their experience and subjective assessment. In apparel industry, forecasting errors are divided into volume error, SKU mix error and seasonality error. Specifically, the volume error is defined as total quantity error for all the SKUs between sales forecast and actual

customer demand in the whole sales season. SKU mix error is one that shows the difference between actual distribution of style, color and size of the garments and the forecasted ones. Seasonality error quantifies the impact of assuming the wrong seasonality pattern. With the integration of fuzzy concept, the forecasting error in linguistic can be converted into fuzzy number. (Details of the implementation of fuzzy concept on forecasting error and converting the fuzzy forecasting error into fuzzy number are explained in Section 3.2).

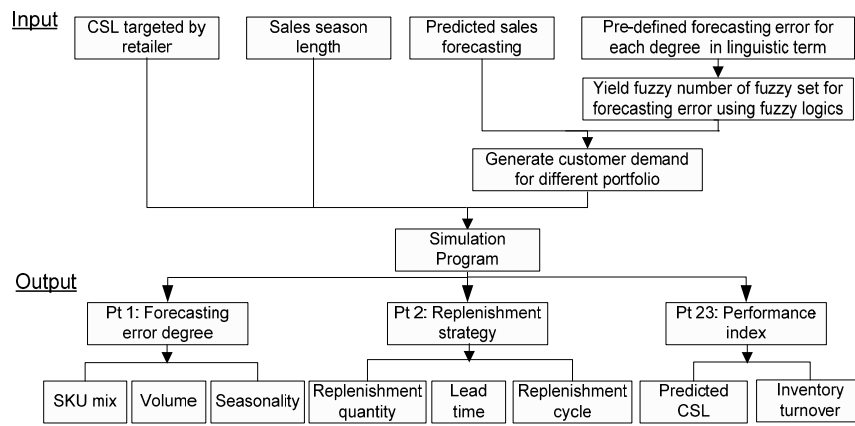


Fig. 1. Structure of the proposed apparel supply chain simulation model

Step 3: Generate a series of replenishment strategy in terms of lead time and replenishment cycle. Generate fuzzy numbers for all degrees of forecasting error in volume, SKU mix and seasonality distribution. For each set of replenishment strategy with different degree of forecasting error, the simulation procedure proceeds as follows:

- a) Predict the customers' demands based on both the sales forecast obtained in step 2 and the selected degree of forecasting error using Eq. 2. Eq. 2 denotes the relationship among sales forecasting S_f , actual customer demand C_d and forecasting error F_e in which C_d and F_e are functions of time series and S_f is a constant predicted by the retailer before sales season. Both the sales forecast and forecasting error are in terms of total quantity of garments, seasonal distribution pattern of the sales and the mixed proportion of the garments.

$$C_d = S_f + F_e \quad (2)$$

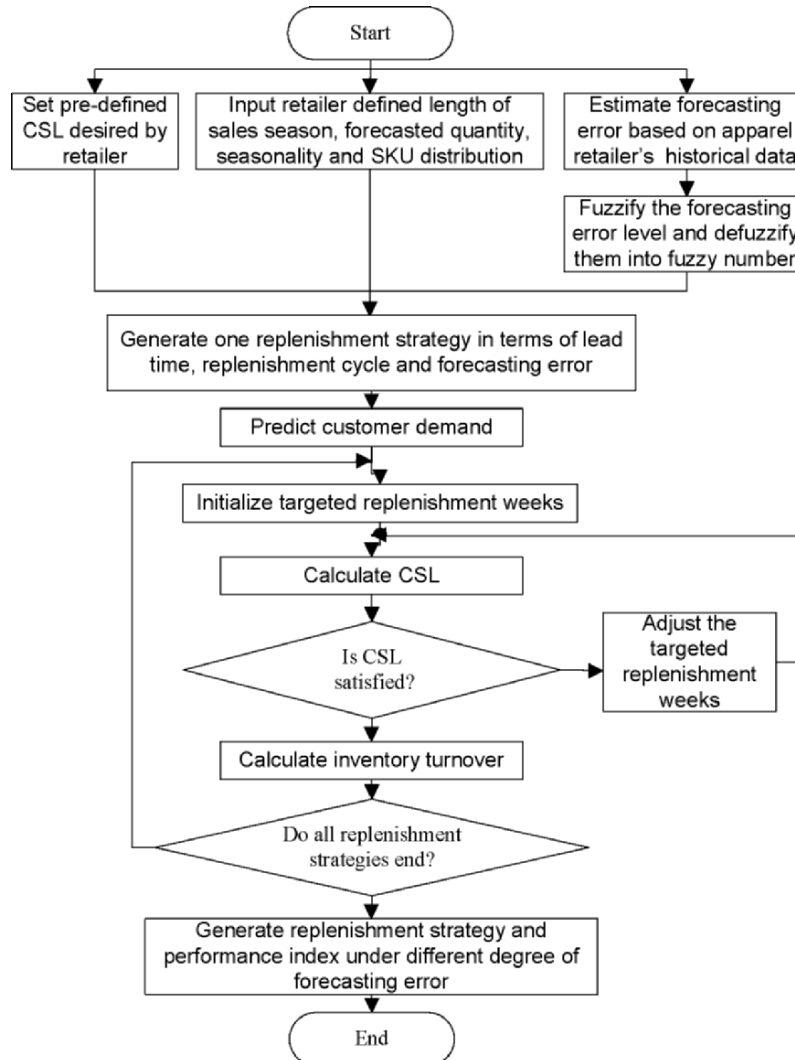


Fig. 2. Flow chart of generating replenishment strategy using the proposed simulation model with fuzzy logics

b) Distribute the sales forecast (obtained in step 2) and predicted customer demand (generated in step a) to each SKU in the sales season based on the SKU distribution and seasonal distribution pattern. Both the sales forecast and the customer demand for each SKU in each week of the sales period therefore are obtained.

c) Initialize the replenishment quantity using replenishment algorithm for all SKUs. The replenishment algorithm is based upon the idea that the retailer should hold inventory to meet the demands expected in the upcoming weeks. These upcoming weeks at least include the gap between the week when replenishment order released from the manufacturer and the week when the next replenishment arrives at the retailers. To overcome the demand's fluctuation, the retailer also keeps inventory to cover extra weeks of customer demand which is called 'safety stock'. The more safety stock the retailer keeps, the higher the probability that the customer can purchase the SKU she/he wants. However, the inventory cost will increase. In general, the length of upcoming weeks is equal to the sum of lead time (LT), replenishment cycle (RC) and week of safety stock (W_{ss}). Thus, $(LT+RC+W_{ss})$ is used to denote the targeted replenishment weeks. Detailed descriptions of the replenishment algorithm refer to (Dong 2006). Since the ideal situation is that the retailer needs not to keep any safety stock, targeted replenishment weeks is set as the minimal value which means W_{ss} is initialed as zero at the beginning of the simulation procedure.

d) Simulate the purchase of customer, track the inventory for each SKU, record the sales as POS data and replenish goods from the manufacturer based on the replenishment algorithm. These procedures are simulated on weekly basis in the sales season as follows:

In the first week, the retailer keeps targeted replenishment weeks of stock based on the sales forecast. If the particular SKU the customer wants is in-stock, POS data increases and the inventory of this particular SKU decreases by one; otherwise, a lost of sales is recorded. This purchasing procedure repeats for all customer demands in the first week. At the end of the first week, the POS data, the in-stock SKU, and the lost sales for each SKU are recorded. Replenishment quantity for each SKU is calculated using replenishment algorithm if a new replenishment is activated. This replenishment will arrive at the retailer after LT weeks.

In the next week, add the garments to the inventory of the retailer if a new replenishment arrives. Repeat step d until the end of the sales season.

e) Calculate CSL using Eq. 2.

f) If the calculated CSL $\neq$ the CSL targeted by the retailer, gradually increase replenishment quantity for all SKUs in terms of targeted replenishment weeks (i.e., increase the value of W_{ss} gradually) and

repeat steps d-e until the CSL targeted by the retailer can be achieved.

g) Calculate the inventory turnover under the circumstance using Eq. 3.

$$\text{Inventory turnover} = \frac{\text{Annual Sales}}{\text{Average inventory level}} \quad (3)$$

Step 4: Repeat step 3 for all sets of replenishment strategy at all degrees of forecasting error. Generate replenishment strategy and performance index under different degree of forecasting error.

3.2 Fuzzy Forecasting Error

In apparel business, sales forecasting can be described as volume, stock keeping unit (SKU) mix and seasonal pattern between the forecast and the actual demand. Table 1 shows an example of mix color error.

Table 1. Example of colour error

SKU	Colour 1	Colour 2	Colour 3	Colour 4	Colour 5
FDD [%]	30	10	25	10	25
ADD [%]	33	8	22	15	22
AE [%]	3	2	3	5	3
CE [%]	16				

FDD: Forecasting distribution, *ADD*: Actual distribution, *AE*: Absolute error, *CE*: Colour error

Retailer and manufacturer predict the degree of forecasting error within a range of value based on their experience. They usually divide the forecasting error into three degrees, i.e., low, median and high degree. For each degree, the error range can be expressed in linguistic terms. For example, the linguistic description for a median level of forecasting error on volume is “about 40% ranging from 20% to 60%”.

Fuzzy set theory is one of the methods to treat the uncertainty (Zedah 1965, Wang 2005). A Fuzzy set is characterized by fuzzy boundaries: unlike crisp sets in which a given element does or does not belong to a given set, each element in fuzzy set belongs to a set with a certain mem-

bership degree. The function that returns the membership degree of each fuzzy set element is called membership function. In this chapter, triangular membership functions have been adopted because they are considered the most suitable form to model market demand (Katagiri 2000, Giannoccaro 2003). Based on the relationship between the forecasting error and market demand that are denoted in Eq. 2, the forecasting error is treated as a triangular membership function. Figure 3 depicts the triangular membership function of the linguistic description “forecasting error is about 40%, ranging from 20% to 60%”.

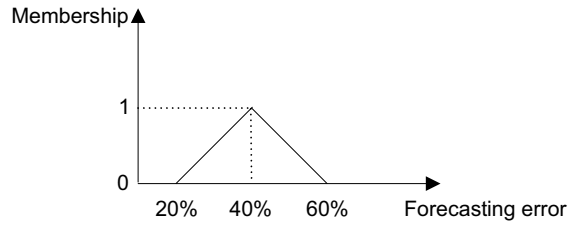


Fig. 3. Example of fuzzy membership

Once the forecasting error can be formulated as membership function, the next step is to fuzzify the forecasting error which will be input into the supply chain simulation model. In order to simplify the manipulation of fuzzy numbers, Heilpern (1992) introduced a method of denoting the expected value of fuzzy number. The expected interval is defined as the expected value of an interval random set generated by the fuzzy number and the expected value of this number is defined as the centre of the expected interval. The method can be summarized as below.

Step 1: Firstly, the membership function $\mu_A(x)$ of the fuzzy number A is described as:

$$\mu_A(x) = \begin{cases} 0 & \text{for } x < a, \\ f_A(x) & \text{for } a \leq x < c, \\ 1 & \text{for } c \leq x \leq d, \\ g_A(x) & \text{for } d < x \leq b, \\ 0 & \text{for } x > b, \end{cases} \quad (4)$$

where the functions f_A and g_A are located between the left and the right sides of A. f_A and g_A are increasing and decreasing functions, respectively. This fuzzy set can be denoted as $N(a, c, d, b)$.

Step 2: The expected interval of a fuzzy number A is denoted by EI (A).

Step 3: The center of the expected interval of a fuzzy member A is called the expected value of this number and denoted by EV (A), i.e.,

$$EV(A) = \frac{1}{2}(Es1 + Es2) \quad (5)$$

where ,

$$Es1 = c - \int_a^c f_A(x) dx \quad (6)$$

$$Es2 = d + \int_d^b g_A(x) dx \quad (7)$$

The steps of integrating the fuzzy sets into the proposed apparel supply chain simulation model to represent different level of forecasting error between the sales forecast before the sales season and the actual demand of the customers are presented as follows:

Step 1: Pre-define forecasting error on volume, SKU mix and seasonality in linguistic term by expert (say retailer).

Step 2: Convert the linguistic description of forecasting error into triangular member function of fuzzy number.

In our study, the forecasting error is considered as a triangular membership function for each kind of forecasting error at different levels. To model the forecasting error by a triangular membership function, the retailer only need to estimate the values that do or do not belong to its domain (fuzzy set). Based on the experiences and historical data, retailer estimates the approximate range of values are not possible at all for forecasting error which determines the lower and upper limits of the set, l and u respectively as well as the value that better represents the set (c). For example, l, u and c in Fig. 3 for median error on volume are 20%, 40% and 60% respectively.

Step 3: Yield the expected value of fuzzy number of fuzzy sets for each forecasting error level.

Applying the method of Heilpern (1992) and denoting the membership function in Eq. 4 with triangular ones generated in step 2, the expected value of fuzzy number of fuzzy sets for each forecasting error degree for different forecasting categories can be obtained.

Step 4: Merge five types of forecasting error for simulation.

There are five types for forecasting error, each with three levels of error, namely high (H), median (M) and low (L). Altogether there are 35 combinations. Typical examples of the combinations showed in Table 2 are selected to be transferred into fuzzy numbers using the algorithm discussed above.

Table 2. Examples of different combination of forecasting error degree

No. of Combination		1	2	3	4	5	6	7	8	9	10
		Forecasting error degree									
Volume		H	H	H	M	M	M	M	L	L	L
SKU mix	Style	H	M	M	M	M	M	L	L	L	L
	Colour	H	H	M	H	M	L	L	M	L	L
	Size	H	H	H	M	M	L	L	M	M	L
Seasonality		H	H	H	M	M	L	M	M	M	L

4 Experiment

Industrial data obtained from an apparel corporation in Hong Kong and its overseas client were input into the simulation model for testing. In the experiment, lead time was set between 7 weeks and 9 weeks based on the existing practice of the apparel manufacturers. The lead time included the manufacturing time and transit time of apparel products to the retailer. The length of replenishment cycle varied from 1 week to 6 weeks depending on different strategic policies adopted by the parties of supply chain. To simplify the analysis, only three combination sets, 1, 5 and 10 at high, median and low levels of forecasting error, in Table 2 were chosen for experimental testing.

Table 3 illustrates typical input parameters. Percentage proportion of different styles, colors and sizes forecasted by the retailer were pre-defined. The proportions of each of the five styles are 30%, 10%, 25%, 10% and 25%, respectively. Similarly, the proportions for seven different colors are 20%, 15%, 20%, 5%, 20%, 10% and 10%, respectively while those for six sizes are 4%, 20%, 28%, 27%, 14%, and 7%, respectively. The seasonality distribution of customer demand is also estimated by the retailer.

Based on the above input parameters, the simulation model generated a series of portfolios in which all of them could satisfy at least 95% CSL. Table 4 lists the result of the simulation model. The result provides possible sets of portfolio in terms of forecasting error degree, replenishment strategy, inventory turnover and predicted CSL. Based on the result, the retailer and manufacturer might select her desired portfolio among these sets before actual operation.

The result also demonstrates relationship among the forecasting error, replenishment strategy and performance of the supply chain. In general, an

increase in forecasting errors degree, as well as the lead time and replenishment cycle, will increase the replenishment quantities in order to keep the same level of customer service. For example, in portfolios 1, 13 and 25 the replenishment cycle and lead time are the same, while the error degrees are low, medium and high, respectively. The targeted replenishment quantity in terms of targeted replenishment week in these three sets are generated as 8, 9, and 11, respectively and the inventory turnover is decreased from 12.5, 8.72 to 5.0. Another example can be found in portfolios 1, 4, 7 and 10. In these three sets, both forecasting error and lead time are of the same value and the replenishment cycles are 1, 2, 4 and 6, respectively. The targeted replenishment quantities in terms of targeted replenishment weeks are generated as 8, 11, 14 and 17, respectively. The inventory turnover is declined from 12.5, 9.64, 6.61 to 4.96. If the forecasting error degree and replenishment cycle were kept constant, the influence of lead time on performance of the supply chain can be identified in portfolios 1, 2, and 3 in which the inventory weeks increase from 8, 10 to 11 and the inventory turnover declines from 12.5, 10.73 to 9.43 respectively.

Table 3. Typical input parameters

Constraint	CSL targeted by the retailer	95%
Input	Sales season [week]	36
	Forecasted quantity of garment [unit]	100,000
	Number of styles	5
	Number of colors	7
	Number of sizes	6
	Forecasted style proportion in [%]	30/10/25/10/25
	Forecasted color proportion in [%]	20/15/20/5/20/10/10
	Forecasted size proportion in [%]	4/20/28/27/14/7
	Seasonality	Retailer defined

Table 4. Simulation result generated by the proposed simulation model

Forecasting Error		Replenishment Strategy			Performance Index	
No.	Degree	RC [Week]	LT [Week]	TRQ	INTO	PCSL
1	Low	1	7	8	12.50	0.951
2	Low	1	8	10	10.73	0.959
3	Low	1	9	11	9.43	0.961

4	Low	2	7	11	9.64	0.954
5	Low	2	8	13	7.86	0.972
6	Low	2	9	14	6.92	0.961
7	Low	4	7	14	6.61	0.961
8	Low	4	8	15	6.10	0.952
9	Low	4	9	16	5.52	0.955
10	Low	6	7	17	4.96	0.961
11	Low	6	8	18	4.71	0.952
12	Low	6	9	19	4.45	0.954
13	Median	1	7	9	8.72	0.951
14	Median	1	8	10	7.72	0.952
15	Median	1	9	11	6.82	0.955
16	Median	2	7	11	5.61	0.958
17	Median	2	8	12	5.15	0.961
18	Median	2	9	13	4.77	0.954
19	Median	4	7	13	5.07	0.952
20	Median	4	8	15	4.48	0.953
21	Median	4	9	16	4.20	0.961
22	Median	6	7	15	3.85	0.965
23	Median	6	8	16	3.58	0.955
24	Median	6	9	17	2.95	0.971
25	High	1	7	11	5.00	0.956
26	High	1	8	12	4.32	0.950
27	High	1	9	14	3.33	0.958
28	High	2	7	13	3.70	0.956
29	High	2	8	14	3.32	0.953
30	High	2	9	16	2.70	0.965
31	High	4	7	17	3.01	0.963
32	High	4	8	19	2.84	0.958
33	High	4	9	20	2.62	0.959
34	High	6	7	18	2.37	0.962
35	High	6	8	20	2.11	0.956
36	High	6	9	22	1.92	0.963

TRQ: Targeted replenishment quantity in terms of targeted replenishment week,
INTO: Inventory turnover, *PCSL*: Predicted CSL

In order to validate whether the procedure of the simulation is consistent with the actual operation in the industry, current practice of the industry was compared with the proposed simulation model. The lead time,

the replenishment cycle, the forecasting error degree and other parameters such as sales season pattern, sales season length etc. from the industry were set as the input of the simulation model. After simulation, the portfolio simulation model generated performance index in terms of inventory turnover and predicted CSL which were 4.57 and 97%, respectively. The industrial data for the same performance index were 4.20 and 95%, respectively. This result showed that the parameters generated by the simulation system were very close to those of industrial practice.

5. Conclusions

In this paper, a simulation model that integrates customer, retailer and manufacturer along the supply chain of the apparel industry is proposed. The simulation model is capable of generating different replenishment strategies given different forecasting errors and CSL. A fuzzy logic technique is designed to represent various forecasting error degree for different forecasting catalogues in terms of quantity, SKU mix and seasonality pattern. The proposed supply chain simulation model integrating with fuzzy concept contributes to the scientific approach of the supply chain practitioners to deal with uncertainties in dynamic market environment. This model is also shown to be an effective simulation tool for retailers and manufacturers to understand how each factor influences the performance of apparel supply chain prior to actual business.

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Part V

Computational Thermal Bioengineering of Textiles

Computational Textile Bioengineering

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Abstract:

Computational textile bioengineering is the integration of physical, chemical, mathematical, and computational sciences and engineering principles to study relationship between clothing and human biology, medicine, behavior and health. It advances fundamental concepts; creates knowledge from molecules to body-clothing systems; and develops innovative materials, devices, and apparel products for healthy lifestyle fashion with functions of comfort, protection, prevention, diagnosis, and treatment of disease, and healthcare. It is application of a systematic, quantitative and integrative way of approaching the solutions of how clothing and textiles can be engineered to the benefits of biology, physiology, medicine, behavior and health of human populations.

Keywords: Computation, Informatics, Bioengineering, Biosensory, Biomechanical, Thermal, Biomedical, Biomaterial and Textiles

1 Introduction

Health and disease prevention have been a major concern of human beings, particularly for consumers in the new century in consumption of textiles and apparel products. Biological health and psychological happiness are critical indexes reflecting quality of our lives, in which textiles and clothing plays very important roles. Clothing is one of the most intimate objects associated with the daily life of individual human beings, as it cover most part our body in most of the time. Consciously or unconsciously, our physiological/biological status and psychological/emotional feelings are closely associated with the clothing we wear. More and more modern consumers understand the importance of textiles and demands apparel products with higher added values in terms of functional performance to satisfy various aspects of their biological and psychological needs in communication, protection, healthcare, medicine and sensory comfort during wear. Naturally, engineering textiles and apparel products for biological and psychological health become an integrated part of the concept of bioengineering:

Then, what is bioengineering? In February 1998, the United States National Institutes of Health organized a Symposium on bioengineering, in which a definition of bioengineering was formulated as:

“Bioengineering integrates physical, chemical, or mathematical sciences and engineering principles for the study of biology, medicine, behavior, or health. It advances fundamental concepts, creates knowledge from the molecular to the organ systems level, and develops innovative biologics, materials, processes, implants, devices, and informatics approaches for the prevention, diagnosis, and treatment of disease, for patient rehabilitation, and for improving health” (Angnew, 1998).

Angnew (1998) pointed out that bioengineering is rooted in physics, mathematics, chemistry, biology, computational sciences, and various engineering disciplines. It is the application of a systematic, quantitative

and integrative way of thinking about and approaching the solutions in problems important in human biology, physiology, medicine, behavior and health of human populations. From this definition, it is clear that the biological problems are too complex to be solved by biologists alone; partners are needed in many disciplines, including physics, mathematics, chemistry, computer sciences, and engineering. Bioengineering integrates principles from a diversity of fields. The creativity of interdisciplinary teams is resulting in new basic understanding, novel products and innovative technologies. Bioengineering also crosses the boundaries of academia, science, medicine, and industry.

Considering that textiles have significant impact on the health and prevention of diseases, creating appropriate microclimates for living and appearances that influence the perceptions and behaviors of human beings, we can define textile bioengineering in a similar way:

“Textile bioengineering integrates physical, chemical, mathematical, and computational sciences and engineering principles to design and engineer textiles for the benefits of human biology, medicine, behavior and health. It advances fundamental concepts; creates knowledge from the molecular to the body-clothing systems level; and develops innovative materials, devices, and apparel products for healthy lifestyle fashion with functions of comfort, protection, prevention, diagnosis, and treatment of disease, and for improving health.”

Such definition shows that clothing bioengineering is rooted in physics, mathematics, chemistry, polymer sciences, biology, computational sciences, and engineering disciplines in polymer, fibers, textile and clothing industries. It is the application of a systematic, quantitative and integrative way of thinking about and approaching the solutions in problems of how clothing and textiles can be engineered to the benefits of biology, physiology, medicine, behavior and health of human populations. From this definition, it is clear that textile bioengineering needs knowledge and close collaborative research of experts from diversity of fields, including

physics, mathematics, chemistry, polymer science, computer sciences, biology, physiology and psychology, as well as engineering disciplines such as polymer, fiber, textile and clothing science and technologies. The creativity of interdisciplinary teams can result in new basic understanding, novel products and innovative technologies in a number of areas such as: (1) textile thermal bioengineering; (2) textile biomechanical engineering; (3) textile biosensory engineering; (4) textile biomedical engineering; (5) textile biomaterial engineering; and (6) Integrated computational bioengineering. The focuses and contents in each area are outlined and discussed.

2 Textile Thermal Bioengineering

Textile thermal bioengineering focuses on application of a systematic and quantitative way of designing and engineering apparel products to meet the thermal biological needs of human body for reducing heat/cold stresses and strains and to maintain an appropriate microclimate for the protection, survival and comfort of the wearer. This involves development of scientific understanding and mathematical description of a number of complex and interacted processes.

The fundamental research to achieve the system function includes a number of areas: (1) development of theories, data and models to describe the heat and moisture behaviors of fiber, yarns and fabric; (2) development of theories, data and models to describe the geometric and thermoregulatory behavior of human body; (3) development of theories, data and models to describe the dynamic thermal and moisture interactions between the body, garments and environment; (4) development of computational methods, computing visualization techniques, engineering databases to integrate all the elements systematically; (5) design and engineering of materials and clothing to achieve desirable thermal biological functions; (6) development of techniques to characterize thermal biological functions from basic materials to final apparel products.

Since 1960s, extensive research has been carried out to study thermal biological functions of textiles and clothing. Test techniques and testing standards have been developed in many countries such as USA, UK and China, as well as ISO testing standards, which has been applied to specify the technical requirements of garments and classify uniforms for wear in different seasons and geographical locations. Theoretical models on the heat and moisture transfer in textile materials and clothing have been developed since 1950s. However, computer simulation and computer aided design of textile thermal biological functions are only reported in late 1990s. There are a number of research monographs and books to review the developments in this area, including: Thermal Comfort (Fanger, 1970); Clothing: Comfort and Function (Fourt and Hollies, 1970); Clothing Comfort (Hollies and Goldman, 1977); Comfort Properties of Textiles (Slater, 1977); Human Comfort (Slater, 1985); Assessment of Comfort (Slater, 1986); The Science of Comfort (Li, 2001); Clothing Comfort and Product Development (Li, 2001); Clothing Thermal Bioengineering. A prototype of textile thermal bioengineering system was developed and reported in Chapter 21, which is shown in Fig. 1.

3 Textile Biomechanical Engineering

Textile biomechanical engineering is defined as the application of a systematic and quantitative way of designing and engineering textile products to meet the biomechanical needs of human body and to maintain an appropriate pressure and stress distributions on the skin and in the tissues and organs for the performance, health and comfort of the wearer.

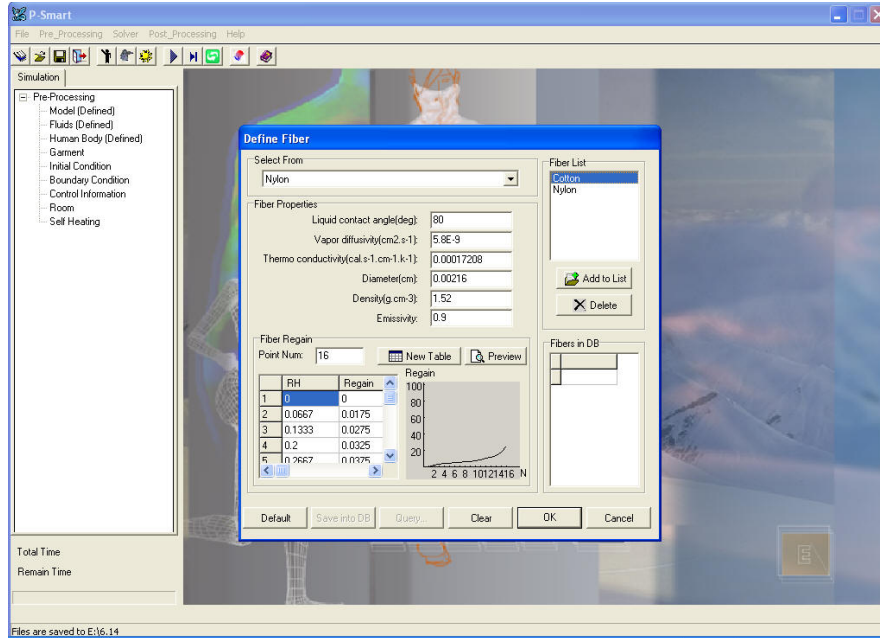


Fig. 1. A Computer software for textile thermal bioengineering

Textile biomechanical engineering involves not only design and engineering fabrics, but also the measurement of body geometric profiles, design and engineering garments to achieve the required biomechanical functions. The fundamental research to achieve the biomechanical functions involves a number of areas: (1) development of theories, data and models to describe the mechanical behaviors of fiber, yarns and fabric; (2) development of theories, data and models to describe the geometric and biomechanical behavior of human body; (3) development of theories, data and models to describe the dynamic mechanical interactions between body and garments; (4) development of computational methods, computing visualization techniques, engineering databases to integrate all the elements systematically; (5) design and engineering of materials and clothing to achieve desirable biomechanical functions; (6) development of techniques to characterize the biomechanical functional performances from basic materials to final apparel products.

Textile biomechanical engineering is a relatively new research area, even though the mechanics of textile materials from fiber, yarns to fabrics have been extensively studied in the past few decades. The publications in the literature mainly focused on measurement of garment pressure and pressure sensations. Theoretical modeling and computer simulation of the dynamic biomechanical functions of clothing and textile products have been reported in the later 1990s. There are a few research monographs and books that review the developments and progresses in this research area, including: *The Science of Clothing Comfort* (Li, 2001); *Garment Bagging and Mechanical Engineering Design* (Zhang et al, 2002); and *Biomechanical engineering of textiles and clothing* (Li and Dai, 2006). A prototype of clothing bioengineering design system has been developed and reported in Chapter 12, which is shown in Fig. 2.

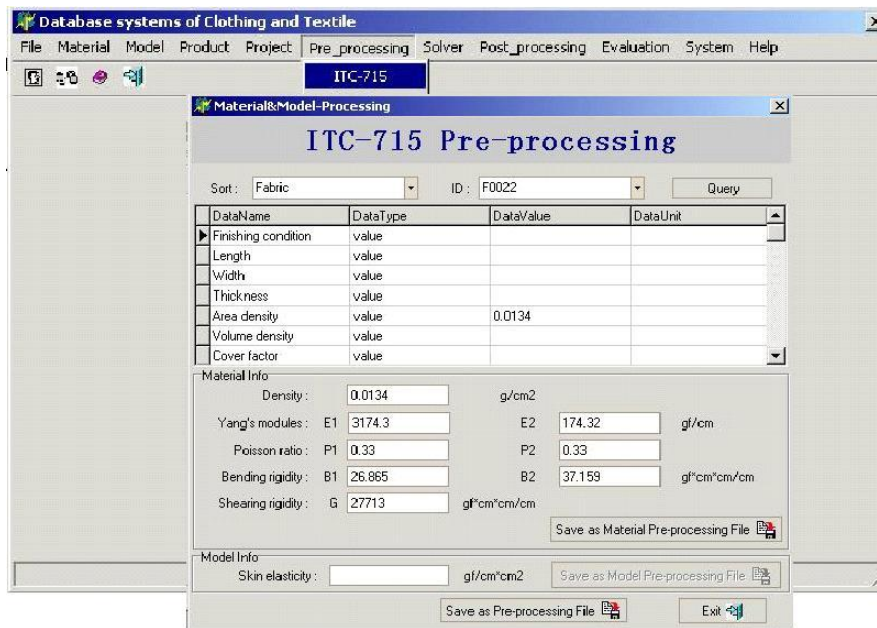


Fig. 2. A CAD system for textile biomechanical engineering

4 Textile Biosensory Engineering

Textile biosensory engineering is defined as the application of a systematic and integrative way of approaching the solutions to translate consumers' biological sensory perceptions, psychological feelings and preferences about a product into perceptual elements of design. Biosensory engineering design is an iterative decision-making process in which the physics, mathematics, neurophysiology and engineering techniques are applied to convert resources optimally to meet a specific and/or a combination of various sensory requirements from visual, thermal to mechanical sensations. It is the link between scientific discoveries and commercial applications by applying mathematics and science to research and to develop economical solutions to practical technical problems.

Textile biosensory engineering can be considered as the further development from the concepts of Kansei Engineering (8,9) and Sensory Engineering (13), with emphasis on integrative application of the sciences behind the human sensory perceptions. Human sensory perception of textiles involves a series of complex interactive processes, including (1) the physical processes of generating various physical stimuli; (2) the neurophysiological processes of receiving, encoding, transporting and decoding the stimuli by relevant biosensors and nervous systems residing inside of human body; (3) neuropsychological processes to the formulation of psychological sensations from the neurophysiological signals; and (4) the psychological processes of making judgments, formulating preferences and making behavioral and/or psychological adaptive feedback actions (4,5). Various computational models have developed to simulate the sensory perception processes for predicting the comfort performance of textiles and apparel products such as:

- Statistical models and linear models to predict the perception of hand, tactile comfort, thermal-moisture comfort, pressure comfort and overall comfort from fabric physical properties;

- Soft computing models such as neural network models, fuzzy logic models and hybrid models to simulate the perception processes and predict the comfort performance of clothing from material properties;
- Mathematical models that integrate the physics, neurophysiological and thermophysiological mechanisms and psychophysics and/or neuropsychological mechanisms to simulate the influence of clothing design and material properties on the physiological and psychological perception processes. For instance, clothing can be designed and engineered to achieve optimum thermal sensory comfort performance by using the modeling and computational system shown in Fig. 3.

Textile biosensory engineering is originated from the research in clothing comfort and fabric hand. There are a number of research monographs and books that reviewed the developments and progresses in this area systemically, including: Clothing Comfort and Function (Fourt and Hollies, 1970), Clothing Comfort (Hollies and Goldman, 1977), Comfort Properties of Textiles (Slater, 1977), Human Comfort (Slater, 1985), Fabrics: Sensory and Mechanical Properties (Bishop, 1994), High-Tech Fibers (Hongu and Philips, 1997), The Science of Comfort (Li, 2001), Clothing comfort and product development (Li, 2001), Clothing Biosensory Engineering (Li and Wong, 2006).

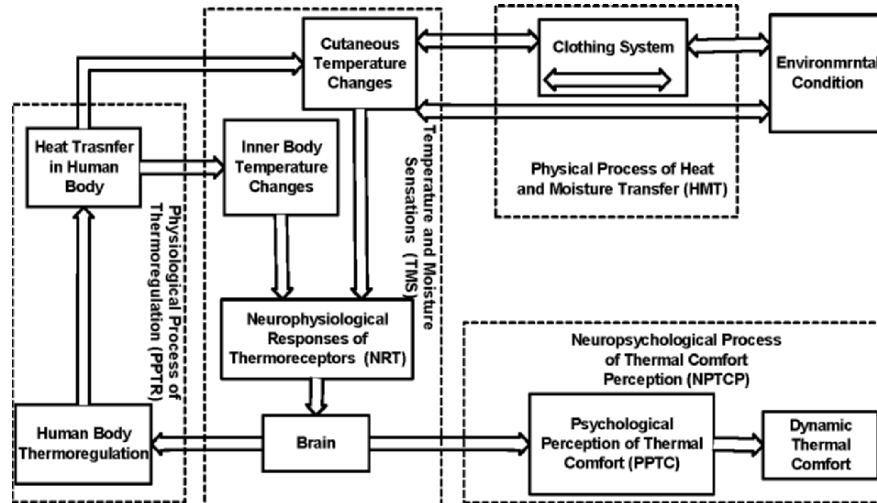


Fig. 3. Engineering clothing for thermal comfort performance

5 Textile Biomedical Engineering

Textiles and clothing have significant influence on various aspects of health and physiological status of humans, as textile devices and apparel products protect human body from various external environments and provide portable microclimate that enable human beings to live and enjoy activities in a wide range of environmental conditions. It has been found that clothing style and the physical properties of clothing materials have great impact on the functions of the thermoregulatory system, digest system, immune systems, Endocrine system, skin and reproduction systems of human body (Ha and Tokura, 1996; Sone et al, 2000; Tokura, 1989; Sone et al, 2000). For instance, garment pressure does not only have impact on the biomechanical performance and sensory perceptions, but also on the health of other physiological functions such as salivary secretion, small intestinal function, melatonin hormone secretion and menstrual cycles. This means that we need taking a holistic and systematic approach to engineer clothing to provide healthy lifestyles and for purpose of medical treatments. Besides the use of thermal and mechanical functions

for health and medical purposes, textiles can also play important roles in a number of areas of healthcare and medical treatments such as bioelectric/biomagnetic diagnosis and therapy, drug delivery, and Chinese medical treatments. Textile based biomaterials play important roles in development of scaffolds for tissue engineering and artificial organs for implants.

Therefore, textile biomedical engineering is defined as application of a holistic and integrative way of designing and engineering textile products to meet the biomedical and healthcare needs of human body to provide various functions such as drug delivery, temperature and/or pressure maintenances, bioelectric/biomagnetic detection and/or stimulation for the health and recovery of the wearer. Textile biomedical engineering is experimental in nature and needs extensive multi-disciplinary collaborations among the experts in medical professionals, physiologists and designers, scientists and engineers in textile and clothing industry. To develop computational engineering tools, it is critical to develop extensive databases and models to quantify the relationships among clothing style and material properties and various physiological responses of human body.

Textile biomedical engineering is a relatively new area, which is originated from the research in clothing physiological and biomaterials for implanting and tissue engineering. There are few research monographs to review the developments in this area symmetrically, including: Biofashion - Clothing Physiological Functions (Tokural et al, in preparation) and Personal Protective Equipments Against Transmittable Respiratory Diseases.

6 Textile biomaterial engineering

Textile biomaterial engineering focuses on the application of a systematic and integrative way of designing and engineering functional, smart and intelligent biomaterials using traditional and nano technologies that can be integrated with design of textile and apparel products to meet the biomedical and healthcare needs of human body. Textile biomaterial engineering is rooted in multi-disciplinary sciences from physics, chemistry to engineering sciences and needs close collaborations among the professionals in these areas to carry out systematic research to develop enabling technologies such as:

- Development and improvement of techniques based on new principles for probing physical and mechanical properties and phenomena at the micrometer and nanometer scale and for characterizing nanoscale materials;
- Development of advanced materials such as nanoparticles, nanospheres, nanotubes and nano fibrils that enable unique physical, mechanical, chemical and biological functions;
- Creation of smart composite materials such as nano-scale capsules and fiber structures and surfaces to achieve specific bio-functions. Approaches may include self-assembling techniques and supra-molecular chemistry for building up functional nano-structures and for modifying and patterning material surface textures;
- Development of engineering techniques to fabricate the nano materials into fibers, yarns, fabrics and apparel products to achieve desirable functions for protection, comfort, healthcare and medical treatment.
- Development of mathematic models and computational techniques to quantify the effect of the structural features and physical-chemical properties of the materials on the biofunctional performance of the textiles products made from the materials.

Extensive research has been carried out to develop high-tech fibers, smart and intelligent materials and textiles as reviewed and summarized in the books:

New Fibres (Hongu and Philips, 1997), High-Tech Fibres (Hongu, 1999), New Fibres from Japan (Kajiwara, 2000), Smart Fibres, Fabrics and Clothing (Tao, 2001), Nano Functional Textiles.

7 Integrative Computational Textile Bioengineering

Combinatorial approaches

It has shown from above discussions that textile bioengineering involves a substantial wide range of knowledge and skills developed or to be developed in different disciplines. Development of generally valid paradigms and techniques based on combinatorial approaches for the design, synthesis, characterization, processing, and end-use evaluation of complex and novel materials and apparel products will become an engine of innovation with particular emphasis on comfort, biological health, protection and disease prevention and treatment for creation of healthy lifestyle fashion for human populations, as shown in Fig. 4.



Fig. 4. Integrated Textile Bioengineering

The development of integrative and combinational approaches shall include a number of aspects:

- (i) Cross-functional integration: the functional requirements in thermal biology, biomechanics, sensory comfort, biomedical and healthcare needs to be taken into account together with consideration of fashion, usability, easy-care and costs in the product design and engineering processes;
- (ii) Cross-disciplinary integration: to design and engineer textiles with any specific biological functional performance, we need to integrate knowledge and skills to carry multidisciplinary research activities from molecular synthesis, nano materials engineering, polymer-fiber-textile and clothing engineering, characterization, apparel design, end-use evaluation by physiological studies, psychological evaluations and clinic trials;
- (iii) Cross-industry, cross-area and cross-organization integration: the relevant knowledge, data, information and skills are developed,

acquired and stored by experts in different nations/regions, different industries/disciplines and organizations. How to get these resources together to formulate effective engineering systems is a critical challenge for the researchers.

Mathematical modeling

The success of advancement in material sciences, engineering sciences and technologies, biological and medical sciences has led to an explosion of information, but progress in integrating information has lagged. We need to make connections among facts, but this is hampered by the data and knowledge distributed in different disciplines, and inherent complexities and problems of interaction and coupling effects of physical/mechanical processes with the neurophysiological, physiological and psychological processes. Mathematical models provide a rational approach for integrating this ocean of data, as well as providing deep insight into multi physical-biological-psychological processes. The integrative capacity of models will be needed in translation efforts to bring knowledge gained from material studies to the physiological and psychological level needed for textile bioengineering. Modeling should not be an afterthought, but as a critical step in the design and engineering processes that start from the specification of biological and functional requirements of textile products down to the specific functional requirements of biomaterials. Mathematical modeling is the glue holding together various experimental data, information, theories and techniques developed in different disciplines.

Informatics and Computation

The informatic databases must be transformed into models of different biofunctions and processes for different bioengineering purposes. Accomplishing this requires harnessing the knowledge of all relevant disciplines, including computer science, mathematics, polymer, fiber, textile and clothing engineering, bioengineering, biological and medical sciences. The models will range from empirical correlation of databases to mechanistic and systemic descriptions of complex physical and biological processes. Comprehensive informatics-based descriptions of models need to be

developed and tested in concert with basic physical, biological and psychological research to uncover the rules of non-linear, interactive and systemic regulations.

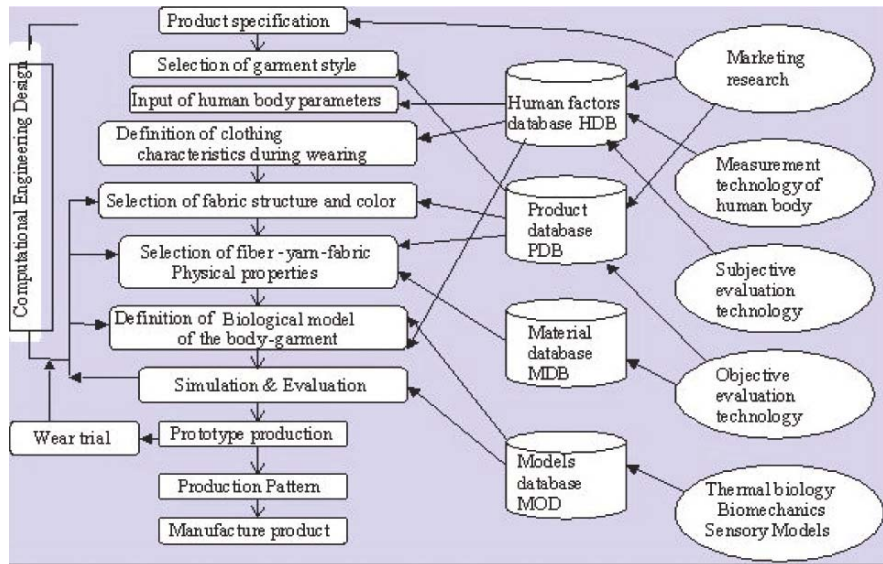


Fig. 5. A computational engineering design system for textile bioengineering

Algorithms and other computational tools for predicting and exploring intrinsic and emergent properties of these modeled processes will be needed. All relevant fields involve acquiring, processing, and analyzing information. They share the need to manage massive, distributed, networked data sets that are compiled from heterogeneous sources. These databases serve a heterogeneous set of users, with roles in research, engineering, production, consumption and education. For example, clothing can be designed and engineered to achieve optimum biofunctional performance by using the modeling and computational system shown in Fig. 5.

The need for such integration shall lead to initiation and organization of multidisciplinary research programmes with participants from medical professors, physiologists, and scientists in chemistry, physics, computational

mathematics, electromechanical engineering and computing technology to textile technologists and fashion designers. For instance, the fundamental research in modeling and simulating the heat and moisture in textiles and fabric mechanics has established a good foundation to develop advanced computing technology for integrated bioengineering design of apparel products. By integrating the computing technologies for fashion design, bio-thermal functional design and biomechanical functional design and bio-sensory design, we are able to reveal the outlook, sensory comfort and bio-functional performance of clothing before it is actually made. Using the mathematical models with advanced computational techniques, we are able to simulate the dynamic heat and moisture transfer processes in the human body, clothing and environment, the dynamic neurophysiological responses and thermoregulatory responses of the body, the dynamic mechanical interactions between the body and clothing, pressure and stress distributions on the skin surface and in the tissues, as well as the sensory perception of discomfort sensations. The simulation results can be visualized and characterized to show the dynamic temperature and moisture distribution profiles in human body, clothing and environment and stress distributions in clothing and on the body. Thus, we are able to illustrate how changes in physical activities, environmental conditions, and different design of clothing and use of different bio-functional materials will influence the thermal biological processes and biomechanical changes of the body, as well as thermal and mechanical comfort of the wearer. Such integrated computing aided design technologies can be developed on the basis of the mathematical models as advanced bioengineering design tool for fiber, textile and clothing industries, as well as healthcare and medical industries.

Acknowledgement

We would like to thank The Hong Kong Polytechnic University for the funding of this research through project A188.

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FeaFur: A Computer Software Package for Simulating Human Thermophysiological Responses in Dynamic Thermal Environment

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Abstract:

A computer software package has been developed in this paper to realize human body thermophysiological response in dynamic thermal environment by using mathematical models describing human body dynamic physiological thermoregulation, neurophysiological responses of thermoreceptors, psychophysical /neuropsychological relationships, and the physical mechanisms of heat and moisture transfer process in clothing. The Human body-Clothing-Environment (HCE) system defined by characteristic parameters is considered as the simulation scenario. The simulation platform, designed by engineering method, aims to predict the dynamic thermophysiological comfort of the human body during the dynamic and

interactive processes in the HCE system, furthermore to optimize the design of textile materials for better thermal performance.

Keywords: thermal comfort, thermoregulation, thermophysiological response, heat and moisture transfer

1 Introduction

The biological effect of heat and cold plays an important role in human being's survival status. Human body must find satisfactory solutions to the problems posed by variations in environmental temperature (Wang, Z., et al, 2003) to keep in a proper thermal state. Through thermoreceptors distributed in tissues and organs, human body is able to detect internal and external temperature changes. The bioelectrical temperature signals produced from thermoreceptors are transferred to the brain to evoke the thermal sensations that further are signals for thermoregulation. With respect to the thermal signals, some thermoregulatory efforts, such as shivering or sweating, will be prompted to establish a thermal equilibrium between human body and its surroundings. In this circular process of thermophysiological response to thermoregulation, the thermal comfort sensation, a whole thermal perception of human body, is the indication of the integration of human body thermophysiological and thermopsychological status. In the HCE system, the ambient environment to human body includes the clothing and the nature environment. When the clothing put on human body, the heat and moisture transfer process in fabric that interacts with the thermoregulation of human body need to be analyzed. While the nature environment just is the boundary condition to both of them. In 1998, Brager and de Dear firstly proposed the conceptual model of adaptive thermal comfort based on an extensive literature review (Lotens, W.A. and G. Havenith, 1995). Related mathematical models describing thermoregulatory process of human body, neurophysiological responses from thermoreceptors, the psychophysical/neuropsychological relationships definition, and the physical mechanism of heat and moisture

transfer in clothing, have been developed and widely agreed (Lotens, W.A. and A.M.J. Pieters, 1995). However, there lacks a computational simulation platform with friendly user interfaces for simulating human body thermophysiological responses in dynamic thermal environment, on the basis of integrating the existing dynamic physical, physiological and psychological processes mathematical models by a smooth process flow.

In this paper, the process developing the simulation platform based on mathematical models is reported. Human body thermophysiological responses in dynamic thermal environment are realized as a visible process in terms with applications interfaces.

2 Theoretical Background

Brager and de Dear suggested that the thermal comfort perception of human body was mainly affected by behavior adjustment, physical acclimation and psychological habituation (Lotens, W.A. and G. Havenith, 1995). In the HCE system, those processes actually boil down to the human physiological and psychological responses in dynamic thermal environment that influenced together by heat and moisture transfer process in clothing and external environment. Furthermore, a series of mathematical models describing the above corresponding process have been developed. Taking account to build up a smooth data flow, however, we deploy systematically the following mathematical models that were reported in detail in references (Gibson, P., 1994). Only brief descriptions are presented here.

2.1 Dynamic Physiological Thermoregulation of Body

An improved Gagge's two-node model of thermoregulation (Li, Y. and Z. Wang, 2002), modified for physiological responses of thermoreceptors of both skin and body core (Ring, K., R. De Dear, 1991), is used to describe dynamic physiological thermoregulation of human body.

$$\begin{aligned}
S_{cr} &= M - E_{res} - C_{res} - W - (K_{min} + c_{pbl} V_{bl})(T_{cr} - T_{sk}) \\
S_{sk} &= (K_{min} + c_{pbl} V_{bl})(T_{cr} - T_{sk}) - E_{sk} - R - C
\end{aligned} \tag{1}$$

2.2 Dynamic Neurophysiological Responses of Thermoreceptors

Ring and De Dear had proposed a mathematical method to calculate the neurophysiological response of cutaneous and core thermoreceptors (Ring, K., R. De Dear, 1991). Further deduced by experimental data, the impulse frequency of thermoreceptors (Hensel, H., 1981) can be calculated by the formulations as follows:

$$\begin{aligned}
FR_{sk}(t) &= K_{sk\_s} T_{sk}(t) + K_{sk\_d} \frac{\partial T_{sk}(t)}{\partial t} + const_{sk} \\
FR_{cr}(t) &= K_{cr\_m} T_{cr}(t) + const_{cr}
\end{aligned} \tag{2}$$

2.3 Dynamic Temperature and Moisture Sensations

The neurophysiological relationships between the comprehensive thermal sensation R_{th} and the neurophysiological response index PSI from thermoreceptors which is the integral of $FR(t)$ curve are defined as the function derived by carrying out psychophysical experiments, and the psychological method is chosen to model the perception of dampness sensations of human body (Ring, K., R. De Dear, 1991).

$$\begin{aligned}
R_{th}(t) &= f(PSI_i) = f(\max(PSI_{iw}(t), PSI_{ic}(t))) \\
R_{dp}(t) &= g(w_{sk}(t))
\end{aligned} \tag{3}$$

2.4 Dynamic Heat and Moisture Transfer in Fabrics

The perception of thermal and moisture sensation of human body is related to the moisture and temperature change of the fabrics that cover the skin. The physical mechanism of heat and moisture transfer process can be

described by following equations (Lotens, W.A. and G. Havenith, 1995; Gibson, P., 1994; Wang, Z., et al., 2003).

$$\begin{aligned}
 \frac{\partial(C_a \varepsilon_a)}{\partial t} &= \frac{1}{\tau_a} \frac{\partial}{\partial x} \left(D_a \frac{\partial(C_a \varepsilon_a)}{\partial x} \right) - \varepsilon_f \xi_1 \Gamma_f + \Gamma_{lg} \\
 \frac{\partial(\rho_l \varepsilon_l)}{\partial t} &= \frac{1}{\tau_l} \frac{\partial}{\partial x} \left(D_l(\varepsilon_l) \frac{\partial(\rho_l \varepsilon_l)}{\partial x} \right) - \varepsilon_f \xi_2 \Gamma_f - \Gamma_{lg} \\
 c_v \frac{\partial T}{\partial t} &= \frac{\partial}{\partial x} \left(K_{mix}(x) \frac{\partial T}{\partial x} \right) + \frac{\partial F_R}{\partial x} - \frac{\partial F_L}{\partial x} + \varepsilon_f \Gamma_f (\xi_1 \lambda_v + \xi_2 \lambda_l) - \lambda_{lg} \Gamma_{lg}
 \end{aligned} \tag{4}$$

2.5 Dynamic Psychological Thermal Comfort

Using the key influential factors, temperature sensations and dampness sensations as input variables, a fuzzy system can be used to simulate the process by which a person deduces the dynamic thermal comfort perception (Klir, G.J. and B. Yuan, 1995). After receiving the fuzzy perception of clothing thermal comfort sensation identified by the fuzzy logic system, the center of gravity defuzzification method is adopted to defuzzy the fuzzy rating to a numerical value.

3 Software Development

On the basis of the models provided above, computing simulation software is designed and developed. Aiming at providing a practical simulation procedure with friendly interfaces, the function of the software includes three main modules: the pre-processing, solver and post-processing. In the pre-processing module, human body, clothing, environment and other needed information for simulation are defined. After the process of solving equations, the post-processing focus on visualizing the data produced in the simulation. The thermophysiological responses of human body in dynamic thermal environment through simulation stages, such as the change of body temperature, relative humidity and sweating rating etc, can

be presented visually. The dynamic perception of thermal comfort sensation of human body is evaluated based on the calculation of the temperature sensation and moisture sensation. Similarly, the thermal behavior of the clothing in the simulation process can also be expressed in scientific plots and/or 3D contour plots to analyze the factors that influence the thermal performance of the clothing.

The schematic illustration of the simulation system is demonstrated in Fig. 1. Some interfaces of the software platform developed with object oriented programming method are shown in Fig. 2~7. Fig. 2~4 define the basic information of human body, clothing and environment displayed in Fig. 1. With respect to the manufacture procedure of clothing production, the clothing is constructed with fabrics that are defined on the basic of the specification of fibers and selectable membranes. Fig. 4 configures the boundary conditions for simulation stage that involves the definition of environment. As visualization windows of post-processing, Fig. 6 shows the temperature distribution of the fabrics in the simulation process with three-dimensional chart, and Fig. 7 illustrates the perception thermal comfort sensation, which is mapped as the color of the skin.

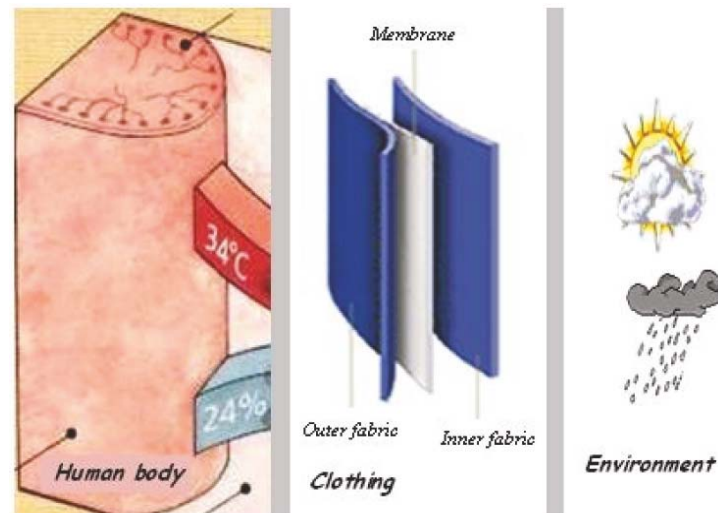


Fig. 1. Schematic illustration of HCE system

Define Body

Body Properties

Neutral volume of blood flow of skin(L.hr-1.cm-1):	0.00063
Maximal volume of blood flow of skin(L.hr-1.cm-1):	0.009
Minimum volume of blood flow of skin(L.hr-1.cm-1):	5E-5
Regulative shivering constant(cal.s-1.cm-2):	0.00046366
Dilation factor of blood vessel(L.hr-1.cm-1):	0.02
Strict factor of blood vessel(L.hr-1.cm-1):	1E-5
Specific heat at constant pressure of blood(cal.hr.L-1.C-1.s-1):	0.277957
Maximum sweating rate(g.hr-1):	0.266666666666
Pow sweating rate:	10.7
Regulative sweating constant(g.hr-1.cm-2):	4.72222222222
Neutral temperature of skin(deg.):	34.1
Neutral temperature of core(deg.):	37.1
Density of blood(g.cm-3):	1.06
Specific heat of body mass(cal.g-1.C-1):	0.834588

Initial Condition

Dubois Body Mass(g)	70000	Dubois Body Area(cm2)	18000

Clear Default OK Cancel

Fig. 2. Human body definition

Define Fabric

Fabric Structure

Fiber List	Selected Fiber	%
PolyFN	PolyFN	25
Cotton	Cotton	75

Add Fiber...

Membrane List

OP	Selected Membrane
OP	OP

Add Membrane...

PCM

Define Phase Change Material...

Volume Percentage of PCM: 0.1

Fabric Properties

Tortuos Gas:	1.2
Tortuos Lqd:	1.2
Emissivity:	0.9
Porosity:	0.85
Thickness(cm):	0.25
Capillary Angle(deg):	20
Density(g.cm-3):	0
Max Distributed Capillary Diameter(cm):	0.12
Mean Surface Tension(g.s-2):	
Mean Fiber Density(g.cm-3):	1.3675
Mean Absorp Constant(1/cm):	42.85714285
Mean Radius(cm):	0.00105
Mean Contact Angle(r):	77.5
Mean Fiber Emissivity:	0.9

Fabric List

Fabric1

Add to List Delete

Fabrics in DB

Default Save into DB Clear Query OK Cancel

Fig. 3. Fabric definition

Boundary Condition

Human Body | Environment | Fabric layers

Physiological Parameter

Skin temperature(deg.) Thermal conductance of body tissue 0.000126192

Core temperature(deg.) Relative humidity of skin(%)

Absorptivity of the skin surface to the solar radiation 0.77

☐ Change the value of human body adaptive variables

Transfer Coefficient

Convective heat transfer coefficient of uncovered body 0.000239

Convective heat transfer coefficient of covered body 0.000239

Linear radiant heat transfer coefficient of uncovered body 0.0001434

Linear radiant heat transfer coefficient of covered body 0.0001434

Human Body State

Metabolic Rate(Met) 2

☐ Cool down

Cool down time(min.)

Default

Stage List

Stage1

Stage2

Stage3

Add to List

Delete

OK Cancel

Fig. 4. Boundary and scenario definition

Control Information

Time Information

Time step(s) 0.001

Save frequency(s) 1

Save relay 1000

Sweating Accumu. (min.) 2

Stage Time(min.)

Stage1 20

Stage2 30

Stage3 10

Fabric Grid

	Layer1	Layer2
Thickness grid of fabric	5	5
Radius grid of fiber	8	8
Delta of fabric grid	0.05	0.05
Delta of fiber grid	0.0625	0.0625

Percentage

Clothing Cover Percentage 50 %

Moisture Transfer Percentage 100 %

Heat Transfer Percentage 100 %

Default OK Cancel

Fig. 5. Simulation control information

Fab01b_1_Flgain

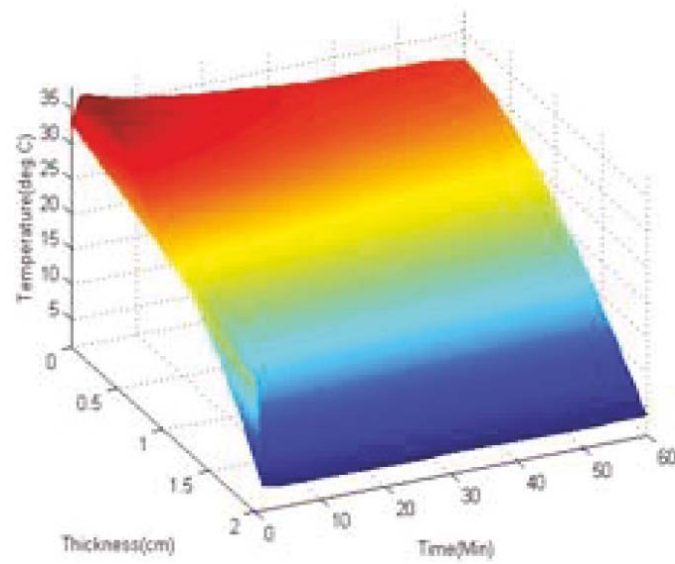


Fig. 6. Temperature distribution of fabric

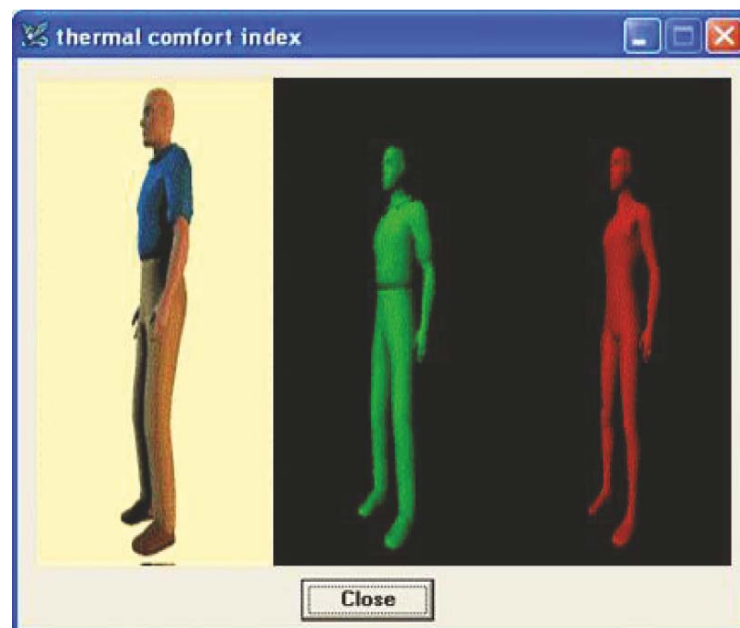


Fig. 7. Thermal comfort evaluation

4 Conclusion

The computational software (FEAFUR), based on an integrated dynamic adaptive mathematical model, provides friendly interfaces for users to simulate the human body thermophysiological response in dynamic thermal environment, which can be used to optimize the design of the textile materials for better thermal performance.

Acknowledgement

We would like to thank Hong Kong Polytechnic University, Research Grand Council, Innovation Technology Commission and the National Natural Science Foundation of China for funding the research through the projects A188, ITS-023-03 and PolyU 5151/01E and 60473131.

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Computational Investigation of Thermoregulatory Effects of Multi-Layer PCM Textile Assembly

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Abstract

On the basis of the mathematical model of heat and moisture transfer through multi-layer PCM textile, four numerical simulations have been carried out to examine the thermoregulatory effects of PCM textile assembly in this paper. In these simulations, the multi-layer assembly is comprised by three layers PCM textiles based on polyester, including two of 2.5mm thick as inner and outer layer, and one of 5mm thick as the middle layer, which separate by 1mm air layer. The distribution of the temperature in the three layers PCM textile assembly, in which with different add-on level of PCM, were numerically computed and compared for the both warming and cooling process. The results indicate that the thermoregulatory effects of the multi-layer PCM textile assemblies are significantly influenced by the distribution of PCM add-on level in each layer. The more PCM contains in the middle layer, the higher thermoregulatory effects of the multi-layer assembly will be.

Keywords: heat and moisture transfer, mathematical model, numerical simulation, porous textile, thermal regulating performance.

1 Introduction

Thermal regulating textiles play a very important role in providing thermal comfort for human beings in temperature changing environments. Since

the early 1980s, there has been an increasing interest in phase change Materials (PCM). Textiles, which incorporate PCM, are called “PCM treated textiles” or “PCM textiles”. Research studying the thermoregulatory effects of PCM treated textiles and their multi-layer assemblies are fundamental for the effective use of such smart thermal functional textiles.

The use of numerical simulation, which is based on the mathematical model developed to describe the processes of coupled heat and moisture transfer through porous textile, is an effective way to investigate the thermal properties of textiles and clothing. After porous textiles incorporate phase change materials, their dynamic thermal properties change significantly. The processes of coupled heat and moisture transfer through such textiles become more complicated than before, because heat will be absorbed or released during the phase change process. When used in clothing or garments, as an assembly of multi-layer PCM textiles, the thermoregulatory effects of such assembly should be studied. In this paper, the thermoregulatory effects of multi-layer PCM textile assembly are examined by numerical simulation. This method can be applied to design and develop smart thermal functional garments by considering use of different phase change materials and transition temperature range, different levels of concentration, and distribution.

2 Theoretical Background

The mechanisms of the coupled heat and moisture transfer in multi-layers porous PCM textiles are the combination of heat and moisture transfer through single layer of the textile which with and without PCM. Based on the model of heat and moisture transfer in the single layer PCM textile (Li Y. 2004), the governing equation for each layer of multi-layer textile assembly can be expressed by the following equations.

Heat balance for fabric without PCM:

$$c_v \frac{\partial T}{\partial t} = \varpi_1 \lambda_v \frac{\partial (C_f \varepsilon_f)}{\partial t} + \varpi_2 \lambda_l \frac{\partial (C_f \varepsilon_f)}{\partial t} - \lambda h_{l \rightarrow g} S_v' (C^*(T) - C_a) + \frac{\partial}{\partial x} \left[K_{mix} \frac{\partial T}{\partial x} \right] \quad (1)$$

Heat balance for fabric with PCM:

$$c_v \frac{\partial T}{\partial t} = \varpi_1 \lambda_v \frac{\partial(C_f \varepsilon_f)}{\partial t} + \varpi_2 \lambda_l \frac{\partial(C_f \varepsilon_f)}{\partial t} - \lambda h_{l \rightarrow g} S_v' (C^*(T) - C_a) + \frac{\partial}{\partial x} \left[K_{mix} \frac{\partial T}{\partial x} \right] - \dot{q}(x, t) \quad (2)$$

Moisture vapor balance:

$$\frac{\partial(C_a \varepsilon_a)}{\partial t} + \varpi_1 \frac{\partial(C_f \varepsilon_f)}{\partial t} - h_{l \rightarrow g} S_v' (C^*(T) - C_a) = \frac{1}{\tau_a} \frac{\partial}{\partial x} \left[D_a \varepsilon_a \frac{\partial(C_a)}{\partial x} \right] \quad (3)$$

Moisture liquid balance:

$$\rho_l \frac{\partial(\varepsilon_l)}{\partial t} + \varpi_2 \frac{\partial(C_f \varepsilon_f)}{\partial t} + h_{l \rightarrow g} S_v' (C^*(T) - C_a) = \frac{\rho_l}{\tau_l} \frac{\partial}{\partial x} \left[D_l \frac{\partial(\varepsilon_l)}{\partial x} \right] \quad (4)$$

In Eq. 1 and eq. 2, the first term on the right-hand side describes the heat of moisture sorption or desorption of vapor by fibers, the second term describes the heat of moisture sorption or desorption of liquid water by fibers, the third term describes the heat of evaporation of water, and the forth term describes the heat change by conduction. The last term on the right-hand side of Eq. 2, that for PCM fabric only, describes the latent heat which gains and losses from PCM. The latent heat related to PCM can be expressed by Eq. 5. (Li Y. 2004)

$$\dot{q}(x, t) = -\frac{3\varepsilon_m}{R_m} h_T K_m (T_p - T(x, t)) / \left[h_T R_m \left(\frac{R_m}{r_l(x, t)} - 1 \right) + K_m \right] \quad (5)$$

For PCM textiles, the relationship between the volume fraction of liquid phase (ε_l), of water vapor (ε_a), of fibers (ε_f), and of PCM (ε_m) is expressed by Eq. 6. For the textile without PCM, that is expressed by Eq. 7. More details about these equations can be found in references (Li Y. 2003; Li Y. 2004).

$$\varepsilon_l + \varepsilon_a + \varepsilon_f + \varepsilon_m = 1 \quad (6)$$

$$\varepsilon_l + \varepsilon_a + \varepsilon_f = 1 \quad (7)$$

Two contact states between each layer, the contact state and non-contact state, are considered in this multi-layer model. In the contact state, no air layer exists between each layer. In the non-contact state, each layer is separated by air layer. (B.A. Ying 2004)

3 Numerical Simulation

In order to examine the thermoregulatory effects of PCM textile assembly, a series numerical simulations were carried out in this investigation. In these simulations, the multi-layer assembly is comprised by three layers PCM textiles based on polyester, including two of 2.5mm thick as inner and outer layer, and one of 5mm thick as the middle layer, which separate by 1mm air layer. In the warming process, the initial conditions are the temperature of $T_0=20^{\circ}\text{C}$, the relative humidity of $RH=60\%$ at both of the internal and the external side of the assembly. At time $t=0$ the boundary conditions change to temperature of $T=33^{\circ}\text{C}$ and the relative humidity of $RH=60\%$. In the cooling process, the initial conditions are $T_0=33^{\circ}\text{C}$, $RH=60\%$ at both side. The boundary conditions change to $T=20^{\circ}\text{C}$, $RH=60\%$ at time $t=0$. The melting and freezing point of PCM is set to 28°C , which are within the warming and cooling temperature changing range.

Four numerical simulations have been done for such three layers PCM textile assembly under warming and cooling process, respectively. The distribution of PCM add-on in each layer in these four simulations is listed in Table 1. In the first simulation, no PCM is contained in all three layers. In other three simulations, the sum of the amount of PCM in the three layers is the same, but the distribution is different. In simulation 2, all PCM is in middle layer; in simulation 3, half of PCM is in middle layer and the other half is divided equally in inner layer and out layer, respectively; in simulation 4, no PCM is in middle layer, all of PCM is divided equally in inner layer and out layer, respectively. By these four simulations, the thermoregulatory effects of multi-layer PCM textile assembly with different PCM add-on distribution can be examined and compared, and the best solution of use PCM in the multi-layer assembly can be found.

Table 1. The distribution of PCM add-on in the three layers PCM textile assembly

Simulation n	In inner layer (%)	In middle layer (%)	In outer layer (%)
1	0	0	0
2	0	20	0
3	10	10	10
4	20	0	20

4 Results and Discussions

The numerical results of temperature distribution in the three-layer PCM textile assembly with different PCM add-on distribution in the non-contact state of 1mm air layer between each layer under the warming process are shown in Fig. 1, Fig. 2, Fig. 3, and Fig. 4, respectively. Compared to the three-layer textile that of without PCM ($\varepsilon_m=0$), there are a ‘temperature plate’, which is the temperature stays at constant for a period of time, existing at the melting point in such textile assembly that combined with PCM. This means that the temperature of the textiles that without PCM rises continuously, because there is no phase changing happened in the textiles. However, for the textiles with PCM, as the phase changing happens during the warming process, the heat energy is absorbed by phase change materials at the melting point, thus the temperature of the PCM textiles stays constant at melting point during this period of time. Comparing the ‘temperature plat’ in Fig. 2, Fig. 3, and Fig. 4, it can be found that more PCM contained in the middle layer, the larger the area of “temperature plat” will be. This indicates that the more PCM used in the middle layer of the three-layers textile assembly, the more heat of the textiles is absorbed by phase change at melting point, the longer time of temperature staying constant at this point is. When more PCM used in the both sides, then more heat exchange occurred with environment, which makes thermoregulatory effects of the PCM assembly decrease.

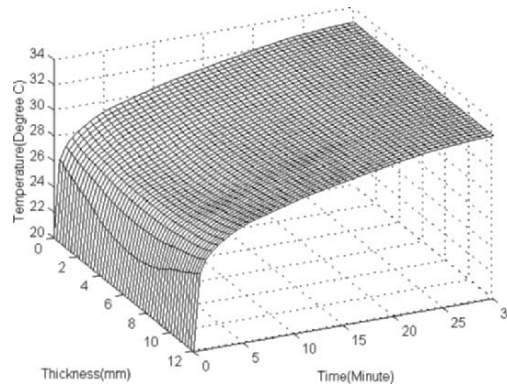


Fig. 1. Temperature distributions of each layer without PCM in warming process

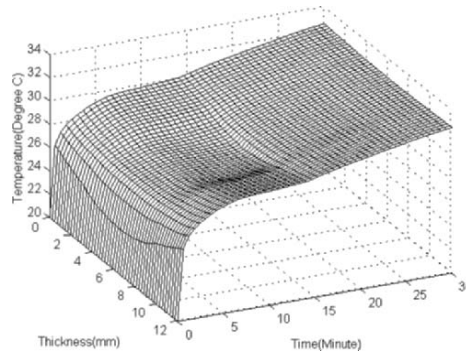


Fig. 2. Temperature distributions of inner layer and outer layer without PCM and middle layer with 20% PCM in warming process

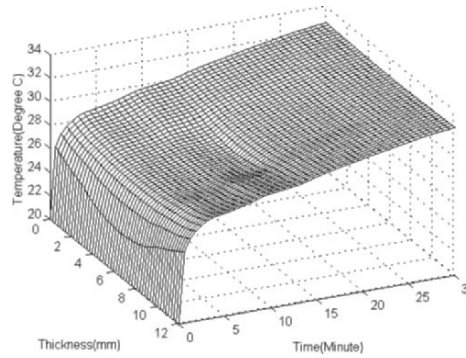


Fig. 3. Temperature distributions of three layers all with 10% PCM in warming process

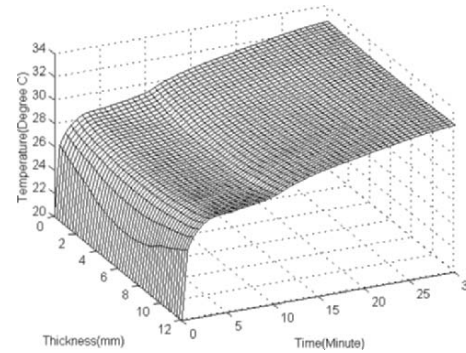


Fig. 4. Temperature distributions of inner layer and outer layer with 20% PCM and middle layer without PCM in warming process

The results of temperature changing at the middle section of the middle layer in these four simulations are compared in Fig. 14.5. The total temperature changing process can be divided into three stages. If we take that of before the phase change happens as the first stage, which the temperature is lower than melting point, we can see that the temperature changes are very similar for the four assemblies, because no phase change happens during this period of time. And the temperature rises dramatically in this stage, because larger temperature difference exists between the middle section and external environment. In the second stage, during which phase change happens, the temperature change is quite different for the different PCM add-on distribution in the multi-layer assembly. While the temperature of the assembly without PCM rises continuously, the temperature of textile with PCM remains at melting point, and the more PCM contained in the textiles, the longer duration time of the textiles temperature remains at melt point is. In the last stage of after phase change happens, all the four of the temperature rise steadily to the environment temperature with the very similar changing trend, but the changing rate is lower than that of in the first stage because the temperature difference is lower in this period of time.

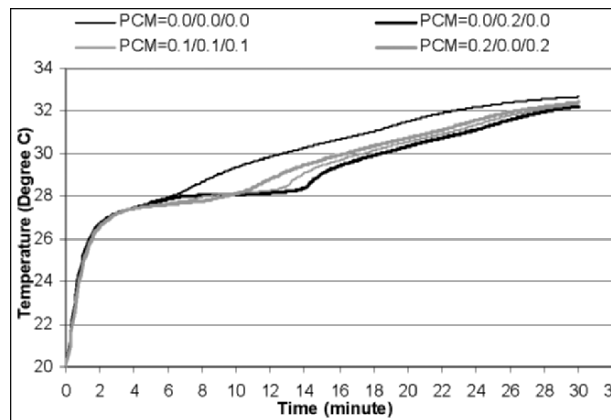


Fig. 5. The comparison of temperature changing at the middle section of middle layer with different distribution of PCM in warming process

Under the cooling process, the temperature distribution of the three-layer PCM textile assembly with different PCM distribution in the non-contact state of 2 mm air layer between each layer are shown in the Fig. 6, Fig. 7, Fig. 8, and Fig. 9, respectively. From these results, it can be found that the more PCM contained in the middle layer, the larger area of

‘temperature plat’ exists. That is, the more heat is released by phase change at freezing point, the longer time of temperature staying constant at this point is.

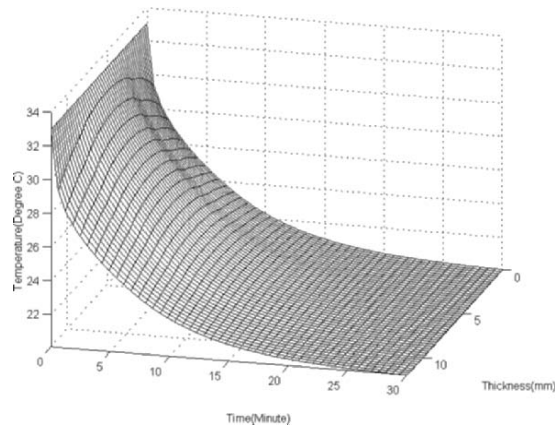


Fig. 6. Temperature distributions of each layer without PCM in cooling process

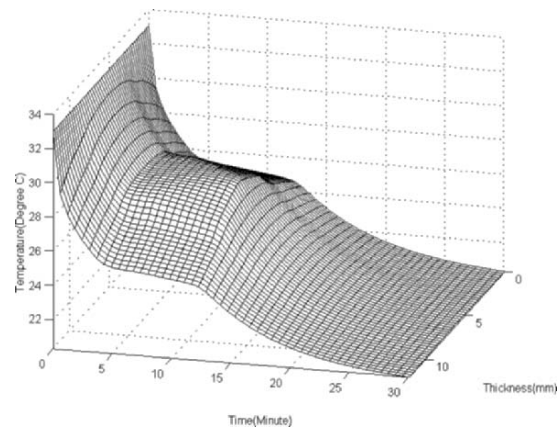


Fig. 7. Temperature distributions of inner layer and outer layer without PCM and middle layer with 20% PCM in cooling process

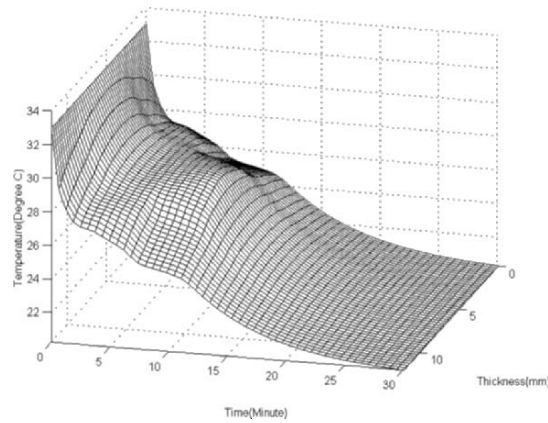


Fig. 8. Temperature distributions of three layers all with 10% PCM in cooling process

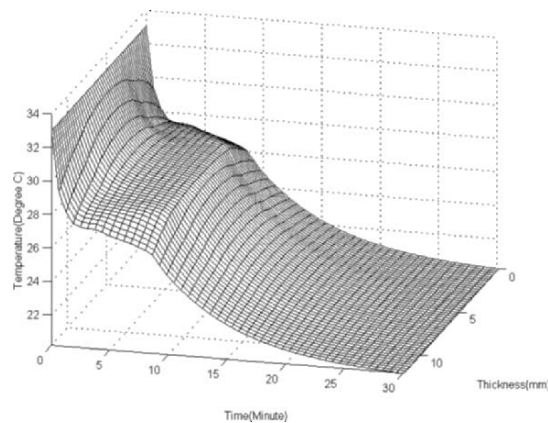


Fig. 9. Temperature distributions of inner layer and outer layer with 40% PCM and middle layer without PCM in cooling process

The results of temperature changing at the middle section of the middle layer in these four simulations under cooling process are compared in Fig. 10. Same with the warming process, the total temperature changing process in cooling process can also be divided into three stages. In the first stage of before the phase change happens, which the temperature is higher than freezing point, we can see that the temperature changing are very similar for the four kind of assemblies, because no phase change happened, and the temperature drop dramatically in this stage because of larger temperature difference exists between the section and the environment.

In the second stage of during phase change happening, while the temperature of the textile without PCM drops continuously, the temperature of the textile with PCM remains at freezing point, and the more PCM contained in the middle layer, the longer duration time of the temperature regulation stays.

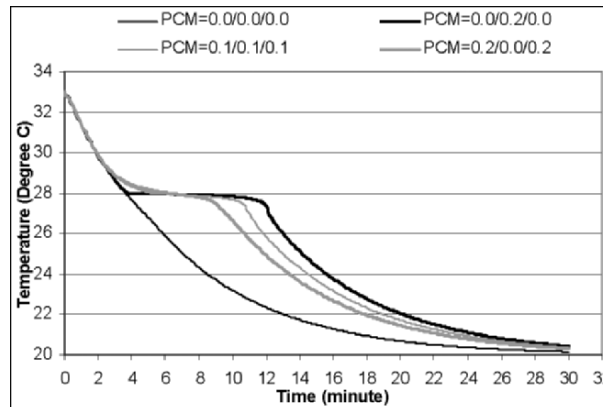


Fig. 10. The comparison of temperature changing at the middle section of middle layer with different distribution of PCM in cooling process

5 Conclusion

In order to examine the thermoregulatory effects of PCM textile assembly, four numerical simulations have been done under warming and cooling process for such three layers PCM textile assembly with different distribution of PCM add-on level, respectively. The distribution of the temperature in the each layer of the three layers PCM textile assembly with different add-on level of PCM were numerically computed and compared. The results indicated that the thermoregulatory effects of the multi-layer PCM textile assemblies are significantly influenced by the distribution of PCM add-on level in each layer. The more PCM contains in the middle layer, the higher thermoregulatory effects of the multi-layer assembly will be.

Acknowledgement

The authors would like to thank The Hong Kong Research Grant Council and The Hong Kong Polytechnic University for funding these researches through projects “PolyU 5150/01E”, “PolyU 5281/03E”, and “A188”.

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Computational Simulation of Multi-Phase Coupled Heat and Moisture Transfer in Phase Change and Self-Heating Porous Materials

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Abstract

The physical processes of the coupled heat and moisture transfer in porous material with phase change materials (PCM) and self heating are simulated in this paper. The paper focuses on the analysis for the interaction between PCM and self-heating material. The results of simulation show that PCM can be recycled to maintain the constant temperature in the fabric in a longer together time with self-heating materials and the method is helpful to optimize the design of the smart clothing. The experiment results are also shown in this paper. Good agreement between the calculated and experimental results was obtained.

Keywords: simulation, multi-phase coupled heat and moisture transfer, phase change material, self heating fabric.

1 Introduction

The clothing system plays a very important role in determining the human body core temperature and other human thermal responses because it determines how much of the heat generated in the human body can be

exchanged with the environment. With the development of science and technology, uses of clothing system for new functions increase constantly, contributing opportunities for further development and incorporation of new technologies and new materials. Smart clothing is a result of integration micro-electronics, smart materials and functional textiles. The application of electronics (self-heating) and phase change materials (PCM) is of growing interest in functional clothing design to improve the thermal protective function of textiles and garments.

In order to understand the thermal and moisture transport behavior of clothing, numerical simulation is an effective way besides the experimental method. There is a temperature zone in which nude human beings feel comfortable (Hensel, H., Thermoreception and Temperature Regulation, 1981), PCM and self-heating technology can be used to maintain a comfortable microclimate in heat transfer progresses. This paper studies the interaction between PCM and self-heating materials. When the temperature regulating function of PCM disappears, self-heating system is switched on to recharge PCM by re-melting or re-condensing. Using the mathematical model on fabric incorporated phase change material and self-heating elements, the progressive coupled thermal and moisture transfer through the fabric can be simulated according to the different initial conditions and boundary conditions. The results of simulation are helpful to optimize the design of smart clothing.

2 Numerical Theory

The physical progress of the coupled heat and moisture transfer in porous material with phase change materials and self heating can be described mathematically by the following equations (Li Y., Zhu Q.Y.,2003)

The conversation of mass equation of water vapor:

$$\varepsilon_a \frac{\partial C_a}{\partial t} + \varpi_1 \frac{\partial (C_f \varepsilon_f)}{\partial t} - h_{l \rightarrow g} S_v (C^*(T) - C_a) = \frac{1}{\tau_a} \frac{\partial}{\partial x} \left[D_a \varepsilon_a \frac{\partial (C_a)}{\partial x} \right] \quad (1)$$

The first term on the left side of Eq. 1 represents vapor accumulation within the void space of the inter-fiber, whereas the second term represents vapor storage within the fiber, the third term is the evaporation flux of the water in the inter-fibers void space. The right side of equation represents water vapor diffusion.

The conversation of energy equation:

$$\begin{aligned}
 & c_v \frac{\partial T}{\partial t} - \varpi_1 \lambda_v \frac{\partial (C_f \varepsilon_f)}{\partial t} - \varpi_2 \lambda_l \frac{\partial (C_f \varepsilon_f)}{\partial t} \\
 & + \lambda h_{l \rightarrow g} S_v (C^*(T) - C_a) + \dot{q}(x, t) - W \\
 & = \frac{\partial}{\partial x} \left[K_{mix} \frac{\partial T}{\partial x} \right]
 \end{aligned} \quad (2)$$

The first term on the left side of Eq. 2 represents energy storage, whereas the second term, the third term and the forth term represent latent heat of fiber sorption of water vapor, latent heat of fiber sorption of liquid water and latent heat due to evaporation/condensation, respectively. The fifth term represents the heat flux between fabric and phase change material. The sixth represents the heat flux from the self heating elements. The right side represents the heat conduction.

The conversation of mass equation of liquid water:

$$\begin{aligned}
 & \rho_l \frac{\partial (\varepsilon_l)}{\partial t} + \varpi_2 \frac{\partial (C_f \varepsilon_f)}{\partial t} \\
 & + h_{l \rightarrow g} S_v (C^*(T) - C_a) = \frac{\rho_l}{\tau_l} \frac{\partial}{\partial x} \left[D_l \frac{\partial (\varepsilon_l)}{\partial x} \right]
 \end{aligned} \quad (3)$$

The first term on the left side of Eq. 3 represents liquid water storage within the void space of the inter-fiber, whereas the second term represents liquid water storage within the fiber, the third term is evaporation flux of the water in the inter-fibers void space. The right side of equation represents liquid water diffusion.

Where, the heat flux between fabric and phase change material is described by Eq. 4 (Li Y., Zhu Q.Y., 2004).

$$\dot{q}(x, t) = - \frac{\frac{3\varepsilon_m}{R_m} h_T K_m (T_p - T(x, t))}{h_T R_m \left(\frac{R_m}{r_l(x, t)} - 1 \right) + K_m} \quad (4)$$

In the prototype of smart clothing, the control system of temperature is divided two parts: heating device and cooling device. In the numerical model, the heat flux from control system of temperature is treated as a constant value which is positive value when heating device works, which is negative value when cooling device works. Detailed description of the symbols used in the equations can be found in reference ((Li Y., Zhu Q.Y., 2003)) and (Li Y., Zhu Q.Y., 2004).

3 Initial and Boundary Conditions

In order to generate a solution to the equations mentioned above, the initial and boundary conditions are necessary in the fabric surface in terms of humidity, temperature, vapor content and liquid content respectively.

The initial condition:

$$\begin{aligned}C_a &= C_{a0} \\T &= T_0 \\ \varepsilon_l &= \varepsilon_{l0} \\RH &= RH_0 \\C_f &= f(RH_0, T_0)\end{aligned}$$

The boundary conditions:

At $x = 0$ and $x = L$, we have the boundary conditions to take into account the convective nature of the boundary air layers:

$$\begin{aligned}D_a \varepsilon_a \frac{\partial C_a}{\partial x} \Big|_{x=0} &= h_c (C_a - C_{ab}) \\K \frac{\partial T}{\partial x} \Big|_{x=0} &= h_t (T - T_{ab}) + \lambda h_{l \rightarrow g} (C_a - C_{ab}) \quad (x = 0) \\D_l \rho_l \frac{\partial \varepsilon_l}{\partial x} \Big|_{x=0} &= h_{l \rightarrow g} (C_a - C_{ab})\end{aligned}$$

$$D_a \varepsilon_a \frac{\partial C_a}{\partial x} \Big|_{x=L} = -h_c (C_a - C_{ab})$$

$$K \frac{\partial T}{\partial x} \Big|_{x=L} = -h_t (T - T_{ab}) - \lambda h_{l \rightarrow g} (C_a - C_{ab}) \quad (x = L)$$

$$D_l \rho_l \frac{\partial \varepsilon_l}{\partial x} \Big|_{x=L} = -h_{l \rightarrow g} (C_a - C_{ab})$$

4 Numerical Solutions and Discussion

In this investigation, we calculate two examples to simulate the heat and moisture transfer of smart clothing. The fabric is a single layer with 10% PCM and self-heating system based on the polyester. The thickness is 2 mm. The melting temperature of PCM is 28°C.

Example 1 simulates the interaction between PCM and self-heating in the hot environment. The initial conditions: $T_0=25^\circ\text{C}$, $RH_0=60\%$. The boundary condition: $T_{ab0}=30^\circ\text{C}$, $RH_{ab0}=60\%$; $T_{abl}=30^\circ\text{C}$, $RH_{abl}=60\%$.

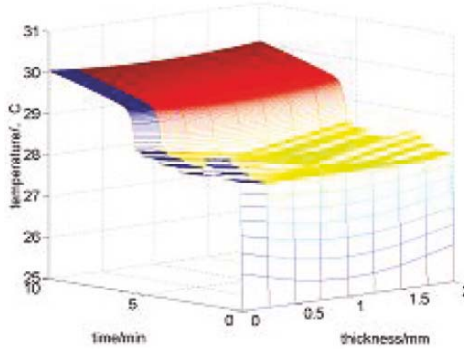


Fig. 1. Temperature distribution in fabric

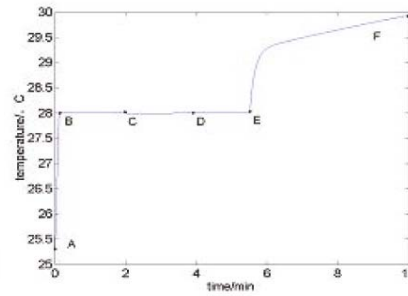


Fig. 2. Temperature changing in the middle of fabric

Example 2 simulates the interaction between PCM and self-heating in the cool environment. The initial conditions: $T_0=32^\circ\text{C}$, $RH_0=60\%$. The boundary conditions: $T_{ab0}=22^\circ\text{C}$, $RH_{ab0}=60\%$; $T_{abl}=22^\circ\text{C}$, $RH_{abl}=60\%$.

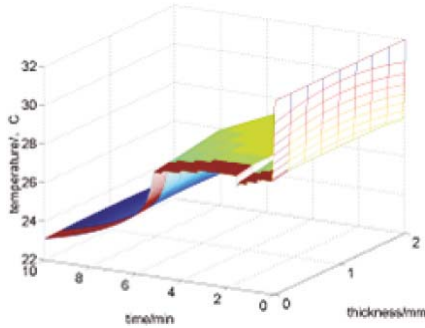


Fig. 3. Temperature distribution in Fabric

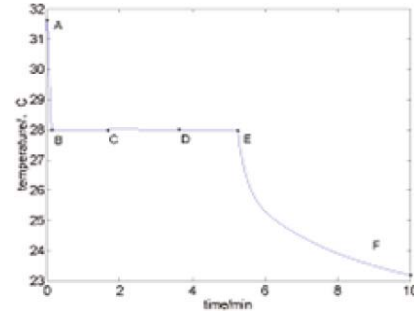


Fig. 4. Temperature changing in the middle of fabric

Example 3 simulates the interaction between PCM and self-heating in the cold environment. The initial conditions: $T_0=32\text{ }^{\circ}\text{C}$, $RH_0=60\%$. The boundary conditions: $T_{ab0}=-15\text{ }^{\circ}\text{C}$, $RH_{ab0}=40\%$; $T_{abl}=-15\text{ }^{\circ}\text{C}$, $RH_{abl}=40\%$.

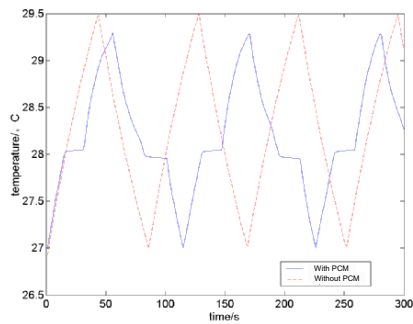


Fig. 5. The simulation results of heating cycle

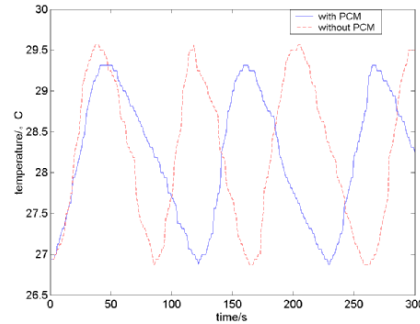


Fig. 6. The experiment results of heating cycle

Figure 1 and Fig. 3 show the three-dimension graphs of the temperature distribution in the fabric in the hot and cool environment. Fig. 2 and Fig. 4 describe the temperature changes in the middle of fabric.

Figure 2 shows the temperature change in fabric in the hot environment. The main process is divided into five segments: AB, BC, CD, DE, EF. From point A to point B, the temperature in fabric increases because of the influence of environment until the temperature reaches the melting point of PCM (point B), which absorbs the heat to maintain the melting temperature in fabric. As the time passes, PCM is liquidized fully. At the point C, cooling element is switched on to make PCM condense until point D. And then,

PCM is solidified fully and resumes regulating temperature. In the segment DE, the cooling system is switched off and PCM melts to contain the constant temperature in fabric. From point E to point F, the temperature in fabric reaches the environment temperature.

Figure 4 shows the temperature change in fabric when it is placed in the cool environment. The total progress has the similar result with Fig.2. It has five segments: AB, BC, CD, DE, EF. In the process AB, the temperature in fabric decreases because of the cool environment. In the process BC, PCM releases heat changing from liquid to solid to maintain constant temperature in fabric. In the process CD, the heating element is switched on to melt PCM. In the process DE, the heating element is switched off and PCM resumes to release heat to maintain constant temperature in fabric. In the progress EF, the temperature in fabric reaches near the environment temperature.

Figure 5 and Fig. 6 are the simulation results and experiment results respectively. There is good agreement between the simulation and experiment. The results show that the heating cycle of the fabric with PCM is longer than that of the fabric without PCM. The average heating cycle of without PCM is about 82s, while the average heating cycle of with PCM is about 128s. In the same condition, the electrical energy consumed by the fabric with PCM is about 30.9% less than that consumed by the fabric without PCM.

5 Conclusion

From the analyzing of the simulation results, we can see that the effective time (from point B to point E) of PCM with self-heating is longer than the one (from point B to point C) without self-heating. The fabric can be kept the constant temperature in a longer time using the interaction between PCM and self-heating. When PCM is functional, self-heating is switched off to save the battery power. So this method can be applied to designing and developing smart clothing by considering the interaction between PCM and self-heating.

Acknowledgement

We would like to thank the Hong Kong Polytechnic University, Innovation Technology Commission and Research Grant Council for funding the research through the projects A188, ITS-023-03, PolyU5151/01E and PolyU5281/03E.

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Numerical Simulation of Heat and Moisture Transfer in Porous Walls with Microencapsulated PCM

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Abstract

This paper reports numerical simulations to analyze the thermal characteristics of three-layer wall with micro-encapsulated PCM based on the theoretical model of heat and moisture transfer in porous materials. The thermal characteristics of the wall system with different boundary conditions are analyzed by the computer simulation. The results show that the wall with encapsulated PCM can delay the temperature rise when the environmental temperature increases. The computational simulations are useful tool for designing building materials that can save energy in heating and air conditioning.

Keywords: Micro-encapsulated PCM; Porous wall; Model; Simulation

1 Introduction

Modern buildings are increasingly constructed by light weight material with low thermal inertia. The use of air conditioning, central or widows unit represents a solution for internal comfort but is usually of high initial

and operating cost. On the other hand, the use of passive thermal techniques, such as thermal energy storage systems, in general, results in large energy and capital reduction.

Latent heat storage uses phase change material (PCM) as a storage medium. PCM is a material that is melting or solidifying in a certain temperature range. PCM absorbs heat from the environment when it is melting, and releases latent heat to the environment when it is solidifying. The major advantages of phase change material are their large heat capacity and approximate isothermal behavior during the charging and discharging process. These make it possible to increase the thermal inertia of a building to provide better indoor climate and to reduce large amount of heating and cooling needs.

In this investigation, the micro-encapsulated PCM developed by ITC of Hong Kong Polytechnic University is chosen due to the following advantages. They are (1) it avoids the leakage during the phase change process; (2) it increases the heat transfer area and (3) provides the possibility to enhance heat transfer performance by using the metallic coating.

This study examines the new concept of multi-layered wall incorporated with PCM as for enhancing the room air quality and reducing the energy consumption consumed by the air conditionings in the buildings. A mathematical model that takes account of the simultaneous heat and moisture transfer in porous building material with PCM, which usually be ignored by the former researchers, was applied. Thermal properties of porous materials is very complex, the material coupled with PCM is much more complicated than the former case. This model provides an effective way to investigate the thermal characteristics of porous building material coupled with PCM during melting and solidifying process. It also provides

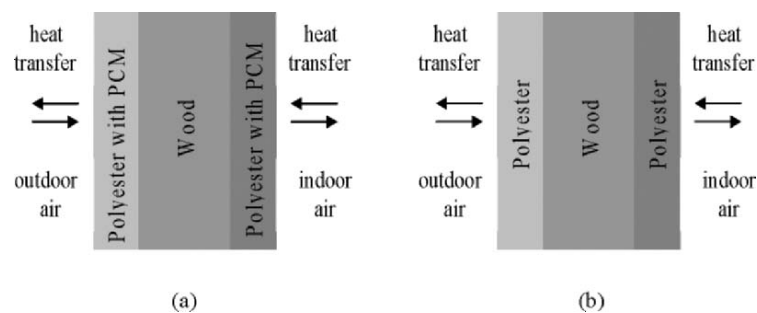


Fig. 1. (a) wall with PCM (b) wall without PCM

the new way to design the smart buildings with light weight by incorporating with phase change materials (PCMs).

2 Theoretical Background

For the purpose of comparison the PCM coupled wall and the conventional wall without PCM are presented in Fig. 1. The inner and outer layer of wall consists of the porous textile, the micro-encapsulated PCM particles is incorporated during the manufacturing process of the textile material. The middle layer of wall consists of wood in order to increase the firmness of the wall.

In the analysis we consider the followings: (i) The PCM is assumed to be uniformly embedded in the porous wall, (ii) each layer of wall is assumed to be closely contacted with the other, (iii) the heat transfer through the wall is assumed to be one-dimensional, (iv) thermal properties of the PCM during phase change process is assumed to be constant.

The mathematical model of heat and moisture transfer in multi-layers porous building materials is based on the model of heat and moisture transfer through the single layer porous materials (Li and Zhou. 2004). For each layer with or without PCM, the governing equations can be considered as follows.

The mechanisms of the coupled heat and moisture transfer in multi-layers porous PCM textiles are the combination of heat and moisture transfer through single layer of the textile which with and without PCM. Based on the model of heat and moisture transfer in the single layer PCM textile (Li Y. 2004), the governing equation for each layer of multi-layer textile assembly can be expressed by the following equations.

The mass balance of the vapor:

$$\frac{\partial(C_a \varepsilon_a)}{\partial t} + \varpi_l \frac{\partial(C_f \varepsilon_f)}{\partial t} - h_{l \rightarrow g} S'_v (C^*(T) - C_a) = \frac{1}{\tau_a} \frac{\partial}{\partial x} \left[D_a \frac{\partial(C_a \varepsilon_a)}{\partial x} \right] \quad (1)$$

Heat balance for fabric with PCM:

$$C_v \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[K_{mix} \frac{\partial T}{\partial x} \right] + \varpi_l \lambda_v \frac{\partial(C_f \varepsilon_f)}{\partial t} + \varpi_2 \lambda_l \frac{\partial(\varepsilon_f C_f)}{\partial t} - \lambda h_{l \rightarrow g} S'_v (C^*(T) - C_a) - \dot{q}(x, t) \quad (2)$$

For wall without PCM, $\dot{q}(x, t) = 0$

The mass balance of liquid moisture:

$$\begin{aligned} \frac{\partial(\rho_l \varepsilon_l)}{\partial t} + \varpi_2 \frac{\partial(C_f \varepsilon_f)}{\partial t} + h_{l \rightarrow g} S'_v (C^*(T) - C_a) = \frac{1}{\tau_l} \frac{\partial}{\partial x} \left[D_l \frac{\partial(\rho_l \varepsilon_l)}{\partial x} \right] \\ + b(\varepsilon_l) \frac{\partial(\rho_l \varepsilon_l)}{\partial x} \end{aligned} \quad (3)$$

where $\varepsilon_a, \varepsilon_l, \varepsilon_f, \varepsilon_m$ represents the volume fraction of the vapor, the liquid moisture, fiber and the PCM, respectively, the relations between them can be expressed by Eq. 4.

$$\varepsilon_a + \varepsilon_l + \varepsilon_f + \varepsilon_m = 1 \quad (4)$$

During phase change process, the PCM releases or absorbs the heat, the last term of right side of Eq. 2 represents the total heat loss rate from the micro-PCM, which can be expressed as

$$\dot{q}(x, t) = -\frac{3\varepsilon_m}{R_m} h_T K_{ml} (T_p - T(x, t)) / \left[h_T R_m \left(\frac{R_m}{r_l(x, t)} - 1 \right) + K_{ml} \right] \quad (5)$$

A detailed mathematical analysis can be found in Li and Zhou (2004) and Li and Zhou (2003).

3 Numerical Simulation

In order to exam the thermal effects of multi-layered wall made from the porous textile integrated with PCM, a series of numerical simulations were implemented with sets of properties and conditions. In the first simulation, the temperature and the relative humidity of the room air and the outer environment are set to be constant in order to find the optimal properties of the wall. Table 1 represents the simulation data used for the computation.

In the second simulation, the temperature and relative humidity of outer environment are simulated as a sine wave with the intermittence of 24 hours, which are showed in Fig. 2. The temperature and relative humidity of indoor environment are set to be 25°C and 60% RH, respectively. The wall with and without PCM were implemented in this simulation, the thermal effect of PCM on the wall temperature variations are compared and examined, which provides the simulation technique to exam the

feasibility of the wall integrated with PCM and to identify the best wall structure.

Table 1. Simulation data

Item	Values
Thickness of the first layer (mm)	10
Thickness of the middle layer (mm)	40
Thickness of the inner layer (mm)	10
Initial temperature of the board, T_0 (°C)	20
Initial relative humidity (%)	60
Air temperature, T_r (°C)	30
Outer environmental temperature, T_{out} (°C)	30
Amount of PCM (volume %)	0 (10,20,30)

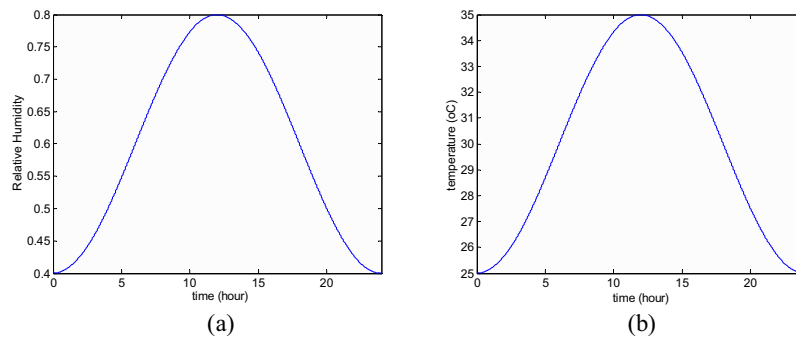


Fig. 2. (a) humidity variations (b) temperature variations

4 Results and Discussions

Through a series of computer simulations with different sets of conditions, the temperature profiles of each layer of the wall were obtained. Considering the symmetrical behaviors of heat release and heat recovery process, only the melting process was simulated in this study. The results for temperature profile of each layer during melting process at constant temperature and relative humidity are presented in Fig. 3 and Fig. 4. The temperature profile of each layer with temperature variations of 24 hours is showed in Fig. 5 and Fig. 6.

4.1 Temperature Profiles of Wall with Constant Boundary Conditions

In this simulation the temperature and relative humidity at the inner and out environment are kept to be constant. The temperature profiles of three-layer wall with different PCM fractions are presented in Fig. 3. As shown in Fig. 3, the PCM integrated wall has distinct temperature regulating function, as compared with the wall without PCM, which happened when the temperature of wall reach the melting temperature. In other words, the temperature of wall with PCM during heat absorption

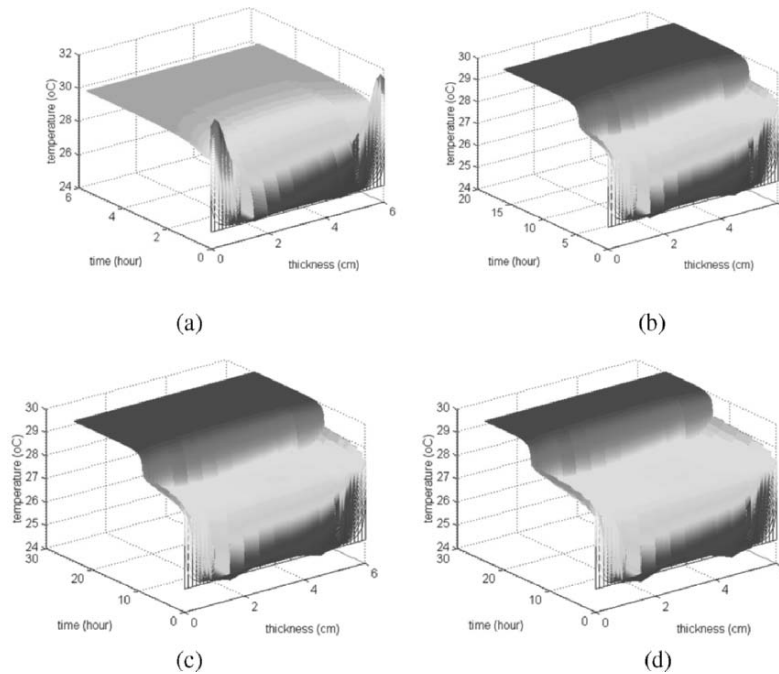


Fig. 3. Temperature profile of wall with different PCM fractions (a) 0% PCM; (b) 10% PCM; (c) 20% PCM; (d) 30% PCM

PCM during heat absorption process is kept constant until it releases its all the latent heat, while for the wall without PCM (see Fig. 3(a)), it increases the temperature continuously until it reaches the equilibrium with boundary conditions. Another phenomenon we can find in Fig. 1 is that the more PCM is integrated into the wall, the longer temperature delay will be, showing that the more PCM used for the wall, the more heat will be

absorbed, which results in a larger energy reduction for the air conditioning machine. However, it takes almost 8 hours for the wall integrated with 20% PCM to finish the phase change process, considering the 8 working hours of the most office rooms, the wall integrated with 20% PCM is much more appropriate in the present case.

The temperature variations in the middle of middle layer for different PCM fraction are compared in Fig. 4. The temperature profile shows three distinct heat absorption processes. In the first stage the wall absorbs heat at a high speed, we notice that the temperature rise for four cases are almost similar. In the phase change of the PCM, we notice that the increase in the PCM concentration results in the extensions of heat absorption process. While in the final stage, we find that the temperature increases for the four cases are also similar. So the higher the PCM concentration is, the longer the heat absorption will be.

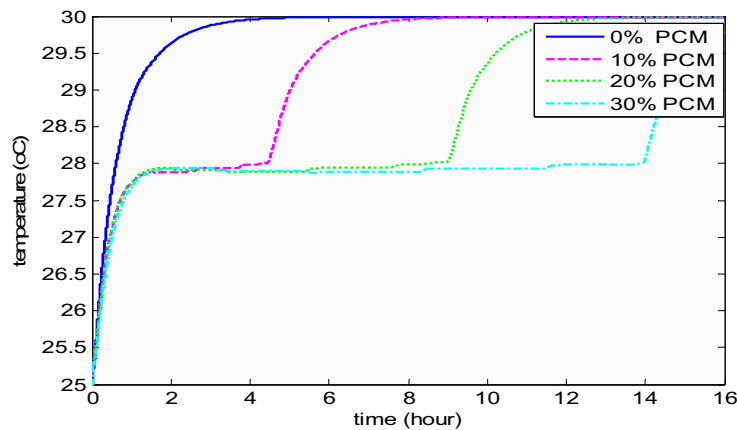


Fig. 4. Comparison of temperature variations at the middle of middle layer of the wall in melting process

4.2 Temperature Profiles of Wall with Variable Temperature at the Boundary

In this simulation, the temperature and humidity of room air are kept to be constant, while the weather temperature and humidity outside the room varies in sine function with the intermittence of 24 hours as showed in Fig. 2. The temperature profiles of wall with PCM and without PCM are presented in Fig. 5. From the comparison, it is found that the Fig. 5 (b) has a bigger lump than the Fig. 5(b). That is, the time delay of the temperature change for the wall integrated with PCM is longer than that of the wall without PCM because of the absorption of latent heat.

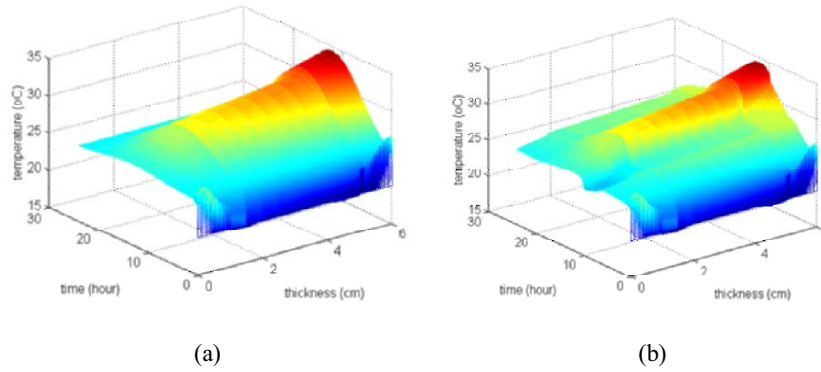


Fig. 5. Temperature profile of wall with the variable temperature at the boundary
(a) 0% PCM (b) 20% PCM

The comparison of temperature variations at the middle of the middle layer with PCM is presented in Fig. 6. It is found that the temperature profile of wall without PCM are similar to Fig. 2(a), which means that temperature of wall without PCM follows with the temperature variations of outer environment. However, there is a big temperature gap between the wall with PCM and the wall without PCM. That is, the wall with PCM can delay the temperature rise when external environment temperature increases.

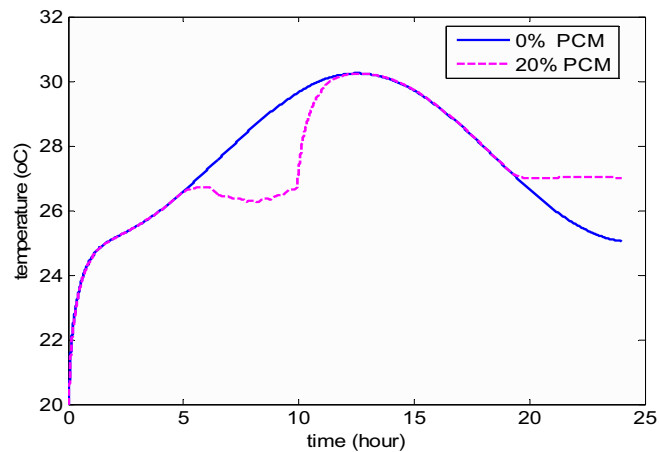


Fig. 6. Comparison of temperature variations at the middle layer

5 Conclusions

The model of the three-layer wall integrated with micro-encapsulated PCM is developed on the basis of the theoretical model of heat and moisture transfer through the single layer porous materials. The wall with constant temperature at the boundary and the wall with changing weather data are simulated by the computer program. The temperatures of the wall integrated with PCM and without PCM are also compared. The results show that the wall with PCM performs thermally better than the wall without PCM. The present model can predict the behaviors of wall during melting and solidifying process. The results also indicate that the appropriate concentration of PCM should be identified before we apply the PCM in the wall.

Experimental evaluation and economical analysis into the porous wall integrated with PCM will be carried out in the future study.

Acknowledgements

We would like to thank the Hong Kong Polytechnic University, Hong Kong Innovation Technology Commission and Research Grant Council for funding the research through the projects A188, ITS-023-03 and PolyU 5151/01E.

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Mathematical Simulation of Human Psychological Perception of Moisture Sensation

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Abstract

This paper reports computational methods for simulating human psychological perception of moisture comfort sensation in multi-dimensions with various kind of conceptual models, which developed on the basis on mathematical, neural networks and fuzzy logic modeling techniques. Models were validated with experimental result. Good agreement between simulated and experimental result was found

Keyword: human psychological perception, moisture comfort sensation, conceptual model.

1 Introduction

Human skin consists of different types of receptors, which function are to response to various physical stimuli including touch, pressure, thermal, cold and pain. However, there is no receptor is responded for moisture or dampness sensation, at least at this moment.

Many researches (Lake and Hughes 1980; Morris et al. 1985; Hong et al. 1988; Tarafder and Chatterjee 1994; Li et al. 1995; Plante et al.

1995) had been carried out over the years in order to understand the perception of this sensation. Sweeney and Branson (Sweeney and Branson 1990a) examined the feasibility of using psychophysical methods to assess moisture sensation in clothing. The psychometric functions demonstrating the relationship between moisture and moisture sensation for these determinations exhibited linear trends. Later on, Sweeney and Branson (Sweeney and Branson 1990b) asked thirteen subjects used the magnitude estimation method to assess the intensities of moisture stimuli, which applied to their backs. Result showed that the relationship between moisture stimulus and moisture sensation demonstrated a psychophysical power function. Magnitude estimation offers the clothing comfort investigator the advantage of maintaining closer correspondence between objective and subjective measures over the usual psychological scaling methods used. In the explaining the relationship between moisture sensation and overall discomfort, Berkowitch (Berkowitch 1982) stated the feeling of wetness was sufficient to define comfort for some subjects in the study. Lau et al. (Lau et al. 2002) reported that overall discomfort is determined by tactile sensations (e.g., itchiness and prickliness) and moisture (dampness and clinginess) related sensations before and after exercise respectively. Wong et al (Wong and Li 1999) found that moisture and thermal related sensations contribute relatively greater percentage of variance than tactile and pressure related sensations toward overall comfort. Mathematical and statistical approaches towards simulation of human perception of different sensations have been introduced for many years. Wang et al. (Wang et al. 2002) used different mathematical models, which describe heat and moisture in fabric and at the interface, neurophysiological responses to temperature changes and psycho-neurophysiological relationships, to develop a mathematical simulation of human perception of thermal and moisture sensations.

The purpose of this paper is to report different computational methods for simulating human psychological perception of moisture comfort sensations, on the basis of perception of moisture sensation at different body locations, in multi-dimensions with various kinds of conceptual models, which developed on the basis of mathematical, neural networks and fuzzy logic modelling techniques.

2 Model Development

2.1 Conceptual Model

Perception of clothing comfort is a complex multi-attribute evaluation process, which involves a lot of attributes in different aspects including environmental condition and fabric properties. However, this paper mainly focuses on the psychological responses at different body locations toward perception of overall moisture comfort. The description of the conceptual model is shown in Fig. 1.

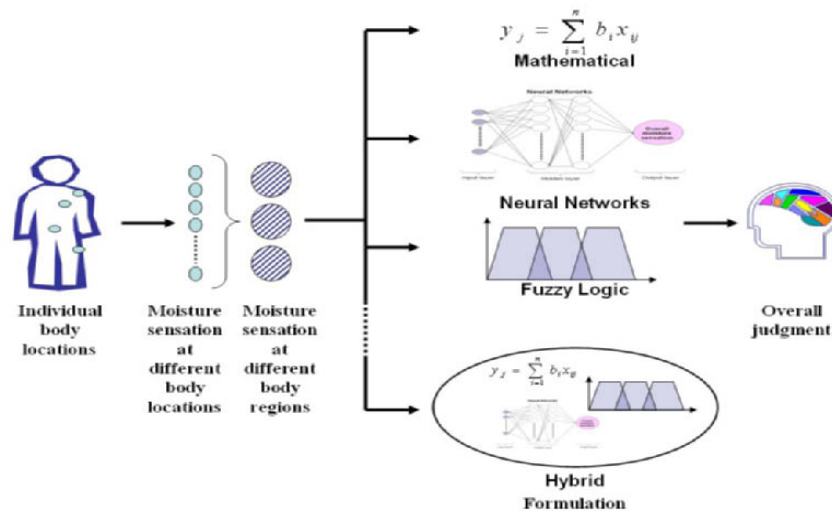


Fig. 1. Description of the conceptual model

The overall judgment can be described as an outcome of the perceptual process, in which many perceptual information are integrated into one. In order to model the human overall judgment of moisture sensation in 3-dimensions, investigating the psychological perception of moisture sensation at different body locations is necessary. Various body locations are selected. One way to identify the similarity between these body locations, in term of the psychological perception of moisture sensation is to classify them into different body regions. Then these moisture sensations at these regions will be formulated by the brain and make the final judgment. The questions are

how these moisture sensations at different body regions came to be organized and how do they relate to overall judgment.

In order to answer these questions, various formulations, mathematical, neural networks, fuzzy logic and hybrid models have been investigated. When applying mathematical model such as linear regression in such case, numbers of assumptions have been made including; there is a linear relationship between the regions' sensations and overall judgment; and weighting of individual regions reflects the importance of that regions. Neural networks and fuzzy logic are used to describe the non-linear and complex relationship between body regions' moisture sensation and overall judgment. Hybrid model is a combination of linear and non-linear approaches, which mathematical, neural networks and fuzzy logic are integrated together. The output of these models would be the final judgment for moisture sensation.

2.2 Mathematical Description

The mathematical expression of a linear regression model is shown below.

$$y_j = \sum_{i=1}^n b_i x_{ij} \quad (1)$$

where y_i = The dependent variable of j th item, b_i = The regression coefficient of i th the independent variable, x_{ij} = The value of i th independent variable on j th item and n = The total number of independent variables.

There are various kinds of transfer functions, which appeared in hidden and output neurons, in neural networks. Two of the most commonly used transfer functions are log-sigmoid, *logsig*, and pure linear, *purlin*. The mathematical expressions of these two functions are:

$$\text{Logsig}(x) = \frac{1}{(1 + e^{-x})} \quad (2)$$

and

$$\text{Purlin}(x) = x \quad (3)$$

where x = The input neuron value.

In fuzzy logic, membership functions such as generalized bell-shaped and sigmoid are used to describe the relationship between input and output components. The mathematical expressions of these membership functions are shown as follows:

Generalized bell-shaped:

$$f(x; a, b, c) = \frac{1}{1 + \left| \frac{x - c}{a} \right|^{2b}} \quad (4)$$

and

Sigmoid:

$$f(x, a, c) = \frac{1}{(1 + e^{-a(x-c)})} \quad (5)$$

where x = The input value and a, b, c = The values appear on the function curves.

3 Implementation

In order to validate the models, experimental result is required. Six female students, as subjects, were participated in a series of experiments, which conducted in an environmental controlled chamber. During the twenty minutes running exercise, subjects were asked to evaluate moisture and overall comfort sensations at every five minutes time interval. The process was repeated until each subject tested all six garments.

4 Data Measurement

4.1 Tennis Wear

Six commercially available tennis wears were selected. The basic description of the garments is shown in Table 1.

Table 1. Basic description of tennis wear

Garment code	Weight (g/cm ²)	Thickness (mm)	Content (%)
A-95P	260±28.1	0.9±0.13	Polyester (95) & Elastane (5)
A-100P	145±6.1	0.7±0.02	Polyester (100)
N-70C	199±6.2	0.8±0.01	Cotton (70) & Polyester (30)
F-60C	245±10.6	1.0±0.01	Cotton (60) & Polyester (40)
N-100C	192±6.4	0.7±0.03	Cotton (100)

4.2 Wear Trial

A group of six female university students, as subjects, were participated in a series of experiments, which conducted in an environmentally controlled chamber, which temperature and humidity was $29\pm0.02^{\circ}\text{C}$ and $65\pm0.28\%$ respectively. The mean $\pm$ s.d of their age, height and weight was 23 ± 2.4 years, 159 ± 4.9 centimetres and 47 ± 4.7 kilograms respectively.

In the trial, a set of thermal and moisture sensors, which used to measure the changes of subjects skin temperature and humidity, were attached to subjects seven body locations, shoulder, chest, front waist, upper back, centre back, lower back and side thigh, through out the wear trial. Each subject required to wear one of the six randomly selected garments and ran on a treadmill for 20 minutes and at every five minutes interval, from time 0 to 20, they had to evaluate thermal and moisture sensations and overall comfort at the seven selected body locations. The process was repeated until each subject tested all six garments. The number of garment can be tested by a subject in one day is two, and subject also did not allow to conduct another trial right after the previous one, this would ensures the quality of the collected data.

5 Results

5.1 Distribution of Skin Surface Humidity and Moisture Sensation

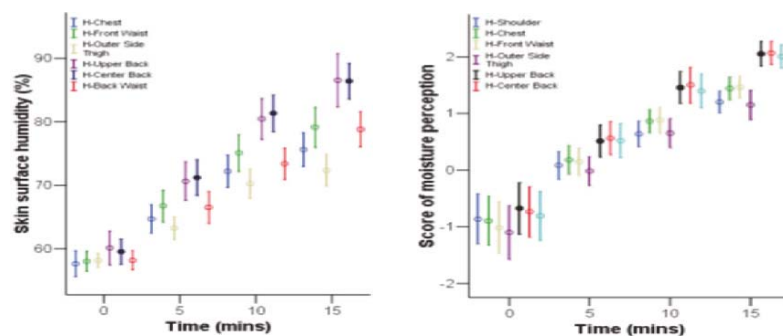


Fig. 2. Distributions of skin surface humidity and moisture sensation at different time periods

Figure 2 illustrates the distribution of objectively measured skin surface humidity and subjective perception of moisture sensation at different time periods respectively.

5.2 Dimension of Moisture Sensation

By using statistical factor analysis, varimax rotation. There are three main dimensions in moisture sensation in terms of body location; upper front (shoulder, chest and front waist), upper back (upper, centre and lower back) and side thigh in this study. Total percentage of variance contributed by these three dimensions is 98.5, in which 44.3, 39.7 and 14.5% are contributed by upper front, upper back and side thigh respectively.

This suggests that upper back is one of the key elements towards overall perception of moisture sensation, followed by upper front and side thigh.

6 Simulation and Validation

In this mathematical modelling process, two assumptions had been made: 1) There is a linear relationship between the sum of moisture sensation scores collected at different body regions and overall moisture sensation score and 2) percentage of variance can be used as weight to explain the importance of individual body regions. Based on these assumptions, their relationship can be expressed as:

$$\text{OMSS} = 0.443 (\text{TOPBACK}) + 0.397 (\text{TOPFRONT}) + 0.145 (\text{SIDETHIGH}) \quad (6)$$

By using the mean of the actual comfort scores against the predicted scores, which derived from the above equation, clear linear relationship ($r^2 \approx 0.992$) was found between the two. This suggests that the predictability of the model is high. In order to validate the model, a new set of data was applied to the model; good linear relationship was also found.

7 Conclusion

Based on the findings from this study, it can be concluded that:

1. The pattern of objectively measured skin humidity agreed with the subjective perception of moisture sensation, which have increasing trend over the exercising period;
2. The selected seven body locations can be abstracted into three body regions; TOPBACK (upper, centre and lower back), TOPFRONT (shoulder, chest and front waist) and SIDETHIGH (side thigh), to describe the perception of moisture sensation.
3. TOPBACK contributes the most towards moisture sensation, followed by TOPFRONT and SIDETHIGH respectively.
4. Human perception of moisture sensation at different body regions can be used to simulate moisture sensation. This study has set up a good foundation for simulating human perception of other sensations including thermal and pressure.

Acknowledgement

We would like to thank the Hong Kong Polytechnic University for the financial support of this research through projects A174 and A188.

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Part VI

Computational Biomechanical Engineering of Textiles

A CAD System for the Biomechanical Sensory Engineering of Clothing

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Abstract

In this paper we present the development of a CAD system for the biomechanical sensory engineering of clothing. This system has the following principal objectives:

- 1) An integrated software system of computer aided design for the biomechanical sensory engineering of clothing;
- 2) A comprehensive database to support the design, simulation and evaluation for the biomechanical sensory engineering of clothing;
- 3) An environment for the visualization, from the 2D apparel pattern, of 3D pressure and stress distributions;
- 4) A software platform for linking mechanical analysis with visualization software packages;
- 5) A software environment enabling the visualization of biomechanical sensory perceptions and preferences which take into consideration

psychophysical models. Each part is designed to meet the engineering needs of the biomechanical design of the clothing.

Key words: clothing, biomechanical engineering, database system.

1 Introduction

The biomechanical engineering design of clothing involves the process of creating new apparel products using iterative-decision-making, in which the basic sciences, mathematics, and engineering sciences are applied to convert a resource optimally to meet a stated objective (Li and Zhang 2005). The biomechanical engineering of clothing design is largely based on the integration of computer aided design, computer graphics, computer display technology, mathematical models, material sciences and experimental methodology to simulate the dynamic mechanical processes and visualize the results.

A CAD system is a knowledge-based design procedure to support the mechanical engineering of clothing design. Figure 1 shows the design procedures.

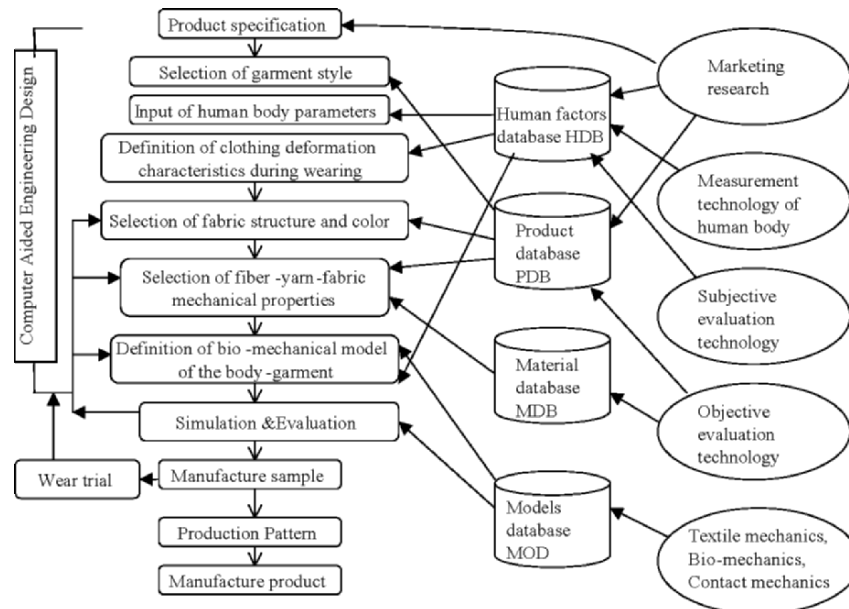


Fig. 1. Design procedure in a CAD system (Li Y. and Zhang X.,2005)

The design starts with a product specification to identify the type of garment (e.g. jeans or bra), followed by the selection of a garment style and human body parameters from the human factor database and the product database. From the input parameters of the human body and the garment, the deformation characteristics of the clothing can be identified, based on the mechanical analysis of the dynamic contact between the human body and the garment. This will govern the next step of selecting a fabric structure and selecting the mechanical properties of the fiber-yarn-fabric. The selection is a revision of the design achieved by searching or reworking previous fabric structures, which reasonably approximate to the current design requirements. The selection of a mechanical model of the body-garment allows a numerical simulation and analysis of the mechanical performance of the garment and the body. The iterative procedure has to be completed before the garment is produced, to demonstrate through the simulation and evaluation steps, that the design will satisfy requirements. The iterative design cycle will be shortened by using the CAD environment which is supported by an engineering database and based on an array of fundamental research.

2 Development of the CAD System

To develop a CAD system with the required functions, fundamental research was undertaken which combined science, engineering and information technologies. There were five objectives:

- 1) An integrated software system of computer aided design for the biomechanical sensory engineering of clothing;
- 2) A comprehensive database to support the design, simulation and evaluation for the biomechanical sensory engineering of clothing;
- 3) An environment for the visualization, from the 2D apparel pattern, of 3D pressure and stress distributions;
- 4) A software platform for linking mechanical analysis with visualization software packages;
- 5) A software environment enabling the visualization of biomechanical sensory perceptions and preferences which take into consideration psychophysical models.

2.1 Development of a System Framework

Using software technology, a theoretical framework for an integrated computer aided design environment can be developed for the biomechanical sensory engineering of clothing. First, the logic of the biomechanical sensory engineering design processes are analyzed, including the selection of the garment, the human model, the garment 2D pattern, the 3D garment formation, the garment-body contact conditions, and the assigning of material properties to the visualization of the 3D garments. The digital data of the 3D garment and the human body is created for the biomechanical design as part of the process of developing a pre-processing file. A mechanical simulation using special FEM software and/or other techniques is then used, to visualize these results, and then it is possible to finally visualize and predict the biomechanical sensations.

2.2 Development of a Database System

To support the systematic design platform, an engineering database was developed for the processes of design, analysis and evaluation with a logical organization of the various types of information. This engineering

database was developed, as shown in Fig. 2, with a number of important features to support the engineering design processes:

- (1) A dynamic database to handle two kinds of information:
 - i. the design environment (rules, methods, standard elements etc.) and
 - ii. data unknown previously but defined during the design process for the iterative-decision making process in the engineering design, which includes analysis and synthesis based on knowledge from the basic sciences, mathematics, and engineering sciences.
- (2) A logical structure to meet the engineering design needs. Engineering design deals with a number of value types, so this database had to support the design, analysis and evaluation phases in a systematic design process which included various types of information. The database structure was defined according to the characteristics of engineering design. It had to meet the needs of user-friendly program packages in order to input, store and display the information of apparel product quickly and effectively in time and space areas. The database was developed using modern database technologies such as objective-oriented technology, component technology and knowledgebase and data mining.

Fig. 2. An interface in DB

2.3 Development of a Simulation Platform

It is possible to support clothing design, where material properties, motion and dynamic mechanical properties are specified. A software environment has been developed to derive a 3D garment data format from a garment's 2D pattern according to a specific human size. This is generated from a traditional 2D CAD system which defines the data structure and geometry information of the pattern, including points, curves and labels. With this 3D garment data file, we can define the material properties, environmental conditions and body-garment contact conditions. Critical analysis can then be carried out and specific solutions developed to handle the difficulties in the data conversion between the various software packages. Figure 3 to Fig. 7 show an example of the application of the CAD system (Dai et al. 2003). The first step is the selection of a 2D pattern in DXF form, as shown in Fig. 2 and Fig. 3.

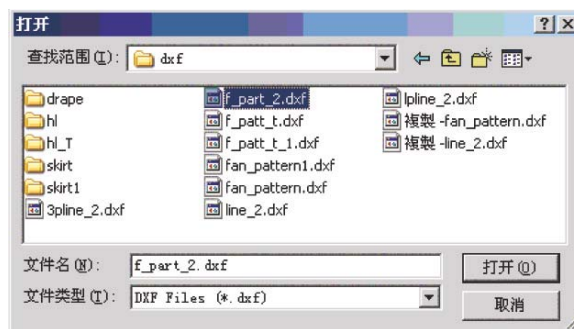


Fig. 3. To select a 2D pattern file

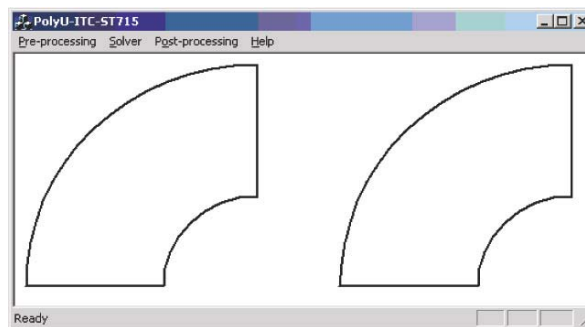


Fig. 4. To display a pattern

The following operation defines the mesh particle size, the garment mesh and defines the seam lines, as shown in Fig. 5 and Fig. 6.

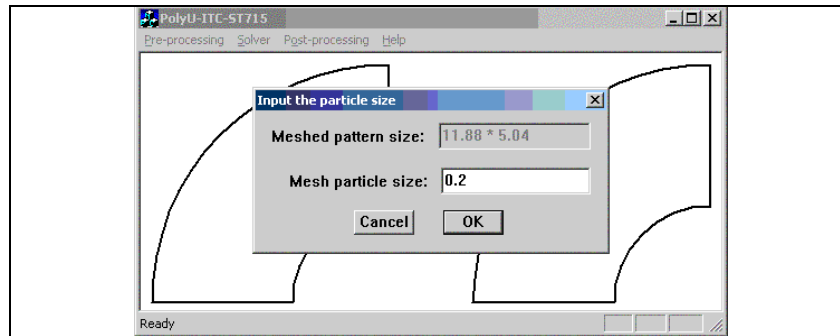


Fig. 5. To define the mesh parameter

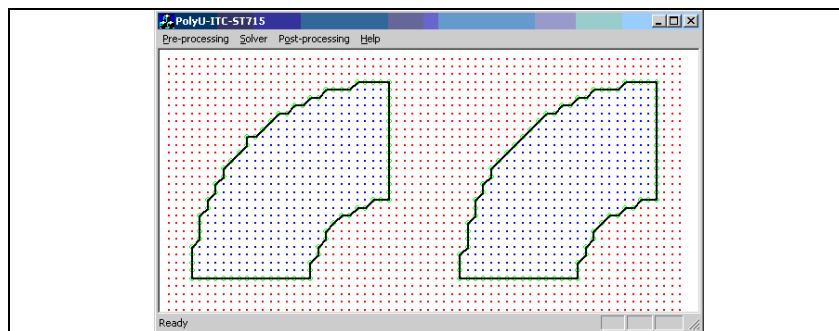


Fig. 6. Mesh data of a 2D pattern

The last step is to select a human model, then set the material mechanical parameters onto the form, and adjust the pattern position to the 3D body.

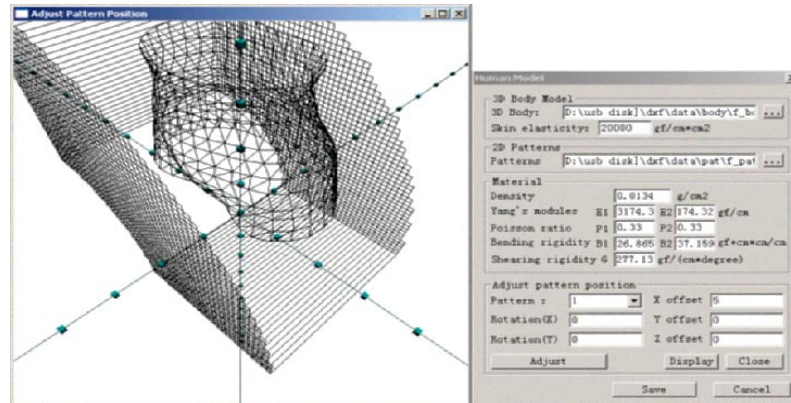


Fig. 7. To adjust the position to a 3D human model

After these operations, clicking the save button will create the pre-processing file, as shown in Fig. 7.

2.4 Development of an Integrated Environment

To enable communication between different software packages, a software platform has been developed. This provides an environment which can link and /or integrate the various commercial mechanical analysis software packages able to carry out mechanical modeling/simulations on the basis of the 3D garment data files prepared earlier (See Fig. 8).

DataName	DataType	DataValue	DataUnit
Finishing condition	value		
Length	value		
Width	value		
Thickness	value		
Area density	value	0.0134	
Volume density	value		
Cover factor	value		

Material Info

Density : 0.0134 g/cm2

Yang's modules : E1 3174.3 E2 174.32 g/cm

Poisson ratio : P1 0.33 P2 0.33

Bending rigidity : B1 26.865 B2 37.159 g*cm*cm/cm

Shearing rigidity : G 27713 g*cm*cm/cm

Save as Material Pre-processing File

Model Info

Skin elasticity : g/cm*cm2 Save as Model Pre-processing File

Save as Pre-processing File Exit

Fig. 8. A link with other software

2.5 Development of the Visualization System

The numerical simulation results are visualized in 3D garments to illustrate the distribution of garment pressure, stresses and shearing in the garment, as shown in Fig. 9. Further, a software environment has been developed to visualize the biomechanical sensory perceptions according to the psychophysical relationships between the psychological sensory perceptions and the mechanical stimuli that are derived from the mechanical analysis. This involved three stages of research: (1) the transformation of the mechanical stimuli data, such as garment pressure and stresses, to biomechanical sensory perceptions, such as tightness, stiffness and prickliness, according to the psychophysical relationships from the experiments; (2) the transformation of the sensory data to colour; and (3) the mapping of the sensory perception colour to human body locations.

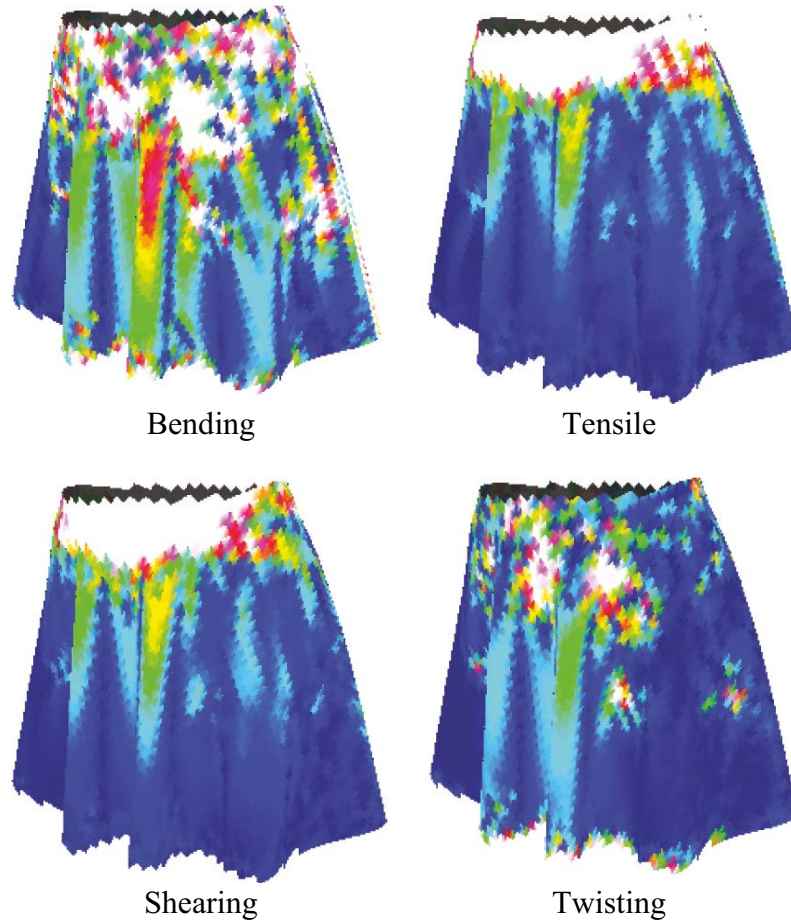


Fig. 9. Visualizations of simulation

3 Summary

The engineering design of clothing can be widely applied, no matter what the fashion design, pattern design, material design or function design, as it is based on mathematics, computer technology and experimental methodology. In this paper we have presented a CAD system for the

biomechanical engineering of clothing. This system is an integrated environment of the functional models of design, analysis and evaluation for the biomechanical engineering of clothing. The system provides a design methodology and a tool for optimization in product development.

Acknowledgements

We would like to thank Hong Kong Polytechnic University for funding this research through projects A188 and G-YD31, and also the National Natural Science Foundation of China through project grant 60273063, 60525213.

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The Simulation of Elastic Human Body Deformation and Garment Pressure with Moving Mesh Method

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Abstract

Simulation of human body elastic deformation and the garment pressure distribution when wearing tight-fitting clothing is critical for biomechanical design of functional apparel products. The distribution of garment pressures on the surface of human body is calculated using elastic human body and mass-spring clothing model under large deformation situation presented in this paper. The displacement of initial coarsest lattice of the deformed elastic human body is calculated by the iterative integration of the Lagrangian dynamic equation, which reflects the interactive reactions between the fabric and elastic human body. To deduce the perturbation of the mesh, we use a smooth procedure to get the better mesh for the further use of the mesh. The moving mesh method is also integrated into the mass-spring system and gets better mesh for the simulation of the pressure distribution.

Key words: functional garment design, moving mesh, Garment Pressure.

1 Introduction

For functional apparel 3D design, computation and visualization of elastic human body deformation and the garment pressure distribution when wearing the tight-fitting clothing can be used in different fields, such as functional garment design, vulnerary band product development, and computer animation.

Garment pressure is a design criterion for functional tight-fitting clothing and is affected by the garment size, the style of garment, the elastic modulus of fabrics, the 3D geometric shape of human body, and the synthesized elastic modulus of human body in (Wang et al.; You et al. 2002a, 2002b). In the past, many research works have been done on conducting wear experimentations to measure wearing garment pressure and the relevant subjective sensations in (Kawabata et al. 1988; Makabe et al. 1993; Nakahashi et al. 1999; Nakahashi et al. 2000). In the early work, Y. Li and X. Zhang et al. in (Li et al. 2003; Zhang et al. 2000a) present a mechanical model for numerical simulations of 3D dynamic garment pressure during wear using finite element method. In the research, the garment is regarded as an elastic shell of geometric nonlinearity and the human body is assumed to be rigid. The contact between body and garment is modeled as a dynamic sliding interface. They also studied the stress distribution in textiles with fabric bagging using the finite element method in (Zhang et al. 2000a, 2000b). It is desirable, however, to construct a biomechanical model of human body for simulating the deformation of elastic human body under the constraints of tight-fitting clothing. They are essential to predicting the garment pressure during wear more accurately.

Mass-spring systems have been extensively used in computer graphics over the last fifteen years, and are still very popular. Easier to implement and faster than finite element methods, these systems allow animation of dynamic behaviors. They have been applied to the animation of inanimate bodies such as cloth or soft materials and to the animation of organic active bodies such as muscles in character animation.

One of the main drawbacks of mass-spring systems is that neither isotropic nor anisotropic materials can be generated and controlled easily. Another problem is that most of the materials found in nature maintain a constant or quasi-constant volume during deformations (this is well known for muscles, but also holds for inanimate materials). Mass-spring models do not have this property. But even we use small time step in the mass-spring system, the mesh can't be uniformly at the balanced position. The mesh is perturbation. We still need a smooth procedure to get the better

mesh for the further use of the mesh. In (Fleitas et al. Liu et al. 1998; Shontz and Vavasis 2003), we have presented the moving mesh methods for the mesh deformation. The methods assure precise control over the cell size in both two and three dimensions. In this methods, the connectivity of the nodes is unchanged if the grid quality is acceptable.

This paper overviews the research background and motivations in section 1. In session 2, we introduce the initial coarsest lattices of human body and calculate the deformation of elastic leg and the garment pressure distribution under the constraint of tight-fitting clothing using the mass-spring fabric model and the elastic human body model, we smooth the meshes using moving mesh method to get better effect of the pressure distribution simulation. We include the conclusions and future works in section 3.

2 Simulation of Deformed Elastic Human Body and Pressure Distribution

2.1 Simulation of the Deformed Human Body under the Tight-Fitting Garment's Pressure

When wearing the tight-fitting clothing, the clothing patterns will be expanded and be superposed with the surface of the human body. The elastic human body will be deformed under the constraints of the garment pressure. We take human leg as an example in the following.

In this paper, the fabric is initially divided into regular quadrangle grids. The vertices of the grids are connected by massless springs and the mass of the fabric is distributed into particles. In the case of large deformation of elastic fabric when wearing tight-fitting clothing, we mainly consider the garment pressure contributed by the stretch forces in the warp, weft and bias directions as showed in the following Fig. 1(a). The contribution of bending force to the garment pressure has been neglected. The number of particles on the mass-spring net of the garment is $17 \times 17 = 289$, which is scattered on the surface of human leg of 560mm height. Each 4-point on the surface of human leg is regarded as a unit, and the surface of the leg is divided into the quadrilateral meshes. These 4 points are connected with the central axis of the leg. Therefore there is a hexahedron as showed in the Fig. 1(b). The positions of the bone can be found in the connecting line

between the particles on the leg's surface and the central axis of leg. The particles of the fabric superpose with the particles on the surface of human leg.

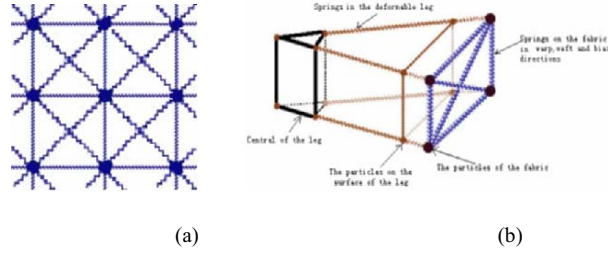


Fig. 1. Mass-spring model of the fabric and elastic model of elastic leg

The elastic human body will be deformed interactively with tight-fitting garment under the garment pressure. After the particles of fabric move to the balanced positions, the positions of fabric particles will be regarded as the initial positions of particles on the human body's surface. Here, the discrete Lagrangian dynamic equation is utilized to control the particles' movement of the garment. The stretch forces of garment particles in the weft, warp, bias directions, and the support forces of elastic human body to garment are calculated in the dynamic Lagrangian (1).

$$m\ddot{p} + f_{bias} + f_{weft} + f_{warp} = f_{sup port} \quad (1)$$

Here $\ddot{p}$ is the acceleration, m is the mass of each particle. f_{bias} , f_{weft} , f_{warp} are the forces that are deduced by the stretch of springs between garment particles in the different directions separately. $f_{sup port}$ is computed by the displacement of deformed elastic human body and the elastic modulus of the human body. All of the above forces are computed with the Hook Law $f = k\Delta x$, k is modulus of the spring and Δx is the stretch of the spring. With the measure instrument of elastic modulus, an elastic modulus of human body can be obtained, which reflects the synthesized elastic modulus of the human body to the external force.

We choose explicit method to integrate the ordinary differential equations with material's properties, mass, elastic modulus because of its

simplicity, but it can be improved to get large time steps and more stability by using implicit methods with solving a large-scale linear system. After all the garment particles arrive at balanced positions, these particles will be smoothed using Moving Grid Method to get nearly uniform mesh, described in this section.

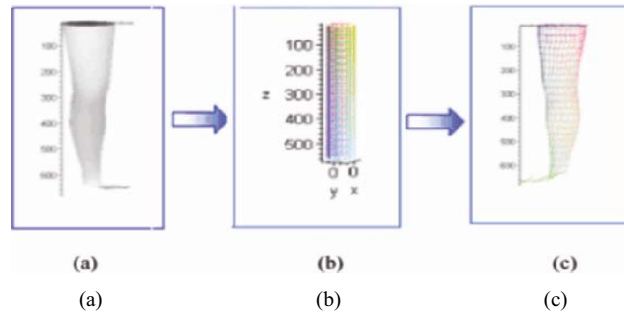
2.2. Calculation of Tight-Fitting Garment's Pressure

After the garment particles move to the balanced positions, the pressure force of the particles $f_{pressure}$ can be calculated using (2), and the pressure force $P_{pressure}$ is computed by the garment pressure $f_{pressure}$ divided by the particle's corresponding area s , as showed in (3).

$$f_{pressure} = f_{bias} + f_{weft} + f_{warp} \quad (2)$$

$$P_{pressure} = \frac{f_{pressure}}{s} \quad (3)$$

Figure 2 is the schematic diagram of the garment pressure's simulation. We choose the cylinder as the initial shape of the garment before wearing, since the cylinder is the common shape of 3D pattern in the tight-fitting clothing. We use the mathematical software Maple to build the mathematic model, and use the C++ Builder and OpenGL to calculate and visualize the experiment results. Here, the color is utilized to express the distribution of pressure. The unit of the color scale is 1000 Pa per each interval.



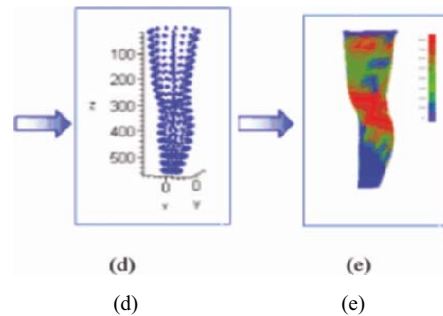


Fig. 2. Schematic diagram of garment pressure's calculation

(a) 3D surface of human leg (b) 3D fabric pattern (c) Initial position of 3D tight-fitting (d) Iteration of integration the dynamic equation (e) Pressure distribution on the surface

In order to compare the effects of computer simulations with the wearing experimentation, we choose the experiment data, which come from our previous work in (You et al. 2002a, 2002b).

2.3 The Deformation Method using Moving Mesh Method

Animating an elastic object using a mass-spring system usually consists of discretizing the object with a given 3D mesh, setting point masses on the mass nodes and damped springs on the mesh edges. Then the most implementations simply integrate point dynamics equations for each mass from the set of applied forces due to the mesh deformation at the previous time step. However there is no easy solution for spring parameters. Since damped springs are positioned along the edges of a given volume mesh, the geometrical and topological structure of this mesh strongly influences the materials behavior. A consequence of this problem is that changing the mesh density during the simulation while maintaining the same global mechanical properties is very difficult in [Bourguignon and Cani 2000]. If all springs are set to the same stiffness, the mesh geometry may generate undesired anisotropy in [Bourguignon and Cani 2000].

In the experiments, we choose fabric, whose parameters are presented in the Table 1 and Table 2.

At the time step $\Delta t = 0.5 \times 10^{-3} \text{s}$, the systems get to balance status at last, see Fig. 3, but at the time step $\Delta t = 0.5 \times 10^{-2} \text{s}$, the systems diverge, see Fig. 4.

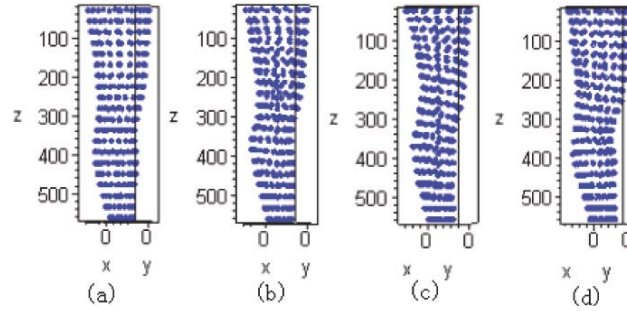


Fig. 3. At time step $\Delta t = 0.5 \times 10^{-3} \text{s}$, system converge to the balance position. (a) $t=0\text{s}$ (b) $t=0.125\text{s}$ (c) $t=0.25\text{s}$ (d) $t=0.5\text{s}$

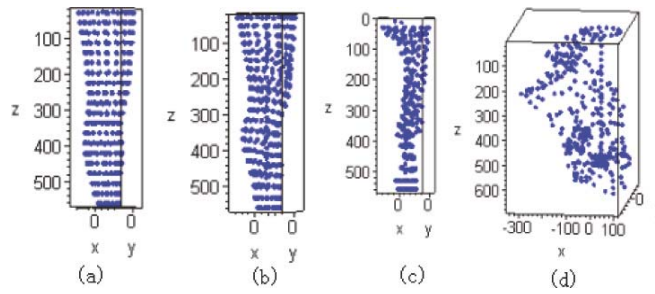


Fig. 4. At time step $\Delta t = 0.5 \times 10^{-2} \text{s}$, systems diverge.

(a) $t=0\text{s}$ (b) $t=0.125\text{s}$ (c) $t=0.25\text{s}$ (d) $t=0.5\text{s}$

2.4 Moving Mesh Methods as a Smoother Filter

But even we use small time step in the mass-spring system, the mesh can't be uniformly at the balanced position. The mesh is perturbation. We still need a smooth procedure to get the better mesh for the further use of the mesh.

In (FLE; LIU, 98; SUZ, 03), we have presented the moving mesh methods for the mesh deformation. The methods assure precise control

over the cell size in both two and three dimensions. Consequently, the grid mapping is injective (one to one) in both two and three dimensions. A positive monitor function $f(x, y, z)$ is used to obtain a vector field that moves the nodes to desired locations so that the element size of the resulting moving mesh is equal to f . Such a monitor function is usually determined according to the solution error or the boundary curvature. In this methods, the connectivity of the nodes is unchanged if the grid quality is acceptable. The moving grid deformation method we use here is based on the LSFEM (Least-Squares Finite Element Method). The method consists of the following steps:

Step 1: Define monitor functions f and form the right hand side of the div equation.

Step 2: Calculate the velocity field v from the linear differential equations

$$\begin{aligned} \operatorname{div}(v / f) &= -\frac{\partial}{\partial t}(1 / f) \quad \text{with} \\ \operatorname{curl}(v) &= 0 \quad v = g \quad \text{on the boundary} \end{aligned} \quad (4)$$

Step 3: Calculate the new location $T(x, y, z)$ of a node by integrating the velocity vector field v .

Implementation: The current version of the deformation method is implemented by the least squares finite element method. The div-curl system is solved for the velocity vector field v . The Dirichlet boundary condition $v = g$ is imposed, where g is determined by the movement of the boundary nodes.

Here, we define the monitor function $f(x) = x(1 - x)$ $0 \leq x \leq 1$, see Fig. 5.

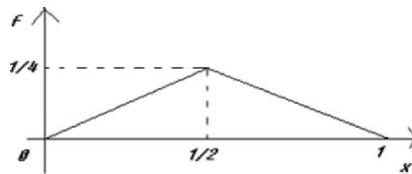
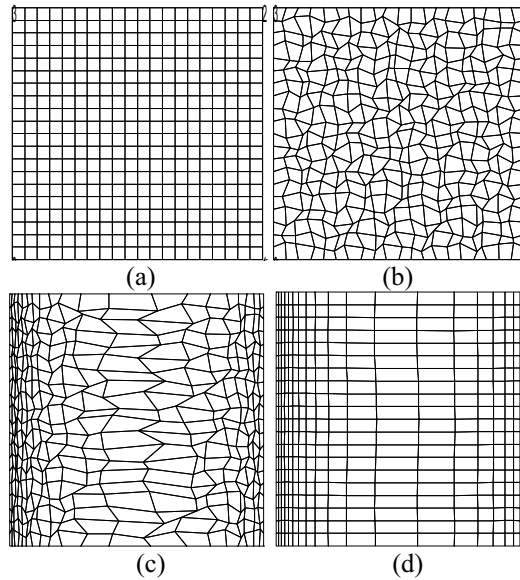


Fig. 5. Monitors function $f(x)$

We can see the defined monitor function reaches to the maximum value at $x = \frac{1}{2}$ and linear move up and down, this monitor function can guarantee the deformed mesh uniformly variety from the center to the two sides. This monitor function f controls the nodes in the mesh to move to the new positions. The meshes in the middle change bigger than the mesh on the edge. And the quantity of the change descends from the middle to the edge.

An example of moving methods: a standard grid is perturbed in Fig. 6 (a-b), The deformation method (div-curl) is applied in Fig. 6(c) followed by a smoothing procedure Fig. 6(d). Meshes in the Fig. 6(b) change to the meshes in the Fig. 6(c), the deformation is controlled by the monitor function f , we defined. The meshes in the Fig. 6(d) is smoothed by the Discrete Laplacian Filter to get smoother deformed mesh from Fig. 6(c).



(a)Original mesh (b)Mesh after perturbation (c)Div-cur without smooth (d)Div-cur with smooth

Fig. 6. Experimental Results of Moving Mesh method

2.5 Experimental Results

The experiment parameters are presented in Table 1 and Table 2.

Table 1. EXPERIMENT PARAMETERS USED IN THE SIMULATION OF LEG'S DEFORMATION

Parameters	Values
Vertex number of the initial lattice	867
The height of leg (mm)	560
The radius of 3D patterns (mm)	40
Time step(ms)	0.5
Particle mass(kg)	49.85064×10^{-6}
The high of 3D patterns (mm)	560

Table 2. ELASTIC MODULUS PARAMETERS OF THE FABRIC

Fabric	Elastic Modulus Parameters		
	weft direction (kg/%)	warp direction (kg/%)	bias direction (kg/%)
A	1.75×10^{-2}	13.33×10^{-2}	7.50×10^{-2}
B	1.75×10^{-2}	13.33×10^{-2}	7.50×10^{-2}
C	1.75×10^{-2}	13.33×10^{-2}	7.50×10^{-2}

In the experiments, we choose fabric A, B, and C, whose parameters are presented in the Table I and Table II. At the time step $\Delta t = 0.5 \times 10^{-3}$ s, the systems get to balance status at last. The meshes are smoothed by the moving mesh method after the mass-spring systems get to the balance position.

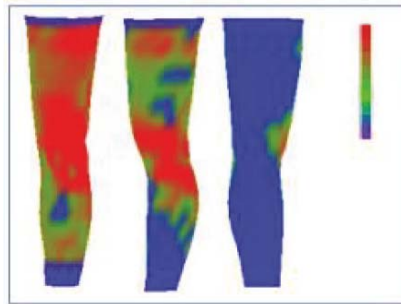


Fig. 7. Experimental results of the pressure calculation after the large deformation following by moving mesh method smooth

3 Conclusions

We introduce a new mesh smoother filter for the mass-spring systems to simulate and visualize the deformed elastic human body and the distribution of garment pressure after wearing thigh-fitting clothing based on the elastic human body model and the fabric mass-spring model. The smooth filter is computing by the moving mesh method. This smooth filter can also extended to unstructured mesh, widely used to calculate and visualize the distribution of pressure, or some other physical properties inside of deformable human body, for instance, the deformation of elastic human body with the bone or some other physiological tissues, etc. It is a potential method for the volumetric object, not only can be used in the human body, but also in other research fields.

Acknowledge

This work is partially supported by the National Natural Science Foundation of China under Grant No. 60403039; the Natural Science Foundation of Guangdong Province of China under Grant No. 031538.

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Numerical Simulation of Skin Pressure Distribution Applied by Graduated Compression Stockings

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Abstract

Graduated compression stockings (GCS) have been demonstrated to be an effective non-operative option to relieve symptoms associated with venous disorders in the human lower limb. The purpose of this study was to develop a three-dimensional biomechanical mathematical model to simulate and predict accurately the mechanical interaction between human lower limb and compression stockings in conjunction with the wear trials and materials objective experiments. The established mathematical model can predict and visualize the skin pressure magnitude and distribution applied by different compression stockings without practical wearing, which provide us with more effective engineering design and scientific evaluation approach. This model also can contribute to improve the medical functions of GCS for preventing and treating venous disorders.

Keywords: Numerical simulation, prediction, skin pressure, distribution, compression stockings

1 Introduction

Graduated compression stockings (GCS), used as one of the important compression therapies, have been demonstrated to be an effective

non-operative option to relieve symptoms associated with venous disorders in the human lower limb (Jones et al. 1980; Abu-own 1995; Elder & Kenneth 1995; Brandjes et al. 1997; Weiss 1999), such as reducing venous hypertension and improving venous blood return. Scientific design of compression stockings not only can enhance their medical functions, but also can bring wearers comfort sensory perceptions.

However, numerous laboratory experiments and clinical practices reveal that the skin pressure performances of compression stockings are variable and unstable, such as producing excess or insufficient pressure and reversed pressure gradients, etc. (Joep et al. 1997; Best et al. 2000), which would bring negative influence on their compression therapeutic efficiencies, such as providing ineffective support for target area, causing some physiological damage, or producing a tourniquet effect, etc. Actually, as a crucial factor in the compression therapy, pressure itself has not been understood sufficiently. Therefore, how the pressure performances and how to develop new stocking products with more satisfactory pressure profiles becomes an urgent matter confronting us.

The purpose of this study was to develop a three-dimensional biomechanical mathematical model to simulate and predict accurately the mechanical interaction between human lower limb and compression stockings in conjunction with the wear trials and materials objective experiments.

The established mathematical model can be used to predict and visualize the skin pressure magnitude and distribution applied by different compression stockings without practical wearing. Meanwhile, this model provides us a scientific and intuitionistic evaluation approach, which helps us further to fundamentally understand the mechanisms of action of compression stockings, thus, making us effectively improve the GCS design to ensure their medical functions for preventing and treating venous disorders.

2 Methods and Materials

2.1 The Objective Measurement of Skin Pressure Exerted by GCS

To obtain a basic understanding of skin pressure profiles exerted by GCS, an objective wear trial was conducted to evaluate the skin pressure magnitudes and distributions.

One healthy female (height 160cm, weight 50kg), with normal leg morphology and without any signs of vascular disease was recruited in this investigation.

Two kinds of GCS with different pressure levels (mild, moderate) were used as testing samples due to their more common clinical applications. The interface pressure located at the four heights levels (ankle, calf, knee and thigh) and four directions (anterior, medial, posterior, and lateral) along the leg were measured by using FlexiForce™ pressure sensors (Tekscan, Inc., USA) and a Multi-point pressure monitoring system when subject was being in upright standing posture. Thus, the skin pressure magnitudes and distributions in both longitudinal and transverse directions along the lower limb were obtained, which would build up a useful data foundation for developing and validating mathematical model.

2.2 Three Dimensional Mathematical Modelling

2.2.1 3-D Biomechanical Model of Lower Limb and Geometric Model of Stocking

To factually simulate the mechanical interaction between the human lower leg and stocking, a mathematical model simulating dynamic wearing process was developed. In this model, two main objects were involved. One is a three-dimensional biomechanical lower limb model and the other is a geometric stocking model. Since for phlebology, ankle is the target area (most of 80% of venous ulcers occurs here) and the gradient distribution from the ankle to the calf are paid more attention, we would focus to simulate the putting-on process of stocking from the ankle to the knee region.

The biomechanical lower limb model mainly consisted of soft tissue and two bones (i.e. the tibia and the fibula), which reconstructed from Magnetic Resonance Imaging (MRI) coronal Images of the subject, and the two important cross-sections, ankle and calf, were parted in order to investigate the skin pressure transverse distribution at cross-sections.

The geometric stocking model was developed to be a cylindrical tube according to the actual size of GCS worn by the female subject. In terms of locations and densities of knitted fabrics, the legging of stocking was divided into two segments. Figure 1 shows the stocking and biomechanical lower leg modelling.

2.2.2 Materials Properties and Modelling

In this model, two bones, the tibia and the fibula, were assumed not to deform during the process of wearing GCS. So the bones were taken as rigid and incompressible. The soft tissues surrounding the bone are assumed to be homogeneous, isotropic and linear elasticity. The young's

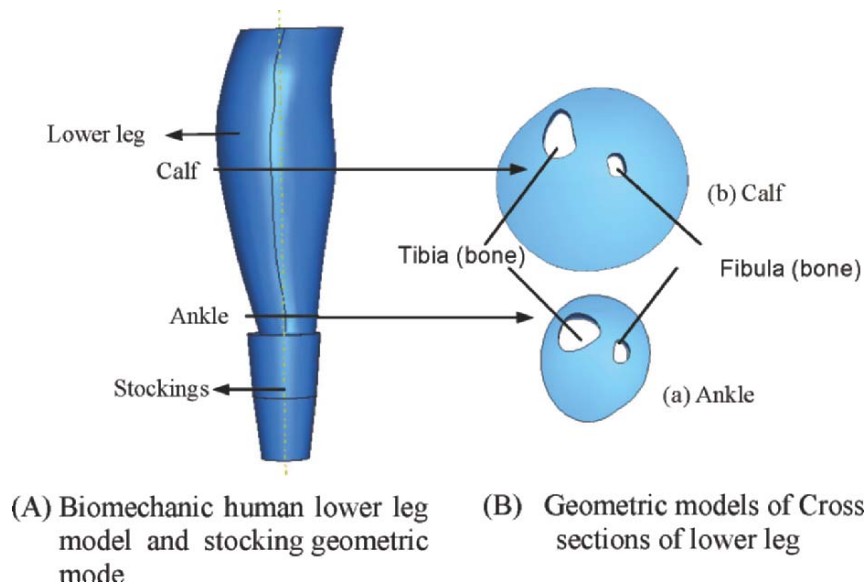


Fig. 1. The stocking and lower leg biomechanical modelling.

modulus, Poisson ratio, and mass density of soft tissues are taken as 0.01 MPa, 0.49, and 9.37×10^{-10} tonne/m³, respectively (Weiss 1999)

The materials properties of compression stockings are defined as orthotropic and linear elasticity. The tensile modulus and Poisson's ratio were obtained by measurements of Kawabata biaxial tensile test. The parameters needed in the numerical analysis were listed in Table 1. In this table, E1 and E2 stand for the Young's modulus in the course and wale

directions respectively; G12 and ν_1 denotes the shear modulus and Poisson ratio, and T means fabric thickness.

Table 1. Materials property of the compression stockings

Positions	W (tonne/mm ³)	E1 (N/mm ²)	E2 (N/mm ²)	G12 (N/mm ²)	ν_1	T (mm)
Ankle	2.1×10^{-10}	0.237	0.157	0.100	0.218	0.75
Calf	2.0×10^{-10}	0.235	0.101	0.093	0.235	0.75

2.2.3 Finite Element Analysis

This model was developed by using the ABAQUS 6.4 FE software package. The Finite Element Method (FEM) was used for numerical analysis of the model. The bone and soft tissue models was meshed using 4-node linear tetrahedron solid elements, while a mesh of 4-node quadrilateral membrane elements was used for stocking legging model.

The interface of stocking legging and the lower leg was considered as a surface-to-surface contact. A penalty method is applied to enforce kinematical constraint. That is, the slave surface nodes (i.e. inner surface of legging) would not penetrate the master surface (lower leg surface). Since the two bones were assumed as no deformations during stocking wearing, the displacements of all the nodes on the two bones were defined to be zero. For stocking legging, its bottom was fixed, while the displacement of its top was defined as 280 mm according to the actual state. There were no constraints for the transverse deformations of stocking legging.

3 Results and Discussion

3.1 Logitudinal Pressure Distribution

The results of the skin pressure objective measurement shows that the highest pressure was exerted at the ankle region, and gradually decreasing up to the knee region (Fig. 2). This indicates that the tested GCS follow the design principle.

Based on the above measured skin pressure distributions, greater differences in pressure were found between ankle and calf regions. Therefore, in this study, we focus on analyzing and simulating the skin

pressure below knee region. Since similar pressure gradient distributions exist among the stockings with two different pressure levels, we take one kind of stocking with mild pressure level for example to numerically simulate the skin pressure profiles.

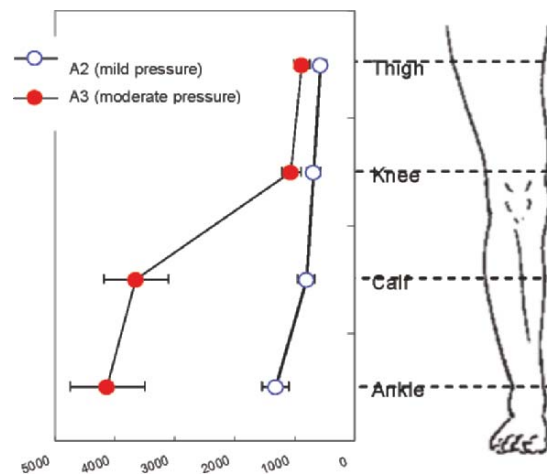


Fig. 2. General skin pressure gradient distributions along the human leg

Figure 3 shows the stress distribution of stocking with mild pressure. Figure 4 shows the simulated longitudinal pressure gradient distributions along the leg of GCS with mild pressure level. It was easily found that the pressure does not distribute uniformly over different parts of the lower leg. Just like the objective measurement results, we can see that the highest skin pressure was produced at the ankle region and decreased up to the knee region, indicating that the simulated skin pressure distributions are in agreement with the measured skin pressure distribution.

3.2 Transverse Pressure Distribution

For phlebology, the ankle region is the target area. Therefore, Fig. 5 showed the simulated skin pressure distribution at cross-sections of ankle region exerted by the stocking with mild pressure level. We found that higher skin pressures occurred at the regions with smaller radius, such as the anterior ankle and the Achilles's tendon. This distribution meets the Laplace Law. To confirm the simulated results, we compared them with

the measured skin pressure shown in Fig. 6. We find that the simulated skin pressure distributions at the ankle cross sectional circumferences obtain a satisfied agreement.

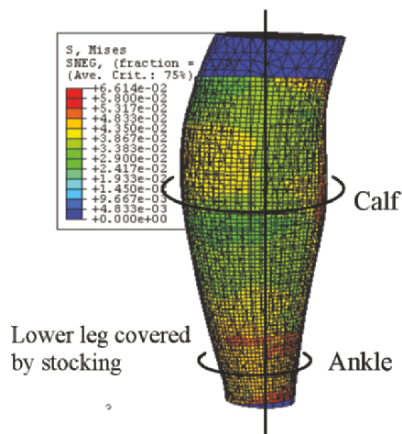


Fig. 3. Stress distributions of GCS being worn on the human

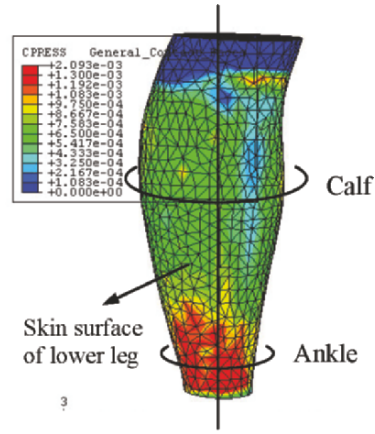


Fig. 4. Skin pressure distributions applied by GCS

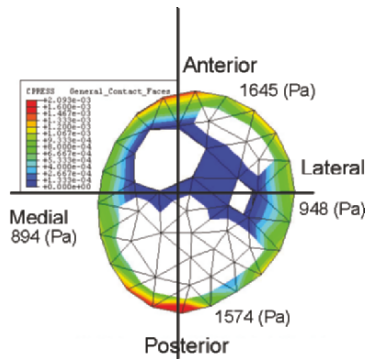


Fig. 5. Simulated skin pressure distribution

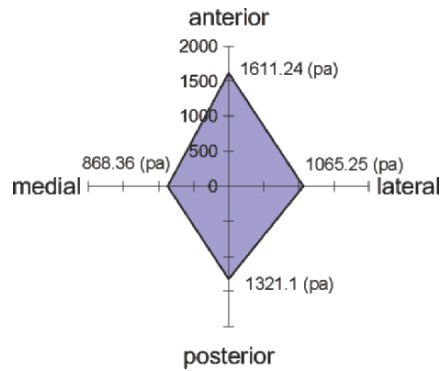


Fig. 6. Measured skin pressure distribution at four directions of the cross-section of ankle region

Figures 7 and 8 show the simulated and the measured skin pressure distributions at the cross-section of the calf region. We can see that the skin pressure values at the four typical directions also have a good agreement between them.

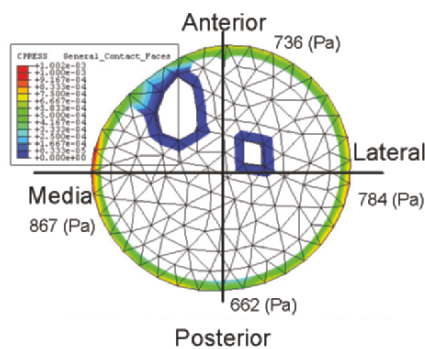


Fig. 7. Simulated skin pressure distribution at cross-section of calf region

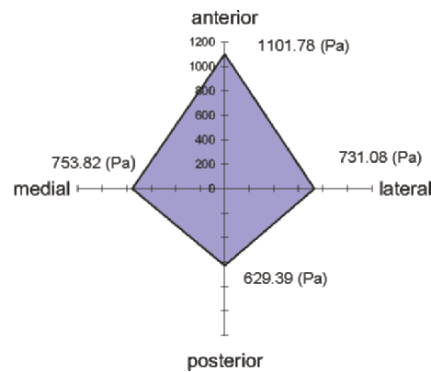


Fig. 8. Measured skin pressure distribution at four directions of the cross-section of calf region

4 Conclusion

By conducting wear trials, the skin pressure distribution and magnitude applied by different compression stockings have been objectively measured and analyzed. Based on the objective experiments, a 3-D biomechanical mathematical model for numerically simulating the skin pressure distributions exerted by compression stockings on the human lower limb has been developed. Comparing with the measured skin pressure distributions at longitudinal and transverse directions along the lower leg, the simulated pressure distribution and magnitude were in accordance with the skin pressure distribution of experimental measurements, indicating that the model can be used to simulate interface pressure between skin and stocking during wear with satisfactory accuracy. Therefore, the model can be used to apply as an engineering design tool to predict the pressure performances exerted by compression stockings and also can optimize the structure and materials properties in the process of compression stocking design. Thus, the occurrence of undesirable pressure

distributions can be avoided and the compression therapeutic efficiencies of GCSs can obtain further improvements.

Acknowledgements

We would like to thank to the Research Grant Council through the project PolyU 5157/02E and The Hong Kong Polytechnic University through the projects A188 and G-YD31 to support this research.

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Computational Modeling the Foot-Insole Interface

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Abstract

A 3D finite element model of the human ankle-foot, considering the bony and soft tissues structures is developed to study the biomechanical interaction between the foot and insole. The developed computational model can serve as a systematic tool to evaluate the functional outcomes of different insole or footwear designs without the prerequisites of replicating subject trials, experimental and product testing

Keyword: finite element model, foot, insole design, plantar pressure, stress

1 Introduction

Many experimental techniques were developed in the literature for the quantification of foot biomechanics, and footwear performances. Due to the difficulties and lack of technology and the invasive nature of experimental measurements, evaluation of biomechanical parameters such as bone and joint motion, shear and frictional properties and internal stress and strain are relatively sparse. Cadaveric studies can provide additional and more accurate measurement of biomechanical parameters and a better control of testing conditions and environment. However, the demand on massive and costly devices and equipment to study human gait or load response of the human foot and ankle is difficult to fulfill. Apart from the issues

of reliability and repeatability, experimental measurements are also time consuming and would need to be conducted on a significant amount of subjects or specimens with different characteristics to yield generalized and promising results.

In order to provide a supplement to the experimental inadequacy, many researchers have turned to the computational methods in search of more clinical information. Computational modeling, such as finite element (FE) method is an adjunct to the experimental approach to predict the load distribution between the foot and different supports, which offer additional information such as the internal stress and strain of the foot structures. The FE method has been used increasingly and with great success in biomechanical research due to its capability of modeling structures with irregular geometry and complex material properties, and the ease of simulating complicated boundary and loading conditions in both static and dynamic analyses. Further, its proficiency to monitor the parametrical effects of different structural, material and testing conditions makes it an ideal tool to investigate the underlying functional biomechanics of different foot structures and footwear designs.

Although many FE analyses of the foot or footwear were performed in the literature (Bandak et al. 2001; Chen et al. 2003; Chu et al. 1995; Jacob & Patil 1999; Siegler et al. 1988), previous models have been developed under certain geometrical and material simplifications. Currently, the major drawbacks for the existing foot models are the inability of accurate representation of the geometrical features of the encapsulated soft tissue and the plantar foot, realistic material behaviour, joint and foot-ground contact conditions. Recently, the authors have developed a geometrical detailed and material realistic FE model of the human foot and ankle, to provide a more accurate representation of the foot and the supporting conditions (Cheung et al. 2005).

Human skin consists of different types of receptors, which function are to response to various physical stimuli including touch, pressure, thermal, cold and pain. However, there is no receptor is responded for moisture or dampness sensation, at least at this moment.

Many researches (Lake and Hughes 1980; Morris et al. 1985; Hong et al. 1988; Tarafder and Chatterjee 1994; Li et al. 1995; Plante et al. 1995) had been carried out over the years in order to understand the perception of this sensation. Sweeney and Branson (Sweeney and Branson 1990a) examined the feasibility of using psychophysical methods to assess moisture sensation in clothing. The psychometric functions demonstrating the relationship

between moisture and moisture sensation for these determinations exhibited linear trends. Later on, Sweeney and Branson (Sweeney and Branson 1990b) asked thirteen subjects used the magnitude estimation method to assess the intensities of moisture stimuli, which applied to their backs. Result showed that the relationship between moisture stimulus and moisture sensation demonstrated a psychophysical power function. Magnitude estimation offers the clothing comfort investigator the advantage of maintaining closer correspondence between objective and subjective measures over the usual psychological scaling methods used. In the explaining the relationship between moisture sensation and overall discomfort, Berkowitch (Berkowitch 1982) stated the feeling of wetness was sufficient to define comfort for some subjects in the study. Lau et al (Lau et al. 2002) reported that overall discomfort is determined by tactile sensations (e.g., itchiness and prickliness) and moisture (dampness and clinginess) related sensations before and after exercise respectively. Wong et al (Wong and Li 1999) found that moisture and thermal related sensations contribute relatively greater percentage of variance than tactile and pressure related sensations toward overall comfort. Mathematical and statistical approaches towards simulation of human perception of different sensations have been introduced for many years. Wang et al (Wang et al. 2002) used different mathematical models, which describe heat and moisture in fabric and at the interface, neurophysiological responses to temperature changes and psychoneurophysiological relationships, to develop a mathematical simulation of human perception of thermal and moisture sensations.

The purpose of this paper is to report different computational methods for simulating human psychological perception of moisture comfort sensations, on the basis of perception of moisture sensation at different body locations, in multi-dimensions with various kinds of conceptual models, which developed on the basis of mathematical, neural networks and fuzzy logic modelling technique.

2 Methods

2.1 The Computational Foot Model

Three-dimensional accurate geometry of the ankle-foot model was obtained from reconstruction of coronal section MR images of 2 mm intervals from a normal male subject. Figure 1(a) shows the FE mesh of the human foot

and ankle, which was built via a combination of commercial available software. The segmentation process, surface to volume conversion and the mesh generation were done via the MIMICS v7.10 (Materialise, Leuven, Belgium), SolidWorks 2001 (SolidWorks Corporation, Massachusetts) and the ABAQUS v 6.4 (Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI), respectively. The depicted FE model consists of 28 distinct bony segments, embedded in a volume of soft tissue boundary. The phalanges were connected together using 2 mm thick solid elements, which simulated the connection of the cartilage and other connective tissues. A total of 72 major ligaments and the plantar fascia were defined by connecting the corresponding attachment points of the bony surfaces. The contour of the insole was obtained from surface digitization (Fig. 1(b)). The assigned material and element properties (Athanasίου KA, Liu GT, Lavery LA, Lanctot DR, Schenck RC, 1998; Bandak FA, Tannous RE, Toridis T, 2001; Jacob S, Patil MK, 1999; Nakamura S, Crowninshield RD, Cooper RR, 1981) of the FE model were listed in Table 1.

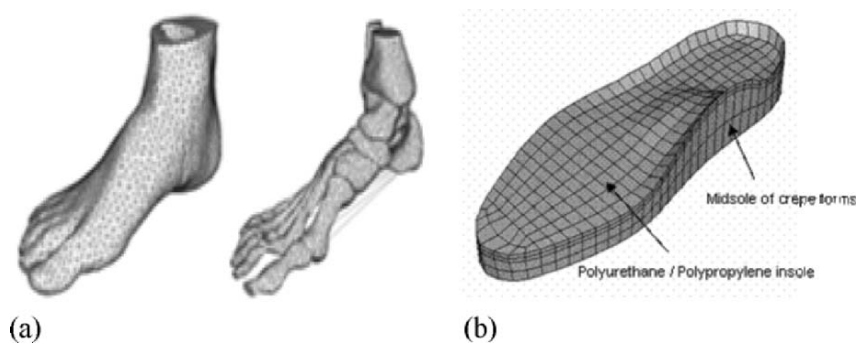


Fig. 1. Finite element meshes of the (a) bony and soft tissue structures and (b) custom-moulded insole support

Table 1. Material properties of the FE model

Component	Element Type	Young's Modulus [MPa]	Poisson's Ratio
Foot Bones	3D-Tetrahedra	7,300	0.3
Cartilage	3D-Tetrahedra	1	0.4
Soft Tissue	3D-Tetrahedra	Hyperelastic	-
Ligaments	Tension-only Truss	260	-

Fascia	Tension-only Truss	350	-
Ground Support	3D-Brick	17,000	0.1
Insole	3D-Brick	0.3, 1000	0.4
Midsole	3D-Brick	0.6	0.4

The hyperelastic material model was used to represent the nonlinear and nearly incompressible nature of the encapsulated soft tissue. A second-order polynomial strain energy potential was adopted with the form:

$$U = \sum_{i+j=1}^2 C_{ij} (\bar{I}_1 - 3)^i (\bar{I}_2 - 3)^j + \sum_{i=1}^2 \frac{1}{D_i} (J_{el} - 1)^{2i} \quad (1)$$

where U is the strain energy per unit of reference volume; C_{ij} and D_i are material parameters; $\bar{I}_1$ and $\bar{I}_2$ are the first and second deviatoric strain invariants defined as

$$\bar{I}_1 = \bar{\lambda}_1^2 + \bar{\lambda}_2^2 + \bar{\lambda}_3^2 \quad (2)$$

$$\bar{I}_2 = \bar{\lambda}_1^{(-2)} + \bar{\lambda}_2^{(-2)} + \bar{\lambda}_3^{(-2)} \quad (3)$$

with the deviatoric stretches $\bar{\lambda}_i = J_{el}^{-1/3} \lambda_i$. J_{el} and λ_i are the elastic volume ratio and the principal stretches, respectively.

2.2 Contact Properties, Loading and Boundary Conditions

The interactions among the bony segments were defined by contact surfaces to allow relative articulating movement. The contacts between the bony surfaces are assumed to be frictionless while the foot-insole interface is defined with frictional coefficient of 0.6 (Zhang & Mak 1999).

Force vectors corresponding to half of the body weight (350N) and the reaction of the Achilles' tendon (175N) were applied to simulate double-limb balanced standing (Simkin 1982). The vertically upward force of the Achilles' tendon, with magnitude was represented by 5 equivalent-force vectors at the posterior extreme of the calcaneus. The normal vertical force was applied at the centre of pressure of the inferior surface of the ground support. The superior surface of the soft tissue, distal tibia, and fibula was

fixed throughout the analysis, while the point of load application at the ground support was allowed to move in the vertical direction only. The prescribed loading and boundary conditions allowed the equilibrium condition of the ankle-foot structures to be established with unconstrained motion of the ankle joint and the insole support during weight bearing.

3 Results

The FE model predicted a sounding difference in plantar pressure distribution with the different uses of foot orthoses. The use of arch-supporting foot orthosis provided a uniform plantar pressure distribution by load shifting to the midfoot region (Fig. 2). Comparing with the barefoot condition, pronounced peak pressure reductions (Fig. 3) and increase in foot-insole contact areas (Fig. 4) were achieved with the use of polyurethane formed ($E = 0.3\text{MPa}$) insoles than the use of polypropylene ($E = 1000\text{MPa}$) insole.

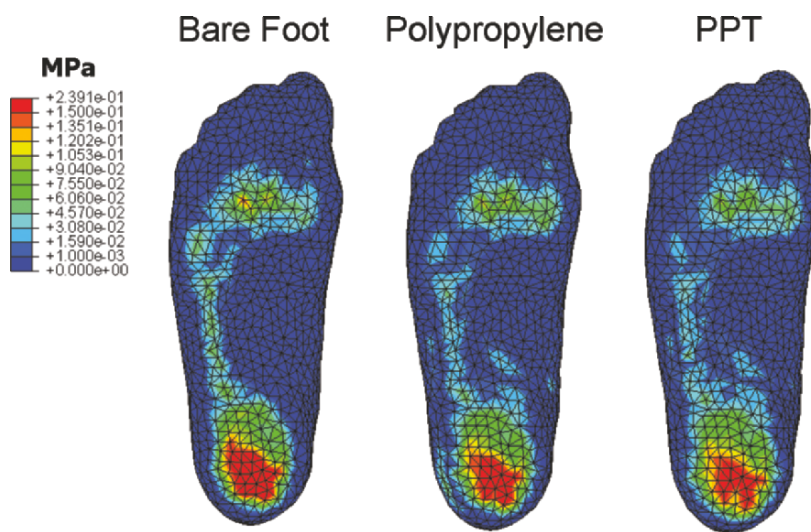


Fig. 2. Effect of different orthoses on plantar pressure distribution

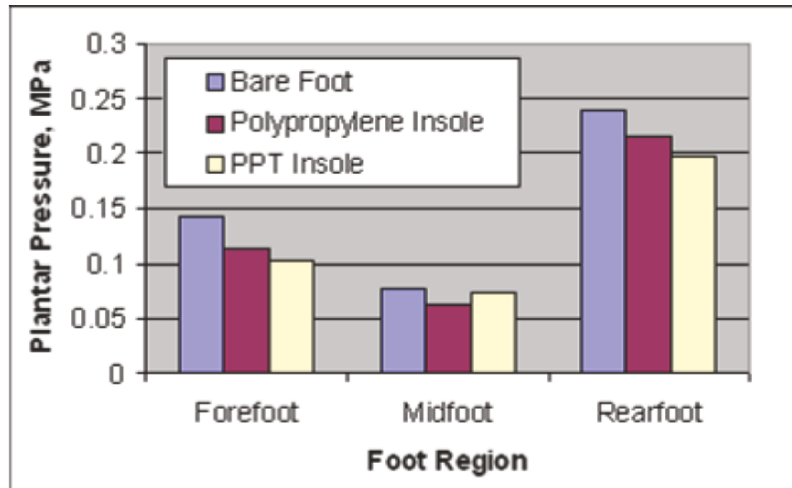


Fig. 3. Effect of different orthoses on peak plantar pressure of the forefoot, midfoot and rearfoot

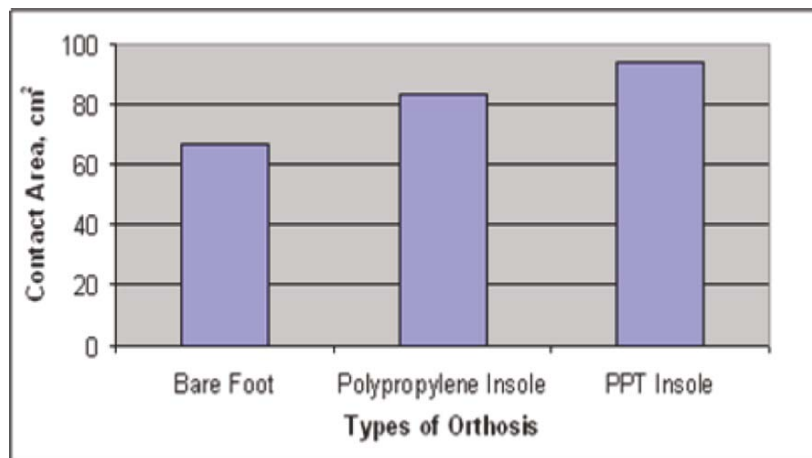


Fig. 4. Effect of different orthoses on area of foot-insole contact

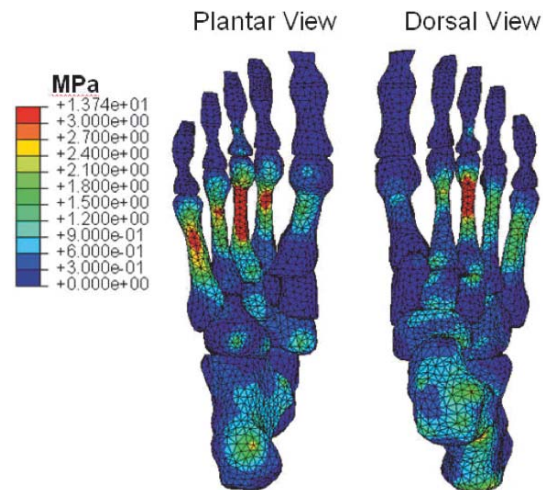


Fig. 5. Prediction of von Mises stress of foot bones during bare foots standing

The von Mises stress distribution of the foot bones during simulated bare foot standing was shown in Fig. 5. The mid-shaft of the metatarsals especially the third metatarsal were found to sustain high bone stress. Although the use of foot orthoses consistently relieves the stress in the forefoot, the overall orthotic effect on bone stress relief was minimal (Fig. 6).

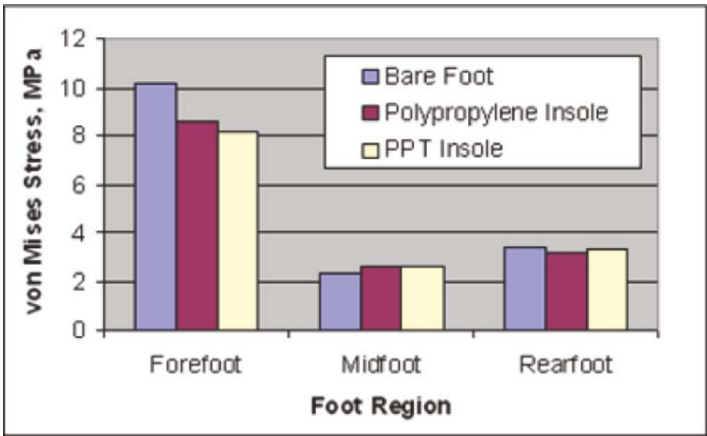


Fig. 6. Prediction of von Mises stress of foot bones during bare foot standing

4 Conclusions

The developed FE ankle-foot model allows parametric evaluations for the outcomes of different design parameters of the orthosis without the prerequisite of fabricated orthosis and replicating patient trials. The FE model can help document systematically and efficiently on how the shape and material properties of an external support will alter the pressure on the plantar side of foot, forces at the joints and the ligaments and stability under different loading and supporting conditions. The biomechanical effects of different design parameters such as a custom-moulded support, heel elevation, rearfoot and forefoot posting, height of the arch support, metatarsal pads and material stiffness at specific region of the orthosis can be evaluated with the developed FE model.

Acknowledgement

The financial support from the Hong Kong Jockey Club endowment, the research grant (A/C No. A-PC91) and research studentship from The Hong Kong Polytechnic University, and the grant from Research Grant Council of Hong Kong (Project No. PolyU 5249/04E) are acknowledged.

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Computational Simulation of Skin and Sock Pressure Distributions

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Abstract

Mechanic interaction between foot and sock is an important factor affecting wearing comfort. In this paper, we introduced a finite element (FE) approach to model the contact between the foot and sock. A biomechanical foot model consisting of bones and soft tissues and an orthotropic and elastic sock model were constructed for simulating the contact process. By using the model, we simulated the process of wearing a sock, which consisted of two kinds of materials. The stress and pressure distributions in the sock as well as that in the foot were predicted. The comparison between the pressure measurements at several geometrically characteristic points and the predicted pressures confirmed that the model was able to simulate the sock wearing condition and predict the pressure exerted by socks. It was also demonstrated that the skin pressure depended on the curvature of the contact surface and the stress in the fabric. The developed FE model allows us to carry out parametric analysis on socks of different styles and materials with a relatively quick and easy way and to provide guidance to the functional design of socks.

Keywords: finite element model, foot, sock design, stress, contact interface

1 Introduction

Sock wearing plays an important role in maintaining the in-shoes foot comfort, reducing the friction between the foot skin and shoes, and good shoes fitting and preventing slippage. Nowadays, various functional socks are available, inducing various physical, physiological and psychological effects. For example, suitable compression support is provided in sports socks to help increasing the movement performance, and in compression stockings and pantyhose for the patients suffering some diseases such as varicose vein (Ramelet 2002). The design for these functional socks is much more complicated. Theoretical understanding of the mechanical interaction between the foot/leg and sock is necessary.

Early research on socks focused on investigating heat and moisture transfer properties (Uchiyama et al. 1982) and hygienic treatment (Sano 1959; Mizunoue 1977). The very few research about mechanics of socks was measuring fabric tension in socks for size testing (Emmanuel 1979; Merrit 1989). The research on mechanical interaction was limited to pressure measurement and prediction. Momota et al. carried out objective measurement and subjective evaluation of clothing pressure caused by Japanese women's and men's socks to study the pressure effect on human comfort feelings (Momota et al. 1993a; Momota, Makabe et al. 1993b). Morooka investigated the relationship between the slippage in shoes and the frictional property and fabric thickness of men's socks via wearing trails. On the other hand, some researchers focused on predicting the pressure from measured stretch of fabric and the geometry of the leg surface (Inoue et al. 1992; Ng and Hui 2001). Model that describes the mechanical interaction between body and socks has not been reported.

In biomechanics research, various 2-D and 3-D foot models by finite element (FE) approach have been employed to model the foot-shoe interface with the aim of investigating plantar pressure and stress in foot during various stance phases of gait. Gefen et al. (Gefen 2000; Gefen 2002), Chen et al. (Chen et al. 2001) and Jacob and Patil (Jacob and Patil 1999) developed 3-D biomechanical foot models consisting of bones, soft tissues, cartilage and ligaments, analyzed the stress distribution in foot during various stance phases of gait mainly for clinical applications. Furthermore, Chen et al. (Chen et al. 2003) and Lemmon et al. (Lemmon 1997) modeled the foot-insole interface to investigate the insole effect on the plantar pressure distribution. Some researchers focused on the in-shoe pressure during walking, running or doing other sports in order to provide guidance for sports shoes design (Geil 2002; Aguinaldo and Mahar 2003). However, since the mechanical contact between foot and flexible sock is

difficult to be modeled, no FE approach has been introduced to simulate the foot-sock contact.

In this paper, we studied the physical mechanisms of foot and sock contact using a FE model based on the theory of contact mechanics. We simulated the contact between a foot model consisting of bones and soft tissue and a sock model. Series of computational analyses were conducted to study the influence of materials on the stress and pressure distributions. Moreover, the predicted pressure was compared to the measured result.

2 Numerical Simulation

2.1 Three-dimensional Biomechanical Foot Model and Sock Model

Since the purpose of the present study is to investigate the pressure and stress in foot resulting from wearing sock, so we assumed that foot deformation was limited to soft tissue. Therefore, simplifications were made such that all the bones and cartilages were combined as a whole skeleton with the rest parts of the foot considered as soft tissue. The geometries of the foot and inner skeleton were reconstructed from coronal magnetic resonance images (MRI) (see Fig. 1) of a 26-year-old normal male subject.

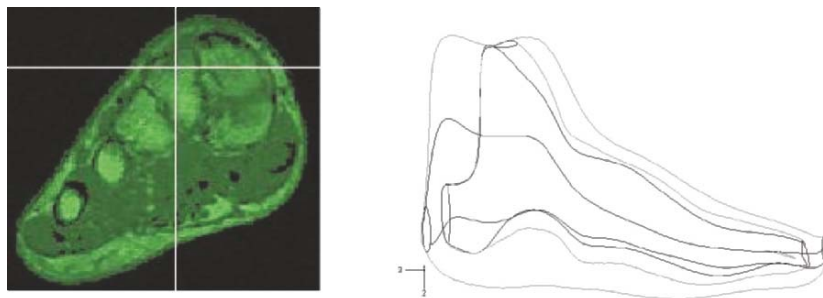


Fig 1. (a) A coronal MR image of the cross-section of the foot and (b) the contour outline of the foot skeleton and soft tissue of the FE foot model

To simplify the problem, the nonlinear material behaviour of the foot and sock while undergoing large deformation was not considered. The foot bones and soft tissue materials were assumed to be homogeneous, isotropic and linearly elastic. For the foot bones, Young's modulus was taken as 7300 MPa, and Poisson's ratio as 0.3 and for the soft tissue, values of 1 MPa and 0.49 were assigned, respectively (Jacob and Patil 1999).

We used the foot surface as the sock geometry, which was modeled by shell elements. Since knitted fabrics often have significantly different mechanical property in wale and course directions, the material for the sock was defined as orthotropic and linearly elastic. We simulated the cases of a sock of crew length worn on foot using two materials, nylon and cotton respectively. The parameters of mechanical properties needed in the simulation were listed in Table 1, where E_1 and E_2 denote the Young's moduli in the course and wale directions, respectively, G_{12} and ν_1 are the shear modulus and Poisson's ratio, and t is the fabric thickness.

Table 1. Assigned mechanical properties of knitted fabrics

Sock	E_1 [N/mm]	E_2 [N/mm]	G_{12} [N/mm]	ν_1	t [mm]
Nylon	0.0446	0.061	0.02	0.195	0.5
Cotton	0.061	0.0728	0.028	0.155	0.85

2.2 Finite Element Analysis

Interaction Constraints

The FE model was established using the ABAQUS/Standard v6.4 FE software package. The interface between the sock and foot was considered as surface-to-surface contact in which the surfaces can undergo relatively finite sliding relative to each other. A kinematical constraint was employed such that the slave surface nodes (inner surface of sock) were enforced not to penetrate the master surface (foot surface). The friction coefficient of the foot-sock interface was set as 0.1 in the simulation.

Boundary Condition

Since our purpose is to investigate the pressure exerted by sock, the pressure due to supporting body weight should not be simulated. Therefore, the foot was assumed to contact with the sock only and we assumed that the foot bones did not deform during sock wearing. To achieve the simulations, the displacements of all the nodes on the foot bones are constrained in all directions as boundary condition in the simulation.

Initial Condition

For the initial condition, an initial stress was prescribed to the sock to simulate the stretched sock condition. It was difficult to measure the stress in sock due to biaxial extension. However, with the FE approach, we can predict the stress according to the stretch and the mechanical properties of the material. We simulated the biaxial extension of a piece of fabric of 10 cm×10 cm rectangle using the stretch of sock in the wale and course directions. The resulted stresses in the two directions were taken as initial stresses for sock. A non-linear general static analysis was performed for the bi-extension simulations. For each sock case, static general nonlinear analysis was performed in ABAQUS/Standard using the Newton-Raphson method.

3 Experimental Results and Discussions**3.1 Initial Stress Prediction**

Both the two sock samples have foot-like shapes. Therefore, we divided the sock model into four parts as shown in Fig. 2, and we assumed that the fabric was evenly stretched in each part. According to the sock sizes and the dimension of the subject's foot, we calculated the fabric stretches in two directions for each part. Figure 2 illustrates the predicted initial stress constructions for the two socks. The stress in the nylon sock was higher than that in the cotton sock.

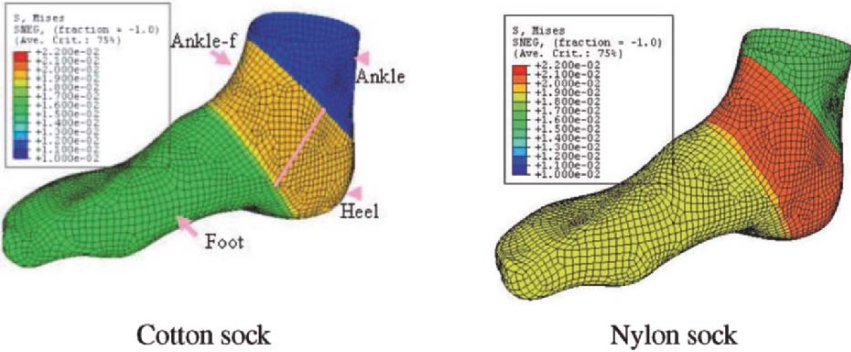
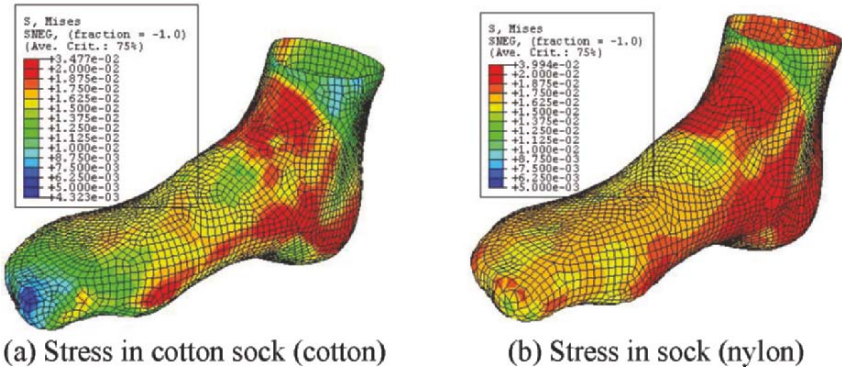


Fig. 2. The predicted initial stress of two cases of socks

3.2 Simulation Results

Figure 3 shows the stress and pressure distributions resulting from the two sock simulations. Before numerical analysis, the sock was in an unbalanced state as shown in Fig.2. After the numerical analysis, the sock stress was balanced by the contact pressure and frictional forces due to the interaction between the sock and foot, reaching a balanced redistribution as shown in Fig. 3 (a) and Fig. (b).



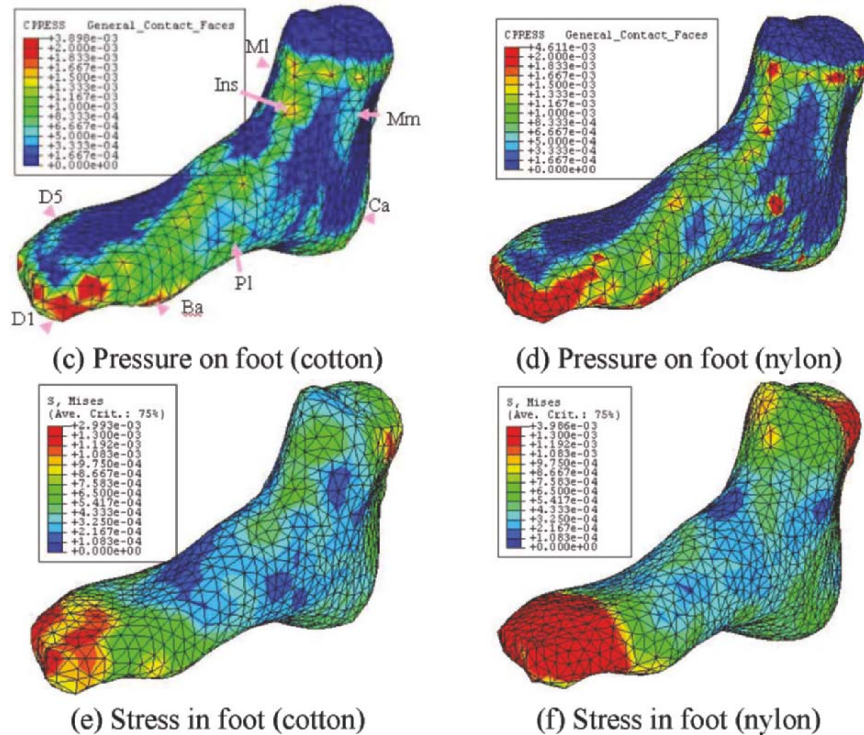


Fig. 3. Predicted stress and pressure distributions with cotton and nylon socks

The stress in the sock, pressure on the foot, and stress in the foot showed significantly different distributions. Higher stress was found at the heel part. The stretched sock induced pressure on the underlying foot. Clearly, the pressure did not distribute uniformly all over the foot. The pressure range for the cotton sock was 0 to 0.0039 MPa and 0 to 0.0046 MPa for the nylon sock. Zero pressure indicated “no contact” between the foot and sock. Due to the complicated geometrical features of the foot surface as well as the tightly stretched state of fabric, the sock was not in contact with the entire foot: only the convex surface of positive Gaussian curvature supported the sock, and the concave surface of negative Gaussian curvature did not contact the sock. Moreover, high pressure occurred where the curvature of the foot surface was high, such as the end of the toes, and the two lateral sides of the foot. As a whole, the two socks resulted in similar pressure distributions. The pressure on the foot deformed the foot. The stress in foot caused by the cotton sock ranges from 0 to 0.00299 MPa while a

range from 0 to 0.00399 MPa was induced by the nylon sock. Higher stress was found at the toe part.

Comparing the two socks, we found that the stress in the nylon sock was higher than that in the cotton sock. As a result, we found that the stress and pressure in foot for the nylon sock were also higher than those for the cotton sock respectively, especially at the toe part. These distributions demonstrated that the pressure depended on the curvature of body surface and the stress in fabric.

3.3 Comparison With Measured Results

According to Momota et al. (Momota et al. 1993a), the pressure was measured at the following positions: Malleolus medialis (Mm), Malleolus lateralis (Ml), Instep (Ins), Ball of foot (Ba), facies mediales of the Digitus 1 (D1), facies lateralis of the Digitus 5 (D5), facies mediales of the Planta (Pl), and facies posterior of the Calx(Ca). These points are the characteristic points of the foot surface geometry; the curvatures at these points were relatively high. From fig. 3(c), we can see that at these points, the pressure is the highest within the vicinity around them. The measured results were shown in Fig. 4, and “M” and “S” means measured and simulated results, respectively.

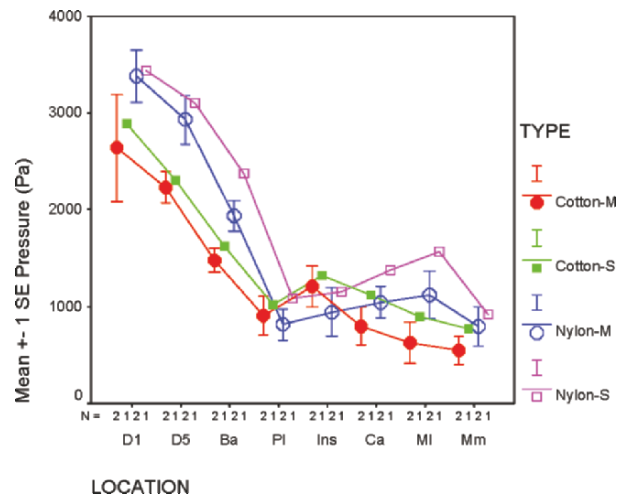


Fig. 4. The simulated and measured pressure of the foot within the sock

Both socks showed the same trend of pressure change: the highest pressure occurred at D1, then D5, both of them are greater than that for the rest parts. This was consistent with the findings reported by Momota et al. (Momota et al. 1993a; Momota et al. 1993b). Comparing the two socks, we can find that the pressure in the nylon sock was significantly higher than that in the cotton sock due to the higher strain, especially at D1. The simulated pressure results agreed with the corresponding measured ones. The difference between the simulated and measured results, especially at the positions, where the pressure was low, was more obvious because the measured positions in simulation and in reality may not be exactly the same; and the measurement error may also account for the discrepancy. The error of stretch measurement for each sock part was also a main factor to cause the difference between the simulation results and the actual state of the sock. The agreement between the real measurement results and simulated ones showed that the developed FE model was useful in predicting pressure on foot caused by sock wearing. With the FE model, not only the pressure values of several feature points, but also the overall pressure distribution in the sock of complicated geometry can be predicted.

4 Conclusions

The FE approach was introduced to simulate the mechanical interaction between foot and sock based on the theory of contact mechanics. The contact model consisting of a biomechanical foot model and a sock model was constructed. Reasonable stress and pressure distributions in sock as well as the distribution of the stress in foot were predicted. It was demonstrated that pressure on the foot depended on the curvature of the contact surface and the stress in fabric. The developed FE model allow us to carry out parametric analysis on socks of different styles and made of various materials with a relatively quick and easy way and to provide guidance to the functional design of socks.

Acknowledgement

We would like to thank Hong Kong Polytechnic University for funding this research through the projects A188 and G-YD31.

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