Part IV

Clothing biomechanical engineering design (CBED) system

14

Integration of mechanical models into numerical simulations

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14.1 Introduction

Mechanical simulation is the heart of the biomechanical engineering design system for textile and clothing products. Mechanical models are key elements in the mechanical simulation. Textile products are of specific hierarchical structure, and each intermediate product may have an influence on the performance of the end product. It is impossible to build a garment model from the fundamental fiber level due to the tremendous demands for the memory and computational cost. Even from the microstructure level of fabric, only a small piece of fabric can be modeled using current computer capacities. However, this does not mean that efforts to model the fundamental structures of the clothing products need be given up. The big problem can be divided into small pieces by separately modeling textile products at different levels. For an end product, the biomechanical design at the highest level of the hierarchical tree can be performed, and then traced backward to the lower level, modeling through the connecting mediate the requirements of geometrical structure and mechanical properties.

Therefore, the system should enable product to be designed from different levels, and fiber, yarn, fabric, and clothing models are fundamental elements in it. Various modeling techniques reviewed in Part II need to be integrated into the system.

14.2 Mechanical simulation system

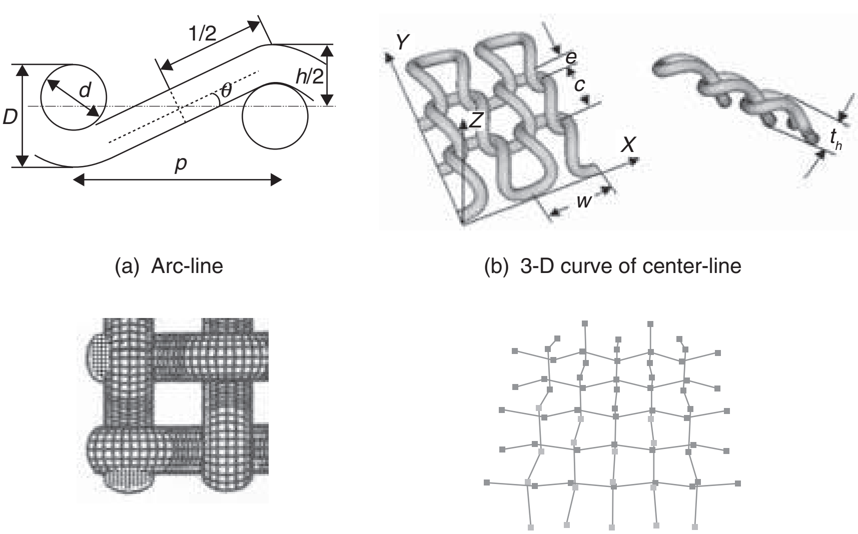
14.2.1 Components of the system

The aim of mechanical simulation is the virtual reproduction of the mechanical behavior of a textile object subject to various geometrical and mechanical conditions. The object needs to be described through a geometrical representation on a computer. At a given time, the current state of the object is defined by its position and velocity. From these geometrical characteristics, the current deformation state is calculated. The mechanical behavior laws describing the material properties are then applied on the state to obtain the current internal energy or forces exerted on the object, which is subjected to external forces and constraints. The evolution of the system obeys the laws of mechanical energy conservation and dynamics. The new state of the object at subsequent times is obtained by mathematical integration.

Geometrical modeling

Fiber, yarn and fabric: Geometrical structures of textile products have a determinant influence on their mechanical performance. It is important to describe them accurately. The geometry of the objects involved in textile products can be very complicated, by including 1-D, 2-D and 3-D elements. The description of an object can also vary greatly. For example, for different purposes, a yarn can be modeled as 1-D line[1], 2-D curve, or 3-D curve[2] or solid[3] as illustrated in Fig. 14.1. Line, arc, sine curve, Bezier curve and patch, B-spline curve and patch, and other mathematic curve or surface can all be used to describe the characteristic curves and surfaces of textile products.

Human body: Usually, there are two kinds of human body models: shell and solid. The shell model only describes the surface of the human body while the solid model may contain more information about the inner layers of the body. In biomechanical engineering design, a solid human body is often preferred. There are many commercial graphical tools to generate the human body's geometric data file. The geometric data of a specific individu-



14.1 Variations of yarn geometry in different models.

al's body can be obtained by using 3-D body scanners, or Computerized Tomography (CT) or Magnetic Resonance Imaging (MRI) scanners. More information about human body modeling is contained in Chapter 16.

Garment prototypes: A 3-D garment primitive can be simply obtained by properly scaling the body surface. It is particularly useful for perfect-fit garments. The 3-D garments are usually described by 3-D mathematic surfaces or polygonal meshes consisting of flat polygons, separated by edges, themselves connected by vertices. A more general approach to obtain a 3-D garment primitive is to arrange 2-D patterns, usually obtained from a 2-D garment CAD system, for the garment properly around a body, and to define the boundaries to be sewn together. If a garment is built from a 2-D pattern assembly, then a description for the 2-D cloth pattern is a necessity. A 2-D pattern can be described as 2-D curves for the boundaries. Seaming information can also be defined on these curves.

Material modeling

The mechanical properties of a material account for how it reacts to given deformations and/or loadings. A material may behave elastically (deformation recoverable), or inelastically (plastic deformation remaining), depending on the range of deformation. During elastic deformation, a material may behave with linear elasticity or nonlinear elasticity. There are various kinds of nonlinear elasticity, such as porous elasticity, hypoelasticity, hyperelasticity, and viscoelasticity. Textile materials are typically time-dependent viscoelastic materials, so the dissipative losses primarily caused by 'viscous' internal damping effects must be modeled in the time domain. Human soft tissues containing lots of vessels need to be modeled as porous elastic material in some cases.

In most cases, for simplification, only the elastic behavior of a material needs to be modeled, so a model of the elastic properties of a material are focused on here. For an anisotropic elastic material, there is the generalized Hooke's law to describe its relationship between strain and stress, as shown in Fig. 14.2, where:

$$\varepsilon_x = a_{11}\sigma_x + a_{12}\sigma_y + a_{13}\sigma_z + a_{14}\tau_{yz} + a_{15}\tau_{zx} + a_{16}\tau_{xy}$$

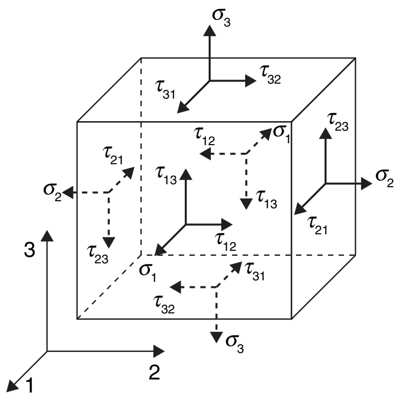
$$\varepsilon_y = a_{21}\sigma_x + a_{22}\sigma_y + a_{23}\sigma_z + a_{24}\tau_{yz} + a_{25}\tau_{zx} + a_{26}\tau_{xy}$$

$$\varepsilon_z = a_{31}\sigma_x + a_{32}\sigma_y + a_{33}\sigma_z + a_{34}\tau_{yz} + a_{35}\tau_{zx} + a_{36}\tau_{xy}$$

$$\gamma_{yz} = a_{41}\sigma_x + a_{42}\sigma_y + a_{43}\sigma_z + a_{44}\tau_{yz} + a_{45}\tau_{zx} + a_{46}\tau_{xy}$$

$$\gamma_{zx} = a_{51}\sigma_x + a_{52}\sigma_y + a_{53}\sigma_z + a_{54}\tau_{yz} + a_{55}\tau_{zx} + a_{56}\tau_{xy}$$

$$\gamma_{xy} = a_{61}\sigma_x + a_{62}\sigma_y + a_{63}\sigma_z + a_{64}\tau_{yz} + a_{65}\tau_{zx} + a_{66}\tau_{xy}.$$



14.2 Stress components.

There are 36 constants $a_{ij}\,(i,j = 1,2,\ldots,6)$. However, since there is $a_{ij} = a_{ji}$, among the 36 constants, there are only 21 independent constants.

For orthotropic materials, the above equations can be simplified as:

$$\varepsilon_x = a_{11}\sigma_x + a_{12}\sigma_y + a_{13}\sigma_z$$

$$\varepsilon_y = a_{21}\sigma_x + a_{22}\sigma_y + a_{23}\sigma_z$$

$$\varepsilon_z = a_{31}\sigma_x + a_{32}\sigma_y + a_{33}\sigma_z$$

$$\gamma_{yz} = a_{44}\tau_{yz}$$

$$\gamma_{zx} = a_{55}\tau_{zx}$$

$$\gamma_{xy} = a_{66}\tau_{xy}.$$

The number of the independent constants reduces to nine. And these equations are usually rewritten using nine engineering constants as:

$$\varepsilon_x = \frac{1}{E_1}\sigma_x - \frac{\mu_{21}}{E_2}\sigma_y - \frac{\mu_{31}}{E_3}\sigma_z$$

$$\varepsilon_y = \frac{\mu_{12}}{E_1}\sigma_x + \frac{1}{E_2}\sigma_y - \frac{\mu_{32}}{E_3}\sigma_z$$

$$\varepsilon_z = -\frac{\mu_{13}}{E_1}\sigma_x - \frac{\mu_{23}}{E_2}\sigma_y + \frac{1}{E_3}\sigma_z$$

$$\gamma_{yz} = \frac{1}{G_{23}}\tau_{yz}$$

$$\gamma_{zx} = \frac{1}{G_{13}}\tau_{zx}$$

$$\gamma_{xy} = \frac{1}{G_{12}}\tau_{xy}$$

where, E_1, E_2, E_3 are the Young's moduli along the three principle directions, μ_{12}, μ_{13}, μ_{23} are Poisson's ratios, and G_{12}, G_{13}, G_{23} are shear rigidities. And there are relations between Young's modulus and Poisson's ratio as follows:

$$E_1\mu_{21} = E_2\mu_{12},\ E_2\mu_{32} = E_3\mu_{23},\ E_3\mu_{13} = E_1\mu_{31}.$$

For isotropic materials, the generalized Hooke's law can be formulated as:

$$\varepsilon_x = [\sigma_x - \mu(\sigma_y + \sigma_z)]/E,\ \gamma_{yz} = \tau_{yz}/G$$
$$\varepsilon_y = [\sigma_y - \mu(\sigma_x + \sigma_z)]/E,\ \gamma_{zx} = \tau_{zx}/G$$
$$\varepsilon_z = [\sigma_z - \mu(\sigma_x + \sigma_y)]/E,\ \gamma_{xy} = \tau_{xy}/G$$

Since there is $G = \dfrac{E}{2(1+\mu)}$, there are only two independent constants.

To account for the material's nonlinearity, a common approach is to use a piecewise linear approximation for the curve, denoting the nonlinear mechanical behavior.

Mechanical modeling

During the deformation of objects subjected to various loads and constraints, they obey fundamental mechanical laws, such as Newton's second and third laws, and conservation laws. Governed by these laws, both force and moment equilibriums are maintained. Therefore, a series of equilibrium equations can be built to govern the evolution of the mechanical model.

For the unit of a deformable object illustrated in Fig. 14.2, the equilibrium equation is derived as: $\sigma_{ij,j} + f_i = 0$, $i,j = 1,2,3$; and for a dynamic system, the motion equation of the unit is: $\sigma_{ij,j} + f_i = \rho u_{i,tt} + \mu u_{i,t}$, where ρ is the mass density, μ is damping coefficient, and $u_{i,t}$, $u_{i,tt}$ denote the first and second derivatives of the displacement u_i.

For a discrete model, Newton's second law is usually formulated as: $f(t) = m\dfrac{d^2X}{dt^2}$, where X is the position of a point mass, and f is the sum of the forces applied to it. This law can be extended to non-point masses by considering the representative action on the mass center and the rotational moment around it. Newton's second law can also be used to describe a deformable object's motion in Lagrange's form:

$$\frac{\partial}{\partial t}\left(\mu\frac{\partial r}{\partial t}\right) + \gamma\frac{\partial r}{\partial t} + \frac{\delta\varepsilon(r)}{\delta r} = f(r,t).$$

Here, $r(X,t)$ is the position of a mass point in the object at time t, μ is the mass matrix of the object, γ is the damping density, $\dfrac{\delta\varepsilon(r)}{\delta r}$ denotes the internal forces resulting from the deformations, and $f(r,t)$ is the externally applied force.

Derived from Newton's second law, conservation laws apply to motion, rotational moment, and mechanical energy. Energy conservation implies that in a given mechanical system, the internal energy evolves according to the work of the external forces applied on the system. For a deformable mechanical model, the internal energy includes potential energy resulting from the work of the internal conservative forces and kinetic energy resulting from the object's motion. Moment conservation is another aspect of mechanical conservation derived from Newton's second law. This law may manifest in the contact problem between objects.

14.2.2 Simulation scheme

To implement mechanical simulation, the behavioral laws of material have to be combined with mechanical laws in a single framework that works on an appropriate geometrical representation of the involved objects to be simulated. The above mentioned three components need to be integrated into a framework; this yields complex systems of equations, usually ordinary or partial differential equations. The equation system needs to be solved under the boundary conditions denoting various constraints. Mathematics provides analytical solutions for only a limited class of simple equations. For complex mechanical simulations, such analytical solutions are often not available, numerical method being the only practical solution.

The numerical solution requires us to discretize the objects in space domain, and maybe time domain for dynamic cases. Space division can be accomplished either through numerical solution techniques or on the mechanical model itself. Depending on the method of discretization, there are two major schemes for performing mechanical simulation: continuum mechanical models and discrete models.

Continuum mechanical models

An object is considered as a continuum and mechanical laws are represented as a set of partial differential equations defined throughout the volume of the material. Numerical resolution for the equations then requires discretization of the equations in the volume space. Finite difference and finite element methods are common methods for the numerical solutions. The finite element method is most powerful and is widely used today.

Finite element methods discretize an object into elements that are basically defined as interpolation functions over a line, area, or volume piece. The interpolation function has a given order (such as linear or quadric), and an associated set of parameters (degrees of freedom) that give the actual shape to the interpolation surface over the element. The higher the order, the more accurately the element would fit the real surface shape, but also the more degrees of freedom it has, and hence the higher its computational cost. The energy related to the deformation of the object for given values of the interpolation parameters is calculated from the mechanical properties of the material. Depending on the kind of mechanical simulation to be performed, these values have to be processed globally on the whole volume. The virtual work statement is often used for building equilibrium equations in the finite element analysis.

Continuity conditions between the interpolation curve or surface of adjacent elements imposes constrain relationships on the degrees of freedom of involved elements. All these relationship are summarized in a huge and sparse equation system defined on all the degrees of freedom and completed by additional constraints, such as various boundary conditions. The huge equation system is built by assembling the contributions of all the elements of the object successively. To simulate the mechanical system, the equation system has to be solved. This is done by using various optimized, iterative techniques, such as the conjugate gradient method for the linear system, or the Newton–Raphson method for the nonlinear system.

The Lagrange equations are also the basis of many continuum mechanical models. The mechanical behavior of the material is expressed as the local deformation energy related to material properties at any point (r) on the object. Various mechanical deformation energies are integrated at this point as its internal energy $\varepsilon(r)$. The equation system is then solved numerically using discretization over the whole object. Usually, a regular grid is defined over the object, expressing the partial derivatives; using the finite differences yields a sparse linear system of equations. The system can then be solved using numerical methods, such as the Guass–Seidel method.

Discrete models

Instead of considering the object volume as a whole, another approach is to discretize the object itself as a set of points with mass (particles), which interact with a set of 'forces', or energy constraints, to model the mechanical behavior of the material. A common way to numerically simulate a discrete model system is to directly integrate Newton's second law for a mass particle over all particles. The forces exerted on each particle include internal elasticity and viscosity forces, gravity, and various external constraints. These forces then determine the current mechanical state of the system, which is represented by the position and the speed of all particles.

14.2.3 Numerical solution

Solution of nonlinear problem

To solve the system of equations resulting from the continuum models, a numerical method is the only solution. Since the problem is often nonlinear due to the large deformation, complicated contact boundary, or material nonlinearity, the solution cannot be obtained by solving a single system of equations, as would be done in a linear problem. Instead, the solution is reached by applying the specified loads gradually, and incrementally working toward the final solution. Usually, an approach combining incremental and iterative procedures is used for solving nonlinear problems. The simulation is broken into a number of load increments and finds the approximate equilibrium configuration at the end of each load increment. It often takes several iterations to determine an acceptable solution to a given load increment. The sum of all of the incremental responses is the approximate solution for the nonlinear analysis. The Newton–Raphson method is often used to obtain solutions for nonlinear problems.

Numerical integration

Dynamic analysis yields a system of ordinary differential equations that needs to be solved numerically along time evolution. To perform such simulation, discretization in time domain is necessary. It results from the numerical computation of a sequence of states during the time period. Interpolation of the successive states provides an approximation of the entire trajectory.

The description for a dynamic system is often a second-order ordinary differential equation system in which the variables are positions of the nodes or particles along the evolving time. To solve a second-order differential equation (for example, a motion equation: $f(X(t), X'(t)) = X''(t)$), a common solution is to convert it to a first-order differential equation by employing a new variable: $v(t) = X'(t)$. Then the equation can be rewritten as:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} X(t) \\ v(t) \end{pmatrix} = \begin{pmatrix} v(t) \\ f(X(t), v(t)) \end{pmatrix}.$$

To solve a first-order differential equation, there are two families of methods: explicit integration and implicit integration.

Explicit approach: The simplest numerical method to solve a differential equation is Euler's method, which can be formulated as: $X(t + \Delta t) = X(t) + \Delta t X'(t)$. Though Euler's method is simple, it may be inaccurate and unstable. The most widely used explicit methods are the Runge–Kutta family methods. The fourth order Runge–Kutta method can be formulated as follows.

$$k_1 = \Delta t f(X(t),t),$$

$$k_2 = \Delta t f(X(t) + k_1/2),t + \Delta t/2),$$

$$k_3 = \Delta t f(X(t) + k_2/2),t + \Delta t/2),$$

$$k_4 = \Delta t f(X(t) + k_3/2),t + \Delta t),$$

$$X(t + \Delta t) = X(t) + k_1/6 + k_2/3 + k_3/3 + k_4/6.$$

Inaccuracy and instability are major problems in explicit methods.

Implicit integration approach: Instead of proceeding the evolution forwards, the implicit integration predicts $X'(t + \Delta t)$ and computes $X(t + \Delta t)$ backwards[4]. The backward Euler's method can be formulated as: $X(t+\Delta t) = X(t) + \Delta t X'(t + \Delta t)$. Applying the method to the motion equation yields:

$$\begin{pmatrix} \Delta X \\ \Delta v \end{pmatrix} = \Delta t \begin{pmatrix} v(t) + \Delta v \\ f(X(t) + \Delta X, v(t) + \Delta v) \end{pmatrix}$$

where $\Delta X = X(t + \Delta t) - X(t)$, and $\Delta v = v(t + \Delta t) - v(t)$. Applying a Taylor series expansion to the function $f(X(t),v(t))$ yields the first order approximation:

$$f(X(t) + \Delta X, v(t) + \Delta v) = f(X(t)) + \frac{\partial f}{\partial X}\Delta X + \frac{\partial F}{\partial v}\Delta v.$$

Substituting the first order approximation into the above motion equation and substituting $\Delta X = \Delta t(v(t) + \Delta v)$ into the equation of Δv yields: $\Delta v = \Delta t(f(t) + \frac{\partial f}{\partial X}\Delta t(v(t) + \Delta v) + \frac{\partial f}{\partial v}\Delta v$. Letting I denote the identity matrix and regrouping the equation, finally:

$$\left(I - \Delta t\frac{\partial f}{\partial v} - \Delta t^2\frac{\partial f}{\partial X}\right)\Delta v = \Delta t\left(f(T) + \Delta t\frac{\partial f}{\partial X}v(t)\right),$$

is obtained from which Δv can be solved and further ΔX.

Implicit methods are often unconditionally stable and allow large time step.

Choosing the suitable integration method: Simulation accuracy, time-step, calculation stability, and computational cost are the main factors to be considered in choosing a numerical integration method. For a given problem, an adequate integration method should be defined considering[5]:

(i) the required accuracy of the simulation that may limit the time-step;
(ii) the required accuracy for a given time-step, which is related to the accuracy order;
(iii) the numerical stability that may limit the time-step;
(iv) the amount of time required for the computation of a single time-step;
(v) other factors limiting the time-step, such as contact between objects.

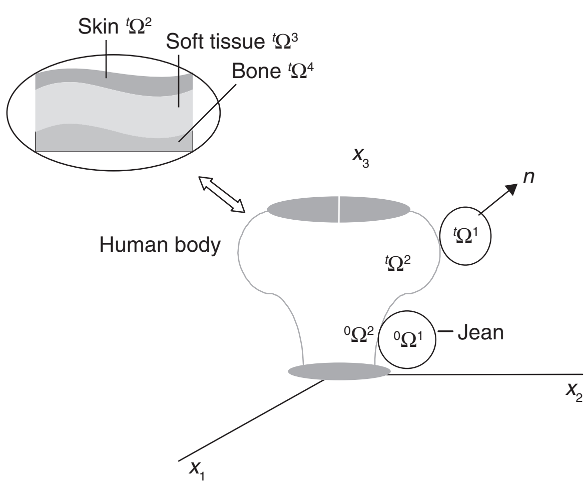
14.3 Numerical simulation systems

14.3.1 Commercial Finite Element Method packages

Commercial Finite Element (FE) software packages are convenient tools to carry out mechanical analysis. Integrating FE software such as 'LS-DYNA' (Livermore Software Technology Corporation), 'ANSYS' (Ansys Inc., USA), 'ABAQUS' (Hibbitt, Karlsson & Sorensen Inc., USA) into a clothing biomechanical engineering system is an effective way to construct the mechanical simulation system. Here, a jeans wearing simulation is taken as an example to briefly introduce how the FE method solves a mechanical problem[6].

Jeans–body contact system

Figure 14.3 shows the time-dependent contact system between a pair of jeans and the human body consisting of three components (skin, soft tissue



14.3 Contact system of the body–jeans.

and bone) in a fixed global coordinate system $\mathbf{x}$ (x_1, x_2, and x_3). The contact system involves four objects (the jeans, the skin, the soft tissue and the bone) and three contact interfaces (between the garment and the skin, between the skin and the soft tissue, between the soft tissue and the bone). At time $t = 0$, the jeans occupy domain ${}^0\Omega^1$ and the human body occupies domains of ${}^0\Omega^2$ for the skin, ${}^0\Omega^3$ for the soft tissue and ${}^0\Omega^4$ for the bone, respectively.

From time $t = 0$, the jeans start to move from foot to waist to fit the body, during which it is occupying new domains ${}^t\Omega^1$ and contacting the domain ${}^t\Omega^2$ of the skin that corresponds to the domain ${}^t\Omega^3$ and ${}^t\Omega^4$ at any time $t > 0$. The human body and the jeans are all simply connected so that there is no interior boundary in any of them, satisfying physical constraint:

$$ {}^t\Omega^1 \cap {}^t\Omega^2 = \varnothing, \quad {}^t\Omega^2 \cap {}^t\Omega^3 = \varnothing, \quad {}^t\Omega^3 \cap {}^t\Omega^4 = \varnothing, \ (t \geqslant 0), $$

where $\varnothing$ denotes a null space, indicating that Ω^1 and Ω^2 do not penetrate each other. The boundaries of ${}^t\Omega^n$ are denoted by ${}^t\Gamma^n$, which consists of three distinct components:

$$ {}^t\Gamma^n = {}^t\Gamma^n_d \cup {}^t\Gamma^n_f \cup {}^t\Gamma^n_c, \quad n = 1,2,3,4, $$

where, Γ_d denotes prescribed displacements boundary, Γ_f denotes prescribed load boundary, and Γ_c denotes the contact boundary where contact may occur, and $\cup$ denotes the union operator.

Governing equations

Motion equations: As long as there is no interior boundary for each contact interface, the motion equations remain uncoupled for the objects. Let $u(x)$ be the displacement field within an object n, and $a(x)$ the acceleration field within an object n. The motion equation of an elastic object n at time t is

$$ \frac{\partial^t \sigma_{ji}(\boldsymbol{x})}{\partial^t x_j} + {}^t q_{g_i}(\boldsymbol{x}) = \rho\, {}^t a_i(\boldsymbol{x}), \ \boldsymbol{x} \in {}^t\Omega^n, \ n = 1, 2, 3; $$
$$ i = 1 \text{ to } 3 \ \text{ and } \ j = 1 \text{ to } 3, $$

where, ${}^t\sigma_{ij}(x)$ are the Cauchy stress components that give the actual traction on an imaginary plane at a point within object n; ${}^t q_{gi}(x)$ is the ith component of the body force vector ${}^t q_g(x)$ of object n; ρ is the mass density of object n which is assumed constant within ${}^t\Omega^n$, and $a_i(x,)$ is the ith component of the acceleration vector of a material particle within object n.

Constitutive equations: The bone is regarded as stiff, the skin and the soft tissue and the garment are assumed to be linear elastic. For materials with linear elasticity, the stress–strain relation may be given by the generalized Hooke's law, i.e.

$$ {}^t s_{ij} = c_{ijkl}\, {}^t\varepsilon_{kl}, \quad \text{on } {}^t\Omega^n, \quad n = 1,2,3; \quad k = 1 \text{ to } 3 \quad \text{and} \quad i = 1 \text{ to } 3, $$

where c_{ijkl} is the matrix of material constants; s_{ij} is a component of the second Piola–Kirchhoff stress tensor that is related to the Cauchy stress component $\sigma_{ij}(x)$; ε_{kl} is a component of the Green–Lagrange strain tensor to describe the deformation of geometric nonlinearity, which consists of linear and nonlinear components ${}^te_{ij}$ and ${}^t\eta_{ij}$:

$$ {}^te_{ij} = ({}^tu_{i,j} + {}^tu_{j,i}) / 2, \quad {}^t\eta_{ij} = {}^tu_{k,i}\,{}^tu_{k,j} / 2 $$

where, ${}^t\mu_{i,j} = \dfrac{\partial^t \mu_i}{\partial X_j}$.

Boundary conditions: Concerning the displacement boundary, the garment fits the body in a constant speed V_0 from the foot to the body waist in the x_3-direction:

$$ V_3\,(x) = V_0, \quad \text{on} \quad {}^t\Gamma_d^1. $$

Concerning the load boundary, the human body is still during the wearing process. Thus the displacement of the bone is zero at x_3-direction in the boundary. These boundary restriction causes boundary force q_b on the bone, which is expressed as:

$$ {}^tq_b = {}^t\sigma N, \quad \text{on} \quad {}^t\Gamma_f^4 $$

where N is a unit normal vector of a fixed boundary point. Gravity exerted on the four objects is expressed as:

$$ q^n{}_g = \rho^n g, \quad \text{on } {}^t\Omega^n, \quad n = 1,2,3,4 $$

where, g is gravity acceleration.

Contact conditions: For the frictionless contact interfaces, denoting the contact force at contact points by q_c^n, then by Newton's third law, we have

$$ {}^tq_{c1}^n = -{}^tq_{c1}^{n+1}, \quad \text{on} \quad {}^t\Gamma_c^n \cup {}^t\Gamma_c^{n+1}; \, n = 1,2,3 $$

where, ${}^tq_{c1}^n$ is the component of contact force ${}^tq_c^n$ in the normal direction of contact points.

The mechanical contact condition as a constraint on the normal contact force ${}^tq_{c1}^n$ is:

$$ {}^tq_{c1}^n \leq 0, \quad \text{on} \quad {}^t\Gamma_c^n \cup {}^t\Gamma_{c1}^{n+1}; \, n = 1,2,3. $$

This means that the interactive pressure is exerted on the object n against its normal direction of the contact boundary points.

Numerical solution

The mechanical analysis of the body–jeans contact system is carried out using the FE package 'LS-DYNA'. The numerical solution procedure consists of finite element discretization, formulation of the governing equations with the principle of virtual work, contact searching and contact constraint, and numerical solution with an explicit method. The geometrical model discretization, definition of material properties, setting of various conditions of boundary, load and interaction and solution method selection are all performed in a pre-processor for 'LS-DYNA'.

14.3.2 Specific solution systems

The generalized tools for mechanical analysis may sometimes be insufficient to solve the complicated problems involved in textile products so many specific systems and models have been developed for textile products, as reviewed in Part II. These systems and models can be integrated to the design system. Here, a skirt construction is taken as an example to illustrate the frame of a specific clothing simulation system.

A common way to construct a 3-D garment fitted on a human body is to assemble the 2-D cloth patterns according to a given topology. In a skirt construction, two patterns are sewn together along the seam line, and then gravity is added to reach the draping shape. For simplification, only the part of the human body (waist, abdomen and hip) potentially contacting skirt is modeled, it is represented as a triangular mesh. The body is regarded as rigid, the cloth is not allowed to inter-penetrate it. The cloth is represented as a particle collection. During the sewing and draping processes, the motion of the cloth patterns abides by the mechanical laws of cloth material. Various deformations (tension/compression, shearing, bending and twisting) result in internal forces. Besides these inner forces, there are also several external forces acting on the cloth. A seaming force, F_M, acts on the seam lines during the sewing process. As the cloth approaches the body, mechanical interaction occurs at the contact surface between the body and the garment. Conditionally, there are interactive contact forces (F_C) at the normal direction of the contact surface, and friction (F_F) as the garment slips on the surface. These external forces, as well as the cloth gravity G, are balanced by the cloth internal forces, the inertia force and viscous force F_I of the cloth during the dynamic formation of garments, as shown in the following equation:

$$F_T + F_B + F_S + F_W + F_I = G + F_M + F_C + F_F.$$

The cloth mechanical behavior is modeled using a particle model[7], in which various springs are imagined to be acting on joining particles for calculating the internal forces due to deformation. For each particle, the inner forces of stretching ($F_{T_{i,j}}$), bending ($F_{B_{i,j}}$), shearing ($F_{S_{i,j}}$) and twisting ($F_{W_{i,j}}$) are calculated according to its position and the positions of several neighbor particles surrounding it, and the mechanical properties of the fabric. Let $\dot{X}(t)$ and $\ddot{X}(t)$ denote the velocity and acceleration of the particle, and let m and c represent the mass of the particle and the viscosity resistance; the particle motion equation can be rewritten as:

$$F_T + F_B + F_S + F_W + m\ddot{X}(t) + c\dot{X}(t) = F_M + F_C + G.$$

The ordinary differential equation is then solved along time evolution using the Runge–Kutta method.

14.4 Conclusion

Mechanical models are key elements in mechanical simulation. Textile products are of specific hierarchical structure, and each intermediate product may have an influence on the performance of the end product. Therefore, hierarchical modeling of textile products is necessary. Geometrical modeling, material modeling and mechanical modeling are essential components in the mechanical simulation system. Furthermore, the three components need to be integrated into a framework, yielding complex systems of equations. The equation system, often nonlinear, needs to be solved using various explicit and implicit numerical methods. Integrating commercial FE packages and also various specific solution systems for clothing products is an effective way to construct a mechanical simulation system.

14.5 Acknowledgement

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15
Database for biomechanical engineering design

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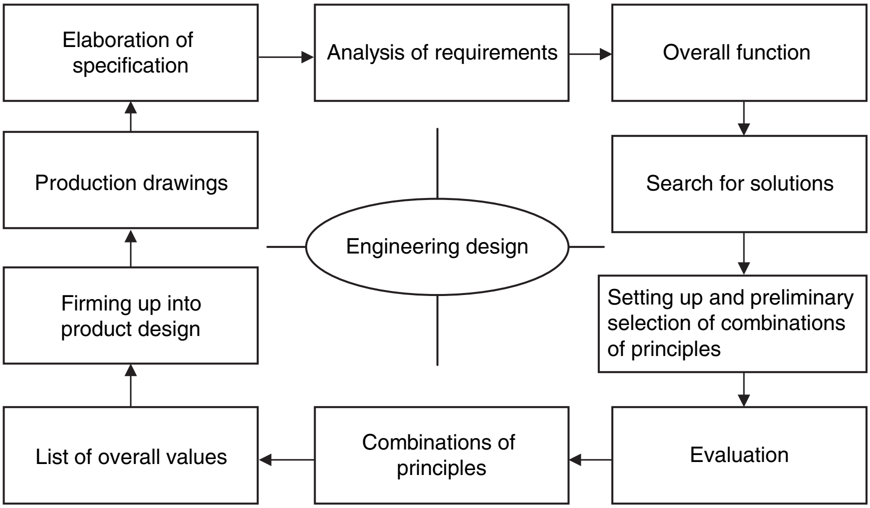
15.1 Introduction

'Database' is one of the most important terms in modern technology. It has been widely used in various fields. A database is a logical collection of related information. The collection of related information is used to support a special purpose, business or engineering design. The fundamental difference between an engineering design database and a business database is the stability of the administrative environment as compared to the dynamic engineering environment. The development of an engineering design database management system (EDDBMS) must carefully consider the character of the engineering design process.

15.2 Characteristics of database for engineering design

Engineering design is a many-sided and wide-ranging activity.[1] It is based not only on mathematics, physics and their branches (mechanics, thermodynamics etc.) but also on production technology, materials science, machine elements, industrial management and cost accounting. Such activity includes not only semantic information, as in the case of business databases, but also information details of the engineering design, whereas a business database is a mere collection of related information used for consultation. Figure 15.1 shows the main concept of the engineering design process.

When the basic ideas of the engineering design approach are discussed, it is found that engineering design demands a constant flow of information. It needs to receive rich information to create elaboration of the design specification. The information can be received in different ways, from market analyses, trend studies, patents, technical journals, questionnaires



15.1 Main concept of engineering design.

from customers, concrete assignments, design catalogues, analyses of natural and artificial systems, calculations, experiments, analogies, general and in-house standards and regulations, stock sheets, delivery instructions, computer data, test reports, accident reports, and through asking questions.[1] Information can be processed by analysis and synthesis, calculation, experiment, the elaboration of layout drawings and the evaluation of solutions. It can be transmitted by means of drawings, reports, production documents etc.

It will be noticed, however, that the engineering process contains many loops in which activities with a routine character, such as analysis, are followed by activities with a creative character, such as selection. The DBMS should support this process.[2]

Data on engineering design is very dynamic in the sense that they are not known *a priori* but are defined during the design process. So the DBMS should not only deal with a constant area for the storage of standardized parts, design procedures and material properties, but also with structures, machines and installations composed from these elements. Furthermore, the DBMS should be used for storage and retrieval of measured and calculated data in such a way that the origin of these data can be traced. The DBMS should support typical engineering activities such as the analysis and modification of complex structures. Various ways of presenting the database contents must be possible, including graphical, representation of objects and measurement data.[2]

Of all the discussions of engineering design and engineering database, the main concept for developing an engineering database has to support the clothing biomechanical engineering design.

15.3 Functional requirement of database for clothing engineering design

Clothing engineering design means creating new clothing by enhancing existing designs or by altering existing ones to perform new functions; it is a complex, iterative-decision making competitive process in which the basic sciences, mathematics, and engineering sciences, are applied to convert resources optimally to meet a stated objective.[3]

Clothing biomechanical engineering design will be largely based on computer aided design, computer graphics, computer display technology, mathematical models, material sciences and experimental methodology developed for clothing biomechanical design.

Clothing biomechanical engineering design involves rich mathematical models. Different models have different requirement for clothing engineering design, the key technology for using these models is to prepare different data formats, different descriptive ways for data. How to manage these mathematical models and data files is very important during clothing biomechanical engineering design.

The clothing engineering design process generates and uses large volumes of dynamic data, rich data structure and different categories of variables, such as specifications, engineering design orders, technical data, problem reports, design models and analysis files. Each data category contains details of specific information, so that clothing engineering design is a product-oriented functional design process, the work being largely based on the experience and intuition of the designer. In order to support this complex design, it is important to develop an engineering database to support the clothing biomechanical engineering, especially for 3D numerical simulation of the mechanical interaction of the body with the clothing and sensory evaluation on clothing mechanical comfort. The aims of developing a database for clothing engineering design are:

- to create communication between researchers, technologists, designers, customers, manufacturers and other related sectors,
- to provide scientific experience data of clothing performance,
- to design diversity of cloth products, and
- to increase design automation in textile and clothing.

At the same time, it can provide management for (i) product development; (ii) design process control; (iii) quality assurance and (iv) performance evaluation.

15.4 The constitution of clothing engineering design

Clothing engineering design involves different subjects: materials (fabrics, yarns, fibers), human body, garment, engineering simulation, comfort evaluation and so on. Materials are important components in clothing engineering design. The properties of the material will affect the clothing biomechanical characteristics from the dynamic analysis, such as its deformation magnitude, stretch-recovery properties and rheological behavior during wear. These physical and mechanical characteristics of clothing materials are the basic information for the biomechanical engineering design of clothing.

The garment is made from 2D patterns of cloth surfaces. These patterns are constructed through software and discretized into a triangular mesh. The planar patterns are then placed around a 3D virtual body using manipulators. Once the patterns have been placed around the body, a mechanical simulation is invoked to make the patterns approach along the seaming lines. As a result, they become attached and seamed on the borders as specified, attaining the shape influenced by the shape of the body. Thus the garment is constructed around the body.

Human factors are concerned as a component of design. The human body is in direct contact with its clothing. Humans can reflect feelings of comfort through wearing the clothing in special environments in different ways: physical, physiological, biomechanical, neurophysiological and psychological. However, human comfort is a complex process, physics, physiology, biomechanics, and neurophysiology are dealt with in pattern and material design, and psychological factors are attended to in designing the aesthetic effects of clothing and comfort evaluation. This is done by using the physical, physiological, biomechanical, and neurophysiological data during the simulation process, and the psychological data in the evaluation process.

Engineering simulation solving is the core of clothing engineering design. It provides or links special software to create a virtual engineering environment. It gives the relationship between clothing mechanical performance and fabric mechanical properties in simple deformation (tension, shearing, bending and compression). When the design phase has determined feasible style and materials parameters, the simulation procedure is called-on to calculate the mechanical performances of the dynamic simulation system, such as the distributions of stresses and strains in the garment.

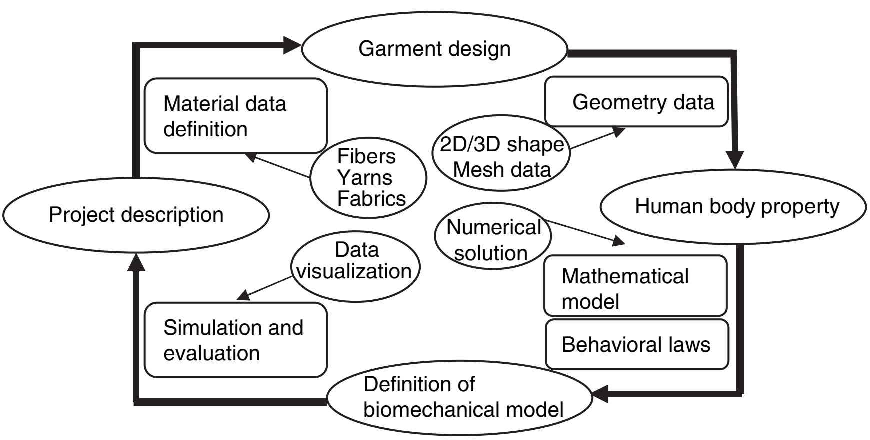
During wearing, clothing comes into contact with the skin of most parts of the body. The mechanical simulation induces responses from various sensory receptors and formulates various perceptions: touch, pressure, prickle, itch and inflammation, which affect the mechanical comfort of the wearer. Therefore, the evaluation model will analyze and evaluate the comfort of clothing. Sometimes the project is used to control and manage the engineering design; it will provide a system design scheme for a design task.

Clothing products depend on the right combination of aesthetic and engineering qualities for their success in the market place. Modern consumers demand clothing products with superior multi-functional and comfort performance to satisfy their physiological and psychological needs. Garment mechanical comfort such as pressure comfort has been identified as one of the important attributes. Therefore, clothing biomechanical engineering design is becoming more and more important.

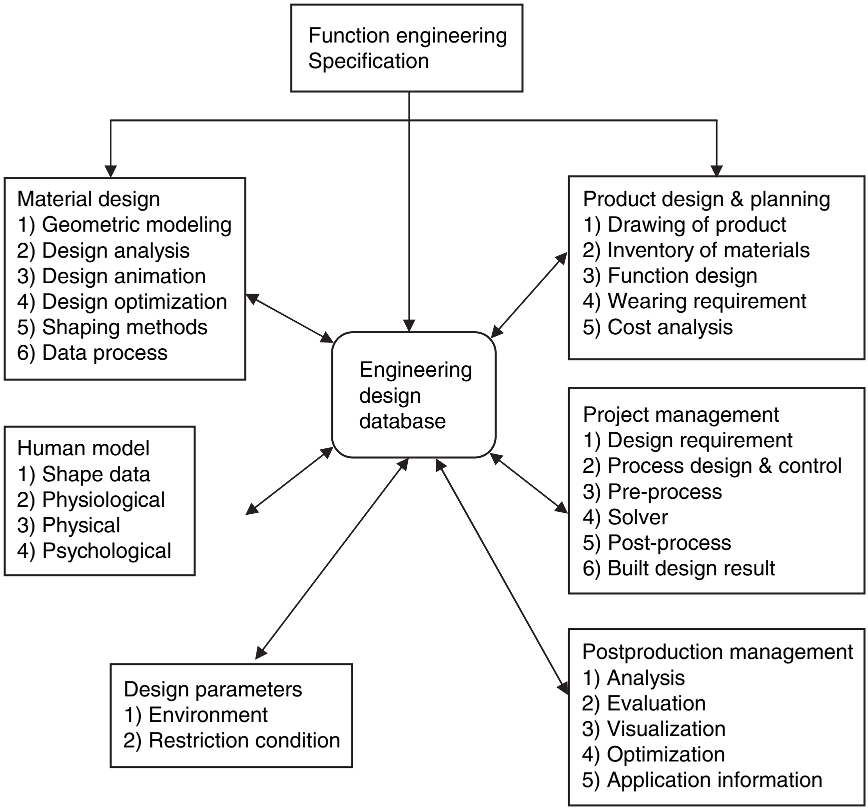
Figure 15.2 shows the design procedures for clothing biomechanics in detail. The design starts with a project, it defines the specification of clothing biomechanical design (e.g. jeans or bra), and this is followed by selecting the fabric structure and the mechanical properties of the fiber–yarn–fabric. The selection is a revision design, by searching or reworking some previous fabric structure that reasonably approximates to the current design requirements. The next step is to define the garment style, to construct the geometry or mesh data. From the input parameters of the human body and the garment, the deformation characteristics of the clothing should be identified, based on the mechanism analysis of the dynamic contact between the human body and the garment. Next comes a decision mechanical model of the body–garment, then a numerical simulation and analysis of the mechanical performance of the garment and the body. Iterative design has to be done before the garment is produced if the design is not satisfied through the simulation and evaluation steps.

The summary of clothing biomechanical engineering design using a database is shown in Fig. 15.3.

The clothing engineering database (DB) can be separated into four main components:



15.2 Clothing biomechanical design.



15.3 Main concepts of clothing biomechanical engineering design and EDDBMS.

(i) Garment DB: storing the structure parameters, geometric parameters and images of products (fiber–yarn–fabric–clothing, two-dimensional and three-dimensional data file).
(ii) Human model DB: storing the information of the model used in the biomechanical engineering design (human model factors (physical, biomechanical), manikin model (structure data) or some others).
(iii) Material DB: storing the structure, mechanical and physical parameters (fiber, yarn, fabric) used in the design and analysis processing.
(iv) Project DB: storing the engineering design specification, methodology, design report and analysis file for different design processes.

Textile and clothing engineering function design is concerned with product performance, from characters of mechanical, thermal, sensory, material and so on. According to the requirements and application of the engineering design, the data can be presented in various categories, as follows:

General data

This is the summary description of the object. Sometimes general data includes the following items:

- Design file and product identification.
- Customer information: name, address and so on.
- Specification of the product's special considerations, and instructions.
- Commerce information.

Property data

This kind of data is about the properties of objects; it includes the following items:

- Objects structure description, including macroscopic and microcosmic: length, thickness, warp count and so on.
- Object mechanical description: warp bend rigidity, shearing modulus.
- Object physical description: thermal conductivity, integral heat of sorption.

Geometric data

This data is about the geometric characteristics of the object; it includes the following items:

- Object's two-dimension geometric description.
- Object's three-dimension geometric description.
- Object's mesh data description.
- Object's other format for analyzing process.

Design data

This kind of data is about design requirements; it includes design environment and specified constraints. The items are as follows:

- Design condition requirement: air density, atmospheric pressure and so on.
- Constraints: specific skin blood-flow rate, thermal conductivity of body tissue.
- Design method description.
- Design processing description.

Project data

This is about design data on previous projects. In cases where a current product has evolved from existing products, duplication of data files should be avoided; the designer can simply build current design data files on the basis of relevant existing ones. The items are as follows:

- Project basic data, designer's name, date.
- Project processing status.
- Project result.
- All documents for this project.

Tables 15.1 to 15.3 describe the fabrics, the fibers, and the human body.

In the database, the fiber–yarn–fabric structure, and mechanical and physical parameters are collated from a series of mechanical experiments using Kawabata and Instron test instruments, including fabric simple deformations by Kawabata instruments, and relaxation deformation of fiber–yarn–fabric and 3D deformation of fabric bagging using the Instron. The major mechanical parameters taken from the experiments are stored in the material database, as shown in Table 15.4. To set up a numerical database of textile properties without any assumption for the material properties, the tension-recovery curves of fiber–yarn–fabric have to be recorded in the material database by direct inputs from the experiments. The experimental curves will be recorded as the images in the database, which can be found during the design process by searching for its identifier number.

Table 15.1 Fabrics

General data	Structural data	Mechanical data	Physical data
Fabric ID	Finishing condition	Poisson's ratio	Surface volume ratio
Fabric name	Length	Warp tensile modulus EA	Absorptivity of outer surface of clothing
Fabric type	Width	Weft tensile modulus EB	Thermal conductivity of fabric
Fabric picture	Thickness	Warp bend rigidity	Thermal capacity
Company	Area density	Weft bend rigidity	Water vapor diffusion
Price data	Volume density	Compression modulus	Liquid water diffusion
	Cover factor	Twisting rigidity	Diffusion coefficient
	Warp count	Shearing modulus	
	Weft count	Hysteresis of shear	
	Warp crimp	Hysteresis of bending	
	...	...	...

Table 15.2 Fibers

General data	Structural data	Mechanical data	Physical data
Fiber ID	Diameter	Tensile modulus	Differential heat of liquid sorption
Fiber name	Volume density	Flexural rigidity	Differential heat of moisture vapor sorption
Fiber type	Length	Shearing modulus	Integral heat of sorption
Fiber picture	Count	Friction factor	Differential radiation absorption constant of the fiber
Company	Effective contact angle between fiber surface and water	Compression modulus	Fiber sorption isotherm
Price data		Bending	Specific heat of fiber
		Torsional rigidity	Volumetric specific heat of fiber
			Diffusion coefficient
			Thermal conductivity of fiber

Table 15.3 Human body

General data	Structural data	Physiological data	Material data
Model ID	Stature	Bone density	Specific heat at constant pressure of blood
Model file	Shoulder	Bone compress mudulus	Specific heat at constant pressure of skin
Model picture	Breast	Torsional rigidity	Diffusion coefficient/Mass diffusivity for moisture vapor diffuse through skin
Model type	Waist	Bone Poisson ratio	Thermal conductance of body tissue
Size	Hip	Soft tissue density	Thermal conductance of the skin
	Arm	Soft tissue shear modulus	Absorptivity of skin surface to the solar radiation
	Leg	Soft tissue Poisson ratio	Emissivity of skin surface
	Neck	Skin density	Dubois body area
	Weight	Skin tensile modulus	Total body mass
		Skin Poisson ratio	

Table 15.4 Items of each database

Human model database items	Garment database items	Material database items	Project database items
Human body ID	Garment ID	Fabric ID	Project ID
Human image ID	Garment name	Fabric bending modulus	Design info.
Stature	Garment image	Fabric shear modulus	...
Shoulder	Garment commercial info.	Fabric Poisson ratio	...
Breast	...	Fabric frictional coefficient	Garment ID
Waist	...	Fabric roughness	Design state
Hip	Garment size	Fabric bagging resist	Pre-process file
Arm	Garment style	Fabric bagging fatigue	Method ID
Leg	Fabric ID	Yarn ID	...
Neck	Fabric ID	Yarn viscoelastic modulus	Post-process file
Weight	...	Yarn relaxation time	Result files
Skin thickness	...	Yarn bending modulus	...
Skin tensile modulus	2D pattern data file ID	Yarn compressor modulus	Evaluation file
Skin density	3D garment data file ID	Yarn torsion modulus	Visualization file
Bone elastic modulus	...	Yarn Poisson ratio	
Bone density	...	Fiber ID	
Soft tissue thickness		Fiber viscoelastic modulus	...
Soft tissue elastic modulus		Fiber relaxation time	
Soft tissue density		Images of experimental curves	
...	...	...	...

15.5 Database design and realization

As mentioned previously, an engineering database has several important differences from an administrative database or a business database. Firstly, engineering design is an iterative-decision process, with analysis and synthesis based on the knowledge and information of basic sciences, mathematics, and engineering sciences. Secondly, engineering design needs a dynamic database that involves two kinds of information: the design environment (rules, methods, standard elements, etc.) and data that are not previously known but are defined during the design process; these are increasing with the design process. Thirdly, engineering design deals with a number of value types (text, numbers, equations, diagrams, graphical, photographic images, etc.).

Therefore, the main thrust in the construction of an engineering design database is to include efficient descriptions of the engineering design of all products and to provide production with the detailed information necessary for manufacturing the final engineering design product. Such descriptions include not only semantic information, as in the case of business databases, but also information details of the engineering design.

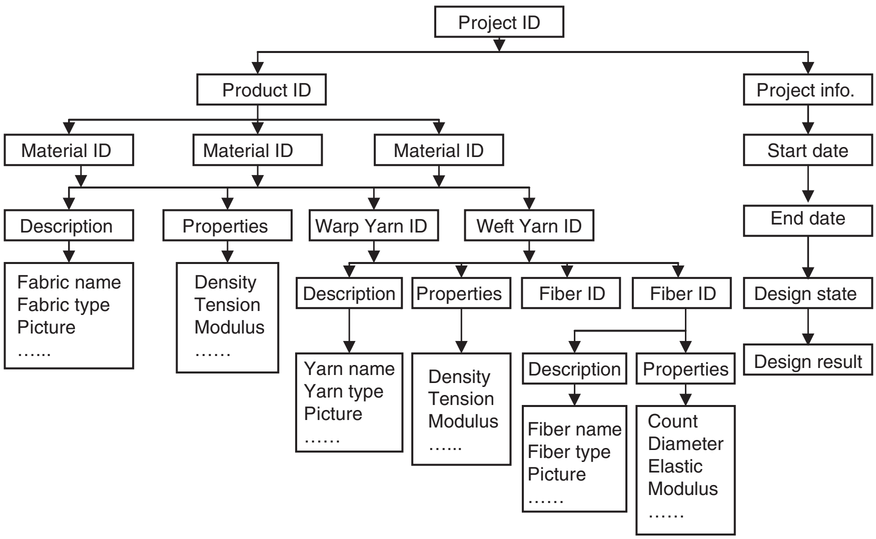
15.5.1 Data model

Configuration management and control of the design processes within the engineering environment are complex problems. Effective configuration management involves controlling not only the product data but the processes that create and affect the product design as well.

There are three major data models that are used in the database system: the relational data model, the hierarchical data model and the network data model.[4] The relational data model, in which all entities and dependencies between entities of the reality can be stored, are described, structurally identified by their domains (names and kind of values). The hierarchical data model represents entities and hierarchical relationships among different entities. In this model, each entity is represented as a record and hierarchical relationships by a tree structure. The network data model allows the representation of an arbitrary relationship between entities. Each entity is represented as a record, and it may be owned by more than one record, leading to a network structure.

Based on analysis of the characteristics of the design process for clothing mechanical performance, the hierarchical data model is used in the database system. The hierarchical relationships among fibers, yarns, fabrics and clothing are shown in Fig. 15.4.

In the data model, a material object in different hierarchies (fiber–yarn–fabric–clothing) can be represented by abstractions: the ‘entity’. An entity



15.4 Hierarchical data model of the clothing engineering database.

has an identifiable number (ID). An entity is a collection of values, each value describing a property of the entity. An ID that involves its father's ID or the tree's node it belongs to indicates the hierarchical relationship. An ID is specified as a unique name of an entity in the engineering database, by which all of its information in the database can be found. As examples of the database, Table 15.5 illustrates the records of nine denim jeans in the product database, and Table 15.6 their mechanical parameters recorded in the material database. For example, the garment ID of 001 is Levis' 3D jeans and its fabric can be identified by the number 001-1. The mechanical parameters of the fabric can be searched in the material database according to the identified number 001-01, and the tension-recovery curves of the fabric in the warp and weft directions, respectively, according to the identified number of Wp001-01 and We001-01, as shown in Table 15.6.[3]

15.5.2 Database description

Each database contains details of specific information. According to the requirement and application of engineering design, the material in the database can be presented in four categories: general information about the material description, and structural, mechanical and physical properties of fibers, yarns and fabrics. These data are recorded and organized in the engineering database according the logical needs of the engineering design

Table 15.5 Records of nine denim jeans in the product database

Price	Garment commercial name	Garment ID	Fabric ID	Fabric image ID	Fabric structure	Fabric weight (g/m^2)	Fabric thickness (mm)	Fabric density		Fiber composite	Yarn count (Ntex)		Fabric cover factor k		Yarn crimp (%)	
								(ends/cm)	(picks/cm)	%	warp	weft	warp	weft	warp	weft
$735	Levi's 3D	001	001-01	E001-01	3 × 1 twill	431	0.88	26	19	25% Ly 75% Cot	6.8	6.0	238.9	191.1	11.7	7.3
$535	Levi's	002	002-01	E002-01	3 × 1 twill	475	1.04	27	20	100% Cotton	6.2	6.2	265.6	192.3	18.0	6.9
$338	Andyrex	003	003-01	E003-01	3 × 1 twill	453	1.12	30	19	100% Cotton	7.0	7.4	274.2	172.1	21.5	8.0
$329.5	Apple	004	004-01	E004-01	3 × 1 twill	451	1.03	27	19	100% Cotton	6.9	6.2	248.2	187.7	18.7	7.1
$148	Mixed	005	005-01	E005-01	3 × 1 twill	438	1.06	28	21	100% Cotton	7.9	7.2	239	189.3	21.4	9.4
$250	Wagner's	006	006-01	E006-01	3 × 1 twill	428	1.04	25	20	100% Cotton	6.7	7.3	237.1	184.4	19.1	10.9
$550	CK	007	007-01	E007-01	3 × 1 twill	458	1.07	27	20	100% Cotton	7.0	6.2	245.9	191.5	20.2	7.7
$679	Edwin	008	008-01	E008-01	3 × 1 twill	459	1.09	28	20	100% Cotton	6.6	7.9	267.8	177.1	23.3	7.8
$190	Giordano	009	009-01	E009-01	3 × 1 twill	400	1.08	27	19	100% Cotton	9.6	5.5	213.1	199.2	21.3	8.9

Table 15.6 Records of nine denim jeans in the material database

Garment commercial name	Garment ID	Fabric ID	Thickness (mm)	Density (kg/m^3)	EA (kgf/m^2)	EB (kgf/m^2)	Poisson's BA	GAB (kgf/m^2)	Curve-Wp	Curve-We
Levi's 3D	001	001-01	0.88	492	50000.0	48000.0	0.38	13179.0	Wp001-01	We001-01
Levi's	002	002-01	1.04	455	40000.0	70000.0	0.48	16645.7	Wp001-02	We001-02
Andyrex	003	003-01	1.12	405	42000.0	80000.0	0.38	20026.4	Wp001-03	We001-03
Apple	004	004-01	1.03	439	36000.0	80000.0	0.45	20771.3	Wp001-04	We001-04
Mixed	005	005-01	1.06	413	40000.0	76000.0	0.38	21974.6	Wp001-05	We001-05
Wagner's	006	006-01	1.04	412	46000.0	52000.0	0.44	25899.6	Wp001-06	We001-06
CK	007	007-01	1.07	427	40000.0	96000.0	0.42	20714.0	Wp001-07	We001-07
Edwin	008	008-01	1.09	421	45000.0	112500.0	0.40	25298.0	Wp001-08	We001-08
Giordano	009	009-01	1.08	370	24000.0	60000.0	0.40	11431.4	Wp001-09	We001-09

process. In the same way, the human model database can present general data, structure data, physiological data and human material data.

The describing and handling of the information elements must both reflect and support the design requirement efficiently, to represent incremental design changes as key elements in an engineering design system's overall ability. This is particularly important when engineering design software is developed for supporting the design process. During the clothing engineering functional design, it will process a large amount of data and this data may involve a number of value types (text, numbers, equations, diagrams, graphical, photographic images etc.). So it is necessary to define the special data type to describe the data used in clothing engineering design. The new definition is shown in Figure 15.5. From this figure, each data is described by five items: data name, data symbol, data type, data value, and data unit.

Data name

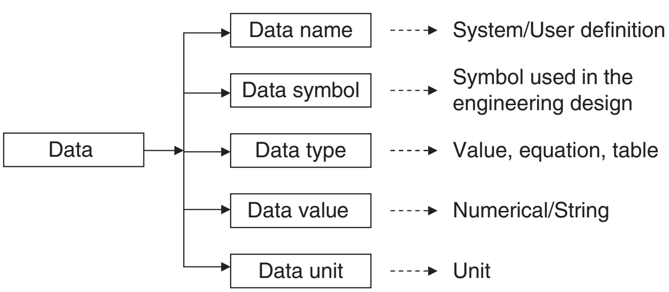
Data name is used to identify special data of a material (fiber, yarn, fabric) and human model. For example, the fabric's tension module, the yarn's compressor module, etc. This item value is a string.

Data symbol

Data symbol is a mathematic symbol of data stored in the database, and will be used in the computing process. For an engineering design process, this data can be imported by an expression with a formalized model. This item's value is a string. Table 15.7 shows a data name and its symbol.

Data type

Data type is used to identify the data stored in the database in three types: Value, Equation, Table/Figure. This representation of data is more useful in



15.5 Data type.

Table 15.7 Data and symbol

Symbol	Data name
S'_v	surface : volume ratio
ε_a	volume fraction of water vapor
ε	porosity of the fabric
ε_f	volume fraction of fiber
δ	$\delta = (\varepsilon_l/\varepsilon)^m$
ε_l	volume fraction of liquid phase
R_f	radius of fiber
C^*	saturated water vapor concentration

design because some data are generated according to engineering experience, and some data are dynamically generated during the engineering design process.

- 'Value' means that this data's value is numerical or a string in the database and this data can be used directly in engineering design.
- 'Equation' means that an equation is stored in the database. When the design process uses these data, the special sub-procedure can compute them using the equation and assign the value to the data variable.
- 'Table/Figure' means there is a table/figure stored in the database. During the engineering design, there are mathematic methods to support the use of these values.

Data value

Data value is the data's real expression. It may be a real value (numerical or string), an equation or a table/figure (file name of table/figure) decided by the item of data type.

Data unit

Data unit identifies this data's unit attribute. Different unit sets are presented in different internal files, and the user can select them directly.

Table 15.8 shows an example that data 'Surface:volume ratio' stored in database. Here, the surface:volume ratio is the woven fabric's physical data; this data is very typical. When it is a real value, it is about 1000/m; however, it can be described in an equation, and the importance of this is that, when the design is begun, it has an initial value, but when the design process is ongoing, its value changes according to the equation. The equation format of surface:volume ratio is:

$$S'_v = 2(\varepsilon_a/\varepsilon)(\varepsilon_f\delta/R_f)\cdot C^*(T)$$

There is another example: data of fabric mechanical (weft tensile modulus EA) stored in database. Sometimes it can be measured to get the result in value, figure, and table style.

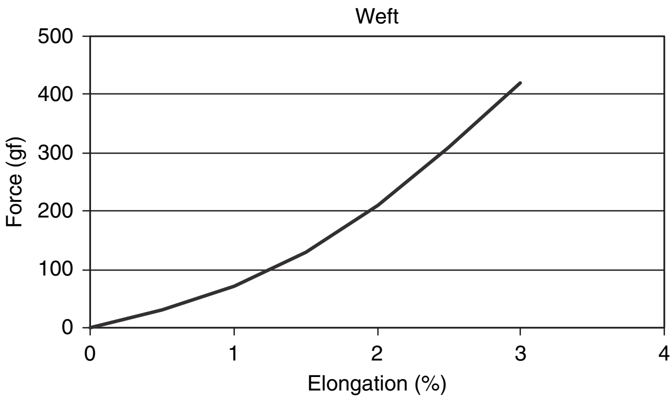
Figure 15.6 shows the woven fabric's mechanical data: 'Weft tensile modulus EA' figure description.

Table 15.9 shows the woven fabric's welt tensile modulus EA's table description.

Table 15.10 shows data 'Weft tensile modulus EA' stored in EDDBMS.

Table 15.8 Surface : volume ratio data

Name	Symbol	Type	Value	Unit
Surface : volume ratio	S_v'	Value	1000	1/m
Surface : volume ratio	S_v'	Equation	$S_v' = 2(\varepsilon_a/\varepsilon)(\varepsilon_f\delta/R_f) \cdot C^*$ (*T*)	1/m



15.6 Weft tensile modulus EA's data.

Table 15.9 Weft tensile modulus EA's data

ε	0.	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F	0.	5.	10.	18.	23.	32.	41.	49.
ε	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
F	60.	71.	80.	90.	102.	114.	130.	144.
ε	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3
F	160.	175.	188.	208.	226.	242.	258.	277.
ε	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1
F	297.	319.	340.	363.	388.	413.	432.	459.

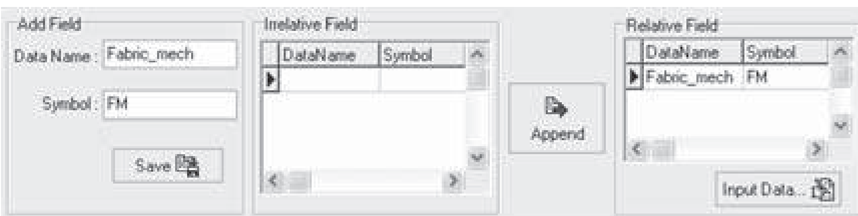
F = force
ε = elongation

Engineering design is a dynamic process that involves engineering data from a previous engineering experiment, or from the design process, so an engineering database should provide a redefinition function. The designer/user can define their new data in the database and use them as usual in their future design. For this purpose, there is an extra structure attached to each database. When the designer/user wants to define their own data, they can define it through the interface. Figure 15.7 shows the redefinition interface.

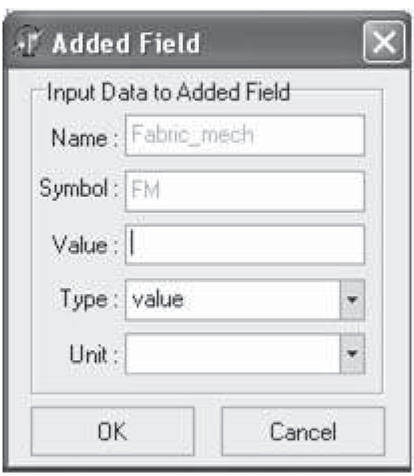
Once new data has been added into the database, the designer can input their value through the input window (shown in Fig. 15.8). When this item

Table 15.10 Weft tensile modulus EA data

Name	Symbol	Type	Value	Unit
Weft tensile modulus EA	E_2	Value	50	gf/cm
Weft tensile modulus EA	E_2	Table	t_p1_t_f.txt	gf/cm
Weft tensile modulus EA	E_2	Figure	tensile.jpg	



15.7 The redefinition interface.



15.8 Data input interface.

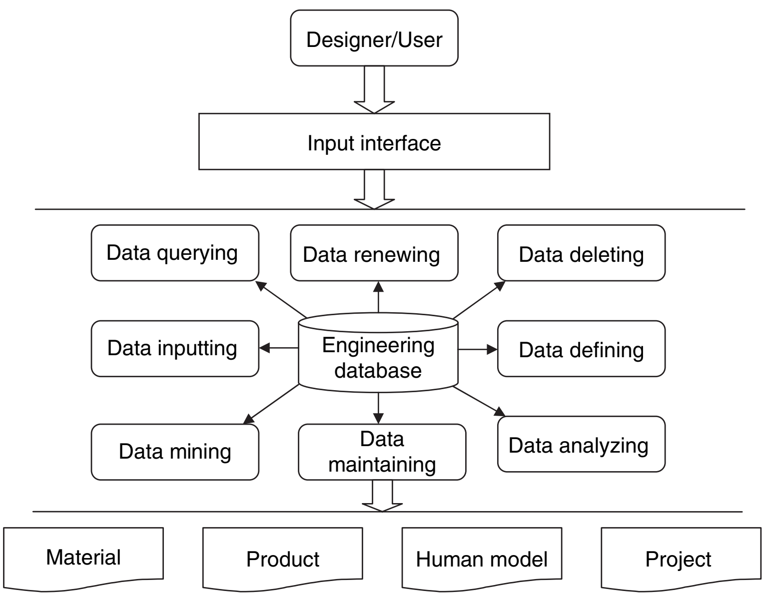
is stored in the database, all users can use it. This function ensures the engineering database system has a flexible character for the dynamic process. It can provide wide application fields.

15.5.3 Database management systems

Database management systems merge the user's need for sophisticated text, data and graphics manipulation techniques with the technological capabilities offered by the computer. In terms of functionality, they include all the issues associated with retrieving, sorting, updating and filing text, data and graphics. They answer the fairly complex demands posed by engineering applications, running concurrently with the applications programs (processes) in the computer. The engineering database system can be shown in different layers. Figure 15.9 shows these different layers. From this figure, users can operate the database through the input interface to support their application requirements.

15.6 Examples

The aim is to develop an engineering database with a high-performance, system availability and user-friendly interfaces. To provide a simple and intuitive, friendly interface for analysis expertise, the user interface of the



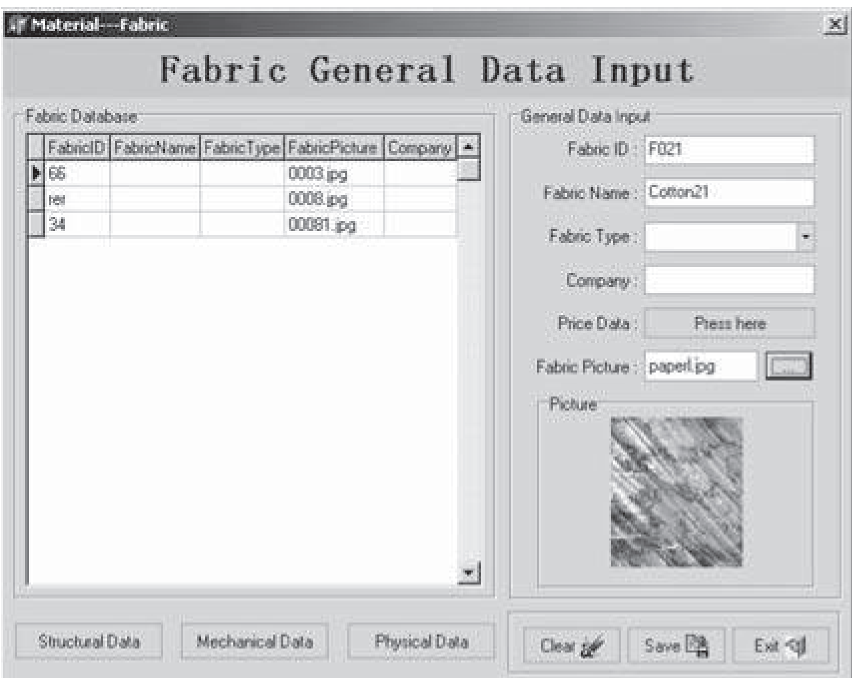
15.9 An engineering database system.

engineering database has been designed with as much image information and associated choices as possible, to clearly present the design environment and the progress of the design process at any time. A high-resolution graphics display is used to meet the geometric information and simulation function in the system. Presentation of choices utilizes pop-up menus with default suggestions to guide the user. The user interface is constructed in the PC operating system by using Delphi + SQL Server. The following figures are the interface windows of the database.

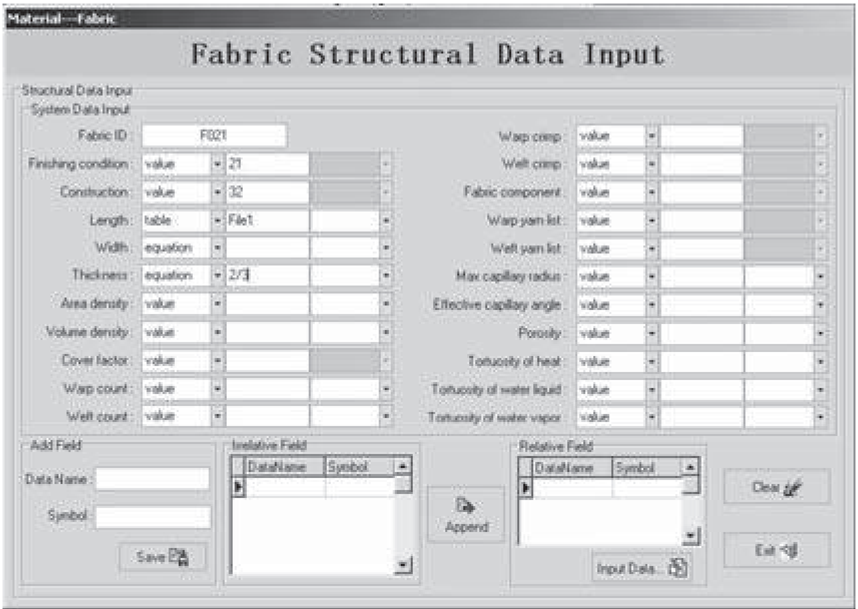
15.6.1 Fabric data management

In this part, fabric data can be managed, by inputting, deleting, modifying, querying and outputting, for the application. Figure 15.10 is the main interface for fabric data input. Four types of data have been put in: general data, structure data, mechanical data and physical data.

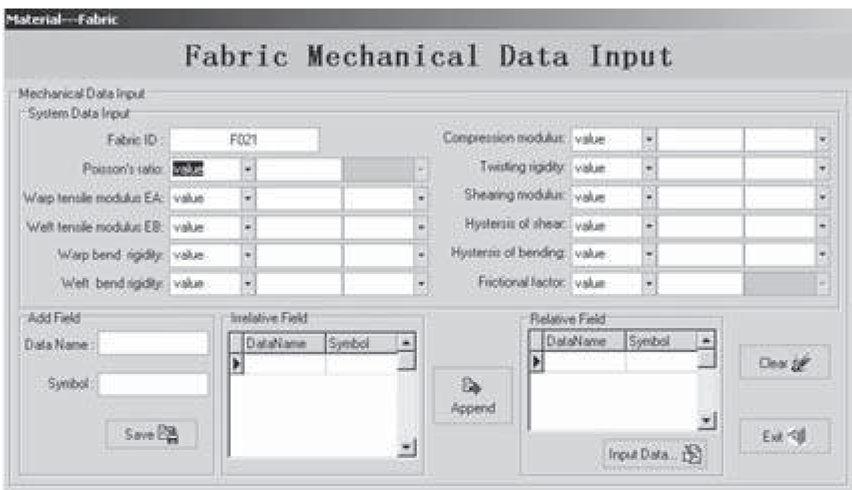
Figures 15.11–15.13 are the input windows of fabric structure, mechanical and physical data.



15.10 Fabric general data input interface.



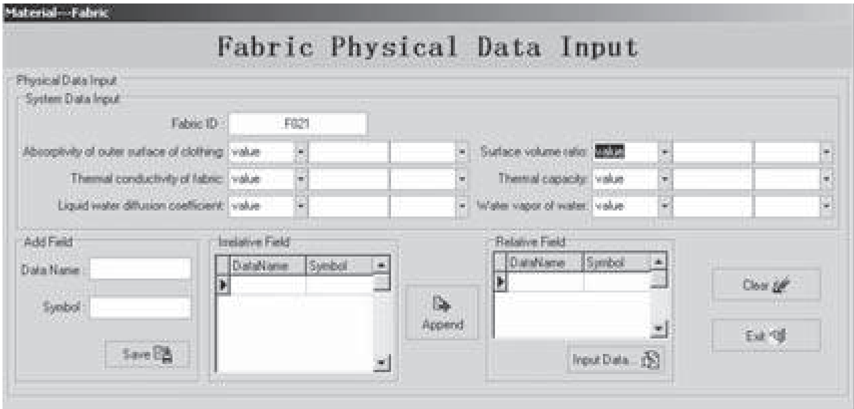
15.11 Fabric structural data input interface.



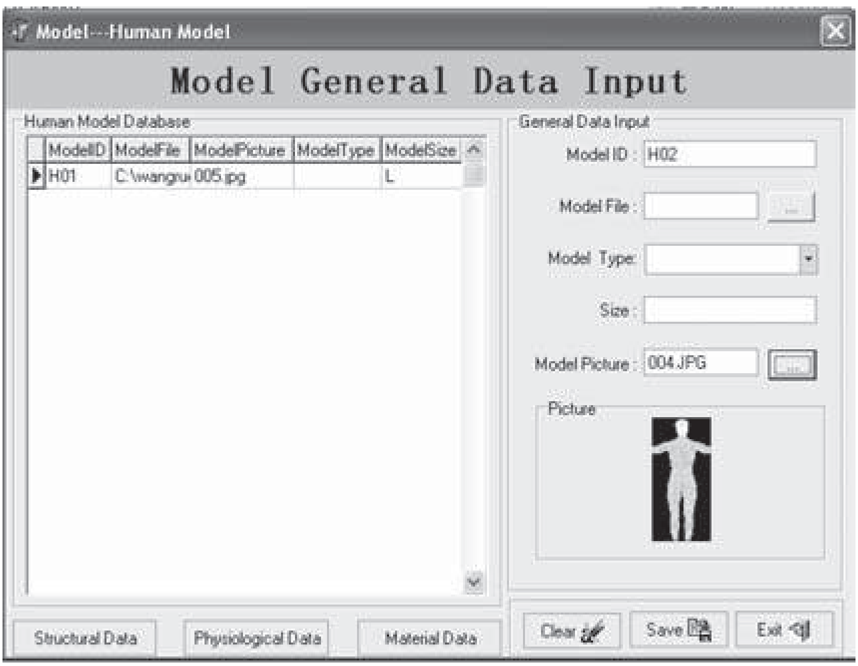
15.12 Fabric mechanical data input interface.

15.6.2 Human data management

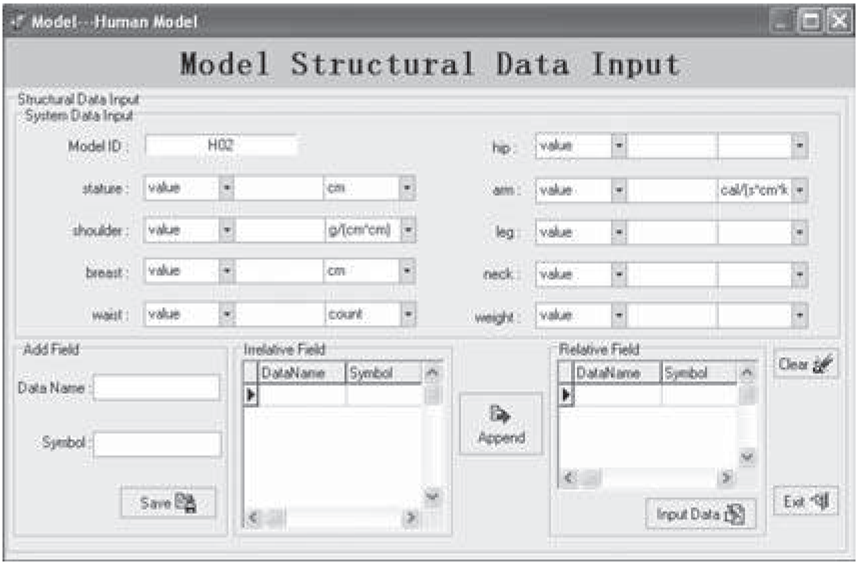
In the human model data management, the human model's general data, structural data, physiological data and material data can be managed. Figures 15.14–15.17 show the input interfaces of the human model data.



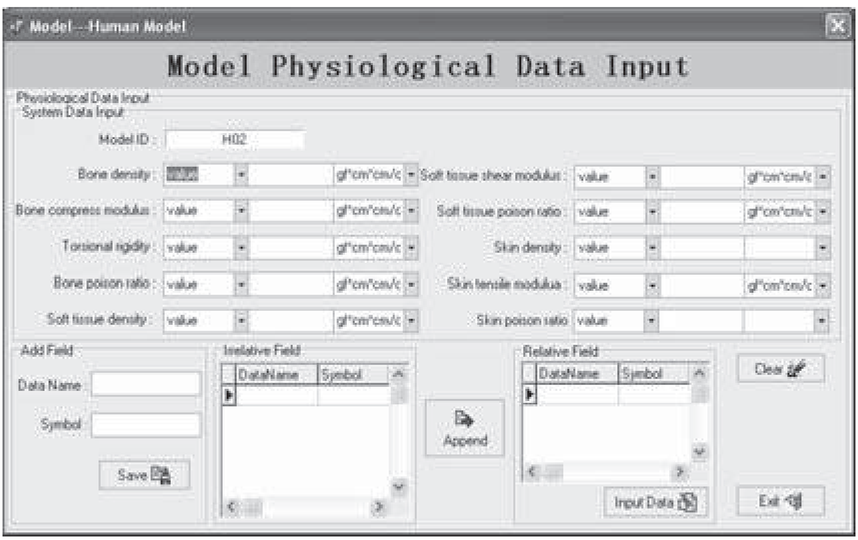
15.13 Fabric physical data input interface.



15.14 Human modes main input interface.



15.15 Structural data input interface.



15.16 Physiological data input interface.

15.6.3 Garment data management

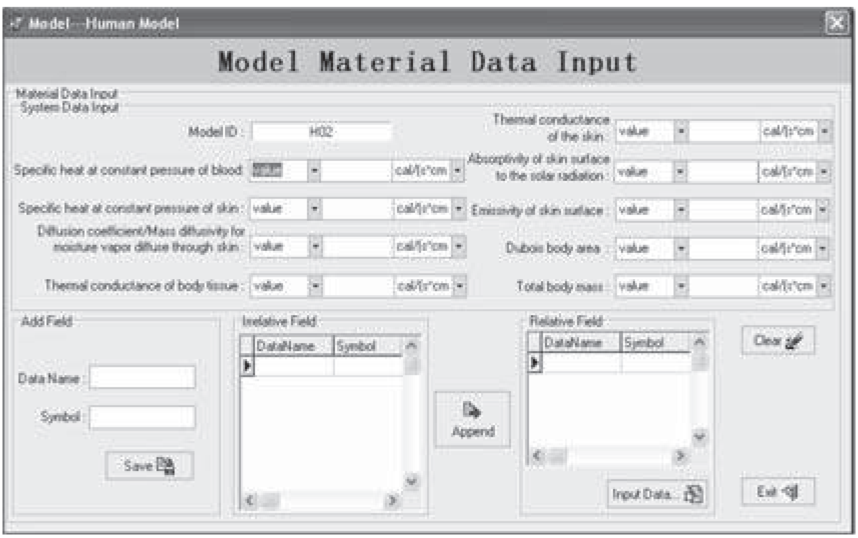
In the database, the product object is defined to describe the garment, manikin, and other textile product. Figure 15.18 shows the input window for garment data.

15.6.4 Project data management

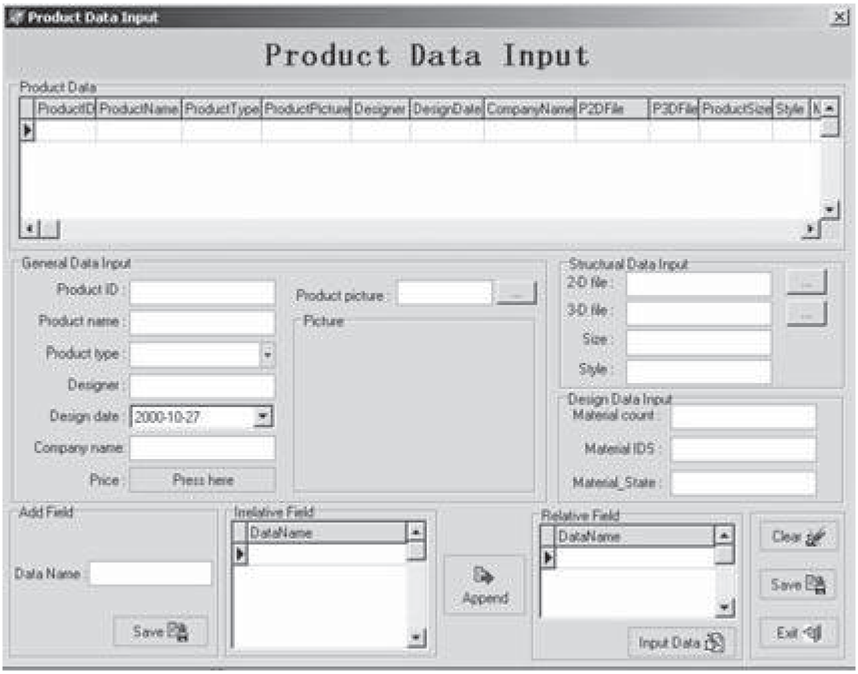
Project data management is the management of the engineering design process. It includes the design specification, definition, implementation, and control. Figure 15.19 is the main input interface for project data.

15.7 Conclusion

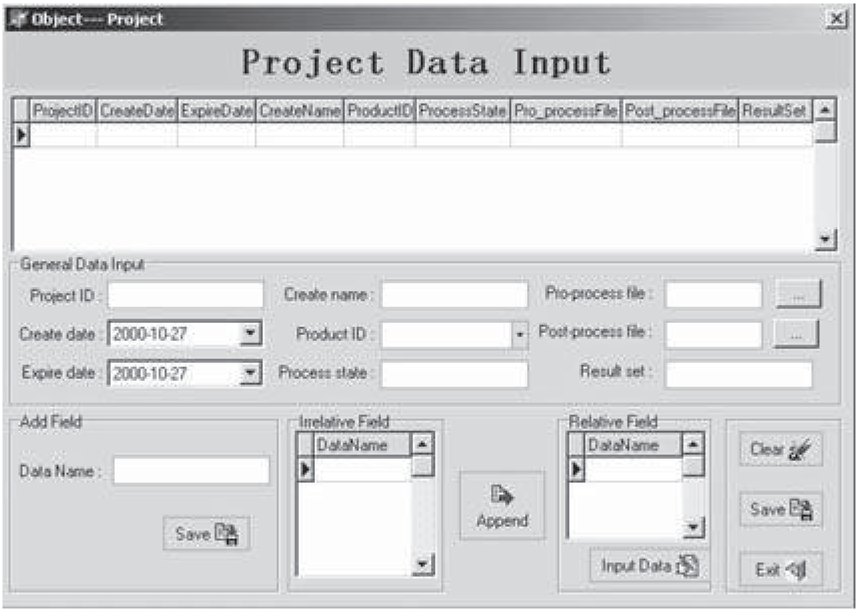
Textile and clothing function engineering design is a complex and dynamic process. It involves various data, and flexible data types. To support this dynamic and complex design process, it is important to develop an engineering database such as the Engineering Design Database Management System (EDDBMS). This database can store various complex structure data, various formal values of data, and can meet the needs of design requirements from design method, design description, design management and many others. It provides a communication environment for different users. It powerfully supports product development, design process control, quality assurance, and product performance evaluation. The system has



15.17 Material data input interface.



15.18 Main interface of product.



15.19 Project data input interface.

been developed with high-level computer technology, multilayer file structure, integrated description of data, flexible data management and a friendly interface; it is easy to use for different users. The system can be used for different purposes.

15.8 Acknowledgement

We would like to thank the Hong Kong Polytechnic University for funding this research through Project A188.

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16
Preparation for mechanical simulation

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16.1 Introduction

Clothing simulation and garment animation raise diverse scientific questions; not just the development of a technique or algorithm for solving a single kind of problem.[1] Clothing biomechanical engineering design is a simulation process to analyze and evaluate the functional performance of clothing. The aim of the biomechanical simulation is the virtual reproduction of the mechanical behavior of a textile object subjected to various geometrical and mechanical conditions, or of the interaction between clothing and the human body. This system requires a whole set of advances in a variety of fields: geometric modeling, mechanical simulation, collision detection and response, interaction with environment, numerical solver and others. Therefore, geometric models should be prepared for the garments and the human body, material parameters should be set and various boundary conditions should be defined; and a proper solver should be chosen for the mechanical simulation system. By going through these pre-processes, the whole system is set ready for numerical calculation.

16.2 Preparing geometrical models

16.2.1 Requirements of geometrical models

Geometrical description of the object shape is the fundamental element in the simulation system. In order to simulate an object's mechanical behavior effectively, a good structural framework for its geometry is necessary. For cloth simulation and garment design, as for other objects, one needs to answer the question: what is the best way to represent the shape of the object? There exist different ways to represent the shape and the geometry of objects in computer graphics, such as polygonal representation, mathematical surface representation and so on. The choice of the representation may not only have to consider the shape alone in a static and passive environment, but may also have to investigate what kind of behavior is being modeled, what the computational requirements of the simulation are, what the details to be shown are, and what rendering method is to be employed. For example, a mere representation of the form of a static garment or a piece of cloth may not be adequate when there is interest in its movement, folds and wrinkles. In fact since a cloth is flexible, it can attain different shapes in different situations, meaning it does not have a fixed shape.

The description of the geometrical models must be accurate enough to capture all the characteristics of the geometry, while minimizing the total amount of geometrical data to be handled. And easy manipulation should also be taken into account. Since the CBED system may integrate various packages, the geometric models need to be convertible for processing in the pre-processors for these packages. So the models should be saved in commonly used graphic formats, such as 'iges', 'dxf', 'sat', '3ds', and so on.

16.2.2 Human body and clothing modeling

Usually, there are two ways to obtain the geometry for a human body: (i) surface shape obtained by using 3-D body scanners; (ii) solid resulting from CT or MRI scanner. Resulting from the first approach, information of discrete points positioned on the body surface are obtained, and they are often reconstructed by using a mathematic surface description, or remain as a discrete description of the points, triangle or rectangle patch. Computerized Tomography (CT) or Magnetic Resonance Imaging (MRI) images contain more information on inner body details. From these images, more complicated 3-D body models consisting of several layers, such as bone, muscle, fat and skin, can be constructed by using 3-D image processing software such as 'MIMICS' (Materilise, Leuven, Belgium). These obtained models, which describe the surfaces of the objects, are shells rather than solids. In biomechanical engineering design, a solid human body is often preferred. The shell models can be converted to solid models by using software such as 'Solidworks' (SolidWorks Corporation, Massachusetts).

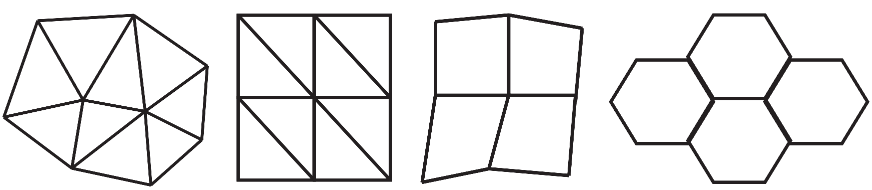
Garment models can be obtained in several different ways. Garment items with simple shapes like tubular surfaces, such as sleeves, leggings and trousers, can be built as 3-D prototypes. For close-fit garments, 3-D garment primitives can be simply obtained by properly scaling the body surface using graphical tools. A more general approach to creating a 3-D garment is to simulate the sewing process by assembling 2-D cloth patterns resulting from a conventional 2-D garment CAD system. All these garment models may be described by mathematic curves, surfaces, or polygonal meshes. Any one of them needs to be positioned properly near to the body model for the body–garment contact simulation. Therefore, both the body and garment models need to be visualized, easily viewed from different view-ports, and easily manipulated. This demands a 3-D interactive interface.

16.2.3 Geometrical discretization

The geometrical models are built for further mechanical simulation. Either in the continuum model or the discrete model approach, the clothing and body models need to be discretized. Geometrical discretization is necessary, not only because numerical solution requires discrete data, but also because it is a convenient way to describe the shape and deformation of the cloth as a compact and easy-to-manipulate set of data.

There are two main types of geometrical descriptions involved in clothing simulation: surface for the clothing object and solid for the human body. The surface is usually represented by a polygonal mesh, which is the simplest data structure for representing geometrical surfaces. The surface is discretized into flat polygons, separated by edges connected by vertices. The vertices are associated with discrete positions representing the sampled geometry. The topological structure of a polygonal mesh corresponds to a locally planar graph. Similarly, a solid is usually represented by a polyhedral mesh consisting of polyhedra separated by polygons.

A 2-D cloth pattern is often described as 2-D curves for the boundaries. The regions enclosed by the curves are then discretized into polygonal meshes. Three-dimensional garment surfaces also need to be discretized. The size and shape of the polygons are chosen to correspond to the desired accuracy of the representation of the 2-D or 3-D objects. The smaller the polygons, the more accurate the mesh, but also the more data are needed to represent them. Several kinds of polygonal mesh can be defined. While it is possible to work with meshes having irregular structures (Fig. 16.1a), imposing the condition of a constant number of edges around each vertex leads to regular meshes, having a globally constant topology. Regular mesh can be triangular (six edges per vertex), quadrangular (four edges per vertex), or hexagonal (three edges per vertex) as illustrated in Fig. 16.1b–d.



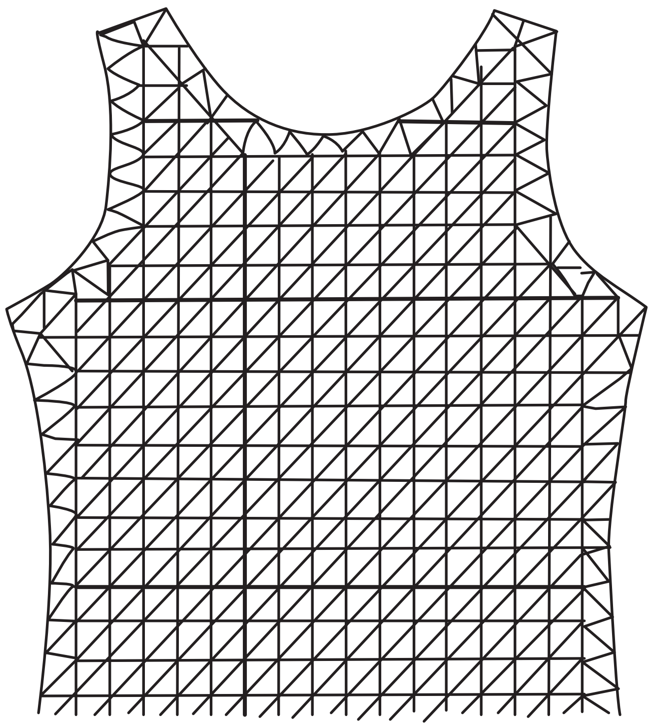
(a) Irregular (b) Triangular (c) Quadrangular (d) Hexagonal

16.1 Mesh variety.

These meshes allow us to take advantage of the local symmetries in performing geometrical computations. Furthermore, global numbering and indexing schemes can be established to provide quick access to any element in the mesh without performing search or traversal operations.

While the most general meshes may be made up of any kind of polygons, it is often useful to restrict them to contain only triangles or quadrangles. This can be helpful in performing certain mechanical analyses on the mesh elements. For example, in numerical calculation, the same formula can be used for elements of the given fixed topology. However, it is not always possible to discretize a surface into mesh containing only triangular or quadrangular meshes. As shown in Fig. 16.2, it is difficult to mesh the boundary part with regular meshes.

In order to reduce the amount of geometrical data to be managed for describing a smoothly curved surface, high-order surfaces are often used. They are described by curved surface primitives, described by a set of curved patches, with a reduced number of control points carrying the geometrical information. The patches may be described by explicit or implicit expressions which have various curvature and continuity



16.2 Mesh of a 2-D pattern.

properties. There are spline and Bezier patches, NURBS, polynomial and rational surfaces, and many of their variations. The patches may also be defined implicitly by a subdivision algorithm which constructs intermediate points hierarchically through a geometrical construction until a given accuracy has been reached. The definition of the patches generally requires that they have a given topology, such as being triangular or quadrangular. Surface continuity between the patches has also to be maintained.

To handle surfaces of complicated geometry, where portions of the mesh may be almost flat interspersed with highly curved portions, or with irregular and sharp deformations, an adaptive topology is often required. The best approach is to subdivide the mesh adaptively, depending on the surface curvature and acceptable geometrical error of the mesh representation. Different levels of detail may be considered, either upward by grouping bigger polygons into bigger and rougher domains, or downward by subdividing mesh polygons into smaller ones. More details about the geometrical representation of cloth surface can be found in reference 2.

Similarly, a solid is usually represented by a polyhedral mesh consisting of polyhedra separated by polygons. The commonly used polyhedra are tetrahedron, wedge and hexagon. The principles concerning polygonal mesh discussed above are also applicable to polyhedral mesh. However, since the human body is of a complicated geometrical shape, the tetrahedron is often used to discretize it. The geometrical discretization can be performed by using general mesh generation tools, a pre-processor for FE software, and specifically designed algorithms.

16.3 Definition of various conditions

Clothing mechanical simulation is the virtual reproduction of the mechanical behavior interacting with its environment. Extended conditions are necessary during simulation. The designer should define these parameters before the simulation.

16.3.1 Material properties

In order to proceed to a mechanical simulation of an object, its mechanical behavior must be described by relevant mechanical parameters and expressed as a set of relations among the geometrical and mechanical values of the object that can be easily manipulated. For clothing objects of different levels, the major elasticity parameters include Young's modulus, Poisson's ratio, bending modulus and shearing modulus. For the human body, the parameters of Young's modulus and Poisson's ratio are usually simplified. For dynamic simulation, the mass density of an object is also necessary. To address the nonlinearity of the mechanical properties, various stress–strain curves can be approximated by piecewise linear expression, polynomials or tables of test data. All these data can be input from the database, in which a large amount of material data should be stored.

16.3.2 Environment parameters

Cloth behavior in isolation has limited meaning. A cloth's behavior is revealed as a consequence of interaction with its environment. This environment could be the wind or other rigid or flexible objects causing collisions with the cloth. It is necessary to include these aspects into the modeling phase. The most obvious external force exerted on the cloth is universal gravity, which acts to accelerate the cloth towards the ground. This acceleration is usually 9.8 m/sec.[2]

Aerodynamic effects result from the interaction between the cloth and the surrounding air. These interactions are usually modeled as viscosity forces proportional to the speed difference between the cloth and the air, and depend on the local surface orientation. These forces are also highly dependent on the actual shape of the cloth, as well as on all the possible aerodynamic turbulences arising at any distance from the surface.

16.3.3 Interactions

The interaction involved in clothing simulation includes contact between clothing and the human body, contact between clothing/body and other objects, self-contact of clothing, and interaction among different layers within the human body. The mechanical features of these interactions need to be modeled properly in the mechanical system. Usually, all these interactions can be defined on contact interfaces between pairs of surfaces. Generally, there are two types of contact interactions: tied contact and sliding contact.

Tied contact: When a surface pair constrains a vertex on one surface to the closest vertex on the other surface, the two vertices will have equal translational and rotational motion as well as other active degrees of freedom in the duration of a simulation. For example, since soft tissue adheres to the underlying bone tightly, the interface between the two objects can be defined as tied contact.[3]

Sliding contact allows the two contacting surfaces to move separately and only interact through mechanical contact. The interface between a human body and a garment is a typical sliding contact. A contact property characterizing the interaction nature needs to be assigned to a sliding contact. The contact property includes the pressure-overclosure relationship that governs the motion in the normal direction of the contact interface, friction that defines the force resisting the relative tangential motion of the surfaces, and the damping property that defines forces resisting the relative motions of the contacting surfaces.

16.3.4 Prescribed conditions

Except for the material and environmental properties, and the interactions, there may be other external conditions needing to be prescribed, such as initial conditions, boundary conditions, loads, and constraints and motions.

Initial conditions: Non-zero initial conditions can be defined for many variables in the mechanical system. For example, initial stress can be assigned to close-fit clothing, accounting for the wearing deformation.[4]

Boundary conditions: Boundary conditions are used to specify the values of all the basic solution variables in the mechanical systems, such as displacements and rotations. Usually, boundary conditions are used to constrain portions of the model to remain fixed or to move by a prescribed amount. For example, in a dynamic garment wearing simulation, a displacement amount is often set to simulate the putting-on process.[5]

Loads: Loads deform the physical structure of the object and thus create stress in it. Various concentrated or distributed loads may need to be added to the objects. The load can be concentrated on several single points or distributed to edge, surface or volume. For example, forces are added to points, edges or planes as foot loads during walking.[6,7] Gravity is a typical load added to a volume.

Constraints and motions: Sometimes, it is necessary to define complex mechanical connections between objects, including actuation with prescribed loads or motions. Sewing simulation is a typical example of this kind of constraint. To assemble cloth patterns together, some motion or load constraint needs to be added to the prescribed seam lines.[8]

16.3.5 Analysis type

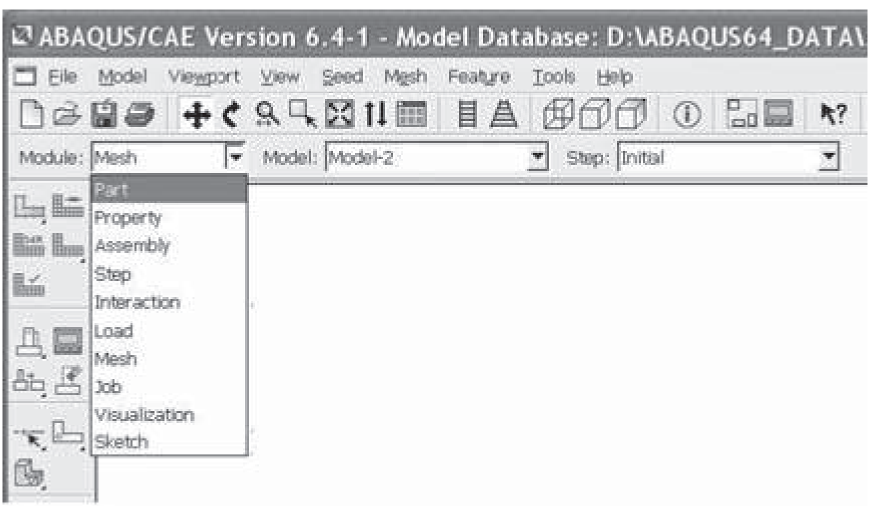
Before starting a numerical simulation, the kind of mechanical analysis to be performed needs to be determined: static or dynamic, linear or nonlinear? If it is dynamic analysis, how long is the time period to be simulated, which integration method is to be applied (implicit or explicit)? To visualize and analyze effectively the simulated results, output variables need to be specified and clearly structured before performing the mechanical analysis.

16.4 Examples

Most of the previously mentioned processing can be performed using general CAD software. Many commercial packages such as 'Exceed' (Hummingbird Ltd., Toronto, Canada), 'Femap' (UGS, Corp., USA), 'Hyperworks' (Altair Engineering, Inc., Michigan, USA) provide pre-processors that can be integrated with many CAD systems and finite element (FE) solvers. Specifically designed pre-processors can also be developed by integrating 'Visual C++' and 'OpenGL' (Silicon Graphics, Inc., USA), or other programming and graphical techniques. Here, ABAQUS/CAE, which is a pre-processor for the FE package 'ABAQUS' (version 6.4, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA),[9] and 'ST-715', which is a software for clothing simulation developed by the Institute of Textiles and Clothing, the Hong Kong Polytechnic University (Hong Kong, China),[10] are taken as examples to illustrate the pre-processing for the mechanical analysis.

16.4.1 FE packages

An ABAQUS model is composed of several components that together describe the physical problem to be analyzed and the results to be obtained. At minimum, an analysis model consists of the following information: discretized geometry, element section properties, material data, loads and boundary conditions, analysis type, and output requests. As illustrated in Fig. 16.3, ABAQUS provides several modules to deal with the information.



16.3 ABAQUS interface.

Discretized geometry: In FE methods, finite elements and nodes define the basic geometry of the object to be modeled. Elements, connected to one another by shared nodes, represent a discrete portion of the physical structure. The collection of all the elements and nodes in a model is called a mesh. The element type, shape, and location, as well as the overall number of elements used in the mesh, will affect the simulation results. The greater is the mesh density, the more accurate the results. However, as the mesh density increases, the analysis results converge to a unique solution, and the computational time cost increases. Individual objects are created in the 'Part' module, and are then assembled into a global coordinate system in the 'Assembly' module. In the 'Mesh' module, each geometrical model in the assembly is further discretized into a finite element mesh.

Element section properties and material data: ABAQUS has a wide range of elements, many of which have geometry not defined completely by the coordinates of their nodes. For example, the thickness of a shell is not defined by the nodes of the element. Such additional geometric data are defined as physical properties of the element. Material properties for all elements must also be specified. The section and material definitions are created and assigned to regions of a model in the 'Property' module.

Various load and boundary conditions are defined in the 'Load' module. The 'Step' module is used to create and configure analysis steps and associated output requests. Mechanical interactions between regions of a model or between models can be specified in the 'Interaction' module. Once the definition of the model is completed, the simulation is performed in the 'Job' module. And finally, the obtained results can be viewed in the 'Visualization' module.

Taking the simulation of a dynamic stocking as an example, the procedure was introduced using ABAQUS/CAE to prepare for the mechanical analysis. Problem description: a body stands still, the legging of a stocking is put-on from ankle to knee; the bone of the leg is considered rigid and has no displacement during the wearing, and the soft tissue deforms due to the pressure induced by the stocking. It is a nonlinear problem due to the large deformation of the stocking and the complicated contact between leg and stocking. An explicit method is chosen for the dynamic simulation. To construct the model for the simulation, the following modules need to be entered and a series of tasks need to be performed step by step.

Part: Input geometrical model for lower leg, and create the tubular model for the legging.

Property: Define homogeneous solid material of isotropic elasticity for the leg tissue, and homogeneous shell material of orthotropic elasticity for the stocking.

Assembly: Assemble the two parts to a global coordinate system with suitable relative positions as shown in Fig. 16.5.

Step: Configure the analysis procedure (nonlinear dynamic explicit) and output requests.

Interaction: Define a finite sliding surface-to-surface contact between the inner surface of the stocking and the leg surface.

Load: Fix the bone surface, and allow the top edge of the stocking to move upward at a constant speed. The boundary condition is illustrated in Fig. 16.5.

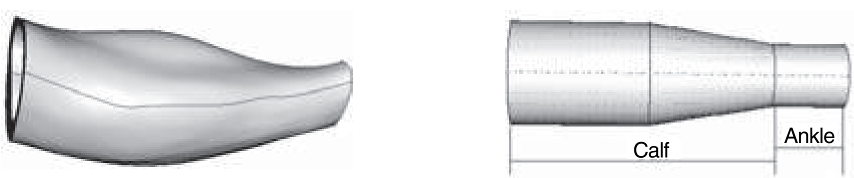
Mesh: Tetrahedron 3-D stress element and quadrangle shell element are used for the leg and the stocking, respectively. The two objects are then discretized into meshes of finite elements.

Job: Create a job and submit it for analysis. A dynamic stress analysis is carried out, and the system is solved using the explicit integration method.

16.4.2 A specifically designed system

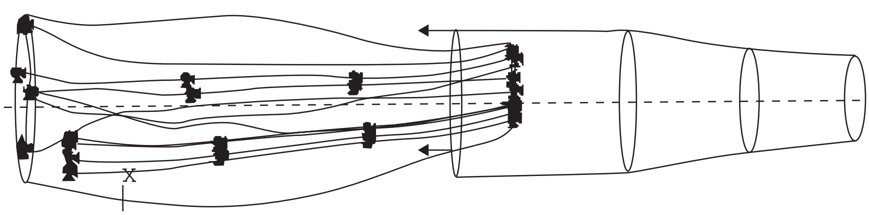
The ST-715 package includes simulations of several tests of fabric mechanical properties, such as the heart-loop test and the drape test, and garment simulation. The system is linked to an engineering database. A skirt simulation is taken as an example to illustrate how to construct a 3-D garment from 2-D patterns.

At first, the user needs to prepare the geometric models. Two-dimensional patterns for a skirt described by boundary curves are input,



(a) Lower leg(male) (b) Legging of stocking

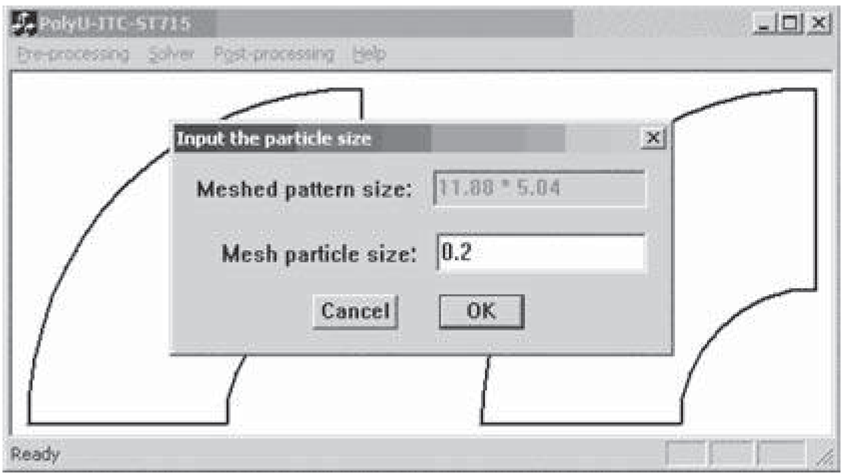
16.4 Geometrical models.



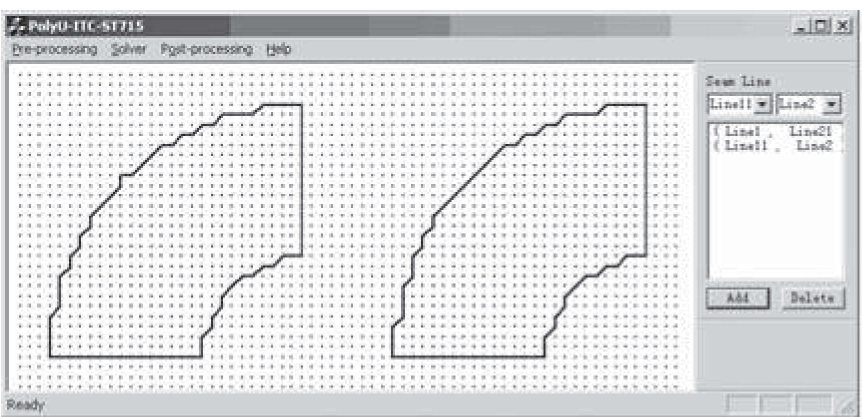
16.5 Boundary condition.

as shown in Fig. 16.6. The patterns are then discretized by the user-defined mesh size. Here, quadrangular mesh is used. After meshing, the points locating within the boundary edges are recorded, representing the cloth patterns for further simulation. Pairs of lines to be sewn together are defined as seam lines (Fig. 16.7).

Figure 16.8 shows the interactive interface to prepare the skirt simulation. The 2-D meshed cloth patterns and the 3-D body model need to be input first. Here, to save the computational cost, only the waist, abdomen and hip parts of a human body that are in contact with a skirt are modeled. The body part is modeled as an elastic shell. The material parameters for both the cloth and the human body can be input from a database supporting the

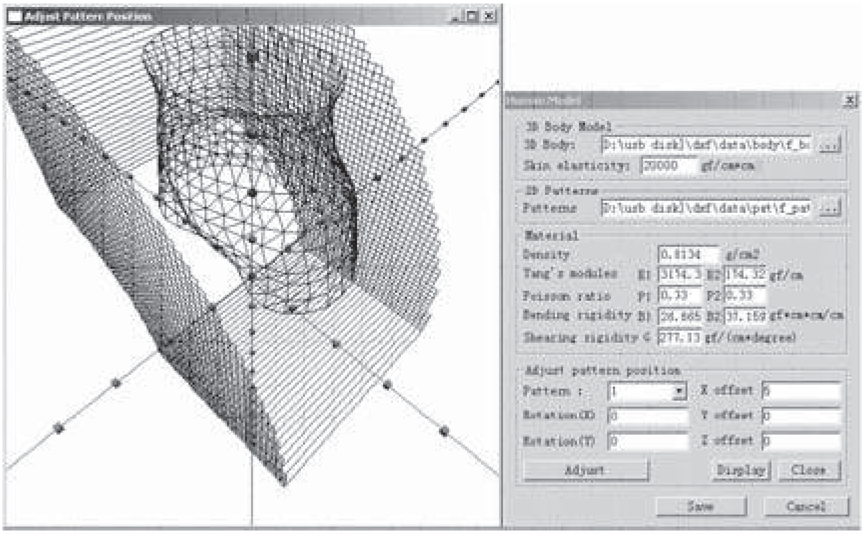


16.6 Mesh 2-D patterns.



16.7 Defining seam line pair.

system, as illustrated in Fig. 16.9. They can also be input and edited through the interface directly. Usually, the relative positions of the body and the patterns need to be adjusted properly. This positioning process can also be



16.8 Editing material parameters and geometric positions of objects.

16.9 Inputting material parameters from database.

performed within this interface. Finally, the whole skirt construction system is set ready for numerical calculation.

16.5 Conclusion

To perform a mechanical simulation, geometric models must be generated to represent the real objects, discretized for the numerical calculation, the material parameters and environment parameters set, various conditions such as interactions, load and boundary conditions defined and a proper solver for the mechanical system chosen. An interactive interface for the pre-processing is necessary. Many general pre-processors for CAD systems or FE solvers can be used for this purpose. Some specifically-designed software can also serve this purpose. Two examples were used to explain how to prepare for a numerical simulation.

16.6 Acknowledgement

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16.7 References

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Visualization for mechanical analysis

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17.1 Understanding the role of visualization

Visualization in scientific computing and engineering design is getting more and more attention from many people. Especially in relation to the fast increase of computing power, graphic tools are required in many cases for interpreting and presenting the results of various simulations, or for analyzing physical phenomena.[1] Visualization of scientific data has become a very important topic for many researchers. Scientists, engineers, medical personnel, business analysts, and others often need to analyze large amounts of information or to study the behavior of certain processes. Numerical simulations carried out on supercomputers frequently produce data files containing thousands and even millions of data values. Similarly, satellite cameras and other sources are amassing large data files faster than they can be interpreted. Scanning these large sets of numbers to determine trends and relationships is a tedious and ineffective process.

The appropriate way to analyze and understand these results is to visualize the data. If the data is converted to a visual form, the trends and patterns are often immediately apparent. Visualization is not just graphics, which itself has the power to present large amounts of numerical information in an efficient and effective way to allow an insight into the numbers, but is concerned with exploring data and information graphically, as a means of gaining understanding and insight into data. Visualization of data is an emerging visual computing technology that uses intuitive and innovative graphical user interface and visualization techniques. This technology helps engineers, scientists, and technicians to access, analyze, manage, visualize, and present large and diverse quantities of data to get information from raw technical data. The technology has evolved from the combination of powerful desktop computers, statistical and analysis tools, graphics and visualization, and sophisticated interaction tools. The data visualized enables scientists to explore their research data, to gain new scientific insight, and to communicate their discoveries to others. Visualization allows the conversion of information that cannot be perceived by the human eye into forms suitable for this most highly developed human sense.

Visualization of data includes a well-defined set of graphics and visualization tools for visually interpreting the data and producing a hard copy of the results. The environment of data visualization includes analysis tools for a better understanding of the data, data management tools for generating, reducing, saving, and restoring the data, and data access techniques to help get the data into and out of the visual data analysis environment. As visualization environments mature, they focus more on integrating the analytical and visual technologies into more complete data interpretation systems. Examples of visualization integrated into CAD, GIS, and spreadsheet software have already been seen. The idea behind visualization data is to put the user in the center of the analysis process, using visualization as a tool to navigate through data.

The biomechanical engineering for textile and clothing products is a typical kind of human factors engineering, in which humans are the most important element. The design should be based on quantitative investigations of the relationship between the mechanical performance of textile and clothing products and human sensory factors, including physiological and psychological aspects. Visualizing and analyzing the results of the mechanical simulation using a broad range of interaction techniques is crucial to the effectiveness of the product development in the CBMD system.

17.2 Methods of visualization

Visualization is to transform experimental data into graphical primitives. There are many different kinds of data sets, and effective visualization schemes depending on the characteristics of the data. A collection of data can contain scalar values, vectors, high-order tensors, or any combination of these data types. And data sets can be two-dimensional or three-dimensional. Graphing and visualization techniques can vary from simple chart-ing to volume visualization. Several academic visualization classification schemes have been proposed. A simplified classification is used here to explain popular graphing and visualization types. The focus is on technical data and real examples of how various graph types are being used, with an interest in both basic and more advanced visualization techniques. Basic techniques include the familiar types of graphs such as scatter, line, contour, as well as 3D surfaces, and various combinations of these. Advanced visualization methods include 3D geometric rendering, volume visualization, multidimensional visualization, vector fields, and animation.

17.2.1 Charts and graphs

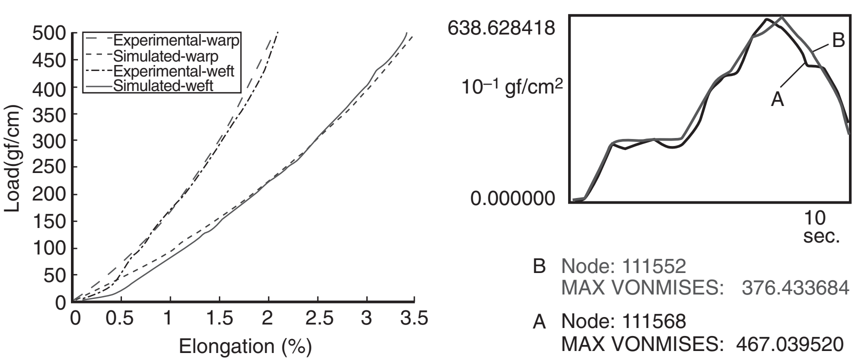
Traditional graph types frequently used in technical or business applications include the scatter, curve, bar, area, pie, and polar charts. The X-Y plot is the most often used curve chart in clothing biomechanical engineering. An X-Y data object is a collection of ordered pairs stored in two columns: an X-column and a Y-column. The X and Y can be any geometrical or physical variables in the mechanical system. For example, an X-Y data object can be stress values versus strain values or time. Attention also needs to be paid to the graph annotation. For presentation graphics, the detailed layout of the graph is an essential component of visual communication. Without the ability to perform detailed annotation of the graph, the entire visual message might be lost. Important layout features include title, notes, legend, axes labeling, fonts, and maybe color scales and some special symbols. Figure 17.1 illustrates two different kinds of presentation graphs: (a) is a fabric load–elongation curve with measured results compared against simulated ones and (b) shows garment stress varying with time during wearing process.

17.2.2 Geometrical modeling

Mechanical simulation is based on geometric data, which describe from 1D to 3D objects that are often constructed out of one or more primitives (lines, curves, polygons, meshes, polyhedra, or spheres).

Contouring

Contouring is the most commonly used basic visualization display technique for 3D objects. Contour maps are normally derived from a two-



(a) Load–elongation curves: Measured results compared with simulated ones

(b) Garment effective stress versus time

17.1 X-Y plots.

dimensional matrix of gridded data. If the data are scattered, various interpolation algorithms are used to construct the data into regular gridded data. The data is then displayed as a contour map with lines of constant height (isolines) showing the shape of the surface, or as a shaded contour map. Shaded contouring is a contour map technique where colors fill in the areas of constant height between isolines.

3D surfaces

A three-dimensional surface is another of the most commonly used basic visualization display techniques for 3D objects. It provides a representation of the surface displayed as a polygonal mesh or a shaded surface.

Rendering

Rendering makes a visualized object look more realistic. A geometric rendering process requires two tasks: hidden surface and shading. Shading is to fill meshes with color; it can be flat shading or smooth shading. Another useful method for adding detail to a 3D model is texture mapping. With texture mapping, arbitrary 2D images can be mapped onto 3D graphics objects. It is a technique very often used in clothing simulation. Various printing patterns can be mapped to garments to show cloth variety.

Volume and multidimensional visualization

In mechanical simulation, the objects involved are not limited to surfaces. In most cases, 3D solid objects are simulated, and the internal structures are considered. For example, in biomechanical analysis, the inner mechanical state of a body subjected to external loads needs to be investigated. Therefore, volume visualization becomes a necessity. Most often the volumetric dataset is defined on a three-dimensional lattice with one or more scalar values, and possibly one or more vector values, at each grid point (x, y, z) on the lattice.

Plane section slicing and dicing is a simple visualization technique to inspect a large 3D data volume. Generally, only display 2D or 3D objects can be displayed on a 2D screen. However, additional variables and data components can be shown through color, icons or other media.

17.2.3 Vector field

In mechanical simulation, many applications involve some kind of magnitude and direction; a vector. Geometrical variables such as displacements and strains, and physical variables such as forces, stresses and velocity are all vectors. Arrows are icons for vectors. An arrow can indicate both the magnitude and the direction of a vector. A complete view of a vector field can help us understand the deformation and state of a mechanical system well.

17.2.4 Animation

An animation is a collected sequence of slightly varying images that show movement through time. In mechanical analysis, changes can be shapes or positions of objects along time or deformation. Animation brings the data to life, helping us to discover things that we cannot see from the static chart or pictures. It is often crucial for understanding complex 3D scenes. Moving 3D objects in relation to each other, or in relation to other fixed-scene attributes, enables insight and understanding.

Animations can be produced either in real time, or simply by play-back of a series of pre-computed images called frames. In real time animation, rendering of each frame is done during display. It has the advantage that the animation may be interactively controlled by the user. A disadvantage is that the screen update time usually depends on image complexity, which may vary per frame. To realize real time animation, the rendering techniques are also limited. Usually, the frame play-back technique is used to produce animation.

17.3 Post-processing: an example

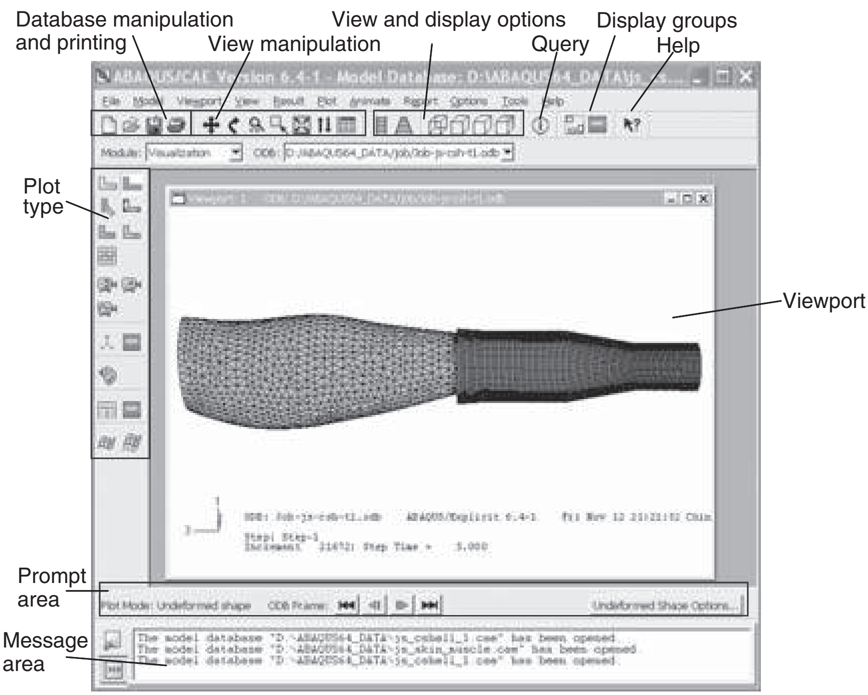
Clothing biomechanical engineering design is a complex procedure. At the end of the design, large number result data will be generated; these then go to the post-processing part to be analyzed and to evaluate the mechanical performance. The post-processing procedure is relatively straightforward. It simply involves obtaining the results from the analysis program, selecting appropriate views, modifying options on these views, and manipulating and/or reporting output. Visual information can be communicated through color, form, plot and animation.

To visualize and analyze the results of the mechanical simulation effectively, the following features are considered essential for the post-processors: linear and logarithmic axis scales, axis annotation, simultaneous display of data and visualization, diverse range of plotting modes, diverse range of 3D display modes, superimposition of mathematical functions, and intuitive user interface.[2] Most finite element (FE) packages have their own visualization modules to view the results of the mechanical analysis. Here, the ABAQUS/Viewer is used as an example to illustrate what is necessary for a typical post-processor for mechanical analysis, and what can be done with it.

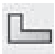
17.3.1 Visualization module basics of ABAQUS/Viewer

ABAQUS/Viewer is a post-processor incorporated into ABAQUS/CAE as the visualization module.[3] The user interacts with ABAQUS/Viewer through the main window. Figure 17.2 shows the components that appear in the main window. The toolbar contains a convenient set of tools for managing the data files and viewing the model. The viewer obtains all model data and analysis results from the output database of ABAQUS. The database manipulation tools allow one to open and save output databases, and to print viewport. The view manipulation tools allow one to specify different views of the model or plot. For example, the user can pan, rotate or zoom the model or plot. The view and display options tools allow one to customize the appearance of the model. For example, the user can specify whether wireframe, hidden line, filled, or shaded render style will be used and whether perspective will be applied. The display group tools allow one to selectively plot one or more output database items.

ABAQUS/Viewer offers several distinct types of plots for viewing a model and results.



17.2 ABAQUS/Viewer interface.

 A fast plot is a quickly drawn representation of the model.

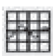
 An undeformed shape plot displays the initial shape or the base state of the model.

 A deformed shape plot displays the shape of the model according to the values of a nodal variable such as displacement.

 A contour plot displays the values of an analysis variable such as stress, strain or pressure at a specified step and frame of the analysis. The visualization module represents the values as customized colored lines, colored bands, or colored faces on the model.

 A symbol plot displays the magnitude and directions of a particular vector or tensor variable at a specified step or frame of the analysis. The visualization module represents the values as symbols, for example arrows, at locations on the model.

 A material orientation plot displays the material directions of elements in the model at a specified step and frame of the analysis.

 An X-Y plot is a two-dimensional graph of one variable versus another.

The animation tools display a series of plots in rapid succession, giving a movie-like effect. There are also several additional capabilities. Visualizing diagnostic information helps to determine the causes of non-convergence in a model. Probing displayed model data and analysis results as the cursor moves around a model plot; probing an X-Y plot displays the coordinates of the graph points. The user can define a path by specifying a series of points through the model, then view results along the path in the form of an X-Y plot.

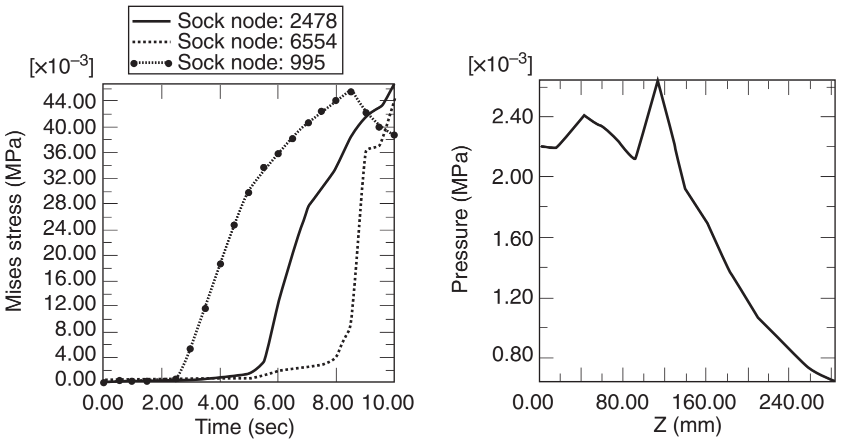
17.3.2 Analyzing simulation results

To understand the visualization module for the CBED system well, the dynamic simulation of wearing a stocking is taken as an example, to go through the general post-processing procedures.

The initial shape for the stocking is tubular, after wearing simulation it takes the shape of the leg surface. This pressure distribution is crucial for compression stocking.

The simulation of the dynamic wearing process can be recorded as animation. By using the X-Y data plot, more detailed information can be visualized. Figure 17.3a plots the changes of the Mises stress of the stocking at three nodes during wearing. Figure 17.3b shows that the pressure varies along a path in the front center of the leg from ankle up to knee.

Not only can the cross-sectional distribution of the pressure on the skin surface be investigated, but also the mechanical state of the volume interior



(a) Changes of stocking stress at several nodes

(b) Skin pressure distribution along a path

17.3 X-Y data plots.

can be looked into. Moreover, by using the probing function, detailed information can be obtained of any a node or an element, such as node/element number, coordinates, stress, pressure and so forth.

17.4 Conclusion

To analyze and understand the results of mechanical simulation effectively, it is necessary to transform numerical data into graphical primitives. Data visualization includes a well-defined set of graphics and visualization tools for visually interpreting the data. Graphs and charts, contour plots, surface modeling and rendering, and color coding are common tools for visualization and visualizations of volume interiors. Additional techniques include visualizations of volume interiors, multidimensional and animations. Through an example to analyze the simulated results of dynamic stocking wearing using the ABAQUS/Viewer, the requirements for a typical post-processor for mechanical analysis have been illustrated, along with what can be done with it.

17.5 Acknowledgement

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