Mathematical Modelling and Analysis 2005. Pages 3–13
Proceedings of the 10th International Conference MMA2005&CMAM2, Trakai
© 2005 Technika ISBN 9986-05-924-0

COLLISION DETECTION AND RESPONSE OF YARNS IN COMPUTATIONAL MODELS OF WOVEN STRUCTURES

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Abstract. The paper deals with the modelling of the physical behaviour of woven structures imitating the textile fabrics. The model is based on a combined approach which presents longitudinal elastic properties of each yarn by a system of non-volumetric structural elements (springs), while the collision search and response algorithm works in the 3D space based on tight-fitting of the yarns by using oriented bounding boxes (OBB). The separation axis theorem (SAT) for collision detection between OBBs is performed. Collision response is obtained by applying the impulse-momentum principle to colliding nodes thus avoiding interpenetrations of the yarns. A simplified approach is applied in order to take into account the deformation of the cross-section of a yarn. It is assumed that the cross-sectional area remains constant all the time while its shape is elliptic with changing lengths of axes. Numerical examples of simulation of tension, warp and shooting-through the fabric are presented.

Key words: finite elements, particle elements, textile, collision detection, collision response

1. Introduction

The problematic of computational models for simulation of textile structures is defined mainly by the necessity to present the behaviour of the material in two different length scales. At the macro-scale one is inclined to regard the fabric as a continuous membrane. At the same time textile fabric is not a continua as at the micro-level its behaviour is defined by the contact interactions of the yarns in a woven structure. The dimension of this micro-structural level is finite and may be very complex depending upon the properties of the yarn and of the weave. The continua based approximations of the fabric behaviour are always only rough approximations of a real fabric. Moreover, different continua-based models for modelling different situations (extension, warping, failure, etc.) may be necessary. Therefore the modelling of the fabric by directly including the weave geometry and physical behaviour into the model is preferable.

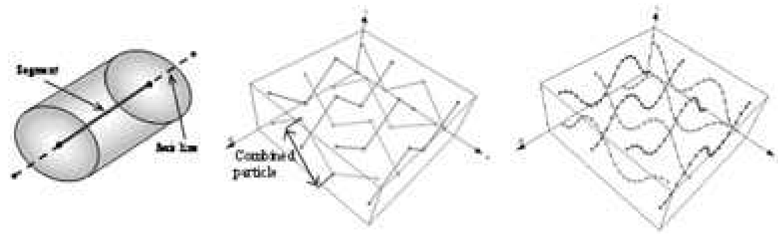
Implementations of the woven structure models can be performed by using the finite element method (FEM) computational environments such as LSDYNA, ABAQUS Explicit, DYTRAN and etc. However, they usually lead to huge dimension of the obtained models as each yarn has to be presented as volumetric finite element structure. Moreover, because of the universality of the software focused to the problem-specific area of a fabric simulation require significant efforts while implementing them. Therefore the development of more efficient "physically-based" approximate models of a yarn structure is an important issue at the present time.

One of the simplest physically-based models in the same time allowing closest to real-time performance is mass-spring system. The concept of a yarn assembled of a pin-connected rod-element chain was presented in [8]. The drawback of the approach was that the cross-sections of the yarns remained unchanged during the deformation of the fabric weave. In [9] a new approach referred to as "multi-chain digital element analysis" has been presented. The main idea was to represent a yarn as an assembly of fibres. Each fibre was modelled as a chain of elastic rods, and a yarn was modelled as an assembly of such chains. The drawback of the model is that weaving implemented in 2D space and the number of nodes of the model becomes huge when simulating a cloth of realistic dimensions.

This paper focuses on a development of an efficient model of the weave of the fabric. We propose a new approach for estimation of volumetric yarns by using combined particles (CP) for presenting them as volumetric structures. It enables to achieve good performance along with the possibility to analyze the deformable yarn structure in the 3D space. A CP is a two-mass system linked by a spring, however, geometrically they are considered as cylindrical elements at initial stage. As the deformation of the weave takes place circular cross-sections of the yarns are allowed to change their shape and become elliptic. So, the approach is a compromise between the simplified uni-dimensional rod system and a fully volumetric model while presenting a yarn in a weave.

Collisions detection and response is an essential part in the simulation process. Dealing with deformable bodies is the main time consuming stage of the computation covering both collision search and response among colliding parts of the yarns. It requires significantly more time for updating OBBs at each time step comparing with rigid bodies collision analysis where the bounding volumes are prepared during the pre-processing stage. Collision detection is performed by using the SAT algorithm and tight-fitted OBBs that fully enclose the yarns. The bottleneck of the collision handling algorithm is to avoid interpenetrations of the yarns. Commonly used penalty-forces method is not suitable in this case because of high frequency oscillations inevitably arising because of the penalty stiffness. The impulse and momentum based method is based on "instantaneous" change of velocities of contacting elements.

The rest of the paper is organized in the following way. The next section briefly presents the geometrical model of a fabric. Physical model of a fabric including an internal structure of the yarns is presented in the third section. It explains the basic steps of a CP adaptation for the textile fabric modelling. Sections 4 and 5 cover the collision handling problems. The collision detection



a) b) c)

Figure 1. Crimped yarns constructed of CP: a) combined particle; b) CP in the yarn; c) smoothed yarns of CP.

algorithm is presented in section 4 and OBBs as the bounding volumes used for the tight-fitting of a yarn is introduced. The collision response of contacting nodes and deformation properties of the cross-sections of the yarns are presented in section 5. The last section illustrates the results obtained by the proposed model. It deals with the extension of the initially over-crimped yarns and the failure of a fabric during a contact with a rigid body.

2. Geometrical Model of the Fabric

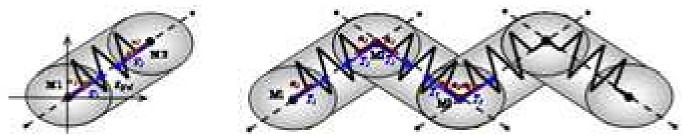
The mechanical behaviour of textiles made of the yarns can be investigated at different scales of length. The scales are determined by several characteristic dimensions: diameter of a fibre 10^{-5} m, diameter of a yarn 10^{-3} m and the linear dimension of a sheet of the fabric under investigation $> 10^{-1}$ m. In our model modelling of a textile fabric is based on the yarns layer.

Geometrically a CP is a segment of a yarn (Fig.1a). Obtaining a weave of a particular pattern is based on the determination of positions of each CP with a respect to other CPs (Fig.1b). Such a way gives as ability to weave different kind of the patterns, besides it perfectly suits at further step when physical model of a fabric is implemented. However, in comparison the manner of the weaving is a toil and time consuming work, especially keeping in mind that real dimensional fabric contains thousands of yarns, moreover yarns assembled of rough elements looks “unnatural”. In this instance, we are processing following actions to solve these problems.

At first, we additionally segment them by approximating B-spline curve (Fig.1c) to obtain smoothed yarns. Dependent on the smoothness we want to achieve extra nodes inside the initial CP are added, thus obtaining the new shape which is closer to natural. Weaving is performed in the pre-processing step, still its time consuming, so the replication is performed. To completely describe a particular weave a small piece of the pattern is enough. A real dimensional fabric is obtained by replicating the piece of the fabric in several directions. As an example, one square meter of a sample paraaramid fabric may contain $\approx 6K$ yarns of the thickness ≈ 0.3mm. So, the piece of the fabric is replicated inasmuch times as required in the direction of X and Z axes until the fabric in its full dimensions are obtained.

3. Model of the Physics Behaviour of a Fabric

Single physical CP consists of two nodes linked by a spring (Fig.2a). We assume that the mass of the CP is concentrated at the ends in equal amounts. A yarn is composed of a chain of such elements (Fig.2b). Volumetric yarns have longitudinal and through-thickness stiffness. Longitudinal stiffness of a yarn is determined by an elasticity modulus of the material and the cross-sectional area of a yarn. As an example, the longitudinal elasticity modulus of the sample paraaramid yarns is 90GPa and their elongation at the failure threshold is about 3-5%.



a) b)

Figure 2. Structure of CP: a) physical CP; b) part of the multi-chain.

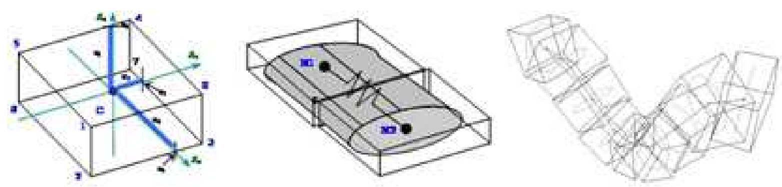
The cross-section of a yarn is composed of cross sections of very thin fibres comprising a yarn. Practically, the change of a yarn's cross-sectional geometry takes places because of an internal re-distribution of fibres inside a yarn. Therefore the through-thickness deformation of a yarn is mainly dependent upon the interaction properties of filaments inside a yarn and only very slightly upon the elasticity modulus of the material. Practically only empirically determined values of coefficients can be used in order to present a through-thickness stiffness of an element. As a primary through-thickness deformation model, we suppose that the mutation of the cross-sections of the yarns depends on internal yarns-yarns interactions.

4. Collision Detection

The handling of inter-element collisions is the most time consuming part of the simulation process. Two steps are commonly distinguished: collision detection as a geometrical problem and collision response as a dynamic problem. The model is implemented in 3D, so collision handling among yarns is treated considering them as volumetric. Collision detection is performed at each time instant by performing the broad search and the narrow search of contacting nodes. We perform the broad search in order to find the nodes that potentially can be in contact interaction and to eliminate the nodes that cannot contact because of the known geometry of the structure. The narrow search is performed in order to check the contact condition of the nodes selected during the broad search.

4.1. Bounding of elements

Mostly used "collision proxies" of potentially colliding elements are: axis aligned bounding boxes (AABB), oriented bounding boxes (OBB), spheres and etc. Our choice is motivated by the article [3] on oriented bounding boxes and on OBB trees that are used to provide a hierarchical way of deciding if two objects intersect. The computational goal is to minimize the time spent for determining the intersections of the objects. An OBB tree essentially provides a multistage representation of the object. The box should be built in such a manner that it encloses the cross-section as tightly as possible as this influences significantly the performance of the algorithm. The root of such a tree corresponds to an approximation of a yarn by a single OBB. The boxes corresponding to the middle levels of the tree represent smaller pieces of a yarn, thus providing a somewhat better approximation than the root. The leaf nodes of the tree represent the actual geometry of yarn elements [5]. It should be noted that we are not constructing the OBB tree in this implementation, the main objective was to validate OBBs at first and to leave construction of OBB tree for the further extensions. Further sections of collision detection covers only a brief description what we are using in our implementation, more detail you can find in papers [4] and [3].



a) b) c)

Figure 3. Bounding volumes in the model: a) an OBB; b) CP bounded by OBBs; c) yarn bounded by OBBs.

4.1.1. Oriented bounding boxes

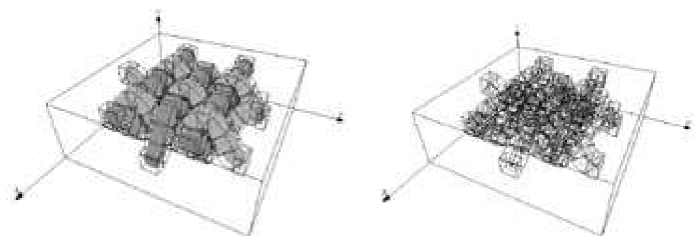
An oriented bounding box is defined by a center C, a set of right-handed orthogonal axes A_0, A_1, A_2 and a set of positive extents e_0, e_1, e_2 (Fig.3a). As a solid box, the OBB is represented by

$$\left\{C + \sum_{i=0}^{2} x_i A_i : \left|x_i\right| \leq e_i \forall i\right\},$$

where x are points on the axes. The eight vertices of the particular box are

$$C + \sum_{i=0}^{2} \xi_i e_i A_i,$$

where sign ξ_i obtain values ± 1.



a) b)

Figure 4. Yarns bounded by OBBs.

Example of a segment and a yarn bounded by OBBs are presented in figures 3b and 3c respectively. A piece of a fabric bounded by OBBs is presented in Fig. 4.

4.2. Testing of the intersections of OBBs

Testing for intersection between several convex polyhedral (OBBs) is performed by applying the separation axis theorem which states that: if there exists a line for which the intervals of a projection of the two object onto that line does not intersect, then the objects do not intersect. Such a line is called a separating line or more commonly a separating axis (SA)[4]. The algorithm tries to determine is it possible to fit a plane between two objects. If such a plane exists, then the objects are separated, and cannot intersect. To determine if the objects are separated, it is simply a matter of projecting the objects onto the normal of the plane, and comparing the intervals and see if they overlap [7]. If a separating axis is found, the remaining ones of course are not processed. Intersection testing for two OBBs consists of comparison of 15 potential SA: 6 for the independent faces of two OBBs and 9 generated by an edge from the first OBB and an edge from the second OBB. The "quick out" provided when a SA is found helps to minimize the computational expense of the collision detection.

The algorithm is formulated for intersection testing of objects as if they are stationary, but the algorithm also applies when the objects are moving. If an object is assumed to have a constant velocity during each time step, the extension of the algorithm to the case of moving objects is mathematically straightforward. Intersection testing of moving objects is identical to intersection testing of the moving intervals of projection on the potential separating axes. If two time-dependent projection intervals are $[u_0(t), u_1(t)]$ and $[\nu_0(t), \nu_1(t)]$, then the two objects do not intersect during time interval $t_{min} \leq t \leq t_{min}$ if $u_0(t) < \nu_1(t)$ or $\nu_1(t) < u_0(t)$ for all $t \in [t_{min}, t_{max}]$. Additional interest for moving objects is to determine the interpenetration depth and the contacting points of intersection of the objects during a specified time interval [3].

5. Collision Response

An each interpenetration of elements violates the reality and requires applying expensive correction procedures. The collision response algorithm includes the measures for preventing interpenetrations and for rendering the cross-sectional shapes of the yarns. Suppose at a given time instant two OBBs bounding elements are overlapping. The simplest approach is to move them back to their previous positions. While this might be sufficient for programming of games, the physically based modelling should be based on the laws of physics. The collision response can be performed in three different ways using *penalty-forces, analytical or impulse-based methods*.

The penalty method (PM) focuses on using the laws of Newtonian dynamics to simulate the collision handling. When a collision between yarn's elements takes place, common actions would be to apply to both elements two forces acting in opposite directions. The drawback of the approach is that forces cannot change the velocities instantaneously. Therefore several small time integration steps have to be performed until the interpenetration is prevented, at the same time small vibration of an elastic nature may occur at the contact point.

Analytical methods (AM) have the same idea as the PM and focuses on the analytic calculation of the forces that would prevent contacting bodies from interpenetration. A method is proposed in [2] for the analytical calculation of the forces between systems of rigid bodies in static contact, but it's not suitable in the case of deformable bodies such as yarns the geometrical shape and sinuosity of which are complicated.

The impulse-based method (IM) is based on the impulse-momentum principle. It enables to calculate instantaneous changes of velocities of two bodies caused by the contact interaction [1].

5.1. Collision response of OBBs

As a result of the collision detection step, we have obtained the contact points and the interpenetration vector. We investigate two colliding OBBs labelled as A and B (Fig.5). The contact takes place when a point of A touches a point of B with a negative relative velocity in contact direction [6]

$$VR^n = V^{Pi} = (\boldsymbol{V}^{APi} - \boldsymbol{V}^{BPi}) \cdot \boldsymbol{n}, \tag{5.1}$$

where $i \in$ [1, number of colliding points], V - velocity of a particular point. Consider three cases:

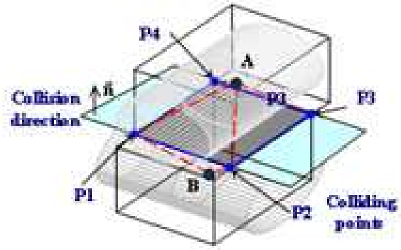


Figure 5. Parts of yarns bounded by OBBs in resting contact.

1) If $VR^{Pi} > 0$, the points are leaving each other and we can ignore them;
2) If $VR^{Pi} = 0$, the points are in resting contact;
3) If $VR^{Pi} < 0$, the interpenetration is inclined to increase ant should be stopped.

In the third case the collision is handed as follows:

1) The interpenetration distance of colliding OBBs are computed (it means the relative cross-section deformation of a yarn);
2) The cross-sectional shapes of the yarns at the contact zone are changed;
3) If the amount of cross-sectional deformation is less then defined maximal cross-sectional deformation (MCD) then repeat steps 1 and 2;
4) Else, the collision response algorithm is applied. It means we do not let the OBBs to penetrate each other any more).

The time interval when the collision occurs and the interpenetration begins is very short. It may be assumed that during the single time integration step "instantaneous" change of velocities of the nodes takes place in such a way that at the next time moment both nodes move together. The magnitude of the interaction impulse relates the incoming and outgoing velocities depending upon the value of the coefficient of restitution. The assumptions that yarns do not spin about their axes and no contact friction exists are made. The equation derived in [6] to compute the impulse magnitude is used as

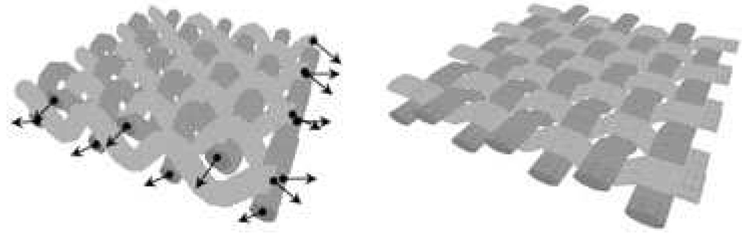
$$j = \frac{-(1+e)v_1^{AB} \cdot \boldsymbol{v}}{(1/m_A + 1/m_B)} \tag{5.2}$$

where e is coefficient of the impact velocity restitution; $\boldsymbol{n}$ collision direction; m mass of the node.

If two OBBs A and B collide, the impulse vector $j\boldsymbol{v}$ acts upon A and the opposite vector $-j\boldsymbol{v}$ upon B.

5.2. Deformations of yarns

Under application of loads yarns can be deformed in longitudinal and through-thickness directions. In our model the longitudinal deformation is strongly ht



a) b)

Figure 6. The piece of the fabric: a) directions of initial velocities; b) tensioned yearns.

based on physical properties of the material and the through-thickness deformation is evaluated geometrically. We assume that the cross-sectional shape of a multi-filament yarn may change significantly from nearly circular to a fully elliptical until a threshold is reached (re-distribution of filaments over the cross-section). Forces necessary to change the cross-sectional shape at the initial stage of deformation can be assumed to be very small as they actually do not cause the deformation of the material. After the cross-section is deformed to the threshold value, the further change of the shape is locked. We are using term maximum cross-sectional deformation (MCD) in order to describe the threshold value. Empirically we set the value to 50%-70%. As long as the deformation of a yarn reaches the MCD, the impulse-momentum principle is applied in order to handle the velocities of contacting nodes. The drawback of the approach that the selected values of MCD is not highly reliable; however, they may be better estimated by comparing the results of simulation of a real fabric against the experimental ones.

6. Results

Two models are presented in this paper: obtaining the initial weave by performing tension of the yarns and the shooting-through the fabric test failure modelling. The implementation was performed in $S\#$ and OpenGL is used for visualization.

6.1. Obtaining the initial fabric structure

Obtaining the initial fabric consists of hierarchical order: firstly geometrical model describing the weave of a fabric is generated; further physical model based on particle elements is implemented. Using geometrical algorithm we obtain a piece of a fabric as a free-fabric structure (Fig.6a), however naturally yarns are tensioned among themselves, so to obtain “natural” state of a fabric initial tension is performed.

In this instance physical model of a fabric is constructed. The implementation is based on using a system of non-volumetric structural elements as described in Section 3. Boundary nodes of a fabric are affected by the velocities and move toward load direction subsequently pulling yarns, thus obtaining tensioned fabric (Fig.6b). During the movement of the yarns internal collisions at intersections of the yarns occur. To ensure properly simulation we distinguish collision handling into two steps: collision detection and response. The SAT algorithm for collision detection and IM for collision response are performed. Both work in a fully 3D space treating yarns as volumetric entities. The SAT algorithm lets perform efficient collision detection between nodes of the yarns thus saving performance time while collision response based on IM helps to ensure avoidance of the interpenetrations of the yarns.

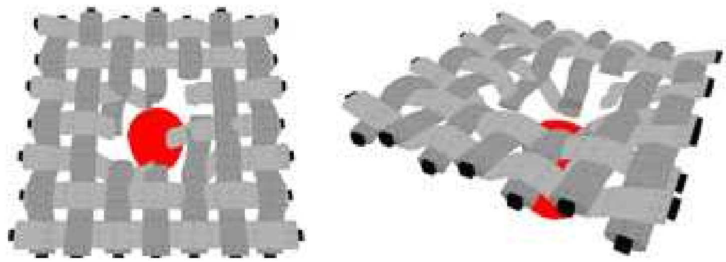
When a part of a fabric is tensioned the replication algorithm for obtaining extension of a fabric is applied. We assume that such a piece of a fabric completely repeats features of a whole fabric, so its let's significantly reduce computational time comparing with time required to tension a whole fabric as a unit. Simulation performance time directly depends from the size of tensioned fabric, as larger as longer. Also, it's partially depends from elasticity modulus of the material, initially applied velocities' magnitude and integration time step.

6.2. Shooting a rigid body through a fabric

The second model presented in this paper is intended to explore the properties of the yarns of a fabric during a ballistic impact. Initially we start with a shooting-through the uni-layer model of a fabric. Actually we use the obtained tensioned fabric assuming that boundary nodes are fixed at the ends. As long as we have fixed fabric a bullet is shouted upon a fabric from a defined distance with an initial velocity equal to 200 m/s. A bullet is visualized as a cone while in implementation of contact handing it is bounded by an OBB and is treated as a cube. Commonly the contact handling is performed at the same manner as in previous example by two steps. The difference in this case is that extra collision detection with an external object is performed. The collision response is based on the same manner. The main interest in this example is a breaking condition of a yarn. We use a simplified assumption which states that yarn breaks as long as first of the assembling elements reaches the defined breaking threshold. So, during simulation process longitudinal deformation of elements of the yarns are verified and if one of them is deformed more then empirically defined threshold then the element is eliminated thus obtaining the broken yarn. The longitudinal deformation threshold of an element is equal to 5%. View of a broken fabric is presented in Fig. 7. The implementation where yarns are based on longitudinal physically lets us practically explore the breaking properties of a fabric from various materials.

7. Conclusions

A new approach for modelling the dynamic behaviour of woven structures has been presented. The yarns are modelled as chains of springs and simultaneously their full 3D geometry is considered while determining inter-element



a) b)

Figure 7. Shooting through the fabric.

collision detection and response. An empiric model has been proposed for evaluating deformations of cross-sections of the yarns based on the assumption that the cross section is always elliptic with changing axes of the ellipse. The advantage in comparison with traditional models presenting a yarn as a full volumetric deformable body is the significantly reduced number of degrees of freedom of the structure. Numerical examples considering the generation of the initial woven structure by tension of the crimped yarn structure and the failure at shooting-through the fabric demonstrate the good performance of the approach. However, future work is necessary in order to improve and validate the model of the cross-sectional deformations of the yarns.

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