Simulation and characterization of circular hexagonal braiding fabric structure

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ABSTRACT – REZUMAT

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Hexagonal braiding technology is a kind of state-of-the-art braiding method, which uses hexagonal horngears to drive yarn carriers and make yarns intertwined into fabrics. In terms of hexagonal braiding principles, the braiding parameters like initial arrangement of yarn carriers, yarn number and horngears sequence were defined, and then the movement paths of yarn carriers in hexagonal braiding process and stitch length were obtained, which could be converted into coordinates on the xoy plane and the coordinates along z-axis. In that case, a group of spatial coordinates were got to create the yarn trajectories and fabric structures in Matlab. And then, B-spline curve was utilized to fit the yarn trajectories. Considering the compactness of hexagonal fabric, the coordinates conversion algorithm and conversion matrix were utilized to optimize the fabric structure, so a more compact fabric structure was established. The braiding angle variation and volume fraction of fabric showed that after coordinates conversion the braiding angles became more stable than original fabric model, and the fiber volume fraction of fabric was improved too. So the fabric structure model was available to describe hexagonal fabric structure, which can offer the reference for the further study on properties of hexagonal braiding technology and application of hexagonal braided fabric.

***Keywords:** Matlab simulation, coordinates conversion, algorithm, braiding angle, volume fraction.*

Simularea și caracterizarea structurii împletiturii tubulare hexagonale

Tehnologia de împletire hexagonală este o metodă de împletire de ultimă generație, care folosește angrenaje cu discuri dințate hexagonale pentru a antrena conducătorii de fir și a realiza încrucișarea firelor în împletitură. În ceea ce privește principiile împletirii hexagonale, s-au definit parametrii de împletire, precum dispunerea inițială a conducatorilor de fir, numărul de fire și succesiunea discurilor, apoi s-au obținut traiectoriile de mișcare ale conducătorilor de fir în procesul de împletire hexagonală și lungimea segmentului de legare a firului în cadrul împletiturii, care ar putea fi transformate în coordonate pe planul xoy și coordonate de-a lungul axei z. În acest caz, un grup de coordonate spațiale a fost obținut pentru a crea traiectoriile firelor și structurile împletiturii în Matlab. Ulterior, curba B-spline a fost utilizată pentru a fixa traiectoriile firelor. Referitor la compactitatea împletiturii hexagonale, algoritmul de conversie a coordonatelor și matricea de conversie au fost utilizate pentru a optimiza structura împletiturii, astfel încât s-a stabilit o structură mai compactă a împletiturii. Variația unghiului de împletire și fracția volumică a împletiturii au arătat că, după conversia coordonatelor, unghiurile de împletire au devenit mai stabile decât la modelul original al împletiturii, iar fracția volumică a împletiturii a fost optimizată. Astfel, modelul de structură a împletiturii a fost utilizat pentru a descrie structura hexagonală a împletiturii care poate sta la baza studiului suplimentar asupra proprietăților tehnologiei de împletire hexagonale și a domeniilor sale de aplicare.

***Cuvinte-cheie**: simulare Matlab, conversia coordonatelor, algoritm, unghiul de împletire, fracția volumică*

INTRODUCTION

Braided fabrics are widely used in different industrial areas, because of its high specific strength, specific modulus and damage tolerance [1–3]. Traditionally, there are two methods to fabricate braided fabrics, one is track-column braiding, and the other one is rotary braiding [4–6]. Researchers study on fabric fabrication process and fabric structures in order to analyse the mechanical properties of braided fabrics. Frank Ko put forward the hexagonal braiding theory in 2008, which used hexagonal horngears as drive mechanism to move yarn carriers and fabricate fabrics. And then, University of British Columbia and RWTH Aachen University built the hexagonal braiding loom, and gave the basic definition of hexagonal braiding. Theoretically, hexagonal braiding technology can be utilized in many complex shapes fabrics braiding, and it has great potential in net-shaped preform fabrication [7–8]. However, the fabric structures and the characterization of hexagonal fabrics have not been studied further yet. In order to study the characterization of hexagonal fabrics, it needs to establish the model of hexagonal fabrics. Based on Matlab, the fabric structure is easy to be simulated in the software. In some references, the simulation process is complicated, because varied programming tools were combined together, which decreased the flexibility of structural model establishment [9–11]. In this paper, a conversion algorithm was proposed to simulate the hexagonal braiding structure according to the characterization of circular hexagonal fabric.

METHOD AND DISCUSSION

The hexagonal braider and braiding principles

The yarn carriers are aligned in gaps among hexagonal horngears, as shown in figure 1, *a*. When motors drive horngears, yarn carriers will move in the gaps and make the yarns intertwine in space to fabricate fabric. The hexagonal braider in University of British Columbia (UBC) was shown in figure 1, *b*. Generally, researchers tried to establish the yarn model through spatial coordinates on yarn trajectory, and the spatial coordinates were determined by every position of yarn carriers' movement and the take-up speed [12–13]. So it needs to confirm horngear rotation sequence, initial positions of yarn carriers and take-up speed for hexagonal fabric structure establishment. And then, these parameters could be converted into spatial coordinates (x_i, y_i, z_i) on yarn trajectories. The arrangement of horngears and yarn carriers was shown in figure 1, *c*, there were 30 yarns arranged circularly on the bedplate. The braiding principle is that the horngears 1-1, 1-3 and 1-5 rotated clockwise, and then horngears 1-2, 1-4 and 1-6 rotated counter-clockwise, these two groups of horngears cannot rotate at the same time, but rotated one by one. The angles of every rotation are 60 degrees. So the paths of yarn carriers can be traced (figure 1, *d*), all 30 yarns would move as two groups equally in two close paths, red path and blue path.

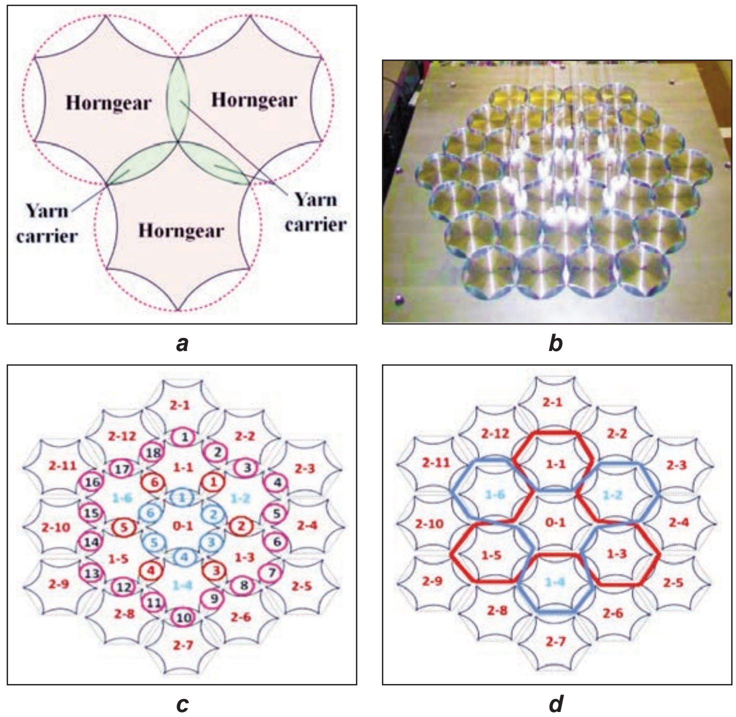

Fig. 1. Hexagonal braiding method: *a* – relationship of horngears and yarn carriers; *b* – hexagonal braider; *c* – braiding bedplate and yarn carriers' positions; *d* – paths of yarn carriers

The coordinate system of braiding bedplate and yarn trajectory fitting

Following the sequence of horngears rotation, yarn carriers move between horngears, which can drive yarns intertwined into fabric. Therefore, during braiding process yarn carrier position of every step can be converted to correspondent coordinates to depict the yarn's trajectory. The coordinates of every position on the braiding bedplate can be defined as in figure 2, *a*. The yarns moved along with yarn carriers, which included the planar movement on plane *xoy* and the vertical movement along *z* axis, and also, the take-up speed was related to the stitch length and braiding angle of fabric. If the yarns in fabric were defined as $yarn_i$, the coordinates of $yarn_i$ on plane *xoy* could be defined as (x_i, y_i), while the coordinate of *z* axis was defined as *b*. So the spatial coordinates of $yarn_i$ at step *N* is (x_i, y_i, b), and the matrix size of $yarn_i$ in one braiding cycle was $3 \times N_{max}$. All the coordinates along yarns were connected with short lines to create original yarns trajectories. The original yarn trajectories were only based on the movement steps of yarn carriers and not smooth. So the B-spline was utilized to fitting yarn trajectories to make them smoother through extract data points in coordinates matrix (figure 2, *b*).

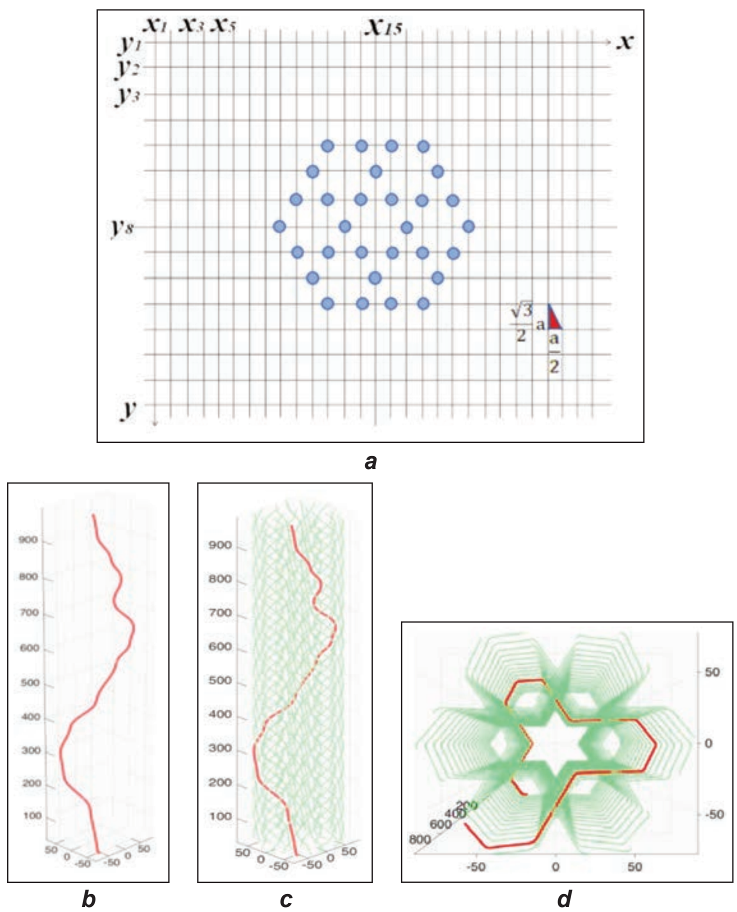

Fig. 2. Bedplate geometry and fabric model: *a* – coordinates of bedplate; *b* – single yarn; *c* – side view of fabric; *d* – top view of fabric

The fabric model establishment and coordinates conversion

If the shape of the yarns' cross-sections was round and had the same diameters along the yarn, the part of original model was shown as in figure 2, *c*. In this model, the distance between yarns was large, which only could stand for the intertwining pattern of yarns. Considering the jamming of fabric would lead to the yarns' displacement in radial direction of cross-section, the conversion function for yarns in radial direction should be:

$$\begin{cases} x' = \rho_{i1} \cdot x \cdot \cos(g) - \rho_{i1} \cdot y \cdot \sin(g) \\ y' = \rho_{i2} \cdot x \cdot \sin(g) + \rho_{i2} \cdot y \cdot \cos(g) \\ z' = \rho_{i3} \cdot z \end{cases} \quad (1)$$

Where $[x', y', z']^T$ and $[x, y, z]^T$ were the yarns' coordinates after and before conversion, g was the conver- sion angle and ρ_{i1}, ρ_{i2}, ρ_{i3} were conversion coefficients.

In braided fabric, the stitch length was related to yarn jamming condition and braiding parameter. If the i data point on yarn was A_i, F_1 and F_2 were the tension of point A_i on the yarn, A_{i+1} and A_{i-1} were two points adjacent to A_i. The direction of F_c was the same as bisector of $\angle A_{i+1}A_iA_{i-1}$, and the direction of displacement X_{FA} (figure 3, *a*). The plane β including lines A_iA_{i+1} and A_iA_{i-1}, and the plane α including A_iA_i' was vertical to β, so the intersecting line of plane α and plane β was the conversion direction of original data point A_i, and $coff\_z_i$ was conversion coefficient. The data point A_i' was the result of point A_{i-1} revolved around A_i by angle φ. After conversion, A_{i-1} became A'_{i-1}. Line $A_{i-1}A_i$ was not coincident to z axis, so it was converted into l_{xoz} (figure 3, *b*), the relationship was shown as:

$$\gamma = <\overrightarrow{l_{xoy}}, \vec{x}> = \arccos \frac{\overrightarrow{l_{xoy}} \cdot \vec{x}}{|\overrightarrow{l_{xoy}}| \cdot |\vec{x}|} = \arccos \left(\frac{\overrightarrow{(x'_{A_{i-1}} - x_{A_i},\, y'_{A_{i-1}} - y_{A_i})} \cdot \vec{x}}{|\overrightarrow{(x'_{A_{i-1}} - x_{A_i},\, y'_{A_{i-1}} - y_{A_i})}| \cdot |\vec{x}|} \right) \quad (2)$$

$$\begin{cases} x''_{A_{i-1}} = x'_{A_{i-1}} \cdot \cos(\gamma) - y'_{A_{i-1}} \cdot \sin(\gamma) \\ y''_{A_{i-1}} = x'_{A_{i-1}} \cdot \sin(\gamma) - y'_{A_{i-1}} \cdot \cos(\gamma) \\ z''_{A_{i-1}} = z'_{A_{i-1}} \end{cases} \quad (3)$$

$$\beta = <\overrightarrow{l_{xoz}}, \vec{z}> = \arccos \frac{\overrightarrow{l_{xoz}} \cdot \vec{z}}{|\overrightarrow{l_{xoz}}| \cdot |\vec{z}|} = \arccos \left(\frac{\overrightarrow{(x''_{A_{i-1}} - x_{A_i},\, z''_{A_{i-1}} - z_{A_i})} \cdot \vec{x}}{|\overrightarrow{(x''_{A_{i-1}} - x_{A_i},\, z''_{A_{i-1}} - z_{A_i})}| \cdot |\vec{x}|} \right) \quad (4)$$

$$\begin{cases} x'''_{A_{i-1}} = x''_{A_{i-1}} \cdot \cos(\beta) + z''_{A_{i-1}} \cdot \sin(\beta) \\ y'''_{A_{i-1}} = y''_{A_{i-1}} \\ z'''_{A_{i-1}} = -x''_{A_{i-1}} \cdot \sin(\beta) + z''_{A_{i-1}} \cdot \cos(\beta) \end{cases} \quad (5)$$

Where γ was the intersecting angle of line $A_{i-1}A_i$'s projection on plane *xoy* and *x* axis. After conversion, new data points Q_{A1} and Q_{A2} were got as:

$$Q_{A1}A_1 = A'''_{i-1}A_i \cdot coff\_z_i \quad (6)$$

$$\begin{cases} X_{QA2} = Y_{QA1} \\ X_{QA2} = Y_{QA1} \cdot \cos(\varphi) - Z_{QA1} \cdot \sin(\varphi) \\ X_{QA2} = Y_{QA1} \cdot \sin(\varphi) + Y_{QA1} \cdot \cos(\varphi) \end{cases} \quad (7)$$

Finally, the optimized model was established as shown in figure 3, *c* and figure 3, *d*.

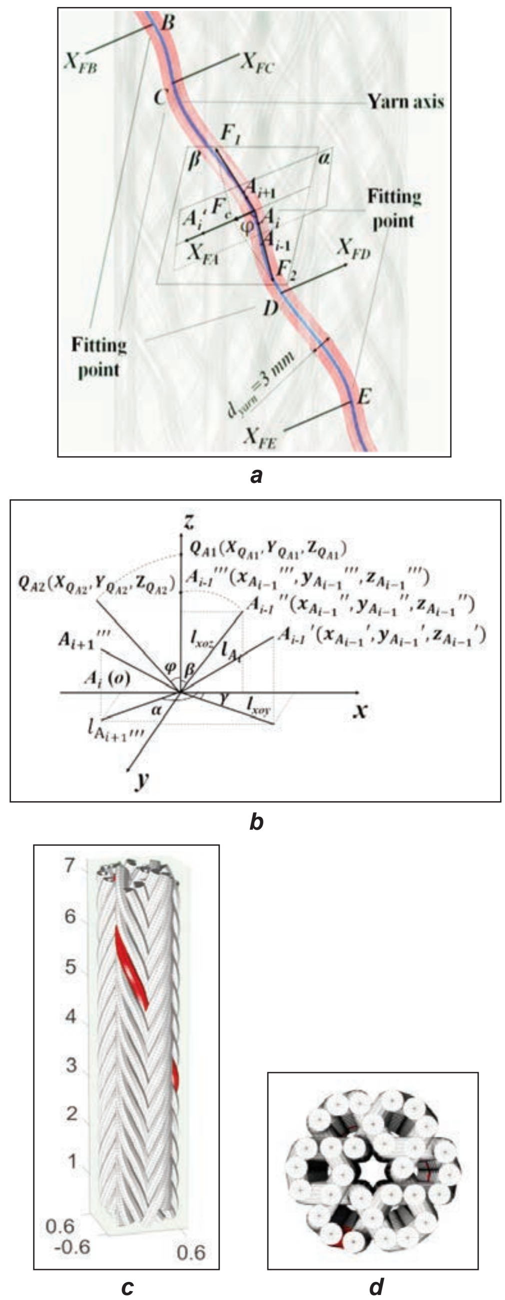

Fig. 3. Fabric model optimization: *a* – fabric surface; *b* – coordinate system; *c* – side view; *d* – top view

The braiding angle and volume fraction

After conversion, the variation of fabric's braiding angle θ could be measured in order to validate the conversion algorithm, and the measurement definition was shown as:

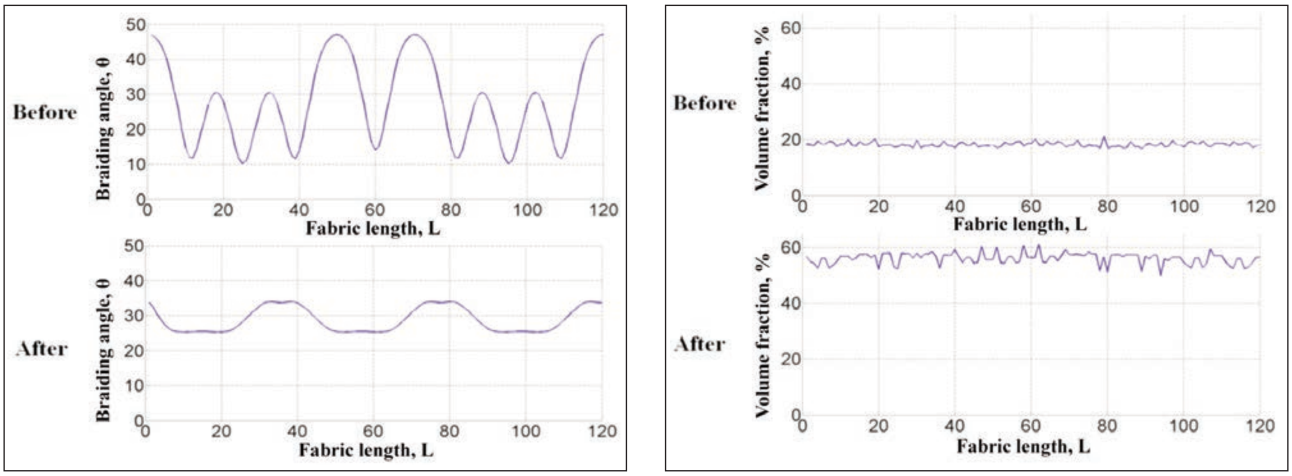

Fig. 4. Braiding angle and fiber volume fraction: *a* – braiding angle variation before and after conversion; *b* – V_f before and after conversion

$$\theta = \angle \overrightarrow{A_{i-1}A_i}, \vec{z} \quad (8)$$

$$\vec{z} = (0, 0, 1) \quad (9)$$

The braiding angle varied periodically and had three wave crests in figure 4, *a*. After coordinates conversion, the range of angle fluctuation reduced from about 35 degree to about 10 degree.

Fiber volume fraction was a parameter to show the characterization of fabric, theoretically, we can use ratio of areas of yarns cross-section and fabric cross-section to calculate it as:

$$V_f = \aleph \frac{A_y}{A_f} \quad (10)$$

Where V_f was fiber volume fraction of fabric, A_y and A_f were areas of yarn cross-section and fabric cross-section, $\aleph$ was fiber packing ration and the value was 0.785. And the fiber volume fraction was improved from about 18% to about 56% as shown in figure 4, *b*, which meant the fabric structure was more compact.

CONCLUSION

In this paper, the process of hexagonal braiding was articulated and a circular hexagonal fabric model was established in Matlab. Based on coordinate conversion algorithm, the original model was optimized. It seemed that the intuitive image, braiding angle and volume fraction of the model were improved significantly after coordinate conversion, which validated the availability of conversion algorithm and could give reference to the foreseeable study on other properties of hexagonal braided fabrics.

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