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Abnormal Shape Mould Winding

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Abstract

A theory of composite material patch winding is proposed to determine the winding trajectory with a meshed data model. Two different conditions are considered in this study. One is Bridge condition on the concave surface and the other is Slip line condition in the process of patch winding. This paper presents the judgment principles and corresponding solutions by applying differential geometry theory and space geometry theory. To verify the feasibility of the patch winding method, the winding control code is programmed. Furthermore, the winding experiments on an airplane inlet and a vane are performed. From the experiments, it shows that the patch winding theory has the advantages of flexibility, easy design and application.

Keywords: filament winding; fiber technology; composite material; airplane inlet; vane

1 Introduction

In recent years, composite materials have been found wide application in the fields of aerospace industry, weapon manufacturing industry and chemical industry thanks to its strong design ability, high carrying capacity, high reliability, light weight and low cost. In the previous researches, most of researchers' work was focused on the model equations[1-7]. However, with the development of technology, the abnormal shape mould winding is drawing more attention because some special parts, such as airplane inlets and vanes, can hardly be produced with traditional winding methods. This paper aims at tackling the problem of abnormal shape mould winding with the patch winding method. Different from the traditional winding methods, it is not founded on the base of model equations, but establishes a data model after meshing the mould and determines the winding trajectory by the points on the mould surface.

2 Patch Winding

The node coordinates can be obtained from the meshed mould surface. In winding, it is important to achieve the doffing points, the points where the fiber falls on the mould surface. The doffing points can be found following the basic winding theory to ensure that the Slip line condition and the Bridge condition will not happen during winding. Obtained according to the doffing points through coordinate change, the spinning points are used to enable NC code to be output to control the winding trajectory. This winding design principle is called patch winding theory.

To obtain the original doffing points before winding, exist two ways: one is to choose any point at one end of the mould; the other is to choose the point on the mould surface where the Slip line condition and the Bridge condition tend to occur. Generally speaking, the first method is applied to the normal non-gyration mould, while the second is for

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those moulds whose surfaces are extremely irregular.

The following work is to find the other doffing points after the original doffing points have been determined. As shown in Fig.1, point A is taken as the original doffing point in order to explain the patch winding theory. If the winding fiber arrives at B, the next doffing point C can be obtained from the first quadrant in X_1BY_1 coordinate system to ensure that no Slip line condition and Bridge condition would happen at B. And then, the new doffing point C is taken as the origin of the new coordinate system. The straight line CX_2, which is parallel with mould axis through C, is taken as X- axis. The Y-axis is the straight line CY_2, which, in the mould, is in a tangential plane at C and in a vertical plane about the line CX_2. Fig.1 shows the directions of the two lines. By repeating the process of finding the point C, the other doffing points (for example, point D etc.) can be found. The winding trajectory design is finished after all the doffing points have been found.

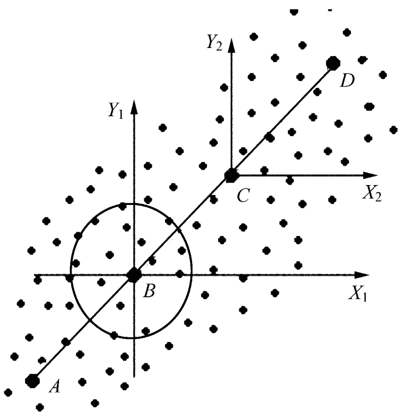

Fig.1 Patch winding theory.

2.1 The judgment of Slip line

Slip line is a phenomenon that the fiber cannot remain stable at the doffing point on the mould surface or on the wound fiber. A relative motion exists between the fiber and the mould surface or the wound fiber. The Slip line condition depends not only on the degree of the winding angle, but also on the superficial friction coefficient. The following illustrates the detailed analysis.

As shown in Fig.2, $P_1P_2 = \Delta s$ is a tiny section of fiber on the curved surface $S(u, \theta)$, with P being its midpoint and $\boldsymbol{T}_1$, $\boldsymbol{T}_2$ the tension vectors at the points P_1 and P_2 respectively. $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ are the tangential vector and the main normal one across the point P on the fiber trajectories, respectively. $\boldsymbol{n}$ is the normal vector across P on the curved surface (pointing to the outside of the mould). $\boldsymbol{v} = \boldsymbol{n} \times \boldsymbol{\alpha}$ is the unit vector through point P on the tangential plane. $\boldsymbol{e}_1$ is the unit tangential vector of the parameter curve u across point P, φ the angle between $\boldsymbol{e}_1$ and $\boldsymbol{\alpha}$, the winding angle at point P, $\boldsymbol{F}_\mathrm{f}$ the friction between the fiber and the mould surface or the wound fiber, $\boldsymbol{F}_\mathrm{n}$ the reacting normal force exerted on the fiber by the mould.

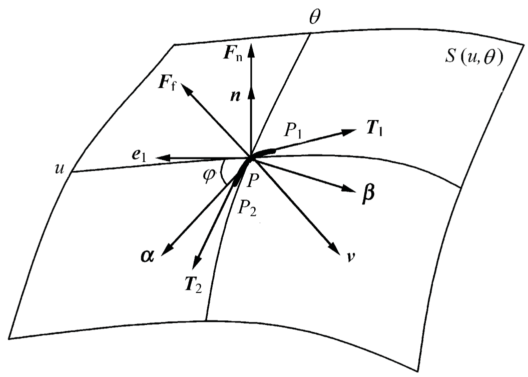

Fig.2 Force analysis of mini fiber.

To keep the fiber stable on the mould surface, the following requirements must be met

$$\boldsymbol{F}_\mathrm{f} + \boldsymbol{F}_\mathrm{n} + \boldsymbol{T}_1 + \boldsymbol{T}_2 = 0 \tag{1}$$

The fiber weight is so small that no attention should be attached to its gravity. After deduction[1], Eq.(1) is developed into

$$\sum_{i=1}^{2} \boldsymbol{T}_i = Tk_\mathrm{g}\mathrm{d}s \cdot \boldsymbol{v} + Tk_\mathrm{n}\mathrm{d}s \cdot \boldsymbol{n} \tag{2}$$

Define the force in the direction v as

$$\boldsymbol{F}_\mathrm{s} = Tk_\mathrm{g}\mathrm{d}s \cdot \boldsymbol{v} \tag{3}$$

Define the force in the direction n as

$$\boldsymbol{F}_\mathrm{p} = Tk_\mathrm{n}\mathrm{d}s \cdot \boldsymbol{n} \tag{4}$$

It can be found that $\boldsymbol{F}_\mathrm{s}$ is the force that makes the fiber move on the mould surface, while $\boldsymbol{F}_\mathrm{p}$ the force making it adhere to or depart from the mould.

In order to keep the fiber stable on the mould surface, the requirements of the following Eq.(2) must be met.

$$|\boldsymbol{F}_{\mathrm{s}}| \leqslant |\boldsymbol{F}_{\mathrm{f}}|_{\max} = |\boldsymbol{F}_{\mathrm{p}}| \cdot \mu_{\max} \tag{5}$$

where $\mu_{\max}$ is the maximal friction coefficient between the fiber and the mould or the wound fiber.

By deleting $|T\mathrm{d}s|$ from Eq.(3) and Eq.(4), these two equations can be developed into

$$\left.\begin{aligned} |\boldsymbol{F}_{\mathrm{s}}| = |\boldsymbol{F}_{\mathrm{p}}| \cdot \frac{|k_{\mathrm{g}}|}{|k_{\mathrm{n}}|} \\ k_{\mathrm{n}} \neq 0 \end{aligned}\right\} \tag{6}$$

Thus, in order to make the fiber remain stable without the Slip line condition, the following requirements should be met:

$$k_{\mathrm{n}} = 0 \quad \text{or} \quad \begin{cases} \dfrac{|k_{\mathrm{g}}|}{|k_{\mathrm{n}}|} \leq \mu_{\max} \\ k_{\mathrm{n}} \neq 0 \end{cases} \tag{7}$$

Taking the specific condition in patch winding into account, the normal curvature k_{n} and the geodesic one k_{g} on the surface can be acquired with data model. The two curvatures through B on the mould surface can be acquired from Fig.3. The points P_1 and P_2 are the two points closest to the point B. If the mesh points on the surface are dense enough, the distance between P_1 and P_2 may be small enough as to be neglected compared with the mould radius, which enables P_1 and P_2 to be considered on the same plane. As a result, the normal vector $\boldsymbol{n}$ can be determined by P_1, P_2 and B in Fig.3. Then, in Fig.1, the tangential vector $\boldsymbol{\alpha}$ of fiber trajectory at the point B can be determined by B and C. At last, the vice normal vector $\boldsymbol{\gamma}$ at B can be found through A, B and C. $|k_{\mathrm{g}}/k_{\mathrm{n}}|$ can be obtained from Eq.(10), which is derived from Eq.(8)[8] and Eq.(9).

$$\boldsymbol{\beta} = \boldsymbol{\gamma} \times \boldsymbol{\alpha} \tag{8}$$

$$\theta = \arccos \frac{\boldsymbol{n} \cdot \boldsymbol{\beta}}{|\boldsymbol{n} \cdot \boldsymbol{\beta}|} \tag{9}$$

$$\frac{|k_{\mathrm{g}}|}{|k_{\mathrm{n}}|} = \tan\theta \tag{10}$$

where θ is the angle between the normal vector $\boldsymbol{n}$ of the tangential plane and the main normal vector $\boldsymbol{\beta}$ of the osculation plane.

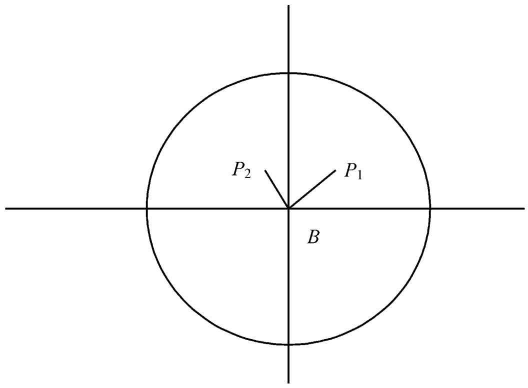

Fig. 3 Normal curvature and geodesic curvature.

If the value of tan θ is zero, k_{n}=0 can be deduced. In this case, the winding trajectory is geodesic, which means a stable winding. Based on the friction coefficient and the result achieved from Eq.(10), it is easy to judge whether Slip line condition occurs as to make further decision on the winding angle and the winding path.

2.2 The judgment of Bridge condition

A Bridge condition[9-10] happens when the fiber departs from the mould surface as shown in Fig.4.

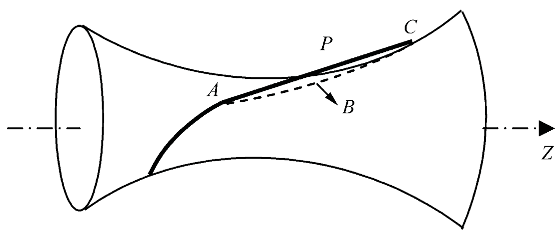

Fig.4 Bridge condition.

The line AC is the wound fiber with Bridge condition. Points A, B and C are doffing points, and P is the point randomly chosen on the line AC. A Bridge condition will occur if there is a distance between the mould and the fiber at point B.

During winding, the Bridge condition is the major factor affecting the capacity of weight tolerance and usage life. Generally speaking, to eliminate Bridge condition, there are two common methods as follows:

(1) To increase the winding angle. Usually, this

is the most effective way to avoid Bridge condition. Therefore, it is the very method with which the paper will use to eliminate the Bridge condition. It should be noted that with a winding angle big enough, the resistance force of a product to axial intensity would be reduced.

(2) To optimize the design. In avoidance of influencing the performance of the product being wound, the sharp convexes or concaves on the mould surface should be obviated or lessened in the design.

(3) To use the paving method[11-12]. By using the paving technology, the tape-shaped fiber can be paved onto the mould surface. The rolling motion of the paving tool would solve the Bridge condition effectively.

In order to solve the problem of Bridge condition, the location where the Bridge condition detected occurs should be at first. With an accurate data model established and the detailed mould surface information obtained, the potential Bridge condition could be detected and well controlled by software. An occurrence of a Bridge condition would suspend the wound fiber between A and C during winding. That is to say, the distance between B and the mould axis should be shorter than that from P to the mould axis. As a result, the fiber Bridge condition would not occur at the doffing point B only if Eq.(11) is met.

$$y_B{}^2 + z_B{}^2 > y_P{}^2 + z_P{}^2 \tag{11}$$

3 Experiments

3.1 Program

To verify the winding theory, the codes are programmed following the patch winding theory. Firstly, based on the design requirements, the data model is established by using CAD/CAM software; then the model is meshed by using ANASYS software. All the node coordinates are output and processed in an orderly way. Finally, following the patch winding theory, the nodes without the Slip line condition and the Bridge condition are chosen as the track doffing points by referring to the original doffing points and the winding angle.

When seeking for the appropriate doffing points, the quadrant of the next doffing point should be determined according to the present doffing points and the winding angle. Then, the inquiry scope should be decided according to the set-up maximal step. All the nodes would be judged stepwise until the most stable doffing point is found. Taking the uncertain condition factors into account, the winding simulation is fulfilled. After having disposed the doffing points into NC code for a winding tool, the practical winding experiments on the winding tool are performed as shown in Fig.5.

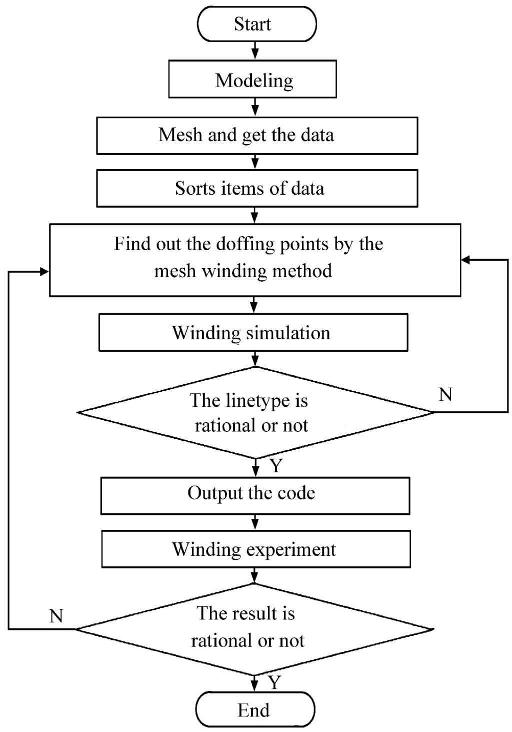

Fig.5 Program frame.

The program includes following three main modules:

(1) To calculate the stable trajectory. With the most appropriate doffing points found following the patch winding theory, all the doffing points on the same track are connected into one to-and-fro on the winding trajectory. The second original doffing point is found by choosing a point from the first original point by one tape width. By using the same

winding angle, the process is repeated until the mould is covered with the fiber.

(2) To simulate the winding trajectory. According to the doffing point track, the winding process simulation is fulfilled to verify whether the trajectory is reasonable by means of three-dimensional animation or not.

(3) To regulate and output the winding data. The mould reference frame should be translated into the machine tool reference frame, and, accordingly, the doffing points are translated into the spinning points. Then the codes could be programmed on the basis of the spinning point coordinates and the NC codes could be output in a certain form to control the tool.

3.2 Mould winding

In order to verify the feasibility of patch winding, two experiments are conducted. The two experimental moulds are of the airplane inlet and the vane, which are of non-gyration and unable to be wound by using the traditional winding theory. Shaped as an "S", the airplane inlet is extremely irregular and intricate to be described by an equation. Although the vane body can be described with two different equations, it does not belong to gyration mould and its tail part has an abnormal shape. Therefore, the two moulds cannot be wound with the traditional winding methods.

(1) Airplane inlet winding

This experiment requires that the tangent length from the spinning point to the doffing point should be constant. Thus the trajectory of the spinning point is not a straight line but a plane curve. The spinning point moves forward toward the axe in accordance with the changes of the inlet outline as the main axe rotates. Fig.6 and Fig.7 show the simulation picture and the experimental one, respectively, at the designed angle of 70°.

In this experiment, the axes cooperate well and run stably, but collision is likely to happen between the spinning mouth and the mould, which means the phase of the original points must be strictly controlled.

(2) Vane winding

To verify the practicability of the patch winding method, another experiment is conducted with a vane. Fig.8 and Fig.9 show its simulation and experimental results respectively.

The difficulty of the vane winding lies in the tail part of the mould due to its highly irregular shape hard to be described with an equation. The results of the simulation and the experiment have shown the effectiveness of patch winding method in solving the problem.

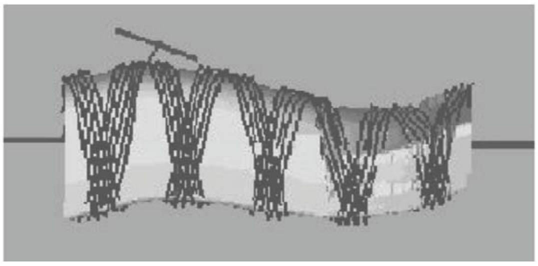

Fig.6 Inlet winding in simulation.

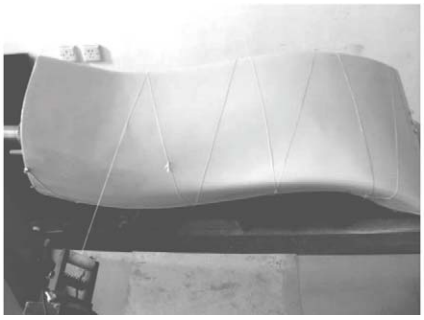

Fig.7 Inlet winding in experiment.

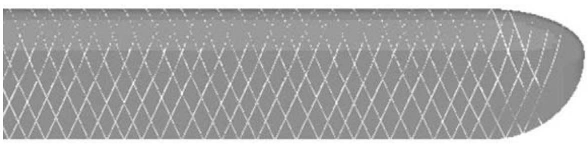

Fig.8 Vane winding in simulation.

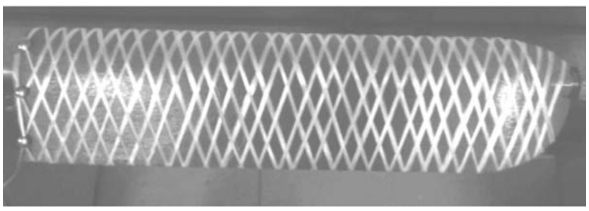

Fig.9 Vane winding in experiment.

4 Results and Discussion

4.1 The advantage of patch winding

(1) It is evidenced that the method is easy to be put into practice. Because of the mould surface friction modulus, the winding angle can change with different doffing points of the mould surface. The winding angle can be fine tuned according to the mould surface, which provides great flexibility for the line design and pressure loading capacity design.

(2) It is easy to design axial and radial intensity. The fiber direction changes along with the winding angle. At the same time, the intensity direction is decided by fiber direction. As a result, it is easy to control the intensity of a product by changing winding angle.

(3) Following the basic winding theory, this method is based on easily obtainable surface nodes, which makes the design process timesaving and convenient, and, moreover, easy to learn and use.

4.2 The shortage of patch winding

It is clear that to acquire discrete points from a mould surface, especially for an abnormal mould proves to be a very burdensome and tedious work. The line type and product quality rely on the point density. Fig.10 shows the trend that gyration error changes with point density and mould size.

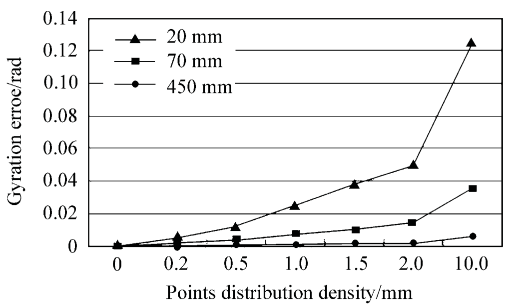

Fig.10 Gyration error changing trend line.

The gyration error turns bigger as these points become more scattered. On the condition that the number of the points is the same, the bigger becomes the mould radium size, the more influences will the point distribution density bring. Therefore, it is a key problem in the future research to acquire the useful abnormal mould surface coordinate more quickly and accurately.

5 Conclusions

Focusing on the characteristics of patch winding, the Slip line condition and the Bridge condition are analyzed in detail and the judgment principles are proposed as well. The feasibility of the patch winding is verified in simulation and winding experiments of two airplane typical parts, an inlet and a vane. Besides, this paper provides certain theoretical evidence for the composite material patch winding of the abnormal shape mould.

The analysis performed herein is only a part of an ongoing research program. Improving this theory will be paid much more attention in the further work.

References

[1] Fu H Y, Huang K B, Zhu F Q, et al. Boundary conditions and stability formulas for the non-geodesic winding. Journal of Harbin Institute of Technology 1996; 28(2): 125-129. [in Chinese]

[2] Wang Z J, Li F, Liu J C. Study design for cone structure. FRP/CM 2005(2): 34-37. [in Chinese]

[3] Beakou A, Mohamed A. Influence of variable scattering on the optimum winding angle of cylindrical laminated composites. Composite Structures 2001; 53(3): 287-293.

[4] Zhao L Y, Mantell S C, Cohen D, et al. Finite element modeling of the filament winding process. Composite Structures 2001; 52(3): 499-510.

[5] Sala G, Cutolo D. Heated chamber winding of the thermoplastic powder-impregnated composites: Part 2. Influence of degree of impregnation on mechanical properties. Composites 1996; 27(5): 393-399.

[6] Henninger F, Hoffmann J, Friedrich K. Thermoplastic filament winding with online-imprehnation: Part B. Exprimental study of processing parameters. Composites 2002; 33(12): 1677-1688.

[7] Polini W, Sorrentino L. Winding trajectory and winding time in robotized filament winding of asymmetric shape parts. Journal of Composite Material 2005; 39(15): 1391-1411.

[8] Wang X F, Fu H Y, Han Z Y. Analysis and realization of patch winding method for complex form. Aerospace Materials and Tech-

Technology 2006; 36(6): 39-41.[in Chinese]

[9] Han Z Y. Research on CAD/CAM technology for filament winding composites and its application. Dissertation for the Doctor Degree of Harbin Institute of Technology. [in Chinese]

[10] Wang X F, Fu H Y, Han Z Y. The validation of the feasibility of abnormal form patch winding. Materials Science Forum 2006; 532-533: 129-132.

[11] Xu Z, Wu Y C, Tian H F. Research of fiber placement molding technology. Fibre Reinforced Plastic/Composites 2002; (5): 44-46. [in Chinese]

[12] Mark A L, Steve F B, Mark B G, et al. Manufacturing flat and cylindrical laminates and built up structure using automated thermoplastic tape laying, fiber placement, and filament winding. SAMPE Journal 2003; 39(2):30-38.

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