Pressure Angle Effect of Concave Cylinder Surface on Motion Characteristics of Fiber Placement Machine

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(Received 16 April 2019; revised 23 December 2019; accepted 17 December 2020)

Abstract: There are amounts of issues to be resolved in the process of designing the fiber placement trajectory of the cylindrical component, such as the interference between the machine and the component and the over-travel of the axis of rotation on the fiber placement head. When the pressure on the cylinder surface inclines in a certain direction or at an angle within the normal plane, the motion characteristics of the rotation axis will be different. This paper analyzes the pressure angle effect of the concave cylinder surface on the motion features of a fiber placement machine. The placement area is enlarged by tilting pressure with the same lifting stroke, which is significant in preventing interference and selecting post-processing algorithm.

Key words: composite materials; fiber placement; inclination angle pressure; cylinder; postprocess

CLC number: TB332 **Document code:** A **Article ID:** 1005-1120(2020)06-0898-05

0 Introduction

Cylindrical component is one of the most common structural components in the field of automatic fiber placement. In the field of the trajectory design and post-processing technology of the cylindrical component, numerous scholars have carries out a large number of valuable research work[1-3]. However, as for the real production and processing, it was seldom mentioned that there is an interference problem between the fiber placement head and the concave cylinder with a small radius. Due to the differences of effective approach angle and departure angle of fiber placement head, on the condition that the fiber placement head is vertically pressed on the concave cylinder, the contact interference is likely to emerge between parts of the fiber placement head and the mold[4-5] based on the larger fiber placement head and the smaller cylindrical radius in the circumferential direction[6]. In order to ensure the fiber placement to proceed smoothly, during trajectory design, inclination pressure method is proposed to replace the vertical pressure. Depending on the interference situation, fiber placement head would lean forward or backward at a certain angle. However, on the basis of the inclination angle, rotation range of the fiber placement head in real-processing is much greater than before[7-8]. In this paper, we analyzed the problem and put forward a method to make a better alternative between normal vector pressure and inclination angle pressure.

As to the trajectory post-process of cylindrical concave surface, the vectors are involved along the 45° trajectory are shown in Fig.1. At any trajectory point p_i, $\boldsymbol{F}$ represents the normal vector, $\boldsymbol{Q}$ the tangent vector, $\boldsymbol{FF}$ the auxiliary normal vector , and $\boldsymbol{QF}$ the inclination angle vector. For the convenience of the following analysis, α represents the

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How to cite this article: WANG Xianfeng, GAO Tiancheng. Pressure angle effect of concave cylinder surface on motion characteristics of fiber placement machine[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(6): 898-902.

http://dx.doi.org/10.16356/j.1005-1120.2020.06.007

cylinder circumferential angle, β the laying angle, and θ the inclination angle[9-11].

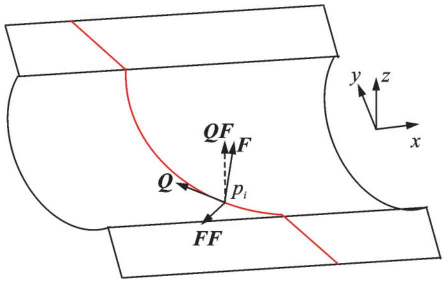

Fig.1 Schematic diagram of cylinder pressure

1 Rotation Range Analysis with Inclination Angle Pressure

At the trajectory point P, the normal vector F is (n_x, n_y, n_z). Its detailed expression of the normal vector can be achieved easily

$$(n_x, n_y, n_z) = (0, \cos\alpha, \sin\alpha) \tag{1}$$

The expression of tangential vector Q is (t_x, t_y, t_z)

$$(t_x, t_y, t_z) = \left(\tan\beta, \cos\left(\alpha - \frac{\pi}{2}\right), \sin\left(\alpha - \frac{\pi}{2}\right)\right) \tag{2}$$

Auxiliary normal vector (f_x, f_y, f_z) could be derived from the multiplication cross of F and Q

$$(f_x, f_y, f_z) = (n_x, n_y, n_z) \times (t_x, t_y, t_z) \tag{3}$$

The inclination vector is (q_x, q_y, q_z). According to Fig.1, if θ is the angle of inclination, the module of the normal vector can be described as $\cos\theta$, and the module of tangent vector is $\sin\theta$. Then normal component could be expressed by $(0, \cos\theta \cdot n_y, \cos\theta \cdot n_z)$, while the Tangent vector is $(\sin\theta \cdot t_x/r, \sin\theta \cdot t_y/r, \sin\theta \cdot t_z/r)$, $r = \sqrt{t_x^2 + t_y^2 + t_z^2}$, And inclination vector can be expressed as

$$(q_x, q_y, q_z) = (\sin\theta \cdot t_x/r, \sin\theta \cdot t_y/r + \cos\theta \cdot n_y, \sin\theta \cdot t_z/r + \cos\theta \cdot n_z) \tag{4}$$

When plugging Eq.(1) and Eq.(2) into Eq.(3), we can get

$$(f_x, f_y, f_z) = \left(\frac{\sin\theta \cdot \tan\beta}{r}, \frac{\sin\theta \cdot \sin\alpha}{r} + \cos\theta \cdot \cos\alpha, \frac{-\sin\theta \cdot \cos\alpha}{r} + \cos\theta \cdot \sin\alpha\right) \tag{5}$$

The fiber placement head comprises three rotation axes $A/B/C$ and three translation axes $X/Y/Z$. The rotation center of the C-axis is vertically downward. The B-axis rotation center line intersects vertically with the C-axis rotation center line. These axes B and C determined fiber placement head located along the normal vector of trajectory points[12-14]. In this paper, in order to avoid interference, instead of normal vector pressure on the mold, we choose the placement head along inclination vector. Therefore, it is necessary to justify the fiber placement head parallel to the inclination vector. $\angle C$ represents rotating angle, and $\angle B$ the swing angle. Theoretically the combined movement of B and C makes the posture of fiber placement head universal available[15-16]. The head structure is shown in Fig.2.

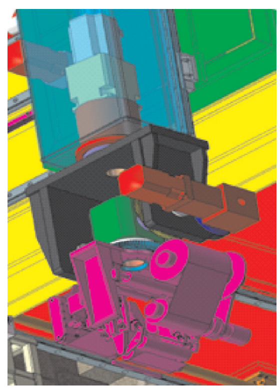

Fig.2 Mechanical structure schematic diagram of rotating shaft

For the C-axis, it is installed at the end of translational axis Z and rotates around Z-axis. So its rotation angle is determined by q_x and q_y.

First of all, $q_x = \dfrac{\sin\theta \cdot \tan\beta}{r}$. For a cylinder, the geodesic trace is a helix. Therefore, the laying angle β is constant. The inclination angle θ is determined by the structure of fiber placement head. The inclination angle is used to keep the free space in front of the roller and the space in the back equally. So the inclination angle θ is also constant during laying. Therefore, the rotation range of C-axis is determined only by the Y-direction component q_y.

Next, $q_x = \dfrac{\sin\theta \cdot \sin\alpha}{r} + \cos\theta \cdot \cos\alpha$, where α represents the cylinder circumferential angle and it varies with the point position on the trajectory. If β

equals to 45°, the inclination angle θ is 10°, then r=1.414 2, sinθ=0.173 6, cosθ=0.984 8, q_y= 0.122 8sinα+0.984 8cosα. we can get

$$q_y = 0.128\,8\sin\alpha + 0.984\,8\cos\alpha \tag{6}$$

$$\angle C = \arctan\left(\frac{q_y}{q_x}\right) \tag{7}$$

$$\angle C = \arctan(\sin\alpha + 8.02\cos\alpha) \tag{8}$$

$\angle C$ varies with the cylinder circumferential angle α, as shown in Fig.3.

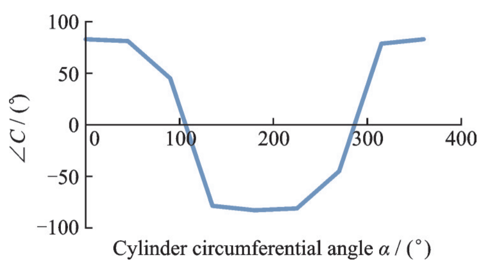

Fig.3 Angle variation of C-axis with inclination pressure method

For the B-axis, it is a swing axis, whose swing angle is determined by q_z. Based on the above analysis, we can get

$$q_z = \frac{-\sin\theta\cdot\cos\alpha}{r} + \cos\theta\cdot\sin\alpha \tag{9}$$

$$q_z = -0.122\,8\cos\alpha + 0.984\,8\sin\alpha \tag{10}$$

$$\angle B = \arccos(-0.122\,8\cos\alpha + 0.984\,8\sin\alpha) \tag{11}$$

The angle B also varies with the cylinder circumferential angle α, as shown in Fig.4.

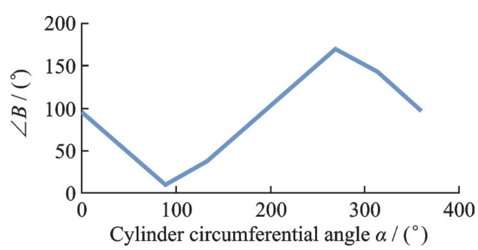

Fig.4 Angle variation of B-axis with inclination pressure method

2 Rotation Range Analysis with Vertical Normal Pressure

The analysis of vertical pressure is based on the normal vector (n_x, n_y, n_z). The specific expression is shown as follows.

In the case of vertical pressure, the C-axis is determined by n_x and n_y, which are normal vector components. Then it is easy to get the rotation angle expression of C-axis, as shown in Eq.(12).

$$\angle C = \begin{cases} 90^\circ & \cos\alpha \geqslant 0 \\ -90^\circ & \cos\alpha < 0 \end{cases} \tag{12}$$

Divided by the lowest line of the mold, the C-axis angle is 90° on one side of the cylinder mold, while the C-axis angle is −90° on the other side. The C-axis angle varies with the cylinder circumferential angle α. The trend is shown in Fig.5.

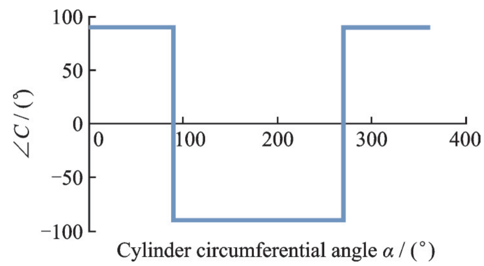

Fig.5 Angle variation of C-axis by vertical pressure method

The B-axis is the swing axis, which determined by the n_z component of the normal vector. The coordinate of B-axis could be got by

$$\angle B = \arccos(\sin\alpha) \tag{13}$$

Swing trend of B-axis is shown in Fig.6.

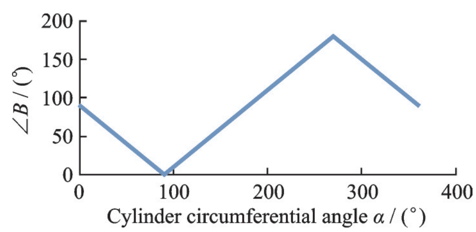

Fig.6 Angle variation of B-axis with vertical pressure method

3 Analysis and Discussion

From Figs. 5 and 6, we can get that the rotation ranges of C-axis and B-axis are very large, which is the same with the case of inclination angle pressure. But different from inclination angle pressure, the axis changes its rotation direction at one limit point, which may be the highest point or the lowest point, without any transient process. That provides operation space for post process. We can realize the placement head adjustment by keeping C-axis still and reversing B-axis. For cylinder surface, whose concave is generally upwards, the B-axis rotation angle would vary like the trend shown in Fig.7.

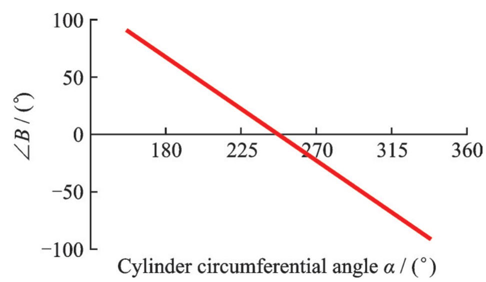

Fig.7 Trend of B-axis after adjustment

For inclination angle pressure, rotating axis of fiber placement head rotates gradually, but not finish its rotation at one point. Therefore, the above-mentioned adjustment method of vertical pressure is not applicable to the case of the inclination pressure. Once introduced, the fiber placement head may run just like drawing arc, which does exactly the opposite. The phenomenon will be discussed in detail in the later work.

4 Conclusions

For inclination pressure, large rotate angle of C-axis and B-axis is inevitable. However, as for vertical pressure, the rotation angle of C-axis and B-axis can be controlled within a small range. Therefore, for equipment design, in order to meet small rotation angle of the vertical pressure, it is necessary to achieve the B-axis rotation range up to [$-90°$, $90°$]. And in order to meet the rotating angle requirements of inclination pressure, it is necessary to design C-axis with a large rotation range, such as [$-180°$, $180°$] or more.

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Acknowledgements This work was supported by the Equipment Development Department Project of China (No. 41422010401) and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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Author contributions Dr. **WANG Xianfeng** designed the research, completed the experiment and wrote the manuscript. Mr. **GAO Tiancheng** contributed to data analysis, result interpretation and manuscript revision. All authors commented on the manuscript and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: SUN Jing)

弧形凹曲面倾斜施压的法向量变化趋势

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摘要：在设计圆柱形模具的纤维丝束铺放轨迹的过程中，有许多问题需要解决，例如机器与模具之间的干涉以及旋转轴在纤维铺丝头上的超程。当汽缸表面上的压力沿某个方向或法线平面内的某个角度倾斜时，旋转轴的运动特性将有所不同。本文分析了凹形圆柱表面对纤维铺放机运动特征的压力角影响，在升降行程不变的情况下，通过倾斜施压的方式扩大了铺放区域，这对于防止干涉和选择后处理算法具有重要意义。

关键词：复合材料；纤维铺放；倾斜施压；圆柱壳；后处理