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A Path Planning Algorithm of Closed Surface for Fiber Placement

Zhenyu Han
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, 150001, China
hanzy@hit.edu.cn

Qiangqiang Fu
Beijing Institute of Space Mechanics & Electricity, Beijing, 100076, China

Fan Yang
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, 150001, China

Yunzhong Fu
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, 150001, China

Hongya Fu
School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, 150001, China

***Abstract*—Fiber placement is an important processing technology for fabricating complex composite structures which offer many advantages over traditional structural material. In this paper, a novel path planning algorithm for closed surface is proposed, which take midline and edge of tows as placement curves alternatively instead of achieving midlines and edges separately. The iterative method for placement curves is introduced under the constraint of curvature of tows. The planning of placement curves for the whole surface is achieved by offsetting curve feature points, which aims to produce uniform lay-up of composite lamina, with controllable gap and overlap between subsequent tows. The method to calculate the number of tow is also put forward no matter the maximum tow number is even or odd. Finally, the proposed algorithm is verified by simulation with CATIA Component Application Architecture (CAA).**

Keywords- fiber placement; closed surface; path planning

I. INTRODUCTION

Fiber reinforced composites offer many advantages over traditional structural material, including strength-to-weight ratio, stiffness-to-weight ratio, and versatility in meeting design requirement [1]. Automatic fiber placement is an important manufacturing technique to fabricate complex composite parts, which are widely applied in aviation and aerospace industries in recent years. The manufacturing of fiber placement components is a procedure in which the placement head lays a number of tows on the surface of mandrel gradually to fill the whole surface in a certain direction. Closed surface composite parts account for a large proportion of composite structures in the aviation and aerospace industry, such as fuselage, inlet duct, etc. A reasonable placement path planning is a prerequisite to guarantee the mechanical property of the part and to facilitate fabricating process for the fiber placement machine.

The path planning for fiber placement in some published literatures was usually performed as follows. Firstly, the initial path was generated according to some principle; then, the next path was got by offsetting along the surface a distance of one tows-width. The edges of tows were calculated to determine the gap or overlap. Sometimes the tow edges were got first and placement paths for compaction roller were achieved by connecting the discrete midpoint of adjacent edges [2-5]. But these kind of algorithms were based on the assumption that the generated new path met the constraints of the placement angle or curvature, or some other algorithms would be adopted to verify the feasibility of new path.

In this paper, a fiber path planning algorithm is proposed, which calculate the placement path and tows' edge alternatively. The first placement curve is treated as the fiber path, and the second placement curve is treated as the edge of tows. The placement curves on the whole surface are generated in like manner. Variable-step method is used in the calculation of the placement curve to ensure the placement angle of this curve in the acceptable range. Meanwhile, the curvature of placement curve is also verified to guarantee that the curvature is smaller than the curvature limit to avoid wrinkling. This method not only ensures that each of the tow meets the limits of the fiber curvature, but also eliminates the mutual derivation process of the placement path and the edge line.

II. ALGORITHM FOR GENERATING PLACEMENT CURVE

A. The Reference Direction for Fiber Placement

To determine placement paths, a reference direction should be determined first. The method below is adopted to calculate the reference direction of placement in this study.

$\{O\}$ is a mandrel coordinate system, in which Z-axis is the mandrel rotary axis. $\sum_t$ is the tangent plane of the local mandrel surface through an arbitrary point $p(x, y, z)$. In $\sum_t$, the vector which starts from p and follows the same direction of Z-axis, is set to be the reference direction of point p, as shown as Fig. 1.

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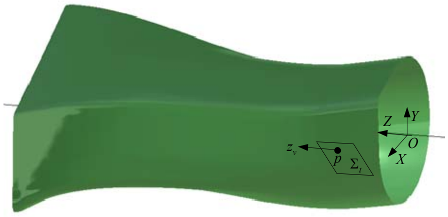


Figure 1. Illustration of reference direction

B. Iterative Method of Placement Curve

Placement curve point is usually obtained by iterative method from one end of the surface to the other for complex closed surfaces, which offers convenience to connect the generated points sequentially to form placement curve. However, in this study, a new iterative method is carried out, in which the points are allowed to calculate from the intermediate towards the both ends of the surface.

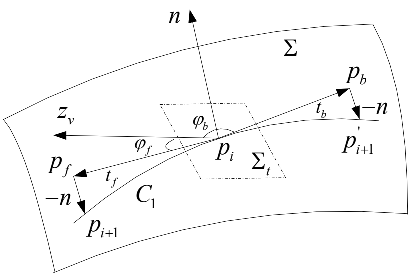


Figure 2. Calculation of the placement curve

The determination of one placement curve C_1 is taken as an example. As shown in Fig. 2, p_i is a point on the mandrel surface Σ; n is the normal vector at p_i; Σ_t is the tangent plane at p_i. To implement the placement angle, the reference vector z_v rotates around the normal vector n counterclockwisely by placement angle φ_f in $\sum_t$, which gets the correct placement direction t_f of p_i. A point p_f is found on the direction of t_f from p_i to satisfy that the distance between p_i and p_f equals l, which l is the step length of iterative method. The point p_{i+1} of which placement angle is φ_f is got by projecting p_f along n-direction onto the mandrel surface Σ, which is one point of placement curve. If curvature calculated at that point is greater than the limit of tow curvature, this point will be abandoned and p_{i+1} will be recalculated in the permitting range of placement angle from initial point p_i. Similarly if Z_v is turned around n clockwise (negative laying direction) by the placement angle φ_b ($\varphi_b = \varphi_f - \pi$) and point $p_{i+1}^{'}$ could be achieved. This process will be repeated to get series of points. When approaching to the end surface, The p_{i+1} or $p_{i+1}^{'}$ which is not on the surface will be abandoned when it goes beyond the boundary of the surface. Points on the boundary are got by intersecting the plane which is through p_f and the normal vector n, and the boundary of the surface. For closed surface, two points will be got and the point near to p_i is chosen to be one end of the placement curve. Then the full placement curve is got by sequencing the points along the Z-axis positive.

C. Calculation of Step Length

The reasonable length of step should get a trade-off between the precision requirement of placement angle and the calculation speed of laying path. In this study, the step length is updated with the curvature, in which smaller step is chosen to adapt the large change in the surface curvature. As shown in (1), variable step length l_{i+1} for p_{i+2} is calculated by point p_i and p_{i+1}, where l_0 is the initial step, $\Delta\theta_i$ is the angle between the normal vector at point p_i and p_{i+1}, and μ is a proportion coefficient (the bigger μ, the faster the calculation speed).

$$l_{i+1} = \mu\sqrt{\frac{2l_0}{\Delta\theta_i}} \tag{1}$$

D. Calculation of Tow Curvature

Although fiber placement technology can be used to manufacture complex surfaces compared to other fabrication technology of composite, there are still some limitations. If the curvature of placement curve is too large, it will lead to wrinkle which will reduce the quality of final part. If this limit is taken into account in the path planning stage, the wrinkling of tow could be avoided and then a lot of design time could be saved.

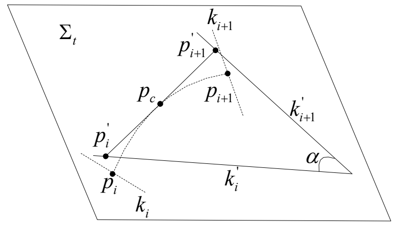


Figure 3. Calculation of tow curvature

As shown in Fig.3, p_i and p_{i+1} are two points on the path and Σ_t is the tangent plane of the surface through the middle point of arc $p_i\, p_{i+1}$. k_i and k_{i+1} are straight lines vertical to the path in the tangent plane of the surface through p_i and p_{i+1} respectively. $p_i^{'}$ and $p_{i+1}^{'}$ are the projections of p_i and p_{i+1} on Σ_t and $k_i^{'}$ and $k_{i+1}^{'}$ are the projections of k_i and k_{i+1}on Σ_t. The angle between $k_i^{'}$ and $k_{i+1}^{'}$ is defined as α. Then the criteria of curvature could be expressed in (2), in which [c] is the maximum curvature that does not produce wrinkles.

$$c = \frac{\alpha}{\left|\overline{p_i^{'} p_{i+1}^{'}}\right|} \le [c] \tag{2}$$

III. Path Planning for Whole Surface

In order to shorten the manufacturing time, it is expected that the placement head working at a state in which the tow number is maximum, where effective area made by placement head is the largest. In this case, tows' bandwidth is the sum of tow width. Correspondingly, the cutting times of the tow is reduced to minimum. In this study, an algorithm which will generate placement paths for the whole ply is put forward by combining offsetting feature points of placement curve and the iterative method mentioned above.

A. Method of Offsetting Feature Points

In this study, the research subject is a S-shaped inlet which has two parallel end surfaces. To avoid wanted feature points falling out of the surface in the updating process, the following method to offset the feature points is proposed. As shown in Fig. 4, p_t is one feature point on placement curve C_n. A plane which is parallel to the XY-Plane of mandrel coordinate system is made through point p_t , which intersects the mandrel by curve l_p. Point $p_t^{'}$ is found on the left of the reference direction on l_p , where the distance between p_t and $p_t^{'}$ is d_w. d_w is calculated in (3), where w is the maximum tow width and the local surface nearby p_t is assumed to be a plane because of the small changes in the local curvature of the mandrel surface. Then $p_t^{'}$ is set to be the initial point of the new calculating curve $C_1^{'}$.

$$d_w = \frac{w}{2\cos\varphi_f} \tag{3}$$

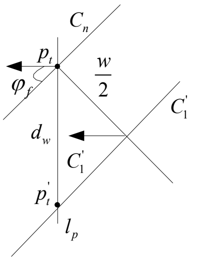


Figure 4. Offset Feature Points

B. Path Planning Algorithm

To cover the mandrel completely, it is essential to get next curve which can meet the placement requirement from an existing curve. The key is to determine feature points and judge whether the surface is covered or not. The specific algorithm proposed in this study is as follows.

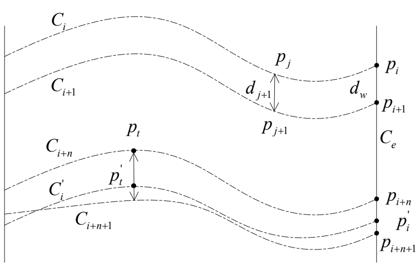


Figure 5. Path planning method for curve

The paths in a ply are obtained by computing each paths and tow edges sequentially in a clockwise direction around the Z axis. As shown as Fig. 5, C_i is a curve on the surface, of which p_i is an endpoint. p_i is taken as a feature point and is offset to get p_{i+1}. Then p_{i+1} is set to be a initial point to calculate new curve. p_{j+1} is a random point of curve C_{i+1}. A plane paralleling to the XY plane of mandrel coordinate system is made through p_{j+1} and intersects C_i on point p_j. The surface distance between p_j and p_{j+1} is d_{j+1}. d_{max} is the maximum distance between curve C_i and C_{i+1}. If d_{max} is less than d_w, C_{i+1} is kept and the endpoint p_{i+1} is chosen as a feature point to get another initial point of next curve. If the largest distance d_{max} between C_{i+1} to C_i is larger than d_w, C_{i+1} will be abandoned and the point p_t whose distance to C_{i+1} is d_{max} is set to be a feature point. $p_t^{'}$ is get by offsetting p_t and is set as the initial point to get a new path $C_i^{'}$. A new path set $\{C_i^{'}\}$（i=1~$n^{'}$）will be get by repeating this process and thus the entire mandrel surface will be covered.

Meanwhile, each curve end point p_i which satisfies the mentioned condition is connected to form a new curve C_e. The length of C_e is l_c. If $l_c > l_b$, it is considered that the whole mandrel has been covered, where l_b is the edge's length on the corresponding end of the surface. The flow chart of the whole procedure is shown in Fig. 6.

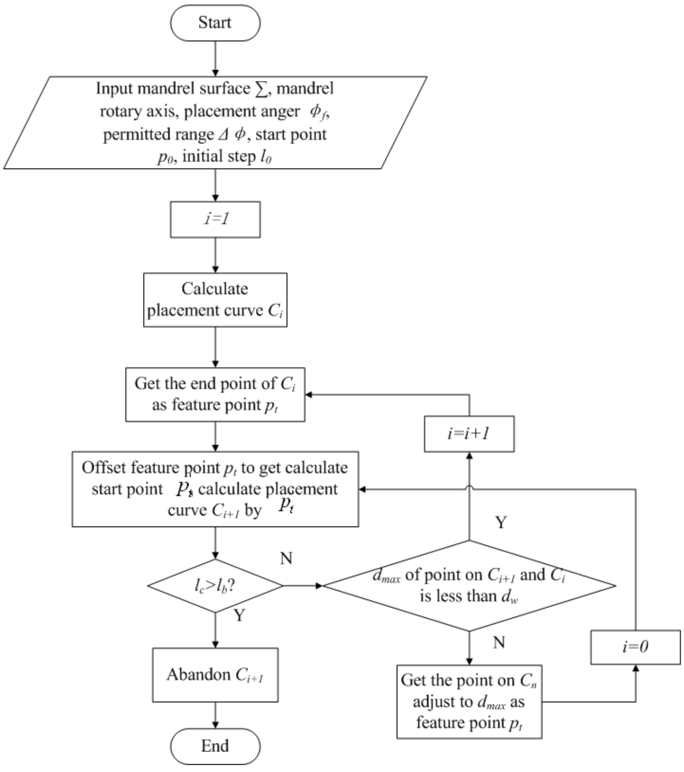


Figure 6. The flow chart of path planning

C. Calculation of the Tow Number

When the maximum tow number N in a tow is even, the maximum tow number on the left and right of the placement path is N/2. In this study, The tow quantities on the left side of p_i (N_l) and the right side (N_r) are calculated respectively according to (4) and (5).

$$N_l = \begin{cases} \left\lfloor \frac{d_l}{d} \right\rfloor \ldots\ldots\ldots\ldots\ldots\ldots 0 \le \frac{d_l}{d} - \left\lfloor \frac{d_l}{d} \right\rfloor < f_l \\ \left\lfloor \frac{d_l}{d} \right\rfloor + 1 \ldots\ldots\ldots\ldots f_l \le \frac{d_l}{d} - \left\lfloor \frac{d_l}{d} \right\rfloor < 1 \end{cases} \quad (4)$$

$$N_r = \begin{cases} \left\lfloor \frac{d_r}{d} \right\rfloor \ldots\ldots\ldots\ldots\ldots\ldots 0 \le \frac{d_r}{d} - \left\lfloor \frac{d_r}{d} \right\rfloor < f_r \\ \left\lfloor \frac{d_r}{d} \right\rfloor + 1 \ldots\ldots\ldots\ldots f_r \le \frac{d_r}{d} - \left\lfloor \frac{d_r}{d} \right\rfloor < 1 \end{cases} . \quad (5)$$

Where d is the width of the single tow; d_l, d_r are the width of distance between placement path and the left placement curve, right placement curve respectively; [] is the sigh of round down operation; f_l and f_r are the overlap factor for the left and right respectively, $f_l \in [0, 1]$, $f_r \in [0, 1]$.

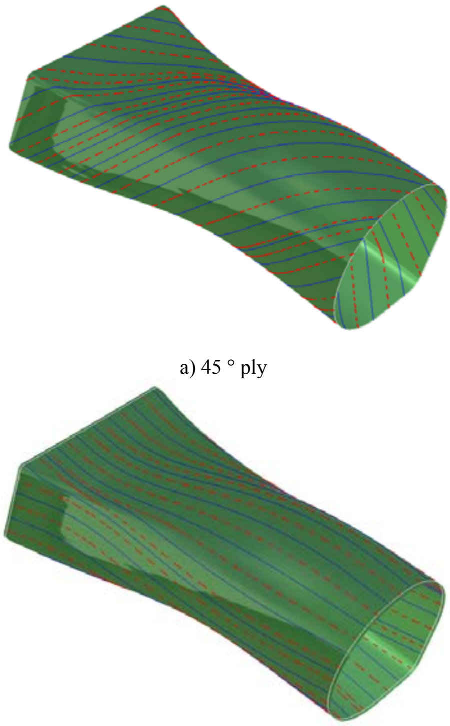
When the maximum fiber number N of tow is odd, the middle tow placed along the path is treated as left. Thus the maximum fiber number on the left is $1 + (N-1)/2$, and on the right is $(N-1)/2$. Equations to calculate the tow quantity is shown as (6) and (7).

$$N_l = \begin{cases} \left.\begin{array}{l} \left\lfloor \frac{d_l - d/2}{d} \right\rfloor + 1 \ldots\ldots\ldots 0 \le \frac{d_l - d/2}{d} - \left\lfloor \frac{d_l - d/2}{d} \right\rfloor < f_l \\ \left\lfloor \frac{d_l - d/2}{d} \right\rfloor + 2 \ldots\ldots\ldots f_l \le \frac{d_l - d/2}{d} - \left\lfloor \frac{d_l - d/2}{d} \right\rfloor < 1 \end{array}\right\} d_l - \frac{d}{2} \ge 0 \\ \left.\begin{array}{l} 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 0 \le \left\lfloor \frac{d_l}{d} \right\rfloor < \min(f_l, f_r) \\ 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \min(f_l, f_r) \le \left\lfloor \frac{d_l}{d} \right\rfloor < 1 \end{array}\right\} d_l - \frac{d}{2} < 0 \end{cases} \quad (6)$$

$$N_r = \begin{cases} \left.\begin{array}{l} \left\lfloor \frac{d_r - d/2}{d} \right\rfloor \ldots\ldots\ldots 0 \le \frac{d_r - d/2}{d} - \left\lfloor \frac{d_r - d/2}{d} \right\rfloor < f_r \\ \left\lfloor \frac{d_r - d/2}{d} \right\rfloor + 1 \ldots\ldots\ldots f_r \le \frac{d_r - d/2}{d} - \left\lfloor \frac{d_r - d/2}{d} \right\rfloor < 1 \end{array}\right\} d_r - \frac{d}{2} \ge 0 \\ 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots d_r - \frac{d}{2} < 0 \end{cases} \quad (7)$$

IV. Simulation of Path Planning

± 45 ° and 0 ° plies are the typical plies in the composite lamina design. Based on the proposed algorithms, the CAA application of CATIA is adopted to develop the simulation software. A S-shaped inlet is selected as research subject. The 45° ply and 0 ° ply are illustrated in Fig. 7, where the red dotted line represents the path of the contact point between the compaction roller and the mandrel, and the blue solid line represents the tows' edge. In this case, the maximum tow width is 64mm, consisting of a total of 10 tows. There are 13 paths and 12 edge lines in the 45 ° ply, 20 paths and 19 edge lines in the 0 ° ply. The maximum distance between the neighbor path is less than the maximum tow width, which guarantee the surface of mandrel can be filled.



a) 45 ° ply

b) 0 ° ply

Figure 7. Simulation of placement paths for S-shaped inlet

V. Conclusion

(1) A new path planning method of fiber placement for closed surface is put forward, in which the placement curves are made up of path and tow edge alternately.

(2) The calculation methods of tow number for conditions where the maximum tow number is even and odd, are proposed on the basis of the proposed path planning algorithm.

(3) The fiber placement simulation of S-shaped inlet is performed, which verifies the correctness and feasibility of the algorithms.

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