

A Novel Path Planning Algorithm in Robotic Fibre Placement for Complex Closed Surface Structures

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Abstract - A novel path planning algorithm based on efficiency and quality evaluation (EQE) in robotic fibre placement (RFP) for complex profile structures is proposed in this paper. The EQE algorithm focus on the concept for the first time that the paths are generated according to the tradeoff between the laying efficiency and quality under the specific process requirement, which will improve the RFP's adaptability to the complicated process environment. Meanwhile, the core of the proposed EQE algorithm is evaluating two different modified paths based on the laying efficiency and quality according to the process requirement during the path angle modification process. Besides, in the EQE, two new path angle modification methods are proposed to generate the modified paths. Thus, the EQE algorithm outperforms the existing path planning algorithms. Finally, some simulation experiments are conducted for a complex closed surface structure. The results verify the effectiveness of the proposed EQE algorithm and also show that it is compared favorably with the existing path planning algorithms.

Index Terms - *Robotic fibre placement, Composites, Path planning, Efficiency and quality*

I. INTRODUCTION

Composites are widely used in aerospace, automotive and renewable energy industries due to their high strength-to-weight ratio, high stiffness-to-weight ratio, resistance to corrosion, resistance to fatigue and versatility in meeting design requirements. In the past, composite parts were mainly manufactured by manual laying which usually results in high material waste, low efficiency and poor quality [1-3]. Therefore, new automated processes like automated tape placement (ATP) and robotic fibre placement (RFP) are developed [4-5]. Since ATP utilizes wide composite tape, it is generally applied to produce parts with developable surface and the lay-up paths are usually consistent with the mould surface geodesics. For a complex surface, ATP may cause gaps or overlaps between tapes, which will reduce the product quality [6]. As an extension to ATP, RFP utilizes a band of narrow prepreg tows and has many significant features and advantages such as achieving any desired tow orientation, cutting and restarting the tows on the fly, high flexibility and repeatability [7]. Therefore, RFP can be used to fabricate complex-shaped composite structures.

An RFP system usually contains a robot manipulator, a mould and a placement head with a compaction roller. The placement head is controlled by the robot manipulator to

simultaneously deliver a large number of tows onto the mould surface and the compaction roller applies force to compact the tows [8].

During the process of RFP, path planning is essential to produce high-quality composite products. Therefore, this field has been widely studied and many path planning algorithms are proposed [9]. Shirinzadeh et al. [10] proposed a novel and practical path planning algorithm for open-contoured structures, entitled the surface curve algorithm for robotic fibre placement (SCAR). An initial path is constructed first based on the surface-plane intersection strategy and then other paths are formulated by perpendicularly offsetting the initial (or the previous) path along the surface. A uniform composite ply without gap and overlap can be acquired through the SCAR. Based on arc-length parameters and projection of straight line (APPSL), Wang et al. [11] developed a method which works like the SCAR. A differential equation of path is acquired by utilizing the differential geometry and vector algebra, which leads to higher computation efficiency than the SCAR. Using the idea which is same to the SCAR and the APPSL, Yan et al. [12] proposed a more accurate path planning algorithm. It changes the offset distance to ensure that the distance between the compression roller and the surface is within a threshold. This algorithm reduces the laying efficiency in part but the fibre will be laid on the surface more completely.

The path planning algorithms above can be classified as the parallel-equidistant offsetting algorithm, and there is also another class of path planning algorithms called the constant angle algorithm [9]. An et al. [13] proposed a path planning algorithm based on the constant angle. With the mould axis being used, it first constructs a cluster of reference lines by equally dividing a series of sections, and then formulates the paths by crossing the reference lines with a fixed angle (0° , $\pm 45^\circ$, 90°). Wang et al. [14] developed a similar algorithm, but the reference lines are constructed by a few key control generatrices according to the geometric features of the mould surface.

For some complex profile structures, using one of the two basic path planning algorithms alone always performs poorly. Thus a new kind of path planning algorithm which combines the parallel-equidistant offsetting algorithm and the constant angle algorithm was developed [15-16]. It first constructs an initial path by the constant angle algorithm, then offsets the initial path by the parallel-equidistant offsetting algorithm; the offset path will be replaced with a new path by the constant

angle algorithm when its laying angle deviation is over the threshold, and the parallel-equidistant offsetting algorithm is used again with the new path; the process will be repeated until the surface is completely covered.

The algorithm above can improve the laying efficiency and quality to some extent. However, different process requirements lay different tradeoffs between the laying efficiency and quality, and the algorithm cannot meet the demand. To overcome this problem, this paper proposes a novel path planning algorithm based on efficiency and quality evaluation (EQE). The EQE algorithm is applied to a complex closed surface structure, and some analysis is conducted to verify the effectiveness and superiority of the EQE algorithm.

In Section II some basic path planning methods are introduced. Then we present our algorithm in Section III and simultaneously show the simulation results in Section IV. Finally, Section V summarizes the research conclusion of this paper and suggests the future work.

II. PRELIMINARIES

A. The Parallel-Equidistant Offsetting Method

The main idea of the parallel-equidistant offsetting method is that given a path, the next path is offset along the surface a distance in a perpendicular direction from the given path.

Consider a mould surface $S(u, v)$ containing a path $P(t)$. And the path $P(t)$ is discretized into a point set $P = \{P(t_i), i = 1, 2, \dots, n\}$. As Fig. 1 shows, for any point $P(t_i)$ in $P(t)$, $P'(t_i)$ is the tangent vector of $P(t)$ in point $P(t_i)$, the plane T passes $P(t_i)$ with $P'(t_i)$ as its normal vector, and the curve $Q(s)$ is the intersection of T and $S(u, v)$. Then $Q(s)$ can be calculated by

$$\begin{aligned} du/ds &= \pm S_v \cdot P'(t_i) / \sqrt{(P'(t_i) \times S_u \times S_v)^2} \\ dv/ds &= \mp S_u \cdot P'(t_i) / \sqrt{(P'(t_i) \times S_u \times S_v)^2} \end{aligned} \quad (1).$$

And the offset point $Q(s_{i0})$ can be acquired easily. In this way, a point set $Q = \{Q(s_{i0}), i = 1, 2, \dots, n\}$ can be obtained, where $s_{i0} = s_0$ is the offset distance. And the offset path is acquired by fitting these points and extending the curve to the surface boundary [11].

B. The Constant Angle Method

The assumed basis for the constant angle method is that the path must cross the reference lines in the set laying angle. And many calculation methods were developed [13-17]. This paper also proposes a method which uses a calculation formula similar to (1). It can make the calculation form more concise and save the computational time. The whole calculation process is as follows. As shown in Fig. 2, p_i is a point on the mould surface $S(u, v)$, S_n is the norm vector at point p_i , v is the reference line (isoparametric line [15]) passing p_i and t_v is the tangent vector of v at p_i ; the reference vector t_v is rotated around the normal vector S_n anticlockwise by the laying angle θ , and the laying direction of p_i , t_i , is obtained; the plane T containing S_n and t_i is constructed, and the curve $Q(s)$ is the intersection of T and $S(u, v)$; the next point $p_{i+1} = Q(s_i)$ is in $Q(s)$, where s_i is the step length. Using the same technique described above, p_{i+1} can be acquired by

$$\begin{aligned} du/ds &= \pm S_v \cdot (t_i \times S_n) / \sqrt{[(t_i \times S_n) \times (S_u \times S_v)]^2} \\ dv/ds &= \mp S_u \cdot (t_i \times S_n) / \sqrt{[(t_i \times S_n) \times (S_u \times S_v)]^2} \end{aligned} \quad (2).$$

This process will be repeated to get a point set and the points that are not on the surface will be abandoned. Fitting these points and extending the curve to the boundary will generate the constant-angle path.

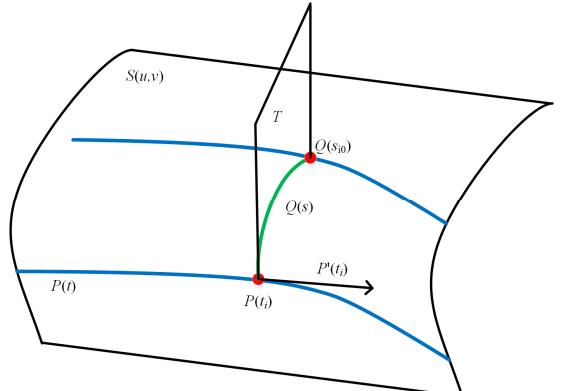


Fig. 1 Calculation of the offset path

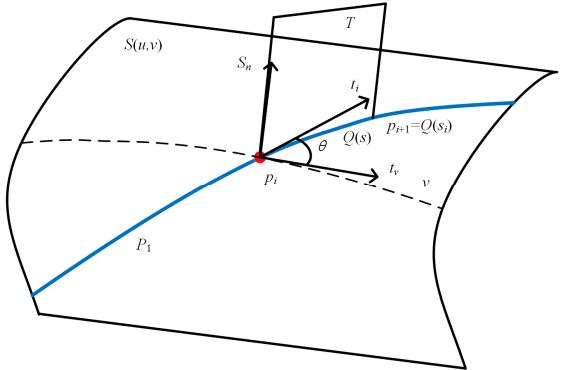


Fig. 2 Calculation of the constant-angle path

III. PROPOSED ALGORITHM: EQE

A. Overview

Since the laying angle is designed for the strength of the composite product, a basic requirement of the EQE is that the laying angle deviation of the path is within the threshold. And the framework of the proposed EQE algorithm is described in Fig. 3. First, the initial fibre boundary path is constructed by the constant angle method, and the next offset path is acquired by the parallel-equidistant offsetting method. Next, the laying angle deviation of the offset path is detected. Instead of calculating the laying angle deviations of every path point alone [15-16], the deviations will be averaged over a specified distance, which can eliminate the accidental error in a certain extent. And the path will be divided into the biased and the normal path segments (The biased path means that the laying angle deviations of the path points on it exceed the threshold). If there are not biased path segments, the path will be offset subsequently. Otherwise, the path will be modified by the proposed retaining the longest normal path segment (RLNPS) method and reducing offset distance (ROD) method.

respectively. Then, a comprehensive evaluation of the RLNPS-path and the ROD-path based on the laying efficiency and quality is made according to the process requirement. And the desired modified path will be chosen to replace the old one to be offset. The process above will be repeated until the surface coverage is complete.

In the following sections, the important procedures of the EQE algorithm are to be described in detail.

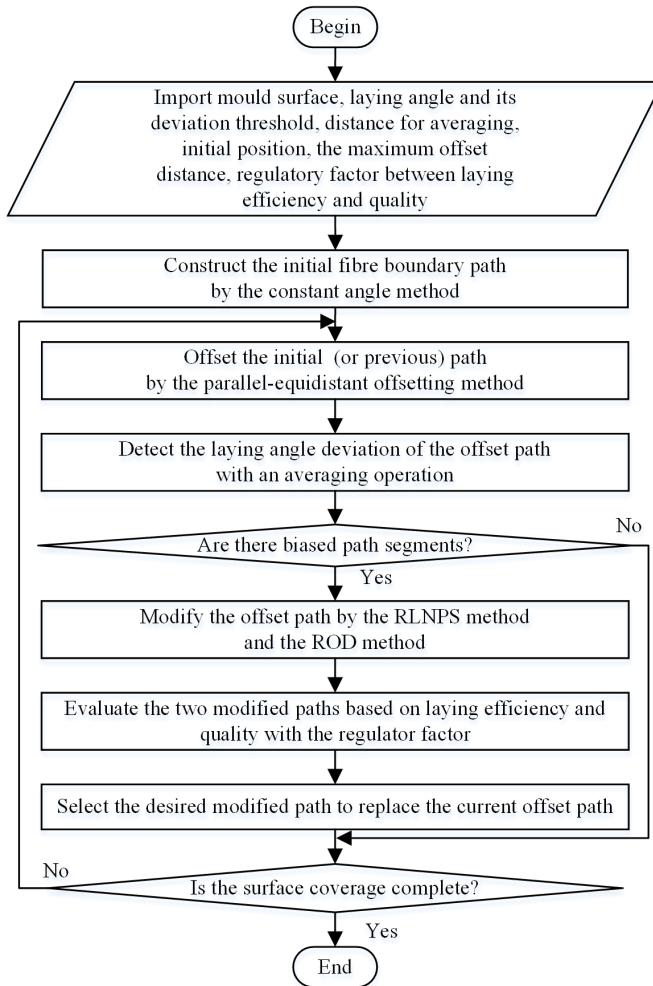


Fig. 3 The framework of the proposed EQE algorithm

B. Two Path Angle Modification Methods

1) The RLNPS Method: The existing path angle modification method replace the offset path fully with a new path constructed by the constant angle method [15-16], when there are biased path segments on the offset path. However, in some situations, it is unnecessary to modify the offset path completely. Therefore, this paper proposes an improved method, the RLNPS method. The procedure of the RLNPS method is as follows:

- 1: Find the longest normal path segment and construct two new path segments from the endpoints of the segment;
- 2: Compute the maximum distance of the two segments of the previous path and record the corresponding point on the previous path;

3: If the maximum distance is over the maximum offset distance, go to step 4; if not, go to step 5;

4: Construct a new path by the constant angle method from the offset point of the recorded point above;

5: Construct a new path by combining the longest normal segment and the two new segments;

6: Replace the offset path with the new path.

Note: Since the path can be modified partly, a natural idea is to merely modify the biased path segments. However, it will result in a discontinuous path when there is more than one normal path segment, as shown in Fig. 4. (a). To solve this problem, the longest normal path segment is chosen and only two new path segments are constructed by the constant angle method from the endpoints of the selected normal path segment. And it can generate a continuous path, as shown in Fig. 4. (b).

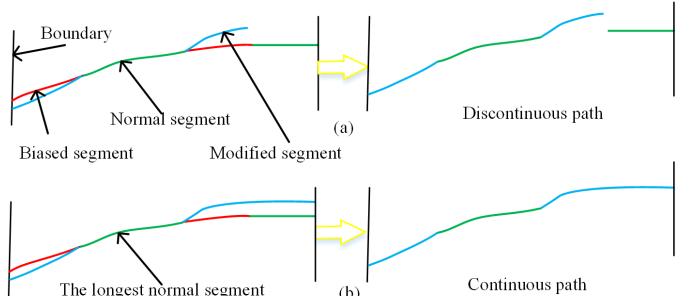


Fig. 4 Path modification based on the constant angle method

2) The ROD Method: The proposed RLNPS method is based on the constant angle method, however we propose another path angle modification method, the ROD method. It is based on the parallel-equidistant offsetting method and the procedure is as follows:

1: Detect the laying angle deviation of the new offset path. If there are biased path segments, go to step 2; otherwise, go to step 5;

2: If the offset distance is equal to the width of one fibre, go to step 4; if not, go to step 3;

3: Reduce the offset distance by the width of one fibre and construct a new offset path. Go to step 1;

4: Output "No modified path by the ROD";

5: Output the offset path and the corresponding offset distance.

Note: For purpose of computational simplification, the offset distance is reduced by the width of one fibre each time.

C. Path Evaluation and Selection

Both the RLNPS method and the ROD method are effective in path modification, but they perform differently on laying efficiency and quality. In terms of laying efficiency, the RLNPS method performs better than the ROD method. That is because the laying area between the RLNPS-path and the previous path is generally bigger than that of the ROD-path. But the ROD method outperforms the RLNPS method on laying quality. The RLNPS-path results in more overlaps and gaps than the ROD-path, because the distance between the

RLNPS-path and its previous path is varying and the fibres need to be cut and restarted during the laying process. Therefore, a comprehensive evaluation of the RLNPS-path and the ROD-path based on laying efficiency and quality can be made according to the process requirement. This paper chooses two indexes for path evaluation: the area of the laying zone between the modified path and its previous path with the calculation method proposed in [18], X_1 ; the total area of the overlap and the gap on the laying zone [19], X_2 . An evaluation model is defined by (3), where q_1 and q_2 are the evaluation value of the RLNPS-path and the ROD-path respectively; f_1 and f_2 are the mapping functions to make the evaluation more reasonable; λ is the regulator factor which reflects the different tradeoffs between the laying efficiency and quality of different process requirements. Therefore, the path with a higher evaluation value will be selected.

$$\begin{aligned} q_i &= \lambda \cdot y_{1i} / (y_{11} + y_{12}) + (1 - \lambda) \cdot y_{2(3-i)} / (y_{21} + y_{22}) \\ y_{1i} &= f_1(x_{1i}), y_{2i} = f_2(x_{2i}) \quad (3) \\ i &= 1, 2 \end{aligned}$$

Note: When the ROD-path is non-existent, as described above, it is unnecessary to make an evaluation, and the RLNPS-path will be selected directly.

IV. NUMERICAL SIMULATIONS AND ANALYSIS

A. Simulation Setup

To verify the effectiveness and superiority of the proposed EQE algorithm, it is applied to a complex closed surface structure. The surface is designed in CATIA and converted to

STP file, and then a parametric form of it is acquired. As shown in Fig. 5, the two port sections are round and square respectively, and their perimeters are 314.178mm and 355.804mm. The longitudinal length is about 401.582mm, and the total surface area is 12500mm².

In addition, the width of one fibre is 3.175mm and the maximum laying number of fibre is 8.

B. Results and Analysis

To make the evaluation model more reasonable, appropriate mapping function f_1 and f_2 must be chosen. It can be found that the difference between x_{11} and x_{12} is normal while the difference between x_{21} and x_{22} is too large during the simulation process. Therefore, the difference between x_{21} and x_{22} need to be amended by f_2 . And a reasonable definition is as follows:

$$f_1(x) = x; f_2(x) = \sqrt[4]{x} \quad (4)$$

Since the regulator factor λ can reflect different tradeoffs between the laying efficiency and the laying quality, λ will vary from 0 to 1 during the simulation experiments to verify the effectiveness of the proposed EQE algorithm. Besides, in order to show the variation in the laying efficiency and the laying quality of the paths under different regulator factors, some indexes are chosen: the number of the paths Z_1 , the total length of the paths Z_2 , the total area of the overlap and gap, Z_3 . And then some simulation experiments based on the flow diagram in Fig. 3 are conducted, and the results are shown in Fig. 6.

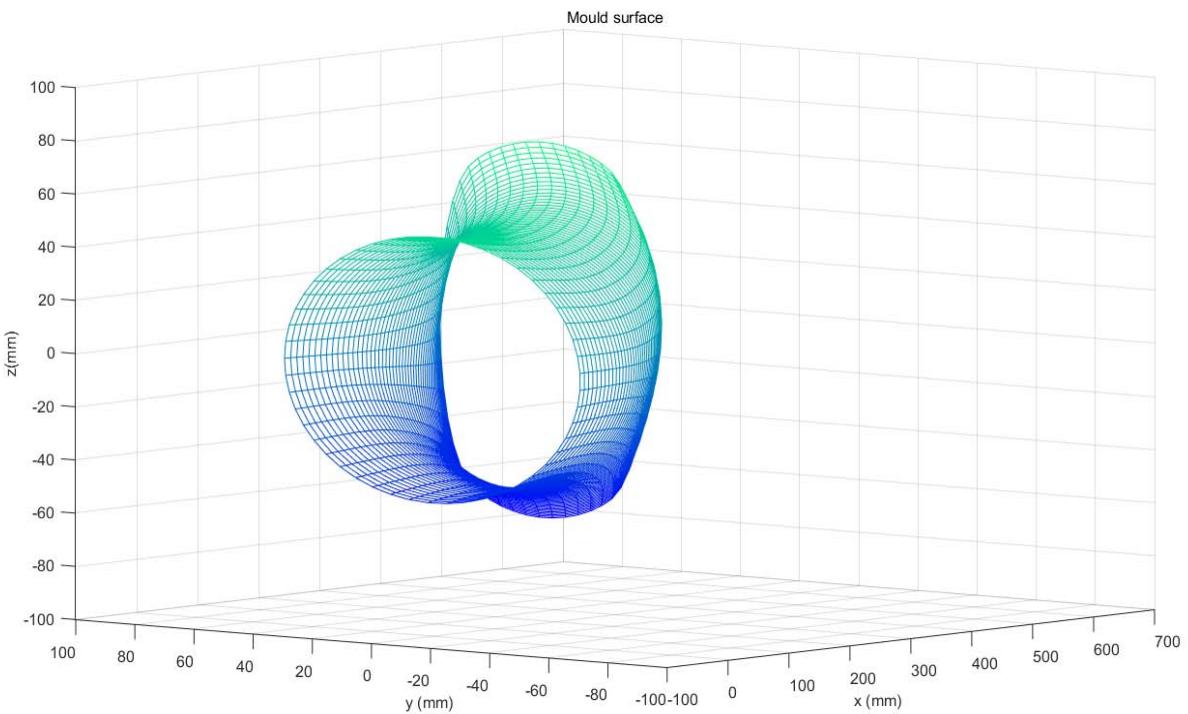


Fig. 5 The three dimensional model of the mould surface

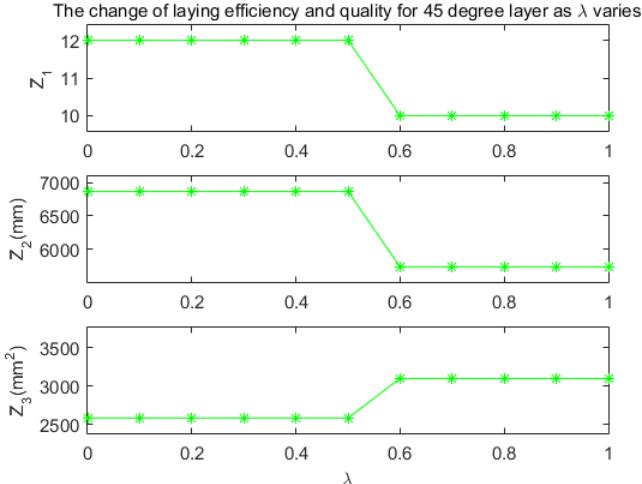


Fig. 6 The results of the EQE algorithm for 45° layer

In addition, to make a comparison between the EQE algorithm and the existing path planning algorithms, a simulation experiment based on the existing path planning algorithm in [15] is conducted. The old path angle modification method in [15] and the proposed RLNPS method are used respectively. The results are shown in Table I.

On one hand, it can be seen from Fig. 6 that Z_1 and Z_2 are decreasing and Z_3 is increasing as λ varies from 0 to 1. Meanwhile it is obvious that the smaller Z_1 and Z_2 are, the higher the laying efficiency is. And smaller Z_3 brings in higher laying quality. On the other hand, as described in Section III, a bigger λ indicates that the process requirement lays greater

importance on the laying efficiency and less importance on the laying quality. Therefore, the variation trend of the laying efficiency and quality of the paths is consistent with the process requirement. It demonstrates that the proposed EQE algorithm is effective in generating the path according to the tradeoff between the laying efficiency and quality under the specific process requirement.

TABLE I
COMPARISON BETWEEN THE EQE ALGORITHM AND THE EXISTING PATH PLANNING ALGORITHM FOR 45° LAYER

Algorithm	Z_1	Z_2 (mm)	Z_3 (mm ²)
The EQE ($\lambda=0.6$)	10	5734.0	3098.8
The existing algorithm with the RLNPS	10	5737.9	3266.1
The existing algorithm	10	5738.2	3562.7

Additionally, as can be seen from Table I, the paths produced by the EQE algorithm with λ equal to 0.6 perform better than those produced by the existing path planning algorithm on the laying quality. But they have almost the same laying efficiency. Further, it can also be found that the laying quality of the paths produced by the existing path planning algorithm with the RLNPS method is higher than that of the old path angle modification method, meanwhile the difference on the laying efficiency between them is tiny.

Lastly, some paths by the EQE are shown in Fig. 7.

V. CONCLUSION

This paper has proposed a novel path planning algorithm based on a comprehensive evaluation of the laying efficiency and the laying quality in RFP for complex closed surface structures, and some conclusions are as follows:

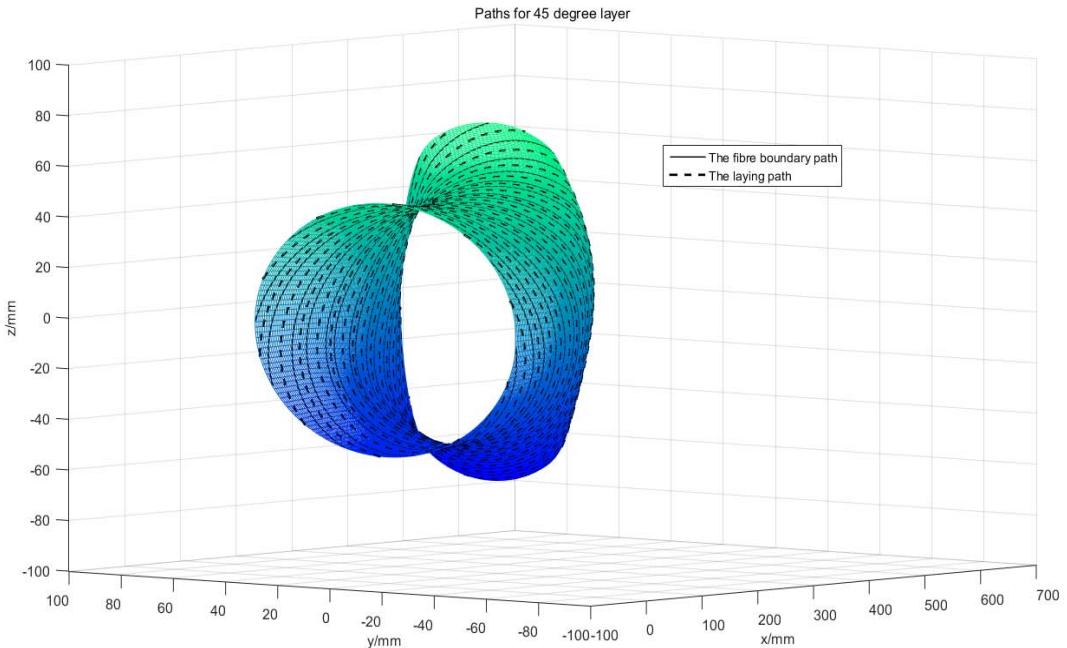


Fig. 7 The paths for 45 degree layer by the EQE algorithm with λ equal to 0.6

1) Meeting the basic demand that the laying angle deviation of the path is within the threshold, the proposed EQE algorithm can generate the RFP path according to the tradeoff between the laying efficiency and quality under the specific process requirement. Therefore, the adaptability of the RFP to the complicated process environments will be improved.

2) Under some process requirements, the paths produced by the EQE algorithm perform better than those produced by the existing path planning algorithm in [15] on the laying quality, without a reduction in the laying efficiency.

3) As a new path angle modification method, the RLNPS method developed in this paper outperforms the traditional method in [15] on the laying quality.

4) Some preliminary attempts are being made to synthetically evaluate the ultimate paths based on the laying efficiency and quality according to the process requirement and optimize the regulator factor λ to acquire the optimal path. Further study will be carried out to perfect the path evaluation model, the optimization model and the optimization algorithm.

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