A Survey on Path Planning Algorithms in Robotic Fibre Placement

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Abstract: In this paper, the research background and development of robotic fibre placement for composites are first reviewed briefly. Then current path planning algorithms are introduced and classified as the fixed angle path planning algorithm and the variable angle path planning algorithm. The formulation of the initial path and surface coverage are mainly presented for the fixed angle algorithm, and the variable angle algorithm is described from the perspective of reducing gap and overlap between tows and enhancing the strength and stiffness of the structure. At last, comparisons between the two path planning methods are discussed and future developments are prospected.

Key Words: Robotic Fibre Placement, Path Planning, Composites

1 INTRODUCTION

Fibre reinforced composites have many advantages over traditional structural materials and have found ever broader application in aerospace and automotive industries. Some advantages include strength to weight ratio, stiffness to weight ratio, and versatility in meeting design requirements. Nowadays the usage of fibre reinforced composites becomes the important symbol of the new generation of aerospace crafts [1-3]. Automated placement technology is counted among one of the most important manufacturing technologies for the fabrication of composite structures. It includes automated tape placement (ATP) and robotic fibre placement (RFP). For ATP, using the composite tape with a certain width, the mould surface is generally a developable surface and the lay-up paths are usually along mould surface geodesics. For an arbitrary surface, ATP may lead to gaps between tapes if no overlap is used, or an uneven surface if too much overlap is used. RFP utilizes a placement head which is mounted on a robotic manipulator to lay down simultaneously a large number (up to 32) of the impregnated fibre tows. Then the tows are placed side by side on the mould surface. An elastomeric roller is used to place and compact the tows. It is capable of achieving all desired tow orientations, cutting and restarting the tows, debulking and consolidation of the material in situ. So many important features and advantages allow RFP suitable for the fabrication of complex structures [4-7]. A possible configuration of the RFP system is showed as figure 1.

In figure 1, the RFP system contains a robotic manipulator, a compaction roller, a placement head, a mould surface, etc. The softwares about the robotic fibre placement abroad have tended to be mature and perfect. The FibreSIM software is an integrated software which can implement the digital manufacturing for the composite material which belongs to VISTAGY company. With the integration of CAD software, it designs and analyzes the system automatically, generates the data for the fibre placement [8-11]. The CGTech company develops the VERICUT Composite Programming and Simulation (VCP&VCS) on the basis of the original numerical control machining simulation software [12]. The Ingersoll company develops the CPS (Composite Programming System) software for the fibre placement. Similarly, the research work has been carried out by some domestic institutions [4], such as Nanjing university of aeronautics and astronautics, Harbin institute of technology, Wuhan university of technology and so on, but the commercial automated laying software has not been developed. In order to complete the entire process of robotic fibre placement, the software should include some important modules [13-15].

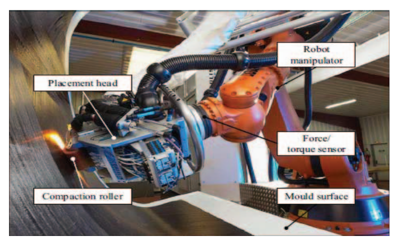

Fig.1 diagram of RFP system

(1) Path planning: based on the width of the tow, the geometry information of the structure surface, the requirement of the laying direction and the number of layers, the placement paths are produced. The generated paths should meet the requirement of the component surface coverage. The gap and the overlap which are easily produced between the tows should be avoided.

(2) Post processing technology: to convert the path planning data into robotic movement instruction and get the cutting/ restarting information about the fibre tow during the RFP.

(3) Robotic fibre placement simulation: simulate the laying process according to the generated trajectory, the robotic paths and the component surface.

(4) Real-time laying: the fibre placement is carried out using the robot's trajectory data and the fibre tow's cutting/restarting information.

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Path planning plays a basic role in the robotic fibre placement process and it is a key technology for the CAD/CAM software. The results of the path planning directly determine the precision of the component forming and the efficiency of the placement. This article aims at the summarization of the path planning methods in robotic fibre placement.

2 PATH PLANNING METHODS OF ROBOTIC FIBRE PLACEMENT

During the robotic fibre placement process, the target of the path planning is to compute the trajectory which the robot moves along, the number of the fibre tows, the gap and the overlap between the tows using the component's geometry surface, the constraints of the forming precision and the layer direction. Specific tasks include as follows.

(1) The tangent vector of each point in the laying path should meet the requirement of the certain layer direction, which is designed to satisfy the mechanical properties of engineering.

(2) The length between the tows is less than the allowed maximum tow width and is also considered to meet the demand of the component forming accuracy.

(3) According to the controllability of the fibre placement equipment, the normal vector of the structure surface should be obtained which is used to control the pose of the placement head. The placement head should always be perpendicular to the surface of the structure.

Path planning methods can be divided into two categories, the fixed angle path planning and the variable angle path planning algorithms based on the fact that whether the fibre laying angle changes. The fibre laying angle refers to the angle between the direction of the fibre tow at a certain point and a reference line. When the angle between the laying path and the reference line is a constant value, the algorithm is called the fixed angle path planning method. On the contrary, if the angle is variable, the algorithm is called the variable angle method.

3 FIXED ANGLE PATH PLANNING ALGORITHM

Generally, the fibre tow is placed at a certain angle and the laying angle is set by the reference line. For instance, the path is called 0^o path when it is paralleled to the reference line. The path is called 90^o when it is orthogonal to the reference line. The reference line can be a straight line or a curve. First of all, an initial reference line should be constructed according to a certain rules, then the rest of the paths are produced on the basis of the reference line as shown in figure 2 [5].

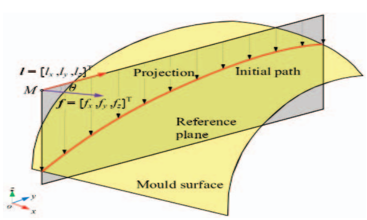

Fig.2 diagram of the fixed angle path planning

In figure 2, the initial reference line is produced by the plane-surface intersection. If the $f = [f_x, f_y, f_z]^T$ is set to be the reference laying direction, and the f connects with the line l at point $M(M_x, M_y, M_z)$, the $l = [l_x, l_y, l_z]^T$ is the fibre laying path direction, θ is the laying angle between f and l. If the angle θ is constant during the fibre placement process, this method can be regarded as the fix angle algorithm. The commonly used laying angles are 0^o, 45^o, 90^o, 135^o respectively.

3.1 Generation of the Initial Reference Line

There are various candidates for the initial reference line, such as a plane-surface intersection, a curve-surface intersection, a parametric function that maps onto the surface, directional projection, and so on.

(1) The plane-surface intersection algorithm

Given a mould surface, the main axis is firstly projected to the surface and the projection of the main axis forms the plane. The initial reference line is formed from a plane-surface intersection, as depicted in figure 3. The initial reference line can be also called initial path, and the next RFP path is found by perpendicularly offsetting the initial path along the surface.

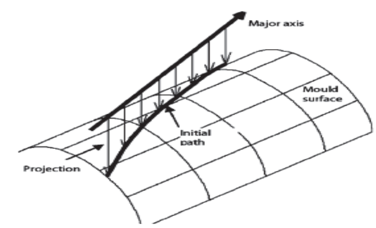

Fig.3 diagram of plane-surface intersection

Wang et al. [17] deduced the algebraic equation to solve the initial path with the help of the differential geometry. The article states the successive iteration solution at a given starting point, and the continuous paths are constructed. This method has advantages of simple calculation and a clear mathematical equation, and it is suitable for the open-contoured structures. Li et al. [18] proposed a path generation algorithm based on orthogonal projection. This method orthogonally projects the space curve to the structure surface to form the reference line. Its essence is also to construct the plane-surface intersection. Under the condition of the surface normal vector specified, the solution of the projection surface is always existed. But it is difficult to construct the suitable initial reference line for the complex surface.

(2) The curve-surface intersection algorithm

For the revolved shaped structure, the reference line with specific angle is produced by the curve-surface intersection [14][19]. The principle of this algorithm is expressed in figure 4. It uses the mandrel axis $D(t)$ as the center line to construct the isometric spiral line with the spiral angle S which is decided by the laying angle. Straight lines are formed through connecting the points belonged to $D(t)$ to that are belonged to $S(t)$ correspondingly. Then the straight lines intersect with the surface to generate the curve $P(t)$ which can be regarded as the reference line. For the complex revolved shaped structure, some improvements of the above method have been made. Lu et al. [20] translated the key points of the surface along their normal vector's forward and reverse directions, then fit the key points after translation respectively, connected the corresponding points of the two fitting curves. The connecting line intersects with the surface to form the initial reference line which can keep the key information of the complicated surface. So the rest paths produced by these initial lines will be more precise.

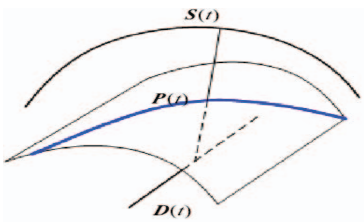

Fig.4 diagram of the curve-surface intersection

(3) The directional projection algorithm

For the closed surface, such as aircraft's inlet, Zhou et al. [21-22] firstly got the geometric center of the core mould by the piecewise circular cutting method, secondly got the axis of the mould through interpolation method, projected the axis along the starting point of the fibre path to the mould surface to get a ridge line. Then the ridge line is set to be the reference line. This is depicted in figure 5.

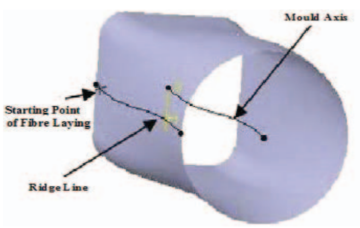

Fig.5 diagram of the directional projection

Zeng et al. [23] took the closed structure's generating line as the initial reference line. In this method, the reference line's equation is easily obtained on the basis of the analytical expression of the structure. Wang et al. [24] took the key control generating line by interpolation as the initial reference line. The generating line can change correspondingly according to the complexity of the mould surface which can meet the accuracy requirement of the fibre placement.

3.2 Surface Coverage Algorithm of RFP

In order to cover the surface during the RFP process, the rest paths should be produced through the initial reference line and make sure that the paths evenly cover the surface without gap and overlap. At the same time, the fibre laying paths should meet the width of the tow and the accuracy of the fibre laying process. The main two surface coverage algorithms are listed as follow.

(1) Parallel equidistant algorithm

In this algorithm, RFP paths are produced by offsetting a distance along the surface in the perpendicular direction of the initial reference line. The distance between two adjacent paths is no more than the maximum tow width [16]. The distance is variable during the different adjacent paths. This algorithm can be attributed to the fixed angle algorithm because of the paths being parallel with the reference line. That is to say, the angle between the reference line and the path is invariable. The principle of this algorithm [16-18] is explained in figure 6.

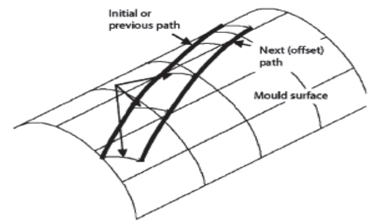

Fig.6 diagram of the next offset path

The specific calculation is depicted in figure 7. $P(t)$ is the initial reference line. $P = \{P(t_i), i=1,2,\ldots,n\}$ is the point sequence by discretizing the reference line $P(t)$.

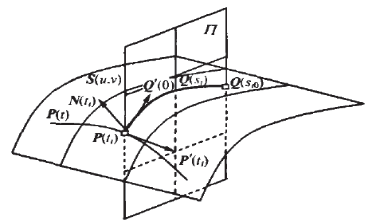

Fig.7 diagram of formulation of the next path

Supposing at point $P(t_i)$, the steps of constructing offset paths are listed as below. Firstly, computing the partial derivative $P'(t_i)$ of the line $P(t)$ at the point, secondly constructing the plane Π with the normal vector $P'(t_i)$, $Q(s)$ is the intersection line between the plane Π and the surface with the arc length parameters s. The discrete point $Q(s_{i0})$ of the offset curve can be computed using the numerical iterative method. When all the discrete points are calculated, the offset paths are obtained by fitting these points and all the offset paths are achieved in this way.

Dang et al. [25] proposed a novel parallel equidistant path generation algorithm based on the geodesic. The distance between neighbouring paths is equal in the geodesic direction along the surface. This algorithm is simple and the precision requirements of robotic fibre placement are satisfied. The calculation accuracy of this algorithm would decrease for the larger equidistant distance. Yan et al. [5] deduced a more accurate computing algorithm. It considers the surface curvature, and takes the allowed distance between the compression roller and the surface as the standard to compute the minimum number of the fibre. This algorithm reduces the efficiency to some extent, but it can guarantee the fibre laid on the surface tightly without the gap and overlap.

(2) The constant angle algorithm

The constant angle algorithm can produce a number of laying paths under the condition that the laying angle is commonly set to be 0^o, 45^o, 90^o, 135^o respectively. The 0^o is used to carry axial stress, the 45^o and 135^o are used to carry shear stress, the 90^o is used to carry the radial stress. This algorithm does not only satisfy the stress but also simplify the design and manufacture which is more suitable for engineering application.

Zeng et al. [23] defined the laying angle as the intersection angle between the tangent vector of any point belonged to fibre laying path and the tangent vector of generating line where the same point is belonged to. The article takes the generating line as the reference line. Lu et al. [26] regarded the mould axis as the reference line, defined the axis direction which the roller runs along as the 0^o direction. Then the rest paths are achieved from the 0^o path. The principle is expressed in figure 8 [27].

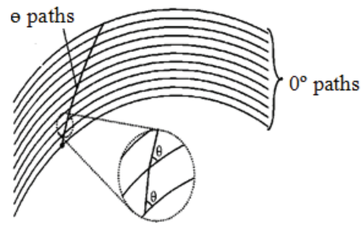

Fig.8 diagram of paths generating process with 0o path as the reference line

In figure 8, a number of 0^o paths can be got by equidistant offset, the rest paths such as 45^o, 90^o, 135^o can be computed by 0^o paths with a fixed angle. Li et al. [28-29] described a fixed angle fibre placement algorithm based on the meshed surface. This method does not depend on the parameter equation and can well meet the practical engineering application. Xiong et al. [30] developed an adaptive fibre placement algorithm. The algorithm can get the adaptive reference line according to the width of the tow and the curvature of the surface and all the fibre placement paths could be achieved by the adaptive reference line, which makes it widely used.

The above two surface coverage methods are not isolated from each other. Connecting the parallel equidistant and the constant angle algorithm together can improve the efficiency of laying with reducing the gap and overlap between the tows [31-32]. When the single layer has been completed, multiple layers need to be considered. Lu et al. [33-34] deduced the multi-layer path planning algorithm. The algorithm constructs the corresponding offset surface for the multi-layer fibre placement, and generates the uniform equation for fibre placement on the basis of the path planning algorithm of the single layer.

4 VARIABLE ANGLE PATH PLANNING ALGORITHM

The path planning algorithm with fixed angle is easy to design and manufacture. It also can satisfy the requirement of general strength and technology, but fails to make full use of the performance of the fibre. The variable angle path planning algorithm is becoming a research hotspot [35-37]. Lopes et al. [38] took the curve of the continuous fibre to design the variable stiffness composite laminated board, applying the variable angle fibre planning algorithm into practical application. The variable angle path planning algorithm is that the fibre laying angle is always changing during the RFP process, as in figure 9. The laying angle is defined as the intersection angle between the direction of the fibre laying and the x axis and which is always changing in this figure [39].

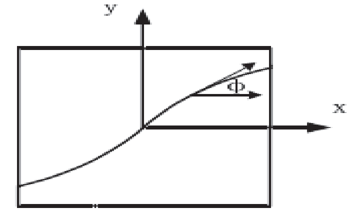

Fig.9 diagram of the variable angle path planning

The variable angle path planning method is also called fibre steering which is a kind of trajectory optimization method based on the load and internal force distribution of the structures. The fibre is anisotropic, changing the laying angle can improve the mechanical properties of components [40-41]. Some advantages of this method are listed below.

(1) It changes the distribution and intensity of the layer stress, avoids the stress concentration.

(2) It can also change the natural frequency of the layer, and avoid the happening of resonance phenomena.

(3) By adopting reasonable path planning algorithm can reduce the gap and overlap between tows when laying the complicated surface.

(4)The better mechanical property of laminated structure can be obtained by different layers with mechanical properties layer overlaying together.

Some researches use the variable angle path planning algorithm to avoid the gap and overlap of tows during the laying process. Lu et al. [26] proposed an arc length partitioning algorithm for the conical composite structures. This method constructs the corresponding relation between surface curvature and fibre bundle. Li et al. [39] showed that the width of the tows varied as the angle between the tow and the vertical direction changed. This method is for the conical structures without gap and overlap. Han et al. [42] deduced another algorithm for the conical structures. A mathematic model of such components based on the geometric feature is constructed, the feasible laying of surface is then analyzed through the relationship between the path of variable angle and surface curvature, finally the analytic equation of a variable angle path planning algorithm is established. The above variable angle path planning algorithms focus on specific shaped structures and use these methods to reduce the gap and overlap between tows in the RFP process.

The outstanding advantage of the robotic fibre placement is the fibre direction can be devised. The path planning algorithm with the fibre direction considering the structure requirements can take full advantage of the fibre's property and improve the strength and stiffness of the structure. Huan et al. [43] advised to construct the distribution function of the laying angle using the least-square method, and plan the paths according to the fibre direction of the key point of a certain layer. Shao et al. [44-45] planned paths through the internal stress state of the structure bearing condition. First, the finite element analysis of the composite structures should be carried out, then the internal stress distribution of the structure which is taken as the basis of the path planning could be got. Wen et al. [40] proposed a self-adjusting path planning algorithm based on structural design. The method analyzes the fibre's laying manufacturability, takes the geodesic curvature as the laying technology measure. It makes the fibre laying offset from the direction of the structure design to the geodesic line direction, and improves the quality of fibre placement. Lopes et al. [38] mainly discussed that the variable angle path planning algorithm could improve the laminated board's performance by means of modifying its load pressure distribution. The numerical simulation is carried out to verify that the variable angle is superior to the fixed angle at the aspect of buckling load analysis and the first layer's failure analysis. Blom et al. [46] put forward a variable angle composite path planning algorithm which was executed by constantly adjusting the laying angle to meet the requirement of the stress state at different parts of the structure under the condition of deformation of the material technology allowed. This article also presents an effective solution for the uniform thickness within the same layer because of the overlap between the tows. Setoodeh et al. [47] took the impact of the fibre placement on structure stiffness as a convex optimization. Through a variable sequence quadratic programming algorithm, it is possible to find that the variable angle fibre placement can significantly increase the stiffness of the structure and improve the structure performance. Legrand et al. [48] proposed to use the genetic algorithm to optimize the direction of the fibre placement on the basis of the analyzing the stress characteristics of the bolt holes around. Blom et al. [49] executed the numerical analysis and experimental verification on the variable angle path planning algorithm, the layer's dynamic and static mechanical properties for conical structure. There are so many realizations of the variable angle path planning algorithm, that their fundamentals are the same which takes advantage of the fibre superiority to improve the structure performance.

According to the stress analysis of the composite structure, the principal stress direction is found to optimize the fibre placement paths, and the density of fibre placement is designed according to the principal stress size. Measures taken above could make use of the performance of composites, raise the strength and stiffness of the structure.

5 CONCLUSION

According to the characteristics of the structure surface, it is necessary to adopt different ways to get the initial reference line, especially the surface curvature changes larger or there are special requirement for the fibre placement [50]. Generally on flat surface, the paths that cover the entire surface can be got by using the parallel equidistant method based on the initial reference line. This method is simple, and it does not need to increase or decrease the number of the fibres during the laying process. It is widely used in engineering practice. But for complex structure surface, it is difficult to construct appropriate initial reference line and the fibre placement direction might not fully meet the structure design requirements. More and more researches have shown that variable angle path planning algorithm is a more flexible design method which can easily reduce the gap and overlap between the tows. It is necessary to optimize the components according to the actual load at different parts of the composite structure, and continuously adjust the laying angle under the condition of the deformation of the material properties allowed. This can meet the overall requirements of the state of stress in different parts of the structure, maximize the efficiency of the material, reduce the component weight, and improve the performance of structure. Path planning algorithm for robotic fibre placement is one of the key technologes of CAD/CAM software, and there are a lot of work which are worth studying and exploring.

(1) The variable angle path planning algorithm needs further research. It is a path optimization method based on the structure stress situation. Under the condition of considering the structure stress, analyzing the influence of the variable angle path planning algorithm on the mechanical characteristic of the structure and relevant changing rule, and improving the performance of forming structure will be the next study focus.

(2) Path planning algorithm for robotic fibre placement mostly in single layer of structure is studied. The layer surface of the mould is changing with the increased layer thickness, and it is necessary to plan the paths on the multilayer surface. Optimizing of composite laminated structure to achieve the minimum weight and lowest cost to meet the given design requirements also needs in-depth analysis and research.

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