Five-axis Ultrasonic Thickness Measurement of Hollow Blade Wall and Evaluation of Internal Chamber Section

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Abstract. Hollow blades play an important role in the aircraft engines. To ensure the manufacturing quality of the hollow blades, an ultrasonic inspection method for inspecting the internal chamber is proposed in this paper. The measured data is obtained by a five-axis Coordinate Measuring Machine with an ultrasonic probe. To fill the vacancy of data in high-curvature regions, an approximation curve is constructed according to the theoretical section line and the measured points. By adjusting the position of the theoretical chamber point and setting the adjustment direction, the non-uniform shrinkage of the ceramic core is simulated and the calculation amount is reduced. Filling points are obtained from the approximation curve and the internal chamber section is reconstructed by these points. The internal chamber of the hollow blade is evaluated from the two aspects of line profile and wall thickness. The experiments have verified the effectiveness of the proposed method.

1. Introduction
Turbine blades, as a key component of an aircraft engine, work in extreme environments of high temperature and high pressure [1]. To improve the engine thrust-to-weight ratio and heat resistance [2-3], the hollow blade design can achieve blade weight reduction and provide air passages to achieve rapid cooling through composite air film hollow cooling technology. Due to the complexity of the structure and the particularity of the material, the processing technology of hollow turbine blades is mainly investment casting technology [4]. The manufacturing process of the hollow turbine blade rough blank based on investment casting is as follows. First, a mold forming process is used to complete the ceramic core required for the precision casting of the hollow turbine blade. The ceramic core is a hollow-filled part. Then use the wax mold process to prepare the turbine blade wax mold on the outer layer of the core. Then, the hollow turbine blade rough blank is prepared through sintering, pouring, demolding, and other processes. The rough blank has to go through subsequent processing steps to complete the preparation of the hollow turbine blade [5]. Generally speaking, the process of hollow turbine blades is complicated, and the manufacturing process parameters are difficult to accurately control. Therefore, the qualified rate of hollow blade manufacturing is very low. The qualification rate of hollow turbine blades in China is only about 30%. Among all unqualified blades, the proportion of unqualified blades whose profile and wall thickness exceed the error is as high as 50%. Therefore, measuring the wall thickness of the hollow blade and evaluating its internal chamber section (ICS) is the key to ensure the quality of the hollow blade.

For the measurement of the wall thickness of the hollow blade, due to the sealing of the hollow turbine blade, the conventional measurement method cannot measure the ICS of the hollow turbine blade [6]. At present, the most commonly used method for measuring the wall thickness of hollow
turbine blades is industrial computerized tomography (CT). However, industrial CT for large parts is extremely high, low efficiency, and lack operational flexibility [7]. Ultrasonic thickness measurement is another effective method for hollow blade wall thickness detection. It has high safety, high detection accuracy, and easy integration with automated equipment for high-efficiency detection. However, the ultrasonic thickness measurement method tends to cause the sound wave to diverge when the curvature of the workpiece is large, which causes data loss and cannot obtain complete ICS measurement data. Therefore, how to evaluate the profile based on incomplete ICS measurement data is a difficult problem in the application of ultrasonic hollow blade measurement.

In terms of hollow blade wall thickness evaluation, Cheng’s team mainly explored methods for wall thickness evaluation based on the measurement point cloud. Cheng [8] proposed a method of defining the wall thickness on the section of hollow blades in 2006. Cheng [9] proposed a three-dimensional definition of the wall thickness of hollow blades in 2009, but the direction of the wall thickness is still limited to the normal direction of the outer wall. When there is a large deviation from the curvature of the inner wall of the blade, the applicability of this definition is poor. Cui [10] proposed a hollow blade wall thickness definition method based on the inscribed sphere, which defined the wall thickness as the distance between the tangent points of the inscribed sphere between the inner and outer walls of the hollow blade, taking into account the normal direction of the inner and outer walls.

In terms of ICS reconstruction based on missing data, Cui [10] proposed a method to adjust the control vertex of the NURBS curve. This method takes the variation of the deformation energy of the NURBS curve as a constraint item and minimizes the distance from the measuring point to the curve. However, when there are many NURBS control vertices, the calculation amount of the algorithm is too large, and the optimization function is difficult to converge. Lan [11] proposed a method of adjusting the weight factor of the NURBS control vertex to fit the measurement point. This method simultaneously takes into account the approximation and smoothing condition. Similarly, the optimization equation has the problems of slow convergence and a large amount of calculation. Huang [12] obtained the incomplete 3D scanning data of the hollow blade through a flow optical scanner. He took the outline of the outer wall of the hollow blade as the initial outline and approximated the outer outline of the ceramic core based on the Snake model to obtain the outer outline of the ceramic core section. However, this method tends to shrink into a straight line between the longitudinal ribs of the ceramic core. Zhang [13] proposed a method based on B-spline to fit the outer contour line of the hollow blade ICS. This method performs B-spline fitting where there are more measurement data, and at the edge of the blade where the measurement data is less fitted to an arc line. This method limits the shape of the ICS of the hollow blade and has poor applicability for hollow blade whose ICS have different shapes.

This article focuses on the application of ultrasonic measurement in hollow measurement, focuses on the method of evaluating hollow blade ICS based on incomplete measurement data, and proposes a method of ICS reconstruction based on incomplete measurement data. By adjusting the position of the theoretical ICS point in the normal direction of the theoretical chamber, the approximation curve is obtained to fill the gap of the measured points and reconstruct the ICS. Compared with existing internal chamber reconstruction algorithms, the algorithm proposed in this paper has the following advantages:

1) The reconstructed cavity ensures that it passes through every measurement point.
2) Because the adjustment direction of the original point is set, the number of parameters in the optimization function is reduced, the optimization function is easier to converge, and the amount of calculation is smaller.

The rest of this article is organized as follows. Section 2 introduces the basic concept of five-axis ultrasonic measurement and measurement path planning. In Section 3, we will explain in detail how to reconstruct the ICS based on incomplete ICS measurement data. The fourth part verifies the effectiveness of the proposed reconstruction algorithm through actual experiments. Section 5 evaluates the hollow blade internal chamber from the line profile and wall thickness. Finally, Section 6 draws conclusions.
2. Measuring Equipment Introduce and Measurement Path Planning

This paper uses a five-axis CMM equipped with an ultrasonic probe to measure the wall thickness of the hollow blade. The five-axis CMM completes the measurement work by carrying the probe on the probe head, and its motion control contains three linear axes (X, Y, Z) and two rotary axes. Three linear axes can uniquely determine the position of the probe head, and two rotary axes can uniquely determine the normal direction of the probe, so the position of probe tip is determined. That is, the position of the probe ball can be uniquely determined by these five parameters. The RUP1 probe is Renishaw's ultrasonic probe product. It uses an innovative elastomer tip ball to provide excellent coupling between the probe and the material, and it does not require a water tank or coupling gel to achieve good signal transmission. The RUP1 ultrasonic probe is fully integrated into the MODUS metrology software. It has functions such as calibration of the sound velocity of the workpiece material, monitoring, and compensation of the tip ball size, and can complete the wall thickness measurement of the workpiece with high precision. When using a five-axis CMM with a RUP1 probe for ultrasonic measurement, the position of the measuring point and the normal direction of the probe are needed, which can uniquely determine the position and normal direction of the probe head and probe.

The blade measurement points are obtained by the STL model slicing algorithm. The basic process is: import the mesh model of the blade and intersect the section planes with different heights along the stacking axis of the blade to generate the section line. The calculation process is based on the mesh topology cutting algorithm of the half-edge data structure [14], that is, first randomly search for the first triangular mesh face that intersects the cross-section plane, and then search for the adjacent faces that have the same intersection according to the half-edge data structure. And search in order, and finally get all the intersection edges and intersection points, and generate a complete slice layer contour line. The set of intersection points obtained by this algorithm is ordered, and there is no need to reorder the intersection line segments obtained. This method can directly obtain the contour line that meets end to end, which simplifies the process of obtaining the sliced contour. Due to the excessive number of intersection points in the collection of intersection points, this paper chooses a sparse strategy based on chord length [15] to obtain measurement path by limiting the Euclidean distance between adjacent measurement points, so that the measurement path is composed of a series of approximately equally spaced measurement points.

Different from ordinary contact measurement, ultrasonic measurement requires the probe to be aligned with the normal direction of the workpiece surface, otherwise, the ultrasonic probe cannot receive the pulse-echo or the received pulse-echo signal is very weak, resulting in the inability to obtain effective thickness measurement data [16]. Since one edge in the half-edge data structure belongs to two triangular faces, and a measurement point corresponds to two faces normal, this paper sets the normal of measurement point to the angular bisector of the two faces normal.

The wall thickness of the measuring point is calculated based on the measurement principle of the ultrasonic pulse-echo method, that is, the wall thickness is half of the sound wave propagation distance in the measured object [16].

\[ T = \frac{v \times t}{2} \]  

In equation (1), \( T \) is the thickness, \( v \) is the sound velocity of the ultrasonic wave in the material, and \( t \) is the time of the ultrasonic wave in the material. As shown in figure 1, the flexible probe ball provides a good coupling between the pulse transmitter and the blade. The \( v \) and \( t \) in equation (1) correspond to the \( v \) and \( t \) of the ultrasonic wave in the propagation process of the blade in figure 1. Figure 2 shows a typical ultrasonic scan signal for ultrasonic thickness measurement of hollow blades. The sound wave first passes through the flexible measuring ball of the RUP1 probe, and then reflects on the outer wall of the blade and then on the inner wall of the blade. Therefore, in the time interval between the outer wall signal and the inner wall signal in the figure 2, the sound wave propagates in the blade. The \( t \) in equation (1) corresponds to the time between the outer wall signal and the inner wall signal.
3. Reconstruction Method of ICS of the Hollow Blade

The hollow blade profile is a space-complex free-form surface, which is composed of a series of designed cross-sectional profile lines superimposed in the direction of the stacking axis, and its profile usually has a certain twist design. The traditional curve and surface are difficult to accurately describe the blade profile. Nurbs curves and surfaces have a series of excellent characteristics such as weight factor adjustment and parameter continuity, so they are very suitable for the description of aviation blade profiles. The blade profile measurement data obtained by the CMM is an orderly data point, and its accuracy is also high, so its profile reconstruction can be achieved by Nurbs curve interpolation [17].

The Nurbs curve equation is:

\[ P(u) = \sum_{i=1}^{n} w_i d_i N_i(u) \]

Where \( P(u) \) is the space point coordinate vector; \( d_i \) is the control vertex coordinate vector; \( w_i \) is the weight factor; \( N_i(u) \) is the basis function, and its value is determined by the node vector and the curve parameter \( u \).

The Nurbs curve reconstruction of the cross-section profile based on the CMM measurement data of the blade profile belongs to the curve reverse process, which includes two main processes: firstly, the reverse algorithm is used to find the curve control vertex based on the measurement data, and then the Nurbs curve is defined according to the definition formulation of the Nurbs curve [17].

Since there are a lot of vacancies in the measurement points of the ICS obtained by the five-axis ultrasonic measurement of the hollow blade, the direct application of Nurbs curve interpolation will cause the distortion of the reconstructed ICS, so an algorithm to fill the vacancy of the hollow blade ICS measurement points is needed. Considering that the ceramic core may have uneven shrinkage, torsion, and bending during processing, there may be differences between the actual ICS and the theoretical ICS. It is not possible to directly extract the points from the theoretical ICS to fill the vacancy of the measuring point.

This paper proposes a method to obtain the approximation curve first, and then select the points from the approximation curve to fill the vacancy of the measuring point. The flow chart of reconstructing the ICS of the hollow blade is shown in figure 3.
3.1. Measurement Points Division
Hollow blades usually have multiple chambers, and different chambers are divided by partitions. It is necessary to divide the measured points to determine which internal chamber each measurement point belongs to.

About theoretical internal chamber point cloud \( A \{ A_1, A_2, A_3, \ldots \} \), \( B \{ B_1, B_2, B_3, \ldots \} \), ICS measurement point \( P \{ P_1, P_2, P_3, \ldots \} \). The distance between the ICS measurement point \( P_i \) and the internal chamber point cloud \( A \) is \( d_{ia} \).

\[
d_{ia} = \min\left\{ |P_i - A_1|, |P_i - A_2|, |P_i - A_3|, \ldots \right\}
\] (3)

Similarly, we can get \( d_{ib} \). If \( d_{ia} < d_{ib} \), \( P_i \) belongs to the internal chamber A. Otherwise, \( P_i \) belongs to the internal chamber B.

3.2. ICP Registration of Theoretical ICS and ICS Measurement Point
Since the ceramic core may be deformed during processing such as bending and torsion, the position of the actual ICS and the theoretical ICS may be different. ICP registration [18] is required for the theoretical ICS point.

3.3. The Theoretical ICS Approaches the ICS Measurement Point as a whole
Based on the NURBS curve interpolation, this paper adjusts the theoretical ICS \( C_1(u) \) to obtain the approximation curve \( C_2(u) \). The original point sequence \( P \{ P_1, P_2, P_3, \ldots \} \) and the original point contraction direction \( F \{ F_1, F_2, F_3, \ldots \} \) are obtained from the theoretical ICS \( C_1(u) \). Approaching the measuring point sequence \( Q \{ Q_1, Q_2, Q_3, \ldots \} \) by adjusting the shrinkage coefficient \( X \{ X_1, X_2, X_3, \ldots \} \) to obtain the approximation curve \( C_2(u) \). Since the bending and torsion of the ceramic core in the processing process can be regarded as rigid deformation, this paper focuses on the deformation of the ICS caused by the non-uniform shrinkage of the ceramic core when obtaining the approximation curve. In this paper, the contraction direction \( F \) of the original point \( P \) is assumed to be the normal direction of the original point \( P \) in the theoretical section line \( C_1(u) \).

According to equation (4), the adjusted point sequence \( N \) can be obtained. As shown in figure 4, the approximation curve is obtained by NURBS interpolation.

\[
N_i = P_i + X_i \times F_i
\] (4)
In order to make the approximation curve \( C_2(u) \) have better approximation accuracy and smoothness, the objective function established in this paper is as follows:

\[
f = \alpha \times f_1 + \beta \times f_2
\]  

(5)

\( f_1 \) is the approximation term, which is used to make the approximation curve as close as possible to the measurement point \( Q \). \( f_2 \) is a smoothing constraint item, used to make the approximation curve have a better smoothness. \( \alpha \) is the coefficient of the approximation term, and \( \beta \) is the coefficient of the smoothing term.

This article uses the least square method to construct \( f_1 \).

\[
f_1 = \sum_i \left| Q - C_2(u_i) \right|^2
\]  

(6)

\( u_i \) is the node value corresponding to the point on the approximation curve \( C_2(u) \) that is closest to the measurement point \( Q_i \).

\( f_2 \) is the smoothing constraint item, which is used to control the smoothing degree of the approximated curve \( C_2(u) \). \( f_2 \) is constructed by controlling the increment of the shrinkage coefficient.

\[
f_2 = \sum \Delta X_i^2
\]  

(7)

\[
\Delta X_i = X_{i+1} - X_i
\]  

(8)

\( \Delta X_i \) represents the increment of the contraction coefficient of adjacent points. Through the minimum over-shrinkage coefficient increment sum, the change range of the shrinkage coefficient between adjacent model value points is limited, so that the shrinkage effect forms a gradual effect in a local range, and the smoothness of the approximate curve is realized.

The shrinkage coefficient \( X_i \{X_1, X_2, X_3, \ldots\} \) is solved by the Genetic Algorithm optimization function of matrix laboratory, and the approximation curve \( C_2(u) \) is obtained.

3.4. Filling up the Measurement Points

When obtaining the ICS approximation curve, it is necessary to consider both the approximation degree and the smoothness degree at the same time. However, the degree of approximation and the degree of smoothness often cannot reach a good level at the same time, otherwise, it will cause problems such as slow convergence of the objective function and a large amount of calculation. Therefore, the approximation curve does not pass through all the ICS measurement points. This article does not take the approximation curve as the final fitting result, but selects the points \( M \{M_1, M_2, M_3, \ldots\} \) located at the partition position from the approximation curve \( C_2(u) \) to fill the gaps in the measurement data \( Q \{Q_1, Q_2, Q_3, \ldots\} \), and combines them to reconstruct the ICS of the hollow blade.

The ICS measurement point sequence \( Q \{Q_1, Q_2, Q_3, \ldots\} \) of the hollow blade can be divided into two parts according to the continuity. The main vacancy that needs to be filled in the area of the two partitions, so according to the clockwise order, the points needed to reconstruct the ICS can be divided into four sequences \( K^1, K^2, K^3, K^4 \subset M, K^2 \subset Q, K^3 \subset M, K^4 \subset Q \). The node range of the filling sequence \( K^1 \) and \( K^3 \) can be determined by calculating the node value corresponding to the mapping point of the starting and ending points of the measurement point sequence \( K^2 \) and \( K^4 \), on the approximation curve \( C_2(u) \). As shown in figure 5, the appropriate node interval is selected to complete the filling of the gap of the ICS measurement point, and finally, the ICS of the hollow blade can be reconstructed.
Figure 5. The relative position of the filling point sequence and measuring point sequence.

4. Experiment

4.1. Measurement

The five-axis ultrasonic measurement path for hollow blade is illustrated in figure 6. Each measurement point contains the coordinate and normal information. Figure 7 is an actual measurement diagram of a five-axis CMM equipped with a RUP1 ultrasonic probe to measure hollow blades.

Figure 6. The five-axis ultrasonic measurement path for hollow blade.  
Figure 7. Measurement process.

4.2. ICS Measurement Point Calculation

After obtaining the wall thickness data of the measuring point through the five-axis CMM, the ICS point of the hollow blade can be calculated by the position of measurement path, the normal direction of measurement path, and the wall thickness data T obtained by the ultrasonic probe according to equation (9). As shown in figure 8, three equidistant surfaces were selected for measurement in this experiment.

\[ P_{in} = P_{out} - T \times N_{out} \]  

(9)

Figure 9 shows the distribution of ICS measurement points on the measured cross-section Z1. The measurement points are missing at the internal chamber partition, and only the point data on the blade body and back can be obtained. There is much data missing.
4.3. Reconstruction of ICS of the Hollow Blade

According to the reconstruction algorithm in the third section of this article, this article reconstructs the four ICS of section Z1 and obtains the reconstructed ICS as shown in the figure 10. The reconstructed ICS passes through all measurement points. And the reconstructed ICS keeps the contour of the theoretical ICS and has good smoothness. The reconstruction results verify the effectiveness of the algorithm proposed in this paper.

5. Evaluation of the ICS of the hollow blade

This paper uses the reconstructed ICS of the hollow blade to evaluate the ICS of the hollow blade from two aspects: the profile of the ICS and the wall thickness of the hollow blade.

5.1. The line profile of the ICS of the hollow blade

Line profile is one of the important indexes to evaluate the quality of section. Now follow the steps below to calculate the line profile error of the hollow blade.

1. Select the point sequence \( P(P_1, P_2, P_3, \ldots) \) on the reconstructed ICS.
2. Calculate the closest point \( Q(Q_1, Q_2, Q_3, \ldots) \) of \( P(P_1, P_2, P_3, \ldots) \) on the theoretical ICS.
3. Calculation deviation \( d(d_1, d_2, d_3, \ldots) \) of \( P(P_1, P_2, P_3, \ldots) \), \( d_i = |P_i - Q_i| \).
4. Calculated symbol of $d(d_1, d_2, d_3, \cdots)$. If the point $P_i$ is within the theoretical contour $d_i$ is negative, otherwise $d_i$ is positive.

5. Calculate line profile:

$$E = \max(d) - \min(d)$$

This paper calculates the line profile of the four chambers on the section Z1, and the results are shown in table 1.

| Internal chamber number | Line profile (mm) |
|-------------------------|------------------|
| Internal chamber 1      | 0.5925           |
| Internal chamber 2      | 0.6684           |
| Internal chamber 3      | 0.4851           |
| Internal chamber 4      | 0.3689           |

5.2. Hollow blade wall thickness error

The wall thickness error of the hollow blade is one of the important indexes to evaluate the processing quality of the hollow blade. This paper chooses the wall thickness definition method based on the inscribed circle to evaluate the wall thickness error of the hollow blade.

As shown in figure 11, suppose point A is a point on the outer wall of the hollow blade. There is an inscribed circle passing through point A and tangent to the hollow blade ICS at point B. Then $|A - B|$ is the wall thickness at point A. For the outer wall point C located at the position of the partition, there are different inscribed circles crossing point C and tangent to the different ICS at point D and point E. Then the wall thickness of the outer wall point C is $\min(|C - D|, |C - E|)$.

For the same outer wall point A, the wall thickness $b_1$ between it and the theoretical ICS can be obtained. The wall thickness $b_2$ between point A and the reconstructed ICS can be obtained. Then the wall thickness error of point A is:

$$b_{error} = |b_1 - b_2|$$

This paper analyses the wall thickness error of the sample section Z1, and selects the analysis points as shown in figure 12. Figure 13 shows the distribution of the wall thickness error at the analysis point.

6. Conclusion

In this paper, the thickness of the hollow blade is measured by an ultrasonic probe on five-axis CMM. By adjusting the position of the theoretical ICS point in the normal direction of the theoretical chamber, the approximation curve is obtained to fill the gap of the measured points and reconstruct the ICS. By setting the adjustment direction of the point, the number of variables in the optimization function is reduced, and the amount of calculation is reduced. The ICS of the hollow blade is
evaluated from two aspects: line profile and wall thickness error. This paper systematically completes the evaluation of the hollow blade ICS based on ultrasonic measurement data and provides an economical, safe and flexible measurement method for hollow blade measurement.

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7. Reference
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