Shape Evaluation Method for Leading and Trailing Edges of Aero-engine Blade

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Abstract—The shape of the leading and trailing edges of aero-engine blades has a significant influence on its aerodynamic performance. At present, the method of manual inspection based on the standard pattern is mainly used to analyze the shape of the leading, and trailing edges, which has the problems of low efficiency, poor repeatability and inconsistent evaluation results. An automatic shape evaluation method based on eigenvalues is proposed in this paper. Firstly, the blade profile and its mean camber line are segmented and fitted. Then, evaluation indexes are given for the five unqualified edge shapes respectively according to the curvature characteristics and profile variation characteristics. Finally, the shape of the blade edge is evaluated with the eigenvalues calculated. Experiments show that the proposed method can realize the automatic shape evaluation of blade leading and trailing edges, and can adapt to different types of blades and different acceptance standards, which effectively improves the efficiency of blade profile quality inspection.

1. Introduction
Blade is not only one of the important parts of aero-engine, but also a key active component related to the safety performance of the engine. Thus, the detection of blade profile is of great significance in the detection of aero-engine parts\textsuperscript{[1]}. Since the leading and trailing edges are the thinnest part of the blade, it is very easy to exceed the tolerance during processing. The ideal leading edge or trailing edge (hereinafter referred to as LE/TE) is generally designed as arc or elliptical arc. But some non-ideal arc shapes may appear in the actual production due to the influence of processing technology. According to the actual production experience of a certain type of integral blade disk, the following unqualified shapes are prone to appear at blade edges: the sharp edge, the blunt edge, the inclined edge, the necking edge, and the large-small-large or small-large-large (hereinafter referred to as LSL/SLS) edge.

Some studies have shown that even a small shape error will affect the propulsion efficiency of the engine\textsuperscript{[3]}. For the blunt leading edge, the thickness of the boundary layer of the suction surface and the width of the wake are greatly increased, so it has a great influence on the Mach number, resulting in a significant increase in the loss of the blade profile. For the inclined leading edge, due to the change of the throat area, it has a great influence on the blocking flow and the range of positive/negative attack angle. Similarly, due to its geometric characteristics, other types of unqualified LE/TE shapes will also have varying degrees of impact on the aerodynamic performance of the engine.

However, no clear quantitative standards and definitions of unqualified blade edge shapes are given in the standard HB 5647-1998 Dimension, Tolerance and Surface Roughness of Blade Profile\textsuperscript{[4]}, which causes great difficulty to study the automatic evaluation method of blade edges shape. Cao Bin\textsuperscript{[5]}
proposed a method to evaluate LE/TE shape based on the thickness changing trend. The blade edge thickness is segmented by the mean camber line, then the automatic analysis of the blade LE/TE shape is realized by evaluating the eigenvalues of the thickness changing trend. But the evaluation methods for other kinds of unqualified shapes are not given.

At present, the evaluation of blade edge shape mainly depends on manual work. This detection method has some disadvantages, such as non-standard image magnification, strong subjectivity of judgment results, and it is easy to have inconsistent detection results from different inspectors. Therefore, designing an automatic evaluation method of blade LE/TE shape is of great significance to improve the efficiency of blade production and quality inspection.

2. Blade Profile Fitting and Calculation of the mean camber line

The data obtained in this paper comes from the CMM measurement software, which is the discrete points data of the blade on different contour sections, including the measure points and theoretical points of the blade profile. The data has been roughly divided into four parts: the leading edge (LE), the trailing edge (TE), the concave (CC), and the convex (CV). The specific division scope depends on the design requirements. Before evaluating the blade LE/TE shape, it is necessary to segment and fit the blade profile and the mean camber line.

2.1. Blade profile segmentation and piecewise curve-fitting

The blade measured data is usually discrete points. Before solving the blade profile parameters, the discrete points need to be fitted into a continuous curve. The theoretical shape of LE/TE is generally a circular arc or an elliptical arc. The ellipse fitting method based on the least square is used to fit the theoretical points of LE/TE[6], then the theoretical arc of LE/TE can be obtained.

For the blade with shape error, the actual shape of LE/TE is a non-ideal arc, so the actual curve can not be constructed by arc fitting. Therefore, the method of free-form curve construction can be used to fit the actual LE/TE curve and the curve of CC/CV. Among the widely used free curve construction methods at present, non-uniform rational B-spline (NURBS) is an appropriate generalization of Bezier and rational spline[7, 8]. Perform NURBS curve-fitting on the measured points of LE/TE, to obtain the actual curve of LE/TE. Perform NURBS curve-fitting on the theoretical points and measured points of CC/CV, to obtain the theoretical curve and actual curve of CC/CV[9].

2.2. Calculation of the mean camber line

The mean camber line is defined as the line connecting the center of the inscribed circle of the blade profile and extending to the line intersecting LE/TE in the tangent direction at the center of LE/TE[4]. Because the center of the inscribed circle must be the intersection of the normals of two points respectively located on CC and CV, and the distance from the center of the circle to these two points is equal. According to the above idea, the equal radius method is used to obtain the mean camber line of the blade profile. Suppose there are two points A and B on CC and CV respectively, and point G is the intersection of the normals at A and B. If the difference between the length of line AG and the length of line BG is less than the pre-set threshold, then the point G can be considered as a point on the mean camber line[10, 11].

(1) Calculation of the theoretical mean camber line

The point set $G_i$ can be obtained by performing the equal radius method on the theoretical CC and CV curves fitted in Section 2.1. The center points of theoretical LE and TE arcs calculated in Section 2.1 are also added into the point set $G_i$. Afterwards, NURBS curve-fitting is performed on the point set $G_i$. Then extend this curve along the tangent direction from the theoretical LE/TE center point to the intersection of the theoretical edge profile[12]. And the final curve is the theoretical mean camber line.

(2) Calculation of the actual mean camber line
The point set $G_0$ can be obtained by performing the equal radius method on the actual LE, TE, CC, and CV curves fitted in Section 2.1. Afterwards, NURBS curve-fitting is performed on the point set $G_0$. Then the actual mean camber line is obtained. The solution results are shown in Fig.1.

![Fig.1 Fitting and calculation results](image)

**3. Shape Evaluation Method for Leading and Trailing Edges of Blade**

The main idea of the shape evaluation method for blade edges is as follows: Analyze the geometric characteristics of the leading and trailing edges under different types of unqualified shapes, evaluate its curvature characteristics, profile deviation changing characteristics and other eigenvalues. Finally, make a judgment for each unqualified shape type respectively.

### 3.1. Definition of Some Parameters

1. **The vertex of LE/TE**

   The theoretical vertex of LE/TE is the intersection of the theoretical mean camber line and the theoretical LE/TE arc. Similarly, the actual vertex of LE/TE is the intersection of the actual mean camber line and the actual LE/TE curve.

![Fig.2 The vertex of LE](image)

2. **Ratio of the curvature radius of vertexes $R_\rho$**

   As shown in Fig.2, the point $V$ is the theoretical vertex of LE/TE, and the point $V'$ is the actual vertex of the LE/TE. Calculate the ratio of the curvature radius of the actual vertex $V'$ to the curvature radius of the theoretical vertex $V$:

   $R_\rho = \frac{\rho(V')}{\rho(V)}$  \hspace{1cm} (1)

3. **Blade profile intersection $Q$**

   Calculate the intersection of the actual profile and the theoretical profile at the LE/TE of the blade, and take this series of points $Q_i (i = 1, 2, \ldots, n)$ as "blade profile intersections".

### 3.2. Evaluation Index of Sharp Edges

The leading/trailing edge is in sharp shape when it meets the following index: the radius of curvature at the actual vertex of the edge is obviously less than its theoretical value. Take the ratio $R_\rho$ as an
eigenvalue for sharp shape evaluation. Set the threshold of this eigenvalue as \((R_v)_{\text{MIN}}\). If \(R_v < (R_v)_{\text{MIN}}\), it can be judged that the edge is in sharp shape.

![Fig.3 Sharp edge](image)

3.3. Evaluation Index of blunt edges

The leading/trailing edge is in blunt shape when it meets the following two indexes simultaneously:

Index(I): The curvature radius of the vertex of the edge is obviously larger on both sides. Take the ratio \(R_v\) as an eigenvalue for blunt shape evaluation. Set the threshold of this eigenvalue as \((R_v)_{\text{MAX}}\). If \(R_v > (R_v)_{\text{MAX}}\) then Index(I) is met.

Index(II): An obvious minimum curvature radius value appears on each side of the vertex. Judge if point \(M\) and point \(N\) with the minimum curvature radius value appear on both sides of the actual vertex, as shown in Fig.4. If so, take the distance \(d_{MN}\) between the two points \(M\) and \(N\) as an eigenvalue for blunt shape evaluation, and set the threshold of this eigenvalue as \((d_{MN})_{\text{MAX}}\). If \(d_{MN} > (d_{MN})_{\text{MAX}}\) then Index(II) is met.

If the leading/trailing edge of a blade profile meets the Index of (I) and (II) simultaneously, it can be judged that the edge is in blunt shape.

![Fig.4 Blunt edge](image)

3.4. Evaluation Index of inclined edges

The leading/trailing edge is in inclined shape when it meets the following two indexes simultaneously:

Index(I): The blade profile on two sides of the mean camber line are obviously asymmetric. Calculate the distance \(l_i\) from the actual vertex of the LE/TE to the theoretical mean camber line, and take it as an eigenvalue for inclined shape evaluation. Set the threshold of this eigenvalue as \((l_i)_{\text{MAX}}\). If \(l_i > (l_i)_{\text{MAX}}\) then Index(I) is met.

Index(II): In the fatter side of the leading edge, the tendency of the actual profile, which starts from the leading edge to the rear, changes continuously from the upper limit to the lower limit of the profile tolerance obviously, and passes through the theoretical profile. The trailing edge has the tendency similarly. Judge whether there are blade profile intersections \(Q\) on the fatter side of the edge profile (i.e. the side with the actual vertex). If so, as shown in Fig.5, take the intersection \(Q_i\) closest to the actual vertex, calculate the maximum positive deviation \(\text{devi}(A)\) and the maximum negative deviation \(|\text{devi}(B)|\) on both sides of point \(Q_i\) respectively. Take \(\text{devi}(A) + |\text{devi}(B)|\) as an eigenvalue for inclined shape evaluation, and set the threshold of this eigenvalue as \([\text{devi}(A) + |\text{devi}(B)|]_{\text{MAX}}\). If \([\text{devi}(A) + |\text{devi}(B)|] > [\text{devi}(A) + |\text{devi}(B)|]_{\text{MAX}}\) then Index(II) is met.

If the leading/trailing edge of a blade profile meets the Index of (I) and (II) simultaneously, it can be judged that the edge is in inclined shape.
3.5. Evaluation Index of necking edges

The leading/trailing edge is in necking shape when it meet the following index: On both sides of the leading edge, the tendency of the actual profile, which starts from the leading edge to the rear, changes continuously from the upper limit to the lower limit of the profile tolerance obviously, and passes through the theoretical profile. The trailing edge has the tendency similarly. Firstly, judge whether there are blade profile intersections \( Q \) on both sides of the actual vertex. If so, as shown in Fig.6, take the blade profile intersection \( Q_k \) and \( Q_{k+1} \) closest to vertex on the CC side and CV side respectively, then calculate the maximum positive deviation \( \text{devi}(A) \) and the maximum negative deviation \( |\text{devi}(B)| \) on both sides of \( Q_k \) and \( Q_{k+1} \) respectively. Take these two \( \text{devi}(A)+|\text{devi}(B)| \) as the eigenvalue for necking shape evaluation, and set the threshold of the eigenvalue as \( \text{MAX} \text{devi} \). If it satisfies the following formula (2):

\[
\begin{align*}
\left[\text{devi}(A)+|\text{devi}(B)|\right]_{CC} &> \left[\text{devi}(A)+|\text{devi}(B)|\right]_{MAX} \\
\left[\text{devi}(A)+|\text{devi}(B)|\right]_{CV} &> \left[\text{devi}(A)+|\text{devi}(B)|\right]_{MAX}
\end{align*}
\]

(2)

Then it can be judged that the edge is in necking shape.

3.6. Evaluation Index of LSL/SLS edges

The leading/trailing edge is in LSL/SLS shape when it meets the following index: The edge profile changes continuously with the tendency of "large-small-large" or "small-large-small", and the changing areas approaches or covers the vertex of the edge. Firstly, analyze the changing tendency of the profile deviation value at the edge. As shown in Fig.7, if the deviation has a continuous change of "negative-positive-negative", it means the blade profile is close to "samll-large-small". If the deviation has a continuous change of "positive-negative-positive", it means the blade profile is close to "large-small-large". Therefore, it can be judged whether there are three continuous changing areas exist the “negative-positive-negative” / “positive-negative-positive” phenomenon at the edge, and one of the areas covers the actual vertex of the edge. If it exists, calculate the extreme value \( |\text{devi}(A)|, |\text{devi}(B)|, |\text{devi}(C)| \) of the deviation in the area between the intersections, and take these extreme values of deviation as the eigenvalue for LSL/SLS shape evaluation. Set the threshold of the eigenvalue as \( \text{devi}_{MAX} \). If it satisfies the following formula (3):
Then it can be judged that the edge is in LSL/SLS shape.

\[
\begin{align*}
|\text{dev(A)}| &> \text{dev}^{\text{MAX}} \\
|\text{dev(B)}| &> \text{dev}^{\text{MAX}} \\
|\text{dev(C)}| &> \text{dev}^{\text{MAX}}
\end{align*}
\]

(3)

4. Experimental Results

In order to verify the effectiveness of the method proposed in this paper, based on the above evaluation method, the shape of the leading and trailing edges of a certain type of blisk is evaluated.

Firstly, read the data of the selected blade profiles, then the proposed method is used to calculate the profile eigenvalues. Afterwards, the threshold of each eigenvalue needs to be set. Since the difference of blade shapes and sizes under different interception heights, it is necessary to adjust the appropriate eigenvalue threshold for each interception height. And the thresholds can also be controlled according to the acceptance requirements of different types of blades, so as to realize the reusability of this algorithm. Finally, the evaluation results of blade edge shape can be obtained by comparing the calculated eigenvalue values with the threshold. The eigenvalue calculation results and shape evaluation results of some blade edges are shown in Table 1.

The experimental results show that the evaluation results of blade edge shape by using the proposed algorithm are highly consistent with the objective facts, and there are no manual evaluation problems such as low efficiency, strong subjectivity, and difficult regulation of acceptance standard, which effectively improves the efficiency of blade profile detection.

| Table 1 The shape evaluation results of blade profile edges |
|------------------------------------------------------------|
| eigenvalues       | threshold | edge 1 | edge 2 | edge3 | edge 4 | edge 5 | edge 6 |
|-------------------|-----------|--------|--------|-------|--------|--------|--------|
| \(R_s(\text{sharp})\) | 0.80      | 106.60 | 77.01  | 247.78| 91.52  | 98.61  | 88.22  |
| \(R_s(\text{blunt})\) | 1.60      |         |        |       |        |        |        |
| \(d_{MN}\)        | 160.00    | 36.58  | 10.75  | 196.52| 52.64  | 11.17  | 7.01   |
| \(d_i\)           | 50.00     | 13.580 | 5.55   | 39.50 | 79.65  | 86.500 | 20.32  |
| \(|\text{dev(A)}+\text{dev(B)}|\) | 60.00    | 38.67  | 95.66  | 104   | 76.28  | 86.50  | 90.833 |
| \(|\text{dev(A)}+\text{dev(B)}|\) | 60.00    | None   | None   | None  | None   | 77.02  | None   |
| \(|\text{dev(A)}|\)     | 30.00    | +22.62 | +40.89 | -25.03| -37.96 | +37.47 |
| \(|\text{dev(B)}|\)     | 30.00    | -16.59 | None   | -41.85| +43.10 | +48.54 | -31.25 |
| \(|\text{dev(C)}|\)     | 30.00    | +5.17  | +105.63| -36.55| -47.15 | +62.42 |

* Except \(R_s\), the unit of all the eigenvalues in the table is % profile tolerance band.

* “+” represents positive deviation and “-” represents negative deviation.

* In the \(d_i\) row of the table, “(CC)” means the vertex is on the CC side, “CV” means the vertex is on the CV side.
5. Conclusion

Aiming at the problems of low efficiency and strong subjectivity of the current methods of shape evaluation of leading and trailing edges of Aero-engine Blades, an automatic evaluation method is proposed. Firstly, the blade profile is segmented and fitted by the least square ellipse fitting algorithm and NURBS curve-fitting method, and its mean camber line is calculated by the equal radius method. Then, evaluation indexes are given for the five unqualified edge shapes respectively according to the curvature characteristics and profile variation characteristics. Finally, the shape of the blade edge is evaluated by comparing the eigenvalues calculated and the thresholds.

The experimental results show that this method can automatically identify several non-ideal shapes of blade edges: the sharp edge, the blunt edge, the inclined edge, the necking edge, and the LSL/SLS edge. It can also adapt to different blade models and different acceptance standards, which effectively improve the efficiency of blade profile evaluation.

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