Adaptive CNC machining process optimization of near-net-shaped blade based on machining error data flow control

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Abstract
This study proposes a high precision machining method of near-net-shaped blade based on multi-process machining errors data flow control. The multi-process machining geometric error and mechanical models of the blade multi-process are firstly constructed. The stiffness of blade-fixture system is secondly analyzed. The machining error flow of the blade multi-process is finally controlled by the adaptive CNC machining process under the sufficient stiffness of blade-fixture system. The results show that the dynamic displacement response of the blade multi-process is controlled within 0.007 mm. The optimized adaptive CNC machining process of the multi-process geometric machining error data flow control can realize the high-precision manufacturing of blade.

Keywords Adaptive CNC machining process · Machining error · Stiffness · Near-net-shaped blade

1 Introduction

Blade, as one of the most commonly used functional parts in aero-engine, is the key part for the realization of aero-engine performance. The manufacture of blade is a challenge due to the extremely complex structure and precision requirements [1]. The contour error of the near-net-shaped blade body formed by the precision forging forming process is in the range of 0.008 to 0.05 mm, which meets the accuracy requirements of the blade body and does not require subsequent CNC machining process. However, the subsequent CNC machining process of the blade leading and trailing edges (LTE), tenon root, and tip is indispensable due to the small radius curvature and high precision requirement [2]. In the CNC machining process of the blade LTE, tenon root, and tip, the only available positioning surface is the blade body profile. However, the formed blade body profile has an initial contour error of 0.008–0.05 mm. The clamping surface is only the blade body which is a 5-mm thick blade. The high processing requirements which the contour error of the tenon root is less than 0.007 mm, the roughness is less than Ra 0.8 μm, and the section torsion is less than 0.15 degree should be finally completed by CNC machining process. Therefore, the machining error control and stiffness improvement are the key challenge for near-net-shaped blade CNC machining process.

The existing CNC machining process for this near-net-shaped blade tenon root is a low-melting-point alloy casting method in which the blade is poured into a block through the low-melting-point alloy to improve the stiffness of the process system. However, disadvantages of the low surface positioning accuracy, long process chain, and blade surface alloy contamination make it difficult to meet the performance requirements of the new-generation aero-engine.

There are currently many studies for this type of blade high precision machining which mainly focus on two aspects. One is the whole-process machining error control, and the other is the improvement of the rigidity of the process system.

The multi-process machining error transmission is not conducive to the improvement of blade CNC machining accuracy because that various machining error features that affect the machining accuracy of blade curved parts are
accumulated in space domain, and a variety of machining errors are transmitted in the time domain along with the blade multiple CNC machining process procedures. The transmission control of the multi-process machining errors is the key to improving the blade machining quality. SJ Hu et al. [3] proposed a theoretical method for the error flow of mechanical product assembly based on the error transmission characteristics of multiple parts. D. Ceglarek et al. [4, 5] further developed the state-space equation method to study assembly error variation relationship modeling, deviation transmission mechanism, and applied it to the quality modeling and process quality control of the multi-process assembly process of auto parts. Walid Ghiea et al. [6] proposed a tolerance zone representation theory based on small displacement torsor (SDT), which represented a typical tolerance zone as a series of standardized numerical models, so as to perform error transfer calculations based on the Jacobian matrix. Rong et al. [7] comprehensively studied the influence of positioning error on the accuracy of parts processing, and established a complete geometric positioning error calculation and sensitive factor analysis method. Mantripragada et al. [8] proposed a state transition model for the deviation transfer of a multi-process manufacturing system, which applies the control system theory to a multi-process manufacturing system. The method of transmitting error data stream can be used to solve the error control problem of blade multi-process machining based on the above researches.

On the other hand, there are also many researches on the enhancement of the rigidity of the blade machining process system. Jiayuan He et al. [9] used the finite element method (FEM) to study and optimize the fixture positioning layout to enhance the rigidity of thin-walled parts and reduce the deformation error. Considering the complexity of the blade-fixture system, the FEM has been widely used in recent years to obtain better results of part stiffness analysis. Asante et al. [10] studied the problem of elastic contact between fixture and workpiece, combining contact modeling and finite element methods to predict the load and pressure distribution in the contact area to determine the actual clamping force of the tangential and normal direction. Wang Ying et al. [11, 12] established a part stiffness analysis model by FEM, and then discussed the correlation between positioning errors and machining errors, geometric errors and deformation errors, and the effect on the final machining accuracy of the blade surface basis on the contact analysis research between blade part and fixture. K.P. Padmanaban et al. [13] proposed a method to improve the layout of fixture through the ant colony optimization algorithm to control the elastic deformation of parts. He Ning et al. [14] paid more attention to the elastic deformation of parts under the cutting motion of the cutter during the machining process and the corresponding surface machining errors. Chen Weifang et al. [15] proposed a multi-objective optimization method based on genetic algorithm to improve part stiffness. E. Budak et al. [16] focused on the milling process of workpieces, and conducted more comprehensive research on cutting force, structural deformation, and surface accuracy.

In summary, in order to achieve high precision machining of near-net-shaped blade, the adaptive CNC machining process should be optimized from the stiffness improvement and machining error control. The structure of this study is arranged as follows. The multi-process adaptive CNC machining process of near-net-shaped blade is studied based on theoretical method in Sect. 2. The experimental conditions and methods for adaptive CNC machining process optimization and dynamic performance testing are shown in Sect. 3. Experimental results and discussion are in Sect. 4. The conclusion is summarized in Sect. 5.

2 The blade multi-process adaptive CNC machining process

As a machining method of near-net-shaped blade, the method of geometric adaptive CNC machining process is mainly based on the idea of closed-loop optimization iteration, on-machine measurement of the spatial pose and shape of the part, plan the processing scheme to improve blade machining accuracy.

Figure 1 is the process flow diagram of adaptive CNC machining process for near-net-shaped blade. Firstly, it is essential to obtain the profile characteristics of each blade by scanning the blade profile based on on-machine measurement due to the contour accuracy of each near-net-shaped blade that is inconsistent. Then, the trajectory adjustment matrix is accurately calculated based on the measurement points and theoretical points. Finally, the machining scheme of blade is planned to achieve high precision machining of blade.

The spline curve is used to generate the blade body curve. In order to obtain the parametric equation of this spline curve, the curve control points need to be obtained.

\[ C(u) = \sum_{i=0}^{n} N_{i,p}(u)\omega_i P_i, \quad a < u < b \]

where \( P_i \) is control point, \( \omega_i \) is weight factor associated with the \( P_i \), and \( \omega_i > 0 \); \( N_{i,p}(u) \) is a 3-order normative B-spline basis function defined on the non-uniform node.

In order to obtain the parametric equation of this B-spline curve, the curve control points need to be obtained.

\[ U = \{0, \ldots, 0, u_{p+1}, \ldots, u_{r-1}, 1, \ldots, 1\} \]

When the control points of the blade section line are known, the one-element basis function is introduced.
The blade curve equation is generated:

$$ R_{i,p}(u) = \frac{N_i(u)w_i}{\sum_{j=0}^{n} N_j(u)w_j} $$

The blade curve equation is generated:

$$ C(u) = \sum_{i=0}^{n} R_{i,p}(u)P_i $$

where $R_{i,p}(u)$ is the piecewise rational basis function defined on the interval $u \in [0,1]$.

In fact, if the measurement points in the actual state are obtained as the spline control points, the measurement model will be obtained according to Formula (1) to (4). The theoretical model corresponding to the measurement model can also be obtained. Therefore, what needs to be calculated in adaptive CNC machining process is the matrix relationship between the measurement points and the theoretical points, and can be obtained by the registration algorithm.

The registration principle is the least square method, and its essence is to obtain the minimum distance between the theoretical points and the measurement points, and to obtain the rotation and translation matrix based on this minimum distance.

$$ F = \min \sum_{i=1}^{n} d_i^2 = \min \sum_{i=1}^{n} \left[ \text{distance}(p_i, q_i) \right]^2 $$

where $P_i$ is the measurement point, and $q_i$ is the theoretical point; $F$ is the target parameter of registration which is also the distance in this registration.

The rotation matrix is shown in Formula (6):

$$ R = \begin{bmatrix} \cos \beta \cos \gamma & \cos \beta \sin \gamma & -\sin \beta \\ \sin \alpha \sin \beta \cos \gamma - \cos \alpha \sin \gamma & \sin \alpha \sin \beta \sin \gamma - \cos \alpha \cos \gamma & \cos \alpha \cos \beta \\ \cos \alpha \sin \beta \cos \gamma + \sin \alpha \cos \gamma & \cos \alpha \sin \beta \sin \gamma + \sin \alpha \cos \gamma & \cos \alpha \cos \beta \end{bmatrix} $$

where $\alpha$ is the rotation angle of the blade along with the machine tool’s $A$ axis, $\beta$ is the rotation angle of the blade along with the machine tool’s $B$ axis, and $r$ is the rotation angle of the blade along with the machine tool’s $C$ axis.

The translation matrix is shown in Formula (7):

$$ T = \begin{bmatrix} T_x & T_y & T_z \end{bmatrix}^T $$

where $T$ is the blade translation matrix, $T_x$ is the blade translation along with the machine tool’s $x$ axis, $T_y$ is the blade translation along with the machine tool’s $y$ axis, and $T_z$ is the blade translation along with machine tool’s the $z$ axis.
The above formulas of (1) to (7) are the geometric flow of the blade adaptive CNC machining process. The position and posture of the blade after clamping can be adjusted based on the above adaptive CNC machining process, and the blade deformation caused by the cutting force can also be adjusted based on the above adaptive CNC machining process. However, the blade deformation caused by the cutting force is a dynamic displacement response due to the cutting force that is a dynamically changing force. The real-time position and posture adjustment during the cutting process will break the continuity of cutting process, and the interruption of the cutting process will cause the existence of tool marks, which will seriously affect the quality of blade. On the other hand, the real-time position and posture adjustment will also reduce the efficiency of blade CNC machining process. The dynamic response value of the blade during cutting processing is controlled within a certain threshold if the stiffness of the blade process system is adequate, and the adaptive CNC machining process will have better processing efficiency and accuracy. Therefore, the sufficient stiffness of the blade process system and small dynamic displacement response are the prerequisite for the optimization of the adaptive CNC machining process.

3 Conditions and methods

The CNC machining process of near-net-shaped blade mainly includes three process procedures. The first process procedure is the CNC machining process of blade LTE. The second process procedure is the CNC machining process of blade tenon root and tip, and the third process procedure is the detection process of the contour error of the blade tenon root and the position error of blade tenon root which is relative to the blade body.

In order to achieve high precision machining of near-net-shaped blade, the experiment is mainly considered from two aspects. One is to improve the stiffness of the blade-fixture system, and the other is to optimize the adaptive CNC machining process based on the multi-process machining error data flow control. The sufficient stiffness of blade-fixture system is the prerequisite guarantee for the subsequent adaptive CNC machining process optimization. The experiment method of the blade-fixture stiffness includes the natural frequency test of the blade-fixture system and the dynamic displacement response test of blade during the CNC machining process. The experiment of adaptive CNC machining process optimization includes the testing of machining errors in blade multiple process. The experimental steps are as follows.

**Step 1**: Natural frequency test of the multi-process blade-fixture system. Figure 2 is the natural frequency test of the first process sequence blade-fixture system. The acceleration sensor (Dytran 3225M23) is used to measure blade dynamic response excited by hammer (Dytran 5850B). The LMS data-acquisition system is used to collect the displacement response signal of the blade from the acceleration sensor.

Figure 2 is the natural frequency test experiment platform of the first process procedure of blade. The natural frequency of blade in the cantilever beam state is firstly tested (see Fig. 2(a)), and the natural frequency of blade in the simply supported beam state acted by machine tool top is then tested (see Fig. 2(b)). Finally, a reasonable clamping plan is obtained through comparative analysis to improve the stiffness of the blade-fixture system.

**Step 2**: Dynamic displacement response test of multi-process blade-fixture system. Figure 4 is the dynamic displacement response test experiment platform, and the laser displacement sensor is used to obtain the blade dynamic displacement response under the action of cutting force. The sensitivity of the laser displacement sensor

![Fig. 2](image-url)
is 0.001 mm, and the measurement frequency is 1024 Hz. The acceleration sensor is used to measure the vibration characteristic of the blade under the cutting force.

**Step 3**: Experimental test of multi-process adaptive CNC machining process optimization based on machining error data flow control. A four-axis and a five-axis CNC machine tool with integrated Renishaw probe are used in this experiment. The Renishaw probe is stored in the cutter magazine of machine tool, and the cutter and Renishaw probe can be switched by the cutter change system of machine tool.

### 4 Results and discussion

#### 4.1 Analysis of the natural frequency of the blade-fixture system

Table 1 is the experiment result of the first-order natural frequency of the blade-fixture system of the first process sequence. It can be seen that the first-order natural frequency of the blade-fixture system is 121.8 Hz in the cantilever beam state, and the first-order damping ratio of the blade-fixture system is 0.3%. The corresponding first-order mode shape is shown in Fig. 5(a). The first-order natural frequency of the blade-fixture system is 400.1 Hz in the simply supported beam state which is under the constraint of the machine tool top, and the corresponding first-order damping ratio is 0.84%. The corresponding first-order mode shape is shown in Fig. 6(a). Under the simply supported beam state, the stiffness and damping ratio of the blade-fixture system are increased by 228% and 180%, respectively. The stiffness of the blade-fixture system under the constraint state of the machine tool top is greatly enhanced.

The second-order natural frequency of the blade-fixture system is 354.1 Hz in the cantilever beam state, and the
second-order damping ratio of the blade-fixture system is 0.73%. The corresponding second-order mode shape is shown in Fig. 5(b). The second-order natural frequency of the blade-fixture system is 537.6 Hz in the simply supported beam state which is under the constraint of the machine tool top, and the corresponding second-order damping ratio is 0.96%. The corresponding second-order mode shape is shown in Fig. 6(b). The stiffness of the blade-fixture system is increased by 51.8%, and the damping ratio is increased by 31.5% under the simply supported beam state. The stiffness

Fig. 5 The mode shape of blade-fixture system of the first process sequence in the cantilever beam state without machine tool top. a The first-order mode shape, b the second-order mode shape, c the third-order mode shape, d the fourth-order mode shape, and e the fifth-order mode shape

Fig. 6 The mode shape of blade-fixture system of the first process sequence in the simply supported beam state with machine tool top. a The first-order mode shape, b the second-order mode shape, c the third-order mode shape, d the fourth-order mode shape, and e the fifth-order mode shape
of the blade-fixture system under the constraint state of the machine tool top is greatly enhanced.

Similarly, it can be seen that the third-order natural frequency of the blade-fixture system is increased by 181% and the damping ratio is reduced by 33% under the constraint state of the machine tool top. The fourth-order natural frequency of the blade-fixture system under the constraint state of the machine tool top is increased by 66%, and the damping ratio is increased by 125%. The fifth-order natural frequency of the system under the constraint state of the machine tool top is increased by 181%, and the damping ratio is reduced by 33% under the constraint state of the machine tool top.

Table 2 Natural frequency of blade-fixture system of the second processing procedure

| Number | Fixture 1# | Fixture 2# |
|--------|------------|------------|
|        | Frequency (Hz) | Damping (%) | Frequency (Hz) | Damping (%) |
| 1      | 1105.5 Hz | 1.78%      | 1040.7 Hz | 1.94% |
| 2      | 1704.8 Hz | 0.475%     | 1684 Hz   | 1.15% |
| 3      | 2385.3 Hz | 1.4%       | 2384.9 Hz | 1.664% |

Fig. 7 Mode shape of blade-fixture 1# system of the second process sequence. a The first-order mode shape, b the second-order mode shape, and c the third-order mode shape.
machine tool top is increased by 73%, and the damping ratio is increased by 126%. Therefore, the stiffness of the blade-fixture system in the first processing procedure is greatly enhanced under the constraints of the machine tool top, which obtains a good dynamic characteristic.

Table 2 is the experiment result of the natural frequency of the blade-fixture system of the second processing procedure. It can be seen that the first-order natural frequency of the blade-fixture1# system is 1105.5 Hz, and the first-order damping ratio of the blade-fixture1# system is 1.78%. The corresponding mode shape is shown in Fig. 7(a). The first-order natural frequency of the blade-fixture 2# system is 1040.7 Hz, and the first-order damping ratio of the blade-fixture 2# system is 1.97%. The corresponding mode shape is shown in Fig. 8(a). The first-order natural frequency of the blade-fixture 2# system is increased by 5%, and the first-order damping ratio is reduced by 8% relative to the blade-fixture 1# system.
Similarly, it can be seen that the second-order natural frequency of the blade-fixture system 2# is increased by 1%, and the second-order damping ratio is increased by 13% relative to the blade-fixture 1# system. The third-order natural frequency of the blade-fixture system 2# is increased by 0.1%, and the third-order damping ratio is increased by 18% relative to the blade-fixture 1# system. Therefore, the stiffness of the blade-fixture 2# system in the second process procedure has the good dynamic characteristics than the blade-fixture 1# system.

From the above analysis, it can be seen that the blade-fixture system with the machine tool top in the first process sequence and the blade-fixture system 2# in the second process sequence are of better stiffness. Therefore, these two blade-fixture systems will be used to carry out dynamic displacement response and adaptive CNC machining process optimization experiments.

### 4.2 Analysis of the dynamic displacement response of blade

Figure 9 is the dynamic displacement response experimental result of blade. Figure 9(a) is the blade vibration value obtained by vibration acceleration.

**Table 3** The processing parameters and the max dynamic displacement value of blade in the first process sequence

| Number | Spindle speed (rpm) | Feed rate (mm/min) | Cutting depth (mm) | The max value of dynamic displacement response (mm) |
|--------|---------------------|--------------------|-------------------|---------------------------------|
| 1#     | 2000                | 1200               | 0.2               | 0.016                           |
| 2#     | 3000                | 800                | 0.2               | 0.017                           |
| 3#     | 3000                | 1000               | 0.2               | 0.007                           |
| 4#     | 3000                | 1200               | 0.1               | 0.021                           |
| 5#     | 3000                | 1200               | 0.2               | 0.011                           |
| 6#     | 3000                | 1200               | 0.3               | 0.017                           |
| 7#     | 3000                | 1200               | 0.05              | 0.007                           |
| 8#     | 3000                | 1400               | 0.2               | 0.038                           |
| 9#     | 4000                | 1200               | 0.2               | 0.023                           |
| 10#    | 5000                | 1200               | 0.2               | 0.025                           |

**Fig. 9** Dynamic displacement response of blade in the first process sequence (with the machine tool top) which is corresponding to number 1# in Table 3. **a** Blade vibration during CNC machining process. **b** Blade vibration during one cycle of cutter force. **c** Blade dynamic displacement response and **d** low-frequency dynamic displacement response of blade.
Figure 9(b) is the blade vibration value during one cycle of cutter force. Figure 9(c) is the blade dynamic displacement response obtained by the laser displacement sensor, and Fig. 9(d) is the low-frequency dynamic displacement response of blade.

It can be seen from Fig. 9 that the max dynamic displacement response value can be controlled to 0.007 mm (see Table 3), and this is the instantaneous displacement change of the blade and essentially the elastic deformation of the blade under the cutting force.

Figure 10 is the blade dynamic displacement response experimental result during the second process sequence. The max dynamic displacement value of blade can be controlled within 0.007 mm (see Table 4), which indicates that the blade-fixture system has sufficient stiffness in the second process sequence.

In summary, the maximum dynamic response value of blade can be controlled within 0.007 mm in the first and second process sequences. There are no weak stiffness links in the CNC machining process considering the first and second process sequence, which provides the sufficient stiffness for the optimization of the whole adaptive CNC machining process.

| Number | Spindle speed (rpm) | Feed rate (mm/min) | Cutting depth (mm) | The blade max dynamic displacement value (mm) |
|--------|---------------------|--------------------|-------------------|---------------------------------------------|
| 1#     | 2000                | 1200               | 0.2               | 0.012                                       |
| 2#     | 3000                | 600                | 0.2               | 0.008                                       |
| 3#     | 3000                | 1000               | 0.2               | 0.013                                       |
| 4#     | 3000                | 1200               | 0.1               | 0.007                                       |
| 5#     | 3000                | 1200               | 0.2               | 0.012                                       |
| 6#     | 3000                | 1200               | 0.3               | 0.009                                       |
| 7#     | 3000                | 1200               | 0.4               | 0.015                                       |
| 8#     | 3000                | 1400               | 0.2               | 0.014                                       |
| 9#     | 4000                | 1200               | 0.2               | 0.014                                       |
| 10#    | 5000                | 1200               | 0.2               | 0.014                                       |

Fig. 9(d) is the low-frequency dynamic displacement response fitted by a low-pass filter.

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4.3 Blade adaptive CNC machining process optimization

During the near-net-shaped blade CNC machining process, the benchmark brings a lot of machining errors. Machining errors between the two process procedures are accumulated in series. It is completely possible to combine the two process procedure benchmarks as a unified benchmark from the perspective of the machining process benchmarks. The process features for the second process procedure are

Fig. 11 The optimized machining process

Fig. 12 The first process sequence. a Measurement points and measurement path and b four-axis machine tool measurement process site
machined after the first process procedure. In this way, the second process procedure feature is directly measured to reconstruct the adaptive CNC machining model to ensure the positioning error of the blade. The main on-machining measurement and model reconstruction focuses on the first process procedure. If the machining error flow of the

Fig. 13 Single-point deviation value of blade body measurement point during the first process sequence. a The initial state of blade in the fixture, b in the first stage, c in the second stage, and d in the acceptable state process

Fig. 14 Single-point deviation value of blade body measurement points during the first process sequence of the adaptive CNC machining process
The benchmark facet for the second process sequence

Fig. 15 The benchmark facets are measured in the first process sequence. a Measurement facet distribution and b measurement site

Fig. 16 The benchmark facets are measured in the second process sequence. a Measurement facet distribution and b measurement site

Fig. 17 Blade benchmark on-machine measurement results. a Measurement point distribution and b measurement results
entire process of the first and second process procedures is controlled, the coordinated control of all machining errors will be realized. The optimized specific machining process is shown in Fig. 11.

Figure 12 shows the first process sequence of the optimized adaptive CNC machining process, and the blade measurement model is obtained through the blade body data measurement. The measurement model and the theoretical model are registered to obtain the adaptive CNC machining process reconstruction model to ensure the position of the blade tenon root relative to the blade body.

Figure 13 is the single-point deviation value of blade body measurement point during the first process sequence of the adaptive CNC machining process. It can be seen from Fig. 13(a) that some of the single-point deviation values of these 24 measurement points of the blade body are greater than 0 mm, and some are less than 0 mm when the blade is initially installed on the fixture, and the specific numerical chart corresponds to Fig. 14. This shows that the blade is not in an ideal position. If the blade LTE and the benchmark facet for the second process sequence are machined at this position, the uncontrollable machining position error of the blade tenon root relative to blade body will inevitably cause. There is a geometric deviation of 0.008–0.05 mm in the blade body. Therefore, when some of the blade body measurement points are less than 0 mm, it can be concluded that the blade is in an undesirable posture, and a subsequent adaptive regulation is required. In Fig. 13(d), the single-point deviation values of all measurement points are greater than 0 mm, showing that the single-point deviation values of the measurement points are all positive values and uniform distribution (see Fig. 14). That is, all measurement points of the blade body are evenly distributed on both sides of the theoretical model of the blade at this time, indicating that the blade is in a better position. Figure 13(a), Fig. 13(b), Fig. 13(c), and Fig. 13(d) are the process of blade position adjustment, indicating that the adaptive CNC machining process plays a certain role to adjust the position and posture of the blade.

Figure 15 is the benchmark facet for the second process sequence measurement in the four-axis machine tool during the first process sequence. As shown in Fig. 11, in the optimized machining process, the LTE of the blade and the benchmark facet for the second process sequence are machined in the first process sequence, and there are four benchmark facets in total as shown in Fig. 15. After the benchmark facet is machined, the position state of the benchmark facet is measured based on the on-machine measurement, and the position of the blade benchmark facet at this time is recorded.

The machined blade LTE and the benchmark facet for the second process sequence measurement will be obtained after the first process sequence, and then the second process sequence will be performed. Figure 16 is the measurement link of the blade second process sequence, and this process is mainly to machine the blade tenon root and tip. In the optimized process, only the benchmark facets machined in the first process sequence are needed to be measured. The position status of the benchmark facets 1#, 2#, 3#, and 4# (see Fig. 15) on the four-axis machine tool (the first process sequence) and five-axis machine tool (the second process sequence) is respectively obtained. Therefore, the same single-point deviation value is obtained under the two fixture installation positions.

The on-machine measurement results are shown in Fig. 17. The single-point deviation of the blade benchmark facet in the second process sequence is consistent with that in the first process sequence. The benchmark transition from the first process sequence to the second process sequence is realized, which is helpful to eliminate the machining error caused by twice positioning.
4.4 Machining error analysis of blade

Figure 18 is the single-point deviation value of the blade body after the two process sequences; it can be seen that the single-point deviation values of the blade body are uniformly distributed, and all the single-point deviation values are positive. This is because that the blade body itself has a positive margin, and the positive margin value is about 

Fig. 19 Single point deviation of blade tenon root and tip. a Blade tenon root measurement points, b deviation distribution value of blade tenon root, c blade tip measurement points, d deviation distribution value of blade tip, e blade tip side measurement points, and f deviation distribution value of blade tip side.
0.008–0.05 mm, and these deviation values still exist due to the blade body that has not undergone subsequent CNC machining process. If these single-point deviation values are all greater than 0 mm, and these single-point deviation values are evenly distributed, it can be indicated that the position of the blade does not deviate during the blade tenon root CNC machining processing, explaining that the stiffness of the blade-fixture system is sufficient, which is consistent with the previous analysis of natural frequency and dynamic displacement response analysis.

Figure 19 is the single-point deviation value of the blade tenon root and tip after the two process sequences. It can be seen that the deviation values of all the measurement points are within the range of 0.007 to 0.007 mm, which shows that the machined surface profile meets the range of the machining error band. Therefore, the proposed adaptive CNC machining process optimization based on machining error data flow control is feasible.

In summary, the optimized adaptive CNC machining process based on machining error data flow control has excellent performance in machining accuracy.

5 Conclusion

In this study, the machining error data flow and dynamic displacement response of the multi-process adaptive CNC machining process of near-net-shaped blade were investigated by theoretical and experimental analysis, and the results can be summarized as follows:

1) The dynamic displacement response of the multi-process adaptive CNC machining process is controlled within 0.007 mm, and the sufficient stiffness of blade-fixture system provides a prerequisite guarantee for adaptive CNC machining process optimization.

2) The optimized adaptive CNC machining process can realize the multi-process machining error control and high-precision manufacturing of near-net-shaped blade based on the multi-process data flow transmission and control with sufficient stiffness of the multi-process blade-fixture system. The coordinated control of the two processing procedures achieves the blade tenon root position and contouring error control.

However, the proposed adaptive CNC machining process is based on the geometric adaptive processing technology, and the improvement of processing precision can be achieved under the premise of the sufficient stiffness of the blade-fixture system. How to achieve blade high precision machining for the weak rigid system will be the future research.

Author contribution Dongbo Wu: experiment, data analysis, original draft writing.
Hongru Lv: experiment and writing.
Hui Wang: methodology, formal analysis, writing—review and editing.
Jie Yu: experiment.

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Declarations

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