Study on Flutter Stability Control Technology of Blade Flexible Machining for Airfoil Fan

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Abstract. The blade of airfoil wind turbine is affected by cross-section aerodynamic and airfoil aerodynamic damping in flexible machining, which results in flutter in the process of machining, affects machining accuracy. A flutter stability control method based on modal parameter identification and aerodynamic damping coupling compensation for flexible machining of airfoil fan sheet is proposed. The flutter mechanics analysis model for flexible machining of airfoil fan sheet is established by using multi-body system dynamics analysis method. The stability control constraint parameters of blade machining flutter are analyzed. The flutter modal parameters of flexible machining are identified by finite element dynamic analysis method with blade flapping, shimmy and section aerodynamic characteristic parameters are taken as the optimization objectives. The steady state error coupling compensation method is used to control the aerodynamic damping of blade machining and the continuous feedback drive method is used to carry out the adaptive calibration of machining parameters to realize the control optimization of the blade flexible machining of the fan. The simulation results show that the method is used to design the blade flexibility of the airfoil fan, which reduces the flutter effect and improves the machining accuracy and stability control ability.

1. Introduction
Airfoil fan blades are widely used in aero-engines, wind turbines, compressors, high pressure compressors and other mechanical devices as the main components of fan. In the machining of the blade of the airfoil fan, because of the complicated composition of the blade, the bending degree of the component and the component composition of the connecting part, different processing techniques are needed in the process of machining processing. The processing technology of airfoil fan blade involves various technological processes such as NC milling, cutting, forging and grinding. In the whole machining process of airfoil fan blade, due to various kinds of machining excess (such as torsion, front and tail edge shape, contour, etc.) the presence of the position degree leads to flutter easily occurring in the blade processing of the airfoil fan. The machining flutter of fan blade comes from the coupling of aerodynamic force, elastic force and inertial force, which makes it difficult to achieve equilibrium state in the process of machining, resulting in large elastic deformation and vibration.

In order to overcome the machining flutter of the blade of the airfoil fan, the flexible machining method is used to control the flutter and stability, to control the machining accuracy of the blade and to
improve the engine performance. The flutter stability control of blade flexible machining of airfoil fan is taken based on the stability adjustment of machining overshoot and the optimization design of machining parameters. Some typical machining flutter control methods have been studied by domestic and foreign scholars, among which, in reference [4], a blade processing method for airfoil fan based on cutting teeth with five blade method is proposed. According to the aerodynamic parameters of the blade section of the fan, the torsional angle is adjusted, and the adjustment parameters of the blade machining machine are studied by numerical method based on the characteristic analysis of tooth surface reference point, the double spiral method is used to optimize the blade machining design to improve the machining performance. However, the anti-interference ability of the method in flutter control is not strong, and the calculation cost of processing parameters is high. In the paper [5], an optimal control method for the parameters of spiral moving cutting tool in fan blade machining based on the analysis of gear tooth contact is proposed. According to the spatial geometry relation of arc bevel gear pair, the coupling control module of blade machining is established based on the sensitivity analysis of machining overshoot type, the problem control ability of machining process can be improved by restraining the influence of overshoot error. This method has the problem that the initial sensitivity of parameters is large and the oscillation amplitude of surge margin is high. In reference [6], the relationship between blade torsion and its power consumption is studied. It is found that the torsion of blade shape causes the increase of airflow angle and the decrease of compressor efficiency, and the error correction of blade processing is carried out according to this principle. The overshoot error of the leading edge profile is reduced and the machining accuracy of the blade is improved, this method cannot effectively suppress the flutter of the blade of the airfoil fan and the contour deviation is large.

Aiming at the above problems, in order to restrain flutter of blade machining of airfoil fan, a flutter stability control method for flexible machining of airfoil fan blade based on modal parameter identification and aerodynamic damping coupling compensation is proposed. The flutter mechanics analysis model for flexible machining of airfoil fan blade is established by using multi-body system dynamics analysis method. The stability control constraint parameter of blade machining is analysed, and the blade branching is carried out. The flutter modal parameters of flexible machining are identified by the finite element dynamic analysis method and the aerodynamic damping control of blade machining is carried out by using the steady-state error coupling compensation method. The continuous feedback drive method is used to calibrate the machining parameters to realize the control and optimization of the flexible machining of fan blades. Finally, simulation tests are carried out to demonstrate the superiority of this method in restraining machining errors and improving the flutter stability control ability of flexible machining.

2. Flutter mechanics analysis model for flexible machining of airfoil fan sheet

2.1. Control constraint parameters for stability control of flexible processing

In order to control flutter stability of airfoil fan blade in flexible machining, a control constraint parameter model is first constructed. The blade of airfoil fan is a fan of a multistage aero-engine in this paper. The mechanical parameters of the fan are analysed and numerically calculated by Numeca Fine/Turbo software. The numerical simulation results and test results of the fan under the condition of zero angle of attack and imported Mach number is about 0.69, the model is analyzed in the geometric model of numerical verification. The aerodynamic damping coefficient of airfoil and its distribution model with geometric parameters of airfoil are constructed by taking static pressure coefficient, tip clearance, tail edge angle, torsion and contour as control constraint parameters. Combined with the aerodynamic damping analysis model of wind turbine blade stall, the aero-elastic coupling multi-body dynamics model of the blade is established, and the aero-elastic response of the blade under various wind speeds is obtained by solving the equation. Combined with the theory of modal superposition, that is, the vibration response of blade is mainly superposed by several main modal responses in front of the blade, the following contact measurement system for flutter stability control in flexible machining of fan is established, which is mainly composed by the mechanical structure of the measuring machine,
numerical control system and industrial control computer IPC. According to the above design principle, starting from the profile change caused by blade fouling, the basic geometric parameter model for flutter stability control is defined in Table 1.

| Table 1. Basic geometric parameter model |
|-----------------------------------------|
| Parameter name                          | Initial value |
| Position error                          | 2.34          |
| Blade curvature                         | 12.65         |
| Machining radians                       | 4.78          |
| Curvature difference                    | 11.09         |
| Concave curvature                       | 12.45         |
| Crossed axis angle                      | 6.54          |
| Mean pressure angle                     | 9.12          |
| Mean cone distance                      | 8.34          |
| Node cone angle                         | 6.98          |
| Root cone angle                         | 2.34          |
| Large end modulus                       | 4.56          |
| Midpoint helical angle                  | 21.23         |

According to the constraint parameter model in Table 1, the flutter control object model for flexible machining of airfoil fan blade is established, and the SA turbulence model for spiral cone blade machining is defined as follows:

\[
X(n) = [x_1(n), x_2(n), ..., x_n(n)]^T
\]

\[
W_j(n) = [w_1(n), w_2(n), ..., w_m(n)]^T, \quad j < m
\]

\[
a_j(n) = [a_1(n), a_2(n), ..., a_m(n)]^T, \quad j < m
\]

\[
Y_{j-1}(n) = [y_1(n), y_2(n), ..., y_m(n)]^T, \quad j < m
\]

$$\lambda_1 > \lambda_2 > ... > \lambda_{j-1} > \lambda_j > ... > \lambda_m$$
According to the spiral motion coefficient of the blade machining, the second order control parameter model of the machine tool is obtained as follows:

\[
\sum_{i=1}^{m} [\theta_{ji}(n+1) - \theta_{ji}(n)] y_{ki} = \sum_{i=1}^{m} \eta \left[ \lambda_{ji} - \delta_{ji}(n) \psi_{ji}(n) q_{ki} + \eta \sum_{i=1}^{m} \lambda_{ji} a_{ji}(n) q_{ki} \right] \tag{4}
\]

According to the vibration direction of blade flutter, the aerodynamic damping parameters are adaptively adjusted and feedback control is carried out to improve the flutter stability control ability of flexible machining.

3. Flutter stability control optimization of blade flexible machining

3.1. Identification of flutter mode parameters in flexible machining

Based on the analysis of control constraint parameters and flutter dynamics, the flutter stability control is optimized. In this paper, a flutter stability control method based on modal parameter identification and aerodynamic damping coupling compensation for flexible machining of airfoil fan blade is proposed. Adaptive geometric calibration of machine tool adjustment parameters is carried out by continuous feedback driving method. The similar geometric characteristic equations are described as follows:

\[
\begin{align*}
W_{ij}^T(x)X(n) & = X_{ij}^T(n)w_{ij}(n) \\
\eta_{ij}^T(n)Y_{ij-1}(n) & = Y_{ij-1}^T a_{ij}(n)
\end{align*}
\]

The uncertain characteristic analysis of over-difference variable of fan blade machining is carried out. The aerodynamic damping characteristic equation of blade machining is established as follows:

\[
w_{ij}(n+1) = w_{ij}(n) + \eta X(n)X^T(n)w_{ij}(n) = w_{ij}(n) + \eta X^T(n)X(n)w_{ij}(n) + X(n)X^T(n)\theta(n) - Y_{ij}(n)w_{ij}(n) \tag{6}
\]

The flutter modal parameters of flexible machining are controlled by O4H topology with the aerodynamic characteristic parameters of blade and section as the optimization objective. The grid structure model is shown in Figure 1.

![Figure 1. Schematic diagram of head type machining grid for airfoil blade](image)

According to the grid model shown in figure 1, the flutter modal parameters of flexible machining are identified with the finite element dynamic analysis method, and the position degree is selected. The contour and torsion are controlled by the input explanatory variables, and the geometric variation of the overpass is obtained by the analysis of the blade profile bias:

\[
x_{ij}(n) = \sum_{j=1}^{M} h_{ij}(n)s_{ij}(n) + v_{ij}(n) \tag{7}
\]
y_j(n) = \sum_{i=1}^{p} f_{ij}(n)^T x_i(n)  \tag{8}

Wherein, \( h_{ij} \) represents the geometric parameters of each section, and \( f_{ij} \) represents the sensitivity characteristic. Thus, the flutter modal parameter identification output of blade flexible machining of airfoil fan is obtained:

\[
f_y(n+1) = f_y(n) + \mu_{MCMA} \frac{\partial J_{MCMA}(n)}{\partial f_y(n)} \tag{9}
\]

Wherein, \( \mu_{MCMA} \) represents the axial position degree, the step length of the super difference parameter is determined as follows:

\[
f_y(n) = [f_y^{(0)}(n), f_y^{(1)}(n), \ldots, f_y^{(L-1)}(n)]^T \tag{10}
\]

The explanatory variables of the flutter control for the blade processing is:

\[
\frac{\partial J_{MCMA}(n)}{\partial f_y(n)} = \frac{1}{4} \left( \sum_{j=1}^{\mu} \frac{\partial J_{R_j}(n)}{\partial f_y(n)} + \sum_{j=1}^{\mu} \frac{\partial J_{I_j}(n)}{\partial f_y(n)} \right) \tag{11}
\]

Partial derivation of real parts is obtained:

\[
\frac{\partial J_{R_j}(n)}{\partial f_y(n)} = \frac{\partial (|y_{R,j}(n)|^2 - R_{z,2})^2}{\partial f_y(n)} = 4(|y_{R,j}(n)|^2 - R_{z,2}) \times y_{R,j}(n)^* \times x_j(n) \tag{12}
\]

With the identification of flutter modal parameters of flexible machining and fusion treatment, the compensation ability of steady state error of fan blade machining is improved.

3.2. Adaptive calibration of fan blade flexible machining parameters

The steady-state error coupling compensation method is used to control the aerodynamic damping of blade machining. The output error function is obtained as follows:

\[
e_{R,j} = (|y_{R,j}(n)|^2 - R_{z,2}) \times y_{R,j}(n)^* \tag{13}
\]

Combined with the Lyapunov derivation method, the virtual part error function of flutter stability control of fan blade is obtained by removing the disturbance of lift and drag characteristics:

\[
e_{I,j} = (|y_{I,j}(n)|^2 - R_{z,2}) \times y_{I,j}(n)^* \tag{14}
\]

The steady-state error coupling compensation method is used to control the aerodynamic damping of blade machining. The control iterative equation is described as follows:
The weighting coefficient is modified, and then the modified aerodynamic parameters are input into the equalizer. The coupling response of the aerodynamic load along the whole blade is obtained as follows:

\[
\mathcal{X}(n) = x(n) - \tilde{h}_j(n)^* \tilde{s}(n)
\]  

(16)

Wherein, \( \tilde{h}_j(n)^* \tilde{s}(n) \) represents the autocorrelation function with \( y_j(n) \), and adopts the continuous feedback driving method for automatic feedback and calibration of machining parameters, then:

\[
E[\mathcal{X}(n)y_j^*(n-k)] = 0
\]  

(17)

Wherein, \( k = K - 1 \), \( \mathcal{X}(n) \) is the Toeplitz matrix of \( \mathcal{X}(n) \). According to the above algorithm design, the flutter control optimization of fan blade flexible machining is realized.

4. Test and analysis of simulation experiment

In order to verify the performance of this method in the control of flutter stability in flexible machining of fan blades, simulation experiments are carried out. The blade model of 5 MW wind turbine is used as the research object, rotation rate of impeller rigid body relative to the center Line of wind Turbine is 12.1r/min, the curvature radius of blade torsional deformation is 8mm, the rated wind speed is 14m/s, the blade aerodynamic load is 2400KN, the aerodynamic damping is 800KN, the blade structure mass is 100kg, the surge margin is 0.96, and the blade height section bias is 0.1mm. The flutter control convergence distribution model under different aerodynamic damping ratio of blade machining is obtained by simulation experiment of fan blade flexible machining as shown in Fig. 2.

Figure 2 shows that the flutter control of the blade of airfoil fan by using this method is more stable, and the flutter suppression ability is stronger. The total pressure ratio is increased by about 0.015 and the wake strength of the profile changes by 0.1 mm. it is obviously larger than the prototype, the Aero elastic damping at each section of the rigid body center of the blade was effectively controlled, and the
Flutter stability of the whole blade is better. In order to compare the performance, the flexible machining control is carried out by different methods, and the machining precision is tested. The comparison results are shown in Fig. 3 and the analytical figure 3 shows that this method has higher accuracy and better performance.

![Figure 3. Machining accuracy comparison](image)

5. Conclusion

In order to overcome machining flutter of airfoil fan blade, flexible machining method is adopted to suppress flutter and control stability. In this paper, a flexible machining method based on modal parameter identification and aerodynamic damping coupling compensation is proposed for flexible machining of airfoil fan blade. The vibration stability control method is used to establish the flutter mechanics analysis model of the airfoil blade flexible machining by using the multi-body system dynamics analysis method. The stability control constraint parameter of the blade machining flutter is analyzed and the blade is welded. The flutter modal parameters of flexible machining are identified by means of finite element dynamic analysis method, and the aerodynamic damping control of blade machining is carried out by using the steady-state error coupling compensation method. The continuous feedback drive method is used to calibrate the machining parameters to realize the control and optimization of the flexible machining of fan blades. The results show that this method can effectively control the flutter of the blade of the airfoil fan, and the output stability is good, and the machining accuracy is improved.

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