Parametric design and simulation analysis of turbine blade

Lida Zhu[1], Hongyu Chen[1], Zhongzi Tian[2], Hai Wang[3]

[1]*School of Mechanical Engineering & Automation, North-eastern University, Shenyang, Liaoning, 110819, P.R. China*

[2]*Beijing Hangke Engine Control System Technology Co., Ltd. Beijing, 102600, P.R. China*

[3]*Shenyang Jin Xin Hongmei Materials Co. Ltd, Shenyang, Liaoning, 110032, P.R. China*

Received 1 October 2014, www.cmnt.lv

Abstract

To improve design quality and efficiency of turbine blade, the geometric model of blade is parameterized by using the quintic polynomial method in this paper. The geometric shape and performance of blade mainly depend on blade profile and cascade with parametric model. First of all, the blade profile lines are designed and generated in different parameters based on the theory of quintic polynomial. The effect of relative parameters on the blade profile is analysed conveniently and rapidly. Then, the geometric shape of blade is generated in the arranged blade profiles according to blade cascade position and consistency. The 3D model of blade is created by the parametric blade profile and cascade. It is shown that parametric model of blade will provide the reference and foundation for application research.

Keywords: turbine blade, quintic polynomial, parametric design, 3D model

1 Introduction

Blade is a main part in aeroengine, which affects directly work performance of engine equipment. Moreover, the geometric shape and performance of blade mainly depend on blade geometric parametric model, so it is important for design process. Since the blade profile is a complex curved surface, the design quality and efficiency have to be improved by some effective methods [1-3].

There are some researchers in parameters design of blade. Song [4] has presented the parametric design of turbine blades based on feature modelling. Bing et al. [5] have developed and achieved three-dimensional design of the mixed-flow pump impeller. The numerical simulation was employed to analyse the effects of the blade parameters. Oh et al. [6] have compared the various parameters in the effects on the cavitation performance of the mixed-flow pump impeller. Yue et al. [7] have presented the multidisciplinary design optimization for aeroengine turbine blade.

This paper is divided into four main sections; the first, entitled the main geometric parameters of blade profile and cascade. The second section: the quintic polynomial designning the blade type line. The next part: the blade type line parameter design. Finally, the 3D model from parametric design.

2 The main geometric parameters of blade profile and cascade

To analyse the blade profile process, it is a necessary to build the parametric model. Blade curve modeling is usually made up of a certain number of sections, which is along the radial in order, while the plain cascade is made up of many same shape blade profiles which is apart some distance. In order to establish the model better, it must consider the cascade in the mass, for the location in the cascade and consistency have an important effect on blade design [7-10]. In this study, the main geometric parameters of cascade are described into two parts: one is the main geometric parameters of blade and another is the blade location's parameters in the cascade, as shown the Figure1.

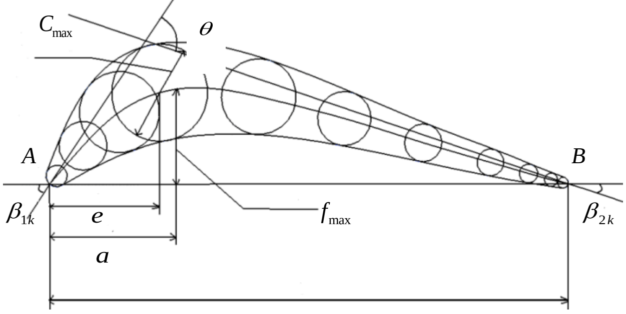

FIGURE 1 Main geometric parameters of the blade

1) Camber line: the line which crosses the centre of inscribed circle usually is called mean camber line. Chord length b: the mean camber line interacts the lending of blade at point A and the edge at point B, the line which links A to B is called chord length, usually is expressed by chord length b.

2) Maximum deflection f_{max} and the relative position: the maximum vertical distance between the mean camber line and chord length is called maximum deflection. Blade front angle β_{1k} and trail angle β_{2k}: the angle between mean camber line tangent in the front point A and chord length is called blade front angle, the angle between mean camber line tangent in the edge point B and chord length is called

trail angle. Maximum thickness $C_{\max}$: the maximum thickness represents blade.

3) Thickness, the maximum diameter of blade inscribe circle is the maximum thickness, the distance between the front point A and maximum inscribe circle centre along the chord length.

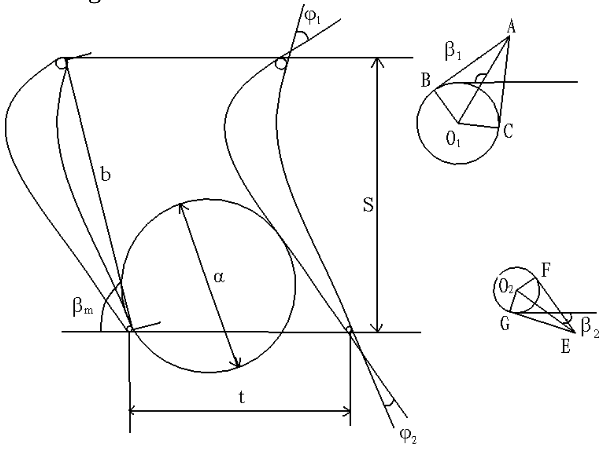

FIGURE 2 Main geometric parameters of blade cascade

4) Blade bending angle θ: the sum of the front angle and the trail angle equals bending angle, the angle between mean camber line tangent in the front point A and in the edge point B represents the bending degree, as the Figure 2 shows: $\theta = \beta_{1k} + \beta_{2k}$. Inlet angle β_1 : the angle between flow direction and frontal line in the leading edge, the frontal line is the line that connects all the blade front point A in the cascade. Exit angle β_2 : the angle between flow direction and frontal line in the trail edge. Blade type installation angle β_m : the angle between the frontal line and chord length represents the blade type's installation in the cascade. Grid pitch t: the distance that two adjacent blade type corresponding points are along the frontal line represents the blade arranges density. The blade section grid pitch shows as: $t = 2\pi R_i / N$. R_i each section radio value. Blade consistency τ : the ratio b/t is called consistency τ , as $\tau = b / t$.

The above parameters are usually used in the blade design, different parameters will design the different blade, but these parameters are not isolated, they can interfere with each other's, sometimes it is impossible that make any parameter to the optimal value, because some of these are incompatible. Such as the selection of chord length and consistency, when selecting the optimal chord length, the blade consistency may be too big or too small, and vice versa. Therefore, parameters selection must be considered synthetically and demonstrated in the test [7, 11-14].

3 The quintic polynomial designing the blade profile

3.1 QUINTIC POLYNOMIAL BLADE MODELLING THEORY

In general, turbine blade type line adopts curve combination, there are some discontinuous curvature derivative points in the curve combination, generating the peak of the velocity and pressure near the blade and degrading the turbine performance. In the analysis of airflow characteristics around the blade: turbine performance mainly depends on the blade surface boundary lawyer flow, while surface curvature radius has an effect on boundary lawyer flow. In order to make the blade surface's velocity and pressure distribute smoothly, it can use the quintic polynomial method to generate the blade type line.

The turbine principle and design parameters determine the flow parameters, formula and experience figure can determine each section geometric parameters, then select the optimal type line. Based on the type line generates the 3D blade. Different parameters generate different blade. The quintic polynomial method can be described that supposes blade type line is a quintic polynomial curve, using special point coordinate and their first derivative and second derivative fits blade section line.

Blade back and blade basin type line are $y_p = f(\mathrm{x})$ and $y_s = g(\mathrm{x})$, which are expressed as follows:

$$\begin{cases} y_p = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \\ y_s = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5 \end{cases}, \tag{1}$$

y_p and y_s first derivative are expressed as follows:

$$\begin{cases} y_p' = a_1 + 2a_2 x + 3a_3 x^2 + 4a_4 x^3 + 5a_5 x^4 \\ y_s' = b_1 + 2b_2 x + 3b_3 x^2 + 4b_4 x^3 + 5b_5 x^4 \end{cases}, \tag{2}$$

y_p and y_s second derivative are expressed as follows:

$$\begin{cases} y_p'' = 2a_2 + 6a_3 x + 12a_4 x^2 + 20a_5 x^3 \\ y_s'' = 2b_2 + 6b_3 x + 12b_4 x^2 + 20b_5 x^3 \end{cases}. \tag{3}$$

Blade basin starting point coordinate $(x_{p1}, \mathrm{y}_{p1})$, first derivative y_{p1}' , second derivative y_{p1}'' . Blade basin final point coordinate $(x_{p2}, \mathrm{y}_{p2})$, first derivative y_{p2}' , second derivative y_{p2}''. Let blade back starting point coordinate $(x_{s1}, \mathrm{y}_{s1})$, first derivative y_{s1}' , second derivative y_{s1}'' . Blade back final point coordinate $(x_{s2}, \mathrm{y}_{s2})$, first derivative y_{s2}', second derivative y_{s2}''. Then substituted equation is expressed as follows:

$$\begin{bmatrix} 1 & x_{p1} & x_{p1}^2 & x_{p1}^3 & x_{p1}^4 & x_{p1}^5 \\ 1 & x_{p2} & x_{p2}^2 & x_{p2}^3 & x_{p2}^4 & x_{p2}^5 \\ 0 & 1 & 2x_{p1} & 3x_{p1}^2 & 4x_{p1}^3 & 5x_{p1}^4 \\ 0 & 1 & 2x_{p2} & 3x_{p2}^2 & 4x_{p2}^3 & 5x_{p2}^4 \\ 0 & 0 & 2 & 6x_{p1} & 12x_{p1}^2 & 20x_{p1}^3 \\ 0 & 0 & 2 & 6x_{p1} & 12x_{p1}^2 & 20x_{p2}^3 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} y_{p1} \\ y_{p2} \\ y_{p1}' \\ y_{p2}' \\ y_{p1}'' \\ y_{p2}'' \end{bmatrix}, \tag{4}$$

$$\begin{bmatrix} 1 & x_{s1} & x_{s1}^2 & x_{s1}^3 & x_{s1}^4 & x_{s1}^5 \\ 1 & x_{s2} & x_{s2}^2 & x_{s2}^3 & x_{s2}^4 & x_{s2}^5 \\ 0 & 1 & 2x_{s1} & 3x_{s1}^2 & 4x_{s1}^3 & 5x_{s1}^4 \\ 0 & 1 & 2x_{s2} & 3x_{s2}^2 & 4x_{s2}^3 & 5x_{s2}^4 \\ 0 & 0 & 2 & 6x_{s1} & 12x_{s1}^2 & 20x_{s1}^3 \\ 0 & 0 & 2 & 6x_{s1} & 12x_{s1}^2 & 20x_{s2}^3 \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \end{bmatrix} = \begin{bmatrix} y_{s1} \\ y_{s2} \\ y'_{s1} \\ y'_{s2} \\ y''_{s1} \\ y''_{s2} \end{bmatrix}. \quad (5)$$

According to the solution set of Equation (4) and Equation (5), the equation of solution will be set to $y_p = f(x)$ and $y_s = g(x)$, and then it will get the blade back and blade basin polynomial expression.

3.2 THE DETERMINING METHOD OF SPECIAL POINT COORDINATE AND DERIVATIVE

When the cascade geometric parameters are known, establish coordinate as the Figure 3 shows, the blade front edge and trail edge circle centre are O_1 and O_2. The inlet edge is in coincidence with y axis and is tangent with circle O_1 at point *d*, exit edge is tangent with circle O_2 .at point *k*, chord length b is tangent with circle O_1, O_2 at point *f*, *h*, y_s and y_p represent a certain point coordinate along the y axis in the blade back and blade basin.

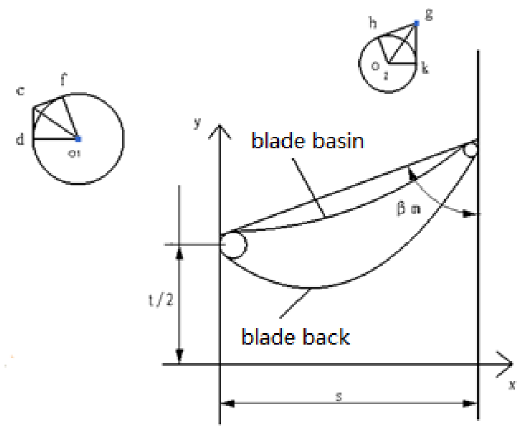

FIGURE 3 Coordinate relations schemes

1) The blade front edge and trail edge key point coordinate:

The front circle centre O_1 coordinates as:

$$\begin{cases} x_{o1} = r_1 \\ y_{01} = \dfrac{1}{2}t \end{cases}. \quad (6)$$

Tangency point *f* coordinates as:

$$\begin{cases} x_f = x_{o1} - r_1 \cos\beta_m \\ y_f = y_{o1} - r_1 \sin\beta_m \end{cases}. \quad (7)$$

The trail edge circle centre O_1 coordinates as:

$$\begin{cases} x_{o2} = s - r_2 \\ y_{o2} = y_f + (s - x_f)\cot\beta_m - r_2\cot|\beta_m/2| \end{cases}. \quad (8)$$

Tangency point h coordinates as:

$$\begin{cases} x_h = x_{02} - r_2\cos\beta_m \\ y_h = y_{o2} - r_2\sin\beta_m \end{cases}. \quad (9)$$

2) The blade back and blade basin first point coordinate and derivative

Blade back first point *C* coordinates as:

$$\begin{cases} x_{p1} = x_{01} - r_1\cos|\beta_1 - \varphi_1/2| \\ y_{p1} = y_{o1} + r_1\sin|\beta_1 - \varphi_1/2| \end{cases}. \quad (10)$$

Blade basin first point *B* coordinates as:

$$\begin{cases} x_{s1} = x_{01} + r_1\cos|\beta_1 + \varphi_1/2| \\ y_{s1} = y_{o1} - r_1\sin|\beta_1 + \varphi_1/2| \end{cases}. \quad (11)$$

Blade back first point *C* first derivative as:

$$y'_{p1} = \cot|\beta_1 - \varphi_1/2|. \quad (12)$$

Blade basin first point *B* first derivative as:

$$y'_{s1} = \cot|\beta_1 + \varphi_1/2|. \quad (13)$$

The blade back first point *C* and blade basin first point B second derivative value is 0.

3) The blade back and blade basin final point coordinate and first derivative and second derivative.

Blade back final point *F* coordinates as:

$$\begin{cases} x_{p2} = x_{02} - r_2\cos|\beta_2 + \varphi_2/2| \\ y_{p2} = y_{o2} + r_2\sin|\beta_2 + \varphi_2/2| \end{cases}. \quad (14)$$

Blade basin final point *G* coordinates as:

$$\begin{cases} x_{s2} = x_{02} + r_2\cos|\beta_2 - \varphi_2/2| \\ y_{s2} = y_{o2} - r_2\sin|\beta_2 - \varphi_2/2| \end{cases}. \quad (15)$$

Blade back final point *F* first derivative as:

$$y'_{p2} = \cot|\beta_2 + \varphi_2/2|. \quad (16)$$

Blade basin final point *G* first derivative as:

$$y'_{s2} = \cot|\beta_2 + \varphi_2/2|. \quad (17)$$

According to the above method, substituting the basic parameters of blade section to the above equals, it will get the quintic polynomial curve, and then determine the type line expression.

4 The blade type line parameter design

The program is developed by using mathematical software in the different parameters to generate the blade section type line, it can save time and clearly find that the effect of each parameter on blade type line and relationship between the parameters and blade type line.

Using the MATLAB Graphical User Interface module, author develops the blade type parameter interface, which is based on MATLAB research. The reason using the GUI module is that computer operation user interface display in GUI graphics mode. Compared with the early computer command line interface, graphics mode interface makes user more easily acceptable in vision and is convenient to the non-professional user. It allows people to avoid remember a lot of basic commands. People can simply click the window menu to accomplish the design conveniently. Different parameters generate different design in the interface, automatic generating the blade type line. Based on the figure parameters establishes the blade section line: the interface can analyse the interaction relationship between the parameters and the blade type line.

4.1 THE INFLUENCE OF EDGE RADIUS AND INSTALLATION ANGLE ON THE TYPE LINE OF BLADE CROSS-SECTION

The Figure 4 shows the radius of different parameters (R1=3, 4, 5) generate the type line curve. The lending edge radius becomes larger; the blade thickness will be bigger, the blade basin and blade back curvature will also increase.

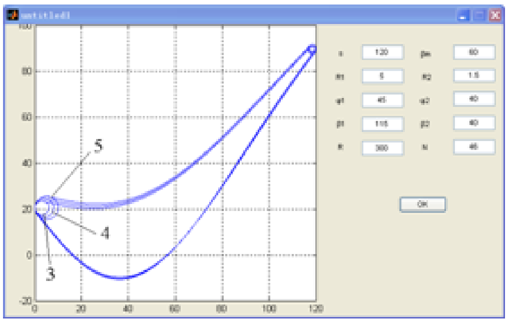

FIGURE 4 Effect of leading edge radius on type line of blade

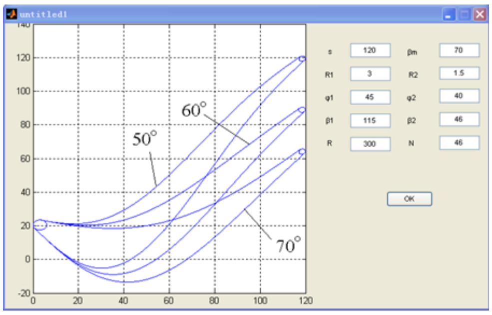

FIGURE 5 Effect of Installation angle on type line of blade

The installation angle generates the blade type line in different parameters (50°, 60°, and 70°) in Figure 5. The installation angle is smaller, the type line is steeper, and otherwise the type line is smooth.

4.2 THE INFLUENCE OF INTAKE SIDE ANGLE OF AND AIR ANGLE ON TYPE LINE OF BLADE CROSS-SECTION

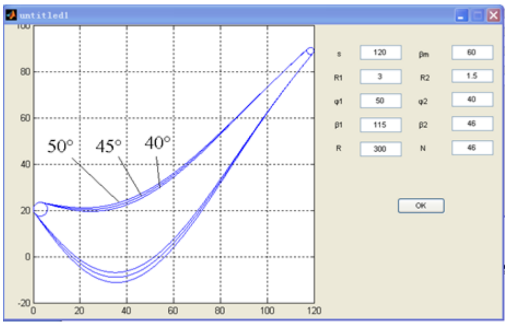

FIGURE 6 Angle of the intake side effects on type line of blade

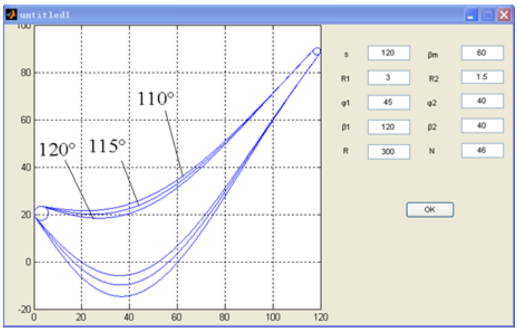

FIGURE 7 Air intake angle effects on type line of blade

As the Figure 6 shows, with angle of the intake side increasing, blade section thickness will increase, yet the blade bending curvature decreases. In the Figure 7, when the air intake angle is 110°, the blade cross-section type line curvature is minimum, while 120° is maximum. The 3D model is created in different parameters based blade profile and cascade, as shown in Figure 8:

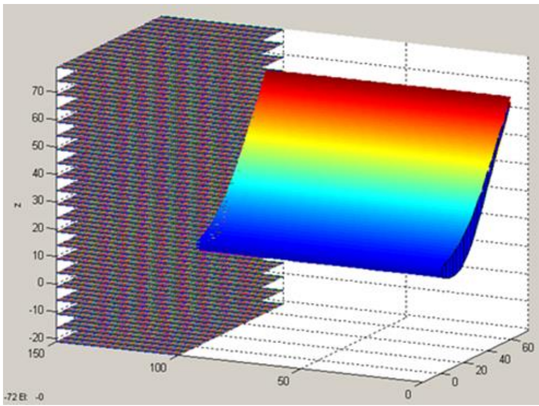

FIGURE 8 3D model of blade in different parameters

5 The 3D model and data exchange

3D model is established by using Unigraphics software based on the blade profile, which results from drawing many curves, ranging them in certain order, and then generating the blade solid model. Utilizing UG law curve function mass, it can draw the quintic polynomial, as shown in Figure 9. Finally, we draw the blade section type line by UG.

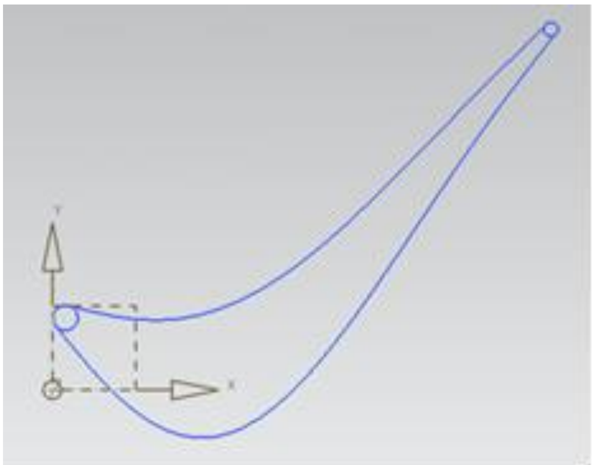

FIGURE 9 Type line of single blade cross-section

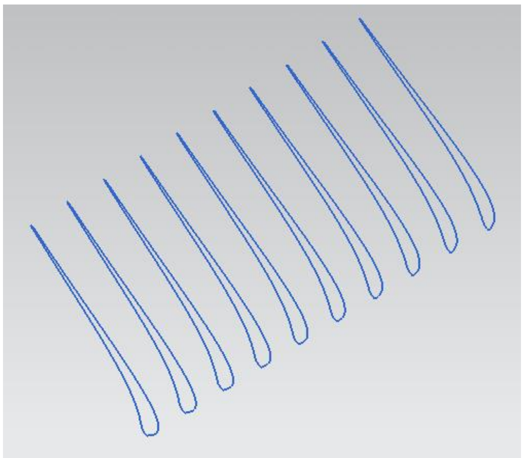

FIGURE 10 Type line of multi-blade cross-section

Many section type line curves are obtained by using the same method, as shown the Figure 10. Generated the type line curve in UG, it will be generated the blade solid model, as shown the Figure 11:

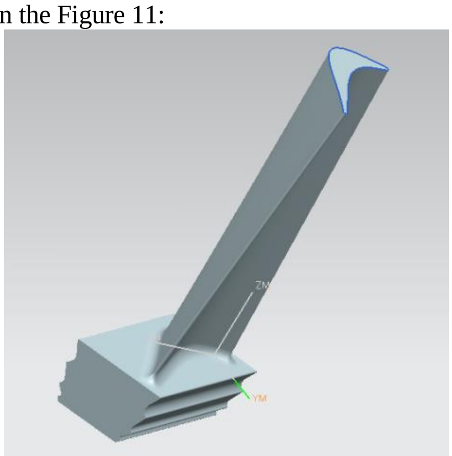

FIGURE 11 Cross-section and three-dimensional model of blade

6 Conclusions

1) In the first part of this paper, the blade design parameters and quintic polynomial method are introduced in detail. The performance of turbine depends on the boundary layer flow on blade surface; In the meanwhile the boundary layer flow is affected by curvature radius of blade surface. In order to get a smooth distribution for surface pressure and speed, quintic polynomial method is a better chose.

2) As the study presented, the blade profile generation interface, whose characters are convenient, rapid, and accurate, combined with quintic polynomial method is used to generate blade profile. As the figures got from simulations with different parameters shows, the type line has correspondent profiles for blade, from which we can understand the influence relation between different parameters clearly.

3) Finally, according to the theory of quintic polynomial method for blade profile line, the blade modeling method is studied, and based on which the blade profile line is generated by MATLAB and the 3D model by UG. Thus, quintic polynomial method can be proved to be a feasible method for generating blade model.

Acknowledgments

This work was supported by (National Natural Science Foundation of China) NSFC (51105072) and (51475087), supported by Fundamental Research Funds for the Central Universities (N130403010).

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Authors

	**Lida Zhu, China** **Current position, grades:** an associate professor at Northeastern University, China. **University studies:** PhD degree in Mechanical Manufacturing and Automation from Northeastern University, China, in 2010. **Scientific interest:** high-speed turn-milling technology, chatter stability of thin-wall.
	**Hongyu Chen, China** **Current position, grades:** a postgraduate at School of Mechanical Engineering & Automation in Northeastern University, China. **University studies:** bachelor degree in Mechanical Engineering & Automation from Northeastern University. **Scientific interest:** high-speed turning-milling, grinding.
	**Tian Zhongzi, China** **Current position, grades:** Beijing Hangke engine control system technology Co., Ltd., China. **University studies:** Master degree in Mechanical Engineering & Automation from Northeastern University in 2011 **Scientific interest:** High-speed turning-milling, Analysis of turbine blade
	**Wang Hai, China** **Current position, grades:** a general manager in Shenyang Jin Xin Hongmei Materials Co. Ltd., China. **University studies:** bachelor degree in Mechanical Manufacturing and Automation from Northeastern University. **Scientific interest:** modeling and simulation analysis.