COMPENSATE ALGORITHM OF DEFORMATION IN WOOD HIGH-SPEED FIVE-AXIS MACHINING

Zhang Wei[*1,2], Wang Shuangyong[1], Zhang Yang[3],Yang Jianhua[1,2], Zhang Pengfei[1] and He Hailong[1]

Based on the essential cooperation principle of high-speed wood machining, a kinematics model of high-speed five-axis wood machining is established, concerning the effect of wood and wooden composite material features on the high-speed milling. and a deviation compensate solution is provided in analysis of the wood deformation effect on the motion deviation. And the deviation compensate model is testified by the stimulation comparison of tool track.

Keywords: high-speed wood machining, five-axis, deformation, stimulation, compensate algorithm.

1. Introduction

Curve surface wood machining should meet higher requirement as the development of national furniture, construction and decoration industry and enhancement of people’s life. Wood machining CNC machine trends high speed, high precision and five-axis cooperating machining center. And high-speed machining technology concerning wood machining features should be improved [1].

Many previous researches on five-axis cooperating machining center have established related mathematical models, but most of them are relatively complex. There are much deviation analysis and compensate study on CNC machine for metal, while deviation analysis of five-axis cooperating machining center in wood high-speed machining is rare [2]. Wood and wooden composite material are quite different from metal materials. The microstructure of the former isn’t uniform like that of metal, but has certain directivity. As a result, the cutting force of high-speed machining fluctuates greatly and further increases the effect of machine motion deviation [3]. In this paper, a five-axis cooperating high-speed wood machining kinematic model has been established in analysis of wood deformation on motion deviations. The validity of this deviation compensate model has been testified and

[1]Beijing Forestry Machinery Research Institute of the State Forestry Administration, Beijing,100029 , China
[2]Forestry New Technology Research Institute, Chinese Academy of Forestry, Beijing, 100091, China
[3] Beihang University, Beijng, 100191, China

a theoretical foundation of deviation compensate and improvement for wood high-speed CNC machine has been provided.

2. The structure and theory of wood high-speed machining center

The high speed wood machining center often uses the bi-rotary milling head structure, which has two additional rotary axis based on the traditional three-coordinates numerical controlled machining center. The main parts include a platform which can move along the three translational axes and bi-rotary milling head. In the structure, the A-axis and C-axis of bi-rotary milling head rotates on the X-axis and Y-axis, and the platform can move on the X, Y, Z-axis. During wood high-speed machining, three linear axes and two rotation axes cooperates and allows the tool to cut workpiece with various positions in the space. All kinds of complex curve surface can be machined in this way [4]. In the paper, the relationship between tool space position, wood deformation and machining deviation is discussed based on the self-made wood high-speed five-axis machining platform. The kinematic chain and structure diagram are shown in Fig. (1).

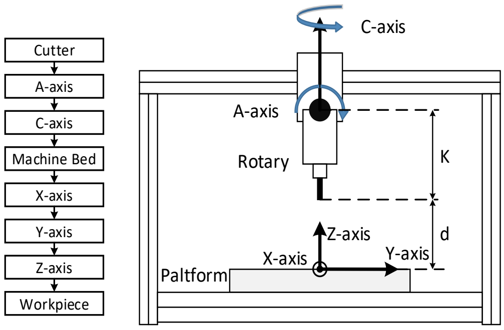

Fig.(1).Kinematic chain and structure diagram of wood high-speed machining center

The five-axis cooperation platform includes 5 parameters, 2 rotation angles and 3 translation distances in order to learn the position and attitude of milling cutter, which is actually related to the fixed platform. In the original A-axis is parallel to X-axis of the platform, and milling central line coincide with Z-axis; distance from milling cutter head to the platform is noted as d, distance from milling cutter head to A-axis as K, swing range of C-axis as$(-\pi,\pi)$, and swing range of A-axis as$(-\pi/2,\pi/2)$.

3. Geometric model of space position

3.1. Coordinate System Definition

Three coordinate systems are introduced for conveniently describing and defined as following.

Platform coordinate system (p). Platform coordinate system is fixed with the platform, which origin is the center of the platform, and X, Y, Z-axis is parallel to the three axes of the platform. It makes translation motion as the platform does.

Machine bed coordinate system (b). Machine bed coordinate system is fixed with the machine. It is coincided with the platform coordinate system in the initial state, but doesn't move with the former.

Tool coordinate system (t). Tool coordinate system has origin at the head of the milling cutter, Z-axis from central line to the end of milling cutter, X-axis parallel to A-axis, Y-axis perpendicular to X and Z-axis. The last three axes are right-hand Cartesian coordinate system.

3.2. Establishment of the Motion Model

Due to previous analysis, the position parameter of milling cutter during the wood machining is related to the position and attitude of the platform, which is the translation and rotation parameter between tool and machine bed coordinate, and connected by the later. Tool coordinate system has a swing relation with machine bed coordinate system while platform coordinate system has a translation relation with machine bed coordinate system. Now we discuss them separately according to the conversion relation [5,6].

Conversion between tool coordinate system and bed coordinate system. The length of milling cutter is noted as *l*. In the tool coordinate, the vector from the head to the end of milling cutter is:

$$L^{\boldsymbol{m}} = (0 \quad 0 \quad l)^T$$

$L$is a vector. The Milling cutter head coordinate in the tool coordinate system is: $P^m = (0 \quad 0 \quad 0)^T$

When there is a rotation angle between A and C-axis, tool coordinate system has rotation related to the machine bed coordinate system. $\theta_A$andθ_C are noted as the rotation angle of swing head on A and C-axis. We can get tool coordinate system from twice rotation of the machine bed coordinate system. First, we get an intermediate coordinate system by rotating θ_C on Z-axis of the machine bed coordinate system. Then we can get the tool coordinate system by continuously rotating $\theta_A$on X-axis of intermediate coordinate system. The matrix form is shown as following:

$$\boldsymbol{C_b^m} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_A & \sin\theta_A \\ 0 & -\sin\theta_A & \cos\theta_A \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

As a result, the vector in the machine bed coordinate system is:

$$\boldsymbol{L^b} = \boldsymbol{C_m^b L^m} = (\boldsymbol{C_b^m})^{\boldsymbol{T}} \boldsymbol{L^m}$$

According to the previous rotation relation, milling cutter position can be described, but the position of milling cutter head can't be described, because the position of milling head should be described in the machine bed coordinate system.

Noted P as the intersection point of A and C-axis, O_m as origin of the tool coordinate system as well as the position of milling cutter head, O_b as the origin of machine coordinate system, there is a relation in the machine bed coordinate system: $\overrightarrow{O_b O_m} = \overrightarrow{O_b P} + \overrightarrow{PO_m}$

The left vector is fixed as bi-rotary milling head is fixed on the machine bed: $\overrightarrow{O_b P} = (0 \quad 0 \quad K+d)^T$

The later can be calculated through rotation relation between coordinate systems. In the tool coordinate system, vector$\overrightarrow{PO_m}^{m} = (0 \quad 0 \quad -K)^T$, which is conversed into machine bed coordinate system as following:

$$\overrightarrow{PO_m}^{b} = \boldsymbol{C_m^b} \cdot \overrightarrow{PO_m}^{b} = \boldsymbol{C_m^b} \cdot (0 \quad 0 \quad -K)^T$$

Therefore, the position vector of milling head in the machine bed coordinate system is: $\overrightarrow{O_b O_m} = (0 \quad 0 \quad K+d)^T + \boldsymbol{C_m^b} \cdot (0 \quad 0 \quad -K)^T$

The coordinate of milling cutter head in the machine bed system is:

$$P^b = (0 \quad 0 \quad K+d)^T + \boldsymbol{C_m^b} \cdot (0 \quad 0 \quad -K)^T$$

Conversion between platform coordinate system and machine bed coordinate system. In the practical machining, workpiece is fixed on the platform. As the platform has translation related to the machine bed, the previous position parameter should be further calculated. As the translation has no effect on the relative attitude of milling cutter, the attitude gets rid of further calculation.

d_x, d_y, d_z is assumed as the translation account of platform related to machine bed on X, Y, Z-axis. In the platform coordinate system, the vector from its origin $O_p$to the machine bed coordinate system's origin O_b is:

$$\overrightarrow{O_p O_b} = (d_x \quad d_y \quad d_z)^T$$

Then, in the platform coordinate system, the vector from its origin to the milling cutter head is:

$$\overrightarrow{O_p O_m} = \overrightarrow{O_p O_b} + \overrightarrow{O_b O_m}$$
$$= (d_x \quad d_y \quad d_z)^T + (0 \quad 0 \quad K+d)^T + \boldsymbol{C_m^b} \cdot (0 \quad 0 \quad -K)^T$$

The coordinate of milling cutter head in the platform coordinate system is:

$$P^p = (d_x \quad d_y \quad d_z)^T + (0 \quad 0 \quad K+d)^T + \boldsymbol{C_m^b} \cdot (0 \quad 0 \quad -K)^T$$

The motion parameter of wood high-speed machining is $(\theta_A \quad \theta_C \quad d_x \quad d_y \quad d_z)$, and the component coordinate of the milling cutter vector in the platform coordinate system is: $\boldsymbol{L^p} = (\boldsymbol{C_b^m})^{\boldsymbol{T}} \boldsymbol{L^m}$

4. Deviation analysis and modelling

4.1. Deviation Propagation Model

Due to the previous analysis, the conversion relation from platform state variables to milling cutter's space position and attitude can be shown as the following function:

$$\boldsymbol{Q} = \boldsymbol{f}(\boldsymbol{\theta})$$

$\boldsymbol{Q}$ is a vector describing the milling cutter's space position and attitude:

$$\boldsymbol{Q} = \begin{bmatrix} P^p \\ \boldsymbol{L^p} \end{bmatrix}$$

$\boldsymbol{\theta}$ is a state parameter of milling cutter :

$$\boldsymbol{\theta} = [\theta_A \quad \theta_C \quad d_x \quad d_y \quad d_z]^T$$

The tool's deviation is:

$$\delta\boldsymbol{Q} = \frac{\partial \boldsymbol{f}(\boldsymbol{\theta})}{\partial \boldsymbol{\theta}} \delta\boldsymbol{\theta}$$

In the equation, $\delta\boldsymbol{Q}$ is the deviation of milling cutter's position and attitude, $\delta\boldsymbol{\theta}$ the deviation of machine parameter, and $\partial\boldsymbol{f}(\boldsymbol{\theta})/\partial\boldsymbol{\theta}$ is the deviation conversion matrix. When the concrete form of $\boldsymbol{f}(\boldsymbol{\theta})$is substituted into the equation described before, the deviation propagation equation is:

$$\begin{bmatrix} \delta m_x \\ \delta m_y \\ \delta m_z \\ \delta p_x \\ \delta p_y \\ \delta p_z \end{bmatrix} = \begin{bmatrix} l\cos\theta_A \sin\theta_c & l\cos\theta_C \sin\theta_A & 0 & 0 & 0 \\ -l\cos\theta_A \cos\theta_c & l\sin\theta_A \sin\theta_c & 0 & 0 & 0 \\ -l\sin\theta_A & 0 & 0 & 0 & 0 \\ -K\cos\theta_A \sin\theta_C & -K\cos\theta_C \sin\theta_A & 1 & 0 & 0 \\ K\cos\theta_A \cos\theta_C & -K\sin\theta_A \sin\theta_C & 0 & 1 & 0 \\ K\sin\theta_A & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \delta\theta_A \\ \delta\theta_c \\ \delta d_x \\ \delta d_y \\ \delta d_z \end{bmatrix}$$

In this equation, the first three dimensions of the left vector is the deviation of milling cutter vector, while the last three dimensions is the deviation of milling cutter head position vector.

4.2. Effect of Wood Deformation on the Milling Cutter Position

Different from metal material, wood is likely to deform. When the cutting force is too large, deviation caused by the deformation will affect machining precision, which should be considered and compensated. In the following part, we will take examples of facing milling and side milling, two typical wood milling ways, to analyze wood deformation during machining. In the facing milling, cutter head is perpendicular to the wood, so deformation occurs on Z-axis of tool coordinate system; in the side milling, wood is touched by the cutter side, so deformation occurs in the XY-plane of tool coordinate system [7-10]. Equivalent deviation caused by wood deformation in the two milling way is analyzed as following.

Facing milling way

During facing milling, ways that cutter touches wood, and wood occurs deformation is shown as Fig. 2 .

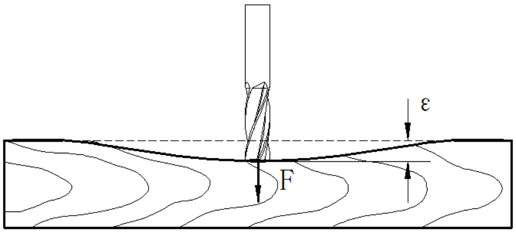

Fig. 2.Wood deformation in the facing milling

The contact pressure between milling cutter and wood is noted as F, and the deformation displacement of contact point between wood and milling cutter on the Z-axis of tool coordinate system noted as ε . When milling cutter retracts and wood deformation restores, andeviationε of machining plane's position occurs. In order to compensate this deviation, we should consider the deformation during cutter feeding through properly increasing feeding amount. Thus, the position of machining plane can meet the requirement when cutter retracts and wood restores.

The wood hardness perpendicular to machining plane is noted ask_v. With reference to relevant standards [11], there is an equation:

$$\varepsilon = \frac{F}{k_v} \times 5.64mm$$

It is equivalent as milling cutter head position in the tool coordinate system has an deviation as $\boldsymbol{\delta p_m} = [0 \quad 0 \quad \varepsilon]^T$.

Converted into the platform coordinate system, the milling cutter position deviation is: $\boldsymbol{\delta p_p} = (\boldsymbol{C_b^m})^{\boldsymbol{T}}\ \boldsymbol{\delta p_m}$

As the attitude of milling cutter is not affected, its deviation is 0.

Due to the calculation above, the tool deviation is: $\delta\boldsymbol{Q} = \begin{bmatrix} \boldsymbol{0_{3\times 1}} \\ \boldsymbol{\delta p_p} \end{bmatrix}$

Side milling

In the side milling, cutter touches machining plane with its side, so the deformation occurs in the XY-plane of the tool coordinate system. It is shown in the Fig. 3.

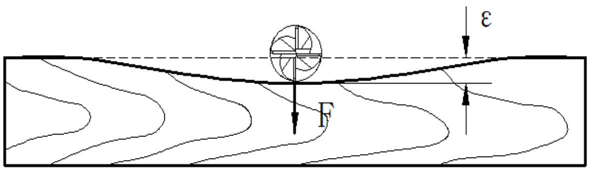

Fig. 3. Wood deformation in the side milling

The force vector from milling cutter to wood has its platform coordinate as following:

$$\boldsymbol{F^p} = \begin{bmatrix} F_x^p & F_y^p & F_z^p \end{bmatrix}^T$$

It is as following after being converted into tool coordinate system:

$$\boldsymbol{F^m} = [F_x^m \quad F_y^m \quad F_z^m]^T = \boldsymbol{C_b^m F^p}$$

F_x^m and F_y^m are forces in the XY-plane of tool coordinate system, which determined the amount and direction of wood deformation. Wood hardness on the side is noted as k_h. With reference to relevant standards, the deformation is:

$$\boldsymbol{\varepsilon^m} = \frac{[F_x^m \quad F_y^m \quad 0]^T}{k_h} \times 5.64mm$$

After converted in platform coordinate system, the deviation of milling cutter position is:

$$\boldsymbol{\varepsilon^p} = (\boldsymbol{C_b^m})^{\boldsymbol{T}} \boldsymbol{\varepsilon^m}$$

As the attitude of milling cutter is not affected, its deviation is 0.

Due to the calculation before, the tool deviation is: $\delta \boldsymbol{Q} = \begin{bmatrix} \boldsymbol{0_{3\times 1}} \\ \boldsymbol{\varepsilon^p} \end{bmatrix}$

4.3. Tool Deviation Compensation

In the previous discussion, wood deformation was analyzed in two milling ways and tool deviation was calculated. The relation between tool deviation and fix-axis platform state parameter deviation is quantified as:

$$\delta \boldsymbol{Q} = \boldsymbol{H} \delta \boldsymbol{\theta} \quad \text{and,} \quad \boldsymbol{H} = \frac{\partial \boldsymbol{f(\theta)}}{\partial \boldsymbol{\theta}}$$

is the Jacobian matrix of $\boldsymbol{f}(\boldsymbol{\theta})$.

After $\delta\boldsymbol{Q}$ is substituted into the deviation propagation equation, the deviation of five-axis platform parameter is solved as:

$$\delta\boldsymbol{\theta} = (\boldsymbol{H^T H})^{-1} \boldsymbol{H^T} \delta \boldsymbol{Q}$$

Substituting $\boldsymbol{H}$ into the equation before, we obtain:

$$\begin{bmatrix} \delta\theta_A \\ \delta\theta_c \\ \delta d_x \\ \delta d_y \\ \delta d_z \end{bmatrix} =$$

$$\frac{1}{l}\begin{bmatrix} \cos\theta_A \sin\theta_c & -\cos\theta_A \cos\theta_C & -\sin\theta_A & 0 & 0 & 0 \\ \cos\theta_C / \sin\theta_A & \sin\theta_C / \sin\theta_A & 0 & 0 & 0 & 0 \\ -K(\sin^2\theta_A \sin^2\theta_C - 1) & -K\cos\theta_C \sin\theta_C (\cos^2\theta_A - 1) & -K\cos\theta_A \sin\theta_A \sin\theta_C & l & 0 & 0 \\ -K\cos\theta_A \sin\theta_C (\cos^2\theta_A - 1) & K(\sin^2\theta_A \sin^2\theta_C - \sin^2\theta_A + 1) & K\cos\theta_A \cos\theta_C \sin\theta_A & 0 & l & 0 \\ -K\cos\theta_A \sin\theta_A \sin\theta_C & K\cos\theta_A \cos\theta_C \sin\theta_A & K\sin^2\theta_A & 0 & 0 & l \end{bmatrix} \begin{bmatrix} \delta m_x \\ \delta m_y \\ \delta m_z \\ \delta p_x \\ \delta p_y \\ \delta p_z \end{bmatrix}$$

Substituting tool deviation $\delta\boldsymbol{Q}$, we obtain relevant five-axis platform parameter deviation. The five-axis platform parameter is: $\widehat{\boldsymbol{\theta}} = \boldsymbol{\theta} - \delta\boldsymbol{\theta}$

After previous compensation, expected machining precision is assured when milling cutter retracts and wood deformation restores.

5. Simulation and analyses of the compensatory algorithm

In order to verify the compensatory algorithm, a simulation test is designed using the Matlab, which makes a comparison of the wood machining precision between using and not using the compensatory algorithm. Considering that the most influential elements of machining precision are cutting force and wood hardness, the variables of the simulation are cutting force and wood hardness, while other parameters remain constant.

The parameters of the simulation are set according to the high-speed wood machining center developed by Beijing Forestry Machinery Research Institute. At the initial state, the distance from the front end of the cutter to the platform$d = 250$mm, the distance from the front end of the cutter to the A-axis $K = 300$mm, the length of the cutter $l = 100$mm. Assume that the theory machine state of processing a workpiece is: $\theta_A = 10°$,$\theta_C = 20°$,$d_x = 200mm$, $d_y = 100mm$, $d_z = 0mm$.

5.1. Influence of the Cutting Force

During wood machining, the cutting force changes with the different cutting speed and cutting depth. According to the reference [12], the available range of the cutting force is 200N~800N. When the hardness of the wood is 5600N, the simulation result of the machining precision using and not using the compensatory algorithm is shown in Fig. 4.

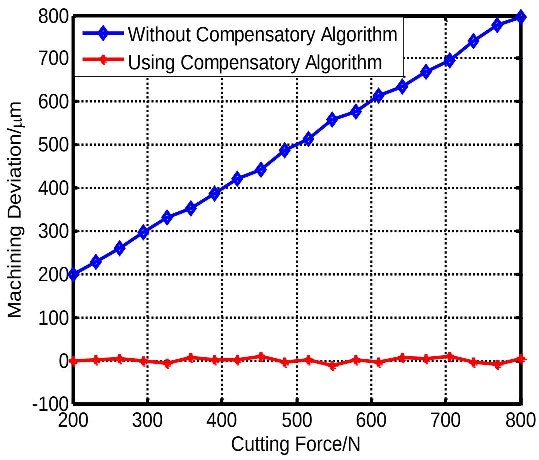

Fig.(4) Machining deviation under different cutting force

In Fig. 4, it can be seen that when the hardness of the wood remains constant, the machining deviation without the compensatory algorithm increases with the cutting force from 200μm to 800μm, while after using the compensatory algorithm, the machining deviation is limited under 20μm. The machining deviation is reduced by at least 90% with the compensatory algorithm. Besides, the effect of the compensatory algorithm becomes more and more significant with the increasing of the cutting force. Under the influence of different cutting forces, the machining deviation can remain stable with the compensation algorithm, so as to ensure the accuracy of the machine.

5.2. Influence of the Wood Hardness

Another important influential element of the machining precision is the hardness of the wood. When the cutting force is given, smaller hardness leads to a larger deformation. In this simulation, the cutting force is set as 600N, and the range of the wood hardness is 4000N~12000N. The simulation result of the machining precision using and not using the compensatory algorithm is shown in Fig. 5.

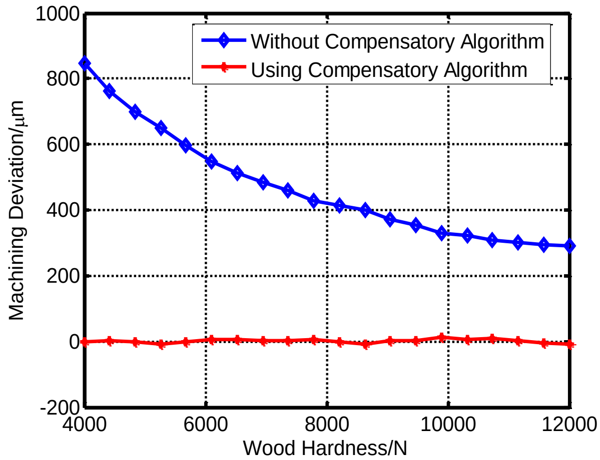

Fig. 5. Machining deviation under different wood hardness

As shown in Fig. 5, when the cutting force is constant, the machining deviation without the compensatory algorithm increases from 300μm to 850μm as the hardness decreases from 12000N to 4000N, while after using the compensatory algorithm, the machining deviation is kept within 20μm. The machining deviation is reduced by at least 93% with the compensatory algorithm, which is an obviously promotion. What's more, it can be seen that the effect of the compensatory algorithm is more obvious when the hardness of the wood is lower. Under the influence of different hardness of the wood, the machining deviation can remain stable with the compensation algorithm, so that the machine can be applied to the cutting of different wood. Therefore, the compensation algorithm is universal.

6. Conclusion

This paper mainly focuses on the wood machining deviation of the high-speed 5-axis machining center caused by the deformation of the wood. Utilizing the movement model of the high-speed 5-axis machining center, a deviation compensatory algorithm is put forward and verified through simulation. Through this study, we draw such conclusion:

(1) The precision of the wood high-speed 5-axis machining is mainly affected by the cutting force and the wood hardness. Large cutting force and low wood hardness will deadly lower the machining precision.

(2) The compensatory algorithm can obviously improve the machining precision. After compensating, the machining deviation caused by the wood deformation is counteracted by the offset of the cutter. Thus, the machining deviation is eliminated and the precision is higher.

In the future, the compensatory algorithm is going to be applied in our real machining center. The rationality and the validity of the algorithm will be verified in real machining center either.

Acknowledgements

This work was financially supported by the Agricultural Science and Technology Achievements Transformation Fund Project (2013GB24320617).

R E F E R E N C E S

[1] *W. Zhang*, "Research& Development of Foreign Wood and Wood-based Panel CNC Equipment and Technology", Forestry Machinery & Wood working Equipment, **vol.** 37, 2009, pp. 9-13.

[2] *Joel Martins Crichigno Filho*, "Prediction of cutting forces in mill turning through process simulation using a five-axis machining center", The International Journal of Advanced Manufacturing Technology, **vol.** 58, 2012, pp. 71-80.

[3] *C.G. Cai, Z. H. Ren, D. X. Li, J. L. Feng, C. L. Du*, "Dynamic error and compensation technology of the swinging angle milling head", Technology and Test, **vol.** 11, 2011, pp. 105-106.

[4] *S. Y. Wang, W. Zhang, Q. W. Zhang, J. H. Yang and PP. F. Zhang*, "Reliability Analysis about A/C-axis of Woodworking Five-axis Milling Head", Applied Mechanics and Materials, **vol.**635-637, 2014, pp. 407-410.

[5] *X. H. Zheng, D. W. Tang*, "Technology and application of industrial robot", Coal Industry Press, 2004.

[6] *J. W. Fan, X. F. Wang, C. X. Wang, B. B. Song*, "Study of Double Rocker Five-axis Machine Tool's RTCP Errors Based on the Multi-body Theory", Journal of Beijing University of Technology, **vol.**38, 2012, pp. 658-662.

[7] *S. Lin*, "Determination of timber cutting force", Woodworking Machinery, **vol.** 3, 1996, pp. 30-36.

[8] *PP. X. CAO*, "Research of wood cutting force", Wood Processing Machinery, **vol.** 4, 1997, pp. 2-5.

[9] Z. *K. Zhang, X. R. Peng, W. G. Li, J. Zeng, J. Zhang*, "Influence of Cutting Parameters on Cutting Forces in Wood Sawing", China Wood Industry, **vol.** 25, 2011, pp. 7-10.

[10] *L.Li*, "Wood Material CNC Cutting Tool Selection and Cutting Specification Determination", Forestry Machinery & Woodworking Equipment, **vol.** 2, 2012, pp. 14-19.

[11] GB/T 1941-2009, Method of testing in hardness of wood, 2009.

[12] *L. P. Cai*, "Relations of wood cutting of wood hardness and density and cutting power", Journal of Northeast Forestry University, **vol.**12, 1984, pp. 156-164.