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Study on Performance of Integral Impeller Stiffness Based on Five-axis Machining System

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Abstract

Integrated stiffness characteristics of machine tool, cutters in various postures and distribution of impeller blade will affect the machining system in processing impeller with complex and thin-wall sculpture surface, and have further effect on machining accuracy of blade. Base on the theories of multi-body small deformation, the point of transfer matrix and the Jacobi matrix, the integrated stiffness model of machining system is established by space force ellipsoid in 3D particular to 5-axis NC machining center. The force ellipsoid method is used to analyze the effect of machining tool joints, cutter and joint of tool holder/cutter on the integrated stiffness field of machining system. And then, the integrated stiffness field distribution of impeller blade in cutting plane is analyzed. Finally, this theoretical model can be effectively optimized path of machining of integral impeller, which is tested by optimization experiments of working table posture.

Keywords: impeller; complex surfaces; five-axis machining; force ellipsoid; stiffness field

1. Introduction

Nowadays, with the development of sophisticated manufacturing technologies, impeller-type parts are widely used in energy field, defense industry and aerospace field. Due to the sculptured surface of impeller blade, multiple-spindle NC machining center and intelligent CNC machining are necessarily used in machining impeller-type parts. Because of the complex structure of multiple-spindle NC machining center, cutter and worktable of NC machining center in various postures will affect the performance of the integrated stiffness of the machining system and kinematic chain gets longer from workpiece movement space to cutter movement space [1]. Deformations of cutter, tool holder/tool coupling section and machining center joints transfer through kinematic chain to tool nose. These deformations are amplified in transfer process and have further effect on the integrated stiffness of the machining system. Overcut or cutter relieving emerge if lack of stiffness of the machining system particularly to high speed milling, which have effect on machining precision and cause machining errors [2, 3, 4]. In addition, the performance of the integrated stiffness of the machining system also affect sculpture surface profile precision, which have further effect on the corrosion resistance, abrasion resistance and ability of resist fatigue [5]. Therefore, it is particularly important to establish the integrated stiffness model considering certain impeller, machining system and kinematic chain.

In recent years, the research on multi-body system stiffness model by foreign scholars have made some progress for dealing with problems of numerical control machine dynamics. Budak [6, 7] regarded cutter as cantilever structure to compute stiffness matrix of cutters, which was used to estimate workpiece machining errors caused by cutter deformation. C.Gosselin [8, 9] et al. considering of the rigidity of machine transmission parts, the Jacobian matrix between the workpiece coordinate system and machine transmission parts coordinate system was established, and established the model of integrated stiffness of the machining system based on the principle of virtual work. Wan Min [10] considering of the machining errors caused by the deformation of cutter and workpiece, the finite element
analysis and calculation were carried out for the deformation of the cutter relative to the arbitrary sampling point of the workpiece in Flank Milling, and the results were used to compensate for the distortion error. The above scholars have calculated and analyzed the integrated stiffness characteristics of the machining system, however, the influence of cutter, worktable posture and workpiece cutting point on the integrated stiffness of machining system is not considered.

Domestic scholars have also done numerous studies about the stiffness field of machining system. Liang Ruijun et al. [11] considering of the integrated machining system of machine tool, cutter and workpiece, dynamic stiffness performance of the system was extracted by experiments for weak rigidity of thin-walled parts and cutters in multi-axis NC machining. Liu Haitao et al. [12] considering of the stiffness performance of machine tool and cutter, the multi-body dynamics finite element model and the generalized stiffness function of the four axis machining center were established, and the dynamic stiffness of the system was obtained by analyzing the generalized dynamic stiffness field function. Peng Fangyu et al. [13, 14] established closed-loop stiffness model for seven-five axis machine and five-axis machine and analyzed integrated stiffness characteristic by force ellipsoid in 3D space. Position and posture of cutter and tool path were optimized, but the influence of workpiece sculpture profile on the integrated stiffness model of machining system was not considered in analysis.

The stiffness matrix of key points on blades are established for open impeller in this paper. Then, kinematic chain model of impeller particular to five-axis machining system is established and solve the coordinate transformation matrix to obtain the theoretical model of integrated stiffness field. Finally, based on force ellipsoid model, the integrated stiffness performance of key points on blades are analyzed, which is guidance to optimize the feed path and processing parameters for machining blades of impeller.

2. Stiffness matrix of key points on open impeller blade

The machined open impeller blades are shown in Fig. 1. According to the structural characteristics of the closed impeller, the five axis vertical machining center UCP Mikron 710 was selected for processing, as shown in Fig. 2.

Because of multiple surface in the integral impeller, the model of impeller is complex, global analysis will cause large number of controlling point sample. Complex grid affects the efficiency of finite element analysis. So finite element analysis is analyzed only against certain impeller blade while ensuring of the surface reconstruction precision. Based on bending moment principle, the impeller blade is sampled by using the method of adaptive sampling [15]. Sampling points are more denser in the range which changes of surface curvature become more violent based on change laws of surface curvature, and vice versa. Setting of 78 sampling points on the surface of open impeller blade are shown in Fig. 3(a). Then these sampling points are reconstructed by using of NURBS interpolation principle. The reconstruction surface as research object, normal vector of sampling points are calculated, and the results are shown in Fig. 3(b).

The axis of the impeller is generally located at the center of the table. So in order to be closer to the actual processing situation, when the finite element model is established, it is not based on the geometric center of the blade, but the axis of the impeller is set as the base coordinate of the blade, namely the coordinate system of workpiece (CSW). According to a certain sampling point of the blade, the 6 directions of the unit load are applied to the point, namely. Deformation from 6 directions, X, Y, Z, \( \theta_x \), \( \theta_y \), \( \theta_z \), are calculated in each unit load. The force or torque applied to the other five directions of \( i \), respectively, and the final deformation matrix is obtained. Due to the analysis is carried out under the CSW, the deformation matrix is the sampling point flexibility matrix in the CSW. The stiffness matrix of the sampling point \( i \) can be obtained from the inverse matrix of the flexibility matrix. Similarly, flexibility matrix of all points are obtained, then, sampling point receptance matrix database are established and the sampling point coordinates and flexibility matrix are saved. In necessary, based on the inverse matrix of the flexibility matrix, the stiffness matrix of the sampling point is obtained.

3. Modeling of integrated stiffness field

According to the motion relationship between the motion axis and the motion joint of machining center Mikron UCP 710, the model of the kinematic chain was established. The processing center has five kinkage axes, which are recorded
as X, Y, Z, A, C, where X, Y, Z for the mobile axis and A, C for the rotation axis. X axis: ram move horizontal; Y axis: ram move back and forth; Z axis: ram move vertical; A axis: table swing around the X axis; C axis: table rotates around the Z axis. Kinematic chain relationship: CSW → CSC → CSA → CSO → CSX → CSY → CSZ → CST. Machine tool coordinate system is CSO, X axis coordinate system is CSX, Y axis correspondence coordinate system is CSY, Z axis correspondence coordinate system is CSZ, A axis correspondence coordinate system is CSA, C axis correspondence coordinate system is CSY, the tool coordinate system is CST.

Assuming that the joints of the machine tool, cutting tool, tool spindle combination part, and the blade itself were elastic deformation, and the deformation of the whole processing system followed the elastic deformation, flexibility matrix of each subsystem of workpiece coordinates can be obtained by transforming the machine coordinate system. A composite compliance matrix can be obtained by adding the flexibility matrix to processing system through the basic principle of deformation.

\[
S_{(x)} = S_{(x)}^{(s)} + S_{(x)}^{(c)} + S_{(x)}^{(o)}
\]

\[
J^{(m)} = J^{(m)}(K_{(0)}) J^{(w)}(K_{(0)}) J^{(c)}(K_{(0)}) J^{(v)}(K_{(0)}) J^{(s)}(K_{(0)})
\]

Where: \( S_{(x)}^{(s)} \), \( K_{(0)}^{(s)} \) are flexibility matrix and matrix stiffness of five axes machine joint, respectively, \( S_{(x)}^{(c)} \), \( K_{(0)}^{(c)} \) are flexibility matrix and matrix stiffness of the combination of cutter and cutter handle, respectively, \( S_{(x)}^{(o)} \), \( K_{(0)}^{(o)} \) are flexibility matrix and matrix stiffness of the tool, respectively, \( S_{(x)}^{(w)} \), \( K_{(0)}^{(w)} \) are flexibility matrix and matrix stiffness to be analyzed.

The inverse matrix of composite flexibility matrix is obtained, and then composite stiffness matrix of five axis machining system \( K^{(m)} \) is obtained. Among them, the solving process that Jacobian matrix of each subsystem of the flexibility matrix transform to the CSW. Jacobian matrix \( J^{(m)} \) represents the speed transformation relationship between the joint movement space of the processing system and the tool movement space in the CSW, which is 6×5 order matrix.

\[
J^{(m)} = \begin{bmatrix}
J_{11} & J_{12} & J_{13} & J_{14} & J_{15} \\
J_{21} & J_{22} & J_{23} & J_{24} & J_{25} \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

\[
J_{11} = -(m_i + x_i) \sin A \cos C + (m_i - x_i) \cos A \cos C
\]

\[
J_{12} = -(m_i - x_i) \sin A \cos C + (m_i + x_i) \sin C \cos A
\]

\[
J_{13} = \cos C
\]

\[
J_{14} = -\sin C \cos A
\]

\[
J_{15} = \sin A \sin C
\]

\[
J_{21} = (m_i + x_i) \cos A \sin C + (m_i - x_i) \sin A \cos C
\]

\[
J_{22} = (m_i - x_i) \cos A \sin C + (m_i + x_i) \sin A \cos C
\]

\[
J_{23} = \cos A
\]

\[
J_{24} = -\sin A \cos C
\]

\[
J_{25} = \sin A \sin C
\]

4. Analysis of integrated stiffness of open blade

After the model of the five-axis machining system was established, the sampling point i on the blade was selected as the research object. The coordinates of the sample point in the CSW is (-2.76E-02, -5.73E-03, -6.34E-03). Flexibility matrix was get refer to the sampling point flexibility matrix database. The sampling point coordinates and flexibility matrix and cutting tool, tool holder/tool coupling section, machine joint flexibility matrix were brought into the equation (1), composite flexibility matrix was calculated, composite stiffness matrix was obtained by inverse matrix.

The rotation angle of the A axis was preset to 0°, 20°, 30°, and the other parameters were fixed. The composite stiffness matrix of the sampling points was calculated to decouple the composite stiffness matrix. Then, the matrix transformation was carried out to generate the force ellipsoid [13] under different rotation angles, as shown in figure 4. When the A axis angle was 0°, 20° and 30°, the ellipsoid semiminor axis was 1.45E6, 2.11E6, 2.76E6 respectively through the calculation. When the A axis angle was 30°, the semiminor axis of ellipsoid was maximum; Therefore, when the working table was A=30°, the composite stiffness of the blade was the best.

In order to introduce the influence of the blade shape on the composite stiffness field into force ellipsoid, the normal vector of the key points i (-0.067, 0.35, 0.95) of the blade was obtained. Then, the plane through the point which normal vector was (-0.067, 0.35, 0.95) set as cutting plane. The intersection of cutting plane and force ellipsoid was drawn,
the intersection was an ellipse (which was blue), as shown in Fig. 4. The ellipse in Fig. 4 indicated the stiffness performance of the cutting plane, the length of an axis along a certain direction indicated the stiffness performance of the sampling point in the cutting plane, the long axis of elliptical showed that stiffness along the direction had the best processing performance, that was, the best feed direction, the direction also can be represented by a space vector \((4.32, 1.21, -0.37)\). System composite stiffness performance machining along this direction was best, which can calculate the optimum feed direction.

In order to obtain the composite stiffness performance of the whole blade, all the key points of composite stiffness matrix was calculated. Then, the stiffness performance evaluation indexes were selected basing on the force ellipsoid, and the stiffness performance evaluation values of the key points were obtained. Finally, the stiffness performance of these key points consisted of the stiffness performance of the whole blade with the interpolation method. Force ellipsoid short semi axial \(\lambda\) was selected as stiffness performance index, assuming machine tool, tool joints, tool shank combination, with no deformation in machining process, which was, the stiffness was infinite. The corresponding composite stiffness performance of the cloud was established basing on the multiple sets of calculation, as shown in Fig. 5. The force ellipsoid was non dimensional, the composite stiffness was also non dimensional, the stiffness of each point of the blade can be compared.

Through the comparison of Fig. 5, when the joint deformation of the five axis machine tool was not considered, it was assumed that the joint stiffness of the machine tool was infinite, the composite stiffness performance of the processing system and the data and the distribution of the joint deformation of the machine tool were almost no change, as shown in Fig. 5(a) and 5(b). The stiffness of the joint of the five-axis machine tool had little contribution to the composite stiffness of the machining system. However, if the assumption of the tool's stiffness was infinite, the system composite stiffness was greatly changed, as shown in Fig. 5(c). Similarly, composite stiffness performance of machining system changes great without considering the tool combination deformation. Therefore, it can be seen that the stiffness of the tool and the main shaft of the cutting tool can contribute greatly to the composite stiffness of the machining system.

In this paper, the carbide ball end milling cutter is used to finish the precision machining of the open blade. Considering the contribution of the stiffness of the tool to the system overall stiffness is larger, as well as the replacement of the tool, simulation is taken by changing tool with stronger stiffness. After replacement (R216.64-10030-A011G) and replacement (R216.64-08030-A009G) of the system composite stiffness of the performance of the cloud is shown in Fig. 6. It shows that by comparing after changing the stiffness of the tool, the blade has a strong range of stiffness, and the stiffness of the root part of the performance increased by nearly 21%, but the stiffness of the blade tip is not too high. That indicates the effect of stiffness of tool selection in the process of the leaf root is large, which is no stiffness slightly too big effect.
Finally, the normal vectors of all the key points of the blade are calculated to introduce the curved surface shape of blades into integrated stiffness field. The composite stiffness performance of the blade surface in the cutting plane and the cutting plane method are considered. The composite stiffness performance is shown in Fig. 7, making the length of the semi axis of the ellipse which is the intersection of the cutting plane and the force ellipsoid, and the semi axis of the ellipse in the cutting plane as index of the stiffness, respectively.

From the analysis of Fig. 7, the blade tip position has poor stiffness in cutting plane, it should decrease the feed rate in the process of machining parts, and the stiffness performance near the hub tip in normal plane of the cutting plane is also poor. This means that the site is prone to deformation in the normal direction, which will greatly affect the processing accuracy. Therefore, it is best to strengthen the tip clamping part in the process to constrained deformation, then the composite stiffness of the processing system is improved.

5. Experiment of attitude optimization of working table basing on stiffness field theory

When the rotation angle of the A axis changes, the attitude of the working table will change, and the composite stiffness of the cutter locations will be changed. The cutter responses decrease with the better stiffness of the cutter locates. It is possible to process higher precision impeller. On the contrary, the cutter responses increase with the worse stiffness of the cutter locates. It is impossible to process higher precision impeller. Set the rotation angle of the A axis in advance in order to determine the optimal table attitude, simulation and experiment are carried out on the same cutting path to obtain the optimal working table attitude for three different blades. To set a cutting path in advance, the actual cutting path is shown in Fig. 8(a), the stiffness field simulation and vibration test of three blades are carried out at different working table.

6 sampling points were selected on the cutting path of blade 1, blade 2, blade 3, shown in Fig. 8(b), the normal vector of sampling points and flexibility matrix was calculated, the composite stiffness field was analyzed with the rotation angle of the A axis as the variable: The blade 1 corresponds to the rotation angle of A axis is 0°, the blade 2 corresponds to the rotation angle of A axis is 20°, the blade 3 corresponds to the rotation angle of A axis is 30°. Composite stiffness model was built to generate force ellipsoid, stiffness of long half axis of cutting plane ellipse (which represents the maximum stiffness performance of the point in the cutting plane) and stiffness of the feed direction of elliptical half shaft (which represents the stiffness performance of the feed direction) was calculated, in order to maximize semi elliptical axis in feed direction as the goal, the best workbench attitude could be predicted.

The experiment of the blade was carried out, the vibration sensor is mounted on the back of the blade processing area as shown in Fig. 9. The feed rate is set to 700mm/min in the test, vibration of blade 1, 2 and 3 under different feed rate were obtained basing on the Donghua test system and the minimum stability of amplitude of best blade corresponding to the attitude of working table at a certain feed rate was obtained. The analysis results of the composite stiffness of different blade along the preset cutting path in different angles with taking 6 sample points on cutting paths are shown in Fig. 10.
At A=0°, the ellipse half axis along the cutting path is very short, almost half of an ellipse, this means that the stiffness performance of the system along the tool feed direction is poor when the blade 1 is processed by A=0°, the maximum amplitude of vibration is 7.4 mm/s².

At A=20°, the ellipse half axis along the cutting path becomes longer, this means that the stiffness of the system along the tool feed direction has been improved, when the blade 2 is processed by A=20°, the maximum amplitude of vibration is 6.1 mm/s².

At A=30°, the elliptical half axis along the cutting path is almost half of the length of the ellipse, length reaches the maximum value, this means that the stiffness performance of the system along the tool feed direction is the best, when the blade 3 is processed by A=30°, the maximum amplitude of vibration is 5.7 mm/s². Through analyzing the result of simulation, it can be predicted that the composite stiffness of the system is best when the blade 3 is processed along the default path, so the stiffness is the minimum, the machining precision and the machining efficiency are the highest; the composite stiffness of the system is worst when the blade 1 is processed along the default path, so the vibration is the maximum, the machining precision and the machining efficiency are the lowest.

6. Conclusion

The composite stiffness model of the impeller processing system was built, influence of machine tool, cutters, tool joints, etc. on the composite stiffness of system performance was analysed, the distribution law of the composite stiffness in the cutting plane was found. This can provide an effective means for the processing staff to understand the composite stiffness of the impeller blades, reduce the vibration of the blades and improve the machining accuracy of the blades.

1) Based on the key points of open blade (-2.76E-02, -5.73E-03, -5.34E-03), the analysis of the composite stiffness field is carried out in research, the stiffness performance of the point is optimized when the A shaft rotation angle is 30 degrees, the best feed direction (4.32, 1.21, -0.37) is calculated. The stiffness field model can be used to optimize the performance of the machining system, and optimize the cutter, the position and orientation of the working platform and cutting path.

2) The joint stiffness of five axis machine has less contribution to the composite stiffness of the machining system basing on the open impeller blades of composite stiffness performance. At the same time, the selection of cutting tool is improved. After changing the tool, the stiffness of the blade root was improved by 21%, but the stiffness of the blade was not greatly improved. It shows that tool choice has great influence on the stiffness performance of the roots, and has almost no influence on the blade tips.

If the curved surface shape of the open impeller is considered to analyze the composite stiffness field of the machining system, that is, analysis of the distribution of the overall stiffness of the cutting plane and the cutting plane method, stiffness in the cutting plane of the blade tip is poor, which is not suitable to increase the feed rate in the process of the process. And near the hub tip in the cutting plane method to the stiffness performance is poor, this means that the site is prone to deformation in the normal direction which will greatly affect the processing accuracy.

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