Design of robotic end-effector for milling force control

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Abstract. In order to realize the precision machining of high-performance materials, a robotic end-effector for milling force control is proposed. Two kinds of end-effectors which are coaxial and non-coaxial structures are designed according to types of motorized spindle and force sensor. The maximum milling force is obtained that is satisfied the safety requirements of force sensor. And the three-dimensional models of coaxial and non-coaxial structure are imported into ABAQUS software for finite element analysis. The simulation results show the non-coaxial structure is better than coaxial structure, and it is suitable to be installed in robot to machine high performance parts.

1. Introduction
With the development of industrialization and production automation, industrial robot has been widely applied in many machining areas that mainly include mechanical parts milling, hardware grinding and optical elements polishing, etc [1]. About manufacturing of titanium, quartz glass and other high-performance parts, using robot is difficult to achieve precision machining. At present the domestic manufacturing enterprises mainly rely on handwork to complete precision machining of high-performance parts. The handwork is low efficiency with poor working conditions, and it is difficult to obtain high surface quality [2]. The precision machining of high-performance intractable materials has become the bottleneck that restricts pervasive application of these materials and need to be improved.

For a long time, one of key problems that restricted the precision machining of high-performance parts is machining force control of machining tool. Controlling the size and direction of machining force is the key to obtain high quality surface [3, 4]. The milling process has high efficiency and wide machining range and is especially suitable for machining of complex parts such as molding [5, 6]. In this paper, a robotic end-effector with milling force control is designed to control milling force and realize the precision machining of high-performance intractable materials.

2. Mechanical design of end-effector
The robotic machining system is applied to automatic machining of high performance parts. As shown in Figure 1, the robotic machining system comprises main parts including industrial robots, end-effector and workbench. The end-effector of robot is a device which is designed to complete a specific task and installed in the end flange of robot. The end-effector can be replaced according to the processing requirement. The precision machining of high performance parts generally includes milling, grinding and polishing. We design an end-effector with force sensor for the application of milling.
In the process of workpiece machining, the machining tool needs high speed to ensure machining quality and efficiency. In the paper, we select high speed motorized spindle to provide the rotary power of machining tool. The motorized spindle can be adjusted the speed of main spindle according to the specific machining requirement. The output power of motorized spindle is 2.4 KW and the maximum speed is 24000 rpm. At the same time, in order to obtain the machining force between machining tool and workpiece in real time, the six-dimensional force-moment sensor is used to measure the force information of three-dimensional space in the cartesian coordinate system. In the sensor coordinate system, the pressure range of the x and y direction is ±330N and the pressure range in the z direction is ±990N. Moreover the torque range of x, y, and z direction is 30N·m.

In the paper, two kinds of end-effectors which are coaxial and non-coaxial structures are designed according to the types of motorized spindle and force sensor. As shown in Figure 2, the end-effector of coaxial structure makes the center lines of motorized spindle and force sensor be in the same axis, and the force sensor is connected to the robot flange. Then the base of motorized spindle is installed on the sensor flange, and the clamping device of motorized spindle is mounted on the base of motorized spindle. The clamping device is used to fix motorized spindle and milling cutter is installed at the end of motorized spindle. The end-effector of coaxial structure doesn’t produce additional torque. And the machining force is easy to measure. The end-effector of non-coaxial structure is illustrated in Figure 3. The non-coaxial structure is simple and easy to assemble by comparing with the coaxial structure. The clamping device of motorized spindle is mounted on the side of sensor flange, so that the barycenter of end tool is close to the flange of mechanical arm. It can reduce overall length of the end tool and improved the rigidity of mechanical arm during processing.

![Figure 1. The robotic machining system](image)
3. Calculation of milling force

Milling force is one of the most important output parameters in milling process, which has important influence on machining surface integrity. The force sensor is used to measure the milling force and cooperated motion of the mechanical arm to realize the control of machining force. In this paper, the milling force is calculated to verify whether the size of milling force is within the measuring range of force sensor. When tools and workpiece materials are constant, main influencing factors of milling force are milling speed, milling depth, feed amount and milling width. According to the calculation manual of metal machining [7], the milling speed $v_c$, the feed per tooth $f_z$ and the milling force $F_c$ can be obtained by

$$
 v_c = \frac{\pi d_n n}{1000} \quad (1)
$$

$$
 f_z = \frac{v_c}{zn} \quad (2)
$$
\[ F_v = \frac{c_p \cdot a_p^{0.86} \cdot f_v^{0.74} \cdot B \cdot z}{d_0^{0.86}} \times K \times K_1 \times 10 \]  

where \( d_0 \) is the milling cutter diameter, \( n \) is the rotate speed of motorized spindle, \( v_f \) is the feed speed, \( z \) is the number of cutting edge, \( a_p \) is the milling depth, \( B \) is the milling width, \( c_p \) denotes the influence coefficient of workpiece material on milling force, \( K \) denotes the influence coefficient of cutter front angle on milling force, \( K_1 \) denotes the influence coefficient of milling speed on milling force.

In the paper, a vertical milling cutter which the diameter is 6 mm is selected to milling titanium alloy. And the corresponding machining parameters are selected in the case of maximum milling force [8], as shown in Table 1.

| Parameter | Value |
|-----------|-------|
| \( d_0 \) (mm) | 6 |
| \( N \) (r/min) | 24000 |
| \( a_p \) (mm) | 0.5 |
| \( B \) (mm) | 4 |
| \( c_p \) | 68 |
| \( K \) | 1.5 |
| \( K_1 \) | 0.68 |

The specific parameters of milling in Table 1 are substituted into Eq. (1-3), and the maximum milling force is got which is 180.5 N. The maximum milling force is less than 75% of the pressure range of the x and y direction, so that it is satisfied the safety requirements of force sensor.

4. Finite element analysis of end-effector
In order to prove the validity and rationality of two structures, finite element analysis of end-effector is needful. The connecting flange and clamping device of end-effector are used same material that is Q345 steel. The parts are connected by bolts, and the material of bolts is 45 steel. The material properties of main parts are listed in Table 2.

| Material | E /MPa | \( \mu \) | \( \sigma_s /\text{MPa} \) |
|----------|--------|---------|------------------|
| Q345     | 2.06\times10^5 | 0.28    | 345              |
| 45       | 2.10\times10^5 | 0.27    | 355              |

The three-dimensional model of end-effector is established in SolidWorks, and the three-dimensional models of coaxial and non-coaxial structures are imported into ABAQUS software for finite element analysis [9]. As the robot flanges and force sensors are bolted to the end of the mechanical arm, the force sensor is set as the immobile part and three degrees of translation freedom are constrained. The bolt pretightening force which is 1.9 KN is applied at the joints of each part. Then
the maximum milling force and the maximum force of sensor range are applied at the end of milling cutter to perform finite element analysis. Through the analysis of ABAQUS software, the deformation and stress nephograms of two structures are obtained, as shown in Figure 4 and Figure 5.

Figure 4. The deformation nephograms of two structures

Figure 5. The stress nephograms of two structures

Figure 4 shows that the maximum deformation of coaxial structure is 0.11 mm and the maximum deformation of non-coaxial structure is 0.03 mm. Figure 5 represents the stress values of clamping device in the two structures. The stress value of coaxial structure is 336.9 MPa, and the stress value of non-coaxial structure is 122.7 MPa. It is easy to see from the deformation and stress nephograms of two structures that the stiffness of non-coaxial structure is larger and the stress and deformation is smaller. Moreover the non-coaxial structure is simple and easy to assemble. So simulation results show the non-coaxial structure is better than the coaxial structure, and it is suitable to be installed in robot to machine high performance parts.

5. Conclusion

In the robot milling, two kinds of end-effectors for milling force control which are coaxial and non-coaxial structures are designed to realize precision milling. In the design, the motorized spindle is used to provide the high-speed rotary power of machining tool and the force sensor is used to measure the machining force to achieve the purpose of machining force controllable. Then the milling force is calculated according to actual situation of milling. The maximum milling force is less than 75% of the pressure range of the x and y direction, so that it satisfies the safety requirements of force sensor. Lastly, the three-dimensional models of coaxial and non-coaxial structure are imported into ABAQUS software for finite element analysis and the deformation and stress nephograms of two structures are obtained. The simulation results show the non-coaxial structure is better than the coaxial structure, and it is suitable to be installed in robot to machine high performance parts. In the following study, the control method of machining force and tool path plan are key research direction of robotic machining with force controllable.
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