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Modeling and Force Control of Robotic Polishing System for the Wheel Hubs*

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***Abstract*— Polishing is a key step in the manufacturing of wheel hubs since it will affect the appearance and performance of the wheel hubs. In this paper, a robotic polishing system is designed for the wheel hubs. To facilitate variable selection and controller design, the polishing process is firstly modeled. A roughness model considering the classic Preston material removal model is proposed. The roughness model aims at controlling the surface roughness rather than the material removal of the workpiece, which is more suitable for the robotic polishing for the wheel hubs. Then, a position-force hybrid control framework is proposed for the robotic polishing system. To improve the performance of the force control, a three-level rule-based adjusting method is designed and robot motion trajectory is planned based on the resolution surface of the wheel hubs. Finally, polishing experiments on the wheel hubs are fully conducted to demonstrate the effectiveness of the proposed modeling and control method of this paper.**

***Index Terms*— polishing, robot, modeling, force control, motion planning**

I. Introduction

Wheel hubs are important parts of the automobile, which have a critical impact on the appearance and safety of the automobile. The manufacturing of the wheel hubs mainly consists of five procedures, i.e., smelting, low pressure casting, thermal treatment, polishing and electroplating or painting. Among them, polishing is a key process since it will greatly influence the final quality of the wheel hubs. At present, manual polishing is widely adopted in the factories of the wheel hubs, whose efficiency is low and the consistency of the quality can not be guaranteed. Therefore, the polishing of the wheel hubs needs to be changed from manual mode to automation.

Robots are adopted into the polishing applications and several robotic polishing systems have been proposed [1]–[3]. Tian [1] adopted the robot for polishing curved surfaces and presented method to ensure the constant pressure during polishing process. In [2], the authors presented a design of macro-mini robot system for polishing applications. The mini robot had a reduced inertial effect. The macro robot (it is a six-axis industrial robot) was used to position the mini robot according to the workpiece profile while the mini robot controlled the polishing force. Gaz [3] designed a human-robot collaborative polishing system for the metallic surfaces with complex geometric shapes, in which the robot firmly kept the workpiece in a prescribed sequence of poses, by monitoring and resisting to the external forces applied by the operator.

To design the robotic polishing systems, modeling about the contact process between the polishing tool and the workpiece surface is needed to be established. Tian [1] established the relation model between removal rate and polishing pressure according to the Preston equation and Hertz theory. In [4], a pressure distribution model of the robotic polishing was derived and validated, and a removal rate model was subsequently proposed. In [5], accurate tool influence functions for deterministic fabrication of smooth curved surfaces was proposed in a computer controlled optical polishing system. The three dimensional tool influence functions were investigated separately from their radial profiles. In [6], the model of the maximum cutting depth of abrasive grains was developed based on the statistics analysis, and by the use of the elastic contact theory and the plastic contact theory.

In the polishing process, force control on the contact between the tool and the workpiece surface needs to be carried out continuously and steadily. Ding [7] proposed an adaptive proportional-integral control algorithm to evaluate the stiffness of polishing system and to adjust the parameters of the force controller in order to ensure the polishing system with different stiffness to have a better tracking performance of the contact force. Luo [8] proposed an adaptive hybrid impedance control algorithm based on subsystem dynamics model design to solve the problem of inaccurate modeling. In [9], a fuzzy logic controller was implemented on a pneumatic robot for application to the polishing of sheet steel. The fuzzy logic controller was supplemented by both system time lag and friction compensators with velocity feedback.

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The above mentioned modeling methods are mainly used in polishing applications with large grinding depth. For polishing the wheel hubs, the grinding depth is small. Therefore, a surface roughness model considering the classic Preston material removal model is proposed in this paper. The new modeling method is more suitable for the robotic polishing for the wheel hubs. Since there is a big lag from the position control demands to the measured changes of the force, a three-level rule-based speed ratio adjusting method is designed to indirectly realize the fore control.

II. Modeling of the Polishing Process

To design the robotic polishing system and the control methods for the wheel hubs, modeling of the polishing process is needed firstly. The model is aimed to describe the relationship between the material removal or surface roughness and the related factors such as the the moving speed of the polishing tool, the contact force between the tool and workpiece surface, and so on. In this paper, the material removal model based on the classical Preston model is firstly established. Then the surface roughness model is established which is more suitable for the robotic polishing system. The Preston model mainly describes the relationship between the material removal depth of the workpiece in the incremental time [10], which is given by

$$dR_m = \lambda F_p v dt \tag{1}$$

where dR_m is the incremental amount of the material removal depth, F_p is the force value in the contact point of the polishing tool and workpiece, v is moving speed of the polishing tool on the workpiece surface, λ is a scale factor.

In the real polishing process, to increase the polishing efficiency and quality, the tool has circular motion in high speed driven by spindle motor except that it moves on the workpiece surface. Therefore, the following equation can be derived from (1)

$$\frac{dR_m}{dl} = \lambda F_p v \frac{dt}{dl} = \lambda F_p \frac{\sqrt{v_s^2 + v_c^2}}{v_s} \tag{2}$$

where dR_m/dl is the amount of the material removal at each moving step of the tool, v_s and v_c are the moving speed and the circular speed of the tool respectively.

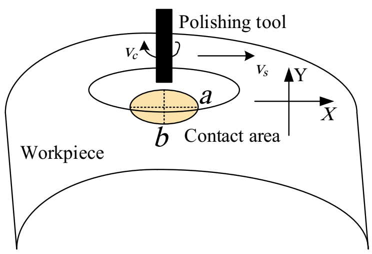


Fig. 1. The relationship between the tool and the workpiece

The relationship between the polishing tool and the workpiece in the polishing process is shown in the Fig. 1. The tool moves along the defined trajectory in a certain manner and the contact area is elliptical in shape [11]. Thus, the material removal depth can be computed from the time when the tool enters the elliptical area to the time when it leaves the area. In the following part, the material removal in the Y direction will be set as an example. In the Y direction, the total amount of the material removal in the contact area can be computed as the integral of material removal from the beginning contact point to the ending contact point as follows.

$$R_m(y) = \int_{b_c}^{e_c} \lambda F_p \frac{\sqrt{v_c^2 + v_s^2}}{v_s} \tag{3}$$

where $R_m(y)$ is the material removal in the Y direction, b_c and e_c are the the beginning and ending contact point of the polishing tool from the workpiece, respectively. b_c and e_c is given by

$$\begin{cases} b_c = -a\sqrt{(1 - y^2/b^2)} \\ \\ e_c = a\sqrt{(1 - y^2/b^2)} \end{cases} \tag{4}$$

where a and b are the long and short axis of the ellipse respectively. a and b can be computed as

$$\begin{cases} a = \left(\dfrac{3\xi^2\gamma(\xi)F_p R}{\pi M}\right)^{\frac{1}{3}} \\ \\ b = \left(\dfrac{3\gamma(\xi)F_p R}{\pi \xi M}\right)^{\frac{1}{3}} \end{cases} \tag{5}$$

where ξ is the ratio of a to b, $\gamma(\xi)$ is the second type of elliptic integral, R is related to a and b, M is related to the elastic modulus of the polishing tool and the workpiece. ξ, R and $\gamma(\xi)$ are computed as

$$\begin{cases} \xi = \dfrac{a}{b} \approx 1.0339\left(\dfrac{A}{B}\right)^{0.636} \\ \\ R = \dfrac{1}{A+B} \\ \\ \dfrac{1}{M} = \dfrac{1-\vartheta_t^2}{M_t} + \dfrac{1-\vartheta_w^2}{M_w} \\ \\ \gamma(\xi) = \int_0^{\frac{\pi}{2}} (1 - (1 - \dfrac{1}{\xi^2}) \sin\phi) d\phi \end{cases} \tag{6}$$

where A and B are the principal curvatures of the polishing tool and the workpiece surface, M_t and M_w are the elastic modulus of the polishing tool and the workpiece, ϑ_t and ϑ_w are the Poisson ratio of polishing tool and the workpiece, respectively.

From the material removal model (3), it can be seen that the material removal is mainly related to the contact force between the tool and the workpiece surface, the moving and circular speed of the tool, the elastic modulus of the polishing tool and the workpiece and the curvatures of the polishing tool and the workpiece surface. Among these related factors, the contact force, the moving and circular speed of the tool can be controlled. Since the amount of the material removal is small enough in the polishing of the wheel hubs, the model mentioned above is served as the theoretical guidance. For the real robotic polishing system, the surface roughness model may be more suitable. According to the factors in the polishing process, the surface roughness model can be expressed as

$$R_a = \lambda r_a^{\sigma_1} F_p^{\sigma_2} V_{s3}^{\sigma} V_c^{\sigma_4} R_e^{\sigma_5} \tag{7}$$

where r_a is surface roughness, λ is a constant coefficient, σ_1 to σ_5 are indexes of the five related parameters which can be calibrated using the experimental data, R_e is the equivalent curvature radius which can be computed by

$$R_e = \left(\frac{A}{B}\right)^{0.636}\left(1.003 + 0.5968\frac{A}{B}\right)R \tag{8}$$

Take logarithms on both sides of the equation (7) and define $y = In(Ra)$, $x_0 = In(\lambda)$, $x_1 = In(r_a)$, $x_2 = In(F_p)$, $x_3 = In(V_s)$, $x_4 = In(V_c)$ and $x_5 = In(R_e)$, the following regression equation can be obtained.

$$y = x_0 + \sum_{i=0}^{5} \sigma_i x_i \tag{9}$$

The linear regression roughness model (9) can be determined using the least square fitting method based on the experimental polishing data.

III. Controller Design and Motion Trajectory Planning

From the surface roughness model it can be seen that the main factors affecting the polishing quality are the contact force between the tool and the workpiece and the moving and circular speed of the tool. The circular motion of the tool is driven the spindle motor. The moving speed of the tool can be transferred to the position of the end effector of the robot. Therefore, the controlled variables of the polishing robot are the position and the force. In this paper, a position-force hybrid controller is designed as shown in Fig. 2.

In the controller diagram, P and V are the reference position and force of the end effector of the robot. q_t and q_t' are the measured position and speed of the end effector of the robot computed from the kinematics module. ω_i and ω_i' are the joint angle and rotation speed of the robot joint. F_t is the joint driving torque. F_c is the force on the polishing process. F_m is the measured force from the force sensor. F_r is the reference force. The position servo module and the kinematics module constitute the position controller of the robot which converts the received position and speed instructions into the output torques of each joint. The joint angle and rotation speed are sent to the position servo module as the feedback signals based on the encoder in each joint. The force sensor and the force control module constitute the force controller. It computes the adjusting position and speed of the end effector of the robot based on the force errors between the reference force F_r and the measured force F_m.

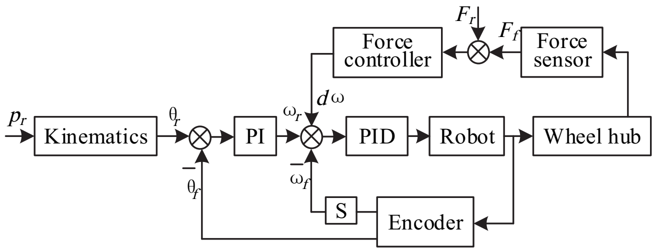


Fig. 2. The position-force hybrid controller of the robotic polishing system

Since there is obvious lag from the position adjusting of the end effector to the measured force of the tool, a rule-based control method is proposed. According to the reference force and the measure force, a speed ratio is applied to the current speed based on the rules. As shown in Fig. 3, three levels are defined. If the measured force is bigger than the reference one, the moving speed of the robot should be increased. The greater the force deviation, the faster the speed should be increased. On the other hand, if the measured force is smaller than the reference one, the moving speed of the robot should be decreased. The greater the force deviation, the faster the speed should be decreased.

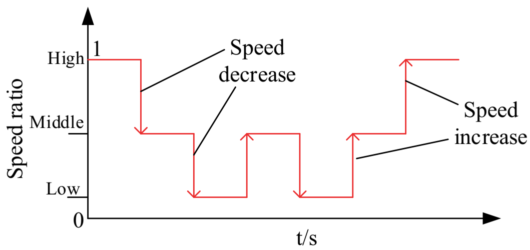


Fig. 3. The speed adjusting of the robot based on the three speed ratio levels

After the position force hybrid controller is designed, the motion trajectory planning of the robot needs to be designed. The polishing area of the wheel hub is a complex revolving surface, which can be regarded as the trajectory surface formed by a two-dimensional curve. The busbar C_m and revolving surface R_s can be described as

$$\begin{cases} C_m = p_t i + z_t k \\ R_s = p_t(i\cos\theta + j\sin\theta) + z_t k \end{cases} \tag{10}$$

where θ is the rotation angle, p_t and z_t are the radius and axial distance at any point on the resolving surface, t is a parameter of the busbar, i, j and k are the unit vectors along the X, Y and Z axis.

Any point on the trajectory of the robot contains the position X, Y, Z and attitude information represented by four elements q_1, q_2, q_3 and q_4. Therefore, the unit vector n_p of any point on the trajectory is given by

$$n_p = x_n i + y_n j + z_n k \tag{11}$$

where x_n, y_n and z_n are as follows

$$\begin{cases} x_n = 2(q_2 q_4 - q_1 q_3) \\ y_n = 2(q_3 q_4 + q_1 q_2) \\ z_n = (q_1^2 - q_2^2 - q_3^2 - q_4^4) \end{cases} \tag{12}$$

The principal curvature radius at latitude direction and longitude direction of any point on the trajectory can be defined as

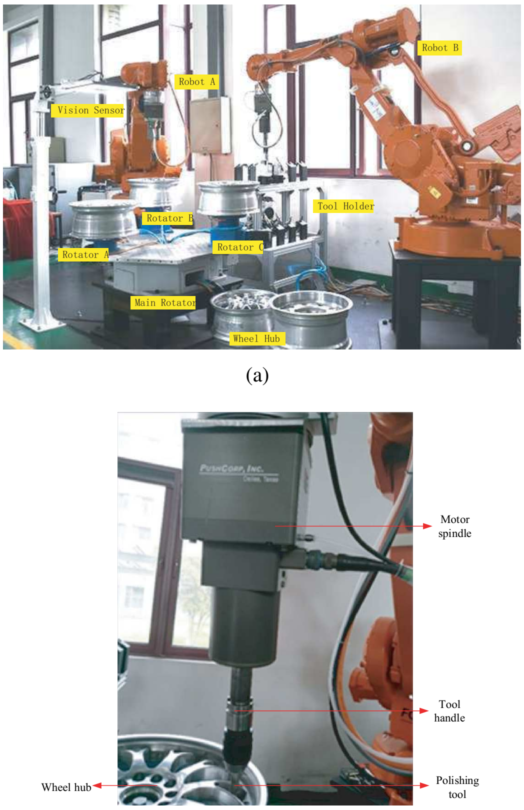
$$\begin{cases} R_{la} = \dfrac{\sqrt{X_k^2 + Y_k^2}}{z_{nk}} \\ R_{lo} = \dfrac{\sqrt{(X_k - X_{k-1})^2 + (Y_k - Y_{k-1})^2 + (Z_k - Z_{k-1})^2}}{x_{nk}x_{nk-1} + y_{nk}y_{nk-1} + z_{nk}z_{nk-1}} \end{cases} \tag{13}$$

where X_k, Y_k and Z_k are the position coordinates of the k-th point on the trajectory, x_{nk}, y_{nk} and z_{nk} are the unit vectors of the k-th point, respectively.

IV. Experiments and Results

To test the effectiveness of the proposed modeling and force control of the robotic polishing system for the wheel hubs in this paper, experiments are carried out. The two robots are ABB IRB4400-60 with six degrees of freedom, whose operating range is 1960 mm, payload is 60kg, repositioning precision is 0.19 mm. The force control is realized based on the force sensor. The type of the force sensor is Omega 160, whose maximum force in X and Y axes is 2500 N, maximum forces in Z axis is 6250 N, resolution in X and Y axes is 0.25 N, resolution in Z axis is 0.5 N. The rotary motion of the polishing tool is driven by the spindle at the end of the robot. The type of the spindle is Pushcorp STC1503-BT30, whose highest speed can reach 15000 rpm. The main rotator is Weiss CR0700C, whose positioning accuracy is 15 arcsec. The parallelism between the turntable and the bottom should be within 0.02 mm. The sub-rotators are positioning accuracy is 30 arcsec.

The planned motion trajectory in the polishing process is shown in Fig.5(a). The contact between the polishing tool and the surface of the wheel hub is shown in Fig.5(b). It can be seen that the polishing tool can track the wheel hub strips well. Four typical wheel hubs were polished using the proposed robotic polishing system. In each wheel hub,



(a)

(b)

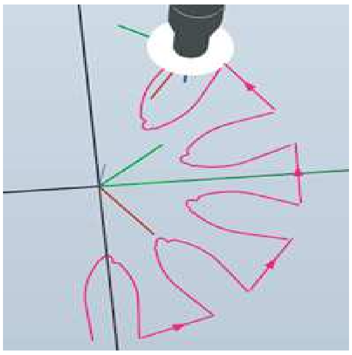
Fig. 4. The experimental platform of the robotic polishing system for the wheel hubs, (a) the robotic polishing system, (c) the motor spindle at the end of the robot

randomly selected five points on the surface of the wheel hub were measured with roughness tester. The roughness tester is TIME 3221, whose measurement range is 50 μm, resolution is 0.001 μm. The measured results were listed in the table I. The results show that the largest roughness was 0.384 μm, the mean roughness was 0.2577 μm. It can be seen that surface roughness of the wheel hubs can reach a value under quality inspection requirements.

To see the effect more clearly, the wheel hubs before polishing and after polishing are given in Fig. 6. It can be seen that the surface of the wheel hub after polishing has mirror shining effect, which indicates a high surface polishing quality.

V. Conclusion

This paper designs a robotic polishing system for the wheel hubs. A roughness model considering the classic Preston material removal model is proposed, which aims at controlling the surface roughness and is more suitable for the robotic polishing system. In designing the position-force hybrid controller, a three-level rule-based speed ratio adjusting method is designed. The new control method can



(a)

(b)

Fig. 5. The planned motion trajectory and polishing process, (a) motion trajectory, (c)polishing process

(a)

(b)

Fig. 6. The polishing results of the wheel hubs, (a) before polishing, (c)after polishing

TABLE I

THE SURFACE ROUGHNESS OF THE POLISHED WHEEL HUB

Group No	**Surface roughness Ra** (μm)				
Group 1	0.332	0.245	0.097	0.339	0.268
Group 2	0.305	0.213	0.193	0.225	0.357
Group 3	0.384	0.247	0.065	0.285	0.276
Group 4	0.320	0.278	0.305	0.189	0.231

reduce the lag impact from the position command of the robot to the measure force change. Then, the robot motion trajectory is planned based on the resolution surface of the wheel hubs. Real experiments on a robotic polishing system demonstrate the effectiveness of the proposed modeling and control method.

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