World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:15, No:9, 2021

Adaptive Control Strategy of Robot Polishing Force Based on Position Impedance

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Abstract**—**Manual polishing has problems such as high labor intensity, low production efficiency and difficulty in guaranteeing the consistency of polishing quality. The use of robot polishing instead of manual polishing can effectively avoid these problems. Polishing force directly affects the quality of polishing, so accurate tracking and control of polishing force is one of the most important conditions for improving the accuracy of robot polishing. The traditional force control strategy is difficult to adapt to the strong coupling of force control and position control during the robot polishing process. Therefore, based on the analysis of force-based impedance control and position-based impedance control, this paper proposed a type of adaptive controller. Based on force feedback control of active compliance control, the controller can adaptively estimate the stiffness and position of the external environment and eliminate the steady-state force error produced by traditional impedance control. The simulation results of the model show that the adaptive controller has good adaptability to changing environmental positions and environmental stiffness, and can accurately track and control polishing force.

Keywords**—**Robot polishing, force feedback, impedance control, adaptive control.

I. Introduction

POLISHING is one of the key processes in the production of many aerospace composite parts. The accuracy of polishing directly affects product quality. Due to the disadvantages of manual polishing, such as low efficiency, difficulty in guaranteeing product consistency, and damage to workers' health, the use of robots instead of manual polishing has gradually become a trend [1]. Accurate tracking and control of polishing force can effectively improve the quality of robot polishing. At present, the force control for the robot polishing is divided into active compliance control and passive compliance control. Because the adaptability of passive compliance control is not strong, and it is difficult to completely solve the contradiction between robot stiffness and flexibility [2], this paper adopts active compliance control scheme to control the force of robot polishing. Force/position hybrid control and impedance control are two classic control methods of active compliance control. For force/position hybrid control, force and position controllers are designed in the constrained and unconstrained directions of operational space, respectively [3]. Impedance control is aimed at regulating desired mechanical impedance specified by target model [4]. Changes of position and stiffness of the workpiece in robot polishing process will have a great impact on the polishing accuracy, so improving the adaptability of robot to environment has become an important research topic at present [5].

Yousefizadeh et al. [6] used the principle of impedance control to establish an online robot trajectory generator and proposed a new force controller based on online identification of the minimum bump trajectory which is tracked by the end effector. Bo et al. [7] proposed a T-S fuzzy controller for the dynamic model of mobile robots under the strong coupling effect during contact processing, which applied robust control methods for linear systems to nonlinear systems. Zhou et al. [8] proposed a new vision-based impedance controller for robot wall polishing, which used specified impedance model as control target and measure movement through vision feedback. Cao et al. [9] analyzed the transient response and steady-state error in classic control methods and proposed a dynamic adaptive hybrid impedance controller to deal with dynamic contact force tracking in uncertain environments. Xu et al. [10] proposed a method of hybrid force-position control combined with PI/PD control for robotic abrasive belt grinding of complex geometries. Fan et al. [11] designed two novel eddy current dampers and integrated into a novel smart end effector to improve the robotic polishing system dynamics and suppress the vibrations.

This paper established a "mass-damping-spring" second-order system between the end of the polishing tool and the external environment, an adaptive impedance control method is proposed on the basis of impedance control, and to build the model in MATLAB/Simulink, simulate and verify the force control performance of the model under the condition of changing environment position and changing environment stiffness. The experiments show that the force control model can adaptively estimate the environmental position and environmental stiffness, so as to track of the polishing force accurately.

II. Modeling

The robot polishing platform built in this article includes KUKA robot and its controller, host computer controller and PC, six-dimensional force sensor system and polishing tool system. The end of the robot is rigidly connected with the six-dimensional force sensor, and the pneumatic polishing tool system is fixed under the six-dimensional force sensor. The main system composition is shown in Fig. 1.

A. Polishing Force Analysis

In the ideal robot polishing process, the polishing tool is perpendicular to the surface of work piece as shown in Fig. 2,

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F is the polishing force that needs to be controlled, and gravity compensation of the polishing tool end is required in order for the six-dimensional force sensor to obtain real polishing force information.

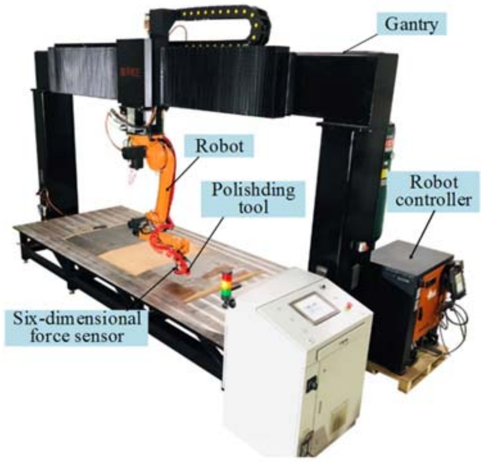

Fig. 1 Robot polishing system composition

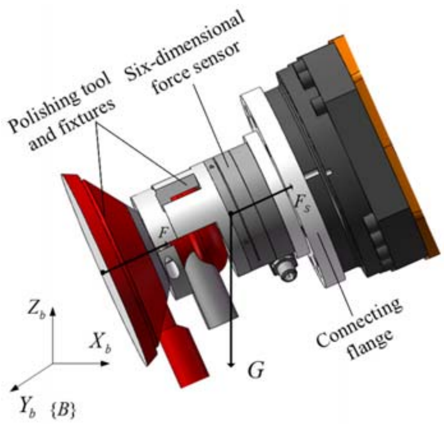

Fig. 2 Diagram of polishing force analysis

The establishment of active compliance control strategy requires real-time force feedback information and the establishment of a suitable interaction model between robot end effector and external environment. The real-time force feedback information can be obtained through the six- dimensional force sensor.

Based on the research of robot kinematics and dynamics, Huang et al. [12] summarized the force and position relationship between the robot and the environment as a "mass-damping-spring" second-order system [12]:

$$F_a = ka(t) + c\dot{a}(t) + M\ddot{a}(t) \tag{1}$$

where F_a donates the actual contact force during polishing, $a(t)$ donates the robot position function, k, c and M denote elastic coefficient, damping coefficient and rigid body mass, respectively.

Due to the strong coupling of force control and position control during robot polishing process, force/position hybrid control is difficult to realize the task distribution of force control and position control during robot processing accurately [13], so impedance control has been widely used in active compliance control due to its good environmental adaptability. Impedance control is an indirect force control method. It dynamically adjusts the relationship between the robot's motion and contact force through mechanical impedance. Impedance control model can be expressed as:

$$M_d(\ddot{x} - \ddot{x}_r) + B_d(\dot{x} - \dot{x}_r) + K_d(x - x_r) = -F \tag{2}$$

where M_d, B_d and K_d respectively donate inertia matrix, damping matrix and stiffness matrix in impedance parameters. F donates the actual polishing contact force, x donates the actual position of the end of the robot, x_r donates the desired position of the robot end.

Taking into account the actual polishing process, in order to ensure the stable tracking and control of the contact force during the polishing process, the deviation of the contact force is introduced into (2):

$$M_d(\ddot{x} - \ddot{x}_r) + B_d(\dot{x} - \dot{x}_r) + K_d(x - x_r) = F_e \tag{3}$$

$$F_e = F_r - F \tag{4}$$

where F_r donates expected contact force of robot polishing.

B. Force-Based Impedance Control Model

In the force-based impedance control, the external loop of the robot system outputs the position error of the system as a force deviation, and the internal loop uses the PID controller to drive the robot. This control method can be expressed as (5):

$$-F_r = M_d(\ddot{x} - \ddot{x}_r) + B_d(\dot{x} - \dot{x}_r) + K_d(x - x_r) \tag{5}$$

In the external loop of the robot system, the current pose of the robot end can be known through positive kinematics, the current speed of the end can be solved by differential motion, and the acceleration information of the robot end $\ddot{X}$ can be obtained by deriving the speed:

$$\ddot{X} = \dot{J}(q)\dot{q} + J(q)\ddot{q} \tag{6}$$

Since the required controlled polishing force is expressed in Cartesian space, however, the robot drive control is performed in the joint space, so it is necessary to use the force Jacobian to convert to obtain the robot drive torque τ. The force-based impedance control model can be described as Fig. 3. Therefore, the driving motor of the robot is required to be in the torque driving mode, and the required joint torque is calculated by the dynamic model, which requires a large amount of calculation, and it is difficult to adapt to the current position drive mode of most robots.

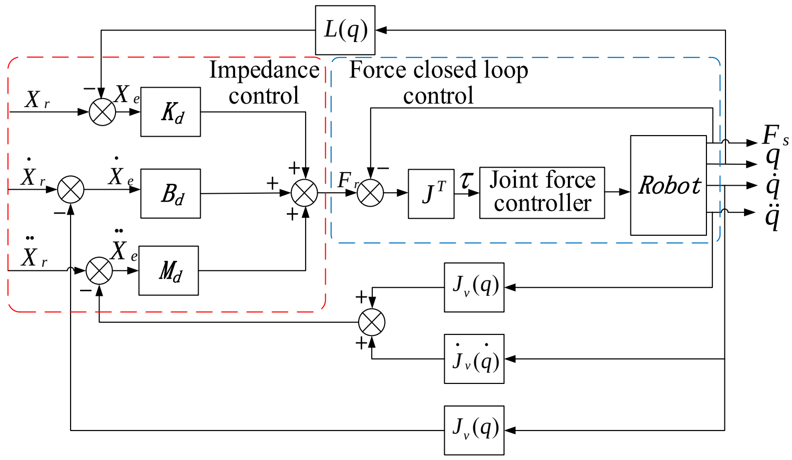

Fig. 3 Force-based impedance control model

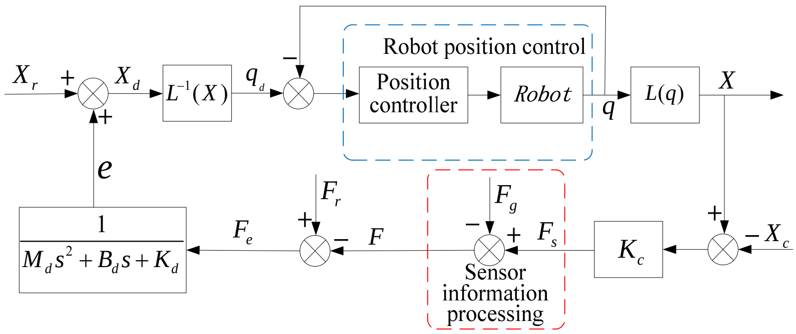

Fig. 4 Position-based impedance control model

C. Position-Based Impedance Control Model

In the position-based impedance control model, the position control is located in the inner loop of the robot control, and the impedance control is located in the outer loop, which is also in line with the current control schemes of most industrial robots with position control as the control core. Position-based impedance control can be expressed as:

$$M_d(\ddot{x}-\ddot{x}_r)+B_d(\dot{x}-\dot{x}_r)+K_d(x-x_r)=-F_e \tag{7}$$

In order to achieve track and control the polishing force accurately, gravity compensation and zero drift compensation are required for the six-dimensional force sensor. The established control model is as Fig. 4. This model can finally achieve closed-loop polishing force control.

The control process is to first obtain the information of the six-dimensional force sensor, and use coordinate transformation to obtain the actual contact force between the robot end effector and the workpiece after gravity compensation and zero drift compensation.

D. Steady-State Error Analysis of Position-Based Impedance Control Model

Based on the impedance control model proposed in this paper, it is necessary to analyze the steady-state error and its influencing factors. To simplify the calculation, simply considering the normal direction of the workpiece, the difference between the expected contact force at the end of the robot and the actual contact force can be defined as:

$$\begin{aligned} f_e &= f_r - f \\ &= f_r - k_c(x-x_c) \\ &= f_r + k_c x_c - k_c[x_r + z(s) f_e] \end{aligned} \tag{8}$$

where *z(s)* represents the transfer function of the impedance control model in the frequency domain, x_c and k_c indicate the environmental location and environmental stiffness respectively. The remaining lowercase characters represent the expression of their corresponding uppercase characters in one-dimensional space. The contact force error in steady state can be obtained after simplification as (9):

$$f_{ess} = \frac{k_d}{k_d + k_c}[f_r + k_c(x_c - x_r)] \tag{9}$$

In the actual contact polishing process, since the real environmental position and stiffness value are difficult to obtain, the environmental position and environmental stiffness can be expressed as two parts of estimated value and error value:

$$\begin{cases} x_c = \hat{x}_c + \Delta x_c \\ k_c = \hat{k}_c + \Delta k_c \end{cases} \tag{10}$$

where $\hat{x}_c$ and $\hat{k}_c$ donate the estimates of the location of the environment and the estimation of the stiffness of the environment respectively, Δx_c and Δk_c represent the environmental position error value and the environmental stiffness error value respectively. Finally, the steady-state error of the contact force of the position-based impedance control can be obtained as (11):

$$f_{ess} = \frac{k_d k_c}{k_d + k_c} \Delta x_c - \frac{k_d f_r}{k_d + k_c} \frac{\Delta k_c}{\hat{k}_c} \tag{11}$$

In the actual polishing process, the stiffness value of the external environment is usually very large, so the steady-state error in (11) can be approximated as:

$$f_{ess} \approx \frac{k_d k_c}{k_d + k_c} \Delta x_c \tag{12}$$

It can be seen from (12) that the position-based impedance control model is difficult to eliminate the steady-state error of the force control, and when the environmental stiffness and the stiffness matrix in the model are large, even if there is a small environmental position error, a large steady state error of the force control will be generated.

E. The Impact of Impedance Parameters on the System

Aiming at the position-based impedance control model established in this paper, we conduct model building and simulation experiment in MATLAB/Simulink, and discuss the influence of inertial parameters m_d , damping parameters b_d and stiffness parameters k_d on the end contact force of the robot in a one-dimensional environment separately.

We establish the position-based impedance control model in MATLAB/Simulink. First, we set one-dimensional inertial parameters m_d=0.2,1,4,10 , and other simulation parameters are fixed. The force control simulation results are shown in Fig. 5. It can be seen that the inertia parameter m_d does not affect the steady-state value of the system, but it will affect the system response speed and overshoot. The inertia parameter m_d is related to the acceleration characteristics, which is the acceleration at the end of the robot. Therefore, the value of the target inertia parameter should be close to the quality of the actual robot tool system. Then we set the damping parameters b_d=10,20,50,100 , other parameters are fixed values, and the simulation results are shown in Fig. 6. It can be seen that the damping parameter b_d also does not affect the steady state value of the system, but it will affect the adjustment speed and overshoot. With the increase of b_d , the response speed firstly increases and then merges. Damping parameters need to be set according to the specific polishing process. Then we set the stiffness parameters k_d =400,600,800,1000 , other parameters are fixed, the simulation results obtained are shown in Fig. 7. It can be seen that the stiffness parameter k_d affects the steady-state value of the system, but has little effect on the response speed of the system. The bigger rigidity parameter of the contact between the end of the robot and the environment, the smaller the adjustment range of the position correction during the process of controlling the contact force, and the higher accuracy of the robot position control is required. Therefore, the inertia parameters, damping parameters, and stiffness parameters have different effects on the control effect of the robot's polishing force. The three together constitute the impedance parameter. When selecting the target impedance parameter, it needs to be set according to the actual situation.

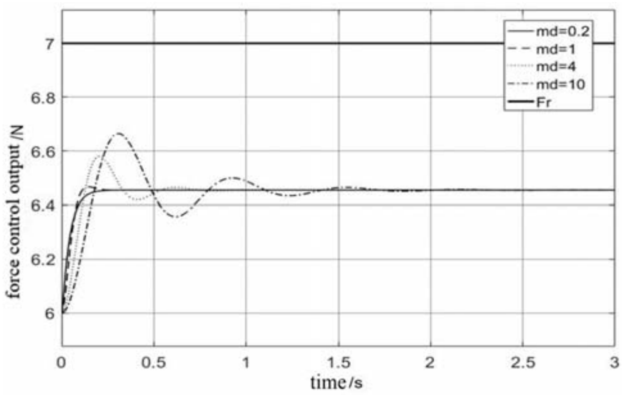

Fig. 5 The influence of inertial parameter on model's output

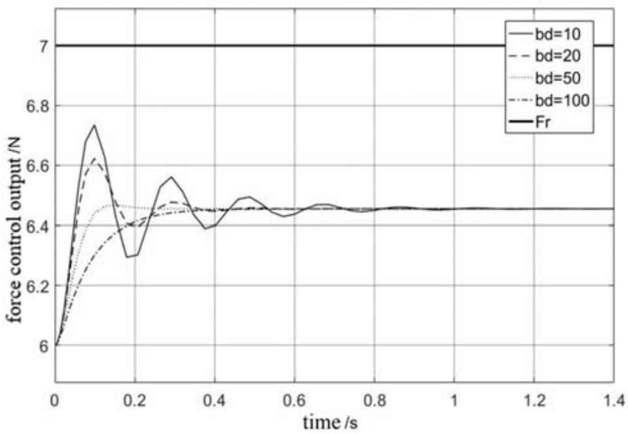

Fig. 6 The influence of damping parameter on model's output

III. Adaptive Controller Design

Due to the positioning error, machining error and assembly error of the workpiece, the external environment has high ambiguity. Therefore, the position-based impedance control model established above is difficult to obtain the real position information of the external environment, and the stiffness information is also difficult to obtain, which directly leads to the steady-state error of control of the polishing contact force. In order to achieve accurate tracking of the polishing contact force and eliminate steady-state error of polishing force, an online evaluation system for external environment stiffness information and position information needs to be established.

During the robot polishing process, the external environment stiffness information and position information are evaluated in real time to eliminate the steady-state error of polishing force.

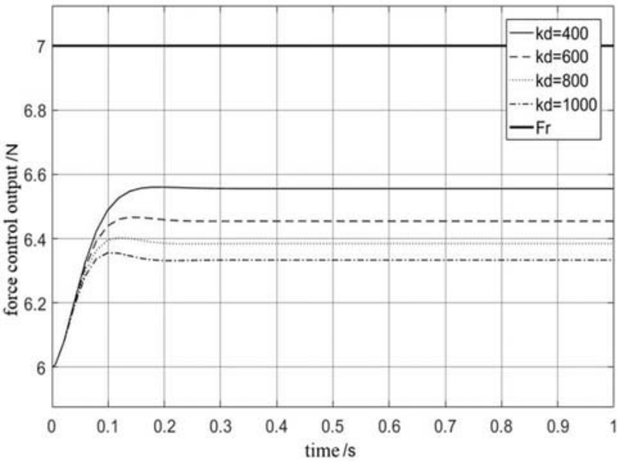

Fig. 7 The influence of stiffness parameter on model's output

The core idea of the adaptive force controller is to use an adaptive adjustment method to replace the expected environmental position and stiffness online, and then obtain an accurate end reference trajectory. When $f_{ess} = 0$, from (9) we can get (13):

$$x_r = x_c + \frac{f_r}{k_c} \tag{13}$$

We define the estimated reference trajectory (14):

$$\hat{x}_r = \hat{x}_c + \frac{f_r}{\hat{k}_c} \tag{14}$$

We assume parameter $K_c = k_c x_c$, obviously there is the following relationship (15):

$$f = k_c(x - x_c) = k_c x - K_c \tag{15}$$

The corresponding estimation relationship is (16):

$$\hat{f} = \hat{k}_c(x - \hat{x}_c) = \hat{k}_c x - \hat{K}_c \tag{16}$$

where $\hat{K}_c$ donates the estimated value of K_c , $\hat{f}$ donates estimated value of actual contact force f . Then we set $\varphi_c = \hat{k}_c - k_c$, $\varphi_x = \hat{K}_c - K_c$, $\varphi = [\varphi_c,\ \varphi_x]^T$. We subtract (15) and (16) and can get (17):

$$\hat{f} - f = [x \ \ \text{-}1]\varphi \tag{17}$$

Now we suppose when $t \to \infty$ we can get $\hat{f} - f = 0$, then there is (18):

$$f = \hat{k}_c(x - \hat{x}_c) = \hat{k}_c(x - \hat{x}_r) + f_r \tag{18}$$

We substitute (18) into the formula of the impedance control model, eliminate $(x - \hat{x}_r)$, we can get (19) after simplification:

$$m_d \ddot{f}_e + b_d \dot{f}_e + (k_d + \hat{k}_c) f_e = 0 \tag{19}$$

where $f_e = f - f_r$. To make (19) hold, there must be $f_e = 0$. So based on these assumptions, we can get $f = f_r$ to eliminate the steady-state error of the contact force and realize accurate force tracking. Therefore, we only need to select the appropriate φ to make the above assumptions true, then the actual contact force tracking reference contact force can be completed. In order to achieve the above process, we use Lyapunov stability to analyze. We define the system state $\dot{\varphi}$ equation of the state vector φ :

$$\dot{\varphi} = -\Gamma \begin{bmatrix} x \\ -1 \end{bmatrix} (\hat{f} - f) \tag{20}$$

where Γ donates diagonal positive constant value matrix, $\Gamma \in R^{2\times 2}$. We combine with (17) and $f(\varphi,\ t) = 0$, and get the only one equilibrium state of the system $\varphi = [0,\ 0]^T$. We select positive definite function as Lyapunov function:

$$V(\varphi,\ t) = \varphi^T \Gamma^{-1} \varphi \tag{21}$$

We calculate the first derivative with respect to time:

$$\dot{V}(\varphi,\ t) = 2\varphi^T \Gamma^{-1} \varphi = -2\varphi^T \begin{bmatrix} x \\ -1 \end{bmatrix} (\hat{f} - f) = -2(\hat{f} - f)^2 \tag{22}$$

It can be seen that the $\dot{V}(\varphi,\ t)$ is always negative, satisfies Lyapunov's stability theorem, and the system is uniform asymptotic stability when the system is on origin. When $t \to \infty$, the system converges near the equilibrium state, then we can get $f \to f_r$. The actual contact force tracks the reference contact force to complete the derivation process. Then we convert (21) to (22):

$$\begin{cases} \dot{\hat{k}}_c = -r_1 x(\hat{f} - f) \\ \dot{\hat{x}}_c = \dfrac{(\hat{f} - f)}{\hat{k}_e}(r_1 x \hat{x}_e + r_2) \end{cases} \tag{22}$$

where r_1 and r_2 donate positive real constant of positive definite matrix. The complete adaptive impedance control model is (23):

$$\begin{cases} \hat{k}_c(t) = \hat{k}_c(0) - r_1 \int_0^t x(\hat{f} - f)dt \\ \hat{x}_c(t) = \hat{x}_c(0) + r_1 \int_0^t \dfrac{\hat{f} - f}{\hat{k}_c}(x\hat{x}_c + \dfrac{r_2}{r_1})dt \\ \hat{f} = \hat{k}_c(x - \hat{x}_c) \\ x_r \equiv \hat{x}_r = \hat{x}_c + \dfrac{f_r}{\hat{k}_c} \end{cases} \tag{23}$$

Corrected reference trajectory can be obtained by adding online parameter estimation to the position-based impedance control model. Then the steady-state force error can be eliminated and achieve accurate contact force track. In the actual application process, the current position of the robot end x, the actual contact force f and expected contact force f_r are required to be input into the system to obtain an accurate expected trajectory of the robot end. Then, we use the position-based impedance control model to achieve accurate force tracking. The established adaptive impedance polishing force control model is shown in Fig. 8.

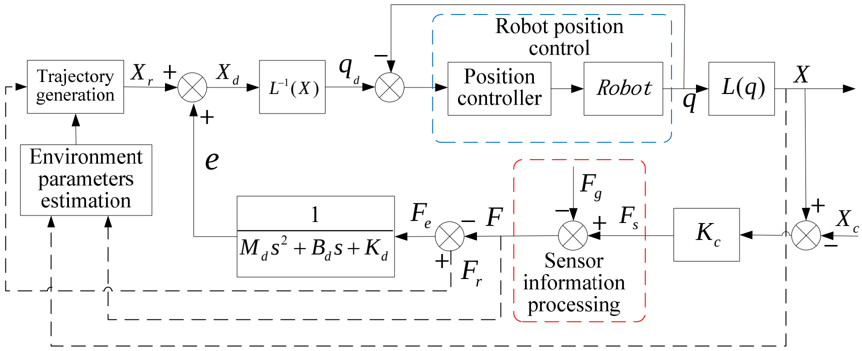

Fig. 8 Adaptive impedance control model

IV. Adaptive Impedance Control Simulation

Aiming at the adaptive impedance control model established in this paper, the model is built and simulated in MATLAB/Simulink, and the single degree of freedom of a single particle is taken as the research object. When the environmental stiffness and environmental position change, we discuss the adaptive adjustment ability of the system and the adaptive adjustment ability of the end contact force.

The initial input parameters of the system are as in Table I. In the case of the initial simulation parameters, the environmental stiffness k_c is suddenly decreased by 30000 N/m during the simulation at 1 s. At this time, the contact force response of the system is shown in Fig. 9.

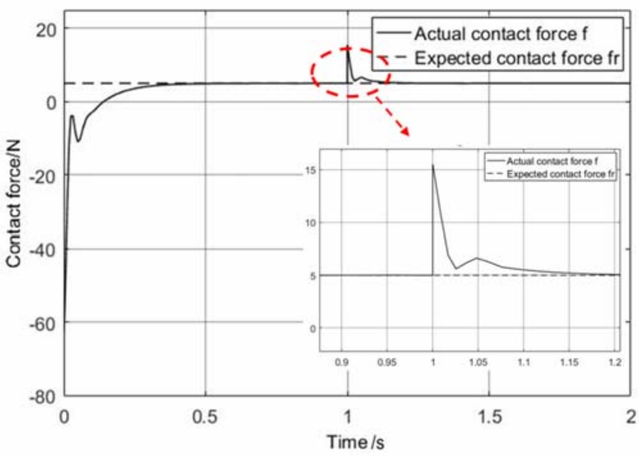

Fig. 9 Contact force response under changing environmental stiffness

At the moment when the robot touched the work piece, the collision produced a maximum contact force of 60 N, within the range of the safety force, then the contact force rapidly decayed to the desired contact force in a very short period of nearly 0.5 s. Then because of the change of environmental stiffness k_c, the contact force suddenly raised from 5 N to 15 N at 1 s, then rapidly reduced to nearly 5 N under the action of the controller and reached the desired steady state value after approximately 0.1 s. The simulation results show that the established adaptive impedance control model can have great adaptive adjustment ability to the change of environmental stiffness.

In the case of initial simulation parameters, the environment position x_c is suddenly increased by 1 mm during the simulation at 1 s. At this time, the contact force response of the system is shown in Fig. 10. It can be seen from Fig. 10 that if the environmental position changes suddenly during the simulation for 1 s, the end contact force will also undergo a certain change, but under the system adaptive adjustment, the end force will be adjusted in a relatively fast time (close to 0.5 s) and return to the desired contact force. This simulation result shows that the adaptive impedance control model can have a great adaptive adjustment ability to the change of environmental position.

V. Conclusion

Based on the establishment and analysis of force-based impedance control model and position-based impedance control model, this paper summarizes the defects of these two-control method in the robot polishing force control, and designs a type of adaptive impedance controller. The established adaptive impedance control model can obtain the corrected reference trajectory by online estimation of the stiffness parameters and position parameters of the external environment, and then use this reference trajectory for impedance control to eliminate the steady-state force error and achieve accurate contact force track. We establish the adaptive impedance model in MATLAB/Simulink, and the simulation results show that the model has good adaptability to changing environmental stiffness and environmental position, and can accurately track the desired polishing force.

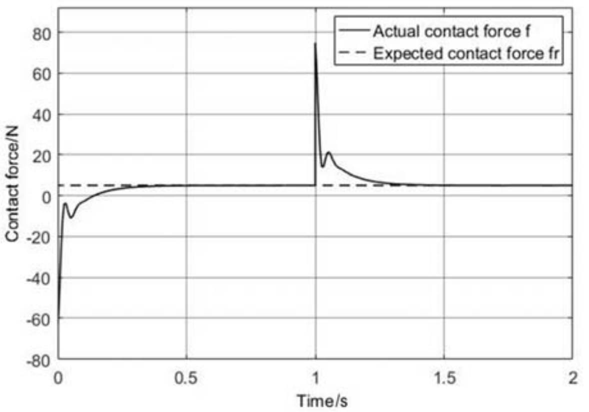

Fig. 10 Contact force response under changing environmental position

TABLE I
SIMULATION PARAMETERS

System parameters	Parameter value	System parameters	Parameter value
f_r	5N	k_d	50000N/m
k_c	70000N/m	$\hat{k}_c(0)$	50000N/m
x_c	0.01m	$\hat{x}_c(0)$	0.009m
m_d	8kg	r_1	5
b_d	80N/(m/s)	r_2	10

ACKNOWLEDGMENTS

This work was financially supported by the key research and development program of Shaanxi province (Grant No. 2020ZDLGY06-10, No. 2021GY-302), national defense basic scientific research program of China (Grant No. JCKY2018607C004).

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