Vietnam Journal of Mechanics, Vol. 45, No. 2 (2023), pp. 105 – 116
DOI: https://doi.org/10.15625/0866-7136/16979

AN ERROR COMPENSATION CONTROLLER FOR MILLING ROBOTS

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Received: 30 March 2023 / Published online: 29 June 2023

Abstract. This paper presents a method of controlling a serial robot for milling by an inverse kinematic controller combined with an outer PD loop (Inverse Dynamics + PD controller), with calibration and compensation of errors in calculating the cutting forces. Because the cutting forces are generated at the time of cutting, at the contact area between the workpiece and the cutting tool, the generalized forces of the cutting forces in the differential equations of motion of robot is always variable and difficult to determine precisely. The cutting forces depend on the cutting mode, the geometric parameters of the cutting layer, the cutting conditions, etc. This study shows an inverse dynamic controller with the outer PD loop and an additional calibration block to compensate the differences between the actual cutting forces and calculated cutting forces (which are calculated by the empirical formula). The cutting forces at each machining time of the calibration block is determined based on the differential equation of motion. The efficiency (convergence time and accuracy) of the proposed controller is evaluated by comparison between the numerical simulation results of the controller with cutting force calibration and the conventional PD controller. In the conventional PD controller, the dynamic model of the robot is assumed to define precisely. The results contribute to design and manufacture the controllers for robotic milling, and to improve the quality of the machined surface.

Keywords: milling robot, robotic machining, robot dynamics, cutting force calibration, robot control.

1. INTRODUCTION

Serial robots which have more than 6 degrees of freedom offer many advantages in flexibility over machine tools. However, machining motion of robots (including its joints and links) is more complex than that of the machine tools. At the same time, at the contact point between the tool and the workpiece, the position, direction, and magnitude of the cutting force is always changes with time. Due to the complexity of the motion and variation of the cutting force, it is difficult to accurately calculate the dynamic model to control the robot in milling process. To meet high precision of the machining surface, the relative motion of the tool and the machining surface (including the position, direction and relative velocity) is demanded accurately. Inverse Dynamics + PD (IDPD) controller or PID (IDPID) controller is commonly used for robots [1–3] because it gives accurate control results when the dynamic parameters of the robot are determined precisely. In order to improve and enhance the machining accuracy for robots, there have been many studies to reduce the influence of cutting force error on the quality of robot controllers [4, 5]. However, this is still an open problem. The application of intelligent control methods gives positive results [6]. In cases where high reliability is required, it is usually based on clear calculations. Therefore, this paper proposes a solution to correct the error of cutting force when milling by robot.

In fact, there are many errors that appear in the dynamic model of robot. The conventional IDPD controller is added with a correction element that can correct the errors. The effect of cutting force is significant during robotic milling process. Therefore, the calculation error of the cutting force affects the control accuracy and ultimately affects the machining accuracy.

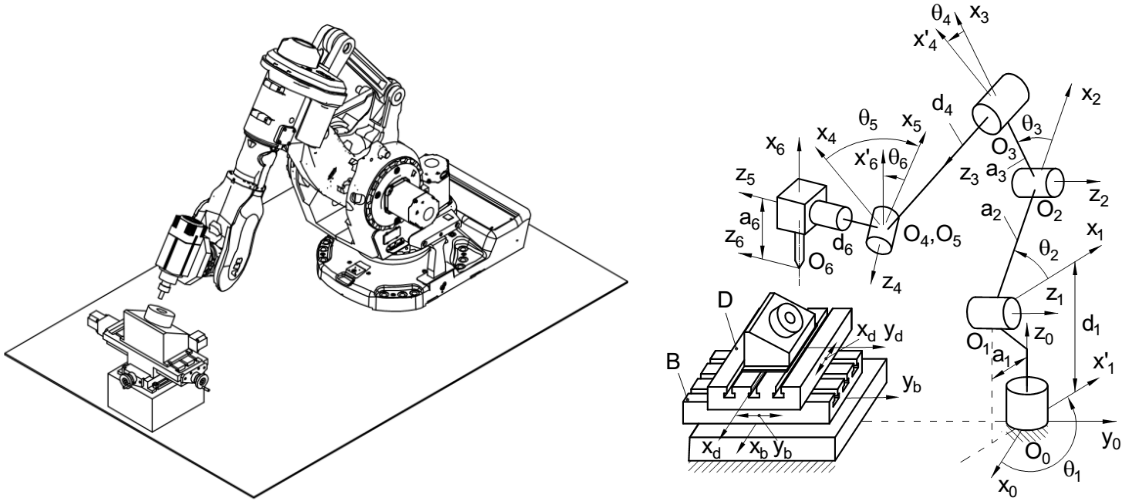
This article presents the IDPD controller with integrated cutting force calibration block. The controller has two closed feedback loops (internal closed feedback loop for inverse dynamics, external closed feedback loop of PD (proportional-derivative), and cutting force calibration block. Assuming the dynamic model is accurately determined, at the time of machining, the controller will determine the deviation signals of the position, velocity, acceleration and control force between the input and output, so that in the next control loop, the controller performs a calibration step that calculates compensation of the cutting force before calculating the inverse dynamics to determine the control force.

This study compares and evaluates the numerical simulation results between the IDPD controller and the IDPD controller with the cutting force calibration block (IDPD-HC) to control the machining robot to shape the part surface in the same machining mode and cutting conditions but the changes of generated cutting force has different values.

The article includes the following sections: Section 1 introduces, Section 2 presents the IDPD controllers. Section 3 presents the IDPD-HC controller. Section 4 presents the numerical simulation results. Section 5 shows the conclusion and development.

2. IDPD CONTROLLER FOR MILLING ROBOT

Fig. 1 shows a robot model with a clamping platform deploying in milling [7]. The task of motion control of the machining robot is to ensure accurate shaping motion between the tool surface and the workpiece surface, so that the tool moves on the forming curve with position, direction, velocity and acceleration according to technical requirements. Motion of the cutter is synthesized from motion of the robot joints. On that basis, there are joint space controllers and task space controllers.



(a) Structure diagram of machining robot (b) Kinematic diagram of machining robot

Fig. 1. Mechanical model of the machining robot system

The controller presented in the paper is a controller in the joint space.

Based on the dynamics model of robot (1) [8]

$$M(q)\ddot{q} + \psi(q, \dot{q}) + G(q) + Q = U. \tag{1}$$

Choose the split control rule (2).

$$U = M(q)u_q + \psi(q, \dot{q}) + G(q) + Q, \tag{2}$$

where: u_q is 6×1 control signal vector selected based on the control law PD

$$u_q = \ddot{q}^d + K_D\dot{e}_q + K_P e_q, \tag{3}$$

$e_q, \dot{e}_q, \ddot{e}_q$ are 6×1 vectors of coordinate error, velocity, and acceleration of the joints

$$\begin{aligned} e_q &= q^d - q = \left[e_{q1}, e_{q2}, \ldots, e_{q6}\right]^T, \\ \dot{e}_q &= \dot{q}^d - \dot{q} = \left[\dot{e}_{q1}, \dot{e}_{q2}, \ldots, \dot{e}_{q6}\right]^T, \\ \ddot{e} &= \left[\ddot{e}_{q1}, \ddot{e}_{q2}, \ldots, \ddot{e}_{q6}\right]^T, \end{aligned} \tag{4}$$

$q^d, \dot{q}^d, \ddot{q}^d$ are 6×1 vectors of desired joint position, velocity, and acceleration (set value) solved from the inverse kinematics problem. $q, \dot{q}, \ddot{q}$ are 6×1 vectors of the actual position, velocity, and acceleration of the robot's joints. $e_{qi}, \dot{e}_{qi}, \ddot{e}_{qi}$ are errors of position, velocity and acceleration of the joint i robot, $i = 1, \ldots, 6$. K_P, K_D are diagonal matrices, which have elements that are positive constants, and represent the proportional and derivative gain coefficients, respectively.

$$K_P = diag\left\{k_{P1}, k_{P2}, \ldots, k_{P6}\right\},\ K_D = diag\left\{k_{D1}, k_{D2}, \ldots, k_{D6}\right\},\ k_{Pi} > 0,\ k_{Di} > 0. \quad (5)$$

Substituting (2) and (3) in (1) obtained the following

$$\ddot{q} + \psi(q, \dot{q}) + G(q) + Q = M(q)\left[\ddot{q}^d + K_D\dot{e}_q + K_P e_q\right] + \psi(q, \dot{q})\dot{q} + G(q) + Q, \quad (6)$$

$$M(q)\left[\ddot{e}_q + K_D\dot{e}_q + K_P e_q\right] = 0. \quad (7)$$

From (7) get the position error differential equation of the closed loop controller (8)

$$\ddot{e}_q + K_D\dot{e}_q + K_P e_q = 0. \quad (8)$$

Since K_D, K_P are diagonal matrices, from (8) we get the position-independent differential equations of errors for the joints (9).

$$\ddot{e}_{qi} + k_{Di}\dot{e}_{qi} + k_{Pi}e_{qi} = 0, \quad i = 1, \ldots, 6. \quad (9)$$

Fig. 2 shows the general structure model of the IDPD controller for machining robots.

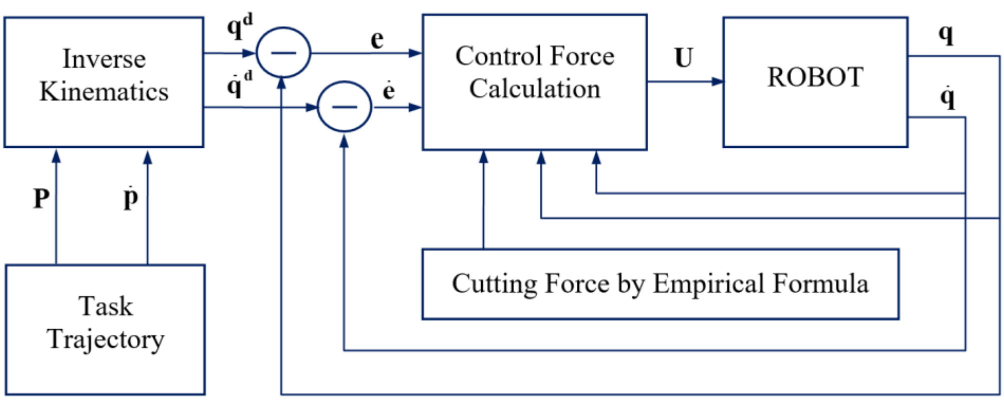


Fig. 2. Structure model of IPPD controller for machining robot

3. IDPD-HC CONTROLLER FOR MILLING ROBOT

With the assumption that the dynamic model of the robot, including the cutting force, is determined accurately, the above IDPD controller will give accurate control results. In order to determine the efficiency of the cutting force calibration block, this paper chooses a simple IDPD model with the assumption that the dynamic model is determined accurately, easy to give accurate control results for comparison. Then, the controller with integrated cutting force calibration block (hereinafter referred to as calibration controller) IDPD-HC is assumed to have errors in the input cutting force calculation. The calibration block will calculate and determine the cutting force before each control loop step based on the signal received from the previous control loop step.

It is assumed that the kinematics and dynamics of the robot system are correct because these parameters can be determined by measuring and calibration when manufacturing and assembling. The cutting force is assumed to have an error because the cutting force constantly changes with the machining process.

Below is the execution sequence of the controller with the cutting force error calibration block when machining:

In the first processing steps, the cutting force is determined according to the formula (9)–(12) [8]. At each subsequent machining steps, the controller measures information about joint position (q), joint velocity ($\dot{q}$), joint acceleration ($\ddot{q}$) and torque through the sensors located at the joints of robots. Thanks to the parameters representing the dynamic state of the robot determined during the control process, combined with the use of the dynamics equation (1) will determine the generalized force Q of the cutting force and thus determine the cutting force R_c (which needs to be calibrated). At each control loop step, a calibration step is performed to calculate the cutting force before calculating inverse dynamics to determine the driving force.

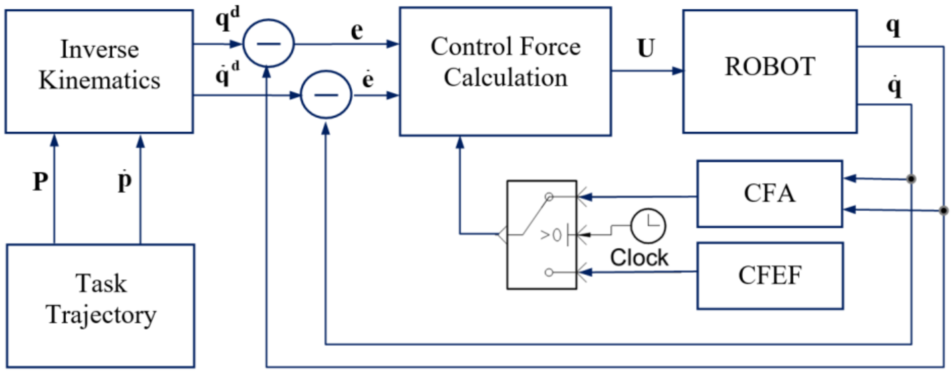
$$Q = U - (M(q)\ddot{q} + \psi(q,\dot{q}) + G(q)). \tag{10}$$

From (7) [8] it is possible to determine the cutting force R_c that needs to be calibrated before each loop of control the machining robot

$$R_c = \left[J_E^T\right]^{-1} \{U - [M(q)\ddot{q} + \psi(q,\dot{q}) + G(q)]\}. \tag{11}$$

The recalculated cutting force according to (11) is included in determining the control force based on the differential equation of motion (1).

Fig. 3 shows the IDPD-HC controller structure model. Unlike the IDPD controller, this controller is integrated with a "Cutting Force Adjustment-CFA" block to recalculate the actual cutting force in the previous control loop instead of the estimated shear force according to the empirical formula.



CFA- Cutting Force Adjustment, CFEF- Cutting Force by Empirical Formula

Fig. 3. Structure model of IDPD-HC controller for robotic milling

The control simulation results of the IDPD-HC controller for the machining robot are shown in Section 4.

4. RESULTS OF NUMERICAL SIMULATION OF CONTROLLERS

Performing numerical simulation to control the motion of a robot carrying a milling cutter (Fig. 4), performing forward milling of the workpiece surface (Fig. 5) made of Ti_6Al_4V titanium alloy material. When machining to ensure the forming motion between the tool surface and the work piece, the cutting point at the tool tip moves on the forming curve C_i (C_i lies on the face of the mold) following the trajectory from outside to inside.

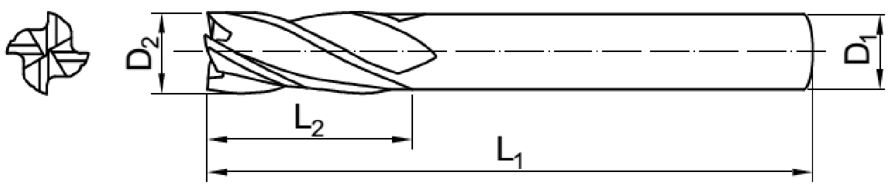


Fig. 4. End mills for mold surface forming

Table 1 describes the kinematic and dynamic parameters of the robot, end mills, clamping platform and workpiece, when the robot performs surface shaping.

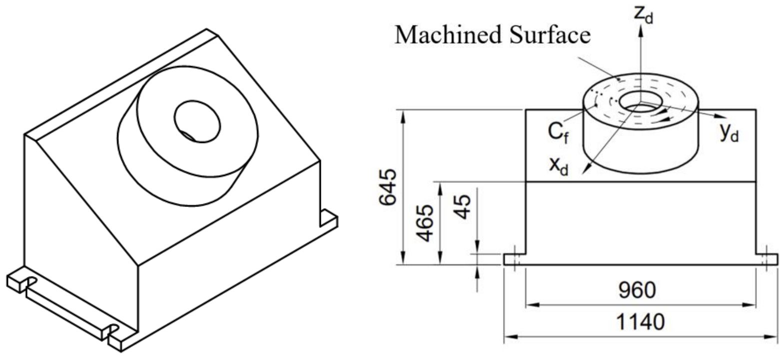


Fig. 5. The workpiece with machined surface and C_i forming curve on the surface

Table 1. Kinematic and dynamic parameters of the robot, end mill, clamping platform and workpiece

Denavit-Hartenberg parameters of the robot				
Link-Joint	θ_i	d_i (mm)	a_i (mm)	α_i
1	θ_1	$d_1 = 514.5$	$a_1 = 300$	$\alpha_1 = \pi/2$
2	θ_2	$d_2 = 0$	$a_2 = 700$	$\alpha_2 = 0$
3	θ_3	$d_3 = 0$	$a_3 = 280$	$\alpha_3 = -\pi/2$
4	θ_4	$d_4 = 1060.24$	$a_4 = 0$	$\alpha_4 = \pi/2$
5	θ_5	$d_5 = 0$	$a_5 = 0$	$\alpha_5 = -\pi/2$
6	θ_6	$d_6 = 377$	$a_6 = -256$	$\alpha_6 = 0$

Kinematic parameters of the position and orientation of the tool in the frame with respect to the frame $O_6x_6y_6z_6$						
E	${}^6x_E = 0$	${}^6y_E = 0$	${}^6z_E = 0$	${}^6\alpha_E = -\pi/2$	${}^6\beta_E = \pi/2$	${}^6\eta_E = 0$

Specifications and technical parameter of flat end mills										
Tool material	D_1 (mm)	D_2 (mm)	L_1 (mm)	L_2 (mm)	z (tooth)	v_c (m/ph)	v_r (mm/s)	S_z (mm/tooth)	B (mm)	h (mm)	Cold solution
Carbide	10	10	70	22	4	61.14	6.7	0.1	2.2	3	Emunxi

Where: z is number of cutting teeth of end mill, v_c is cutting speed; v_r is relative velocity between the milling tool and the workpiece surface; S_z is tool feed per tooth, B is milling width; h is milling depth

Kinematic parameters of the workpiece and clamping platform							
Machining material	(HB) Stiffness (HB)	l (mm)	w (mm)	c (mm)	${}^0x_d$ (mm)	${}^0y_b$ (mm)	${}^0z_d$ (mm)
Ti_6Al_4V	200	1140	600	715	0	−1361	296.6

Where l, w, c are the length, width, and height of the workpiece

Dynamic parameters of the robot										
TT	Position of the center of gravity relative to the frame i (mm)			Mass (kg)	Inertial moment of the links with respect to the frame attaching at the center of mass (kg.mm^2)					
	x_{Ci}	y_{Ci}	z_{Ci}		I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{zx}
1	101.27	−161.53	17.51	979.776	107464105.457	106997584.679	76391174.876	−15737765.261	1079510.623	2528210.401
2	−389.98	57.61	15.15	255.520	3908083.112	12110291.517	11739707.489	−454581.588	110524.194	877218.740
3	−70.78	−52.67	−194.76	356.302	15150531.425	15511051.346	10981064.424	−843859.157	109739.085	349159.306
4	0	−344.49	−14.39	268.237	25403793.206	3355342.987	23996196.983	−13888.740	1000831.563	9449.097
5	0	40,29	1.05	55.235	465398.004	441427.864	231978.283	70.639	9848.368	19.282
6	290.94	40.29	−64.09	36.306	305737.658	512275.019	383507.486	−92.536	−36.246	−41461.026

The coefficient of cutting force in formula (11) [8] depends on the cutting mode, the geometrical parameters of the cutting layer, the cutting conditions, etc. It is assumed that two ways of calculation from the experiment are used to select the cutting force coefficient, as shown in Table 2. According to [8], the cutting force F_x, F_y, F_z, M_x, M_y, M_z can be calculated (usually M_x, M_y are very small, so they should be ignored).

Table 2. Cutting force coefficient in milling determined experimentally

Case	K_{tc} (N/mm^2)	K_{rc} (N/mm^2)	K_{ac} (N/mm^2)	K_{te} (N/mm)	K_{re} (N/mm)	K_{ae} (N/mm)
1	1844.4	513.2	1118.9	24	43	−3
2	1455	310	112	26	43	−2.8
...						

Thus, with different experimental calculation methods, it will give different results for calculating the cutting force, leading to the existence of an error in the cutting force. Fig. 6 shows the results of the cutting force calculation for the two cases of choosing the cutting coefficient.

The parameters of the diagonal matrices of the proportional and derivative gain, K_P, and K_D, respectively, of the IDPD and IDPD-HC controllers are chosen to be the same

$$K_P = diag\left\{22500, 22500, 22500, 22500, 16900, 16900\right\}$$

$$K_D = diag\left\{300, 300, 300, 300, 260, 260\right\}$$

The following shows the numerical simulation results of the controllers in the following cases:

- IDPD controller with the assumption of existing of cutting force error, the numerical simulation results shown in Fig. 7(a).

- IDPD-HC controller with the assumption of existing of cutting force error, numerical simulation results are shown in Fig. 7(b).

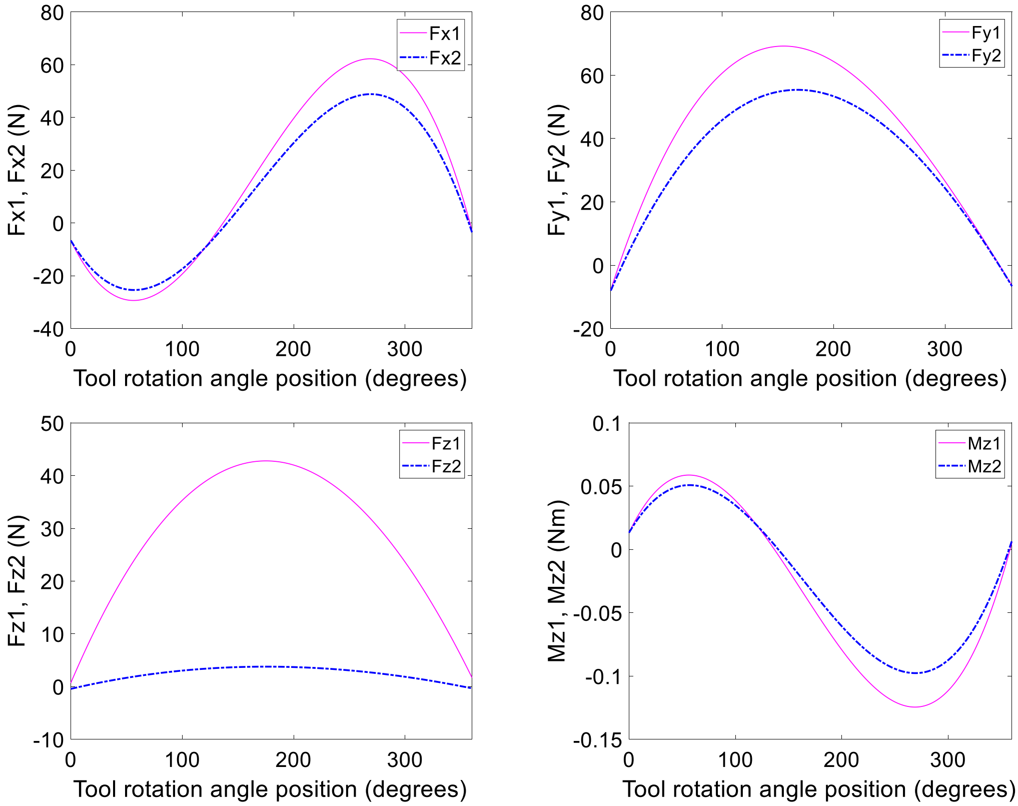
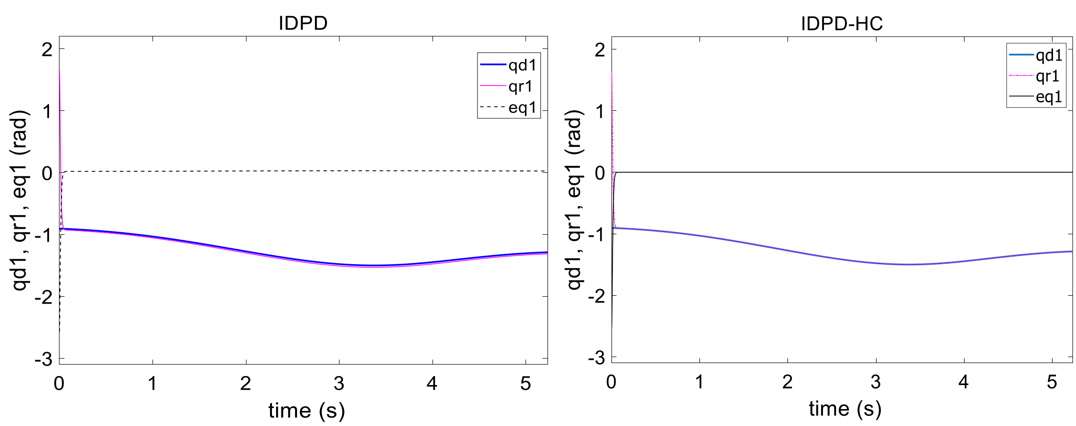
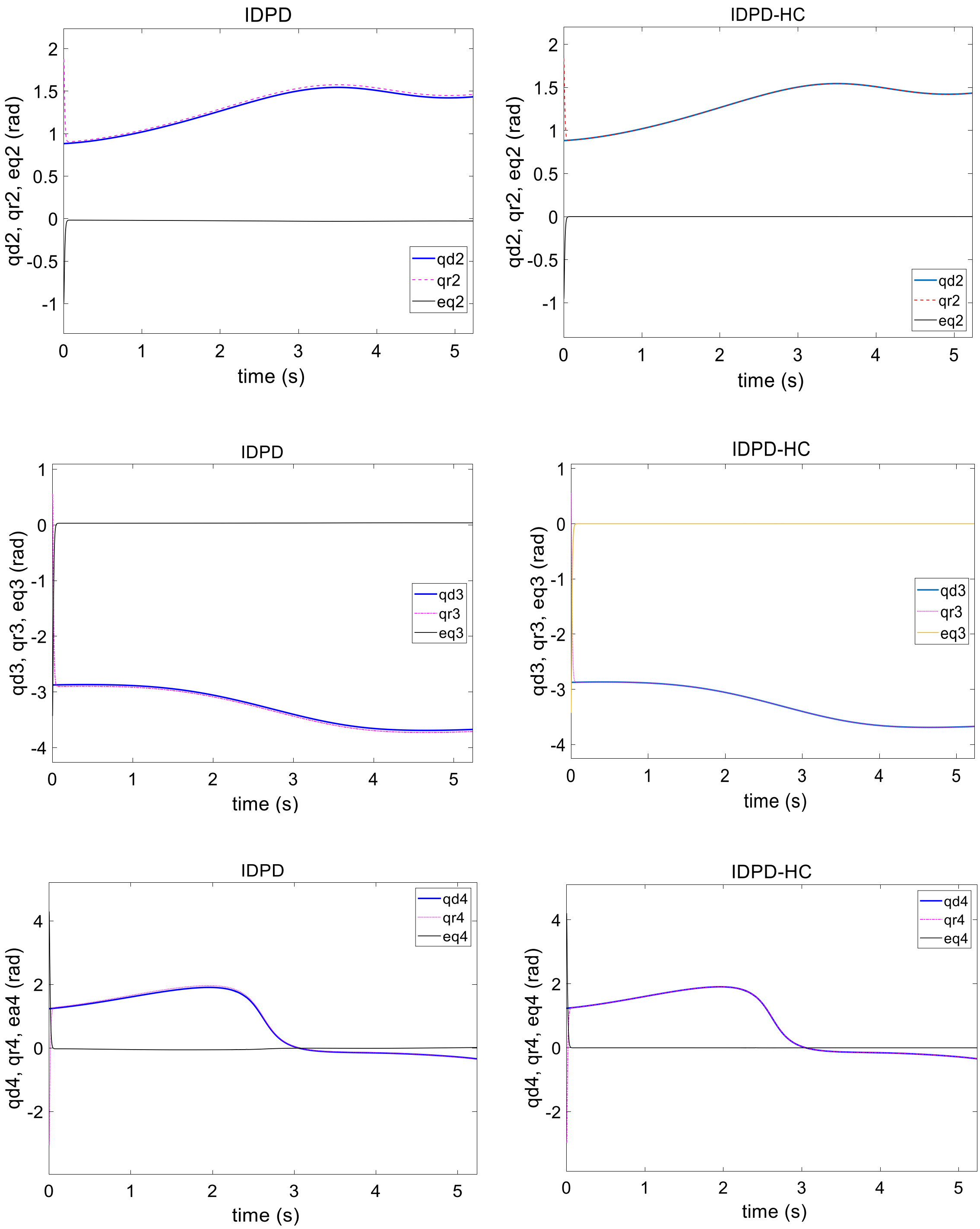
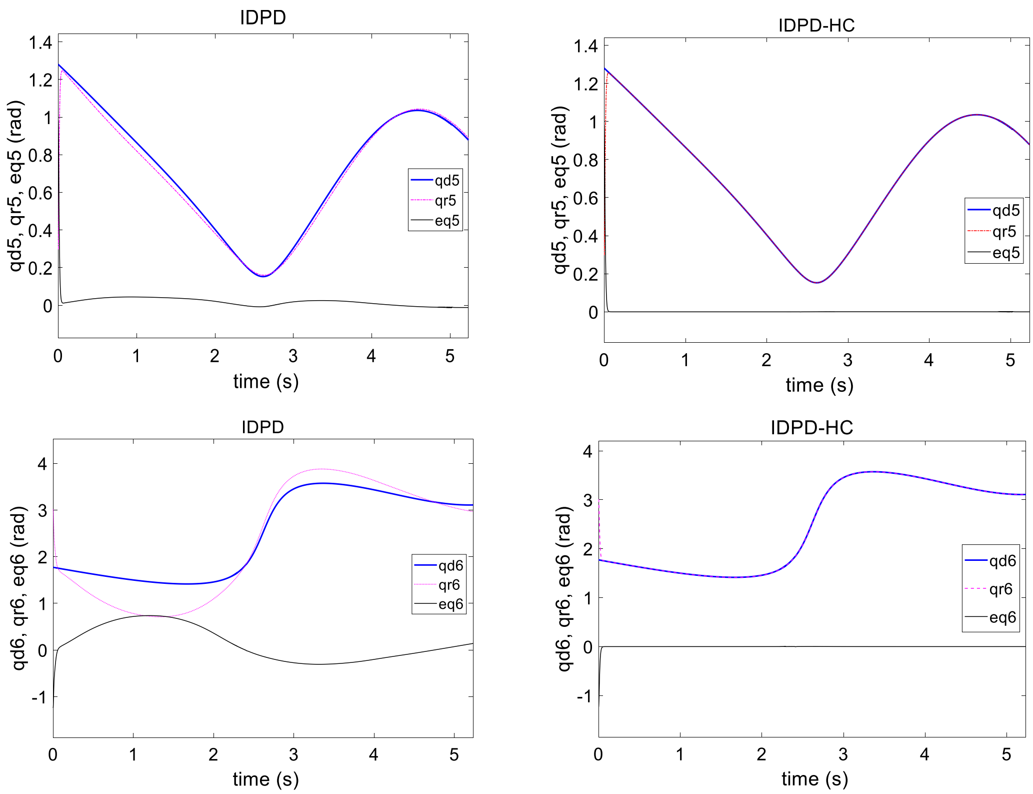


Fig. 6. Description of cutting force F_x, F_y, F_z and cutting moment M_z corresponding to two different cutting force coefficients




IDPD
IDPD-HC
qd2, qr2, eq2 (rad)
qd2
qr2
eq2
qd3, qr3, eq3 (rad)
qd3
qr3
eq3
qd4, qr4, ea4 (rad)
qd4, qr4, eq4 (rad)
qd4
qr4
eq4
time (s)



(a) IDPD controller results (b) IDPD-HC controller results

Fig. 7. Results of numerical simulation of the controllers

The numerical simulation results show that the cutting force calibration block improves control results, which can be applied to achieve machining accuracy.

Because the cutting force acts directly on the last link of the robot (the end effector), the joint position of the last link is more affected than the other links.

5. CONCLUSION

The paper presented the design of IDPD and IDPD-HC controllers for robots with 6 degrees of freedom in milling. The IDPD-HC controller has overcome the effect of cutting force error on the quality of robot control when machining and shaping surfaces with undefined cutting forces. The IDPD controller is applicable to cases where the cutting forces calculated in advance through empirical formulas are accurate or have small errors. The applied IDPD-HC controller with a compensation block for calculating the cutting force has solved the difficult problem in the machining process that it is impossible to accurately calculate the cutting force, because the cutting force is always changing during the machining process. So that it is able to improve the machining quality.

In addition to the calculation error of the cutting force, there are also errors in the calculation of dynamic quantities. Then the cutting force correction is related to other factors. The problem becomes "multiple solutions". Overcoming this will combine the proposed cutting-force correction method and intelligent solutions such as fuzzy control, neural networks, ... In addition, modern evolutionary algorithms can help identify dynamic error types in "multiple solutions" problems to improve the controller.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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