Robust Motion Control of Industrial Robot Based on Robot Parameter Identification and Feedforward Control Considering Resonant Frequency

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In control application of industrial robot manipulator, a two-inertia resonant system is normally represented as the basic plant model for various control schemes. Various control techniques with partially feedback linearization have been proposed to achieve high performance motion control. The design of such controllers basically relies on system mechanical parameters. The proper parameters of the model cannot be obtained by the parameter identification based on only manipulator force and motion measurements. In this paper, the open-loop resonant frequency characteristic of the flexible joint is employed to identify the proper mechanical parameters of the two-inertia model. The nominal link inertia and spring constant of gear drive can be readily measured by this novel identification method.

The identified parameters are used in independent-joint controller design for conventional PD control scheme and robust control scheme to verify the effectiveness of the proposed identification method. Moreover, the accuracy improvement of the proposed robust control scheme based on feedforward inverse dynamic compensation and D-PD position control gives support the validity of the proposed identification method.

Keywords: D-PD position control, feedforward inverse dynamic compensation, parameter identification, resonant frequency, two-inertia system

1. Introduction

Industrial robot manipulator plays an important role in growing industry. Light weight and high load-to-weight ratio construction is required in present robots, in order to fit the fast motion and high efficiency in operation. The compact high-gear reduction with small backlash, such as planetary gear, is frequently used for the driving system in robotic applications⁽¹⁾. Demandingly, the servo system must achieve the fast speed response and precise positioning at the same time. Such gear and coupling which are used as an essential part in power transmission cause the flexibility in robot's joint. The elasticity in coupling components of the gear drive system causes not only the decrement in stiffness but also the performance of the servo system in comparison with the rigid-joint robot.

Many control laws that are well applied to rigid robots⁽²⁾ have been reviewed and simple controllers have been developed for flexible joint control⁽³⁾⁽⁴⁾. Controllers are designed based on mechanical parameters of the elastic joint robot that can be modeled as a two-inertia mechanical structure⁽⁵⁾⁻⁽⁷⁾ in Fig. 1, where θ_M is angular position of driving motor, θ_L is angular position of link, θ_S is torsional angular position, K_S is elastic constant of joint, and R_g is gear ratio ($R_g > 1$). The rigid link and rotor inertias are denoted by J_L and J_M , respectively. The controller design is dependent on these mechanical parameters. The parameter identification techniques

Fig. 1. Mechanical model of flexible joint

based on manipulator force and motion measurements have appeared in the literature⁽⁸⁾⁻⁽¹⁰⁾. However, these techniques are time-consuming processes and require different special test motions depending on the complex structure of the robot dynamics. Moreover, the elastic constant of joint cannot be identified by these methods.

This paper proposes a new identification method based on mechanical resonance is proposed. This method provides simple and fine determination of the nominal parameters of the two-inertia model. The identification technique utilizes the resonant and anti-resonant characteristic of each joint to estimate the nominal link inertia and elastic constant of the flexible joint.

Moreover, this paper proposes a new robust control scheme based on feedforward inverse dynamic compensation and D-PD position control⁽⁷⁾.

2. Conventional Joint Motion Control for Industrial Robot

In this paper, the mathematical model of each flexible joint

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Fig. 2. Conventional joint motion control scheme (*Controller1*) for industrial robot

is regarded as two independent inertias, robot link inertia J_L and motor inertia J_M , which is coupled by a linear torsional spring with stiffness K_S , as shown in Fig. 1. Damping coefficients of the link and motor are denoted by D_L and D_M , respectively. These damping coefficients represent the viscous friction in the rotor and the coupling gear. The torque required for driving each joint is τ that relates to the command current of motor I^{cmd} by torque constant K_T . The coupled torque T_L from other links is considered as a disturbance torque to the system. The PD position controller has been proved to be applicable to elastic-joint manipulators⁽⁴⁾. The conventional PD position controller including PI speed control with state feedback is used as a conventional control scheme for trajectory tracking control. This conventional scheme is illustrated by block diagram in Fig. 2 and will be denoted by *Controller1* hereafter.

The vibration induced by flexibility of the joint is suppressed by state feedback and PI controller in speed control loop. The PD controller is employed to stabilize the desired reference position θ_M^{ref} with proportional gain K_{pp} and derivative gain K_{pd} .

The dynamic model of robot is given in joint-space by Lagrange-Euler equations⁽¹¹⁾, where τ is the generalized n torque input vector. The matrix $M(\theta)$ is an $n \times n$ symmetric positive-definite mass matrix, $V(\theta, \dot{\theta})$ is an n vector of centrifugal and Coriolis terms, $G(\theta)$ is an n vector of gravity terms, and $F(\dot{\theta}_L)$ is viscous friction terms.

$$\tau = D(\theta_L)\ddot{\theta}_L + V(\theta_L, \dot{\theta}_L) + G(\theta_L) + F(\dot{\theta}_L). \quad (1)$$

The only nominal terms of link inertia and viscous friction are used in two-inertia model parameters. Other terms are regarded as disturbance of the system. These nominal terms are necessary in controller design and the control performance relies on these parameters. The parameter identification techniques based on manipulator force and motion measurements⁽⁸⁾⁻⁽¹⁰⁾ are generally divided into two steps of motion test:

- constant speed test, and
- constant acceleration test.

The drawback of this identification method is that the different special motions depending on the complex structure of robot dynamics are necessary in identification process. In addition, the elastic constant of the gear drive cannot be identified experimentally by this method. Therefore, the conventional model based PD controller does not earn a good

Table 1. Nominal robot arm parameters from conventional identification method

Manipulator joint No.	Identified parameters	Known parameters		
	J_L (kgm ²)	K_S (Nm/rad)	J_M (kgm ²)	R_g
Jt1	14.34	67000	1.2×10^{-3}	100
Jt2	49.50	180000	3.4×10^{-4}	160
Jt3	13.0	60000	2.5×10^{-5}	160

position control response for flexible joint robot.

The only nominal link inertia is explicitly identified from motion test and used in two-inertia model. Other necessary parameters for two-inertia model are not actually obtained from this motion test. Hence, the accuracy of the identified parameters is not guaranteed for the conventional identification method. Especially, the deviation in elastic constant of the gear can deteriorate the response of the control system. Table 1 shows the identified link inertia based on the known values of motor inertia and elastic constant of the gear.

3. Parameter Identification in Frequency Domain

With consideration of two-inertia characteristic in each joint, the frequency response of each robot arm identifies both the link inertia (J_L) and the elastic constant (K_S) of the coupling gear. The equations for the two-inertia flexible model are expressed in

$$J_M \ddot{\theta}_M + D_M \dot{\theta}_M + \frac{K_S}{R_g} \theta_S = \tau, \quad (2)$$

$$J_L \ddot{\theta}_L + D_L \dot{\theta}_L - K_S \theta_S = 0. \quad (3)$$

In parameter identification experiment, motor speed is used as the output of the system on the assumption that the effects of damping coefficients (D_M and D_L) are negligible. The relationship from the current command to the motor speed gives the characteristic of mechanical resonant frequency ω_r , and anti-resonant ω_{ar} . The mechanical resonant and anti-resonant frequency can be shown by two-inertia parameters as

$$\omega_r = \sqrt{\frac{K_S}{J_L} + \frac{K_S}{J_M R_g^2}}, \quad (4)$$

$$\omega_{ar} = \sqrt{\frac{K_S}{J_L}}. \quad (5)$$

When the ω_r and ω_{ar} are obtained, the nominal values of link inertia and elastic constant is identified on the assumption that the motor inertia and gear ratio are already known as shown by Eq. 6 and 7. This paper utilizes the physically parameterized model in frequency domain on the assumption that motor inertia is already known. By investigating the frequency response of the two-inertia system, the nominal link inertia and the elastic constant, are identified in accordance with the resonant and anti-resonant point of the system characteristic.

$$J_L = \left(\frac{\omega_r^2}{\omega_{ar}^2} - 1 \right) J_M R_g^2 \quad (6)$$

$$K_S = (\omega_r^2 - \omega_{ar}^2) J_M R_g^2 \quad (7)$$

The new parameter identification method explicitly obtains more accurate parameters in comparison with the conventional method, which assumes the known values of elastic constant of the gear. Normally, the deviation of elasticity in gear drive has more influence than the deviation of motor inertia. Therefore, the improper value of elastic constant may substantially degrade the performance of the control system.

The identification experimental system is the open loop system without any state feedback and motor position. The motor position response is observed during the motion under swept sine command current. The parameter identification experiment is depicted in Fig. 3.

The motor driver system contains a fast current control loop for motor torque control. The data collection for parameter identification of the robot is obtained by measuring the input signal I^{cmd} and the output signal θ_M including the reconstructed motor speed.

The frequency response from the experiment is then plotted and examined for the resonant and anti-resonant frequency. Bode plot for the identified model of the second joint (Jt2) of the experimental setup robot is shown in Fig. 4. This bode plot corresponds to the two-inertia flexible model with input I^{cmd} and output $\dot{\theta}_M$. The resonant and anti-resonant frequencies of all three joints are obtained and shown in Table 2 with the known values of motor inertia and gear ratio.

To show the control performance of these identification methods, the trajectory tracking control is implemented by *Controller1* on the planar circle reference path. The

movements of the experimental robot are executed as illustrated in Fig. 5. The robot is driven with trajectory velocity at 0.25 (m/s) for low speed motion and 0.5 (m/s) for high speed motion. The high speed motion is realized by accelerating the actuator beyond the rated speed to reach 85% of its maximum speed. For low speed, actuator is driven up to 40% of the maximum speed. The radius variation of the measured tracking path $|\Delta r|$ is evaluated through the trajectory as shown in Fig. 6. The control performance is investigated based on $|\Delta r|$ of the tracking path. Fig. 7 and 8 show the circle trajectory tracking response of *Controller1* designed by the parameters based on the conventional identification method in comparison with the parameters based on the proposed identification method. It is obvious that to improve the performance of the control system, link inertias and elastic constants should be identified and used as the nominal parameters in speed and position controller design. The proposed parameter identification technique realizes the improvement of conventional controller design. However, nonlinear effects should be eliminated in order to achieve the quick response in motion control. The robust control scheme is therefore demanded to implement on the robot to improving the overall performance of the motion control.

Fig. 3. Parameter identification experiment

Fig. 4. Frequency characteristic from identification experiment of Jt2

Table 2. Resonant and anti-resonant frequencies with identified parameters for two-inertia flexible joint model

Manipulator joint No.	Identified parameters from proposed method				Known parameters	
	ω_r (rad/s)	ω_{ar} (rad/s)	J_L (kgm ²)	K_S (Nm/rad)	J_M (kgm ²)	R_g
Jt1	129	105	6.0	67000	1.2×10^{-3}	100
Jt2	147	98	10.88	105000	3.4×10^{-4}	160
Jt3	330	220	0.8	38720	2.5×10^{-5}	160

Fig. 5. Circle trajectory tracking experiment

Fig. 6. Evaluation of circle trajectory tracking

Fig. 7. Comparison of low-speed tracking path errors in conventional control scheme

Fig. 8. Comparison of high-speed tracking path errors in conventional control scheme

4. Robust Motion Control Scheme

The robust motion control scheme is introduced to cope with parameter variation and coupled torque from other joints while the manipulator is moving. In addition, the gravity compensation in feedforward manner is also included in the robust motion control scheme. This robust control scheme, which is denoted by *Controller2*, comprises feedforward inverse-dynamic torque compensation and two-degree-of-freedom D-PD position control with robust pole assignment and feedforward pole cancellation in speed control. The control scheme block diagram is shown in Fig. 9. The *Controller2* scheme is also designed corresponding to the two-inertia model of flexible-joint robot.

4.1 Robust Speed Control The improvement of PI and state feedback in inner speed control loop of the *Controller1*, is to employ the feedforward controller to eliminate the dominant complex conjugate closed-loop poles of the inner control loop which depend strongly on the link parameters⁽⁶⁾⁽⁷⁾. The inner speed control loop is expressed by the transfer function,

$$\frac{\omega_M}{\omega^{*cmd}} = \frac{K_P(s + \beta)(b_2 s^2 + b_1 s + b_0)}{(s + \alpha_1)(s + \alpha_2)(s + \alpha_3)(s + \alpha_4)} \quad (8)$$

The feedforward controller are designed to eliminate the dominant poles, α_1 and α_2 . The unity steady state gain of the feedforward controller is guaranteed by the designated gain K_F . The transfer function of this feedforward controller is expressed by,

Fig. 9. Proposed robust control scheme (*Controller2*) for motion control system

Fig. 10. Robust pole location with pole fluctuation caused by inertia variation

$$FF(s) = \frac{K_F(s + \alpha_1)(s + \alpha_2)}{(s + \beta)(s + \alpha_5)} \quad (9)$$

Since the dominant poles are strongly depend on link parameters, such as J_L and D_L , the fluctuation of these assigned poles occurs by the attitude change during robot movement. The inertia moment of each joint changes during robot movement and may bring the system to undesired response. In *Controller2* scheme, the robust pole allocation against the inertia variation for two dominant complex conjugate poles $-(Re \pm jIm)$ is considered.

The pole fluctuation from inertia variation to the maximum value J_{Lmax} , which is set at five times of the nominal value J_L , and robust pole locations of one joint of the tested manipulator are shown in a three dimensional plot in Fig. 10.

The abscissas are coordinates representing the relationship of the complex poles and the two-inertia parameters. The logarithmic values of ratio (Re/Im) and (Im/ω_{ar}) for the designated pole-pair are used for the coordinates. The ordinate represents the damping ratio between the designated pole $\zeta_{designated}$ and the fluctuated value $\zeta_{fluctuated}$ which occurs from inertia fluctuation. This ratio is expressed in decibel unit as shown in Eq. 10. It is obvious that if this ratio is approaching zero, the pole fluctuation against inertia variation is small. Hence, the robust pole locations are on the intersections of the 0dB-line and the pole fluctuation graph as shown in Fig. 10.

$$\Delta a = 20 \log \left(\frac{\zeta_{fluctuated}}{\zeta_{designated}} \right) \quad (10)$$

For the experimental setup robot, this paper points out that

the robust dominant conjugate poles should be allocated on the straight line from $-(0.1\omega_{ar} \pm j\omega_{ar})$ to $-(\omega_{ar} \pm j\omega_{ar})$.

4.2 Feedforward Inverse Dynamic Compensation

Coupled torque and gravity torque have to be compensated to achieve the linearized two-inertia model. The feedforward inverse-dynamic torque compensation is used to compute this regarded disturbance torque. The dynamic torque required for driving robot motion is already shown in Eq. 1. This dynamic torque can be separated into nominal term and non-linear disturbance term. The nominal term consists of the torque required for nominal link inertia and viscous friction as shown in Eq. 11. The disturbance term that represents both the coupled torque from other links, the inertia variation, and the gravity force are shown in Eq. 12.

$$\tau_{Ln} = J_L \ddot{\theta}_L + D_L \dot{\theta}_L \dots\dots\dots (11)$$

$$\begin{aligned} \tau_L &= \tau - \tau_{Ln} \\ &= (D(\theta_L) - J_L)\ddot{\theta}_L + V(\theta_L, \dot{\theta}_L) + G(\theta_L) \dots\dots\dots (12) \end{aligned}$$

In this paper, viscous friction is considered as the friction term appeared in the robot model. The feedforward compensation is realized by applying the position reference to compute the disturbance torque and compensate into the system. In this compensation technique, the load-side position and the load-side speed are necessary to compute the dynamic torque. They are calculated from motor-side position reference θ_M^{ref} , by using the transfer function $Wr(z)$.

$$\begin{aligned} Wr(z) &= \frac{\theta_{L(k)}}{\theta_{M(k)}^{ref}} \\ &= \frac{b_{w3}z^3 + b_{w2}z^2 + b_{w1}z + b_{w0}}{z^4 + a_{w3}z^3 + a_{w2}z^2 + a_{w1}z + a_{w0}} \dots\dots\dots (13) \end{aligned}$$

The coefficients of numerator and denominator of this transfer function depend on parameters of the two-inertia model. The disturbance torque at the load side of each joint is computed by using the inverse dynamic equation. The computed disturbance torque from the dynamic model is then transferred to the compensation current I_{cmp} , by the transfer function $T^m(z)$. The unit time delay (z^{-1}) has to be included to make it a proper transfer function.

$$\begin{aligned} T^m(z) &= \frac{I_{cmp(k)}}{\tau_{L(k+1)}} \\ &= \frac{z^5 + a_{t4}z^4 + a_{t3}z^3 + a_{t2}z^2 + a_{t1}z + a_{t0}}{b_{t4}z^5 + b_{t3}z^4 + b_{t2}z^3 + b_{t1}z^2 + b_{t0}z} \dots\dots\dots (14) \end{aligned}$$

To implement this current compensation, the motor position reference used for the feedforward compensation is required to be one sampling-time future value to make exact current compensation to the system. In practice, the motor position reference for the main control system is delayed at one sampling time by putting in process with unit time delay as shown in Fig. 9. Then, the position reference for the feedforward compensation is relatively one sampling future value. From this technique, the inverse-dynamic torque compensation can be implemented by feedforward method.

4.3 D-PD Position Control

The robust position

control with straightforward design method for robot application is introduced in this paper. It consists of PD control and velocity feedforward part. PD controller gains, K_{pp} and K_{pd} , are designed by employing robust control design approach, CDM (Coefficient Diagram Method) ⁽¹²⁾⁽¹³⁾. These gains are designed by considering the stability condition and settling time of the system. Since CDM uses the closed-loop characteristic polynomial in design, the stability and response of the system can be arbitrarily designated. By using the desired value of stability index γ_1 , and the equivalent time constant τ_c , the characteristic of the system can be improved. In the two-inertia system, the recommended value for γ_1 is 2 and for τ_c is 0.05 ⁽¹³⁾.

$$\begin{aligned} \begin{pmatrix} K_{pd} \\ K_{pp} \end{pmatrix} &= \begin{pmatrix} \alpha_3\alpha_4\alpha_5J_L \\ \alpha_3\alpha_4\alpha_5J_L(1 - (D_L\gamma_1/(K_S\tau_c)) \\ \alpha_3\alpha_4\alpha_5J_L(D_L - K_S\tau_c)/K_S \\ \alpha_3\alpha_4\alpha_5J_L(D_L - J_L\gamma_1/\tau_c)/K_S \end{pmatrix}^{-1} \\ &\begin{pmatrix} -\alpha_3\alpha_4\alpha_5J_{Ln} \\ -\alpha_3\alpha_4\alpha_5J_{Ln} + J_L\gamma_1(\alpha_3\alpha_4 + \alpha_4\alpha_5 + \alpha_3\alpha_5)/\tau_c \end{pmatrix} \dots\dots\dots (15) \end{aligned}$$

To improve the transient position response and reduce the state error of the position control, the feedforward gain F_{pd} , is determined by a zero assignment based on the minimum-phase condition. The transfer function of position control system is then

$$\frac{\theta_M}{\theta_M^{ref}} = \frac{K_P K_F (K_{pp} + sF_{pd})(b_2s^2 + b_1s + b_0)}{s^4 + a_{n3}s^3 + a_{n2}s^2 + a_{n1}s + a_{n0}} \dots\dots (16)$$

5. Experimental Results

The experimental results with comparison of the control performance between the conventional *Controller1* and the proposed *Controller2* scheme are inspected. The nominal parameters used in controller design are also compared between the conventional identification method and the proposed identification method.

The *Controller2* scheme shows the considerable improvement in tracking response based on parameters from both conventional and proposed identification method. The experimental results are shown in Fig. 11 for low speed motion

Fig. 11. Comparison of low-speed tracking path errors in robust control scheme

Fig. 12. Comparison of high-speed tracking path errors in robust control scheme

Table 3. Maximum tracking error and area of error from experimental results of Controller1

Motion Speed	Maximum error (mm)		Area of error (mm-s)	
	Conventional Identification Method	Proposed Identification Method	Conventional Identification Method	Proposed Identification Method
Low	1.25	0.87	2.83	1.97
High	2.91	2.41	4.22	3.51

Table 4. Maximum tracking error and area of error from experimental results of Controller2

Motion Speed	Maximum error (mm)		Area of error (mm-s)	
	Conventional Identification Method	Proposed Identification Method	Conventional Identification Method	Proposed Identification Method
Low	0.44	0.33	1.23	1.12
High	1.01	0.91	1.71	1.52

and in Fig. 12 for high speed motion.

The maximum value of tracking error and the area of tracking error are calculated from the experimental data. These values are used as an index in performance comparison between the conventional and the proposed parameter identification method as well as the both control schemes. Table 3 and Table 4 show the maximum and the area of tracking error from experimental data of *Controller1* and *Controller2* scheme, respectively.

From the results in Fig. 7 and 8, the tracking control with *Controller1* scheme shows that the tracking error is apparently reduced when the parameters from the new identification method are employed. In the *Controller2* scheme, the same results are also noticeable in Fig. 11 and 12; however, the difference in tracking path error is not obvious as in the case of *Controller1*. Hence, the *Controller2* scheme gains the robust characteristic against the nominal parameter variation in two-inertia model.

6. Conclusion

The new nominal parameter identification method based on frequency domain was proposed. Inertia of robot link and elastic constant of gear drive are related to the frequency response of the open loop two-inertia system. Improvement in the performance of the experimental results affirms the effectiveness of the identified parameters. For conventional control scheme (*Controller1*) with the proposed parameter

identification method, the performance of the control system improves up to 30% for low speed motion and up to 17% for high speed motion.

In addition, the proposed robust control scheme (*Controller2*) proves its performance on the parameter variation. The experimental results confirmed the robust performance when using both parameters from the conventional and the proposed identification method. The robust control scheme has an advantage to implementing on the highly nonlinear system such as a robot manipulator.

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