Precise Joint Torque Control Method for Two-inertia System with Backlash Using Load-side Encoder

Shota Yamada^{*a)} Student Member, Hiroshi Fujimoto^{*} Senior Member

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Force/torque control is attracting considerable attention for the realization of compliant motion in mechatronic systems such as industrial robots and human-support robots. They have transmission mechanisms such as gear reducers, which introduce resonance in the low frequency range and nonlinearity by backlash. To achieve high precision even with transmission mechanisms, the reduced cost of high-resolution encoders has increased the number of devices with load-side (gear-output-side) encoders in industry. Therefore, this study proposes a precise joint torque control method with backlash compensation by using load-side encoder information. The effective use of the load-side encoder information enables the proposed method to compensate the fast backlash effect in a feed forward manner. Moreover, based on the experimental analyses, the novel backlash compensation model is proposed to solve the problems caused by the conventional backlash compensation model. Simulation and experimental results demonstrate the advantages of the proposed method.

Keywords: backlash, motion control, nonlinearity, robot control, torque sensorless control, two-inertia system

1. Introduction

Force control has attracted considerable attention recently⁽¹⁾⁽²⁾. In the industry, there is an increasing demand for constructing automated manufacturing systems with the flexibility to handle various types of low quantity production. There are two requirements for industrial robots to construct the aforementioned automated flexible product lines. The first requirement is that robots are required to complete tasks that are difficult for conventional position-controlled robots to perform such as assembling parts and polishing processing⁽³⁾. The application of force/torque-control enlarges the field of automation. The second requirement is that robots are required to concurrently work with human workers. Position-controlled industrial robots require large spaces surrounded by fences for safety purposes⁽⁴⁾. However, force-controlled robots do not require fences, and this allows collaboration with human workers to complete complex and various tasks. Additionally, there is an increasing demand for human-support robots (especially in welfare fields) to deal with the issue of an aging society. A series elastic actuator (SEA) is intensively examined as a promising actuator for human-support robots⁽⁵⁾⁽⁶⁾.

Industrial robots and SEAs typically include geared structures with low rigidity and nonlinearities such as backlash. These features severely affect the control performance, and thus, the geared structures are often modeled as two-inertia systems to consider resonance and backlash effects⁽⁷⁾⁽⁸⁾. Therefore, several studies focus on two-inertia control^{(9)–(11)}. The system with backlash is often modeled as a

Fig. 1. Block diagram of a two-inertia system

two-inertia system with deadzone as shown in Fig. 1. The definitions of the variables are given in Table 1. Subscripts *M* and *L* indicate the motor side and load side, respectively. Motor side and load side are separated by a deadzone, and collisions occur when the direction of the motion changes.

In order to obtain precise positioning at the load side even with nonlinearities in transmission mechanisms, feedback of the load-side encoder information is required⁽¹²⁾⁽¹³⁾. It is typically difficult to equip industrial robots with encoders at the load side due to the lack of space available for mounting the encoder and due to the scattering of lubricant. However, we expect an increase in the application of load-side encoders to robots due to cost reduction. Therefore, we proposed a novel machine structure with both motor-side and load-side encoders for robots' application⁽¹⁴⁾. Additionally, SEAs normally include both motor-side and load-side encoders for joint torque measurement⁽¹⁵⁾⁽¹⁶⁾. We expect that the effective use of the load-side information will improve joint torque control performance.

Precise control of the joint torque realizes safe and flexible

a) Correspondence to: Shota Yamada. E-mail: yamada.shota13@ae.k.u-tokyo.ac.jp

* The University of Tokyo

5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8561, Japan

Table 1. Definition of plant variables

Inertia moment	J	Torque constant	K_t
Viscosity coefficient	D	Current	i
Torsional rigidity	K	Angular velocity	ω
Motor torque	T_M	Torsional angular velocity	$\Delta\omega$
Joint torque	T_s	Motor-side disturbance	d_M
External torque	d_L		

motion in robots, and delicate tasks such as assembling and polishing. Additionally, joint torque feedback suppresses the effect of load change (see e.g., (17)). Therefore, several studies on joint torque control methods were conducted⁽¹⁸⁾⁽¹⁹⁾. Oh *et al.* in (20) proposed a disturbance observer (DOB) by using torsional angle instead of motor-side angle to enhance zero impedance characteristics, which indicates the backdrivability of the mechanical system. Backdrivability is important for human-support application⁽²¹⁾. Therefore, the backdrivability performance of our proposed method will be discussed and evaluated in section 4.3 of this paper. Several studies consider the backlash effect for more precise joint torque control⁽²²⁾⁽²³⁾. Most studies consider backlash effect as joint torque disturbance. Kaneko *et al.* in (24) deal with the nonlinear torsional rigidity in harmonic drive gears by compensating joint torque disturbance calculated by torque sensor information and both motor- and load-side encoders information. Odai *et al.* in (25) compensate joint torque disturbance by DOB. This framework is further examined in (26) and (27). However, it is necessary to compensate backlash not by FB controllers (such as DOB) but by FF controllers, since the backlash effect is fast. It is necessary to move the motor side very quickly during the reversal motion.

This study proposes precise joint torque control method by considering the backlash effect. The effective usage of load-side encoder information enables the extraction of the backlash nonlinearity to compensate by a FF controller based on an inverse model of backlash. This compensation becomes possible by controlling the torsional velocity by using both motor- and load-side encoder information. The main contributions of this study are as follows:

- (1) improvements in the precision of the joint torque control by the FF controller that deals with the fast backlash phenomenon by using both motor- and load-side encoders,
- (2) enhancement of backdrivability by the joint torque control by using both motor- and load-side encoders,
- (3) evaluation of control performance in simulations and experiments.

This study adds further to extant studies⁽¹⁴⁾⁽²⁸⁾. This study is organized as follows. The experimental setup is introduced in section 2. In section 3, the proposed methods are explained in detail. In sections 4 and 5, the performance of the proposed methods is quantitatively analyzed in simulations and experiments. Based on the results, a novel and simple backlash compensation model is proposed and experimentally analyzed in section 6. Finally, the conclusion is discussed in section 7.

2. Experimental Setup

A motor bench with a low stiff joint between two motors is used as the two-inertia system setup in the study.

(a) Outlook of the motor bench

(b) Schematic of the motor bench

Fig. 2. Two-inertia system motor bench setup

A photograph and a schematic of the setup are shown in Figs. 2(a) and 2(b), respectively. A high-bandwidth (1 kHz) torque sensor allows the comparison of the measured torque and estimated torque. A flexible joint between the motor side and torque sensor is inserted to exhibit low resonance that is usually introduced by transmission gears. The length and diameter of the flexible joint are 340 mm and 7.8 mm, respectively. Additionally, backlash is introduced by a gear coupling. Backlash width identification with only motor-side encoder corresponds to another research field (see e.g. (29)). Nevertheless, it is easy to identify the width when the system includes both motor- and load-side encoders. The identified backlash width in the setup is ± 6 mrad.

Controllers are implemented in DSP. The control sampling of current control loop is 10 kHz, and thus, the PI current controller is implemented. The current control bandwidth is experimentally confirmed as 1.2 kHz. Frequency characteristics measurements are performed by inputting chirp signals to the current reference. Frequency characteristics of the setup from the motor current to the motor-side angle and from the motor current to the load-side angle are shown in Figs. 3(a) and 3(b), respectively. As shown in the figures, the setup is modeled as a two-inertia system with an antiresonance frequency of 57 Hz and resonance frequency of 71 Hz. The fitted model is denoted by blue solid lines while the measurement results are denoted by the red dashed lines. The parameters identified by the fitting are shown in Table 2.

3. Proposed Method

3.1 Overview of the Proposed Method Conventional studies compensate the backlash effect by only using a FB controller such as DOB⁽²⁵⁾⁽²⁷⁾. However, it is necessary to also compensate the backlash effect in the FF controller since its effect is fast and it always appears at the reversal points of motion (i.e., The joint torque reference value indicates when the backlash effect appears. With respect to the disturbance responses, it is necessary to compensate for the backlash effect by using FB controllers). Therefore, a proposed method includes the FF backlash compensator. Figure 1 shows that backlash is extracted when torsional angular velocity is controlled in the inner loop, and it can be compensated with an inverse model of the deadzone in a FF manner.

Figures 4 and 5 show an overview and a detailed block diagram of the proposed method, respectively. The proposed method mainly consists of the following three parts: motor-side velocity control (ω_M FF, ω_M FB, and DOB), joint torque

Fig. 3. Frequency characteristics of the setup. Blue solid line indicates the fitted model, while red dashed line indicates the measured frequency response characteristic

Table 2. Parameters of the two-inertia system motor bench

J_M	1.03e-3 kgm ²	J_L	0.870e-3 kgm ²
D_M	8.00e-3 Nms/rad	D_L	1.71e-3 Nms/rad
K	99.0 Nm/rad	K_t	0.173 Nm/A
Backlash width	±6 mrad

Fig. 4. Overview block diagram of the proposed method

FF control (T_s FF), and joint torque FB control (T_s FB and T_s OB). Specifically, T_s OB indicates a joint torque observer. Also, the definition of the controller parameters used in Fig. 5 is shown in Table 3.

3.1.1 Motor-side Velocity Control In order to control torsional velocity, the motor-side velocity P control with a DOB is implemented. In Fig. 5, $C_{\omega MP}$ indicates a P controller with gain $K_{\omega MP}$, and $Q_{DOB}(s)$ indicates a first-order low pass filter (LPF) whose cutoff frequency determines the bandwidth of DOB. The motor-side velocity exhibits less phase delay when compared with the load-side velocity, since

it corresponds to the collocated side. Therefore, motor-side velocity is first controlled and subsequently load-side velocity obtained by the load-side encoder is used to control $\Delta\omega$ based on Eq. (1):

$$\Delta\omega = \omega_M - \omega_L \dots \dots \dots (1)$$

The reference value of the motor-side angular velocity is generated by using the reference value of the torsional angular velocity and the obtained load-side angular velocity as follows:

$$\omega_M^* = \Delta\omega^* + \omega_L \dots \dots \dots (2)$$

where superscript * indicates the reference value.

A motor-side angular velocity FF controller is also applied to achieve a high control bandwidth. High control bandwidth of the inner loop is required to quickly compensate the backlash, and it improves the performance of the outer loop. Thus, the FF controller is implemented as $(J_{Mn}s + D_{Mn})$ based on the assumption that the reaction joint torque to the motor side is decoupled by DOB. The subscript n indicates the nominal value. The DOB decouples the motor side and load side under its bandwidth, and thus, the plant is considered as $\frac{1}{J_{Mn}s + D_{Mn}}$ within the DOB bandwidth. Furthermore, $Q_{\omega FF}(s)$ is a first-order LPF to realize the FF controller.

3.1.2 Joint Torque FF Control The joint torque FF control compensates for the backlash and improves the reference-tracking performance. It is possible to deal with the fast backlash effect by using the FF controller for precise control. The joint torque FF controller generates the torsional angular velocity reference value from the joint torque reference value. We consider an inverse model of the transfer function from $\Delta\omega$ to T_s (see Fig. 1), and thus, the reference value of the torsional angular velocity is generated by using the reciprocal of the torsional rigidity, the inverse model of backlash, and the derivative. The derivative is implemented as a pseudo differential with the first-order LPF $Q_{TsFF}(s)$. The backlash is modeled as a deadzone, and thus, the inverse model of the deadzone is applied.

In Fig. 5, the load-side angular velocity is filtered with $Q_{TsFF}(s)$. The load-side angular velocity is delayed with the filter to synchronize the torsional angular velocity generated by the joint torque FF controller that exhibits delay due to $Q_{TsFF}(s)$.

3.1.3 Joint Torque FB Control The joint torque FB control suppresses modeling errors and disturbance by using the joint torque estimated by a joint torque observer with a PI controller. The joint torque observer uses only the motor-side parameters, which do not vary much compared with the parameters of the load side and the transmission mechanism. Also, the joint torque observer estimates the joint torque even with nonlinearities in transmission mechanisms since it estimates the reaction torque. Therefore, the joint torque observer can estimate the joint torque robustly⁽³⁰⁾⁽³¹⁾. FF controller cannot compensate the backlash effect caused by modeling errors and disturbance. However, it can be suppressed by the joint torque FB controller. Specifically, $Q_{T,OB}(s)$ is a first-order LPF that determines the estimation bandwidth. The PI controller $C_{T,PI}(s)$ is designed by the pole placement to the plant, namely $T_s = \frac{k}{s} \Delta\omega$.

Fig. 5. Detailed block diagram of the proposed method

Table 3. Definition of the controller parameters used in Fig. 5

$C_{\omega MP}$	Motor-side velocity P controller
$Q_{DOB}(s)$	1st order LPF of DOB
$Q_{\omega FF}(s)$	1st order LPF to realize the motor-side velocity FF controller
$Q_{TsFF}(s)$	1st order LPF to realize the joint torque FF controller
$Q_{TsOB}(s)$	1st order LPF of reaction torque observer for joint torque estimation
$C_{TsPI}(s)$	Joint torque PI controller

3.2 Controller Design Procedure

First, DOB is designed. The nominal parameters of the torque constant K_{tn} and the inverse model of motor-side plant ($J_{Mn}s + D_{Mn}$) are designed based on the identified parameters in Table 2. Subsequently, the cutoff frequency of $Q_{DOB}(s)$ is experimentally tuned as 80 Hz in our setup. The cutoff frequency is influenced by the precision of parameter identification and quantization noise by encoder signals. Second, motor-side velocity P controller is tuned by considering the stable margin. Open loop characteristics of P controller, DOB, and the plant are shown in Fig. 6. The vector locus has a large circle going through the point (1.1, 1.5) and coming back around the point (-0.4, -1.5) due to the resonance of the two-inertia plant, though the whole view of the large circle is not shown in Fig. 6. Please note that backlash nonlinearity is removed from the plant in the analysis. In this study, P gain $K_{\omega MP}$ is increased till phase margin reaches 60 degrees. Third, the motor-side velocity FF controller is designed based on the identified values of the motor-side parameters (J_{Mn} and D_{Mn}). As discussed in previous subsection, the FF controller design is based on the decoupling by DOB. Therefore, the bandwidth of the FF controller is designed based on the DOB bandwidth. The bandwidth of the FF controller is determined by the cutoff frequency of the first-order LPF $Q_{\omega FF}(s)$, and thus, the cutoff frequency of $Q_{\omega FF}(s)$ is designed as identical to that of $Q_{DOB}(s)$.

Fourth, the joint torque FF controller is designed. The deadzone model is uniquely determined by the deadzone width that is identified by using both motor- and load-side encoders as stated in section 2. The filter of $Q_{TsFF}(s)$ is designed based on $Q_{\omega FF}(s)$. The joint torque FF controller generates the reference value of the torsional angular velocity that generates the reference value of the motor-side velocity based on Eq. (2). Therefore, the bandwidth of the joint torque FF controller should not exceed the bandwidth of the motor-side velocity FF controller. Subsequently, the

Fig. 6. Open loop characteristic of P controller, DOB, and the plant. Black circle indicates the unit circle. Blue solid line indicates the vector locus of the open loop characteristic of the motor-side velocity FB controller

cutoff frequency of $Q_{TsFF}(s)$ is designed as identical to that of $Q_{\omega FF}(s)$ and $Q_{DOB}(s)$.

Finally, the joint torque FB controller is designed. PI controller $C_{TsPI}(s) = K_{TsP} + \frac{K_{TsI}}{s}$ is designed by the pole placement to the plant, $T_s = \frac{k}{s} \Delta\omega$. The poles are placed on the real axis and tuned experimentally. In this study, the poles are placed at 35 Hz. The cutoff frequency of the first-order LPF $Q_{TsOB}(s)$ is designed to significantly exceed the bandwidth of the PI control. The cutoff frequency is designed as 80 Hz.

4. Simulations

4.1 Simulation Conditions

The model used in simulations is the two-inertia system model whose parameters are shown in Table 1. It should be noted that the deadzone model is not included in the plant in section 4.2 and 4.3 for the basic analyses of the joint torque control. The effect of deadzone is analyzed in section 4.4 and the experiments in the next section.

4.2 Effects of the FF Controllers

First, the effectiveness of applying FF controllers is evaluated. Figure 7 compares the frequency characteristics of the transfer function from the reference to the joint torque between with and without two FF controllers, the joint torque FF controller, and motor-side angular velocity FF controller. The response with FF in the blue solid line exhibits higher control bandwidth characteristics. Two FF controllers improve the reference

Fig. 7. Frequency responses from the reference to the joint torque with and without two FF controllers (T_sFF and ω_MFF). Blue solid line indicates that the frequency response with T_sFF and ω_MFF , while red dashed line indicates that without two FF controllers

Fig. 8. Step responses of joint torque with and without ω_MFF . Black dotted line indicates the reference value of the joint torque. Blue solid line indicates the response with the motor-side angular velocity FF controller, and the red dashed line denotes that without the motor-side angular velocity FF controller

tracking performance.

Figure 8 evaluates the effect of the motor-side angular velocity FF controller. In Fig. 8, a 0.50 Nm step reference is input at 0.050 s and a -1.0 Nm step load-side disturbance is input at 0.10 s. The black dotted line denotes the reference value of the joint torque, the blue solid line denotes the response with the motor-side angular velocity FF controller, and the red dashed line denotes the response without the motor-side angular velocity FF controller. The joint torque responses are precisely controlled in both cases. However, the motor-side angular velocity FF control slightly improves the initial responsiveness. Disturbance suppression is also improved by applying the motor-side angular velocity FF controller that increases the inner loop control bandwidth.

4.3 High Backdrivability The joint torque control method also improves backdrivability. Backdrivability is important for realizing human-machine interactive motion⁽⁶⁾ because it indicates the ease of moving the devices from the load side. Specifically, backdrivability is essential in wearable robots since it determines the ease for the users to

(a) Joint torque responses

(b) Load-side angular velocity responses

Fig. 9. Realization of high backdrivability. Comparison between the proposed control system shown in blue solid line and a system without any control shown in red dashed line, when the load-side step disturbance is input

move⁽¹⁶⁾. The main factors that deteriorate the backdrivability include motor-side impedance and friction amplified by the gear. An enhancement in the backdrivability in industrial robots and human-support robots allows workers to easily move the robots and prevent injury to humans or hardware destruction when robots collide with humans⁽¹⁹⁾.

Backdrivability is enhanced by controlling the joint torque at 0 Nm because the joint torque works as a disturbance when a human inputs external torque on the load side. Backdrivability is evaluated by the load-side velocity with an input to the load side. The joint torque reference is set as 0.0 Nm, and a -1.0 Nm step load-side disturbance is input at 0.050 s in Fig. 9. The blue solid line indicates the response with the proposed control, while the red dashed line indicates the response without any control. As shown in Fig. 9(a), the proposed method enables the joint torque to reach 0.0 Nm within 0.050 s. As shown in Fig. 9(b), the load-side angular velocity response with the proposed method is faster with the same amount of load-side disturbance input, thereby suggesting that the proposed method enhances backdrivability by removing the motor-side impedance. Additionally, the vibration in the velocity response is reduced because $T_s = 0$ control decouples the load and motor sides. Our simulation model does not include friction and the reduction ratio is 1. However, the improvement of backdrivability by the proposed method

(a) Sinusoidal responses of the joint torque

(b) Zoom of Fig. 10(a)

Fig. 10. Simulation comparison between the sinusoidal responses of the joint torque with and without backlash compensation. Blue solid line indicates the response in the proposed method with inverse model of deadzone for backlash compensation, while red dashed line indicates that without backlash compensation

(a) Sinusoidal response of the joint torque in the proposed method without backlash compensation

(b) Zoom of Fig. 11(a)

Fig. 11. Joint torque response of the sinusoidal inputs without backlash compensation in the experiment. Black dotted line denotes the sinusoidal reference of the joint torque. Blue solid line denotes the estimated joint torque by the joint torque observer, while the red dashed line denotes the measured joint torque by the joint torque sensor equipped for the performance evaluation of the joint torque observer

is clear.

4.4 Backlash Compensation Backlash affects the response at motion reversal points, and thus, sinusoidal responses are shown in Fig. 10. The blue solid line denotes the joint torque response with an inverse model of deadzone in the FF controller, while the red dashed line denotes the response without the inverse model in the FF controller. The initial position corresponds to the middle point of the dead-zone. Without backlash compensation, the response remains at 0 Nm at the reversal points. After the deadzone width, the response exhibits large vibration due to a collision between the motor and load side. The results clearly show that the proposed backlash compensation method improves the response.

5. Experiments

In the experiments, backlash compensation performance is evaluated in our setup. The conditions in the experiments are the same as those in the simulations. Controllers are discretized by using a Tustin conversion with a sampling frequency of 2 kHz. Figure 11 shows the joint torque sinusoidal responses of the proposed method without backlash compensation. The black dotted line denotes the reference of the joint torque, and the blue solid line denotes the estimated

joint torque by the joint torque observer. The red dashed line denotes the measured joint torque by the joint torque sensor equipped for the performance evaluation of the joint torque observer. Deterioration in the joint torque response due to backlash is clearly observed at the reversal points. Therefore, backlash compensation is clearly required. Additionally, the results show that the joint torque is precisely estimated by the joint torque observer even with backlash nonlinearity.

The joint torque responses with backlash compensation based on the inverse deadzone model are shown in Fig. 12. In the experiments, the cut-off frequency of the pseudo-differential in the joint torque FF controller is decreased to 10 Hz to avoid exceeding the maximum motor current. Figure 12 shows the maximum amplitude of the response after the reversal points are suppressed when compared to Fig. 11. However, a spike in the joint torque and current is produced in the compensation timing as shown in Figs. 12 and Fig. 13(a). This spike is caused by the differential of the inverse deadzone model in the FF controller. Therefore, it is also necessary to improve the compensation model such that the differential of the model is smooth. A novel compensation model

(a) Sinusoidal response of the joint torque in the proposed method with the inverse model based backlash compensation

(b) Zoom of Fig. 12(a)

Fig. 12. Joint torque response of the sinusoidal inputs with the inverse model based backlash compensation in the experiment. Black dotted line denotes the sinusoidal reference of the joint torque. Blue solid line denotes the estimated joint torque by the joint torque observer, while the red dashed line denotes the measured joint torque by the joint torque sensor equipped for the performance evaluation of the joint torque observer

is proposed based on this requirement in the next section.

6. Backlash Compensation Model based on a Sigmoid Function

In order to improve the response and reduce the maximum motor current, a novel backlash compensation model is proposed by using the following sigmoid function:

$$\zeta(x) = K_{sig} \left(\frac{1}{1 + e^{-ax}} - \frac{1}{2} \right) \dots \dots \dots (3)$$

Specifically, K_{sig} is the total gain, and a is the gain that determines the similarity to the inverse deadzone model as shown in Fig. 14(a). As shown in Fig. 14(b), tangential lines are drawn at the points $-x_1$ and x_1 where the slope of sigmoid function is 1. By defining the new model as Eq. (4), a smoothed inverse deadzone model is developed as follows:

$$\zeta_p(x) = \begin{cases} x + x_1 + \zeta(-x_1), & (x < -x_1) \\ \zeta(x), & (-x_1 \leq x \leq x_1) \dots \dots \dots (4) \\ x - x_1 + \zeta(x_1), & (x > x_1) \end{cases}$$

The pseudo differential of this smoothed model is the output

(a) Current required in backlash compensation with the inverse dead-zone model

(b) Current required in backlash compensation with the proposed sigmoid-based model

Fig. 13. Comparison of the current responses with backlash compensation in two backlash compensation models

of the FF controller, and thus, a lower maximum motor current is required. After a is tuned experimentally, K_{sig} is tuned by comparing the intercepts of the tangential lines and the identified deadzone width.

A comparison of the joint torque response between systems with and without the proposed model based backlash compensation is shown in Fig. 15. Specifically, K_{sig} and a are tuned to 0.050 and 5000, respectively. The black dotted line denotes the reference of the joint torque, the blue solid line denotes the joint torque response with the proposed backlash compensation, and the red dashed line denotes the response without backlash compensation in the FF controller. The results indicate a clear improvement with no spike in the joint torque response in the proposed method. The current response is shown in Fig. 13(b). The proposed compensation method significantly decreases the required maximum motor current.

7. Conclusion

In this study, a novel control method is proposed by using load-side encoder information to improve the performance of joint torque control. The effective use of the load-side encoder information enables the proposed method to exhibit high control bandwidth characteristics and compensate for the backlash in the FF controller. The performance of the proposed method is evaluated through simulations and

(a) Sigmoid function plots with variable a . See equation (3) (b) Inverse model of deadzone and the proposed model. Blue solid line indicates the inverse model of deadzone. Magenta dashed line indicates the sigmoid function. Red solid line and black dotted line indicate the tangential lines at $+x_1$ and $-x_1$, respectively (See equation (4))

Fig. 14. Backlash compensation models

experiments. Moreover, the experimental results indicated that the inverse deadzone model based backlash compensation produced a spike in the compensation timing, and thus, a novel backlash compensation model is proposed. The experimental results verify that the proposed model exhibits better performance when compared to that of the inverse deadzone model and reduces the required maximum current. A future study will consider a backlash compensation method that more effectively utilizes the load-side encoder information to further improve the performance.

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References

- (1) T.T. Phuong, K. Ohishi, C. Mitsantisuk, Y. Yokokura, K. Ohnishi, R. Oboe, and A. Sabanovic: "Disturbance Observer and Kalman Filter Based Motion Control Realization", *IEEJ J. Ind. Appl.*, Vol.7, No.1, pp.1–14 (2018)
- (2) T. Yoshioka, A. Yabuki, Y. Yokokura, K. Ohishi, T. Miyazaki, and T.T. Phuong: "Stable Force Control of Industrial Robot Based on Spring Ratio and Instantaneous State Observer", *IEEJ J. Ind. Appl.*, Vol.5, No.2, pp.132–140 (2016)

(a) The sinusoidal responses of the joint torque

(b) Zoom of Fig. 15(a)

Fig. 15. Experimental comparison of the sinusoidal responses of the joint torque with and without the proposed model based backlash compensation. Black dotted line denotes the sinusoidal reference of the joint torque. Blue solid line denotes the joint torque response in the proposed method without backlash compensation, while the red dashed line denotes that in the proposed method with backlash compensation based on the proposed model

- (3) C. Mitsantisuk, M. Nandapaya, K. Ohishi, and S. Katsura: "Design for Sensorless Force Control of Flexible Robot by Using Resonance Ratio Control Based on Coefficient Diagram Method", *Automatika*, Vol.54, No.1, pp.62–73 (2013)
- (4) G.B. Avanzini, N.M. Ceriani, A.M. Zanchettin, P. Rocco, and L. Bascetta: "Safety Control of Industrial Robots Based on a Distributed Distance Sensor", *IEEE Trans. Control Syst. Technol.*, Vol.22, No.6, pp.2127–2140 (2014)
- (5) E. Sariyildiz, G. Chen, and H. Yu: "An Acceleration-Based Robust Motion Controller Design for a Novel Series Elastic Actuator", *IEEE Trans. Ind. Electron.*, Vol.63, No.3, pp.1900–1910 (2016)
- (6) K. Kong, J. Bae, and M. Tomizuka: "A Compact Rotary Series Elastic Actuator for Human Assistive Systems", *IEEE/ASME Trans. Mechatronics*, Vol.17, No.2, pp.288–297 (2012)
- (7) M. Ruderman and M. Iwasaki: "Sensorless Torsion Control of Elastic-Joint Robots With Hysteresis and Friction", *IEEE Trans. Ind. Electron.*, Vol.63, No.3, pp.1889–1899 (2016)
- (8) Y. Hori, H. Iseki, and K. Sugiura: "Basic consideration of vibration suppression and disturbance rejection control of multi-inertia system using SFLAC (state feedback and load acceleration control)", *IEEE Trans. Ind. Appl.*, Vol.30, No.4, pp.889–896 (1994)
- (9) K. Sakata, H. Asaumi, K. Hirachi, K. Saiki, and H. Fujimoto: "Self Resonance Cancellation Techniques for a Two-mass and its application to a Large-Scale Stage", *IEEJ J. Ind. Appl.*, Vol.3, No.6, pp.455–462 (2014)
- (10) K. Szabat and T. Orłowska-Kowalska: "Vibration Suppression in a Two-Mass Drive System Using PI Speed Controller and Additional Feedbacks—Comparative Study", *IEEE Trans. Ind. Electron.*, Vol.54, No.2, pp.1193–1206 (2007)
- (11) K. Yuki, T. Murakami, and K. Ohnishi: "Vibration Control of 2 Mass Resonant System by Resonance Ratio Control", *Proc. of the Annu. Conf. of IEEE*

- Ind. Electron. Soc. (IECON), pp.2009–2014 (1993)
- (12) M. Iwasaki, M. Kainuma, M. Yamamoto, and Y. Okitsu: “Compensation by Exact Linearization Method for Nonlinear Components in Positioning Device with Harmonic Drive Gearings”, *J. JSPE*, Vol.78, No.7, pp.624–630 (2012)
 - (13) Z. Jamaludin, H.V. Brussel, and J. Swevers: “Friction Compensation of an XY Feed Table Using Friction-Model-Based Feedforward and an Inverse-Model-Based Disturbance Observer”, *IEEE Trans. Ind. Electron.*, Vol.56, No.10, pp.3848–3853 (2009)
 - (14) S. Yamada, K. Inukai, H. Fujimoto, K. Omata, Y. Takeda, and S. Makinouchi: “Joint torque control for two-inertia system with encoders on drive and load sides”, Proc. of the 13th IEEE Int. Conf. Ind. Informat. (INDIN), pp.396–401 (2015)
 - (15) W. Roozing, J. Malzahn, N. Kashiri, D.G. Caldwell, and N.G. Tsagarakis: “On the Stiffness Selection for Torque-Controlled Series-Elastic Actuators”, *IEEE Robotics and Automation Letters*, Vol.2, No.4, pp.2255–2262 (2017)
 - (16) N. Paine, S. Oh, and L. Sentis: “Design and Control Considerations for High-Performance Series Elastic Actuator”, *IEEE/ASME Trans. Mechatronics*, Vol.19, No.3, pp.1080–1091 (2014)
 - (17) H. Zhang, S. Ahmad, and G. Liu: “Torque Estimation for Robotic Joint With Harmonic Drive Transmission Based on Position Measurements”, *IEEE Trans. Robotics*, Vol.31, No.2, pp.322–330 (2015)
 - (18) J. Luh, W. Fisher, and R. Paul: “Joint torque control by a direct feedback for industrial robots”, *IEEE Trans. Ind. Electron.*, Vol.28, No.2, pp.153–161 (1983)
 - (19) Y. Kuroki, Y. Kosaka, T. Takahashi, E. Niwa, H. Kaminaga, and Y. Nakamura: “Cr–N Alloy Thin-film Based Torque Sensors and Joint Torque Servo Systems for Compliant Robot Control”, Proc. IEEE Int. Conf. on Robotics and Automation (ICRA), pp.4954–4959 (2013)
 - (20) S. Oh and K. Kong: “High-Precision Robust Force Control of a Series Elastic Actuator”, *IEEE/ASME Trans. Mechatronics*, Vol.22, No.1, pp.71–80 (2017)
 - (21) S. Yamada and H. Fujimoto: “Proposal of High Backdrivable Control Using Load-Side Encoder and Backlash”, Proc. of the 42nd Annu. Conf. of IEEE Ind. Electron. Soc. (IECON), pp.6429–6434 (2016)
 - (22) M. Nordin and P. Gutman: “Controlling mechanical systems with backlash –a survey”, *Automatica*, Vol.38, No.10, pp.1633–1649 (2002)
 - (23) D.K. Prasanga, E. Sariyildiz, and K. Ohnishi: “Compensation of Backlash for Geared Drive Systems and Thrust Wires Used in Teleoperation”, *IEEJ J. Ind. Appl.*, Vol.4, No.5, pp.514–525 (2015)
 - (24) K. Kaneko, T. Murakami, K. Ohnishi, and K. Komoriya: “Torque Control with Nonlinear Compensation for Harmonic Drive DC Motors”, Proc. of the 20th Annu. Conf. of IEEE Ind. Electron. Soc. (IECON), pp.1022–1027 (1994)
 - (25) M. Odai and Y. Hori: “Speed control of 2-inertia system with gear backlash using gear torque compensator”, Proc. of the 5th Int. Workshop on Adv. Motion Control (AMC), pp.234–239 (1998)
 - (26) I. Kolnik and G. Agranovich: “Backlash compensation for motion system with elastic transmission”, Proc. of the 27th Convention of Electrical and Electronics in Israel (IEEEI), pp.1–5 (2012)
 - (27) M. Yang, C. Wang, D. Xu, W. Zheng, and X. Lang: “Shaft Torque Limiting Control Using Shaft Torque Compensator for Two-Inertia Elastic System With Backlash”, *IEEE/ASME Trans. Mechatronics*, Vol.21, No.6, pp.2902–2911 (2016)
 - (28) S. Yamada, H. Fujimoto, and Y. Terada: “Joint Torque Control for Backlash Compensation in Two-Inertia System”, Proc. of the 25th IEEE Int. Symp. Ind. Electron. (ISIE), pp.1138–1143 (2016)
 - (29) S. Villwock and M. Pacas: “Time-Domain Identification Method for Detecting Mechanical Backlash in Electrical Drives”, *IEEE Trans. Ind. Electron.*, Vol.56, No.2, pp.568–573 (2009)
 - (30) T. Murakami, F. Yu, and K. Ohnishi: “Torque sensorless control in multidegree-of-freedom manipulator”, *IEEE Trans. Ind. Electron.*, Vol.40, No.2, pp.259–265 (1993)
 - (31) S. Yamada and H. Fujimoto: “Design of Load-side External Force Observer with a Load-side Encoder Considering Modeling Errors”, Proc. of the Annu. Conf. of IEEE Ind. Electron. Soc. (IECON), pp.7589–7595 (2017)

Shota Yamada (Student Member) received the B.S. and M.S. degree in the Department of Electrical Engineering and frontier sciences from The University of Tokyo in 2014 and 2016. He is currently working towards the Ph.D. degree in the Department of Electrical Engineering and Information systems at The University of Tokyo. He is also a research fellow (DC1) of Japan Society for the Promotion of Science from 2016. His research interests include force control, two-inertia system control.

Hiroshi Fujimoto (Senior Member) received the Ph.D. degree in the Department of Electrical Engineering from the University of Tokyo in 2001. In 2001, he joined the Department of Electrical Engineering, Nagaoka University of Technology, Niigata, Japan, as a research associate. From 2002 to 2003, he was a visiting scholar in the School of Mechanical Engineering, Purdue University, U.S.A. In 2004, he joined the Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan, as a lecturer and he became an associate professor in 2005. He is currently an associate professor of the University of Tokyo since 2010. He received the Best Paper Awards from the IEEE Transactions on Industrial Electronics in 2001 and 2013, Isao Takahashi Power Electronics Award in 2010, Best Author Prize of SICE in 2010, and The Nagamori Grand Award in 2016. His interests are in control engineering, motion control, nano-scale servo systems, electric vehicle control, motor drive, visual servoing, and wireless motors. Dr. Fujimoto is a member of the Society of Instrument and Control Engineers, the Robotics Society of Japan, and the Society of Automotive Engineers of Japan.