Improvement of Disturbance Suppression Based on Disturbance Observer

Mariko Mizuochi *, Toshiaki Tsuji * and Kouhei Ohnishi*
*Department of System Design Engineering, Keio University, Yokohama, JAPAN

***Abstract*— This research focuses on improvement of disturbance suppression even under existence of observation noise. Disturbance observer is an effective tool to estimate and compensate disturbance. There is a problem, however, that it cannot accomplish desired disturbance suppression when a large observation noise exists. In this research, a method with which influence of disturbance can be suppressed greatly even with a large observation noise is proposed. The authors focus on an LPF used in velocity calculation. The method is proposed based on the analysis on the characteristics and mechanism of disturbance suppression in disturbance observer with a focus on its cut-off frequencies. In the method, the cut-off frequency of disturbance observer is set higher than that for velocity calculation. Validity of the proposal was confirmed in theoretical analysis, simulation, and experiments.**

I. INTRODUCTION

As the robots become popular in many fields, the needs for acquiring high performance with relatively inexpensive equipment have been increasing these days. In order to acquire high performance in motion control or to perform complicated motions, suppression of disturbance on the system is the key technique. Disturbance observer has been proposed to estimate and compensate the whole disturbance torque imposed on the system [1]. Disturbance observer is used in a number of industrial machines since it largely reduces influence of disturbance with simple structure. Disturbance observer has a low pass filter (LPF) in its structure and the cut-off frequency of the LPF decides the performance of disturbance suppression. It is therefore important to set the cut-off frequency high. The cut-off frequency is limited, however, by a sampling period [2] and observation noise. A high cut-off frequency makes the system susceptible to the noise contained in the estimated disturbance torque. There is thus trade-off relationship. Most of the noise is derived from a quantization error of an optical encoder. Since the disturbance calculation is performed in acceleration dimension, derivative calculation is inevitable, but it makes the quantization error larger. A large observation noise makes it difficult to set the cut-off frequency high. As a result, there remains a problem that disturbance suppression performance is insufficient.

Since performance highly depends on the design of the LPF in disturbance observer, many researches have been published on filter design and its analysis [3]-[6]. Umeno proposed the n-th order filter and its simple parameterization [3]. Analysis on high order disturbance observer was conducted in [4]. Sensitivity becomes low and response speed becomes high with increasing the order of disturbance observer. The increase exerts adverse effects on robust stability, however. Filter design and analysis in discrete-time have also been performed [5][6]. The filter is designed based on sensitivity minimization in [5]. [6] analyzed disturbance rejection performance and measurement noise effect of discrete-time disturbance observer. In order to solve the problem of noise in acceleration calculation, a disturbance observer based on velocity information has been proposed [7]. It improves noise sensitivity while it is unstable without an outer loop controller. In practical use, disturbance observer with a 1st order LPF is commonly used due to easiness of design. When position information from an encoder is used for control, pseudo-derivative calculation with an LPF is often utilized for velocity calculation to keep data noise small. In this case, two LPFs are required to calculate disturbance torque. It is believed that the cut-off frequency of disturbance observer should not be higher than that for velocity calculation.

In this research, the authors propose a method to suppress influence of disturbance greatly even in the system with a large observation noise. In most of motion control systems, magnitude of disturbance is usually large in a low frequency range while noise affects the systems severely in a high frequency range. The authors therefore focus on disturbance suppression in a low frequency range and noise sensitivity in a high frequency range. The characteristics of disturbance suppression in disturbance observer are analyzed and investigated with a focus on its cut-off frequencies. A disturbance suppression method is then proposed based on the analysis. The cut-off frequency of disturbance observer is set higher than that for velocity calculation in the method. A comparison with conventional observers is conducted for the results of analysis on disturbance suppression and noise sensitivity. Simulation results on sinusoidal disturbance in various frequencies are presented to show performance of the proposed method. Finally, the proposed method is applied to position control and a bilateral control to verify its validity. Cut-off frequencies are expressed in a unit rad/sec.

II. DISTURBANCE OBSERVER

This section introduces disturbance observer as an effective tool to estimate and compensate disturbance torque. The total disturbance torque defined in disturbance observer τ_{dis} contains mechanical load τ_l, varied self-inertia torque $\Delta J\ddot{\theta}$, and torque ripple from a motor $\Delta K_t I_a^{ref}$. Disturbance torque is obtained by the equation below.

$$\tau_{dis} = K_{tn} I_a^{ref} - J_n \ddot{\theta} \tag{1}$$

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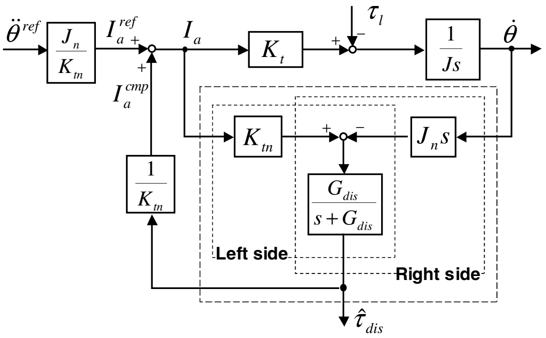


Fig. 1. 1st order disturbance observer

Here, I_a^{ref} denotes the current reference, K_t denotes the torque constant, J denotes the inertia, and the subscript n denotes the nominal value. This paper assumes that a gain of a current minor loop is large enough to treat the current reference as a real current input. The first term $K_{tn}I_a^{ref}$ in (1) is based on input information, and the second term $J_n\ddot{\theta}$ is based on output information. Considering derivative calculation in the second term, the estimated disturbance torque is usually obtained through an LPF.

A. 1st Order Disturbance Observer

Fig. 1 shows disturbance observer with a 1st order LPF, which is the simplest form of the disturbance observer. Here, $\hat{\tau}_{dis}$ denotes the estimated disturbance torque and G_{dis} denotes the cut-off frequency of disturbance observer. Disturbance torque is calculated by the equation below.

$$\hat{\tau}_{dis} = \frac{G_{dis}}{s+G_{dis}}(K_{tn}I_a^{ref} - J_n s\dot{\theta}) \tag{2}$$

The equation shows that disturbance calculation is performed in an acceleration dimension. Influence of disturbance can be suppressed largely by heightening the cut-off frequency. On the other hand, high G_{dis} makes a system easily susceptible to a noise contained in estimated disturbance torque.

In practical use, derivative calculation is required to acquire velocity information when only position information is obtainable. Since the derivative calculation increases the data noise, pseudo-derivative calculation with an LPF shown in the following equation is often utilized.

$$\hat{\dot{\theta}} = s\frac{G_v}{s+G_v}\theta \tag{3}$$

where, G_v denotes the cut-off frequency of the LPF. The block diagram of the disturbance observer therefore becomes as in Fig. 2 and the equation below.

$$\hat{\tau}_{dis} = \frac{G_{dis}}{s+G_{dis}}(K_{tn}I_a^{ref} - J_n\frac{G_v}{s+G_v}s^2\theta) \tag{4}$$

The cut-off frequency for velocity calculation G_v is set higher than G_{dis} in the researches so far conducted since setting G_{dis} higher than G_v has been believed meaningless. Influences of G_v and G_{dis} on disturbance suppression ability and noise sensitivity are analyzed in the later section.

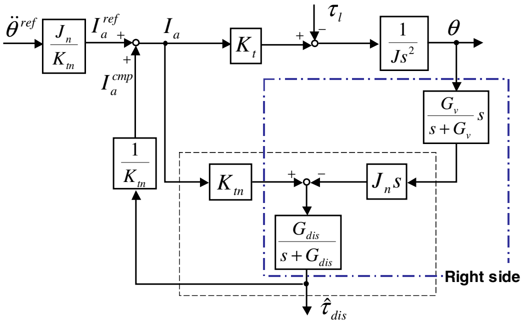


Fig. 2. 1st order disturbance observer in practical use

B. 2nd Order Disturbance Observer [1]

In 2nd order disturbance observer, which contains a 2nd order LPF, disturbance estimation is performed with position information as shown in the following equation.

$$\hat{\tau}_{dis} = \frac{k_1}{s^2+k_2s+k_1}(K_{tn}I_a^{ref} - J_n s^2\theta) \tag{5}$$

The advantages of the observer are as follows:

- the position information can be used directly; and
- many methods are available to design 2nd order filters such as Chebyshev filter and Butterworth filter.

C. Simplified Disturbance Compensator [7]

Disturbance observers shown above require acceleration information and have a problem when the observation noise is large. The simplified disturbance compensator, or velocity-based observer, solves this problem by calculating disturbance torque based on velocity information as shown in the equation below.

$$\hat{\tau}_{dis} = \frac{G_{disv}}{s+G_{disv}}(K_{tn}I_a^{ref} - D\dot{\theta}) \tag{6}$$

A constant value D is used instead of an inverse model of a motor Js. The use of the compensator reduces a risk of instability caused by noise in acceleration information. On the other hand, the observer is unstable when used alone and always requires an outer loop to avoid the instability.

III. MECHANISM OF IMPROVEMENT IN DISTURBANCE SUPPRESSION

This section focuses on disturbance suppression with 1st order disturbance observer and proposes a method to improve the suppression while keeping influence of noise small. As mentioned above, the cut-off frequency of the disturbance observer G_{dis} decides magnitude and the maximum frequency of disturbance suppression. When an observation noise of a system is large, G_v is set low to keep noise in velocity information small. In conventional cases, G_{dis} is also set low in order not to exceed G_v. In this case, G_v rather than G_{dis} limits the performance. Although setting G_{dis} higher than G_v is believed meaningless, analysis of the influence of G_v on disturbance suppression has not yet been performed. In order to verify the influence, disturbance observer was divided into two loops: the outer loop corresponding to the right side of

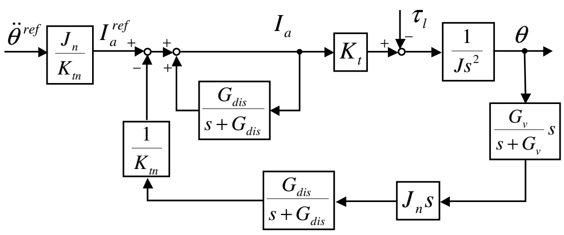


Fig. 3. Equivalent transform of practically used disturbance observer

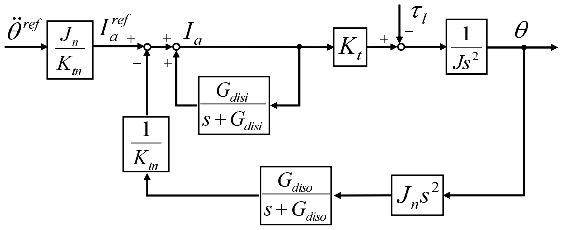


Fig. 4. Decomposition of disturbance observer

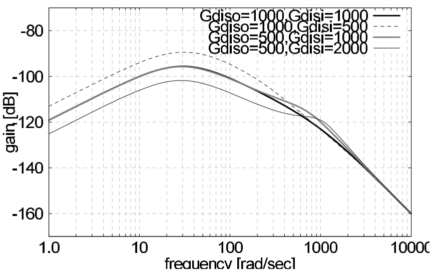


Fig. 5. Bode diagram of disturbance suppression in decomposed observer

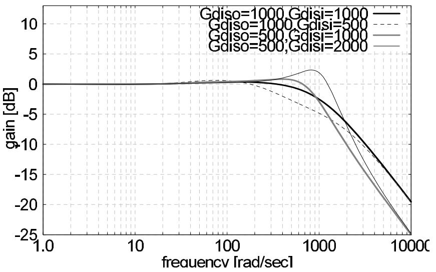


Fig. 6. Bode diagram of noise sensitivity in decomposed disturbance observer

observer in Fig. 1 and the inner loop corresponding to the left. Equivalent transform of practically used disturbance observer shown in Fig. 3 has the factor of G_v only in the outer loop. It implies that the influence of G_v can be clarified by investigating how inner and outer loops contribute to disturbance suppression ability. Analysis was therefore performed with a focus on the cut-off frequencies of inner and outer loops and with reference to Fig. 4 for simplicity.

Position control with a PD controller was assumed as an analysis object. The position information was assumed to contain a observation error ϵ. The closed-loop transfer function from lord torque τ_l to position response θ was used to examine disturbance suppression ability. Noise sensitivity was examined using the closed-loop transfer function from the error ϵ to position response θ. The ratio of nominal inertia to real inertia J_n/J was 1 in all cases. Fig. 5 shows that disturbance suppression ability in a low frequency range was improved by heightening the cut-off frequency of the inner loop G_{disi}. The characteristics became the same when G_{disi} was the same even with different G_{diso}. It seems that the cut-off frequency of the outer loop G_{diso} imposes no influence in a low frequency range while it has small influence in a middle frequency range. The middle range here is around the range between G_{diso} and G_{disi}. In Fig. 6, noise sensitivity seems not to be affected by either G_{disi} or G_{diso} in the low frequency range and to be affected by both of them in the middle frequency range. The characteristics in the high frequency range were determined mainly by G_{diso}.

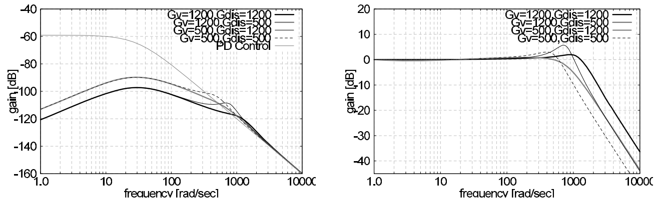
According to the analysis, improvement of disturbance suppression can be expected by heightening only G_{disi}, even if G_{diso} is kept low due to noise. It is therefore preferable to set G_{disi} high to improve disturbance suppression ability, while G_{diso} should be set with a consideration of disturbance suppression in the middle frequency range and noise sensitivity. It shows the usefulness of setting G_{disi} higher than G_{diso}. Returning to the original discussion, G_{disi} corresponds to G_{dis} and G_{diso} corresponds to both G_{dis} and G_v. The advantage of setting G_{dis} higher than G_v is therefore confirmed from the analysis above. The authors propose to set G_{dis} higher than G_v when the influence of observation noise is large enough to limit the performance of disturbance suppression. Disturbance suppression ability in a low frequency range improves dramatically with the proposed method while keeping the influence of observation noise in the high frequency range low. The effect of the proposal is analyzed in detail and compared with that of other disturbance observers in the next section.

IV. CHARACTERISTICS OF PROPOSED METHOD

A. Analysis on Disturbance Suppression and Noise Sensitivity

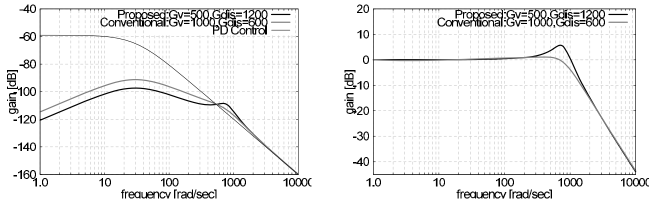
Analysis on disturbance observer shown in Fig. 2 is demonstrated in Fig. 7. The results show that disturbance suppression in a low frequency range was determined by G_{dis} and noise sensitivity in a high frequency range was determined by the product of G_v and G_{dis}. In Fig. 8, G_v and G_{dis} were set to keep $G_v G_{dis}$ at the same value; $G_v = 500$, $G_{dis} = 1200$ in the proposed method and $G_v = 1000$, $G_{dis} = 600$ in the conventional. Disturbance suppression in a low frequency range improved in the proposed method as compared with the conventional case, while noise sensitivity in a high frequency range was the same.

Characteristics of the proposed method were compared with those of other observers. The cut-off frequencies were set at $G_v = 500$, $G_{dis} = 1000$ in the proposed method. G_{disv} in the velocity-based disturbance observer was set to be equal to G_{dis}. In the 2nd order observer, k_1 and k_2 were designed with Butterworth filter. The cut-off frequency of the filter was 1000. Figs. 9 and 10 show comparison. The 2nd order observer was inferior to the proposed method on disturbance suppression in a low frequency range while the velocity-based observer showed almost the same performance. Here, disturbance suppression depends on a cut-off frequency of the



(a) Disturbance Suppression (b) Noise Sensitivity

Fig. 7. Bode diagram of practically used disturbance observer



(a) Disturbance Suppression (b) Noise Sensitivity

Fig. 8. Comparison on bode diagram of proposed and conventional method

left loop of the observer. The 2nd order observer contains a 2nd order LPF in the left loop in addition to the right loop. This is considered to be attributable to the inferiority of the 2nd order observer mentioned above. In the velocity-based observer, performance deteriorated in a particular frequency range around the middle frequency range. The deterioration was confirmed also in the proposed method, but it was much smaller. In terms of noise sensitivity, sensitivity was larger in the 2nd order observer than in the proposed method in a high frequency range. The difference may arise from the following reasons. Influence of noise is reduced by two LPFs whose cut-off frequencies are 500 and 1000, respectively in the proposed method, while it is reduced only by one 2nd order LPF with cut-off frequency of 1000 in 2nd order observer. An LPF with a cut-off frequency of 500 in the proposed method may play a large role in reducing the influence of noise. In case of the velocity-based observer, sensitivity became large in the range performance where deterioration confirmed, while it became smaller than that of other observers in a high frequency range.

According to these comparisons, the proposed observer kept noise sensitivity lower and achieved better disturbance suppression compared with the 2nd order observer in low and high frequency ranges. The proposed observer is therefore superior to the 2nd order observer both in disturbance suppression ability and noise sensitivity. The velocity-based observer achieved performance almost equal to the proposed method except magnitude of the performance deterioration. A large difference from the proposal is that the velocity-based observer always requires an outer loop to avoid instability. In this point, the proposed method is superior to the velocity-based observer.

B. Response to Sinusoidal Disturbance

The responses to sinusoidal disturbance of various frequencies in a real system are verified in this subsection. The proposed method set the cut-off frequencies at $G_v = 100$ and $G_{dis} = 500$. Frequency of disturbance was changed from 10 Hz to 100 Hz. A comparison with conventional manners of setting is demonstrated in Fig. 11. When the frequency of disturbance was low, the proposed method worked the same as the disturbance observer with $G_v = G_{dis} = 500$. The performance deteriorated a little when the frequency was bit higher than G_v. When disturbance was 50 Hz, the performance became worse in the proposed method. This result well corresponds to the deterioration confirmed in the analysis. The performances were almost the same for all the settings with extremely high frequency disturbance. According to these results, improvement of disturbance suppression with the proposed method was confirmed in a low frequency range, though there was the influence of performance deterioration in a certain frequency range. It seems that the bandwidth of disturbance suppression was not improved with the proposed method. Therefore, in practical use, it is better to heighten both G_v and G_{dis} to the maximum value of permissible oscillation. Then, G_{dis} should be heightened further while keeping G_v at the maximum value. This procedure enables the system to prevent deterioration of the bandwidth and to improve the disturbance suppression in a low frequency range. In most motion control systems, magnitude of disturbance is usually large in a low frequency range and the influence of noise is severe in a high frequency range. Improvement of disturbance suppression in a low frequency range while reducing the influence of noise in a high frequency range must therefore be useful.

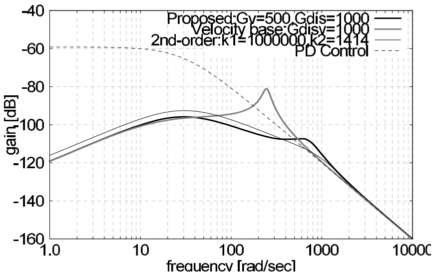


Fig. 9. Bode diagram of disturbance suppression in disturbance observers

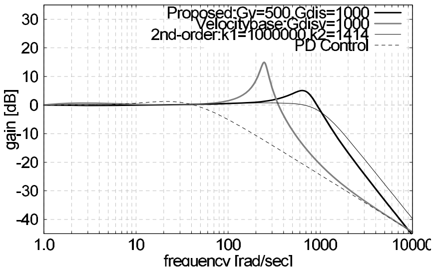
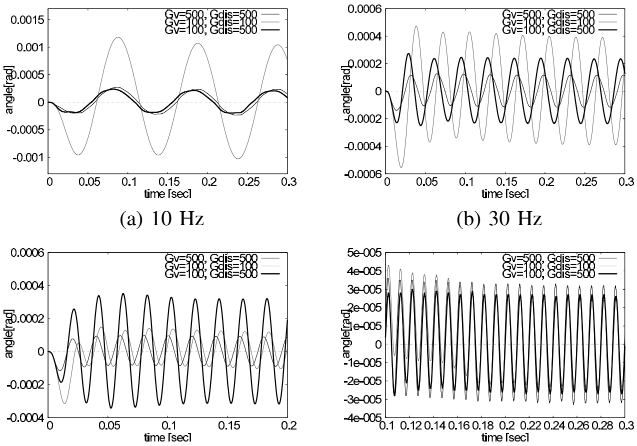


Fig. 10. Bode diagram of noise suppression in disturbance observers

V. APPLICATIONS

A. Experimental Setup

Experimental equipment is a single-link direct-drive manipulator composed of a motor, an encoder and an arm. The length of the manipulator is 0.06 m, and inertia of it is 0.0000272 Kgm^2. Since the arm is light and friction is small, the



(a) 10 Hz (b) 30 Hz

(c) 50 Hz (d) 100 Hz

Fig. 11. Position response to various frequencies disturbance

manipulator easily oscillates and becomes unstable with noise. The simulations were performed in an ideal model without any quantization error. The encoder with 81,000 pulses/rev was used in the experiments for data acquisition. The performance of the encoder was reduced to 2,000 pulses/rev in software to build the system with a low resolution encoder.

B. Experiments on Position Control

PD control with disturbance observer was applied to control the manipulator to the trajectory shown in the equation below.

$$\theta^{cmd} = 0.5 \cos 2t - 0.5 \tag{7}$$

Virtual disturbance torque 0.05 Nm was given from $t = 7.0$ sec to $t = 7.5$ sec. A sampling period was 0.2 msec in all cases. Position gain K_p and velocity gain K_v were $K_p = 1600$ and $K_v = 80$, respectively.

Figs. 12 and 13 show the position error when the disturbance was added. Fig. 12 compares the results at $G_v = 500, G_{dis} = 400$ and $G_v = 300, G_{dis} = 400$ to show the influence of setting G_v lower. Even though G_v was set lower than G_{dis}, the response to the disturbance was almost the same in both cases. It shows that not G_v but G_{dis} decides the performance, and the adverse effect was not confirmed. It verifies the effectiveness of improvement in disturbance suppression in a low frequency range. Then in Fig. 13, G_{dis} is heightened while keeping G_v at 500. G_{dis} could be heightened to 1000 without divergence. As a result, influence of disturbance was greatly reduced with the proposed method.

C. Bilateral Control

In bilateral control, high robustness to disturbance is required since bilateral systems are envisioned to be utilized in remote places and are made contact with unknown objects during operation. This research utilized a bilateral controller proposed in [8]. This controller divides the system into two coordinates; common and differential. Position control with disturbance observer is applied to the differential coordinate, while force control is used in the common coordinate. External torque of each system is acquired through reaction torque observer[9]. Input of an operator and environmental force in simulation are represented in a spring and damper model. Parameters are demonstrated in TABLE I.

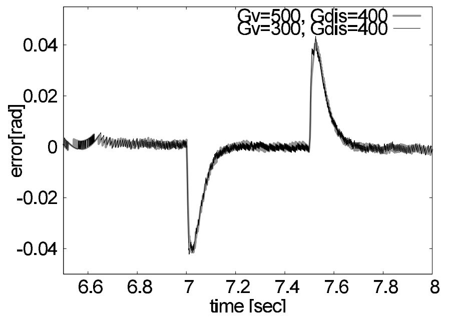


Fig. 12. Position error in position control: different G_v

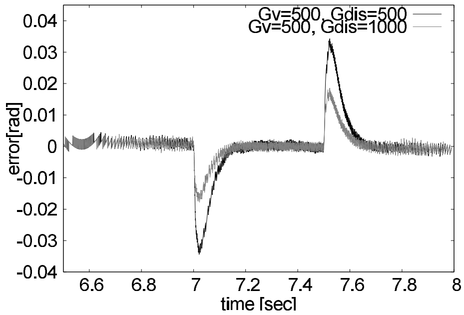


Fig. 13. Position error in position control: different G_{dis}

1) Simulations: Simulations were conducted to confirm the influence of setting G_v lower than G_{dis}. The master manipulator was moved with a step input. The master manipulator moved excessively at the moment that the slave manipulator was made contact with an object. This excess prevents the operator from feeling the real sensation of touching the object. The authors therefore focus on the difference between master and slave positions in Fig. 14. The results were almost the same when G_{dis} was the same value even with lower G_v, and the proposed method imposed no adverse effect on performance. The fact indicates that the performance of following each other was decided by G_{dis} rather than G_v. Moreover, improvement in following ability is therefore expected with the proposed method when the product of G_v and G_{dis} is limited due to observation noise.

2) Experiments: The master manipulator was moved by an operator so that the slave manipulator touched an aluminum object with about 0.2 Nm torque. When G_v and G_{dis} were

TABLE I

PARAMETERS IN BILATERAL CONTROL

S_t	Sampling period	[msec]	0.1
K_{p-}	Position gain	[rad/sec]	2500
K_{v-}	Velocity gain	[rad/sec]	100
K_f	Force gain	[rad/sec]	1.0
K_{hum}	Spring coef. of operator	[N/m]	400
D_{hum}	Damper coef. of operator	[N·sec/m]	40
K_{env}	Spring coef. of environment	[N/m]	12000
D_{env}	Damper coef. of environment	[N·sec/m]	100

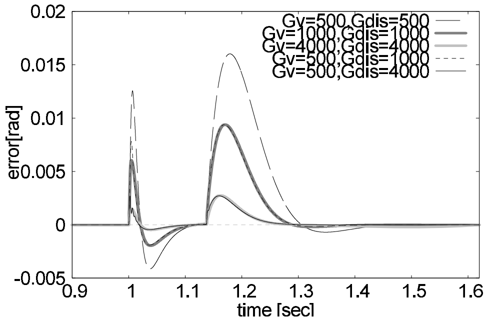


Fig. 14. Position difference between master and slave in simulation

set equal, manipulators oscillated with $G_v = G_{dis} = 600$. G_v was therefore set to 500 and G_{dis} was heightened. G_{dis} could be increased to 4000 without any oscillation recognized. Responses of the master and slave and the difference of position at a contact moment are shown in Fig. 15. The difference became small by heightening G_{dis} even though G_v was kept low. Although the object was made of aluminum and hard, the operator felt the object soft when $G_{dis} = 500$. On the other hand, sense of a hard object was acquired with $G_{dis} = 3500$. The results verify that bilateral control performance was improved dramatically with the proposed method. Bilateral control with vivid sensation was then accomplished with a low resolution encoder, which has not been achieved so far.

VI. CONCLUSION

This paper proposed the method to improve disturbance suppression based on the characteristics analysis of disturbance suppression in disturbance observer. Disturbance suppression performance in a low frequency range was greatly improved while keeping the influence of observation noise in a high frequency range small. Since magnitude of disturbance is usually large in a low frequency range while the influence of noise is severe in a high frequency range, the method must be highly effective in most of motion control systems. A comparison with conventional observers in the analysis on disturbance suppression and noise sensitivity shows superiority of the proposed method. Influence of disturbance became much smaller with the proposed method in experiments. In bilateral control, improvement was confirmed in response at contact moment. As a result, bilateral control with vivid force sensation was accomplished in the system with a low resolution encoder.

ACKNOWLEDGEMENT

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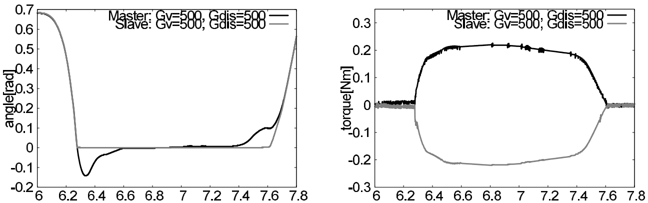
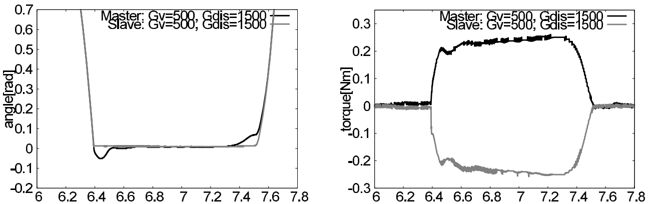


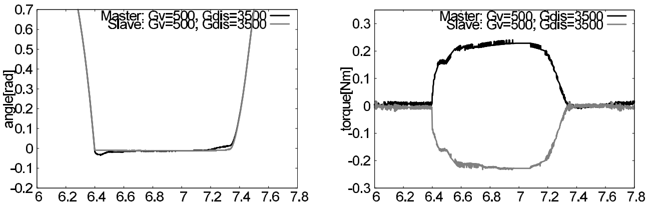
(a) Position response ($G_v = 500,\ G_{dis} = 500$)

(b) Force response ($G_v = 500,\ G_{dis} = 500$)



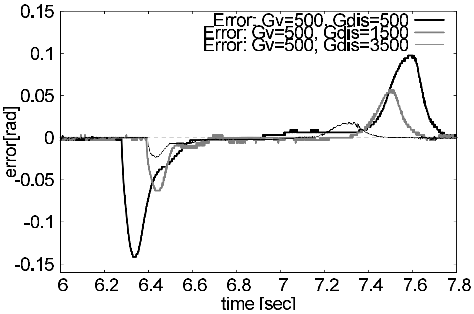
(c) Position response ($G_v = 500,\ G_{dis} = 1500$)

(d) Force response ($G_v = 500,\ G_{dis} = 1500$)



(e) Position response ($G_v = 500,\ G_{dis} = 3500$)

(f) Force response ($G_v = 500,\ G_{dis} = 3500$)



(g) Position difference of master and slave

Fig. 15. Experimental results of bilateral control

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