External Disturbance Rejection Control based on Identification of Transfer Characteristics from the Acceleration Sensor for Access Control of Hard Disk Drive System

Nobutaka Bando, Sehoon Oh and Yoichi Hori

Department of Electrical Engineering, The University of Tokyo,
7-3-1 Hongo Bunkyo-ku, Tokyo 113-8658, JAPAN
Tel: +81-3-5841-6778, Fax.: +81-3-5841-8573
E-mail: bando@hori.t.u-tokyo.ac.jp, sehoon@hori.t.u-tokyo.ac.jp, hori@hori.t.u-tokyo.ac.jp

Abstract: In this paper, a new method for the external disturbance rejection control which is based on the identification of transfer characteristics from the acceleration sensor is proposed. For hard disk drives, the external disturbance which should be reduced is growing with widespread use of movable computers and other independent machines. In order to reject the effect of the external disturbance we apply the feedforward controller which is designed by Recursive Least Squares (RLS) algorithm and Fixed Trace (FT) algorithm utilizing the acceleration signal and the estimated disturbance signal. Some experimental results in which a disk drive is shaken in the vertical direction are shown to verify the effectiveness of the proposed method.

Key words: Hard Disk Drive, Accelerometer,
External Disturbance Rejection, Feedforward Control
Recursive Least Squares Algorithm

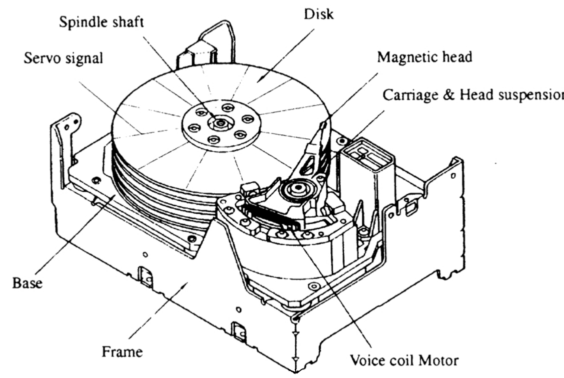


Fig.1: Overview of Hard Disk Drive System

1 Introduction

Control performance of the hard disk drive system has been desired to be more quick and accurate for the demand of high density and capacity. As a result of several researcher's efforts, the hard disk drive system has achieved very high performance. But while movable computers are in widespread use, it is necessary to work well under vibrational circumstances.

In tracking control of hard disk drive system, two kinds of servos are applied, the **seek** mode and the **following** mode. In the **seek** mode, the head moves from the current track to the desired track. In the **following** mode, the head should stay in the certain track to read/write data on the disk. Especially in the **following** mode robustness against disturbance and fluctuation of the plant is required.

In order to improve the performance of the **following** mode, many methods have been proposed[1]. Due to development of low cost but high quality accelerometers, accelerometers can be used for compensating external and internal disturbances[2]. White and Tomizuka proposed a feedforward controller to reduce the rotational vibration by matching the electromechanical impedance between the accelerometer and **PES**(Position Error Signal)[3]. Pannu and Horowitz also proposed an adaptive feedforward controller using the dynamics between the accelerometer and **PES**[4]. Beak and Lee canceled the phase delay of the accelerometer[5].

This paper also proposes a feedforward controller with accelerometer, too. The proposed feedforward controller differs from the existing controllers at the point that we use the dynamics between the accelerometer and the disturbance of the system, which isn't directly observed. In order to resolve this problem, we utilize the Disturbance Observer[6]. Using this method, we can directly reject the external disturbance very effectively.

2 Identification from the Acceleration Sensor

2.1 Structure of the System

Block diagram for the access control of hard disk drive system under vibration is drawn in Fig.2. In Fig.2, P is the actuator dynamics, C is the conventional feedback controller, ref represents the control reference, which is usually 0 in the **following** mode, $Noise$ has the forms of **RRO**(Repetitive RunOut) and **NRRO**(Non-Repetitive RunOut), PES is the Position Error Signal and vcm is the control input of the

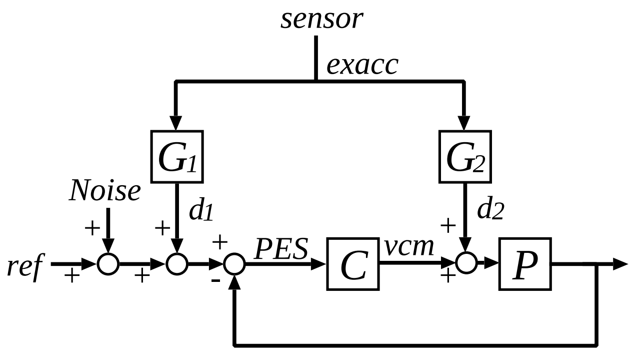


Fig.2: Block Diagram for Access Control of Hard Disk Drive System Under Vibration

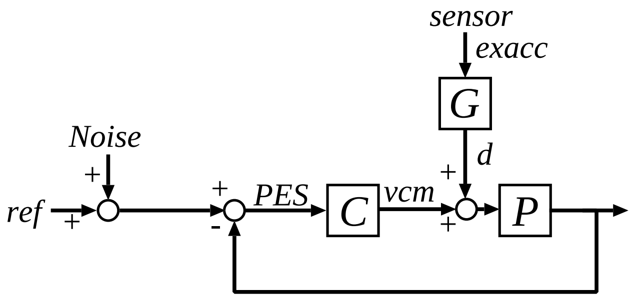


Fig.3: Transfer Characteristics from the Acceleration Sensor to Disturbance of the System

Voice Coil Motor. The external disturbance *exacc* exerts bad influence to the system by the disk fluctuation d_1 and the head fluctuation d_2 through G_1, G_2 which denote the dynamics between *exacc* and d_1, d_2. The transfer characteristics from *exacc* to PES can be described in (2) in which S expresses the sensitivity function in (1).

$$
\begin{aligned}
S &= \frac{1}{1+CP} && (1)\\
PES &= (G_1 + P \cdot G_2) \cdot S \cdot exacc && (2)
\end{aligned}
$$

Here, the transfer characteristics from the acceleration sensor to the disturbance of the system d is redefined as G in Fig.3 and (3). This transfer characteristics is expressed by the general discrete transfer function with limited order as in (4).

$$
\begin{aligned}
G &= \frac{G_1 + P \cdot G_2}{P} && (3)\\
d &= G \cdot exacc = \frac{B(z^{-1})}{A(z^{-1})} \cdot exacc && (4)\\
A(z^{-1}) &= 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{N_a} z^{-N_a} \\
B(z^{-1}) &= b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{N_b} z^{-N_b}
\end{aligned}
$$

2.2 Identification with Disturbance Observer

Various methods were reported to identify such systems. In this paper, we apply two well-known algorithms. Recursive Least Squares (RLS) algorithm and

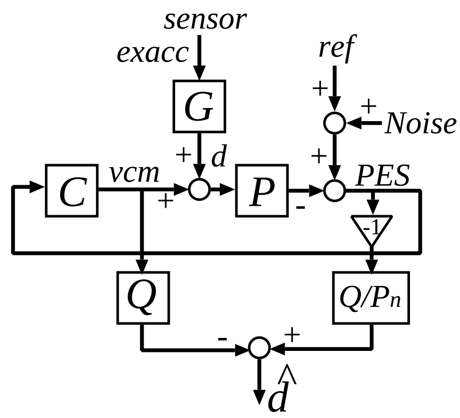


Fig.4: Block Diagram of the Disturbance Observer to Get the Estimated Disturbance

Fixed Trace (FT) algorithm to identify the transfer characteristics. Both algorithms can be formulated as (5) $\sim$ (8).

$$
\begin{aligned}
\hat{\boldsymbol{\theta}}(k) &= \hat{\boldsymbol{\theta}}(k-1) + \frac{\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}\varepsilon(k) && (5)\\
\varepsilon(k) &= \hat{d}(k) - \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}(k-1) && (6)\\
\boldsymbol{\Gamma}(k) &= \frac{1}{\lambda(k)}\{\boldsymbol{\Gamma}(k-1) \\
&\quad - \frac{\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}\} && (7)\\
\lambda(k) &= 1 - \frac{\|\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)\|^2}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}\frac{1}{tr\boldsymbol{\Gamma}(0)} && (8)
\end{aligned}
$$

Here, $\boldsymbol{\Gamma}(k)$ is the covariance matrix, $\hat{\boldsymbol{\theta}}(k)$ is the identified parameter as expressed in (9) and $\boldsymbol{\varphi}(k)$ is the signals of the input and the output of the identified transfer characteristics as in (10). In RLS algorithm the identified parameter $\hat{\boldsymbol{\theta}}(k)$ is determined so that the error as (6) is minimized. In addition, using FT algorithm the parameter of the transfer function can be identified properly, because FT algorithm automatically sets the forgetting factor $\lambda(k)$ by the magnitude of the signals of the input and the output $\boldsymbol{\varphi}(k)$ as (8).

$$
\begin{aligned}
\hat{\boldsymbol{\theta}}(k) &= [\hat{a}_1, \cdots, \hat{a}_{N_a}, \hat{b}_1, \cdots, \hat{b}_{N_b}]^T && (9)\\
\boldsymbol{\varphi}(k) &= [-d(k-1), \cdots, -d(k-N_a), \\
&\quad exacc(k-1), \cdots, exacc(k-N_b)]^T && (10)
\end{aligned}
$$

But in practice, the external disturbance $d(k)$ can't be observed directly. In order to resolve this problem, we utilize the Disturbance Observer in Fig.4 to estimate disturbance. Here, Q is the low-pass filter, P_n is the transfer function of the nominal plant and $\hat{d}$ is the

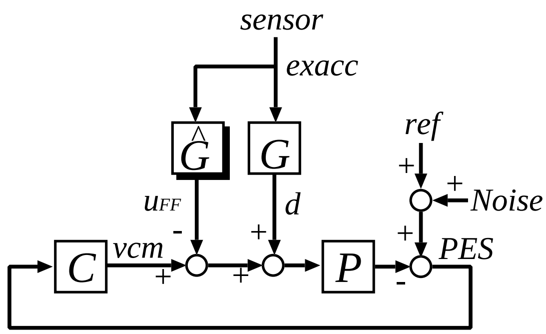


Fig.5: Block Diagram of Disturbance Rejection Control with Feedforward Input

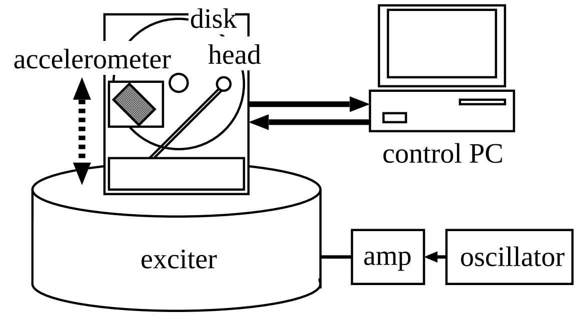


Fig.6: Configuration of Experimental System

estimated disturbance.

$$
\begin{aligned}
\hat{d} &= \{-\frac{-CP}{1+CP}\cdot Q+\frac{Q}{P_n}\frac{P}{1+CP}\}\cdot d \\
&\quad -\frac{Q}{P_n}\frac{1}{1+CP}\{ref+Noise\} \qquad (11)\\
&= \frac{\frac{P}{P_n}+CP}{1+CP}\cdot Q\cdot d+\xi \qquad (12)\\
&\approx Q\cdot d+\xi \qquad (13)
\end{aligned}
$$

In (12) we assumed that P is close to P_n, and ξ expresses the influence of the $Noise$ and the difference between P and P_n. With the estimated disturbance $\hat{d}$, (10) is substituted by (15). In (15), low-pass filter Q is added to $exacc$ to make Q and $\hat{d}$ consistent.

$$
\begin{aligned}
\boldsymbol{\varphi}'(k) &= [-\hat{d}(k-1),\cdots,-\hat{d}(k-N_a),\\
&\quad Q\cdot exacc(k-1),\cdots,Q\cdot exacc(k-N_b)]^T \qquad (14)\\
&\approx [-Q\cdot d(k-1),\cdots,-Q\cdot d(k-N_a),\\
&\quad Q\cdot exacc(k-1),\cdots,Q\cdot exacc(k-N_b)]^T \qquad (15)
\end{aligned}
$$

3 Design of Feedforward Input

In previous section, we proposed an identification of the transfer characteristics. Using this transfer characteristics, we design the feedforward input u_{FF} in (16). The external disturbance $d(k)$ is rejected by feedforward input u_{FF}(Fig.5). As a merit of this method, feedforward input u_{FF} can be applied to the system without reconstruction of the system.

$$
\begin{aligned}
u_{FF}(k) &= \hat{G}\cdot exacc(k) \qquad (16)\\
&= \hat{B}(z^{-1})exacc(k)+\{1-\hat{A}(z^{-1})\}u_{FF}(k) \qquad (17)\\
&= \hat{b}_1 exacc(k-1)+\cdots+\hat{b}_{N_b}exacc(k-N_b)\\
&\quad +\hat{a}_1 u_{FF}(k-1)+\cdots+\hat{a}_{N_a}u_{FF}(k-N_a) \qquad (18)
\end{aligned}
$$

4 Experiment with Hard Disk Drive

4.1 Experimental Setup

In previous sections, we described the identification from the acceleration sensor and the design of the feedforward input. In experiments both algorithms run at the same time in the **following** mode.

Fig.6 shows the configuration of the experimental system. The accelerometer is mounted on the base of a hard disk drive to measure the external disturbance and the hard disk drive is shaken by the exciter in the direction, perpendicular to the spindle motor's axis by the sinusoidal wave. The accelerometer is installed in the direction so as to maximize the sensitivity of the accelerometer for the carriage's movement.

In each sampling time the hard disk drive sends PES and the acceleration signal to the control PC and the control PC sends vcm and u_{FF} to the hard disk drive. The conventional FB controller is composed of PID controller which is already tuned. All system is carried out by the sampling time of 158[μs]

The cut-off frequency of the low-pass filter in the Disturbance Observer is set to 500[**Hz**]. The order of the identified parameter $\hat{\boldsymbol{\theta}}(k)$ are decided to $N_a = N_b = 4$ in the experiments.

4.2 Experimental Result

Figs.7 $\sim$ 12 show the experimental result. In Figs.7, 9 and 11 the time series of **PES** under 60[**Hz**], 100[**Hz**] and 300[**Hz**] vibration(2.0[**G**]) are shown. The hard disk drive is controlled by the conventional FB controller (0[**ms**] $\sim$ 500[**ms**]) and by the conventional FB controller including the proposed FF controller (500[**ms**] $\sim$ 2000[**ms**]). Additionally characteristics of Fourier transform about **PES** are shown in Figs.8, 10 and 12 under each vibration. As below, control performances for each frequency disturbance are discussed.

1. Control Performance for Low Frequency Disturbance($\sim$80[**Hz**])
   Figs.7, 8 show the experimental result for 60[**Hz**] disturbance. For low frequency disturbance, conventional FB controller can suppress the dis-

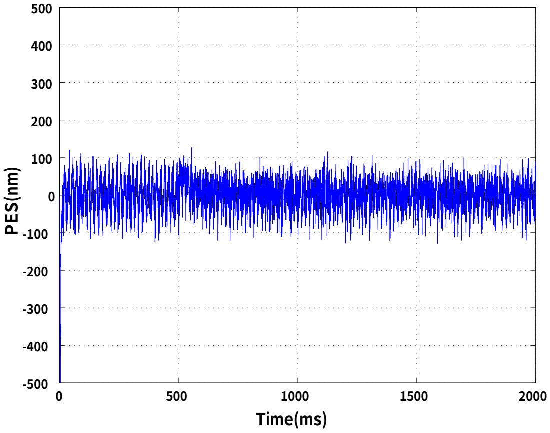


Fig.7: Time Series of PES under 60[**Hz**] vibration

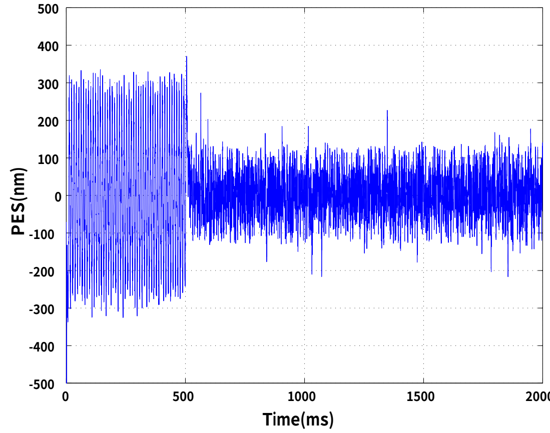
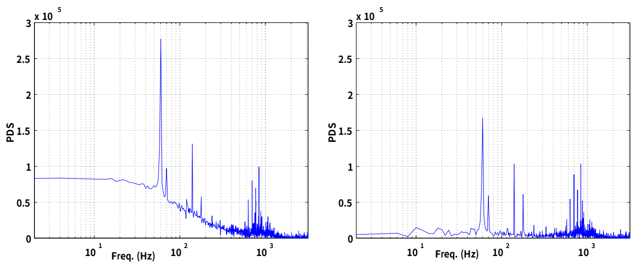


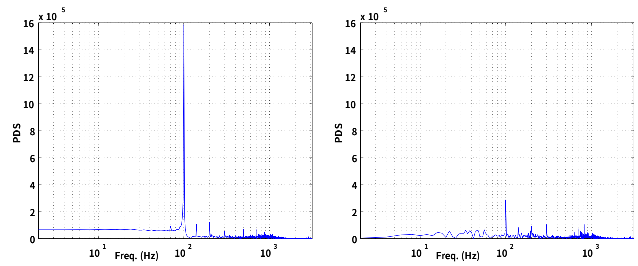
Fig.9: Time Series of PES under 100[**Hz**] vibration



(a)0[**ms**] $\sim$ 500[**ms**] without the proposed FF

(b)1500[**ms**] $\sim$ 2000[**ms**] with the proposed FF

Fig.8: Characteristics of Fourier Transform about PES under 60[**Hz**] vibration



(a)0[**ms**] $\sim$ 500[**ms**] without the proposed FF

(b)1500[**ms**] $\sim$ 2000[**ms**] with the proposed FF

Fig.10: Characteristics of Fourier Transform about PES under 100[**Hz**] vibration

turbance well. After applied the proposed FF controller, the proposed controller can additionally suppress the 60[**Hz**] vibration without harm to performance of the conventional FB controller(Fig.8).

2. Control Performance for Middle Frequency Disturbance(90[**Hz**]∼200[**Hz**])
   Figs.9, 10 show the experimental result for 100[**Hz**] disturbance. For middle frequency disturbance, the conventional FB controller can't suppress disturbance because the frequency of disturbance goes beyond the controllable band of the conventional FB controller. On the contrary, after applied the proposed FF controller, middle frequency disturbance can be suppressed remarkably.

3. Control Performance for High Frequency Disturbance(300[**Hz**]∼)
   Figs.11, 12 show the experimental result for 300[**Hz**] disturbance. In high frequency, though the frequency of disturbance goes beyond the controllable band of the conventional FB controller, disturbance influence doesn't appear strongly because the transfer function between the disturbance and **PES** has the low gain characteristics. But after applied the proposed FF controller, high frequency disturbance can be suppressed additionally.

Fig.13 shows the 3σ of **PES** in experiments. 3σ expresses the possible maximum error statistically. In Fig.13, 2.0(**G**) means the acceleration amplitude of the external disturbance. By the comparison with the proposed controller and without the proposed controller, the proposed FF controller can remarkably suppress the vibration which is not possible for the conventional FB controller in all frequency of disturbance.

5 Conclusion

In this paper, we propose a novel method for the external disturbance rejection control, based on the identification of transfer characteristics from the acceleration sensor for access control of hard disk drive system. In this method, we can identify the transfer characteristics from the acceleration sensor with the Disturbance Observer and design the feedforward controller. In the experiments **PES** is reduced by the proposed feedforward controller under vibration, especially in middle frequency that the conventional FB controller can't perform sufficiently. Recently, hard disk drives are used not only for computers but also

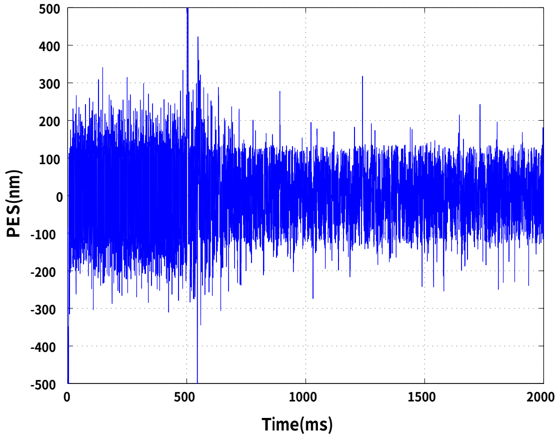
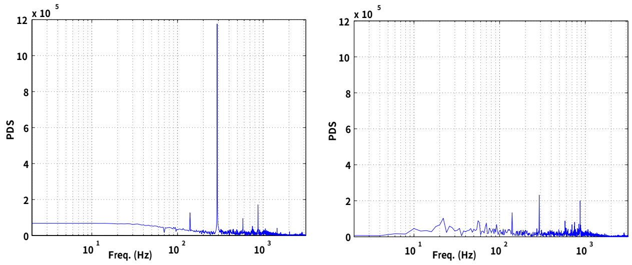


Fig.11: Time Series of PES under 300[**Hz**] vibration



(a)0[**ms**] $\sim$ 500[**ms**] without the proposed FF

(b)1500[**ms**] $\sim$ 2000[**ms**] with the proposed FF

Fig.12: Characteristics of Fourier Transform about PES under 300[**Hz**] vibration

for other machinery to utilize the performance and the capacity of disk drives. In the future this tendency is expected to continue and therefore hard disk drives are significant subject of research.

6 Acknowledgement

The authors would like to acknowledge TOSHIBA co. ltd. for supporting and providing experimental equipments used in this work, and H. Suzuki, S. Yanagihara, M. yatsu, M. Iwashiro and H. Sado of TOSHIBA co. ltd. for their useful discussion and arrangement of experimental setup.

References

[1] Ho Seong Lee: "Controller Optimization for Minimum Position Error Signals of Hard Disk drives", *IEEE Trans. on Industrial Electronics*, Vol. 48, No. 5, 2001.

[2] Jun Ishikawa, Masayoshi Tomizuka: "Pivot Friction Compensation Using an Accelerometer and Disturbance Observer for Hard Disk Drives", *IEEE/ASME Trans. on Mechatronics*, Vol. 3, No. 3, 1998.

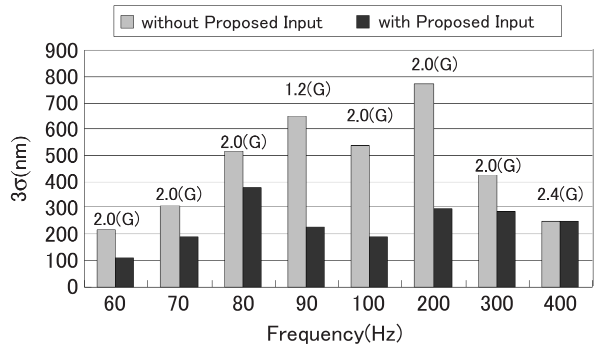


Fig.13: Comparison of 3σ of PES with Proposed Input and without Proposed Input

[3] Matthew T. White, Masayoshi Tomizuka: "Increased Disturbance Rejection in Magnetic Disk Drives by Acceleration Feedforward Control", *Proceedings of the 13th IFAC*, San Francisco, USA, 1996.

[4] Satinderpall Pannu, Roberto Horowitz: "Accelerometer Feedforward Servo for Disk Drives", *Proceedings AIM'97*, Tokyo, Japan.

[5] Sang-Eun Beak, Seung-Hi Lee: "Vibration Rejection Control for Disk Drives by Acceleration Feedforward Control", *Proceedings of the 38th Conference on Decision and Control*, Phenix, Arizona USA, 1999.

[6] Takaji Umeno, Tomoaki Kaneko, Yoichi Hori: "Robust Servosystem Design with Two Degrees of, Freedom and its Application to Novel Motion Control of Robust Manipulators", *IEEE Trans. on IE*, Vol. 40, No. 5, pp. 473-485, 1993.