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Robust and Quick Response Tracking Servo System for High Rotational Speed Optical Disk System

Kiyoshi Ohishi * Toshimasa Miyazaki ** Yasuharu Yoshida * Yoshiya Kamigaki * Daiichi Koide *** Haruki Tokumaru ***

* *Nagaoka University of Technology, Niigata, JAPAN (e-mail: ohishi@vos.nagaokaut.ac.jp, y0210y@stn.nagaokaut.ac.jp, kamigaki@stn.nagaoka-ct.ac.jp).*
** *Nagaoka National College of Technology , Niigata, JAPAN (e-mail: miyazaki@nagaoka-ct.ac.jp)*
*** *NHK Science and Technical Research Laboratories, Tokyo, JAPAN (e-mail: koide.d-jy@nhk.or.jp, tokumaru.h-dy@nhk.or.jp)*

Abstract: Generally, tracking control for optical disk system is accomplished by the feedback control designed by using PID control, repetitive control and so on. However, it is difficult to reduce the tracking error on condition of high disk rotation speed. In the near future, the disk rotation speed of the optical disk system becomes higher than 10000[rpm]. Therefore, the tracking servo system for optical disk system must have the new structure and highly performance. This paper proposes a new free parameter and desgin method of feedback servo system, which suppresses the high speed periodic disturbance. It has the widebandwidth and high gaim margin. Moreover, in order to suppress this periodic disturbance, this paper proposes a new control structure of robust feedforward servo system, which includes the prediction of tracking error, a new design method of disturbance observer and the zero error phase tracking control. The experimental results point out that the proposed system well regulates the high precision tracking servo control on condition of the disk rotation speed 8000[rpm], which is equal to CD system of 40 X speed.

1. INTRODUCTION

In the near future, the disk rotation speed of the optical disk system becomes higher than 10000[rpm][1]. Therefore, the tracking servo system for optical disk system must have the quick response on condition of high disk rotation speed. Since the optical disk systems have a radial run-out, its phenomenon becomes the periodic disturbance whose bandwidth depends on the disk rotational speed. It is difficult to keep the residual tracking error on condition of high disk rotation speed. Because the optical disk system will become the narrower track pitch and the more high rotation speed, the tracking control system of optical disk should be reducing the tracking error caused by periodic disturbance. Moreover, optical disk system sometimes has the influence of sudden disturbance such as force disturbance caused by shaking. Therefore, the tracking control system for high rotation speed optical disk system must have the high precision performance and the wide bandwidth.

The current method of tracking control for mass product optical disk system also becomes to the digital feedback control system based on PID controller, phase lead-lag compensator and so on[2],[3]. These control system has a very simple structure, then it is easy realization on mass-product system. The hardware of tracking control system, such as DSP and so on does not have high-performance system in any mass-product models. However, it is difficult for only feedback control system to reduce the tracking error below the target tolerance. On the other hand, the repetitive control or PTC has carried out the precise tracking control[4],[5],[6],[7]. However, it is difficult to keep the robust performance on parameter variation[8] and to realize the math product system which caluclate step is very large.

In our previous work[1], the feedforward tracking control system with ZPET[9].[10] controller and the prediction of tracking error is able to reduce the residual tracking error and keep tracking error on condition of high disk rotation speed. The feedforward tracking control is very effective. It is not same to repetitive control. However, the conventional method for prediction of tracking error becomes complex. And the amount of the operation for feedforward control system becomes large. It is difficult to realize the tracking control system on mass-product optical disk system.

For the purpose of applying the mass-product optical disk system, the tracking control system requires both the high precision control under the condition of high disk rotation speed and the simple structure. Hence, this paper proposes a new control method and realizes the high precision tracking control on condition of the disk rotation speed. First, this paper proposes a new free parameter for robust feedback control system including the sudden disturbance observer structure[11],[12]. Second, this paper proposes a simple structure for ZPET-FF controller. The

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experimental results point out that the proposed system realizes the high precision tracking control on condition of the disk rotation speed 8000[rpm], which is equal to CD system of 40 X speed.

2. ROBUST FEEDBACK CONTROL DESIGN BASED ON LOOP SHAPING METHOD

As the target system, this paper uses the optical disk system DDU-1000, whose maximum disk revolution speed is 8000[rpm]. The specification of this system is shown in Table1. The tracking actuator for this system is the current-driven voice-coil motor. For compact disc system, the residual tracking error has to become below than 0.1[μm] as shown in Table2. At the current generation disk system such as DVD, the tolerance of residual tracking error is 0.022[μm]. This paper proposes the tracking control system that achieves the same residual tracking error as DVD on condition of a high-speed CD device. As the results, the proposed tracking control system can apply to the next generation optical disk system.

Fig.1 shows the frequency characteristics of tracking actuator. The plant system has both the first resonant frequency and second resonant frequency. This paper defines the second order system of tracking actuator without including second resonant frequency as shown in (1).

Table 1. Specification of DDU-1000

Optical disk	Type	CD-ROM
	disk Size	ϕ120[mm]
	Track Pitch	1.6[μm]
	Rotation Speed	200 - 8000[rpm]
Optical Pick-up	Type	SANYO SF-P151EX
	Semiconductor laser	Wavelength 785[nm]
	Detection Method	3-spot method

Table 2. Specification of Residual Tracking Error

Media Type	residual trackig error
CD	0.1[μm] (always)
DVD	0.022[μm] (always)

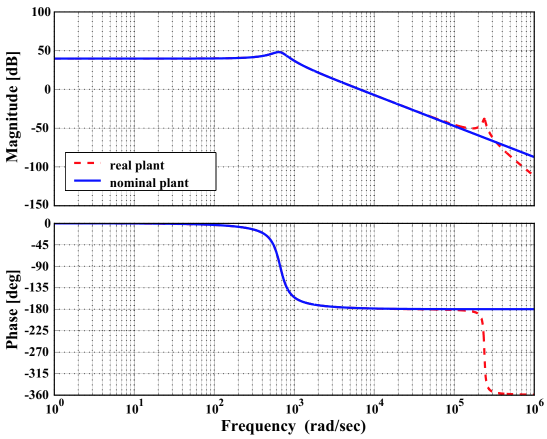


Fig. 1. Frequency characteristics of plant

$$P_n(s) = \frac{4.347 \times 10^7}{s^2 + 259.9s + 4.458 \times 10^5} \quad (1)$$

For realizing the high performance tracking control of optical disk system, this paper proposes a digital robust feedback control system based on coprime factorization and disturbance observer. The proposed feedback control system has a dual loop system as shown in Fig.2[12]. The proposed control system is directly designed as the digital controller.

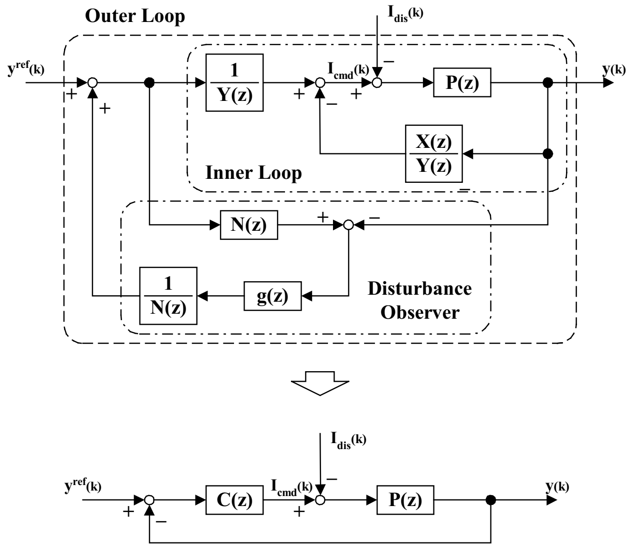


Fig. 2. Robust feedback control system

The inner loop system is equivalent to the closed loop system based on state feedback and state observer. The outer loop system is equivalent to the closed loop system based on disturbance observer. The proposed robust feedback controller $C(z)$ is determined by the coprime factorization $N(z)$, $D(z)$, $X(z)$, $Y(z)$, and the free parameter $g(z)$ as shown in (4) and (5)[12]. $g(z)$ is equivalent to a low pass filter of disturbance observer. A gain of $g(z)$ is unity in steady state.

$$P_n(z) = \frac{N(z)}{D(z)} = \frac{\mathbf{C}adj(s\mathbf{I} - \mathbf{A})\mathbf{B}}{det(s\mathbf{I} - \mathbf{A})} \quad (2)$$

$$N(z)X(z) + Y(z)D(z) = 1 \quad (3)$$

$$C(z) = \frac{X(z)}{Y(z)} + \frac{1}{Y(z)} \cdot G(z) \cdot \frac{1}{N(z)} \quad (4)$$

$$G(z) = \frac{g(z)}{1 - g(z)} \quad (5)$$

Using $C(z)$, the robust feedback control system suppresses the tracking error in condition of 3600[rpm]. However, it is difficult to keep the residual tracking error under the high disk rotation speed. In condition of 8000[rpm], the conventional tracking control system dosenot trace the disk track sometimes. The conventional feedback controller is not have a enought bandwidth and phase margin because this control syseterm cannot desgin the cut-off frequency directly. In order to overcome this problem, this paper proposes the new free parameter $g'(z)$ as shown in (6). $g'(z)$ is designed by using the loop shaping method in frequency domain using the additional transfer function $G_f(z)$. In this case, the additional transfer function $G_f(z)$ includes the inverse system of high pass filter suppressing the sudden disturbance, the inverse system of notch filter suppressing the periodic disturbance and the phase lead element improving the phase margin. Hence, the robust feedback controller with the new free parameter $g'(z)$ also includes the sudden disturbance observer.

$$g'(z) = \frac{G(z) \cdot G_{lag}(z) \cdot G_{lead}(z)}{1 + G(z) \cdot G_{lag}(z) \cdot G_{lead}(z)} \tag{6}$$

$$G_{lag}(z) = \frac{s + \beta_1}{s + \alpha_1} \tag{7}$$

$$G_{lead}(z) = \frac{s + \beta_2}{s + \alpha_2} \tag{8}$$

$$G'(z) = \frac{g'(z)}{1 - g'(z)} \tag{9}$$

As the results, the new feedback controller $C'(z)$ becomes (10). Moreover, the frequency characteristic of open loop system is shown in Fig.3. From Fig.3, the gain margin, cut-off frequency and steady state gain become large. Hence, the proposed feedback controller $C'(z)$ suppresses the residual tracking error on condition of high disk rotation speed. As the results, this paper allocates the poles of robust feedback control system as shown in Table.3. Its specification is shown in Table.4.

$$C'(z) = \frac{X(z)}{Y(z)} + \frac{1}{Y(z)} \cdot G'(z) \cdot \frac{1}{N(z)} \tag{10}$$

$$= \frac{X(z)}{Y(z)} + \frac{1}{Y(z)} \cdot G_f(z) \cdot G(z) \cdot \frac{1}{N(z)} \tag{11}$$

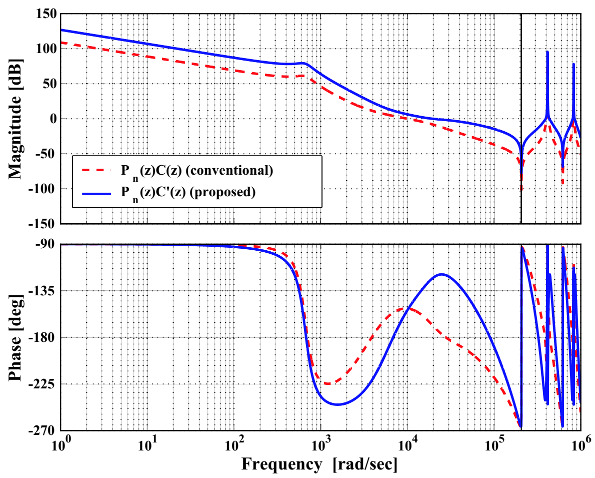


Fig. 3. Frequency characteristics of open-loop

Table 3. Designed parameters of robust feedback controller

Poles of state feed back	$0.902 + 0.030i, 0.902 - 0.030i$
Poles of state observer	$0.894 + 0.127i, 0.894 - 0.127i$
$g(z)$	$\frac{0.01758(z+0.9987)}{(z-0.8126)^2}$
$g'(z)$	$\frac{0.01758(z+0.9987)(z^2-1.641z+0.674)}{(z^2-1.719z+0.7463)(z^2-0.9506z+0.3683)}$
Sampling frequency	66[kHz]

Table 4. Specification of feedback control system

	conventional
Gain margin	11.4[dB]
Phase margin	27.8[deg]
Gain crossover frequency	9.97×10^3[rad/sec]
	proposed
Gain margin	11.4[dB]
Phase margin	56.4[deg]
Gain crossover frequency	1.92×10^4[rad/sec]

3. FEEDFORWARD TRACKING CONTROL FOR OPTICAL DISK

3.1 Zero Error Phase Tracking Controller

Zero Error Phase Tracking Control(ZPETC) is the one of the feedforward control system. It is very useful control method in motion control application. ZPETC compensator is designed by the closed loop transfer function $G_{closed}(z)$ of robust feedback control system as shown in (12),(13).

$$G_{closed}(z^{-1}) = \frac{C(z^{-1})P(z^{-1})}{1 + C(z^{-1})P(z^{-1})} = \frac{z^{-1}B_c^+(z^{-1})B_c^-(z^{-1})}{A_c(z^{-1})} \tag{12}$$

$$G_{ff}(z^{-1}) = \frac{A_c(z^{-1})B_c^-(z^{-1})}{B_c^+(z^{-1})[B_c^-(1)]^2} \tag{13}$$

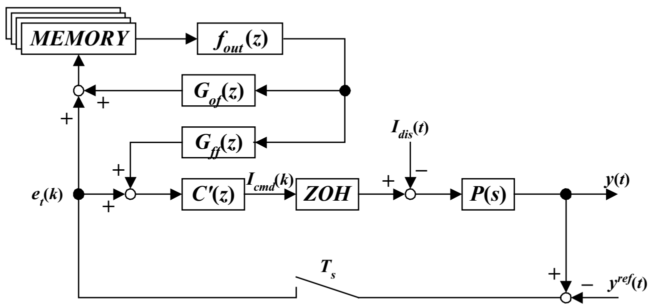


Fig. 4. ZPET-FF tracking servo system

3.2 Prediction of tracking error

A feedforward control such as ZPETC and PTC, requests to obtain the position reference signal. However, in the optical disk system, its detecting signal is only a tracking error e_t. It is difficult for ZPETC-FF control system to apply to optical disk systems.

In order to overcome this problem, this paper proposes the prediction method of tracking error on the periodicity of tracking error. This paper estimation method of the two sampling forward tracking error $e_t^{feedback}(k+2)$[6]. This paper treats the tracking error $e_t(k)$ as a periodic function such as Eq.(17). Using a memory of DSP, the proposed estimation method obtains the two sampling forward tracking error $e_t^{feedback}(k+2)$.

$$I_f(k) = G_{ff}(z^{-1})e_t^{feedback}(k+2) \tag{14}$$

$$e_t^{feedback}(k) = e_t(k) + G_{closed}(z^{-1})I_f(k) \quad (15)$$

$$= e_t(k) + G_{of}(z^{-1})e_t^{feedback}(k+n-2) \quad (16)$$

$$e_t^{feedback}(k) = e_t^{feedback}(k+n) \quad (17)$$

$$n = \frac{60}{NT_s} \quad (18)$$

The proposed estimation method of tracking error has a feedback element from memory output to memory input. Therefore this prediction method and ZPET control method is not same as repetitive control as the commonly used.

3.3 Design Method of ZPLPF

For the stability of feedforward tracking control, ZPETC-FF system has to use the low-pass filter $f_{out}(z)$. Because $f_{out}(z)$ reduce the high frequency noise of ZPETC-FF controller, the bandwidth of $f_{out}(z)$ is narrower than 1kHz. As the results, the residual tracking error does not reduce on condition of high rotation speed over 5000[rpm], because the phase error of $f_{out}(z)$ becomes large over 5000[rpm]. In this paper, tracking error is a periodic and continuous signal. Then the phase lag of feedforward control signal becomes a very serious problem.

In order to overcome this problem, this paper uses the Zero-Phase-Low-Pass-Filter(ZPLPF) as the $f_{out}(z)$. ZPLPF is a digital filter eliminating the high frequency element without phase lag[13]. ZPLPF is designed by using its sampling time T and its cut-off frequency ω. The frequency characteristics of ZPLPF is shown in Fig.6. From Fig.6, in comparison with the conventional low-pass-filter, the phase lag of ZPLPF becomes zero, and the desired cut-off frequency is kept. However, the value of l sample forward is necessary for this calculation. The proposed tracking control system is realized by assigning the low-pass filter after the memory. Therefore, the total structure of proposed robust tracking control system of optical disk system is constructed as shown in Fig.5.

$$G_{ZPLPF}(z) = \alpha_n z^n + \cdots + \alpha_1 z + \alpha_0 + \alpha_1 z^{-1} + \cdots + \alpha_n z^{-n} \quad (19)$$

$$\alpha_l = \frac{\tilde{\alpha_l}}{\tilde{\alpha_0} + 2(\tilde{\alpha_1} + \tilde{\alpha_2} + \ldots + \tilde{\alpha_n})}, (l = 0, 1, \cdots, n) \quad (20)$$

$$\tilde{\alpha_l} = \sum_{j=l}^{n} \delta_j \delta_{j-l}, (l = 0, 1, \cdots, n) \quad (21)$$

4. EXPERIMENTAL RESULTS

In order to confirm the validity of the proposed tracking control system, this paper shows the experimental results by using the tested optical disk system DDU-1000. The proposed tracking control system is constructed by the software algorithm of DSP.

Fig.7 shows the experimental results of only robust feedback control system by using both the conventional $C(z)$ and the proposed $C'(z)$, on condition of 3600[rpm]. From Fig.7, the robust feedback control system realizes the stable response and reduces the influence of both the periodic disturbance and the sudden disturbance. In Fig.7-(c) an (d), the proposed feedback control system suppresses the residual tracking error in comparison with the results of Fig.7-(a) and (b). The residual tracking error of proposed feedback control system with $C'(z)$ becomes 25% of that of conventional feedback controller $C(z)$ with periodic disturbance and sudden disturbance.

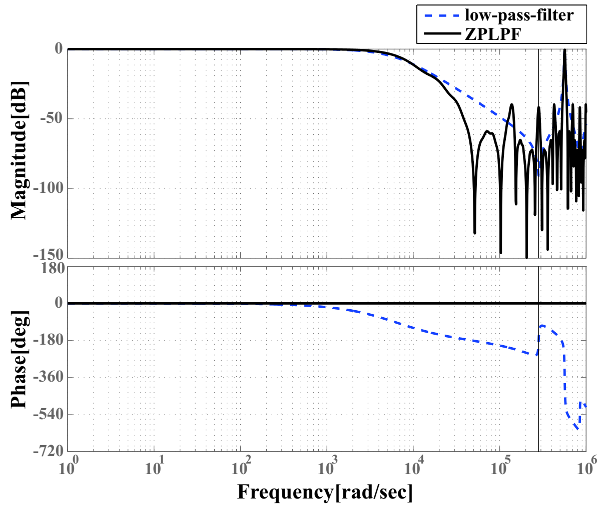


Fig. 6. Frequency characteristics of ZPLPF

Fig.8 show the experimental results of proposed robust feedback controller $C'(z)$ on condition of 8000[rpm]. In Fig.8, the proposed robust feedback controller $C'(z)$ can operate on condition of high rotation speed such as 8000[rpm]. However, it is difficult for the only robust feedback controller $C'(z)$ to reduce the influence of both the periodic disturbance and the sudden disturbance, on condition of high rotation speed over 5000[rpm].

Fig.9 shows the experimental results of the tested ZPETC-FF with the proposed feedback control system as shown in Fig.4. From Fig.9, the tested ZPETC-FF system can not reduce the tracking error on condition of rotation speed 8000[rpm]. Because, the phase lag of low pass filter $f_{out}(z)$ becomes large when the rotation speed becomes high. However, it is difficult to use more wide band low-pass filter compared with the cut-off frequency of $f_{out}(z)$.

Fig.10 shows the experimental results of ZPETC-FF with both ZPLPF and the proposed feedback control system. By using ZPLPF, the proposed tracking control system suppresses the residual tracking error to 16.94[nm] on condition of the disk rotational speed 8000[rpm]. This tracking error is 40% of that of only robust feedback control system with $C'(z)$.

5. CONCLUSION

This paper poroposed that the feedfoward tracking control system based on robust feedback control system, ZPETC and ZPLPF.

At first, this paper proposed the new free parameter $g'(z)$ which is designed by disturbance observer. In order to realize the quick response of tracking actuator at high disk

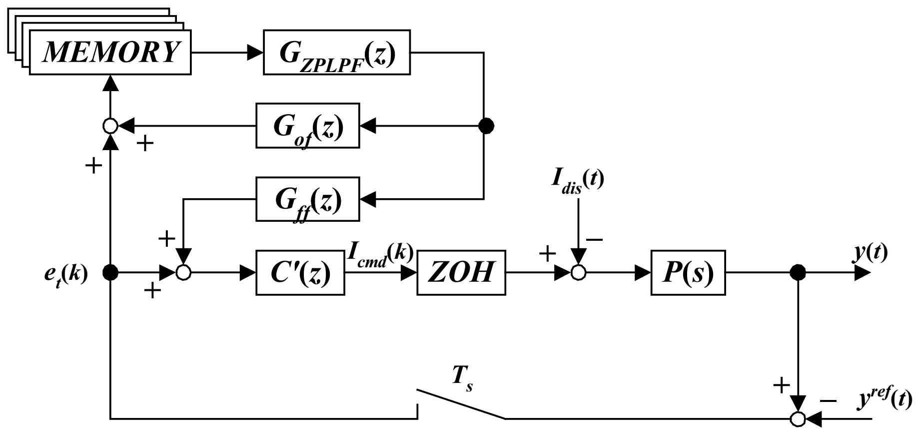
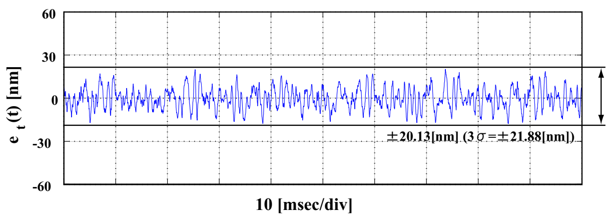
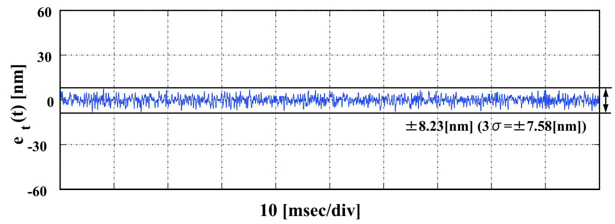


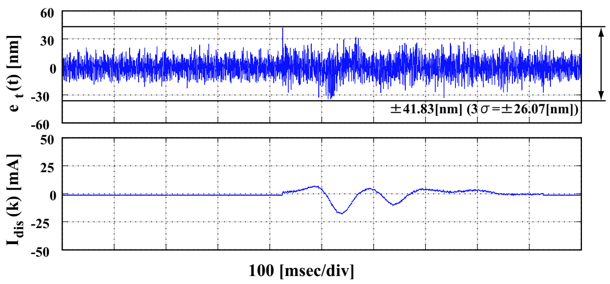
Fig. 5. ZPET-FF servo system with ZPLPF



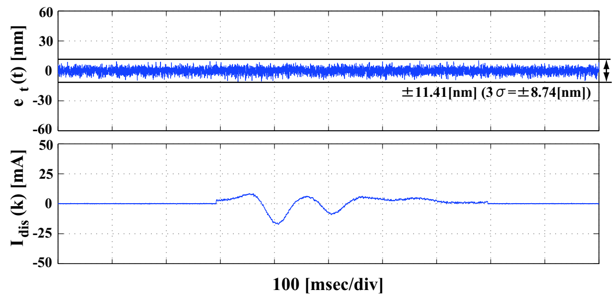
(a) Using conventional $C(z)$ with periodic disturbance



(c) Using proposed $C'(z)$ with periodic disturbance



(b) Using conventional $C(z)$ with periodic and sudden disturbances



(d) Using proposed $C'(z)$ with periodic and sudden disturbances

Fig. 7. Experimental results of feedback control system on condition of 3600[rpm]

rotation speed, the new free parameter of robust feedback controller shapes the characteristics of open loop system at frequency domain. The experimental results point out that the proposed robust feedback control system with new free parameter well reduces the tracking error caused by periodic disturbance and sudden disturbance on condition of rotation speed 8000[rpm].

Moreover, this paper proposes a Zero Error Phase Tracking Control-Feedforward(ZPETC-FF) controller using the "Zero Phase Low Pass Filter". The proposed ZPETC-FF tracking control system with ZPLPF well suppresses the influence of periodic disturbance on condition of high disk rotation speed. The experimental results confirm that the proposed total tracking control system with both the new free parameter and the zero phase low pass filter well reduces both the residual tracking error and the influences of sudden disturbance on condition of rotation speed 8000[rpm].

From these results, when the proposed tracking control system will be used, the residual tracking error on condition of disk rotation speed 10000[rpm] or over will become less than 22[nm],

Table 5. Residual tracking error on condition of 3600[rpm]

Disturbance	periodic	periodic and sudden
conventional FB	±20.13[nm]	±41.83[nm]
proposed FB	±8.23[nm]	±10.47[nm]
FB + ZPETC-FF	±10.38[nm]	±12.98[nm]
FB + ZPETC-FF + ZPLPF	±11.71[nm]	±13.43[nm]

Table 6. Residual tracking error on condition of 8000[rpm]

Disturbance	periodic	periodic and sudden
proposed FB	±24.27[nm]	±32.63[nm]
FB + ZPETC-FF	±20.42[nm]	±26.33[nm]
FB + ZPETC-FF + ZPLPF	±16.94[nm]	±18.70[nm]

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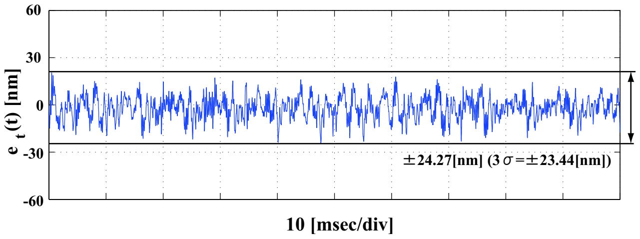
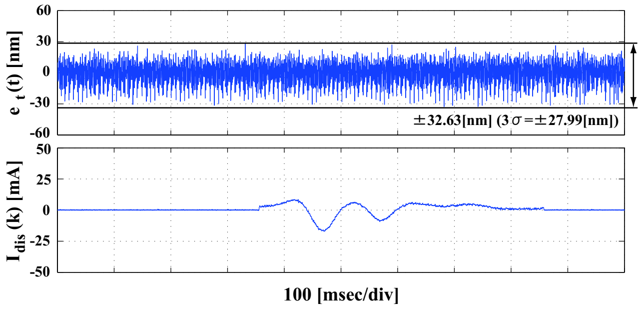
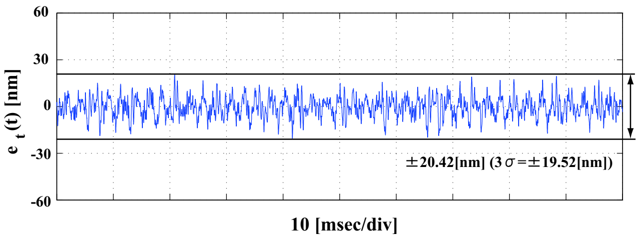


(a) periodic disturbance

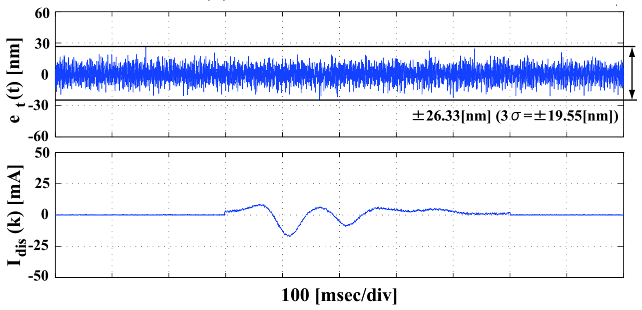


(b) periodic and sudden disturbances

Fig. 8. Experimental results of proposed feedback control system on condition of 8000[rpm]



(a) periodic disturbance



(b) periodic and sudden disturbances

Fig. 9. Experimental results of ZPETC-FF control system with conventional LPF on condition of 8000[rpm]

Digest CD, Mo-C-04

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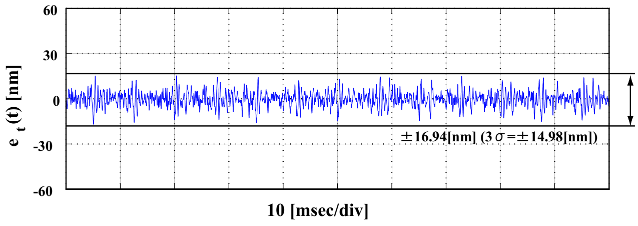
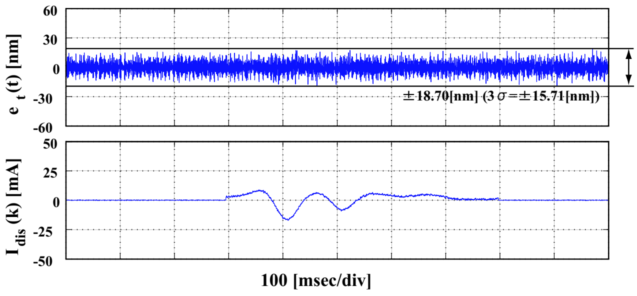


(a) 8000[rpm],periodic disturbance



(b) 8000[rpm],periodic and sudden disturbances

Fig. 10. Experimental results of ZPETC-FF control system with ZPLPF on condition of 8000[rpm]

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