Paper

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

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In this paper, a new method for disturbance rejection control which is based on adaptive identification of transfer characteristics from acceleration sensor is proposed. For hard disk drive, external disturbance which should be reduced is growing with widespread use of movable computers and other independent machinery. In order to reject the effect of the external disturbance we apply the feedforward controller which is designed by the adaptive identification algorithm. In adaptive identification, the proposed method uses Disturbance Observer to get the estimated disturbance as a substitute for the system disturbance which can't be observed. By this, the proposed method can identify the transfer characteristics directly which was impossible before and can design the feedforward input easily. Some experimental results in which a hard disk drive is shaken in the vertical direction are shown to verify the effectiveness of the proposed method.

Keywords: Hard Disk Drive, Accelerometer, External Disturbance Rejection, Feedforward Control, Recursive Least Squares Algorithm, Disturbance Observer

1. Introduction

Control performance of hard disk drive system has been desired to be more quick and accurate for the demand of high density and capacity. As results of several researcher's efforts, 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 actuator is required.

In order to improve the performance of the **following** mode, many methods have been proposed (1). Due to the development of low cost but high quality accelerometers, accelerometers can be used for compensating external and internal disturbances (4) (6) (7). 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) (2). Pannu and Horowitz also proposed an adaptive feedforward controller using the dynamics between the accelerometer and **PES** (3). In these methods, though the effective controllers were realized, it was complicated to design because the feedforward controller was made from the transfer characteristics between acceleration and **PES** with involved calculation. Consequently these methods were obliged to apply in offline calculation and can't adjust to variations of product's characteristics and environmental factors like temperature.

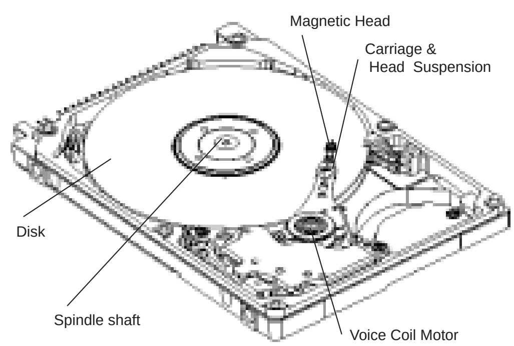

Fig. 1. Overview of 2.5inch Hard Disk Drive

This paper also proposes a feedforward controller with the accelerometer, too. The proposed feedforward controller differs from the existing controllers at the point that we directly use the dynamics between the accelerometer and the disturbance of the system, which can't be observed. In order to resolve this problem, we use Disturbance Observer (5) to estimate disturbance. By utilizing the estimated disturbance, the

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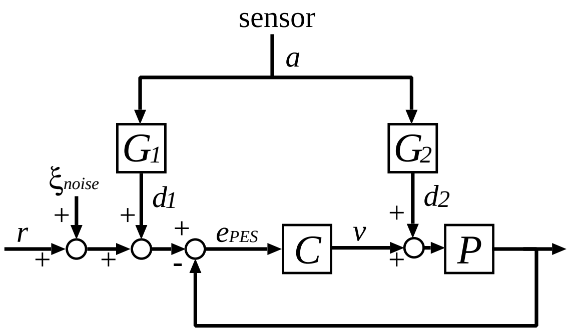


Fig. 2. Block Diagram for Access Control of Hard Disk Drive System with Excitation

dynamics can be directly identified by RLS (Recursive Least Squares) and FT (Fixed Trace) algorithm, and the feedforward input can be designed easily. In this wise, it is simply realized to design the feedforward controller in online calculation for adaptation to variations of characteristics and environmental factors and we can reject the external disturbance very effectively.

2. Identification from Acceleration Sensor

2.1 Structure of Hard Disk Drive System

Block diagram for the access control of hard disk drive system with excitation is drawn in Fig.2. P is the actuator dynamics, C is the conventional feedback controller, r is the control reference which is usually 0 in the **following** mode, e_{PES} is the Position Error Signal and v is the control input to the voice coil motor. ξ_{noise} is the typical error in hard disk drive system which is consist of **RRO**(Repetitive RunOut) synchronous to the disk rotation and **NRRO**(Non-Repetitive RunOut) asynchronous to the disk rotation, which are caused by disk deflection, rotational wind and etc. The external acceleration a 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 a and d_1, d_2. The transfer characteristics from a to e_{PES} can be described in (2) in which S expresses the sensitivity function in (1).

$$S = \frac{1}{1+CP} \quad \cdots\cdots\cdots\cdots \quad (1)$$

$$e_{PES} = (G_1 + P \cdot G_2) \cdot S \cdot a \quad \cdots\cdots\cdots\cdots \quad (2)$$

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

$$G = \frac{G_1 + P \cdot G_2}{P} \quad \cdots\cdots\cdots\cdots \quad (3)$$

$$d = G \cdot a = \frac{B(z^{-1})}{A(z^{-1})} \cdot a \quad \cdots\cdots\cdots\cdots \quad (4)$$

$$A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{N_a} z^{-N_a}$$

$$B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{N_b} z^{-N_b}$$

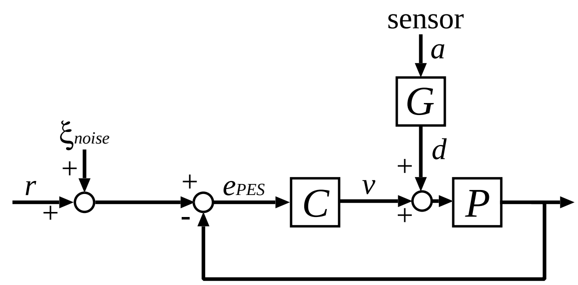


Fig. 3. Transfer Characteristics from Acceleration Sensor to Disturbance of System

2.2 Adaptive Identification Algorithm

Various methods were reported to identify several systems. In this paper, we apply two well-known algorithms, RLS algorithm and FT algorithm, to identify the transfer characteristics. Both algorithms can be formulated as (5) $\sim$ (8).

$$\hat{\boldsymbol{\theta}}(k) = \hat{\boldsymbol{\theta}}(k-1) + \frac{\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}\varepsilon(k) \quad \cdots\cdots\cdots\cdots \quad (5)$$

$$\varepsilon(k) = d(k) - \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}(k-1) \quad \cdots\cdots\cdots\cdots \quad (6)$$

$$\boldsymbol{\Gamma}(k) = \frac{1}{\lambda(k)}\{\boldsymbol{\Gamma}(k-1) - \frac{\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)}\} \quad \cdots \quad (7)$$

$$\lambda(k) = 1 - \frac{\|\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)\|^2}{1+\boldsymbol{\varphi}^T(k)\boldsymbol{\Gamma}(k-1)\boldsymbol{\varphi}(k)} \frac{1}{tr\boldsymbol{\Gamma}(0)} \quad \cdot \quad (8)$$

Here, $\boldsymbol{\Gamma}(k)$ is the covariance matrix, $\hat{\boldsymbol{\theta}}(k)$ is the identified parameters 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 parameters $\hat{\boldsymbol{\theta}}(k)$ is determined so that the error as (6) is minimized. In addition, using FT algorithm the parameters of the transfer characteristics 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). Additionally a designer can set the trace of the covariance matrix $tr\boldsymbol{\Gamma}(0)$ for renewal degree of the identified parameters $\hat{\boldsymbol{\theta}}(k)$.

By the adaptive identification online, transfer characteristics from acceleration sensor can be identified precisely even if transfer characteristics is varying, as is the case with frequency or gain of the external disturbance is time-varying.

$$\hat{\boldsymbol{\theta}}(k) = [\hat{a}_1, \cdots, \hat{a}_{N_a}, \hat{b}_1, \cdots, \hat{b}_{N_b}]^T \quad \cdots\cdots\cdots\cdots \quad (9)$$

$$\boldsymbol{\varphi}(k) = [-d(k-1), \cdots, -d(k-N_a), a(k-1), \cdots, a(k-N_b)]^T \quad \cdots \quad (10)$$

2.3 Identification with Disturbance Observer

But in practice, the external disturbance $d(k)$ can't be observed directly. In order to resolve this problem, we

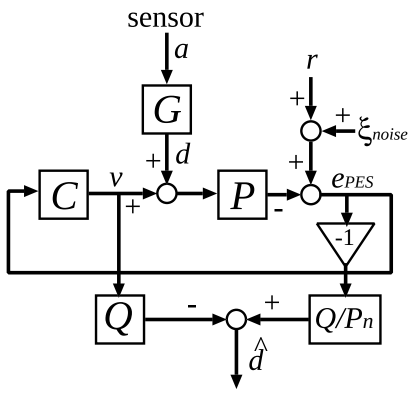


Fig. 4. Block Diagram of Disturbance Observer to Estimate Disturbance

utilize 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 estimated disturbance signal.

$$\hat{d} = \{-\frac{-CP}{1+CP}\cdot Q + \frac{P}{1+CP}\frac{Q}{P_n}\}\cdot d - \{\frac{C}{1+CP}\cdot Q + \frac{1}{1+CP}\frac{Q}{P_n}\}\{r+\xi_{noise}\} \quad \cdots (11)$$

$$= \frac{\frac{P}{P_n}+CP}{1+CP}\cdot Q\cdot d + \frac{\frac{P}{P_n}+CP}{1+CP}\cdot\frac{Q}{P}\cdot\{r+\xi_{noise}\} \quad \cdots (12)$$

$$\approx Q\cdot d + \xi \quad \cdots (13)$$

From block diagram(Fig.4), the estimated disturbance can be expressed in (11). We assumed that P is close to P_n, and ξ expresses the influence of the ξ_{noise} and the difference between P and P_n in (12). With the estimated disturbance $\hat{d}$, (10) is substituted by (14). In (14), $\hat{d}$ can be approximated to $Q{\cdot}d$ from (13). Therefore by low-pass filter Q added to a to make Q and $\hat{d}$ consistent, (14) is equivalent with (10) for identification of the transfer characteristics. In identification algorithm, (6) is also substituted by (16).

By utilizing Disturbance Observer, the transfer characteristics between the acceleration sensor and system disturbance can be identified directly which was impossible in the past.

$$\boldsymbol{\varphi}'(k) = [-\hat{d}(k-1),\cdots,-\hat{d}(k-N_a), Q\cdot a(k-1),\cdots,Q\cdot a(k-N_b)]^T \quad \cdots (14)$$

$$\approx [-Q\cdot d(k-1),\cdots,-Q\cdot d(k-N_a), Q\cdot a(k-1),\cdots,Q\cdot a(k-N_b)]^T \quad \cdots (15)$$

$$\varepsilon(k) = \hat{d}(k) - \boldsymbol{\varphi}^T(k)\hat{\boldsymbol{\theta}}(k-1) \quad \cdots (16)$$

3. Design of Feedforward Input

3.1 Principle of Feedforward Input Design

In the previous section, we proposed the adaptive identification of the transfer characteristics with Disturbance Observer. Using this transfer characteristics in (4), we can calculate the feedforward input u_{FF} with only past signals.

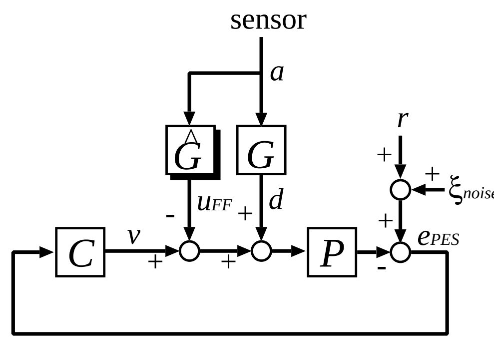


Fig. 5. Block Diagram of Disturbance Rejection Control with Feedforward Input

Generally speaking, feedforward input u_{FF} can be calculated with the identified parameters and the input and output signals in (17). But in practice, the external disturbance $d(k)$ can't be observed directly as related before.

$$u_{FF,1}(k) = \hat{G}\cdot a(k) \quad \cdots (17)$$

$$= \hat{B}(z^{-1})a(k) + \{1-\hat{A}(z^{-1})\}d(k) \quad (18)$$

$$= \hat{b}_1 a(k-1) + \cdots + \hat{b}_{N_b} a(k-N_b) + \hat{a}_1 d(k-1) + \cdots + \hat{a}_{N_a} d(k-N_a) \quad \cdots (19)$$

3.2 Practical Design of Feedforward Input

To resolve the problem in the previous section, the estimated disturbance $\hat{d}$ can be used as a substitute for the external disturbance like identification in (20).

But, $\hat{d}$ has considerable noise in (12), the error between P and P_n, ξ_{noise} and etc. Therefore in the proposed method, since the identification is assumed to be true, the feedforward input u_{FF} itself can be used as a substitute for the external disturbance in (21).

$$u_{FF,2}(k) = \hat{b}_1 a(k-1) + \cdots + \hat{b}_{N_b} a(k-N_b) + \hat{a}_1 \hat{d}(k-1) + \cdots + \hat{a}_{N_a} \hat{d}(k-N_a) \quad \cdots (20)$$

$$u_{FF,3}(k) = \hat{b}_1 a(k-1) + \cdots + \hat{b}_{N_b} a(k-N_b) + \hat{a}_1 u_{FF}(k-1) + \cdots + \hat{a}_{N_a} u_{FF}(k-N_a) \quad \cdots (21)$$

Hereby, the feedforward input can be realized recursively. In this case, the feedforward input can be calculated with only acceleration signals and identified parameters. After this section $u_{FF,3}$ is applied as the proposed feedforward input.

The external disturbance $d(k)$ is rejected by the feedforward input u_{FF}(Fig.5). As a merit of this proposed method, the feedforward input u_{FF} can be applied to the system without reconstruction of the system.

4. Advantage of Proposed Method

The advantages of the proposed method using Dis-

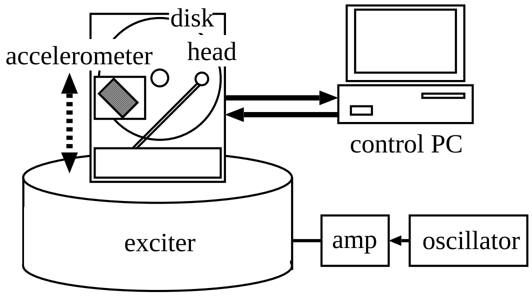


Fig. 6. Configuration of Experimental System

turbance Observer are

- Only one identification of transfer characteristics from accelerometer and disturbance
- No need to calculate any transfer functions for feedforward controller.

In the proposed method, feedforward controller can be designed sequentially under the favor of these advantages. Moreover, the proposed method can be applied in a realtime manner due to the fast estimation of Disturbance Observer. In fact, all calculation of the proposed method including realtime identification and design of feedforward input can be completed within 168[μs], the sampling time of the original control system. Herewith the proposed feedforward controller can adjust to variations of product's characteristics and environmental factors like temperature.

On the contrary, in the conventional methods, several identification of transfer characteristics of system are needed because external disturbance can't be observed directly. Besides, calculation between the transfer functions is also needed to design the feedforward controller. Therefore, the conventional feedforward controllers need to be designed by offline calculation in advance. But designed like this, the feedforward controller can't adjust to variations of product's characteristics and environment factors.

In the proposed method, it is possible to omit the complicated procedure and have high performance to reject the external disturbance.

5. Experiment with Hard Disk Drive

5.1 Experimental Setup

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 a exciter in the direction, perpendicular to the spindle motor's axis by the sinusoidal wave which amplitude is about 2.0[G]. Without the proposed method under excitation of such an amplitude, **PES** can't be suppressed and the error the head can read/write data on the disk on the safe side. The accelerometer is installed in the direction so as to maximize the sensitivity of the accelerometer for the carriage's movement. In these experiments, a 2.5 inch hard disk drive(36[kTPI]) is used, for the proposed method aims at improvement of performance of movable machinery.

In each sampling time the hard disk drive sends **PES** and the acceleration signal to the control PC and the control PC calculates the transfer characteristics and sends v and the proposed feedforward input u_{FF} to the hard disk drive. The conventional feedback 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 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.

5.2 Experimental Result

To verify the effectiveness of the proposed method, specific-frequency disturbance is given to the hard disk drive. Figs.7 $\sim$ 12 show the experimental results. In Figs.7, 9 and 11 the time series of **PES** with 60[Hz], 100[Hz] and 300[Hz]

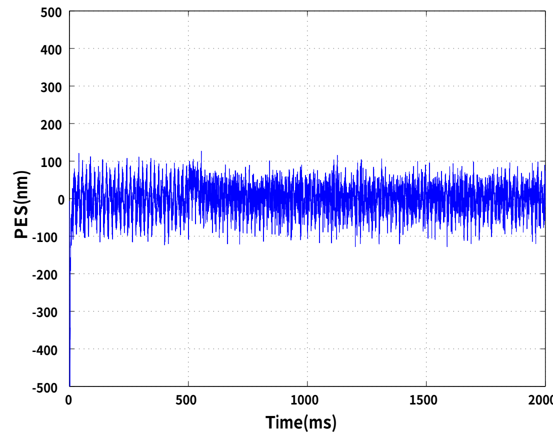
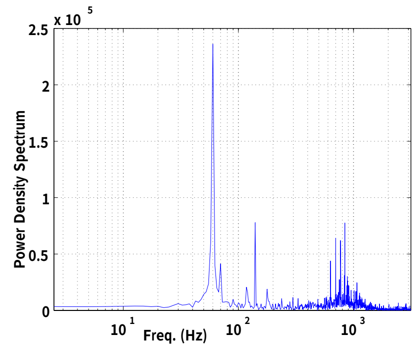
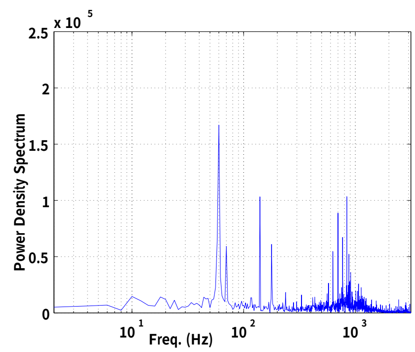


Fig. 7. Time Series of **PES** with 60[Hz] Excitation



(a)Without Proposed Feedforward Input



(b)With Proposed Feedforward Input

Fig. 8. Fourier Transform of **PES** with 60[Hz] Excitation

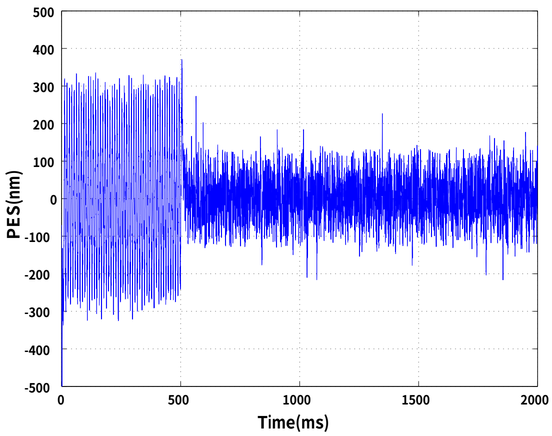
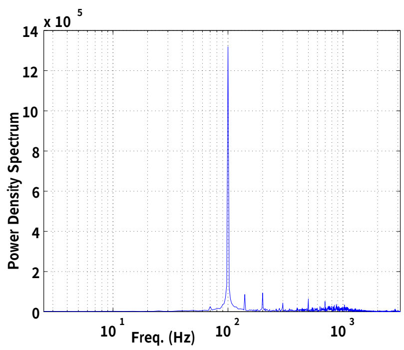
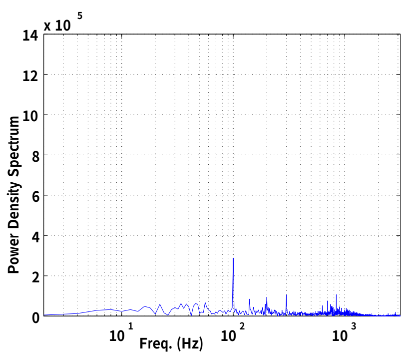


Fig. 9. Time Series of **PES** with 100[Hz] Excitation



(a)Without Proposed Feedforward Input



(b)With Proposed Feedforward Input

Fig. 10. Fourier Transform of **PES** with 100[Hz] Excitation

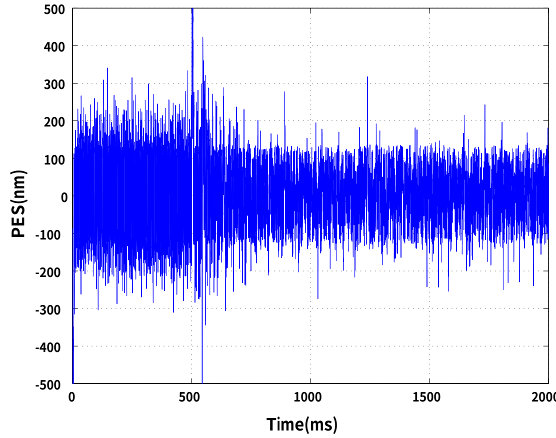
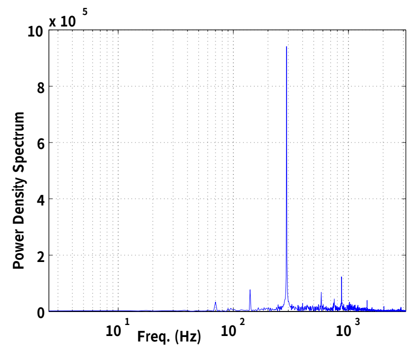
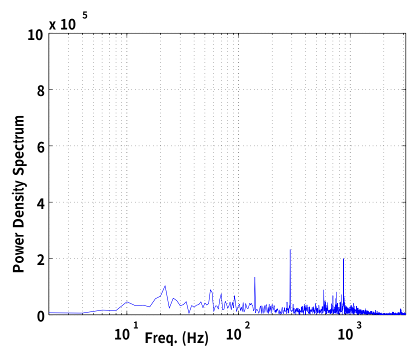


Fig. 11. Time Series of **PES** with 300[Hz] Excitation



(a)Without Proposed Feedforward Input



(b)With Proposed Feedforward Input

Fig. 12. Fourier Transform of **PES** with 300[Hz] Excitation

excitation are shown. In these experiments The hard disk drive is controlled by the conventional feedback controller (0[ms] ∼ 500[ms]) and by the conventional feedback controller including the proposed feedforward controller (500[ms] ∼ 2000[ms]). Additionally Fourier transform of **PES** are shown in Figs.8, 10 and 12 with each excitation. In these experiments, the time series of **PES** should be no error ideally. But in fact, for **RRO** and **NRRO** are existed, the time series of **PES** have vibrational error in high frequency band within an allowance. As below, control performances against each frequency disturbance are discussed.

5.2.1 **Control Performance against Low Frequency Disturbance** Figs.7, 8 show the experimental results for 60[Hz] disturbance. For low frequency disturbance(80[Hz]), conventional feedback controller can suppress the disturbance well. After applied the proposed feedforward controller, the proposed controller can additionally suppress the 60[Hz] excitation without harm to performance of the conventional feedback controller(Fig.8).

5.2.2 **Control Performance against Middle Frequency Disturbance** Figs.9, 10 show the experimental results for 100[Hz] disturbance. For middle frequency disturbance(90[Hz]200[Hz]), the conventional feedback controller can't suppress disturbance because the frequency of disturbance goes beyond the controllable band of the conventional feedback controller. On the contrary, after applied the proposed feedforward controller, middle frequency disturbance can be sup-

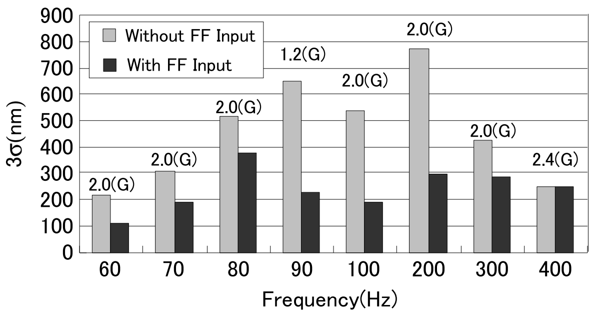


Fig. 13. Comparison of 3σ of **PES** with/without Proposed Feedforward Input

pressed remarkably.

5.2.3 **Control Performance against High Frequency Disturbance** Figs.11, 12 show the experimental results for 300[Hz] disturbance. In high frequency disturbance(300[Hz]), though the frequency of disturbance goes beyond the controllable band of the conventional feedback 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 feedforward controller, high frequency disturbance can be suppressed additionally.

Fig.13 shows 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 feedforward controller and without the proposed feedforward controller, the proposed feedforward controller can remarkably suppress the excitation which is not possible for the conventional feedback controller in all frequency of disturbance.

6. Conclusion

In this paper, we proposed a novel method for the external disturbance rejection control, based on the adaptive identification of transfer characteristics from acceleration sensor for access control of hard disk drive system. In this method, we can identify the transfer characteristics from acceleration sensor with Disturbance Observer and design the feedforward controller. In the experiments, a 2.5 inch hard disk drive(36[kTPI]) is shaken, but **PES** is reduced by the proposed feedforward controller, especially in middle frequency band that the conventional feedback controller can't perform sufficiently. As a result of this experiments, we can design the proposed feedforward controller in online calculation and verify the effectiveness of the proposed feedforward controller. Recently, hard disk drive is used not only for computers but also for other machinery to utilize the performance and the capacity of hard disk drive. In the future this tendency is expected to continue and therefore hard disk drive against disturbance is significant subject of research.

7. Acknowledgment

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