Two-degree-of-freedom control scheme for flying-height and tracking-position controls with thermal actuators in HDDs

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Abstract
To improve positioning accuracy of a magnetic head in hard disk drives (HDDs), a triple-stage-actuator system was proposed with a thermal positioning actuator for a magnetic head positioning system. This positioning system has three types of actuators: a voice coil motor (VCM), piezoelectric (PZT) actuators, and the thermal positioning actuator. In this system, a magnetic head has a heater located in a horizontal direction of read/write elements as the thermal positioning actuator. By using this structure, the control system can move the position of read/write elements of the magnetic head in a horizontal direction with thermal expansion induced by the heater with an electric current. The thermal actuator systems have simple characteristics without mechanical resonant modes even in a high frequency range. This means that the thermal actuator is good for positioning control in high frequency range. As a result, the triple-stage-actuator system enable us to improve the positioning accuracy during a track-following control from conventional dual-stage-actuator systems. However, the thermal positioning actuator causes flying height fluctuations of the magnetic head that could lead to fall of magnetic recording performances. In HDDs, the magnetic head has another heater located in a vertical direction of read/write elements in order to control flying height of the read/write elements. This control system is called thermal flying height control system. In previous study, we can compensate for the flying-height fluctuations by using a feedforward control scheme of the TFC system. However, the feedforward control has little robustness against the plant perturbations. To address this issue, this paper employs a two-degree-of-freedom (TDOF) control scheme for the coordinated control with the TPC and the TFC systems. By using proposed TDOF method, we can compensate for the flying-height fluctuations against the plant perturbations. Simulation results showed that the proposed method is able to improve robust performance against the plant perturbations.

Keywords: Hard disk drive, Positioning control, Multi-Input-Single-Output system, Micro-actuator

1. Introduction

In the 21st century, technologies for data-storage fields are important factors for Internet services, cloud computing, Big Data analytics, and social networking. In the data storage systems, the most widely used device is a hard disk drive (HDD), and positioning accuracy of magnetic heads in HDDs must be improved to meet increasing demands for larger storage capacity (Abrahamson and Huang, 2015).

To improve the positioning accuracy of the magnetic head, a magnetic head positioning system has to compensate for disturbances caused by mechanical vibrations. The control system can compensate for the disturbances at frequencies lower than a servo bandwidth of the control system. However, the servo bandwidth is limited by the mechanical characteristics (Atsumi et al., 2006; Zheng et al., 2016). Therefore, the magnetic head positioning system should be fabricated with new actuator systems that can overcome these servo-bandwidth limiters (Atsumi, 2016b).

As a result, magnetic-head-positioning control systems have employed dual-stage-actuator systems that consist of a voice coil motor (VCM) and a piezoelectric (PZT) actuator (Mori et al., 1991; Takaishi et al., 1996; Li and Horowitz,
In this dual-stage-actuator system, the VCM drives a head-stack assembly (HSA) that is the whole of the magnetic head positioning system. On the other hand, the PZT actuator moves the suspension that is a tip of the HSA. Thus, frequencies of primary mechanical resonances in the PZT actuator are much higher than these in the VCM. Therefore, by using the dual-stage-actuator system, we can achieve higher servo bandwidth than that of a single-stage-actuator system with the VCM only. Similarly, to achieve the higher servo bandwidth than that of the dual-stage-actuator system, we must add a new microactuator as the third actuator that lies closer to the magnetic head than the PZT actuator (Naniwa et al., 2009).

To achieve higher servo bandwidth than that of the dual-stage-actuator system, we have developed a triple-stage-actuator system with a thermal actuator for the magnetic head positioning control (Atsumi et al., 2013). The thermal actuator uses a heater located in the magnetic head, and it can move the read/write elements with thermal expansion induced by the heater in a horizontal direction of the read/write elements (Choe et al., 2010). This control system is called thermal positioning control (TPC) system. By using the TPC system, we can dramatically improve the positioning accuracy during a track-following control from conventional dual-actuator systems.

However, the TPC system has a problem that the TPC actuator must move the read/write elements not only in horizontal direction but also in vertical direction (Furukawa et al., 2012; Liu et al., 2012). This means that the TPC actuator is a cause of disturbances for the flying height of the magnetic head that must be controlled within several nanometers.

On the other hand, in current HDDs, we have a thermal flying-height control (TFC) system. For this TFC system, the magnetic head has a heater located in a vertical direction of read/write elements in order to control flying height of the read/write elements with thermal expansion (Shiramatsu et al., 2008; Ookubo et al., 2010; Boettcher et al., 2011).

To compensate for the flying-height fluctuations of the magnetic heads caused by the TPC actuator, this paper presents a coordinated control system with TPC and TFC systems. In the previous study, we can compensate for the flying-height fluctuations by using a feedforward control scheme of the TFC system (Atsumi, 2017b). However, the feedforward control has little robustness against the plant perturbations. To address this issue, this paper employs a two-degree-of-freedom (TDOF) control scheme for the coordinated control with the TPC and the TFC systems. By using proposed TDOF method, we can compensate for the flying-height fluctuations against the plant perturbations. Simulation results showed that the proposed method is able to improve robust performance against the plant perturbations.

2. Magnetic head positioning system in HDDs

As shown in Fig. 1, the HDD is comprised of a VCM, an HSA, a spindle motor, a cover, and a base. The HSA has a coil of the VCM, several PZT actuators, and several magnetic heads. The magnetic heads are attached to suspensions in the HSA.

The magnetic head position signal is generated by reading special magnetic patterns, called servo sector, embedded at regular intervals on disks. This means that the control system for the magnetic head position is a sampled-data control system which should control not only sampled position but also intersampling position. Therefore, we have to evaluate performances of the control system by using continuous-time signals instead of measurable discrete-time signals (Atsumi and Messner, 2013; Atsumi and Messner, 2014; Atsumi, 2016; Atsumi, 2017a).
2.1. Feature of thermal actuator

A magnetic head for the TFC and TPC systems is shown in Fig. 2. This system employs two heaters, one is located in a vertical direction of the read/write element for the TFC system, and the other is located in a horizontal direction of a read/write element for the TPC system.

Fig. 3 shows the positional relationship between the TPC heater, the TFC heater, and the Read/Write element. By using the heater for TFC system, we can move the read/write elements in the vertical direction without moving in the horizontal direction. On the other hand, in the TPC system, the thermal actuator must move the read/write elements not only in horizontal direction but also in vertical direction. Because the vertical position of the TPC heater is higher than that of the read/write elements, and a moving-direction angle of the Read/Write element by the thermal expansion from the TPC heater depends on the positional relationship between the TPC heater and the Read/Write element (Furukawa et al., 2012; Liu et al., 2012). This means that the TPC actuator is a kind of disturbance for the TFC system.

2.2. Magnetic head positioning control

Fig. 4 shows the basic schematic of the triple-stage-actuator system for the magnetic head positioning control. The first actuator is the VCM for moving the HSA, the second actuator is the PZT actuator for moving the suspension, and the third actuator is the TPC actuator for moving the read/write elements. The control input signals are input command values to a VCM-drive amplifier, a PZT-drive amplifier, and a TPC-drive amplifier.

2.2.1. Transfer characteristics of thermal actuators

In this study, we have employed transfer characteristics of TFC and TPC actuators that are shown in references (Shiramatsu et al., 2008; Atsumi et al., 2013). The frequency response of the TFC actuators are shown by solid lines in Fig. 5(a), and the frequency responses of the TPC actuator are shown by solid lines in Fig. 5(b).

We can determine mathematical models of the TPC and TFC actuators so that the model’s frequency responses coincide with the measurement results of the frequency responses based on curve-fitting method. As a result, a mathematical model of the TFC actuator system, $P_{TFC}(s)$, can be given as follows:

$$P_{TFC}(s) = \frac{47300(s + 18200)(s + 50300)}{(s + 20100)(s + 40800)(s + 52800)}.$$

A mathematical model of the TPC actuator system, $P_{TPC}(s)$, can be also given as follows:

$$P_{TPC}(s) = \frac{1.18 \times 10^8(s + 5030)}{(s + 1860)(s + 6280)(s + 50300)}.$$
Fig. 5 Frequency responses of thermal actuators: (a) TFC actuator and (b) TPC actuator. Solid lines indicate the result of the measurement data. Dashed lines indicate the result of mathematical models.

Fig. 6 Frequency responses of VCM and PZT actuator: (a) VCM and (b) PZT actuator. Solid lines indicate the result of the measurement data. Dashed lines indicate the result of mathematical model.

The frequency responses of $P_{TFC}$ are shown by dashed lines in Fig. 5(a), and the frequency responses of $P_{TPC}$ are shown by dashed lines in Fig. 5(b).

Here, $P_{FH}$ means transfer characteristics from input signal for TPC actuator to the position of the read/write elements in vertical direction. In this study, we have assumed that the moving-direction angle of the Read/Write element by TPC heater (shown in Fig. 3) is $\arctan(1/5)$. As a result, $P_{FH}(s)$ can be given by the following equation,

$$P_{FH}(s) = 0.200P_{TPC}(s).$$

(3)

The frequency responses of the thermal actuators and the mathematical models showed that the thermal actuator systems have simple characteristics without mechanical resonant modes even in a high-frequency range. As a result, thermal actuators enable us to control the magnetic head position in the high-frequency range (Shiramatsu et al., 2008; Atsumi et al., 2013).

2.2.2. Transfer characteristics of VCM and PZT actuators

In the previous study, we have developed the triple-stage-actuator system on a spin-stand tester (Atsumi et al., 2013). In the spin-stand tester, characteristics of the VCM and PZT actuators are different from those in HDDs. Consequently, in this paper, we employ characteristics of the VCM and the PZT actuators shown in the reference paper (Atsumi et al., 2015) that employed the VCM and PZT actuators used in HDDs. The frequency responses of the VCM system are shown by solid lines in Fig. 6(a), and the frequency responses of the PZT actuator system are shown by solid lines in Fig. 6(b).

A mathematical model of the VCM, $P_{VCM}(s)$, is given as follows:

$$P_{VCM}(s) = K_{VCM} \sum_{i=1}^{l_{VCM}} \frac{\alpha_{VCM}(i)}{s^2 + 2\zeta_{VCM}(i)\omega_{VCM}(i)s + \omega_{VCM}(i)^2},$$

where $l_{VCM}$ is a number of modes for $P_{VCM}$, $\alpha_{VCM}$ is a residue of each mode, $\omega_{VCM}$ and $\zeta_{VCM}$ are a natural frequency and damping ratio of the resonance, respectively, and $K_{VCM}$ is a plant gain. These parameters are determined so that the
model’s frequency response coincides with the measured frequency responses shown by the solid lines in Fig. 6. Dashed lines in Fig. 6(a) represent the frequency response given by this VCM model. In this model, \( l_{VCM} \) is sixteen for a model order of 32. \( K_{VCM} \) is 647.8, and the values of the other parameters are listed in Table 1.

A mathematical model of the PZT actuator, \( P_{PZT}(s) \), is given as follows:

\[
P_{PZT}(s) = K_{PZT} \sum_{i=1}^{l_{PZT}} \frac{\alpha_{PZT}(i)}{s^2 + 2\xi_{PZT}(i)\omega_{PZT}(i)s + \omega_{PZT}(i)^2}.
\]  

where \( l_{PZT} \) is the number of modes under consideration, \( K_{PZT} \) is the plant gain, \( \alpha_{PZT} \) is the residue of each mode, \( \omega_{PZT} \) and \( \xi_{PZT} \) are the natural frequency and damping ratio of the resonance, respectively. The dashed line in Fig. 6(b) represents the frequency response given by this PZT model. In this model, \( l_{PZT} \) is nine for a model order of 18, \( K_{PZT} \) is \( 6.83 \times 10^3 \), and the values of the other parameters are listed in Table 2.

| \( i \) | \( \omega_{VCM}(i) \) | \( \alpha_{VCM}(i) \) | \( \xi_{VCM}(i) \) |
|---|---|---|---|
| 1 | 0 | 1.00 | 0 |
| 2 | 2\pi \cdot 5300 | -1.00 | 0.020 |
| 3 | 2\pi \cdot 6100 | 0.10 | 0.040 |
| 4 | 2\pi \cdot 6500 | -0.10 | 0.020 |
| 5 | 2\pi \cdot 8050 | 0.04 | 0.010 |
| 6 | 2\pi \cdot 9600 | -0.70 | 0.030 |
| 7 | 2\pi \cdot 14800 | -0.20 | 0.010 |
| 8 | 2\pi \cdot 17400 | -1.00 | 0.020 |
| 9 | 2\pi \cdot 21000 | 3.00 | 0.020 |
| 10 | 2\pi \cdot 26000 | -3.20 | 0.012 |
| 11 | 2\pi \cdot 26600 | 2.10 | 0.007 |
| 12 | 2\pi \cdot 29000 | -1.50 | 0.010 |
| 13 | 2\pi \cdot 32200 | 2.00 | 0.030 |
| 14 | 2\pi \cdot 38300 | -0.20 | 0.010 |
| 15 | 2\pi \cdot 43300 | 0.30 | 0.010 |
| 16 | 2\pi \cdot 44800 | -0.50 | 0.010 |

Table 2 Parameters of \( P_{PZT}(s) \).

| \( i \) | \( \omega_{PZT}(i) \) | \( \alpha_{PZT}(i) \) | \( \xi_{PZT}(i) \) |
|---|---|---|---|
| 1 | 2\pi \cdot 6560 | 0.007 | 0.020 |
| 2 | 2\pi \cdot 8050 | 0.012 | 0.020 |
| 3 | 2\pi \cdot 9200 | 0.015 | 0.025 |
| 4 | 2\pi \cdot 12900 | 0.010 | 0.007 |
| 5 | 2\pi \cdot 15500 | 0.100 | 0.010 |
| 6 | 2\pi \cdot 17200 | 0.200 | 0.010 |
| 7 | 2\pi \cdot 18050 | 0.400 | 0.009 |
| 8 | 2\pi \cdot 27100 | 1.500 | 0.007 |
| 9 | 2\pi \cdot 39500 | 1.300 | 0.040 |

3. Feedback control system for magnetic head position

In our previous studies, the design method of the feedback controller is shown for the magnetic head positioning system with the triple-stage actuator (Atsumi et al., 2013). This section explains the design method of the feedback controller for the magnetic head position that is not different from that in our previous studies. A block diagram of the control system for magnetic head position is shown in Fig. 7. Here, \( C_{TPC} \) is a feedback controller for the TPC actuator, \( C_{PZT} \) is a feedback controller for the PZT actuator, \( N_{PZT} \) is a multi-rate notch filter for the PZT actuator, \( C_{VCM} \) is a
feedback controller for the VCM, $N_{\text{VCM}}$ is a multi-rate notch filter for the VCM, $\mathcal{H}$ is a zero-order hold (ZOH), and $S$ is a sampler, $I_p$ is an interpolator, $\mathcal{H}_m$ is a multi-rate ZOH. $e$ is a reference signal for the magnetic head positioning system, $d$ is an error signal for the magnetic head positioning system, $d$ is a disturbance signal for the magnetic head positioning system, $u_{\text{TPC}}$ is the input signal to $C_{\text{TPC}}, u_{\text{PZT}}$ is the output signal to $N_{\text{PZT}}, u_{\text{VCM}}$ is the input signal to $N_{\text{VCM}}, u_{\text{VCM}}$ is the output signal from $N_{\text{VCM}}, y_c$ is the magnetic head position signal in continuous time, and $y_d$ is the magnetic head position signal in discrete time, $y_{\text{FHM}}$ is a flying-height signal in continuous time.

A sampling time of $\mathcal{H}$ and $S$ was 23.15 $\mu$s (the sampling frequency: 43.20 kHz), and a multi-rate number for $I_p$, $N_{\text{PZT}}$, and $\mathcal{H}_m$ is set as two. In this study, the interpolator $I_p[z]$ consists of an up-sampler and an interpolation filter. Thus, $I_p[z]$ can be given as follows (Vaidyanathan, 1993):

$$I_p[z] = \sum_{m=1}^{2} z^{-m}.$$  \hfill (6)

The feedback controller for the VCM, $C_{\text{VCM}}[z]$, is a transfer function from $e$ to $u_{\text{VCM}}$. It has to provide an integral action, and stabilize a rigid-body mode of the VCM. It also has to stabilize the first primary resonance of the VCM (called “butterfly mode”) at 5.3 kHz by phase condition (Atsumi et al., 2006). The multi-rate notch filter for the VCM, $N_{\text{VCM}}[z]$, is a transfer function from $u_{\text{VCM}}$ to $u_{\text{VCM}}$. It has to decrease the gain at the mechanical resonances beyond the Nyquist frequency of the hold $\mathcal{H}$ and the sampler $S$. As a result, $C_{\text{VCM}}[z]$ and $N_{\text{VCM}}[z]$ are set as shown in Figs. 8, and 9, respectively.

The feedback controller for the PZT actuator, $C_{\text{PZT}}$, is a transfer function from $e$ to $u_{\text{PZT}}$. It has to provide a low-pass effect so that the gain of the PZT-actuator loop has low gain around the Nyquist frequency. The multi-rate notch filter for the PZT actuator, $N_{\text{PZT}}[z]$, is a transfer function from $u_{\text{PZT}}$ to $u_{\text{PZT}}$. It has to decrease the gain of the mechanical resonances beyond the Nyquist frequency. As a result, $C_{\text{PZT}}[z]$ and $N_{\text{PZT}}[z]$ are set as shown in Figs. 10, and 11, respectively.

For the triple-stage actuator system, the TPC actuator has little negative impact caused by mechanical resonances. This means that the TPC actuator is good for control in high frequency range. On the other hand, a stroke of the TPC actuator is too short to compensate for a low-frequency disturbance. Therefore, the feedback controller for the thermal actuator $C_{\text{TPC}}[z]$, that is a transfer function from $e$ to $u_{\text{TPC}}$, has to provide a high-pass effect except the Nyquist frequency.
Moreover, the thermal actuator loop ($P_{TPC}[z]C_{TPC}[z]$) has to work mainly around 10 kHz in the triple-stage-actuator system so that $H_\infty$ norm of the sensitivity function of the triple-stage-actuator system becomes small (Atsumi et al., 2013). As a result, $C_{TPC}[z]$ is set as shown in Fig. 12.

Fig. 13 shows the frequency response of the open-loop characteristics in the triple-stage actuator system (transfer characteristics from $e$ to $y$ in Fig. 7). Fig. 14 shows the frequency response of the open-loop characteristics in the VCM loop (dashed), the PZT-actuator loop (dot-dashed), and the TPC actuator loop (solid). These results showed that the open-loop characteristics of the triple-stage actuator system consist mainly of the VCM loop below 2 kHz. On the other hand, the TPC actuator loop is a major part of the triple-stage actuator system above 10 kHz. The PZT actuator loop works mainly between 2 kHz and 10 kHz in the triple-stage actuator system. Fig. 15 shows the gain frequency response of sensitivity function of the triple-stage actuator system. This sensitivity function shows that this control system can compensate for the disturbance below 3 kHz.

4. Flying-height fluctuation caused by TPC actuator

To estimate an adverse effect of the TPC actuator on the flying height, we performed simulations of the track-following control system shown in Fig. 7. Here, the reference signal $r$ is set as 0, and the disturbance signal $d$ is set as shown in Fig. 16.

The simulation results of the magnetic head position, $y_c$, are shown by dashed lines in Fig. 17. Fig. 17(a) indicates the results of frequency domain, and Fig. 17(b) indicates the results of time domain. In this simulation, 3 $\sigma$ value (three times the standard deviation) of $y_c$ was 4.20 nm. This means that this control system was able to achieve the positioning accuracy within 10% of the track width on about 600 kTPI (kilo track per inch).
The solid lines in Fig. 17 show the flying-height fluctuation caused by the TPC actuator, $y_{FH}$. In this simulation, $3\sigma$ value of $y_{FH}$ was 0.2036 nm. Supposing that an acceptable flying height is 2 nm, this flying-height fluctuation caused by TPC actuator is equivalent to about 10% of the flying height. Such a fluctuation causes a large negative impact for magnetic recording performance in HDDs (Shiramatsu et al., 2008).

5. Control system design for flying-height fluctuation

To compensate for the flying-height fluctuations caused by the TPC actuator, a TDOF control system by using the TFC actuator is proposed. A block diagram of the proposed control system is shown in Fig 18. In this system, $C_{ff}[z]$ is a feedforward controller for the TFC actuator, $C_{fb}[z]$ is a feedback controller for the TFC actuator, and $y_{FH}$ is a flying-height signal in discrete time.

In Fig. 18, the transfer characteristics from $u_{TPC}$ to $y_{FH}$ at $\omega_0$ is given as follows:

$$
\frac{P_{dFH}(\omega_0) + P_{dTFC}(\omega_0)C_{ff}[e^{j\omega_0 T_s}]}{1 + P_{dTFC}(\omega_0)C_{fb}[e^{j\omega_0 T_s}]}.
$$

(7)

where

$$
P_{dFH}(\omega_0) = \frac{1}{T_s} \sum_{k=-\infty}^{\infty} \mathcal{H}(j\omega_0 + j\omega_s k)P_{FH}(j\omega_0 + j\omega_s k),
$$

(8)

$$
P_{dTFC}(\omega_0) = \frac{1}{T_s} \sum_{k=-\infty}^{\infty} \mathcal{H}(j\omega_0 + j\omega_s k)P_{TFC}(j\omega_0 + j\omega_s k),
$$

(9)

$T_s$ is the sampling time of the control system, and $\omega_s$ is $2\pi/T_s$. $\mathcal{H}(j\omega)$ can be given as follows (Franklin et al., 1998):

$$
\mathcal{H}(j\omega) = \frac{1 - e^{-T_s j\omega}}{j\omega}.
$$

(10)
In the TDOF control system, the feedforward controller moves the TFC actuator so that the output signal of the TFC actuator cancel the flying-height fluctuations caused by the TPC actuator. To do so, the control system must make the gain of $P_{dT FC} C_{ff}$ small enough. This means that $C_{ff}[z]$ should have similar characteristics to $R_{FF}$:

$$R_{FF} (\omega_0) = \frac{P_{dFH}(\omega_0)}{P_{dT FC}(\omega_0)}.$$  \hfill (11)

The solid lines in Fig. 19 show the frequency response of $R_{FF}$. Consequently, the parameters of $C_{ff}[z]$ are determined so that the $C_{ff} [e^{i\omega_0 T_s}]$ coincides with $R_{FF} (\omega_0)$. As a result, $C_{ff}[z]$ for this case study is given as follows:

$$C_{ff}[z] = \frac{0.00641(z + 0.665)(z - 0.628)(z - 0.890)(z - 0.389)(z - 0.295)}{(z - 0.957)(z - 0.865)(z - 0.655)(z - 0.313)(z - 0.312)}.$$ \hfill (12)

The dashed lines in Fig. 19 show the frequency response of $C_{ff}$.

In the TDOF control system, the feedback controller can decrease the amplitude spectrum of the $y_{dFH}$ at $\omega_0$ when

$$\left| \frac{1}{1 + P_{dT FC}(\omega_0) C_{fb}[e^{j\omega_0 T_s}]} \right| < 1.$$ \hfill (13)

The solid line in Fig. 17 shows that the amplitude spectrum of the $y_{dFH}$ has a peak around 2 kHz in this case study. Therefore, $|1/(1 + P_{dT FC} C_{fb})|$ has to be small at 2 kHz so that a standard deviations of $y_{dFH}$ becomes small. To do so, $C_{fb}$ is designed with the Bode and Nyquist plots of $P_{dT FC} C_{fb}$. As a result, $C_{fb}$ is given as a following lead-lag filter:

$$C_{fb}[z] = \frac{0.538(z + 1)(z - 0.993)}{(z - 0.803)^2}.$$ \hfill (14)
Fig. 21  Frequency response of open-loop characteristics for feedback control of TFC, \( P_{dTFC}C_{fb} \): (a) Bode plot and (b) Nyquist plot.

Fig. 22  Frequency response of \( |1/(1 + P_{dTFC}C_{fb})| \).

Fig. 20 shows the frequency response of \( C_{fb} \), Fig. 21 shows the frequency response of \( P_{dTFC}C_{fb} \) ((a): Bode plot, (b): Nyquist plot), and Fig. 22 shows the gain frequency response of \( 1/(1 + P_{dTFC}C_{fb}) \). These figures show that the feedback controller can compensate for the flying-height fluctuation around 2 kHz.

6. Performance evaluation against plant perturbations

In this section, we compare with the flying-height fluctuations during the track-following control between three track-following control systems. The first control system does not employ flying-height controls. The second control system employs the flying-height control with the feedforward control only. In this case, the feedback controller, \( C_{fb} \), is set as 0. The third control system employs the flying-height control with the proposed TDOF scheme.

In an HDD manufacturing, we have to check the plant gain perturbations because sensitivities of magnetic heads or actuator’s gains are variable. Moreover, the actuators have phase perturbations on the frequency domain because its pole frequencies depend on temperature or individual variations. Therefore, to verify the effectiveness of the proposed method, we perform track-following simulations by using one nominal plant (without perturbation) and four perturbed plants of \( PFH \) in Fig. 18.

The nominal plant is given as (3) that is used for designing of \( C_{ff} \). In the first perturbed plant of \( PFH \), the plant gain is increased by 10% from that in the nominal plant. In the second perturbed plant of \( PFH \), the plant gain is decreased by 10% from that in the nominal plant. The frequency responses of the first and second perturbed plants are shown in Fig. 23(a). In this figure, solid lines show the frequency responses of the nominal plant, dot-dashed lines show that of the perturbed plant with +10% plant gain, and dashed lines show that of the perturbed plant with -10% plant gain.

In the third perturbed plant \( PFH \), the pole frequencies are increased by 10% from that in the nominal plant. In the fourth perturbed plant \( PFH \), the pole frequencies are decreased by 10% from that in the nominal plant. The frequency responses of the third and fourth perturbed plants are shown in Fig. 23(b). In this figure, solid lines show the frequency responses of the nominal plant, dot-dashed lines show that of the perturbed plant with +10% pole frequencies, and dashed lines show that of the perturbed plant with -10% pole frequencies.

Table 3 shows the simulation results of 3 \( \sigma \) values of the flying height signals, \( y_{cFH} \). Fig. 24 shows the simulation
Fig. 23 Frequency response of perturbed plants for $P_{FH}$. (a): Gain-perturbed plants. Solid lines show the frequency responses of the nominal plant, dot-dashed lines show that of the perturbed plant with +10% plant gain, and dashed lines show that of the perturbed plant with -10% plant gain. (b): Pole-perturbed plant. Solid lines show the frequency responses of the nominal plant, dot-dashed lines show that of the perturbed plant with +10% pole frequencies, and dashed lines show that of the perturbed plant with -10% pole frequencies.

Table 3 3 σ values of the flying-height signals, $y_{cFH}$, with and without plant perturbations [nm].

| Perturbation   | w/o Control | w/ Feedforward | w/ TDOF |
|----------------|-------------|----------------|---------|
| none           | 0.2036      | 0.0216         | 0.0216  |
| +10% gain      | 0.2240      | 0.0331         | 0.0256  |
| -10% gain      | 0.1833      | 0.0257         | 0.0217  |
| +10% pole freq.| 0.2222      | 0.0334         | 0.0276  |
| -10% pole freq.| 0.1843      | 0.0299         | 0.0250  |
7. Performance evaluation with measurement noise or time delay

In this section, we discuss the sensing of the feedback signal for the TFC system, and we perform other track-following simulations with measurement noises or time delays. In this section, $P_{FH}$ is set as the first perturbed plant in which the plant gain is increased by 10% from that in the nominal plant. This means that the 3σ values of the feedback control signal for the TFC control is 0.0331 nm (the 3σ values of $y_{cFH}$ with the feedforward control).

Fig. 25 shows the comparison results between with and without measurement noises in the feedback control signal for the TFC control. In this figure, the dot-dashed line indicates the amplitude spectrum of $y_{cFH}$ without measurement noises. The solid line indicates the amplitude spectrum of $y_{cFH}$ with the measurement noise in which 3σ value is 0.0200 nm (about 60% of the 3σ values of $y_{cFH}$). The dashed line indicates the amplitude spectrum of $y_{cFH}$ with the measurement noise in which 3σ value is 0.0265 nm (about 80% of the 3σ values of $y_{cFH}$).
between with and without time delays in the feedback control signal for the TFC control. The dot-dashed line indicates the amplitude spectrum of $y_{cFH}$ without the time delay. The solid line indicates the amplitude spectrum of $y_{cFH}$ with 4.6 $\mu$s time delay (20% of the sampling time of the feedback control system). The dashed line indicates the amplitude spectrum of $y_{cFH}$ with 6.9 $\mu$s time delay (30% of the sampling time of the feedback control system). Table 4 shows the simulation results of 3 $\sigma$ values of the flying height signals, $y_{cFH}$ in Figs. 25 and 26.

These results showed that the proposed TDOF control system can improve the flying-height fluctuations caused by the TPC system when the measurement noise is smaller than about 80% of the feedback control signal. These results also showed that the proposed TDOF control system can improve the flying-height fluctuations caused by the TPC system when the measurement time delay is smaller than about 6.9 $\mu$s (about 30% of the sampling time of the feedback control system).

**Fig. 25** Comparison of simulation results between with and without measurement noises in the feedback control signal for the TFC control. The dot-dashed line indicates the amplitude spectrum of $y_{cFH}$ without measurement noises. The solid line indicates the amplitude spectrum of $y_{cFH}$ with the measurement noise in which 3 $\sigma$ value is 0.0200 nm. The dashed line indicates the amplitude spectrum of $y_{cFH}$ with the measurement noise in which 3 $\sigma$ value is 0.0265 nm.

**Fig. 26** Comparison of simulation results between with and without time delays in the feedback control signal for the TFC control. The dot-dashed line indicates the amplitude spectrum of $y_{cFH}$ without the time delay. The solid line indicates the amplitude spectrum of $y_{cFH}$ with 4.6 $\mu$s time delay. The dashed line indicates the amplitude spectrum of $y_{cFH}$ with 6.9 $\mu$s time delay.

**Table 4** 3 $\sigma$ values of the flying-height signals, $y_{cFH}$, with the first perturbed $P_{FH}$ in which the gain is increased by 10%

|                     | w/o Control | w/ Feedforward | w/ TDOF |
|---------------------|-------------|----------------|---------|
| w/o measurement noise and time delay | 0.2240 | 0.0331 | 0.0256 |
| w/ measurement noise (3 $\sigma$ value: 0.0200 nm) | 0.2240 | 0.0331 | 0.0301 |
| w/ measurement noise (3 $\sigma$ value: 0.0265 nm) | 0.2240 | 0.0331 | 0.0330 |
| w/ 4.6 $\mu$s time delay | 0.2240 | 0.0331 | 0.0300 |
| w/ 6.6 $\mu$s time delay | 0.2240 | 0.0331 | 0.0329 |
8. Summary

To employ a triple-stage-actuator system with a thermal actuator on a magnetic head positioning system in HDDs, we have to compensate for the flying-height fluctuations caused by the thermal positioning actuator. To overcome this issue, we have studied a coordinated control system with tracking-position and flying-height control systems.

In the previous study, we have compensated for the flying-height fluctuations by using a feedforward control scheme. However, the feedforward control has little robustness against the plant perturbations. To address this issue, this paper proposed a TDOF control scheme for the coordinated control with the TFC and the TPC systems. By using proposed TDOF method, we can compensate for the flying-height fluctuations against the plant perturbations. Simulation results showed that the proposed method is able to improve robust performance against the plant perturbations.

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