Emerging Technology for Head-Positioning System in HDDs

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The recent rapid growth of the information industry has strongly increased the demand for large-capacity hard disk drives (HDDs). This means that increasing the areal recording density has become an important technical challenge in HDD development. To increase the HDD areal recording density, we have developed emerging technologies for high-accuracy positioning control of magnetic heads in the head-positioning system of HDDs. This paper introduces two examples of emerging technologies for future HDDs: “Vibration Control with Thin-Film-Coil Actuator” and “High-Bandwidth Control with Thermal Actuator”. The former utilizes a film-coil actuator attached to a coil of a voice-coil motor. The latter utilizes a thermal actuator in the magnetic head. These control systems employ triple-stage-actuator systems to improve the control performance of the head-positioning system. The validation results showed that these control systems enable us to achieve high-accuracy positioning control of magnetic heads for future HDDs.

Keywords: hard disk drive, positioning control, vibration control, triple-stage-actuator system, thermal actuator, thin-film-coil actuator

1. Introduction

In the 21st century, data-storage drives are a core technology, enabling the digital universe as a result of the ever-increasing volume of content created by Internet services, cloud computing, Big Data analytics, social networking, and mobile devices. In the data-storage drives, a hard disk drive (HDD) is the most widely used device, and the positioning accuracy of magnetic heads in the HDD must be improved to meet this increasing demand for the larger storage capacity.

To realize the high-accuracy head-positioning control, we have to compensate for a disturbance which causes a positioning error between the magnetic head and a target track on a disk. However, it is generally indicated that compensable frequency-ranges for the disturbance are restricted due to effects of mechanical resonances. Therefore, we have many studies about the HDD head-positioning control system to overcome this problem through integrated designs of the mechanical and the control systems(1)(2).

This paper introduces two examples of the emerging technologies for the head-positioning system in HDDs by the author and his colleagues: “Vibration Control with Thin-Film-Coil Actuator” and “High-Bandwidth Control with Thermal Actuator(3)(4)(5)”.

2. Head-Positioning System in HDDs

An HDD is comprised of a voice coil motor (VCM), several magnetic heads, several disks, a spindle motor, a head-stack assembly (HSA), a cover, and a base, as shown in Fig. 1. Magnetic heads are attached to suspensions in the HSA. The head-position signal is generated from embedded information in servo sectors located at regular intervals on the disks. The head-position signal therefore is only available as a discrete-time signal at a sampling time determined by the rotation rate of the spindle and the number of servo sectors.

3. Vibration Control with Thin-Film-Coil Actuator

3.1 Background In the head-positioning system of HDDs, vibrations of the mechanical system may degrade the positioning accuracy. Most of these vibrations are caused by mechanical resonant modes of the head-positioning system. In these mechanical resonant modes, a torsional mode of an HSA, in which a frequency is between 3 and 4 kHz, has a large negative impact for the performance of HDDs because its resonant frequency is located in an unstable phase area of the feedback control system of the head-positioning system. The torsional mode can be easily and undesirably excited by operational vibrations of HDDs in a data-storage server. An example of the modal shape of the torsional mode in the head-positioning system is shown in Fig. 2. This modal shape was calculated with an FEM (Finite Element Method) simulation.

3.2 Thin-Film-Coil Actuator To compensate for vibrations caused by this torsional mode, we have developed a vibration control method with a thin-film-coil actuator (called
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Atsumi(1) . A photograph of the film actuator is shown in Fig. 3, and a photograph of the HSA with the film actuator is shown in Fig. 4. This film actuator has two layers of coils in a flexible-printed circuit. In this structure, the film actuator can generate torsion moment around the coil of the VCM without generating rotational moment of the HSA. Thus, the film actuator can move the torsional mode of the HSA without moving a rigid-body mode of the HSA. On the other hand, the VCM actuator generate the torsion moment and rotational moment of HSA. In this control system, the number of heads are ten (five disks), and the heads are numbered from bottom (the base side: H0) to top (the cover side: H9).

Frequency responses of the VCM actuator are shown in Fig. 5. The frequency responses indicate that a primary resonance of the VCM actuator is so-called “VCM butterfly mode”, and its frequency is around 5.3 kHz. This frequency responses also indicate that the torsional mode shown in Fig. 2 is located at 3.4 kHz in this VCM actuator. The gain characteristic of the torsional mode are large in outer-side heads (H0 and H9), and small in inner-side heads (H4). The phase characteristics of the torsional mode in bottom-side heads (H0 and H4) fall within a range from 0 to −180 degrees, and that in top-side heads (H9) fall within a range from −180 to −360 degrees.

3.3 Control System with Film Actuator To compensate for vibrations caused by the torsional mode of the HSA, we have developed a control system that uses a triple-stage-actuator system: the first stage is the VCM actuator for moving the HSA, the second stage is a piezoelectric (PZT) actuator for moving the suspension in the HSA, and the third stage is the film actuator to control the torsional mode of the HSA(7).

A block diagram with the triple-stage-actuator system is shown in Fig. 7. Here, C_{VCM} is the feedback controller for the VCM actuator, N_{VCM} is the multi-rate notch filter for the VCM actuator, P_{VCM} is the VCM actuator, C_{PZT} is the feedback controller for the PZT actuator, N_{PZT} is the multi-rate notch filter for the PZT actuator, P_{PZT} is the PZT actuator, C_{film} is the feedback controller for the film actuator, P_{film} is the film actuator, I_p is the interpolator, H is the zero-order hold (ZOH), H_m is the multi-rate ZOH, and S is the sampler. The sampling time of H and S is 23.39 µs (the sampling frequency: 41.76 kHz). r is the reference signal, e is the position error signal, d_c is the disturbance signal, and y_d is the measured head-position signal.

In this study, the multi-rate number for I_p and H_m is defined as two. The interpolator I_p consists of an up-sampler and an interpolation filter. I_p can be given as follows.

\[ I_p(z) = \sum_{m=0}^{2} z^{1-m} \]  

(1)

3.4 Control System Design To design the feedback controller for the film actuator, C_{film}, we evaluate the
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The dual-stage-actuator system consists of the VCM-actuator loop and the PZT-actuator loop. Figure 8 shows the frequency responses of the open-loop characteristics in the dual-stage-actuator system. Figure 9 shows the vector loci of the open-loop characteristics in the dual-stage-actuator system. Figure 10 shows the gain-frequency responses of the sensitivity functions in the dual-stage-actuator system. The gain-frequency responses of the sensitivity functions indicate that the head-position signal $y_d$ will have oscillations in which the amplitude is about 1.6 times as large as the amplitude of the disturbance signal $d_c$ at 3.4 kHz. This means that the dual-stage-actuator control system increases the negative impact of the disturbance signal induced by the torsional mode at 3.4 kHz.

To decrease the gain of the sensitivity function at 3.4 kHz, we designed the controller for the film-actuator loop, $C_{\text{film}}$. In this control system design, we aim to add a circle of the vector locus that recedes from the critical point $[-1,0]$ on the Nyquist diagram. Figures 8 and 9 show that the gains of the open-loop characteristics are about −2 dB and the phases of the open-loop characteristics are about −140 degree at 3.4 kHz (coordinate $[-0.51,-0.61]$ on the Nyquist diagram) in the dual-stage-actuator control system. This means that the open-loop characteristics of the film-actuator loop have to include the resonant characteristic at 3.4 kHz in which the phase is about −50 degree at the resonant frequency.

To meet the above-mentioned characteristics, the feedback controller for the film actuator, $C_{\text{film}}$, was designed as shown in Fig. 11. Here, the dashed line indicates $C_{\text{film}}$ for the base-side heads (H0, H1, H2, H3, and H4), and the solid line indicates $C_{\text{film}}$ for the cover-side heads (H5, H6, H7, H8, and H9). Figure 11 shows that the controller for the base-side heads has different phase characteristics from that for the cover-side heads. Figure 6 shows that the phase characteristics of the torsional mode are opposite direction between the base-side heads and the cover-side heads. Hence, the phases of $C_{\text{film}}$ for the base-side heads vary by 180 degree from that for the cover-side heads.

Figure 12 shows the frequency responses of the open-loop characteristics in the triple-stage-actuator system. Figure 13 shows the vector loci of the open-loop characteristics in the triple-stage-actuator system. Figure 14 shows the gain-frequency responses of the sensitivity functions in the triple-stage-actuator system. The vector loci of the open-loop characteristics in the triple-stage-actuator system showed that the film-actuator loop added the circle in the vector locus that recedes from the critical point $[-1,0]$ on the Nyquist diagram in the triple-stage-actuator system. As a result, the control system with the film-actuator loop can reduce the gain of the sensitivity function at 3.4 kHz by about 7 dB from that without the film-actuator loop shown in Fig. 10.
4. High-Servo-Bandwidth Control with Thermal Actuator

4.1 Background The control system in the head-positioning control of HDDs can compensate for disturbances at frequencies lower than a servo bandwidth. Consequently, the servo bandwidth of HDDs has to be increased with the increasing track density of HDDs. However, the servo bandwidth is limited by mechanical characteristics in the control system.

To overcome this issue, dual-stage-actuator systems have been widely studied for the head-positioning control systems in HDDs. The popular dual-stage-actuator system consists of a VCM and a PZT actuator. In this dual-stage-actuator system, the VCM drives an HSA, and the PZT actuator moves the suspension to control the head position. The mechanical resonance frequencies of the PZT actuator are much higher than those of the VCM actuator. Therefore, the dual-stage-actuator system can achieve higher servo bandwidth than that of a single-stage-actuator system with the VCM actuator only. This means that, to achieve 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.

4.2 Thermal Actuator 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 head-positioning control. Figure 15 shows a magnetic head which includes a thermal actuator for the head-positioning control system. This magnetic head has a heater located in a horizontal direction of a read element. In this structure, the control system can move the position of read element (head position) in a horizontal direction with thermal expansion induced by the heater with an electric current. When the electric power is applied to the heater, the read element will be pushed to move in the slider width direction by thermal expansion. The negative thermal expansion is induced by flowing air between the magnetic head and the disk. This thermal actuator has linear transfer characteristics from the heat amount to the head position. As a result, the control input to the thermal actuator is given by wattage.

Figure 16 shows a photograph of a spin-stand tester used in this study. Figure 17 illustrates the basic schematic of the triple-stage-actuator system with the thermal actuator built on the spin-stand tester. The first actuator is a VCM, the second actuator is a PZT actuator for moving the suspension, and the third actuator is the thermal actuator in the magnetic head. The control input signals are input command values to power amplifiers. They are calculated by a digital signal processor at specified intervals. The controlled variable is the head-position signal. Therefore, this head-positioning control system can be modeled as a triple-input-single-output control system.

4.3 Control System Design A block diagram of the triple-stage-actuator system with the thermal actuator is shown in Fig. 18. Here, \( C_f \) is the feedback controller for the VCM actuator, \( P_f \) is the VCM actuator, \( C_s \) is the feedback controller for the PZT actuator, \( P_s \) is the PZT actuator, \( C_t \) is the feedback controller for the thermal actuator, \( P_t \) is the thermal actuator, \( H \) is the ZOH, and \( S \) is the sampler. The sampling time of \( H \) and \( S \) was 21.70 \( \mu \)s (the sampling frequency: 46.08 kHz). \( r \) is the reference signal, \( e \) is the position error signal (PES), \( u_f \) is the control input for the VCM actuator, \( u_s \) is the control input for the PZT actuator, and \( u_t \) is the...
control input for the thermal actuator, \( d_i \), is the disturbance signal, and \( y_d \) is the measured head-position signal.

To design the control system, we measured frequency responses of controlled objects in this triple-stage-actuator system. The controlled object in the first-stage actuator is given by the transfer characteristics from \( u_f \) to \( y_d \). The measured transfer characteristics from \( u_f \) to \( y_d \) are shown in Fig. 19. This figure shows that this controlled object has mechanical resonances above 2.5 kHz. A primary resonance of the first-stage actuator is a “VCM butterfly mode”, and its frequency is around 4.5 kHz. The VCM actuator has various mechanical resonances below 4 kHz. Because this VCM actuator is used for the spin-stand tester, and not upper and lower symmetric structure.

The controlled object in the second-stage actuator is given by the transfer characteristics from \( u_s \) to \( y_d \). The measured transfer characteristics from \( u_s \) to \( y_d \) are shown in Fig. 20. This figure shows that this controlled object has mechanical resonances above 8 kHz. A primary resonance of the second-stage actuator is so-called “suspension-sway mode”, and its frequency is around 22 kHz.

The controlled object in the third-stage actuator is given by the transfer characteristics from \( u_t \) to \( y_d \). The measured

The dashed lines in Fig. 21 represent the frequency responses of \( M_t[z] \). The frequency responses of the thermal actuator and the mathematical model showed that the thermal actuator system has no mechanical resonant mode. This means that the thermal actuator has little negative impact caused by mechanical resonances.

4.4 Performance Evaluation

Figure 22 shows the comparison of the measured frequency responses of the open-loop characteristics between the single-stage-actuator system (dot-dashed), the dual-stage-actuator system (dashed), and the triple-stage-actuator system (solid).

The servo bandwidth (the open-loop gain 0 dB cross frequency) of the single-stage actuator was 950 Hz, that of the dual-stage actuator was 1400 Hz, and that of the triple-stage actuator was 2300 Hz.

Figure 23 shows the comparison of the measured frequency responses of the sensitivity functions between the single-stage-actuator system (dot-dashed), the dual-stage-actuator system (dashed), and the triple-stage-actuator system (solid).

These results indicate that the servo bandwidth of the proposed triple-stage-actuator system was higher than that of the conventional dual-stage-actuator system. As a result, the gain of the sensitivity function below 1 kHz is reduced by about
7 dB from the dual-stage-actuator system to the triple-stage-actuator system. This improvement is similar to the improvement from the single-stage-actuator system to the dual-stage-actuator system.

We also measured PESs during the track-following control. Figure 24 shows the amplitude spectra of the PESs in the single-stage, the dual-stage, and the triple-stage-actuator systems. In this figure, a dot-dashed line represents the result with the single-stage-actuator system, a dashed line represents the result with the dual-stage-actuator system, and a solid line represents the result with the triple-stage-actuator system. This figure indicates that the gain of the amplitude spectrum of the triple-stage-actuator system is lower than that of the dual-stage-actuator system by about 7 dB below 1 kHz.

The 3σ values of PES, repeatable run-out (RRO) of PES, and non-repeatable run-out (NRRO) of PES are listed in Table 1. The difference between the results of the dual-stage and the triple-stage actuator means the improvement of the positioning accuracy by using the thermal actuator. These results show that the proposed control system can dramatically improve positioning accuracy during a track-following control.

5. Conclusion

To realize the high-accuracy head-positioning control, we have to compensate for a disturbance which causes a positioning error in the head-positioning system. However, we have a problem with the HDD head-positioning control system in that its compensatable frequency-ranges for the disturbance are restricted due to the effect of mechanical resonances in the positioning system.

To overcome this issue, we have developed emerging technologies for head-positioning system in HDDs. This paper introduced “Vibration Control with Thin-Film-Coil Actuator” and “High-Bandwidth Control with Thermal Actuator”. These results showed that the proposed triple-stage-actuator systems with the novel actuators enable us to achieve high-accuracy positioning control of magnetic heads for future HDDs.

Table 1. 3σ values of PES, RRO and NRRO [nm]

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<thead>
<tr>
<th></th>
<th>Single-stage actuator</th>
<th>Dual-stage actuator</th>
<th>Triple-stage actuator</th>
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<tbody>
<tr>
<td>PES</td>
<td>16.79</td>
<td>9.93</td>
<td>6.88</td>
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<tr>
<td>RRO of PES</td>
<td>13.94</td>
<td>8.75</td>
<td>6.21</td>
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<tr>
<td>NRRO of PES</td>
<td>9.37</td>
<td>4.71</td>
<td>2.97</td>
</tr>
</tbody>
</table>

References


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