Experimental Evaluation of Triple-Stage-Actuator System with Thermal Actuator for Hard Disk Drives*

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Abstract

To improve positioning accuracy in a head-positioning control system for hard disk drives, we have developed a triple-stage-actuator system on a spin-stand tester. In this system, the first stage is a VCM actuator for moving a head-stack assembly, the second stage is a PZT actuator for moving a suspension, and the third stage is a thermal actuator for moving read/write elements. The frequency response of the thermal actuator showed that the thermal actuator system has no mechanical resonant mode. Therefore, this head-positioning system with a thermal actuator can control the head position in high frequency range without negative impact from mechanical resonances. As a result, the servo bandwidth of the proposed triple-stage-actuator system can be higher than that of the conventional dual-stage-actuator system which consists of the VCM and the PZT actuators. This improvement is similar to the improvement from the single-stage-actuator system to the dual-stage-actuator system. Experimental results on the spin-stand tester showed that the proposed control system can dramatically improve the positioning accuracy during a track-following control.

Key words : Hard Disk Drive, Positioning Control, Triple Stage Actuator System, Thermal Actuator, Vibration Control

1. Introduction

The head-positioning accuracy of hard disk drives (HDDs) must be improved to meet today's increasing demand for data storage. The control system in the head-positioning control of HDDs can compensate for disturbances at frequencies lower than the servo bandwidth. However, the mechanical characteristics limit the servo bandwidth, and the disturbances exist in a wide frequency range⁽¹⁾⁻⁽⁷⁾. The positioning errors caused by external vibrations below 1 kHz are also critical issues for HDDs. As a result, the servo bandwidth of HDDs has to be increased with the increasing track density of HDDs. Therefore, to improve positioning accuracy, the head-positioning control system should be fabricated with new actuator systems that can overcome these limitations of the servo bandwidth.

To address this issue, dual-stage-actuator systems have been widely studied for the head-positioning control systems in HDDs⁽⁸⁾⁻⁽¹⁷⁾. The popular dual-stage-actuator system consists of a voice coil motor (VCM) and a piezoelectric (PZT) actuator. In this dual-stage-actuator system, the VCM drives a head-stack assembly (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 the higher servo bandwidth than that of

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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.

We previously reported on a flying height control with a thermal actuator that was able to compensate for the repeatable run-outs (RROs) in the flying height fluctuations of magnetic heads⁽¹⁸⁾. The experimental results showed that the control system reduced the RROs below 5 kHz.

For the head-positioning control system, we previously reported on a thermal actuator for the head-positioning control in HDDs^{(19),(20)}. In this previous report, the various characteristics of the thermal actuator were evaluated on simulations and experiments. These results showed the feasibility of head-positioning control with a thermal actuator. We also reported about the simulation results of a dual-stage-actuator system that consists of the VCM and the thermal actuator⁽²¹⁾.

To achieve further improvement, we have developed a triple-stage-actuator system with the thermal actuator for the head-positioning control⁽²²⁾. In this paper, we develop the triple-stage-actuator system on a spin-stand tester. The first stage is the VCM actuator, the second stage is the PZT actuator for moving the suspension, and the third stage is the thermal actuator. Experimental results showed that the proposed triple-stage-actuator system can dramatically improve positioning accuracy during a track-following control.

2. Head-positioning control systems with triple-stage actuator

2.1. Thermal actuator

Figure 1 shows a magnetic head which includes a thermal actuator for the head-positioning control system⁽¹⁹⁾. 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 slider width direction by thermal expansion⁽²⁰⁾. This thermal actuator has linear transfer characteristics from the heat amount to the head position⁽¹⁹⁾. As a result, the control input to the thermal actuator is given by wattage.

Fig. 1 Magnetic head with thermal actuator.

2.2. Triple-stage-actuator system

Figure 2 shows a photograph of a spin-stand tester used in this study. Figure 3 illustrates the basic schematic of the triple-stage-actuator system 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, which is generated from embedded information in servo sectors located at regular intervals on the disks. Therefore, this head-positioning control system can be modeled as a triple-input-single-output control system.

Fig. 2 Photograph of spin-stand tester.

Fig. 3 Basic schematic of the triple-stage-actuator system.

A block diagram with the triple-stage-actuator system is shown in Fig. 4. In this study, we use a parallel structure of the control system that is a general structure for multi-input single-output (MISO) systems. 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, $\mathcal{H}$ is the zero-order hold (ZOH), and S is the sampler. The sampling time of $\mathcal{H}$ and S was $21.70 \mu\text{s}$ (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, u_t is the control input for the thermal actuator, d_c is the disturbance signal, and y_d is the measured head-position signal.

Fig. 4 Block diagram of control system using triple-stage actuator.

2.3. Controlled Object

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. 5. This figure shows that this controlled object has mechanical resonances above 2.5 kHz . A primary resonance of the first-stage actuator is so-called “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.

Fig. 5 Frequency response of controlled object in first-stage-actuator system.

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. 6. 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.

Fig. 6 Frequency response of controlled object in second-stage-actuator system.

The controlled object in the third-stage actuator is given by the transfer characteristics from u_t to y_d . The measured transfer characteristics from u_t to y_d are shown by solid lines in Fig. 7. The mathematical model of controlled objects in the third-stage actuator, $M_t[z]$, was determined so that the model’s frequency response coincides with the measured frequency response. As a result, $M_t[z]$ is given by a following equation.

$$M_t[z] = \frac{0.0025523(z + 12.79)(z - 0.8552)(z - 0.2319)}{z(z - 0.3359)(z - 0.8376)(z - 0.9599)} \quad (1)$$

The dashed lines in Fig. 7 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.

Fig. 7 Frequency response of controlled object in third-stage-actuator system.

2.4. Controller design of triple-stage-actuator system

In this paper, feedback controllers were designed based on the frequency responses of the controlled objects. Note that the frequency response of the controlled object in the third-stage-actuator system is given by the mathematical model $M_l[z]$ because the measured frequency response has large noise in high-frequency area. We assume that the H_∞ norm of the sensitivity function must be lower than or equal to 7.0 dB in the controller design.

The feedback controller for the VCM actuator, C_f , has to provide integral action, and stabilize the rigid-body mode of the VCM actuator. C_f also has to stabilize the butterfly mode of the VCM actuator^{(23)–(26)}. Moreover, C_f has to provide sharp peak gains at repeatable run-out (RRO) frequencies below 800 Hz^{(27)–(30)}. As a result, C_f is set as shown in Fig. 8.

Fig. 8 Frequency response of feedback controller for VCM actuator, C_f .

The feedback controller for the PZT actuator, C_s , has to provide the low-pass effect so that the gain of the PZT-actuator loop has low gain in high frequency range, especially around the suspension-sway mode. The frequency responses of C_s are shown in Fig. 9.

Fig. 9 Frequency response of feedback controller for PZT actuator, C_s .

Figure 7 shows that the thermal actuator has little negative impact caused by mechanical resonances. This means that the thermal actuator is good for control in high-frequency range. On the other hand, the stroke of the thermal actuator is too short to compensate for the low-frequency disturbances⁽¹⁹⁾. Therefore, the feedback controller for the thermal actuator C_t has to provide the high-pass effect except around the Nyquist frequency. The frequency responses of C_t are shown in Fig. 10.

Fig. 10 Frequency response of feedback controller for thermal actuator, C_t .

Figure 11 shows the simulation results of the open-loop characteristics in the triple-stage-actuator system. Figure 12 shows the simulation result of the sensitivity function in the triple-stage-actuator system. The sensitivity function indicates transfer characteristics from the disturbance signal d_c to the head-position signal y_d . Figure 13 shows the simulation results of the open-loop characteristics in the VCM-actuator loop (dot-dashed), the PZT-actuator loop (dashed), and the thermal actuator loop (solid). In these simulations, the frequency responses of the thermal actuator are given by mathematical model $M_t[z]$ shown by the dashed lines in Fig. 7. These results showed that the open-loop characteristics of the triple-stage-actuator system consist mainly of the VCM-actuator loop below 1 kHz. On the other hand, the PZT actuator loop is a major part of the triple-stage-actuator system above 2 kHz. The thermal actuator loop works mainly around 10 kHz in the triple-stage-actuator system so that H_∞ norm of the sensitivity function becomes small. Figure 14 shows simulation results of the sensitivity functions with and without the thermal actuator loop. The solid line means the result with the

VCM, PZT, and the thermal actuator loop. The dashed line means the result with the VCM and PZT-actuator loop only (without the thermal actuator loop). This figure indicates that the control system can reduce the H_∞ norm of the sensitivity function by about 4 dB with the thermal actuator loop.

Fig. 11 Simulation result of the open-loop characteristics for triple-stage-actuator system.

Fig. 12 Simulation result of the sensitivity function in triple-stage-actuator system.

Fig. 13 Simulation results of the open-loop characteristics for VCM actuator loop, PZT actuator loop, and thermal actuator loop.

Fig. 14 Simulation results of the sensitivity functions with and without thermal actuator loop.

2.5. Controller design of single-stage and dual-stage-actuator systems

To show the validity of the proposed triple-stage-actuator system, we design other two control systems. One is a single-stage-actuator system that consists of the VCM actuator only. The other is a dual-stage-actuator system that consists of the VCM and the PZT actuator. Figure 15 shows the block diagram of the single-stage-actuator system, and Fig. 16 shows that of the dual-stage-actuator system.

Fig. 15 Block diagram of control system using single-stage actuator.

Fig. 16 Block diagram of control system using dual-stage actuator.

Figure 17 shows the frequency responses of C_f for the single-stage-actuator system. Figures 18 and 19 show the frequency responses of C_f and C_s for the dual-actuator system, respectively. Figure 20 shows the comparison of the simulated 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 1000 Hz, that of the dual-stage actuator was 1450 Hz, and that of the triple-stage actuator was 2500 Hz. Figure 21 shows the comparison of the simulated 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.

Fig. 17 Frequency response of C_f for single-stage-actuator system.

Fig. 18 Frequency response of C_f for dual-stage-actuator system.

Fig. 19 Frequency response of C_s for dual-stage-actuator system.

Fig. 20 Comparison of open-loop characteristics between single-stage-actuator system, dual-actuator system, and triple-stage-actuator system.

Fig. 21 Comparison of sensitivity functions between single-stage-actuator system, dual-actuator system, and triple-stage-actuator system.

3. Experiments

To see the validity of the proposed method, experiments were conducted for the track-following control with the above mentioned control systems.

Figures 22 and 23 show the measured frequency responses of the open-loop characteristics and the sensitivity functions, respectively. In these figures, solid lines represent the results with the triple-stage-actuator system, dashed lines represent the results with the dual-stage-actuator system, and dot-dashed lines represent the results with the single-stage-actuator system. The servo bandwidth 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. These results showed that experimental results were similar to the simulation results shown in Figs. 20 and 21.

Fig. 22 Experimental results of open-loop characteristics.

Fig. 23 Experimental results of sensitivity functions.

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 solid line represents the result with the triple-stage-actuator system, a dashed line represents the result with the dual-stage-actuator system, and a dot-dashed line represents the result with the single-stage-actuator system. This figure indicates that the amplitude spectrum below 1 kHz is reduced by about 7 dB from the dual-stage-actuator system to the triple-stage-actuator system. The 3σ values of PES, 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.

Fig. 24 Amplitude spectra of the PESs in the single-stage, the dual-stage, and the triple-stage-actuator systems.

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

	Single-stage actuator	Dual-stage actuator	Triple-stage actuator
PES	16.79	9.93	6.88
RRO of PES	13.94	8.75	6.21
NRRO of PES	9.37	4.71	2.97

4. Conclusion

We have developed a triple-stage-actuator system with a thermal actuator on a spin-stand tester. In this system, the first stage is a VCM actuator for moving a head-stack assembly, the second stage is a PZT actuator for moving a suspension, and the third stage is the thermal actuator for moving read/write elements. Measured frequency responses of sensitivity functions indicated that the servo bandwidth of the proposed triple-stage-actuator system was much higher than that of the conventional dual-stage-actuator system. As a result, using the triple-stage-actuator system was dramatically able to improve the positioning accuracy during a track-following control. This means that the triple-stage-actuator system with the thermal actuator is a very good candidate for the head-positioning system in future HDDs.

References

- (1) Atsumi, T., Shimizu, T., Arisaka, T. and Masuda, H., "Integrated Design of a Controller and a Structure for Head-positioning in Hard Disk Drives", *Journal of Vibration and Control*, Vol. 12, No. 7, (2006), pp. 713–736.
- (2) Atsumi, T., "Head-Positioning Control of Hard Disk Drives Through the Integrated Design of Mechanical and Control Systems", *International Journal of Automation Technology*, Vol. 3, No. 3, (2009), pp. 277–285.
- (3) Yamaguchi, T., Hirata, M., Pang, C., *High-Speed Precision Motion Control*, (2012), CRC Press.
- (4) Atsumi, T., Okuyama, A. and Nakagawa, S., "Vibration Control Above the Nyquist Frequency in Hard Disk Drives", *The IEEE Transactions on Industrial Electronics*, Vol. 55, No. 10, (2008), pp. 3751–3757.
- (5) Atsumi, T., "Disturbance Suppression beyond Nyquist Frequency in Hard Disk Drives", *Mechatronics*, Vol. 20, No. 1, (2010), pp. 67–73.
- (6) Atsumi, T. and Messner, W., "Analysis of Unobservable Oscillations in Sampled-Data Positioning Systems", *The IEEE Transactions on Industrial Electronics*, Vol. 59, No. 10 (2012), pp. 3951–3960.
- (7) Atsumi, T. and Messner, W., "Estimation Method for Unobservable Settling Vibration of Head-Positioning Control in Hard Disk Drives", *Mechatronics*, Vol. 23, No. 1, (2013), pp. 37–45.
- (8) Mori, K., Munemoto, T., Otsuki, H., Yamaguchi, Y. and Akagi, K., "A Dual-Stage Magnetic Disk Drive Actuator Using a Piezoelectric Drive for a High Track Density," *The IEEE Transaction of Magnetics*, Vol. 27, No. 6, (1991), pp. 5298–5302.
- (9) Takaishi, K., Imamura, T., Mizoshita, Y., Hasegawa, S., Ueno, T. and Yamada, T., "Microactuator Control for Disk Drive," *The IEEE Transaction on Magnetics*, Vol. 32, No. 3, (1996), pp. 1863–1866.
- (10) Koganezawa, S., Uematsu, Y., Yamada, T., Nakano, H., Inoue, J. and Suzuki, T., "Dual-Stage Actuator System for Magnetic Disk Drives Using a Shear Piezoelectric Microactuator," *The IEEE Transaction on Magnetics*, Vol. 34, No. 4, (1998), pp. 1910–1912.
- (11) Rapley, H. and Messner, W., "Designing Controllers for Two Stage Disk Drive Actuator Systems Using the PQ Method and the Sode Plot," *The IEEE Transactions on Magnetics*, Vol. 37, No. 2, (2001), pp. 944–948.
- (12) Li, Y. and Horowitz, R., "Mechatronics of Electrostatic Microactuators for Computer Disk Drive Dual-Stage Servo Systems," *The IEEE/ASME Transactions on Mechatronics*, Vol. 6, No. 2, (2001), pp. 111–121.
- (13) Kuwajima, H. and Matsuoka, K., "Thin-Film Piezoelectric DSA for HDD," *The IEEE Transaction on Magnetics*, Vol. 38, No. 5, (2002), pp. 2186–2188.
- (14) Kobayashi, M., Nakagawa, S. and Nakamura S., "A Phase-Stabilized Servo Controller for Dual-Stage Actuators in Hard Disk Drives," *The IEEE Transactions on Magnetics*, Vol. 39, No. 2, (2003) pp. 844–850.
- (15) Pang, C., Guo, G., Chen, B. and Lee, T., "Nanoposition Sensing and Control in HDD

- Dual-Stage Servo Systems,” *Proceedings of The 2004 IEEE International Conference on Control Applications*, (2004), pp. 551–556.
- (16) White, M., Hingwe, P. and Hirano, T., “Comparison of a MEMS microactuator and a PZT milliactuator for high-bandwidth HDD servo,” *Proceedings of The 2004 American Control Conference*, (2004), pp. 541–546.
- (17) Naniwa, I., Sato, K., Nakamura, S. and Sato, K., “Active-Head Slider with Piezoelectric Actuator Using Shear-Mode Deformation,” *Microsystem Technologies*, Vol. 15, No. 10–11, (2009), pp. 1619–1627.
- (18) Shiramatsu, T., Atsumi, T., Kurita, M., Shimizu, Y. and Tanaka, H., “Dynamically Controlled Thermal Flying-Height Control Slider,” *The IEEE Transactions on Magnetics*, Vol. 44, No. 11, (2008), pp. 3695–3697.
- (19) Furukawa, M., Xu, J., Liu, J., Li, J., Nosaki, S., Otsuki, H., Suzuki, K. and Ono, K., “Feasibility Study of Thermal Positioning Control Actuator for Hard Disk Drives,” *Microsystem Technologies*, Vol. 18, No. 9–10, (2012), pp. 1383–1388.
- (20) Liu, J., Ono, K., Xu, J., Li, J. and Furukawa, M., “Thermal Actuator for Accurate Positioning Read/Write Element in Hard Disk Drive,” *Microsystem Technologies*, Vol. 18, No. 9–10, (2012), pp. 1583–1589.
- (21) Odai, M., Atsumi, T., Ohtsuki, H. and Arisaka, T., “Head-Positioning Control System Using Thermal Actuator in Hard Disk Drives”, *Microsystem Technologies*, vol. 19, no. 9–10, (2013), pp. 1483–1494.
- (22) Atsumi, T., Nakamura, S., Furukawa, M., Naniwa, I. and Xu, J., “Triple-Stage-Actuator System of Head-Positioning Control in Hard Disk Drives”, *The IEEE Transactions on Magnetics*, , Vol. 49, No. 6, (2013), pp. 2738–2743.
- (23) Atsumi, T., Arisaka, T., Shimizu, T. and Yamaguchi, T., “Vibration Servo Control Design for Mechanical Resonant Modes of a Hard-Disk-Drive Actuator,” *JSME International Journal Series C*, Vol. 46, No. 3, (2003), pp. 819–827.
- (24) Atsumi, T., “Feedforward Control Using Sampled-Data Polynomial for Track Seeking in Hard Disk Drives”, *The IEEE Transactions on Industrial Electronics*, Vol. 56, No. 5, (2009), pp. 1338–1346.
- (25) Atsumi, T. and Messner, W., “Optimization of Head-Positioning Control in a Hard Disk Drive Using the RBoDe Plot”, *The IEEE Transactions on Industrial Electronics*, Vol. 59, No. 1, (2012), pp. 521–529.
- (26) Atsumi, T. and Messner, W., “Modified Bode Plots for Robust Performance in SISO Systems with Structured and Unstructured Uncertainties”, *The IEEE Transactions on Control Systems Technology*, Vol. 20, No. 2, (2012), pp. 356–368.
- (27) Atsumi, T., “Head-Positioning Control Using Virtual Resonant Modes in a Hard Disk Drive”, *Journal of Advanced Mechanical Design, Systems and Manufacturing*, Vol. 1, No. 3, (2007), pp. 408–417.
- (28) Atsumi, T., Okuyama, A. and Kobayashi, M., “Track-Following Control Using Resonant Filter in Hard Disk Drives,” *The IEEE/ASME Transactions on Mechatronics*, Vol. 12, No. 4, (2007), pp. 472–479
- (29) Yabui, S., Okuyama, A., Kobayashi, M. and Atsumi, T., “Optimization of Adaptive Feedforward Repeatable Run-out Cancellation for Positioning Control System of Hard Disk Drives”, *Microsystem Technologies*, Vol. 18, No. 9–10, (2012), pp. 1703–1709.
- (30) Yabui, S., Okuyama, A., Atsumi, T. and Odai M., “Development of Optimized Adaptive Feed-forward Cancellation with Damping Function for Head Positioning System in Hard Disk Drives”, *Journal of Advanced Mechanical Design, Systems and Manufacturing*, Vol. 7, No. 1, (2013), pp. 39–51.