Adaptive feedforward cancellation with gain and damping control system considering helium leakage in HDDs

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Abstract

This study developed an adaptive feedforward cancellation system with gain and damping control for hard disk drives (HDDs). The system was developed to compensate for fluid-induced vibration due to helium leakage. Helium-filled HDDs are used in data servers around the world to support the information society. One of the concerns in helium-filled HDDs is the deterioration of positioning accuracy of the control system due to helium leakage. The proposed head positioning control system can compensate for the fluid-induced vibration by updating the characteristics of the control system in real-time. Real-time simulations based on MATLAB/Simulink were performed to demonstrate that fluid-induced vibrations due by helium leakage in the head positioning control system of HDDs can be compensated. The results indicated that the characteristics of the control system were updated in real-time to compensate for fluid-induced vibrations in conformity with the variation in characteristics due to helium leakage and that the fluid-induced vibrations can be adequately compensated.

Keywords Hard disk drive · Positioning control · Adaptive control · Flow-induced vibration

List of symbols

s	Laplace operator	L_{vcm}	Open loop in VCM control loop
z^{-1}	One sample operator	L_{pzt}	Open loop in piezo actuator control loop
D_{he}	Model of flow induced vibration in helium filled condition	L_{dual}	Open loop in dual (VCM + piezo actuator) control loop
m	Number of vibration mode in D_{he}	S_{vcm}	Sensitivity function in VCM control loop
α_{he-m}	m -th gain factor in D_{he}	S_{pzt}	Sensitivity function in piezo actuator control loop
ζ_{he-m}	m -th damping ratio in D_{he}	S_{dual}	Sensitivity function in dual control loop
ω_{he-m}	m -th angular frequency in D_{he}	t	Continuous time
D_{air}	Model of flow induced vibration in air filled condition	k	Sample number
n	Number of vibration mode in D_{he}	r	Reference signal
α_{air-n}	n -th gain factor in D_{air}	e	Position error signal
ζ_{air-n}	n -th damping ratio in D_{air}	d	Disturbance due to the flow induced vibration
ω_{air-n}	n -th angular frequency in D_{air}	T	Sampling time in control system
P_{vcm}	Model of plant for voice coil motor (VCM)	k	Sample number in control system
P_{pzt}	Model of plant for piezo actuator	i	Number of adaptive feedforward cancellation (AFC)
C_{vcm}	Feedback controller for VCM	ω_{afc-i}	i -th angular frequency in AFC
C_{pzt}	Feedback controller for piezo actuator	u_i	i -th output of AFC
D	Decouple filter		

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λ_i	i -th learning rate of AFC
θ_i	i -th phase of AFC
e_i	i -th forgetting factor of AFC
p_i, q_i	i -th learning parameters of AFC
F_i	Transfer function model of i -th AFC
ζ_{afc-i}	Damping ratio in F_i
J	Evaluation function
η_{λ_i}	Update rate in gradient method for λ_i
u_{idl-i}	Ideal i -th output of AFC
p_{idl-i}, q_{idl-i}	Ideal i -th learning parameters of AFC
$\delta\lambda_{idl-i}$	Error between ideal value and current value for λ_i
V_{λ_i}	Lyapunov function in gradient method for λ_i
δV_{λ_i}	Gradient of V_{λ_i}
η_{e_i}	Update rate in gradient method for e_i
δe_{idl-i}	Error between ideal value and current value for e_i
V_{e_i}	Lyapunov function in gradient method for e_i
δV_{e_i}	Gradient of V_{e_i}

1 Introduction

The Japanese Cabinet proposed a policy called “Society 5.0” to solve economic development and social issues [1]. “Society 5.0” stores a huge amount of information in a cloud space, and artificial intelligence analysis based on big data is feedback to the real world. Big data is actually stored in hard disk drives (HDDs) in data servers around the world [2]. To realize “Society5.0,” the capacity of HDDs should be increased in order to store more big data in a cloud space. The diameter of disks is standardized at 2.5 inch or 3.5 inch. It is necessary to increase the recording density that can be written on the disks. Reading/writing data on HDDs is performed using a magnetic head. The positioning accuracy should be improved to read/write data in a smaller area. Therefore, various technologies have been developed to improve positioning accuracy [3–7].

Fluid-induced vibrations deteriorate positioning accuracy. The disks rotate at approximately 5000–15,000 rpm, and the magnetic head or disk may be deformed by the fluid force caused by the rotation. It leads to the deterioration of the positioning accuracy of the control system. In recent years, helium-filled HDDs have been developed to reduce fluid-induced vibrations [8–10]. The density in helium-filled HDDs is lower than that in conventional HDDs, which are filled air, and fluid-induced vibrations can be reduced. Accordingly, helium filled HDDs are being employed in data centers. The positioning accuracy can be improved by reducing fluid-induced vibrations. However, helium leakage may occur during long-term operation of such drives. When helium leakage occurs, fluid-induced vibrations increase owing to increasing fluid density [11, 12]. Therefore, head positioning

accuracy cannot be maintained, and it may not be possible to read/write data correctly.

This study develops a control system by considering the influence of helium leakage. The proposed control system employs adaptive feedforward cancellation (AFC) to compensate for fluid-induced vibrations [13–15]. The AFC can compensate for repeatable runouts of the head positioning system of the control system [16–20]. Moreover, an enhanced AFC system was developed to compensate for non-repeatable disturbances such as flow-induced vibrations [21, 22]. The proposed system can update step size parameters and forgetting factors in the algorithm of the enhanced AFC system in real-time. These parameters are equivalent to gain and damping in the transfer function expression, respectively. The control system compensates for fluid-induced vibrations by considering the variation in characteristics due to helium leakage. The stability of the control system can be guaranteed by setting the parameters that satisfy the Lyapunov function. A real-time simulation is performed to verify the effectiveness of the proposed AFC system by using MATLAB/Simulink. In the simulation, the proposed system is applied to the head positioning control system consists of dual-stage actuator [23–28]. The effectiveness of the proposed system is verified through the simulation results.

2 The fluid-induced vibration of the helium filled HDDs

The positioning accuracy of the control system has to be improved to increase the storage capacity of HDDs. Currently, helium filled HDDs are mainstream in the market. A previous study reported that flow-induced vibrations can be decreased by approximately 90% compared with that of the conventional air-filled HDDs. However, helium leakage may occur from long-term operation of HDDs in the data server. Previous studies estimated the variation in characteristics of flow-induced vibrations due to helium leakage [11, 12], and another study developed a device to detect helium leakage [29]. The variation in characteristics due to helium leakage is shown in Fig. 1 as the amplitude spectrum in position dimension. The amplitude spectrum of the air-filled condition (Air 100%) is increasing by about 30 dB with comparison to the helium filled condition (He 100%). In addition, fluid-induced vibrations are identified from the amplitude spectrum defined by

$$D_{he}(s) = \sum_{m=1}^9 \frac{\alpha_{he-m}}{s^2 + 2\zeta_{he-m}\omega_{he-m}s + \omega_{he-m}^2}, \text{ He 100\%} \quad (1)$$

Fig. 1 Amplitude spectrum of flow-induced vibration

$$D_{air}(s) = \sum_{n=1}^9 \frac{\alpha_{air-n}}{s^2 + 2\zeta_{air-n}\omega_{air-n}s + \omega_{air-n}^2} \text{ Air 100\%} \quad (2)$$

The parameters are shown in Table 1. Although ω_{he-m} is similar to ω_{air-n} , α_{air-n} and ζ_{air-n} are from several times to tens of times of α_{he-m} and ζ_{he-m} .

3 Head positioning system of HDDs considering helium leakage

The head positioning control system cannot maintain positioning accuracy when fluid induced vibration increases because of helium leakage. The proposed control system is developed to minimize the effect on the positioning accuracy.

3.1 Current head positioning system of HDDs

The current control system is shown in Fig. 2.

The control system is defined as the dual-stage actuator system. In this study, The main feedback controller is designed by the decouple controller design, which is the representative design method [23–28]. $D(z)$ is designed to be equal to $P_{pzt}(s)$ in the decouple controller design, i.e., $D(z) = P_{pzt}(s)$. The frequency responses of $P_{vcm}(s)$, $P_{pzt}(s)$ are shown in Fig. 3, and the frequency responses of $C_{vcm}(z)$, $C_{pzt}(z)$, $D(z)$ are shown in Fig. 4. In addition, the frequency responses of the open loop $L_{vcm}(z)$, $L_{pzt}(z)$ and $L_{dual}(z)$ are shown in Fig. 5.

These transfer functions are represented as

$$L_{vcm}(z) = P_{vcm}(z)C_{vcm}(z), \quad (3)$$

$$L_{pzt}(z) = P_{pzt}(z)C_{pzt}(z), \quad (4)$$

Table 1 Parameters of the flow-induced vibration model

	Frequency	Gain	Damping ratio
m	ω_{he-m}	α_{he-m}	ζ_{he-m}
1	$1095 \times 2\pi$	0.79	$0.21e^{-2}$
2	$1213 \times 2\pi$	0.39	$0.10e^{-2}$
3	$1249 \times 2\pi$	1.09	$0.84e^{-2}$
4	$1331 \times 2\pi$	0.70	$0.29e^{-2}$
5	$1689 \times 2\pi$	0.87	$0.09e^{-2}$
6	$2125 \times 2\pi$	1.62	$0.05e^{-2}$
7	$2843 \times 2\pi$	1.51	$0.04e^{-2}$
8	$3669 \times 2\pi$	0.82	$0.03e^{-2}$
9	$4627 \times 2\pi$	0.96	$0.03e^{-2}$
n	ω_{air-n}	α_{air-n}	ζ_{air-n}
1	$1075 \times 2\pi$	10.9	$0.73e^{-2}$
2	$1202 \times 2\pi$	7.10	$0.27e^{-2}$
3	$1216 \times 2\pi$	20.7	$1.52e^{-2}$
4	$1306 \times 2\pi$	13.2	$0.57e^{-2}$
5	$1676 \times 2\pi$	12.2	$0.19e^{-2}$
6	$2107 \times 2\pi$	9.90	$0.13e^{-2}$
7	$2818 \times 2\pi$	15.1	$0.12e^{-2}$
8	$3646 \times 2\pi$	9.70	$0.09e^{-2}$
9	$4594 \times 2\pi$	12.5	$0.14e^{-2}$

Fig. 2 Block diagram of head positioning control system using dual-stage actuator

$$L_{dual}(z) = L_{vcm}(z) + L_{pzt}(z)(1 + L_{vcm}(z)) \quad (5)$$

The frequency responses of the sensitivity functions $S_{vcm}(z)$, $S_{pzt}(z)$, and $S_{dual}(z)$ are shown in Fig. 6. These transfer functions are represented as

$$S_{vcm}(z) = \frac{1}{1 + L_{vcm}(z)}, \quad (6)$$

$$S_{pzt}(z) = \frac{1}{1 + L_{pzt}(z)}, \quad (7)$$

$$S_{dual}(z) = \frac{1}{1 + L_{vcm}(z)} \frac{1}{1 + L_{vcm}(z)} \quad (8)$$

In the control system, the amplitude spectrum of $e(k)$ under acting the flow-induced vibration is shown in Fig. 7. Figure 7 indicates the amplitude is increasing due to the helium leakage.

3.2 Proposed control system of HDDs

To compensate for the flow-induced vibration, the proposed AFC is designed for the head positioning control

Fig. 4 Frequency responses of controller in the decouple controller design

Fig. 5 Frequency responses of the open loop in the decouple controller design

Fig. 3 Frequency responses of control object

(a) Transfer characteristics of $P_{VCM}(s)$

(b) Transfer characteristics of $P_{PZT}(s)$

Fig. 6 Frequency responses of sensitivity function in the decouple controller design

Fig. 7 Amplitude spectrum of position error signal $e(k)$: He 100% and Air 100%

system. The block diagram is shown in Fig. 8. The adaptive algorithm of the proposed AFC is represented as

$$u_i(k) = p_i(k) \sin(\omega_{afc-i}Tk) + q_i(k) \cos(\omega_{afc-i}Tk), \quad (9)$$

$$p_i(k) = \epsilon_i(k)p_i(k-1) + \lambda_i(k)e(k) \sin(\omega_{afc-i}Tk + \theta_i), \quad (10)$$

$$q_i(k) = \epsilon_i(k)q_i(k-1) + \lambda_i(k)e(k) \cos(\omega_{afc-i}Tk + \theta_i) \quad (11)$$

$p_i(k)$, $q_i(k)$ are updating to compensate for the disturbance in real time. The difference between the proposed AFC and the conventional AFC is that $\lambda_i(k)$ and $\epsilon_i(k)$ are updated in real-time. From previous studies, the recurrence equation can be written by the transfer function [21, 22]. The transfer function is represented as

$$F_i(s) = \lambda_i(k) \frac{\cos \theta_i s + \omega_{afc-i}(\sin \theta_i + \zeta_{afc-i} \cos \theta_i)}{s^2 + 2\zeta_{afc-i}(k)\omega_{afc-i}s + \omega_{afc-i}^2} \quad (12)$$

where $\zeta_{afc-i}(k)$ can be derived from $\epsilon_i(k) = e^{-\zeta_{afc-i}(k)\omega_{afc-i}T}$ equivalently [22]. By comparing the coefficients of Eqs. (9), (10), (11) and (12), it can be seen that the behavior of $\epsilon_i(k)$ is the same as the forgetting factor and that of the $\lambda_i(k)$ is the same as the gain. The proposed AFC can update its frequency responses in real-time by updating $\epsilon_i(k)$ and $\lambda_i(k)$. To compensate for the flow-induced vibration, the parameters $\lambda_i(k)$ and $\epsilon_i(k)$ are updated according to the variation in the characteristics because of the helium leakage. These parameters are updating based on the gradient method. The adaptive algorithm for each parameter is shown below. In this part, the proposed AFC is parallel connected to the controller C_{PZT} .

• Adaptive algorithm for step size λ_i

The step size parameter $\lambda_i(k)$ is updated by the gradient descent given by

$$\lambda_i(k+1) = \lambda_i(k) - \eta_{\lambda_i} \frac{\partial J}{\partial \lambda_i(k)} \quad (13)$$

where J is defined as $e^2(k)$. Equation (13), the gradient $\frac{\partial J}{\partial \lambda_i(k)}$ is represented as

$$\begin{aligned} \frac{\partial J}{\partial \lambda_i(k)} &= \eta_{\lambda_i} \frac{\partial e^2(k)}{\partial \lambda_i(k)} \\ &= 2\eta_{\lambda_i} e(k) \frac{\partial e(k)}{\partial \lambda_i(k)} \end{aligned} \quad (14)$$

where Eq. (14) can be represented as

$$\begin{aligned} \frac{\partial J}{\partial \lambda_i(k)} &= 2\eta_{\lambda_i} e(k) \frac{\partial (S_{dual}d(k) + R_{PZT}u_i(k))}{\partial \lambda_i(k)} \\ &= 2\eta_{\lambda_i} e(k) R_{PZT} \frac{\partial (p_i(k) \sin(\omega_{afc-i}Tk))}{\partial \lambda_i(k)} \\ &\quad + 2\eta_{\lambda_i} e(k) R_{PZT} \frac{\partial (q_i(k) \cos(\omega_{afc-i}Tk))}{\partial \lambda_i(k)} \end{aligned} \quad (15)$$

Fig. 8 Block diagram of control system with resonant filter

where $e(k) = S_{dual}d(k) + S_{dual}P_{PZT}u_i(k)$. $S_{dual}P_{PZT}$ is calculated as the discrete-time transfer function fitted to its frequency response, and it is defined as $R_{PZT} = S_{dual}P_{PZT}$. By substituting Eqs. (10) and (11), (15) is rewritten as

$$\begin{aligned} \frac{\partial J}{\partial \lambda_i(k)} &= 2\eta_{\lambda_i} e(k) R_{PZT} \sum_{a=1}^k \frac{\partial \epsilon_i^{k-a}(a) \lambda_i e(a) \sin(\omega_{afc-i}Ta + \theta_i)}{\partial \lambda_i} \\ &+ 2\eta_{\lambda_i} e(k) R_{PZT} \sum_{a=1}^k \frac{\partial \epsilon_i^{k-a}(a) \lambda_i e(a) \cos(\omega_{afc-i}Ta + \theta_i)}{\partial \lambda_i} \\ &= 2\eta_{\lambda_i} e(k) R_{PZT} \sum_{a=1}^k \epsilon_i^{k-a}(a) e(a) \cos \theta_i \end{aligned} \quad (16)$$

where $w_i(k) = e(k) \sum_{a=1}^k (\epsilon_i^{k-a}(a) e(a) \cos \theta_i)$. By substituting Eqs. (16), (13) is rewritten as

$$\lambda_i(k+1) = \lambda_i(k) - 2\eta_{\lambda_i} R_{PZT} w_i(k) \quad (17)$$

The stability of the gradient descent Eq. (17) can be theoretically analyzed using the Lyapunov function. When the control system completely eliminates the error, the relation between the disturbance $d(k)$ and the AFC output $u_{idl-i}(k)$ is represented as

$$\begin{aligned} d(k) &= -P_{PZT} u_{idl-i}(k) \\ &= -P_{PZT} (p_{idl-i} \sin(\omega_{afc-i}Tk) \\ &\quad + q_{idl-i} \cos(\omega_{afc-i}Tk)) \end{aligned} \quad (18)$$

By substituting $e(k) = S_{dual}d(k) + R_{PZT}u_i(k)$, Eq. (18) is rewritten as

$$\begin{aligned} e(k) &= S_{dual}u_{idl-i} + R_{PZT}u_i(k) \\ &= -(R_{PZT}(p_{idl-i} - p_i(k)) \sin(\omega_{afc-i}Tk) \\ &\quad - (q_{idl-i} - q_i(k)) \cos(\omega_{afc-i}Tk)) \end{aligned} \quad (19)$$

The ideal step size parameter is defined as λ_{idl-i} , and Eq. (10) is rewritten as

$$p_{idl-i} = \sum_{a=1}^k \epsilon_i^{k-a}(a) \lambda_{idl-i} e(a) \cos(\omega_{afc-i}Ta + \theta_i) \quad (20)$$

$$\begin{aligned} R_{PZT}(p_{idl-i} - p_i(k)) \sin(\omega_{afc-i}Tk) \text{ is rewritten as} \\ R_{PZT}(p_{idl-i} - p_i(k)) \sin(\omega_{afc-i}Tk) \\ = R_{PZT}(\lambda_{idl-i} - \lambda_i(k)) \sum_{a=1}^k \epsilon_i^{k-a}(a) e(a) \sin(\omega_{afc-i}Ta \\ + \theta_i) \sin(\omega_{afc-i}Tk) \end{aligned} \quad (21)$$

$$\begin{aligned} R_{PZT}(q_{idl-i} - q_i(k)) \cos(\omega_{afc-i}Tk) \text{ is rewritten as} \\ R_{PZT}(q_{idl-i}(k) - q_i(k)) \cos(\omega_{afc-i}Tk) \\ = R_{PZT}(\lambda_{idl-i} - \lambda_i(k)) \sum_{a=1}^k \epsilon_i^{k-a}(a) e(a) \cos(\omega_{afc-i}Ta \\ + \theta_i) \cos(\omega_{afc-i}Tk) \end{aligned} \quad (22)$$

By substituting Eqs. (21), (22), (19) is rewritten

$$\begin{aligned} e(k) = S_{dual}u_{idl-i}(k) + R_{PZT}u(k) \\ = R_{PZT}(\lambda_{idl-i} - \lambda_i(k)) \sum_{a=1}^k \epsilon_i^{k-a}(a) e(a) (\sin(\omega_{afc-i}Ta \\ + \theta_i)) \sin(\omega_{afc-i}Tk) \\ + \cos(\omega_{afc-i}Ta + \theta_i)) \cos(\omega_{afc-i}Tk) \\ = R_{PZT}(\lambda_{idl-i} - \lambda_i(k))w_i(k) \end{aligned} \quad (23)$$

where the error $\delta\lambda_i(k)$ is defined as $\delta\lambda_i(k) = \lambda_{idl-i} - \lambda_i(k)$. By subtracting λ_{idl-i} from both sides of Eq. (32), the gradient of $\delta\lambda_i(k)$ is represented as

$$\delta\lambda_i(k+1) = \delta\lambda_i(k) - 2\eta_{\lambda_i} e(k) R_{PZT} w_i(k) \quad (24)$$

The Lyapunov function is defined as

$$V_{\lambda_i}(k) = \delta\lambda_i^2(k) \quad (25)$$

$\delta V_{\lambda_i}(k)$ is represented as

$$\begin{aligned} \delta V_{\lambda_i}(k) = V_{\lambda_i}(k+1) - V_{\lambda_i}(k) \\ = \delta\lambda_i^2(k+1) - \delta\lambda_i^2(k) \\ = (\delta\lambda_i(k) - 2\eta_{\lambda_i} e(k) R_{PZT} w_i(k)) (\delta\lambda_i(k) \\ - 2\eta_{\lambda_i} e(k) R_{PZT} w_i(k)) - \delta\lambda_i^2(k) \\ = -4\eta_{\lambda_i} e(k) R_{PZT} \delta\lambda_i(k) w_i(k) \\ + 4\eta_{\lambda_i}^2 e^2(k) R_{PZT}^2 w_i^2(k) \end{aligned} \quad (26)$$

By substituting Eqs. (23) into eq.(26), (26) is rewritten as

$$\begin{aligned} \delta V_{\lambda_i}(k) = -4\eta_{\lambda_i} e^2(k) + 4\eta_{\lambda_i}^2 e^2(k) R_{PZT}^2 w_i^2(k) \\ = -4\eta_{\lambda_i} e^2(k) (1 - \eta_{\lambda_i} R_{PZT}^2 w_i^2(k)) \end{aligned} \quad (27)$$

The adaptive algorithm for λ_i is stable if $\delta V_{\lambda_i}(k)$ is negative. η_{λ_i} should satisfy the following equation

$$0 < \eta_{\lambda_i} < \frac{1}{R_{PZT}^2 w_i^2(k)} \quad (28)$$

• Adaptive algorithm for forgetting factor ϵ_i

The forgetting factor $\epsilon_i(k)$ is also updated to minimize the position error signal $e(k)$ in the proposed AFC. The gradient descent for ϵ_i is represented as

$$\epsilon_i(k+1) = \epsilon_i(k) - \eta_{\epsilon_i} \frac{\partial e^2}{\partial \epsilon_i(k)} \quad (29)$$

$\frac{\partial J(k)}{\partial \epsilon_i(k)}$ is represented as

$$\begin{aligned} \frac{\partial e^2}{\partial \epsilon_i(k)} \\ = 2\eta_{\epsilon_i} e(k) \frac{\partial (R_{PZT} d(k) + R_{PZT} u_i(k))}{\partial \epsilon_i(k)} \\ = 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (p_i(k) \sin(\omega_{afc-i}Tk))}{\partial \epsilon_i(k)} \\ + 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (q_i(k) \cos(\omega_{afc-i}Tk))}{\partial \epsilon_i(k)} \end{aligned} \quad (30)$$

By substituting Eqs. (10) and (11), (30) is rewritten as

$$\begin{aligned} \frac{\partial e^2}{\partial \epsilon_i(k)} \\ = 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (\epsilon_i(k) p_i(k) \sin(\omega_{afc-i}Tk))}{\partial \epsilon_i(k)} \\ + 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (\epsilon_i(k) q_i(k) \cos(\omega_{afc-i}Tk))}{\partial \epsilon_i(k)} \\ + 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (\lambda_i e(k) \sin(\omega_{afc-i}Tk + \theta_i))}{\partial \epsilon_i(k)} \\ + 2\eta_{\epsilon_i} e(k) R_{PZT} \frac{\partial (\lambda_i e(k) \cos(\omega_{afc-i}Tk + \theta_i))}{\partial \epsilon_i(k)} \\ = 2\eta_{\epsilon_i} e(k) R_{PZT} u_i(k) \end{aligned} \quad (31)$$

where the gradient descent for ϵ_i is defined as

$$\epsilon_i(k+1) = \epsilon_i(k) - 2\eta_{\epsilon_i} e(k) R_{PZT} u_i(k) \quad (32)$$

The stability of the gradient descent is given by Eq. (32); it can be derived using the Lyapunov function. If the ideal forgetting factor is defined as ϵ_{idl-i} , $R_{PZT}(p_{idl-i} - p_i(k)) \sin(\omega_{afc-i}Tk)$ is rewritten as

$$\begin{aligned} & -R_{PZT}(p_{idl-i} - p_i(k)) \sin(\omega_{afc-i}Tk) \\ & = R_{PZT}(\epsilon_i(k) - \epsilon_{idl-i}) p_i(k) \sin(\omega_{afc-i}Tk) \end{aligned} \quad (33)$$

$R_{PZT}(q_{idl-i}(k) - q_i(k)) \cos(\omega_{afc-i}Tk)$ is rewritten as

$$\begin{aligned} & -R_{PZT}(q_{idl-i} - q_i(k)) \cos(\omega_{afc-i}Tk) \\ & = R_{PZT}(\epsilon_i(k) - \epsilon_{idl-i}) q_i(k) \cos(\omega_{afc-i}Tk) \end{aligned} \quad (34)$$

By substituting Eqs. (33) and (34), (19) is rewritten as

$$\begin{aligned} e(k) &= -R_{PZT} u_{idl-i} + R_{PZT} u_i(k) \\ &= R_{PZT}(\epsilon_i(k) - \epsilon_{idl-i})(p_i(k) \sin(\omega_{afc-i}Tk) \\ &\quad + q_i(k) \cos(\omega_{afc-i}Tk)) \\ &= R_{PZT}(\epsilon_i(k) - \epsilon_{idl-i}) u_i(k) \end{aligned} \quad (35)$$

where the error $\delta\epsilon_i(k)$ is defined as $\delta\epsilon_i(k+1) = \epsilon_{idl-i} - \epsilon_i(k)$. By subtracting ϵ_{idl-i} from both sides of Eq. (32), the gradient descent $\delta\epsilon_i(k)$ is represented as

$$\delta\epsilon_i(k+1) = \delta\epsilon_i(k) - 2\eta_{\epsilon_i} e(k) R_{PZT} u_i(k) \quad (36)$$

In Eq. (36), the Lyapunov function is defined as

$$V_{\epsilon_i}(k) = \delta\epsilon_i^2(k) \quad (37)$$

Fig. 10 Time responses of flow induced vibration in the simulation

$\delta V_{\epsilon_i}(k)$ is rewritten as

$$\begin{aligned} \delta V_{\epsilon_i}(k) &= V_{\epsilon_i}(k+1) - V_{\epsilon_i}(k) \\ &= \epsilon_i^2(k+1) - \delta\epsilon_i^2(k) \\ &= (\delta\epsilon_i(k) - 2\eta_{\epsilon_i} e(k) R_{PZT} u_i(k))(\delta\epsilon_i(k) \\ &\quad - 2\eta_{\epsilon_i} e(k) R_{PZT} u_i(k)) - \delta\epsilon_i^2(k) \\ &= -4\eta_{\epsilon_i} e(k) R_{PZT} \delta\epsilon_i(k) u_i(k) \\ &\quad + 4\eta_{\epsilon_i}^2 e^2(k) R_{PZT}^2 u_i^2(k) \end{aligned} \quad (38)$$

By substituting $e(k) = R_{PZT} \delta\epsilon_i(k) u_i(k)$, Eq. (38) is rewritten as

$$\begin{aligned} \delta V_{\epsilon_i}(k) &= -4\eta_{\epsilon_i} e^2(k) + 4\eta_{\epsilon_i}^2 e^2(k) R_{PZT}^2 u_i^2(k) \\ &= -4\eta_{\epsilon_i} e^2(k)(1 - \eta_{\epsilon_i} R_{PZT}^2 u_i^2(k)) \end{aligned} \quad (39)$$

Fig. 9 Detail of the block diagram in adaptive parts of the proposed AFC

Table 2 Parameters of AFCs

No	Frequency ω_{afc-i}	Step size		Damping ratio	
		λ_i		ζ_{afc-i}	
	Fix	Min	Max	Min	Max
For VCM: $i = 1 - 5$					
1	$1095 \times 2\pi$	0.0	0.0025	0.001	0.5
2	$1213 \times 2\pi$	0.0	0.0025	0.001	0.5
3	$1249 \times 2\pi$	0.0	0.0025	0.001	0.5
4	$1331 \times 2\pi$	0.0	0.0025	0.001	0.5
5	$1689 \times 2\pi$	0.0	0.0025	0.001	0.5
For piezo actuator: $i = 6 - 9$					
6	$2107 \times 2\pi$	0.0	0.0025	0.001	0.5
7	$2818 \times 2\pi$	0.0	0.0025	0.001	0.5
8	$3646 \times 2\pi$	0.0	0.0025	0.001	0.5
9	$4594 \times 2\pi$	0.0	0.0025	0.001	0.5

Fig. 11 Frequency responses of sensitivity function with AFCs; $\lambda_i = 0.0025$, $\zeta_{afc-i} = 0.001$

Fig. 12 Frequency responses of open loop with AFCs; $\lambda_i = 0.0025$, $\zeta_{afc-i} = 0.001$

The adaptive algorithm for ϵ_i is stable if $\delta V_{\epsilon_i}(k)$ is negative. η_{ϵ_i} should satisfy the following equation.

$$0 < \eta_{\epsilon_i} < \frac{1}{R_{PZT}^2 u_i^2(k)} \quad (40)$$

The block diagram of the control system with the proposed AFC that updates λ_i and ϵ_i is shown in Fig. 9.

4 Verification of the proposed method in real-time simulation

A real-time simulation was conducted using MATLAB/Simulink to verify the effectiveness of the proposed method. In this simulation, the model of the flow-induced vibration $D_{sim}(s)$ is represented as

$$D_{sim}(s) = \sum_{i=1}^9 \frac{\alpha_{sim-i}}{s^2 + 2\zeta_{sim-i}\omega_{sim-i}s + \omega_{sim-i}^2} \quad (41)$$

The characteristic variation owing to helium leakage is defined as the following condition.

- The simulation time is 60 s.
- The initial values of ω_{sim-i} , α_{sim-i} , and ζ_{sim-i} are the same as ω_{he-m} , α_{he-m} , and ζ_{he-m} , respectively.
- The values of ω_{sim-i} , α_{sim-i} , and ζ_{sim-i} are updated to be close to the values of ω_{air-n} , α_{air-n} , and ζ_{air-n} at a rate of 5% every second, respectively.
- The only input for $D_{sim}(s)$ is white noise, as defined in the HDD benchmark model [3].

Fig. 13 Vector locus of open loop with AFCs; $\lambda_i = 0.0025$, $\zeta_{afc-i} = 0.001$

Table 3 Stability of the control system

	Gain margin (dB)	Phase margin (°)	Max gain of S_{dual} (dB)
w/o AFCs	6.4	38.0	3.9
w/ AFCs	9.1	37.5	5.0

The time response of the flow-induced vibration is shown in Fig. 10. $D_{sim}(s)$ is equal to $D_{he}(s)$ at 0 s and $D_{sim}(s)$ is equal to $D_{air}(s)$ after 20 s.

The parameters of the proposed AFCs are listed in Table 2.

where the equivalent damping coefficient is calculated by $\zeta_{afc-i} = \omega_{afc-i} T \ln \epsilon_i$. The stability of the AFC depends on the phase characteristics of the plant [30]. In general, the AFC should not be implemented around the resonance frequencies. Therefore, the AFCs are implemented to compensate for flow-induced vibration

under 2 kHz in the VCM control loop, and the AFCs are implemented above 2 kHz in the piezo actuator control loop in this case. The maximum values of λ_i and ζ_{afc-i} are determined by considering the waterbed effect in the frequency response of the sensitivity function [31, 32]. The condition for the largest negative impact due to the waterbed effect is $\lambda_i = 0.0025$ and $\zeta_{afc-i} = 0.001$ for the all AFCs. The frequency response of S_{dual} at this condition is as shown in Fig. 11. Moreover, the frequency responses of the open loop L_{dual} and its vector locus are shown in Figs. 12 and 13, respectively. The gain margin, phase, margin, and maximum gain of S_{dual} are listed in Table 3. These values satisfy the design specifications for stability [27, 33]. That is, they indicate that stability can be maintained regardless of the values of λ_i and ζ_{afc-i} .

Figure 14 indicates that the characteristics of the transfer functions R_{VCM} and R_{PZT} in calculation of the gradient methods. The frequency response of R_{VCM} is close to that of $S_{dual}P_{VCM}$ up to 2 kHz and the frequency response of R_{PZT} is close to that of $S_{dual}P_{PZT}$ up to 5 kHz.

Fig. 14 Frequency responses of R_{VCM} and R_{PZT}

Fig. 15 Simulation results of time responses of λ_i

Fig. 16 Simulation results of time responses of ζ_{afc-i}

Fig. 17 Simulation results of frequency response of the sensitivity function S_{dual}

The time responses of λ_i and ζ_{afc-i} are shown in Figs. 15 and 16, respectively. These parameters increasingly conform to the variation of $D_{sim}(s)$. The frequency responses

of the sensitivity functions at 0 s (start) and at 60 s (last) are shown in Fig. 17. The proposed AFCs decrease the gain of the sensitivity function at disturbance frequencies. Figure 18 shows the simulation results of the position error signal $e(k)$ in the time and frequency domains. For comparison, the results obtained without the AFC case are also shown in Fig. 18. The amplitude of $e(k)$ can be decreased by using the proposed AFC method.

Even if the proposed AFC compensates for the flow-induced vibration, the amplitude of $e(k)$ at 60 s is larger than that at 0 s. This is because the baseline of the flow-induced vibration is increased by approximately 30 dB as shown in Fig. 1. However, the peaks of the amplitude spectrum of $e(k)$ are decreased by the proposed method. The negative impact due to the helium leakage is suppressed. The presence or absence of the helium leakage can be confirmed from the time responses of the parameters λ_i and ζ_{afc-i} . It is expected that the proposed AFC can be applied as a sensor for detecting helium leakage by setting the threshold in λ_i and ζ_{afc-i} .

Fig. 18 Simulation results of position error signal $e(k)$ **Fig. 19** Frequency responses of the plant with the variation

5 Discussion

In this study, the simulation time is set as 60 s for quick confirmation of the effectiveness of the proposed AFC. In actually, the Helium leakage can be considered as a kind of aging problem in HDDs. The disturbance model of $D_{he}(s)$ will be changing gradually. In such case, the characteristics of $P_{vcm}(s)$ and $P_{pzt}(s)$ also can be changing by time-related deterioration. The proposed AFC should be robustness under variation of the plant characteristics. To evaluate robustness of the proposed AFC, the simulations were also conducted with consideration to the variation. The uncertainty is decided in reference to the previous study [34]. The frequency responses of the plant are shown in Fig. 19. The stability of control system with the proposed AFC are estimated in the frequency

response of L_{dual} and S_{dual} . The parameters of the all AFC are set as $\lambda_i = 0.0025$ and $\zeta_{afc-i} = 0.001$, namely the negative impact due to the waterbed effect is the largest in this estimation. The frequency response of the control system is shown in Fig. 20. The worst case of the gain margin, phase, margin, and maximum gain of S_{dual} are listed in Table 4. Although the stability performance worsens, the gain margin and phase, margin satisfy the design specifications for stability [32]. The AFCs are implemented away from the mechanical resonances. Therefore, the characteristic variation doesn't affect greatly for the stability.

However, if the proposed AFC are implemented close to the mechanical resonances, the stability performance can deteriorate due to the variation. Figure 21 indicates the frequency responses of the control system, when the all AFCs are implemented to the VCM control loop. In this

Fig. 20 Frequency responses of the control system under the variation

Table 4 Worst case of the stability of the control system under the variation

	Gain margin (dB)	Phase margin (°)	Max gain of S_{dual} (dB)
w/o AFCs	5.2	37.8	9.4
w/ AFCs	4.6	34.7	9.9

case, the frequency of 9th AFC ($\omega_{afc-9} = 4594 \times 2\pi$) is close to the resonance frequency of $P_{vcm}(s)$ as shown in Fig. 19a. The vector locus of L_{dual} can be close to the unstable

point $[-1, 0j]$ on the Nyquist diagram due to the variation. As a result, there can be sharply peaks in the frequency responses of the sensitivity function around ω_{afc-9} . The stability performances about the worst case are listed in Table 5. The gain margin is insufficient and the maximum gain of S_{dual} is greatly increasing. For robustness of the control system, the proposed AFC should be implemented away from the mechanical resonances.

Fig. 21 Frequency responses of the control system under the variation: the all AFCs are implemented to the VCM control loop

Table 5 Worst case of the stability of the control system under the variation: the all AFCs are implemented to the VCM control loop

	Gain margin (dB)	Phase margin (°)	Max gain of S_{dual} (dB)
w/o AFCs	5.2	37.8	9.4
w/ AFCs	0.5	34.5	24.4

6 Conclusion

In this study, AFC with gain and damping control system was developed for helium-filled HDDs. The control system can compensate for fluid-induced vibration by considering helium leakage. In real-time simulation, the proposed control system could compensate for the fluid-induced

vibration adequately. The proposed AFC can update the step size parameter and forgetting factor according to the variation in the characteristics because of the helium leakage. Moreover, the results indicated that the helium leakage can be detected by these parameters.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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