VCM Design to Improve Dynamic Performance of an Actuator in a Disk Drive

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***Abstract*—Position error signal (PES) design margin of a current hard disk drive is getting smaller as the track density of high-capacity disk drives increases. In the present work, a new actuator design concept is introduced for suppressing one of the actuator vibration modes, the so-called butterfly mode, that normally limits the expansion of servo bandwidth. The new actuator has a single coil with four sections having respective particular directions. By adjusting the length and inclined angle of the sections of the voice coil motor (VCM) coil, the forces perpendicular to track-seeking direction can be balanced with each other. Consequently, the butterfly mode is not excited by the resultant force of the VCM. Contribution of the proposed actuator design for the PES management is verified by numerical simulations. Our results show that the servo bandwidth can be increased from 1207 to 1680 Hz so that the PES can be decreased by 27% due to the use of the improved actuator.**

***Index Terms*—Actuator, disk drive, position error signal (PES), servo bandwidth.**

I. Introduction

DATA storage capacity of hard disk drives has been gradually increased. Consequently, so has the number of tracks on a disk. When the number of tracks increases, the width of a track has to be decreased. As the tracks are becoming narrower, more sophisticated servo schemes for accurate head positioning are needed. Thus, an actuator design has to be able to carry out precise head positioning capability so that position error signal (PES) is maintained at minimum, despite the narrowed track width. But the servo performance, particularly the expansion of servo bandwidth, is limited by the mechanical resonances of actuator-suspension system.

In this paper, a new design of voice coil motor (VCM) is proposed and some numerical simulations to evaluate its performance are performed. As a result, excitation forces perpendicular to track-following direction can be cancelled out so that forces acting on the actuator do not excite the in-plane resonance mode of the actuator.

II. Dynamic Performance of Actuator

A. *Effect of Actuator Dynamics on Servo Bandwidth*

Fig. 1 shows the shape of an in-plane resonance mode of the conventional actuator. As shown in Fig. 1, the in-plane resonance mode in the conventional actuator has a shape of the swing arm and the coil support portion being twisted at the same phase around the actuator pivot. Such in-plane resonance mode is typically called a butterfly mode.

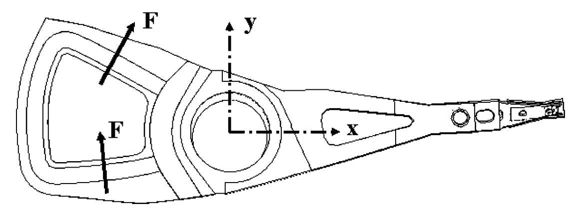

Fig. 1. Butterfly mode of a conventional actuator.

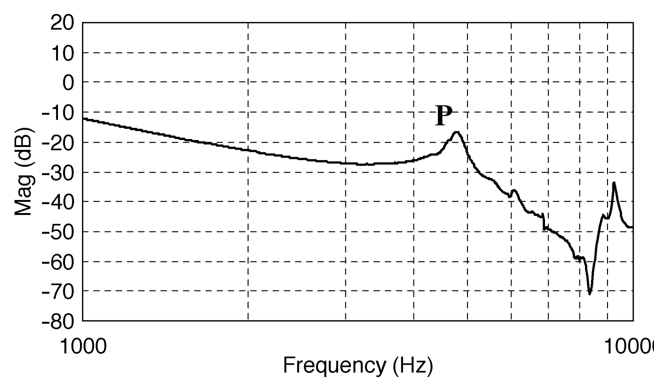

Fig. 2. Bode plot of a conventional actuator.

The force F applied on the VCM coil of the actuator is divided into a component force in a direction X parallel to the direction of the track and a component force in a direction Y perpendicular to the direction of the track. Among them, the component force in the direction Y works as a vibrating force to excite the butterfly mode.

Fig. 2 is a graph showing the in-plane response of the head in the tracking operation of the conventional actuator shown in Fig. 1. A peak P having a great magnitude appears at a frequency of about 5000 Hz and the peak P is due to the in-plane resonance mode, that is, the butterfly mode.

In order to examine the effect of the butterfly-mode frequency on the servo bandwidth, plant models for various actuators are depicted on Fig. 3 with the corresponding error sensitivity functions shown in Fig. 4. In this prediction, the butterfly-mode frequency of the plant model is increased by 500 Hz in the range of 4500–8000 Hz and the relative peak magnitude of the butterfly mode is kept constant with respect to $1/s^2$. The calculated servo bandwidth for every plant model is summarized in Table I. As the butterfly-mode frequency goes up, the peak magnitude of the frequency goes down and servo bandwidth goes up. Thus,

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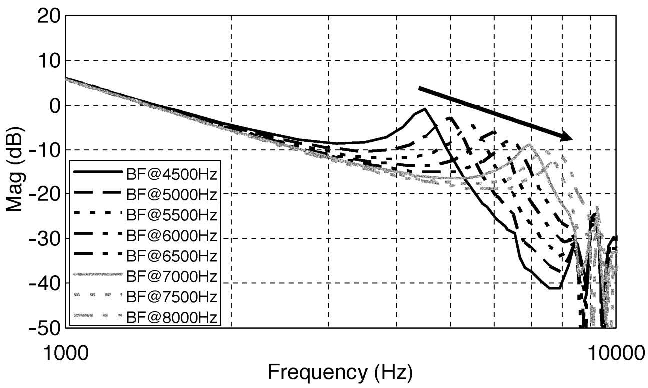

Fig. 3. Plant models for various actuators in the range of 4500–8000 Hz butterfly-mode frequency.

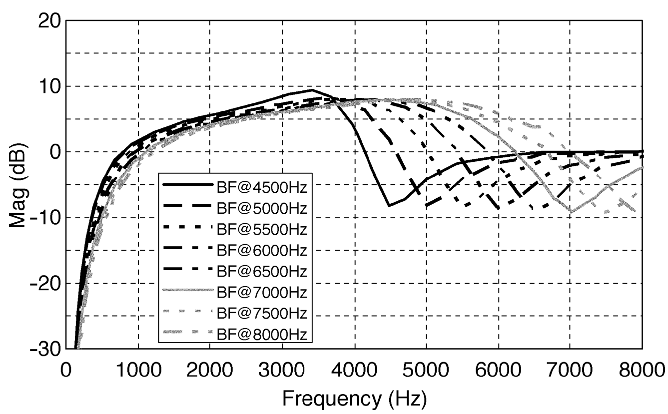

Fig. 4. Error sensitivity functions for various actuators in the range of 4500–8000 Hz butterfly-mode frequency.

TABLE I
EFFECT OF BUTTERFLY MODE FREQUENCY ON SERVO BANDWIDTH

Butterfly mode (Hz)	4500	5000	5500	6000
Servo Bandwidth (Hz)	1140	1207	1316	1420
Butterfly mode (Hz)	6500	7000	7500	8000
Servo Bandwidth (Hz)	1518	1623	1703	1803

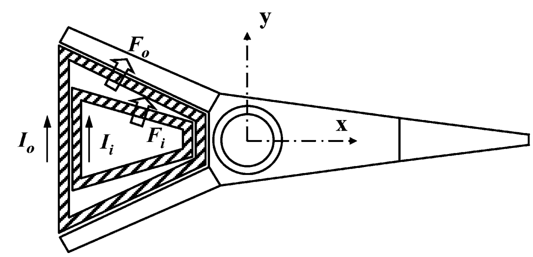

Fig. 5. Construction of actuator proposed in [2].

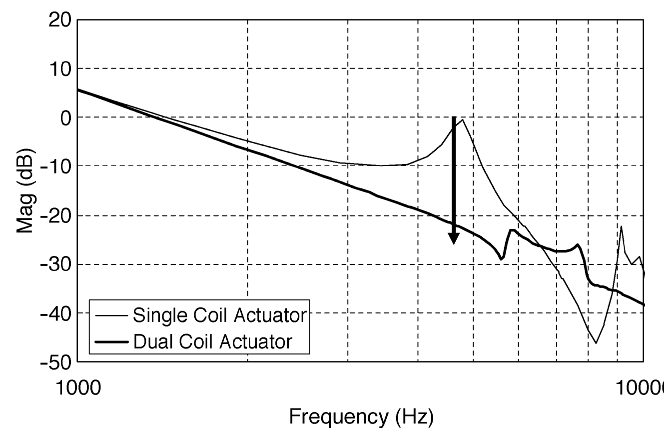

Fig. 6. Suppression of the butterfly mode.

the error sensitivity function for the actuator system with a high servo bandwidth can be easily adjusted to reject external disturbance. High servo bandwidth can make high-precision positioning possible and reduce total PES as a result.

B. Actuator Dynamics

As described above, the in-plane resonance mode, that is, the butterfly mode of the actuator, is excited by the component force in the direction Y acting on the VCM coil so that the resonance peak P having a great magnitude is generated. As the width of the track decreases, more precise servo control is needed to achieve stable operation. However, the expansion of the bandwidth for servo control is restricted by the frequency and magnitude of the peak P corresponding to the butterfly mode.

There are two ways to solve the above problem. As shown in Fig. 3, it is possible to make the high-stiffness actuator with high butterfly-mode frequency. This can make the butterfly-mode frequency, as well as other resonance frequencies, go up. However, it is very difficult to increase the stiffness of the actuator which has a conventional shape and material. The other way is the suppression of the butterfly mode. That is, actuator system has the butterfly mode at the low-frequency range, but the resultant force produced by the VCM does not activate the butterfly mode.

Several investigations [1]–[3] have been performed to suppress the butterfly mode. Aruga *et al.* [1] developed an orthogonal actuator with dual flat coils and showed that orthogonal driving could decrease the peak gain of the butterfly mode. A dual VCM coil having an outer coil and an inner coil is proposed by Huang *et al.* [2]. The construction of the actuator is shown in Fig. 5. When a seeking operation is performed, the direction of the current I_o flowing through the outer coil and the direction of current I_i flowing through the inner coil are made identical. Since the forces F_o acting on the outer coil and F_i acting on the inner coil are generated in the same direction, the actuator performs the seek operation at a fast speed. For the case of the track-following operation, however, the directions of the current flowing through the two coils are made opposite. Because the direction of the force F_o on the outer coil and the direction of the force F_i on the inner coil are opposite, the two forces F_o and F_i are offset so that the sum of the two forces acting on the actuator is minimized. In Fig. 6, the in-plane response for the dual coil actuator is compared with the in-plane response obtained for the coil current flowing only to the outer coil to simulate the single-coil actuator condition. In the simulation for the dual coil actuator, the current ratio I_o/I_i is adjusted to minimize excitation of the butterfly mode. The in-plane response for the dual coil actuator shows a decrease in the peak magnitude of the butterfly mode by the result of suppression of the butterfly mode.

Miyamoto *et al.* [3] designed a new actuator which uses the two coils laid one over the other. While the lower coil is positioned in the same way as the VCM coil of the conventional actuator, the upper one is positioned opposite the lower coil. For track-seeking operation, current flows in the same direction through the two coils and the resultant force produced is almost the same as in the conventional actuator. For track-following operation, on the other hand, the current flows in the opposite directions through two coils. The resultant forces are orthogonal to the seek direction and the actuator has no vibrating force working in the track-seeking direction during track-following operation.

When the head follows the track, although the actuator system in [1]–[3] has the butterfly mode at the low-frequency range, the magnitude of the peak corresponding to the butterfly mode is lowered because the excitation by the component force in the track-seeking direction has disappeared. As a result, a dynamic characteristic of the actuator is improved. However, since the actuators in [1]–[3] use the two coils, manufacturing the actuator is difficult and two input powers which can independently drive the two coils are needed. In addition, it is difficult to perform servo control because the directions of the currents flowing through the respective coils need to be changed.

The single-coil actuator with four polarities in the magnet was investigated in the work of Lin *et al.* [4]. The coil and magnet members can generate forces in the four portions of coil. These forces generated are orthogonal to the track-seeking direction so that the reaction force in that direction can be substantially suppressed. The butterfly mode of proposed actuator can also be eliminated in an ideal case. But, in order to generate orthogonal forces to the track-seeking direction, effective coil members, which are the driving force on actuator, are disposed in parallel with the track-seeking direction, and, then, the actuator needs a very wide fantail. To construct this actuator, the limitation problem on space can occur.

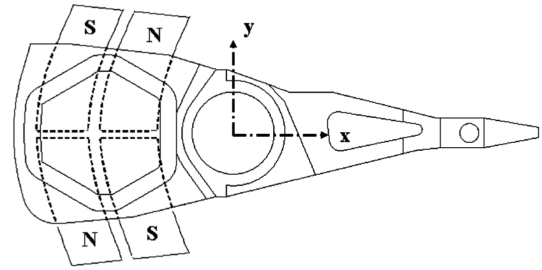

Fig. 7. Construction of a new actuator.

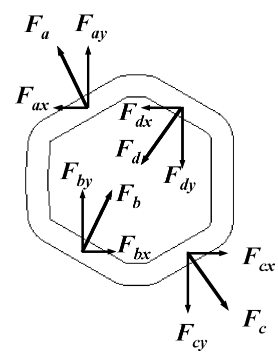

Fig. 8. Force generation of a new actuator.

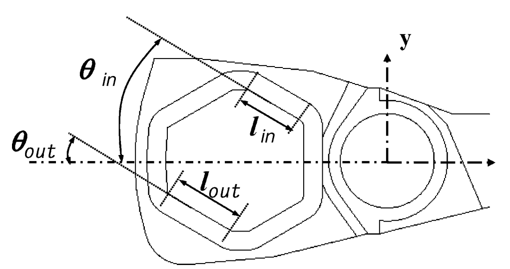

Fig. 9. Design parameters of a new actuator.

III. Design of High Servo Bandwidth Actuator

A. Design of the New Actuator

Fig. 7 shows the construction of the new actuator. The actuator has single coil with four sections having respective particular directions, and magnets are arranged to face corresponding to four sections of the VCM coil. When the current is applied to the VCM coil, directions of the force produced in the four sections of the VCM coil are different from one another. Four sections are constructed to be symmetrical with each other with respect to the X-direction center line.

Fig. 8 is a view illustrating component forces in directions X and Y acting on the respective sections of the VCM coil of the actuator of Fig. 7. The four forces F_a, F_b, F_c, and F_d acting on the respective first, second, third, and fourth sections of the VCM coil can be divided into X-directional component forces and Y-directional component forces. Design parameters of four portions of coil are the length and inclined angle of each portion (Fig. 9). By adjusting the length and direction of the sections of the VCM coil, the Y-directional component forces, that is, the forces parallel to the track-seeking direction can be balanced with each other, and then the resultant force along the Y direction can be zero or minimized as follows:

$$\begin{aligned} F_{ay} + F_{dy} &= F_{by} + F_{cy} = 0, \\ Binl_{\text{in}} \cos\theta_{\text{in}} &= Binl_{\text{out}} \cos\theta_{\text{out}} \end{aligned} \tag{1}$$

where B is the magnetic gap flux density, i is the applied current, and n is the turns of the coil.

The Y-directional component force acts as a major vibrating force to excite the butterfly mode of the actuator. This component force generates a reaction force on the pivot-bearing assembly. The reaction force on the pivot-bearing assembly potentially excites the butterfly mode of the actuator. Thus, when the resultant force of the Y-directional component forces becomes zero, the reaction force on pivot bearing cannot be generated, and the in-plane resonance mode of the actuator preferably can be suppressed.

B. Numerical Simulation of the New Actuator

The dynamic analysis of the new actuator is performed using ANSYS. To verify the simulation performance and to know the

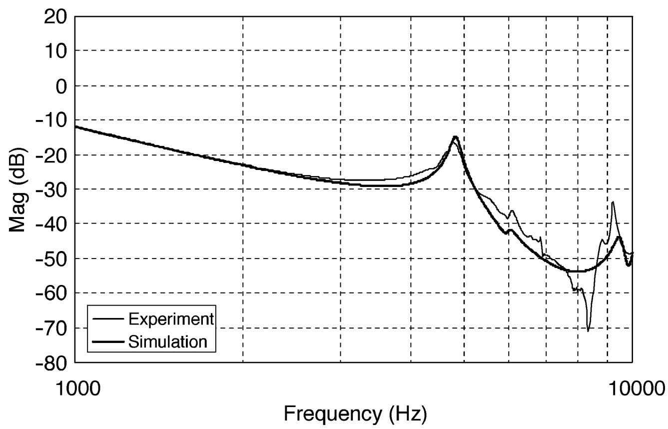

Fig. 10. Bode plots of a conventional actuator obtained by experiment and by simulation.

TABLE II
DIMENSIONS OF FACTORS FOR DOE

Factor	Min	Center	Max
l_{out}(mm)	9	10	11
θ_{out}(deg)	45	50	55
l_{in}(mm)	9	10	11
θ_{in}(deg)	45	50	55

dynamics of the conventional actuator, modal analysis and harmonic analysis for the conventional actuator is performed. In the simulation, a dummy plate is used to model the head-gimbal assembly (HGA) instead of the suspension-head system, and a constant damping ratio is set to 2%. In Fig. 10, the numerical frequency response by ANSYS is compared with the experimental frequency response. Fig. 10 shows that the simulation results are in good agreement with the experimental results. The butterfly-mode frequency of the conventional actuator is 4.8 kHz, and the gain margin at the butterfly mode is 16.6 dB.

To get the optimal shape of the new actuator, the optimization process is performed by using DOE. A commercial statistical analysis code "Minitab" [5] is used for the optimization work. As depicted in Fig. 9, design parameters for the new actuator are the length l_{in} and inclined angle θ_{in} of inside part and the length l_{out} and inclined angle θ_{out} of outside part. Each parameter is assumed to have three levels. Levels for each parameter are summarized in Table II. A total of 27 iterations using the three-level response surface method (RSM) is performed to get optimal values. Table III shows the combination of four factors and corresponding results for each case. The objective function is the peak gain at the butterfly-mode frequency and two constraints are applied. One is the minimization of the Y-directional resultant force and the other is the maximization of torque constant. In Fig. 11, the response contours are constructed for response optimization with constraints of Y-directional force difference and torque constant. As a result, the optimal values of four parameters are selected for the maximum gain at the butterfly-mode frequency and they are listed in Table IV.

Fig. 12 shows the butterfly mode of the new actuator. As shown in Fig. 12, a dummy plate is also used to model HGA. Dynamic performances for the new and conventional actuators are plotted in Fig. 13. Each response is normalized with gain at 500 Hz. The butterfly-mode frequency of the new actuator is 4.4 kHz, which shows that the butterfly-mode resonance of the

TABLE III
RSM DESIGN TABLE

	l_{out}	θ_{out}	l_{in}	θ_{in}	Gain (dB)	F_{ay}-F_{by}	Torque Constant
1	10	50	9	55	31.62	1.27	49.79
2	10	55	9	50	31.48	-0.05	49.96
3	9	50	11	50	25.13	-1.29	50.77
4	11	45	10	50	29.10	1.35	51.14
5	10	55	10	55	32.07	0.00	54.27
6	11	55	10	50	30.87	-0.12	55.21
7	10	55	11	50	23.77	-1.33	55.05
8	10	45	9	50	28.69	1.29	46.26
9	10	45	10	45	40.85	0.00	46.85
10	10	45	11	50	40.61	0.00	51.35
11	11	50	9	50	32.11	1.29	50.73
12	10	50	10	50	36.22	0.00	50.75
13	11	50	10	45	36.15	0.00	51.32
14	10	50	11	55	37.71	0.12	55.24
15	10	50	9	45	37.22	0.06	46.44
16	10	50	11	45	25.17	-1.35	51.14
17	11	50	11	50	36.22	0.00	55.83
18	9	45	10	50	40.54	-0.06	46.47
19	9	50	10	55	36.77	0.05	49.99
20	10	45	10	55	28.82	1.34	50.57
21	9	55	10	50	23.36	-1.27	49.80
22	11	50	10	55	32.09	1.33	55.05
23	9	50	9	50	36.22	0.00	45.68
24	9	50	10	45	24.61	-1.29	46.26
25	10	50	10	50	36.22	0.00	50.75
26	10	55	10	45	23.30	-1.34	50.54
27	10	50	10	50	36.22	0.00	50.75

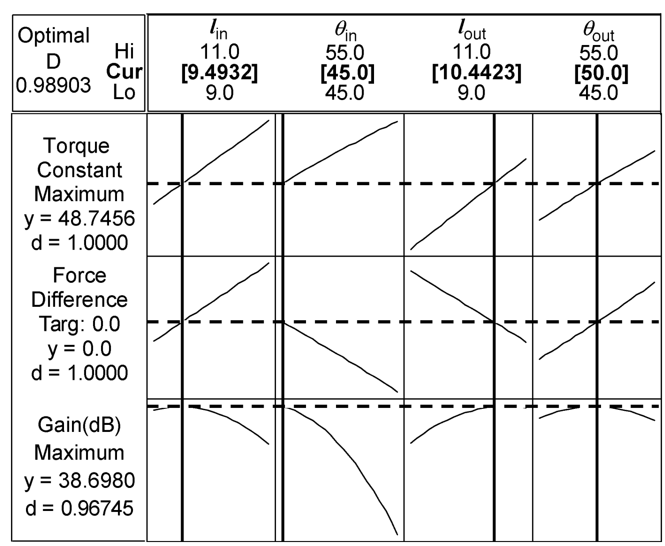

Fig. 11. Minitab response optimizer.

TABLE IV
OPTIMIZATION RESULTS

l_{out}(mm)	θ_{out}(deg)	l_{in}(mm)	θ_{in}(deg)
10.44	50	9.49	45

new actuator is reduced as compared with that of the conventional actuator due to the increase of mass. However, we note that the peak magnitude of the butterfly mode of the new actuator is nearly suppressed. This means that the resultant force of the proposed actuator does not excite the butterfly mode and the actuator has no vibrating force orthogonal to the track-following direction.

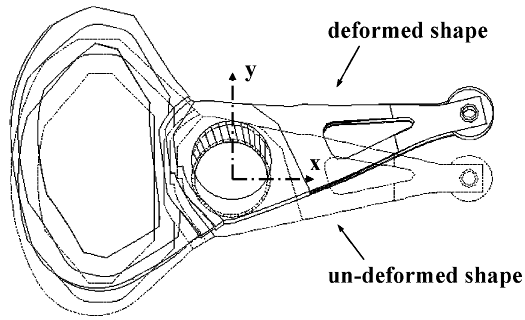

Fig. 12. Butterfly mode of a new actuator.

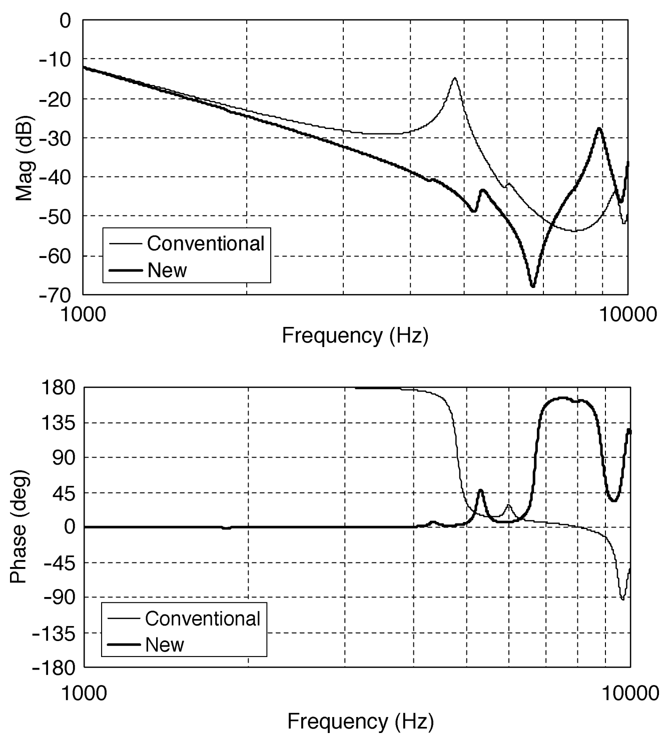

Fig. 13. Dynamics of the new and conventional actuators.

C. PES Estimation of the New Actuator

Error sensitivity functions for the new and conventional actuators are depicted in Fig. 14. As shown in Fig. 14, the new actuator system does not boost error at the low-frequency range, and, thus, makes the actuator system more robust to external disturbance.

Referring to Table V, the servo bandwidth of the actuator, according to the new actuator, is increased by about 39%, compared to that of the conventional actuator. PES by an overall vibration, including the repeated vibration and the nonrepeated vibration in the new actuator system, is decreased by about 27%, compared to that of the conventional actuator.

As described above, the exciting force of the new actuator in a direction perpendicular to the track which excites the butterfly mode of the actuator can be minimized or become zero. Thus, the magnitude of a peak corresponding to the butterfly mode decreases so that accuracy and performance in the track-following operation of the head are improved. Also, since the servo bandwidth needed for servo control can be increased compared to the conventional actuator system, PES is decreased so that performance of a disk drive is improved.

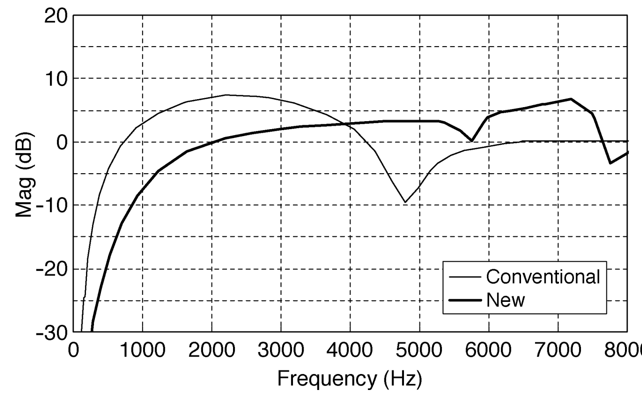

Fig. 14. Error sensitivity functions of the new and conventional actuators.

TABLE V
SERVO BANDWIDTH AND PES PERFORMANCE OF THE NEW ACTUATOR

Actuator Type		Conventional	New
Servo Bandwidth		1207Hz	1680Hz
Stability Margins	Gain Margin (dB)	4.9	6.2
	Phase Margin (deg)	36.4	35.7
	ESF Peak (dB)	7.4	6.8
PES (count)	RRO	14.5	11.1
	NRRO	14.5	10.2
	Total	20.6	15.0

IV. CONCLUSION

An actuator providing wide servo bandwidth is designed and the dynamics of the actuator is verified by numerical simulations. The new actuator has a single coil with four sections having respective particular directions. By adjusting the length and the inclined angle of the sections of the VCM coil, the forces parallel to the track-seeking direction can be balanced with each other, and then the butterfly mode is not excited by the resultant force of the VCM. As a result, the servo bandwidth created with the proposed new actuator design is expanded and the overall PES of a drive is reduced. Furthermore, since the number of tracks can be increased based on the improved dynamic characteristic of the actuator, a disk drive having a large storing capacity can be realized.

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