On Improving Head-Disk Interface in Hard Disk Drives Using Active Control

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Abstract. How to improve head disk interface (HDI) characteristics in the mechanical design of hard disk drives (HDDs) has become increasingly important due to ever-growing demand for storage density and access speed. In this paper, an active actuation and control of the suspension structure in HDDs utilizing the piezo-films is investigated. Its applications in reducing head-disk friction/wear and suppressing induced vibrations are studied. An analytical model for a cantilever beam like structure with the bonded piezo-films is presented. A direct output feedback control is proposed and its effectiveness in suppressing induced vibrations is demonstrated both theoretically and experimentally.

1. Introduction

Hard disk drives (HDDs) are the sophisticated electro-mechanical, rotational memory devices. In recent years, its areal density and storage capacity have been dramatically increased at a rate of about 60% a year, and this growth rate is expected to continue [1]. In order to increase track density and storage capacity, the slider is required to be maintained at an extremely low flying height from the disk surface. This slider-disk spacing is currently at 20-50 nm and is targeted to be at 5-10 nm if we are to achieve 40 GB/in^2 areal density in the near future [2]. To reach such a low flying height, a super smooth disk surface is necessary to enhance slider's flying stability. However, extremely smooth disk surface may result in a higher level of stiction, and the surface lubricant would also be damaged over a period of time due to low flying height [3]. This will cause a serious head-disk friction/wear problem when a conventional contact-start-stop (CSS) operation is utilized. In order to resolve this, while maintaining a reasonable flying height, zone texturing has been proposed and applied in the pre-product or product stage [4]. Though, so far few researches have been focused on the application of active actuation in the suspension-slider assembly. It is believed that this application may provide an efficient alternative in reducing head-disk contact time and contact force and, as a result, improving HDI tribological properties.

It is essential for a high performance data storage system to be able to read and write digital-bits at fast speed and with high accuracy. But this speed and accuracy is directly influenced by the vibrations of mechanical components in HDDs, especially by the vibration of the flexible and miniaturized suspension on which the slider is attached. For example, small form factor HDDs are being commonly used in portable computers where they are often subjected to external shocks due to mishandling [5]. This may result in HDI failure when the slider on the suspension overcomes the preload and separates itself from the disk surface intermittently. Smaller and smaller head-disk spacing for high density storage makes slider's flying stability, especially during track-seeking operation, a subject of great importance [6]. The acceleration and deceleration during track-seeking process may introduce additional variation to the slider's flying height and may also induce the suspension to vibrate in vertical direction, which is directly related to the natural frequencies of the suspension. The impact between the slider and disk surface caused by track-seeking process could seriously affect HDI reliability and tribological properties. Therefore, it is important to develop active control methodologies to suppress vibrations of the suspension structure in HDDs.

Active vibration control has been a well-established subject of research [7]. Moreover, vibration control of mechanical systems incorporating with smart materials like the ceramic-based piezoelectric materials PZT (lead zircornate titanate) and the polymer-based piezoelectric materials PVDF (polyvinylindine fluoride) has been proven successful in applications to such structures as robot arms and large space structures [8-10]. However, little attention has been paid to active control of the miniaturized suspension structure in HDDs using piezoelectric materials. In this paper, we propose an active velocity feedback control methodology, which is designed to excite and induce deflections in PVDF that in turn will suppress the vibration in suspension structure. Both theoretical analysis and experimental results will be presented. The objectives of this research are to develop the usage of smart materials/structures in HDDs, to reduce or completely eliminate possible damages on both disk surface and read/write head caused by CSS process, and to alleviate the shock or track-seeking operation induced vibrations in HDDs.

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2. Theoretical analysis

Due to its higher resolution and flexibility, piezo-films are used in this study as both the actuator and sensor, which can convert electrical energy into mechanical energy through the converse piezoelectric effect, and mechanical energy into electrical energy through the direct effect. Consider a head assembly in HDDs as shown in Fig. 1(a), which consists of the slider, the suspension and the arm. A magnetic transducer is installed in the slider for reading/writing data from/to the disk. In this configuration, the vertical (out-of-plane) compliance is mainly provided by the suspension, which is rigidly connected to the arm which has relatively high stiffness. The piezo-films are bonded on both sides of the suspension using double-sided adhesive tape. The suspension structure integrated with such piezo-films can be simplified as a smart cantilever beam structure, as shown in Fig. 1(b).

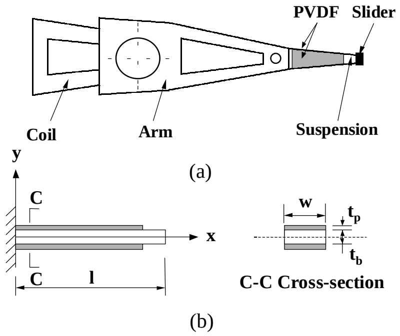


Figure 1. (a) Head assembly in HDDs with bonded piezo-films, and (b) smart cantilever beam structure model.

When voltage V is applied to PVDF, the strain ε_p in the piezo-film is induced and given by [11]

$$\varepsilon_p = d_{31} V / t_p \qquad (1)$$

where d_{31} is the piezoelectric charge constant. This induced strain has two effects on the beam structure. The first effect is to generate a longitudinal strain ε_x in x-direction, which can be obtained by solving the force equilibrium equation to render

$$\varepsilon_x = -\frac{E_p t_p}{E_b t_b + E_p t_p} \varepsilon_p \qquad (2)$$

where E_p and E_b are Young's modulus of the PVDF and the beam structure, respectively. The second effect is to produce a bending moment M_b to the cantilever beam, which can be expressed by

$$M_b = -\frac{E_p E_b d_{31} t_b w (t_p + t_b)}{2(E_b t_b + E_p t_p)} V = cV \qquad (3)$$

If a PVDF is used as a sensor, then the general charge-deformation relation of PVDF for a beam structure can be expressed by [12]

$$Q = -Gwd \int_{x_1}^{x_2} e_{31} \frac{d^2 y}{dx^2} dx = -GAde_{31}\psi \qquad (4)$$

where Q is the signal charge, G is the total electronic circuit gain, d is the distance from the surface of a sensor to the center of beam structure, e_{31} is a piezoelectric field intensity constant, A is the sensor area, and ψ is the averaged local structure curvature. Note that the sensor signal is proportional to its area and the local structure curvature.

A structural control system is often represented by the following finite dimensional, time-invariant, dynamic model:

$$M\ddot{q}(t) + C\dot{q}(t) + Kq(t) = Bu(t) + Dv(t)\,, \qquad (5a)$$

where $q(t) \in R^n$ is the displacement vector in generalized coordinates, and M, C, and K are positive definite symmetric matrices denoting the mass, damping and stiffness, respectively. Moreover, B denotes the control input matrix and $u(t) \in R$ is the applied control voltage input. The matrix D is the disturbance input matrix while $v(t) \in R$ denotes the external disturbance input. Judging from the arrangement of the piezo-films shown in Fig. 1, it is reasonable to assume that the actuator and the sensor are co-located, since the upper and the lower piezo-film are to be operated cooperatively. In this study, the structural velocity is measured for feedback design. This implies that the measurement output can be expressed by

$$y(t) = B^T \dot{q}(t)\,. \qquad (5b)$$

The simplest form of feedback design would be the static gain direct output feedback. Consider a direct output feedback controller of the form

$$u(t) = -ky(t)\,, \qquad (6)$$

where $k \geq 0$ is the control gain to be determined experimentally. After substituting the output feedback control given above into (5a), we obtain the closed-loop system given by

$$M\ddot{q}(t) + (C + BkB^T)\dot{q}(t) + Kq(t) = Dv(t) \qquad (7)$$

where $BkB^T \geq 0$ is the control-induced damping. It can be seen from above that, by utilizing PVDF and velocity feedback control, the structural damping can be increased. Consequently, the induced vibration by external disturbance can be effectively suppressed.

3. Source of disturbance

Smaller head-disk spacing for high density data storage poses great challenges in maintaining the integrity of the

HDI tribological characteristics. The potential cause of damages on HDI include: contact-start-stop (CSS) process, external shock induced vibration and disk surface adhesion (pullout force) induced vibration, etc. A schematic illustration of CSS process is depicted in Fig. 2. The analytical solution of the static displacement at the tip of a smart cantilever structure is given by [13]

$$\delta(l) = \frac{cl^2}{2K_f} V \tag{8}$$

where K_f denotes the flexural rigidity of the cantilever structure. It should be noted from equation (8) that the deflected displacement is linearly proportional to the applied voltage. When a positioning signal (dc voltage) is applied to activate PVDFs, the suspension structure is forced to bend. This motion can be utilized to lift up the slider from contacting disk surface when CSS process is involved. Subsequently, this will improve HDI tribological properties in HDDs. The induced displacement in the suspension can be increased by applying a higher voltage. However, in HDDs the use of lower voltage is always preferable. As the size of the HDDs is getting smaller and more compact, they are inevitably more prone to any sort of external disturbances; typically shock induced and pullout force induced vibrations need to be closely examined. For these, we are mainly concerned with reducing the effect of residual vibrations. A shock resistant test is conducted in order to study the performance of the proposed active control PVDFs. Pullout force is induced by the disk surface adhesion, which is omniscient on any smooth surface. The magnitude of pullout force and its effective range (or meniscus radius) is directly related to the tribological properties of the disk surface. Due to limited scope, the subject is omitted in this paper.

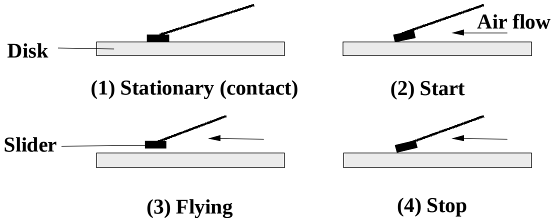


Figure 2. Schematic illustration of CSS process.

4. Experimental study

The head assembly of a hard disk drive is removed from its base and clamped at the bottom of the arm. Since the suspension is a very flexible structure compared with the arm, and also the slider has very lightweight and exhibits almost the same dynamic behavior as the suspension, it is reasonable to assume that the suspension is attached to the "rigid" arm. Two piezo-films were bonded on both sides of the suspension. The coordinate system for a piezo-film is given in Fig. 3. Note that 3-axis is in the direction of polarization and 1- and 2-axis determine a plane perpendicular to the polarization. The material properties for PVDF and suspension are listed in Table 1.

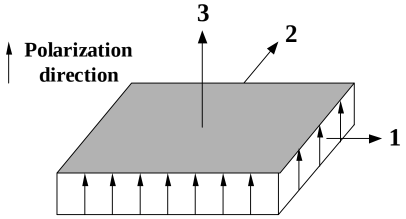


Figure 3. Coordinate system for a piezo-film.

Table 1. Material properties for PVDF and suspension.

Properties	PVDF	Suspension
Thickness (mm)	0.02	0.075
Elastic modulus (GPa)	2	193
Density (kg/m^3)	1780	7890
Piezoelectric charge constant d_{31} (mV^{-1})	-23×10^{-12}	--
Piezoelectric field intensity constant (C/m^2)	54×10^{-3}	--
Relative permittivity	1200	--

Figure 4 shows a schematic diagram of the experimental setup for studying active actuation and control of the suspension structure. An ultra high accuracy laser displacement meter (LC-2400 Series, KEYENCE) with a resolution of 10 nm was used to measure the displacement at the tip of the suspension structure. Figure 5 shows a static displacement at the tip of suspension structure as a function of applied voltage. The deflected displacement is almost linearly proportional to the applied voltage as predicted analytically in equation (8). The maximum deflection reaches 1310 nm when an input voltage of 22.5 V is applied. The static displacement can be utilized to lift up the slider to reduce or eliminate head-disk friction/wear under the CSS operation. Therefore, an active actuation strategy can be implemented in HDDs that, before the disk starts to rotate, the PVDFs are activated to lift up the slider at a certain airborne position. It is then gradually released until the slider reaches a stable flying height. This indicates that a piezo-driven load/unload operation for suspension will be involved during the conventional CSS process. This would improve HDI tribological properties by reducing the contact time and contact force between the slider and the disk surface.

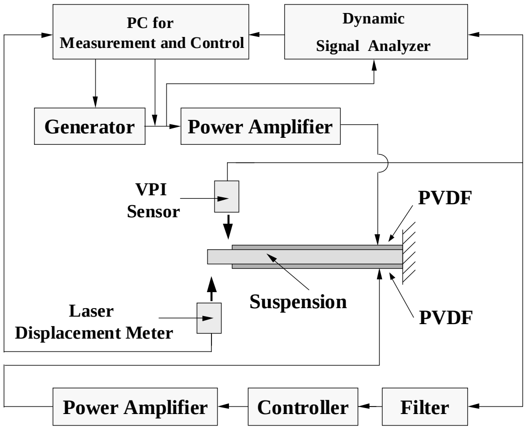


Figure 4. Experimental setup for active actuation and control of suspension structure.

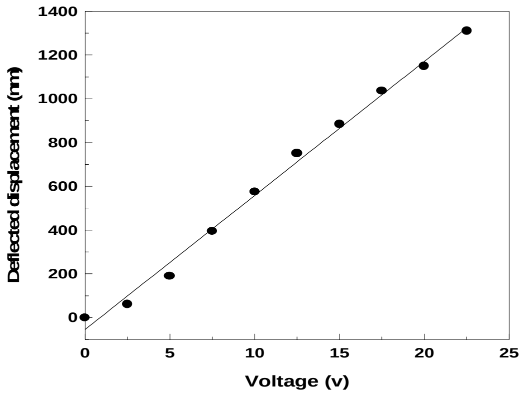


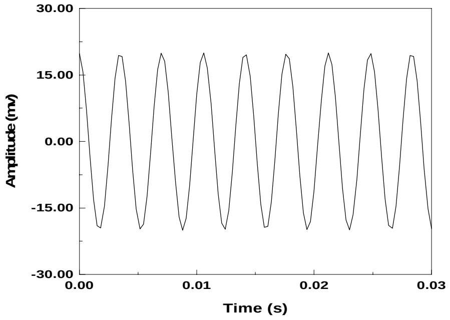
Figure 5. Static displacement at the tip of suspension versus applied voltage.

It is important to note that the suspension in HDDs is extremely sensitive to any sort of vibrations, because the induced vibrations are the main factor that will eventually limit the accuracy and speed of data storage systems. Therefore, it is fundamental to study the potential use of an active control methodology to suppress induced vibrations in the suspension structure. In this regard, we refer to Fig. 4 and note that the smart suspension structure has two piezo-films. One of them was used to generate a disturbance from a signal generator and the other was used to produce a control signal. A VPI laser sensor (Ometron 4000 vibration pattern image system) with measurement range of 0±1000 mm/s was used to measure the small amplitude vibration at the position close to the piezo-film. A dynamic signal analyzer was used to analyze and record transfer function data. The modal parameters at the frequency range of 100-400 Hz were identified using the standard circle-fit method and summarized in Table 2. It is noted from this table that we have three vibration modes which are close to each other. This is due to the coupling effect from other suspension arms in the head actuator assembly.

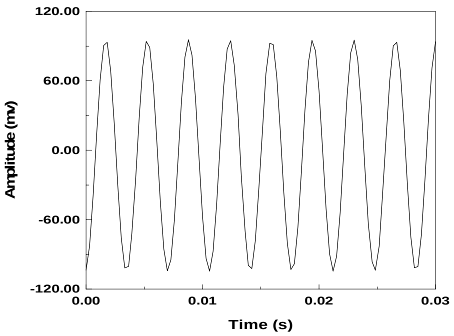
Table 2. Modal parameters from experiments.

Mode #	Natural Frequency (Hz)	Damping Ratio (%)	Modal Constant Phase (degree)
1st	281.80	1.8625	98.096
2nd	292.55	1.7115	113.301
3rd	350.30	2.5644	70.266

In our preliminary experimental studies, an analogue controller was used (rather than digital one) because of its faster response time, and it also enables us to regulate both the gain and phase between the input and the output signal easily. Generally speaking, it is of most interest in structural control to suppress the first vibration mode, since it dominates the transient behavior of a dynamic system. Thus, the setting of gain and phase for the proposed controller was based on the modal parameters of the first vibration mode. Figure 6(a) shows the input vibration waveform of the filter when a sinusoidal signal of 281.80 Hz is applied, whereas Fig. 6(b) shows the resultant output from the controller. It is known that a filter can reduce high frequency noise, but it also has the non-ideal phase lag property, which was compensated by the controller in our experiment. It can be seen from Fig. 6 that the amplitude gain is close to 5, and the phase variation is close to 180°. An active vibration control experiment was carried out based on the given control parameters. A sweep sinusoidal signal from the signal generator was amplified and applied to one of the PVDFs to excite the suspension. The output signal measured by VPI sensor was transferred into an input signal of another PVDF through the filter, controller and power amplifier so as to suppress the induced vibration in the suspension. The experimental results for both open-loop and closed-loop frequency responses are shown in Fig. 7. It can be observed that the proposed direct output feedback controllers suppress the first vibration mode effectively.



(a)



(b)

Figure 6. Vibration waveforms: (a) filter input; (b) controller output.

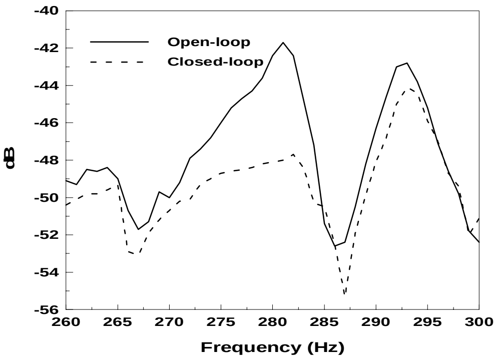


Figure 7. Frequency responses for open-loop and closed-loop cases.

We have also conducted an exploratory shock-resistant test for the actual HDDs. Details of the experimental setup are shown in Fig. 8. The head assembly with bonded piezo-films has been mounted back to its base. One of the PVDFs was used as a sensor and the other as an actuator. The output charge of PVDF sensor was transformed into the voltage signal through charge amplifier (B&K type 2635). A small ball was dropped onto the rotating disk surface to produce a shock input signal. The time history of the suspension response measured by PVDF sensor for both open-loop and closed-loop tests is shown in Fig. 9. Experimental results indicate that the suspension deflection builds up quickly and then dies down gradually. The suspension first displays a forced vibration at the initial stage, and is followed by a residual vibration subsequently, which is dominated by the first natural frequency of the suspension. The residual vibration takes time to decay, and this is one of the major factors affecting HDI characteristics and data read/write accuracy. A zoomed-in view of Fig. 9 for two cases studied is shown in Fig. 10. It can be observed from Fig. 10 that the decay time of the residual vibration is decreased significantly if the velocity feedback is applied. This is yet another indication that the use of smart materials/structures in HDDs provides an effective alternative for improving HDI characteristics.

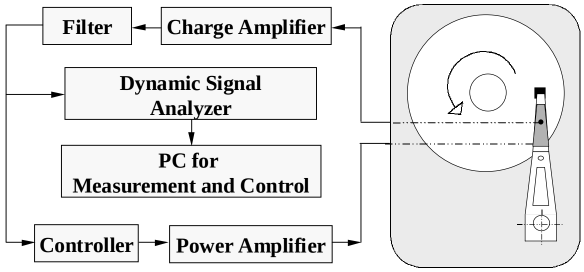
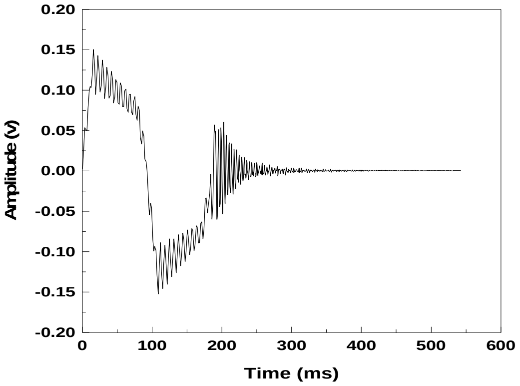
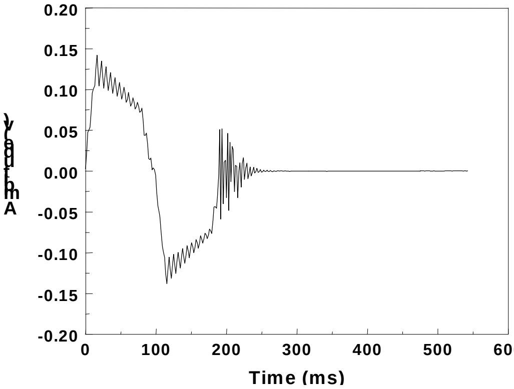


Figure 8. Experimental setup for shock-resistant test.



(a) open-loop test



(b) closed-loop test

Figure 9. Time responses from shock-resistant test for (a) open-loop and (b) closed-loop cases.

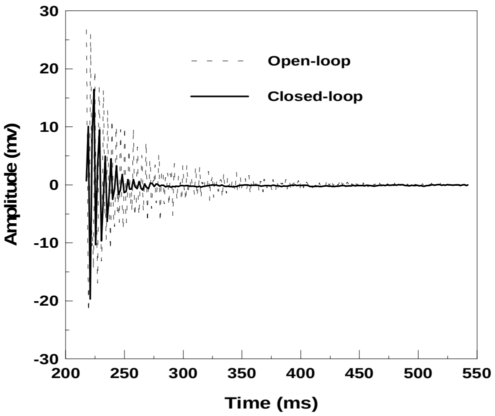


Figure 10. Zoomed-in view of the residual vibration for open-loop and closed-loop tests.

5. Conclusions

Both theoretical and experimental studies have demonstrated the feasibility and the effectiveness of using active actuation and control methodologies to improve HDI characteristics. More specifically, an active suspension structure utilizing PVDFs in improving CSS process and reducing residual vibrations has been developed. However, it is desirable to develop an integrated active suspension structure capable of self-actuation and control when a command signal is applied. In this regard, the piezo materials may be deposited onto the suspension surface through MEMS fabrication technology, and the read/write head may be used as a sensor to monitor the variation of the flying height. This will be a subject of our future research.

Acknowledgments

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