Research Article

Active Vibration Control of a Microactuator for the Hard Disk Drive Using Self-Sensing Actuation

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This paper presents the self-sensing control of a microactuator for hard disk drives. The microactuator uses a PZT actuator pair installed on the suspension assembly. The self-sensing microactuator forms a combined sensing and actuation mechanism. Direct velocity feedback and positive position feedback are used in this paper. Our experimental results show that both strategies are effective in suppressing vibrational modes and successfully demonstrate the feasibility of using a self-sensing actuator on an HDD suspension assembly.

1. Introduction

A suspension assembly in a hard disk drive (HDD) is subject to excitation by many disturbances, including the airflow due to the rapidly spinning disks, and noncircular track motion of the head and slider due to resonance in the components. A servo system that can cope with these problems requires a very high servo bandwidth and position error signal sampling frequency. In conventional servo systems, the sampling frequency is limited by data storage efficiency. The desire to more effectively suppress the effect of disturbances has led many researchers to propose the addition of more sensors and actuators. One example which has been proposed is to use a piezoelectric actuator on the suspension in a dual-stage system with one of the two strips as the sensor and the other as the actuator [1, 2]. This, however, reduces the effectiveness of the actuator by half and is not efficient. An alternate approach is to use it as a self-sensing microactuator [3–9], which is the subject of this paper. For dual-stage servo system, the performance of self-sensing actuator systems exceeds that of other vibration compensation systems.

We implemented two active strategies in order to experimentally demonstrate the effectiveness of a self-sensing

system in structural vibration control. The strategies are direct velocity feedback (DVF) and positive position feedback (PPF). DVF, also known as strain rate feedback (SRF) has been used in the active damping of a flexible space structure [10]. In DVF, the structural velocity coordinate is fed back to the compensator and the compensator velocity coordinate multiplied by a negative gain is applied to the structure. DVF has a wide active damping region and can stabilize more than one mode given sufficient bandwidth. In PPF, the structural position coordinate is fed directly to the compensator where a scalar gain is applied and the result sent to the structure [11, 12]. PPF offers quick damping for a particular mode provided the modal characteristics are known. PPF is also easy to implement. Song and Agrawal experimentally demonstrated that it is robust against a varying modal frequency [13]. Pang et al. [14] used the self-sensing technique for active-mode damping in the dual-stage servo system. Chan and Liao [15] used self-tuning adaptive compensation with the self-sensing actuation. We try to demonstrate two active vibration control methods using two types of the sensing signal. This paper is very different from previous publications.

In this paper, we demonstrate the use of these control methods with self-sensing actuators to actively damp

FIGURE 1: Suspension assembly.

FIGURE 2: CR bridge circuit.

vibrations in an HDD suspension assembly. Experimental results have shown that PPF and DVF control methods are effective in actively increasing damping in an HDD suspension assembly using self-sensing PZT actuators.

2. Microactuator for HDD

Figure 1 shows a suspension assembly from a dual-stage HDD servo. A suspension based microactuator uses a PZT actuator pair located between the suspension and the base plate. A slider is installed at the tip of the suspension. When a control voltage is applied to the PZT pair, one of them expands while the other contracts in the x direction. As a result, the slider moves in the y direction. The PZT actuator achieves large displacements of the head element by using the length of the suspension as a radius arm. However, the resonance frequency of the suspension limits the servo bandwidth. The configuration of the assembly seems to make it amenable to control using self-sensing actuation. We investigate this in the following sections.

3. Self-Sensing Actuation

A piezoelectric self-sensing actuator is a piezoelectric transducer used simultaneously as a sensor and an actuator. The key is capacitance. If the capacitance of a piezoelectric device is known [4], applying the same voltage to a capacitor of the same value and subtracting its electrical response from that of the piezoelectric yields the signal due to the piezoelectric's mechanical response. A bridge circuit using additional resistors and a capacitor is used to obtain the time rate of change of strain (velocity).

FIGURE 3: CC bridge circuit.

A CR bridge circuit is shown in Figure 2. The difference between the output voltages v_1 and v_2 gives the sensor voltage v_s . In terms of the Laplace transform, we have

$$V_s(s) = \left\{ \frac{C_p R_1 s}{1 + C_p R_1 s} - \frac{C_r R_2 s}{1 + C_r R_2 s} \right\} V_c(s) + \frac{C_p R_1 s}{1 + C_p R_1 s} V_p(s). \quad (1)$$

If the values of the components are adjusted, so that

$$C_p R_1 = C_r R_2. \quad (2)$$

The first term vanishes, giving us the Laplace transform of the sensor voltage V_s in terms of the transform of the piezoelectric voltage V_p as seen in (3):

$$V_s(s) = \frac{C_p R_1 s}{1 + C_p R_1 s} V_p(s). \quad (3)$$

Taking the inverse Laplace transform gives the time domain equation (4):

$$v_s = R_1 C_p \dot{v}_p \quad \left(\text{where } \omega_c \ll \frac{1}{C_p R_1} \right), \quad (4)$$

where the dot indicates the time derivative and ω_c is the frequency of the input voltage, and the value of C_p and R_1 have been chosen to satisfy (4). The charge developed on the sensor can be found from

$$v_s = R_1 C_p k_s \frac{\partial^2 w(l, t)}{\partial x \partial t}. \quad (5)$$

Thus, a distributed piezoelectric sensor with a rate of strain sensing bridge can measure the total angular deflection velocity of the piezoelectric beam at a point l . The constant k_s is determined by the size and material of the piezoelectric elements [3–9]. Taking account of the bridge circuit, applied input voltage of the microactuator is

$$V_{\text{piezo}}(s) = V_c(s) - V_1(s) = \frac{1}{1 + C_p R_1 s} V_c(s). \quad (6)$$

The CC bridge circuit corresponding to the self-sensing actuator is shown in Figure 3. An analogous development starts with (7):

$$\begin{aligned} V_s(s) &= V_1(s) - V_2(s) \\ &= \frac{C_p R_1 s}{1 + (C_p + C_1) R_1 s} \{ V_c(s) + V_p(s) \} \\ &\quad - \frac{C_r R_2 s}{1 + (C_r + C_2) R_2 s} V_c(s). \end{aligned} \quad (7)$$

FIGURE 4: Experimental system.

FIGURE 5: Frequency response of the tip displacement.

FIGURE 6: Frequency response of the strain rate sensor.

Using the simplifying component values in (8) gives an expression for the Laplace transform of sensor voltage V_s .

$$\text{If } C_p = C_r, \quad C_1 = C_2, \quad R_1 = R_2, \quad (8)$$

$$V_s(s) = \frac{C_p R_1 s}{1 + (C_p + C_1) R_1 s} V_p(s). \quad (9)$$

Taking the inverse Laplace transform and limiting ourselves to lower frequencies leads to an equation for the input voltage of the actuator (12).

$$v_s = \frac{C_p}{C_p + C_1} v_p \quad (10)$$

when $\omega_c \geq 1/((C_p + C_1)R_1)$. The charge developed on the sensor can be found from

$$v_s = \frac{C_p}{C_p + C_1} k_s \frac{\partial w(l, t)}{\partial x}. \quad (11)$$

FIGURE 7: Frequency response of the strain sensor signal.

FIGURE 8: Block diagram of the direct velocity feedback control.

FIGURE 9: Time response of the tip displacement with DVE.

FIGURE 10: Time response of the sensor voltage with DVE.

FIGURE 11: Frequency response of the tip displacement with DVE.

Thus a distributed piezoelectric sensor with a strain sensing bridge can measure the total angular deflection of the piezoelectric beam at a point l [3–9]. Taking account of the bridge circuit, applied input voltage of the microactuator is

$$v_{\text{piezo}} = v_c - v_1 = \frac{C_1}{C_p + C_1} v_c. \quad (12)$$

FIGURE 12: Frequency response of the strain rate sensor output voltage with DVF.

FIGURE 13: Block diagram of the PPF control.

FIGURE 14: Time response of the tip displacement with the PPF control.

4. Experimental Setup

Figure 4 shows the setup for our experiments. The experiments were carried out on a spin test stand. An input control voltage is calculated by a DSP every 0.01 millisecond and applied to the bridge circuit through a D/A converter and a piezo driver. Sensor voltage v_s from the bridge circuit is passed through a differential amplifier and A/D converter to the input of the DSP. For monitoring purpose only, a laser doppler vibrometer (LDV) was used to obtain measurements of tip displacement and velocity.

Figure 5 shows the measured frequency response of the slider tip displacement to an applied control voltage with and without the spinning disk. Figure 6 shows the frequency response of the strain rate sensor. Figure 7 shows the frequency response of strain sensor. In these figures, the red line indicates the response with the spinning disk while the blue line is without the spinning disk. There are four major vibration modes of the suspension assembly while on the spinning disk. There are three suspension bending modes: B1 at 2.7 kHz; B2 at 5.4 kHz, B3 at 9.8 kHz. The fourth major mode is a sway mode: S at 9.2 kHz. The suspension bending modes are vibrations in the vertical direction. The sway mode is the PZT microactuator actuation mode and is a vibration in the horizontal direction. With the disk rotating, the third suspension mode (B3) combines with the sway mode (S). When the experiment is done with a rotating magnetic disk, the suspension modes disappear and the sway mode appears alone as shown in Figure 5.

Corresponding results are shown in Figures 6 and 7, where on the spinning disk, only the sway mode is observed. In these figures, the signals are similar to a velocity signal and a position signal.

5. Direct Velocity Feedback Control

Estimating the modal states of a distributed structure in order to apply modal feedback control is difficult. The problem of observation spillover is potentially more serious than the problem of control spillover as it can lead to instability. Hence, a method not requiring modal state estimation is desired. One such method is direct output feedback control where the sensors are collocated with the actuators and a given actuator force is a function of the sensor output at the same point. The self-sensing piezo actuator is a perfect candidate for this control method. DVF is a form of this control method and it stabilizes all vibrational modes.

Figure 8 shows a block diagram of the DVF control system. The microactuator, controlled with collocated velocity feedback giving the strain rate, is unconditionally stable at all frequencies [4]. With the feedback gain at $P = -60$, the transfer function for the phase lead compensator is

$$G_c(s) = \frac{s + 809.1}{s + 1.057 \times 10^5}. \quad (13)$$

We implemented real-time DVF on the suspension assembly. Figure 8 shows the actuator input voltage. The input voltage of the actuator is rectangular wave at 5 V in 500 Hz. The DVF controlled time response is compared to

FIGURE 15: Time response of the sensor voltage with the PPF control.

FIGURE 16: Frequency response of the tip displacement with the PPF control.

the vibrations of the uncontrolled system (Figure 9). Under control, suspension assembly vibrations taper off within 0.2 milli seconds of the input signal becoming constant. This is shown in Figure 10. A 20 dB drop in the energy of the sway mode accompanied the damping of the vibrations, as shown in Figures 11 and 12.

FIGURE 17: Frequency response of the strain sensor output voltage with the PPF control.

6. Positive Position Feedback Control

Positive position feedback (PPF) control was first proposed by Goh and Caughey for collocated sensors and actuators. Fanson and Caughey later demonstrated PPF control in space structures. PPF control is done by feeding the structural coordinate directly to compensator where a positive gain is applied before the signal is sent back to the structure. PPF offers quick damping of a particular mode provided the modal characteristics are known. The scalar equation governing a single mode of the vibration of a structure and the PPF controller is

$$\text{PPF filter} = \frac{\omega_f^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2}, \quad (14)$$

where the natural frequency and the damping ratio of the compensator are $\omega_f = 7.3$ [kHz], $\zeta_f = 0.2$, respectively. The frequency $\omega_f = 7.3$ [kHz] is slightly lower than the target frequency [12]. A block diagram of the PPF control system appears in Figure 13. It was implemented using the same experiment setup described in Section 4. The mode targeted for control was the sway mode (S) at 9.2 kHz. The control was done in real time with a sampling period of 0.01 milliseconds. Figure 14 shows the uncontrolled and controlled vibrations of the suspension assembly for comparison. Under PPF control, the vibrations damp out within 0.3 milliseconds of the input signal becoming constant. The sensor output from 0 to 2 milliseconds is shown in Figure 15. Under active control, the energy of vibrations drops by 15 dB. PPF control damps down vibrations slightly faster than DVF control.

FIGURE 18: Power spectral density comparison of PPF control and without control cases.

With PPF control, maximum damping is achieved when the controller is tuned to the natural frequency of the structure (Figures 16 and 17). As a counterexample, under PPF, the frequency response of tip displacement at 6 kHz increases by 10 dB. However, the power spectrum density comparison in Figure 18 shows no peak at 6 kHz, implying that PPF control does not affect vibrations at that frequency.

7. Conclusions

Our experiments successfully demonstrate vibration suppression of a hard drive suspension assembly using signals from a self-sensing actuator by Direct Velocity Feedback (DVF) control and Positive Position Feedback (PPF) control. The self-sensing actuator is a piezoelectric transducer acting simultaneously as sensor and actuator mounted on the suspension itself. The sensor generates an estimate of the strain signal and its derivative. In particular, the DVF method was able to attenuate the suspension assembly's dominant sway mode of vibration by 20 dB. Both DVF and PPF were successful at damping suspension assembly vibrations. Both strategies are good enough for use in real hard disk drives.

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