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Active Control of Flow-Induced Vibrations on Slider in Hard Disk Drives: Experimental Demonstration

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This paper presents an experimental demonstration on the active control of flow-induced vibrations on a head gimbals assembly (HGA) bearing a slider in a hard disk drive (HDD). The feedback control closed-loop consisted of a laser Doppler vibrometer (LDV), a narrowband frequency filter, a signal conditioner, an in-house made phase shifter, and a piezoelectric disk mounted on the inner surface of the HDD cover. The HGA vibrations detected by the LDV were used as feedback error signals, and the signals were then phase shifted and amplified to drive the piezoelectric disk to generate feedback acoustic pressure around the HGA. The phase shift and gain of the feedback loop were adjusted such that the HGA vibrations were reduced. The experiments of active control have been conducted on five principal peaks in the HGA off-plate vibration spectrum, around 1256, 1428, 2141, 2519, and 3469 Hz, respectively. The results show that reduction of the HGA vibrations can be achieved on all these principal peaks, with a maximum suppression of 16 dB on the peak around 1428 Hz. It is also observed that simultaneous reduction can take place among these peaks when the narrowband feedback control is focused only on one of them.

Index Terms—Acoustic pressure, active control, experimental demonstration, flow-induced vibration.

I. INTRODUCTION

RECENTLY, Min *et al.* [1] proposed an active control strategy for flow-induced vibration on a head gimbals assembly (HGA) in working hard disk drives (HDDs). Based on numerical simulations, they showed that it was possible to suppress HGA flow-induced vibrations by introducing feedback acoustic pressures closely around the HGA. The HGA vibration induced by high speed circumferential airflows in working HDDs limits the positioning accuracy of the slider magnetic head on the HGA tip, and is therefore receiving much attention associated with the development of high magnetic storage density in disks, such as 10 Tb/in² [2]. Passive methods have proved difficult for the fine control on this issue [3]. The previous work on active control of disk flutter inside working HDDs by Huang *et al.* [4], [5] suggested a possible active control on the HGA flow-induced vibration through suppressing unsteady airflows around the HGA by acoustic pressure disturbance. Many researchers have experimentally demonstrated the effect from active acoustic pressure on the unsteady airflows, such as frequency shift [6] or instability stabilization [7], [8] on vortex shedding from circular cylinders, and control on shear layer instability past a cavity in a pipeline [9]. For active suppression of the HGA flow-induced vibration

Fig. 1. Schematic diagram of the experimental setup, including a Seagate hard disk drive (HDD) with a motor driver and a feedback control closed-loop for the HGA flow-induced vibration. In the closed-loop, a laser Doppler vibrometer detects the HGA off-plate vibration as feedback error signal, a piezoelectric transducer (PZT) stuck on the inner surface of the HDD cover actuates the active acoustic pressure, and a combination of an analog filter, a signal conditioner and an in-house made phase shifter acts as a simple narrowband controller.

by acoustic pressure, Min *et al.* [10], [11] experimentally investigated the spectrum characteristics of pressure fluctuations around the HGA, as well as those of the HGA flow-induced vibration. In their study, good correspondence was found between the spectra of the pressure fluctuations detectable from the HDD cover and the HGA flow-induced vibration. This suggests that an active control may be applied in this case.

This paper reports an experimental validation of active control of the HGA flow-induced vibration by feedback acoustic pressure. It is an extension of the numerical simulations [1], and also serves as a step towards actual implementation on the active control of flow induced vibrations in hard disk drives.

II. EXPERIMENTAL SETUP

Fig. 1 is a schematic diagram on the experimental setup. The HDD was a Seagate 3.5-inch model ST3160215A with one disk.

Fig. 2. Images of (a) the laser beam into the HDD through a hole drilled on the HDD cover right above the HGA, and (b) the PZT actuator and its position relative to the inner structures of the HDD during experiments.

It was driven by a motor driver (HC6250B-PT) at its default rotation speed of 7200 r/min. During the experiments, the HDD arm was glued at its axis such that the HGA on the arm tip can be fixed at the middle track following position. In the feedback control closed-loop, a laser Doppler vibrometer (LDV, Polytec PSV300) was used to detect the HGA off-plate vibration as the feedback error signal. The laser beam from the LDV head went vertically into the HDD through a hole drilled on the HDD cover, as illustrated in Fig. 2(a), and was focused on the tip of the HGA, as shown in Fig. 2(b). The LDV output was split into two ways—one was input to a fast Fourier transfer (FFT) analyzer (ONO SOKKI CF-5220Z) as data acquisition, and the other was filtered by a band-pass filter (KH 3940) for the feedback control closed-loop. The bandwidth and center frequency of the filter were set according to the principal peaks to be controlled in the HGA off-plate vibration spectrum. The reduction was more than 10 dB for signals outside the frequency band. The feedback signals were then passed through a signal conditioner (Rion NA-80) for amplification and input to an in-house made phase shifter. The phase shifter can provide continuous phase change from 0 to 2π on signals between its output and input. The combination of the frequency filter, signal conditioner and phase shifter formed a narrowband analog controller in the closed-loop, which provided feedback signals with proper phase and gain to enable the active control. A piezoelectronic

Fig. 3. Measured spectral coherence between the pressure fluctuations near the HDD cover and the HGA off-plate vibrations, by comparison to the spectrum of the HGA off-plate vibration.

transducer (PZT, RS 516-7669) was used as an acoustic pressure actuator in the closed-loop and was driven by a voltage amplifier (Trek 2210). The PZT actuator was a thin disk with a diameter of 35 mm and thickness of 1.7 mm, and had a damper ring made of soft rubber at the circumference. It was glued onto the inner surface of the HDD cover through the damper ring. Fig. 2(b) illustrates the PZT actuator and its position. The damper ring could also isolate the vibration transmission from the PZT disk onto the HDD cover.

In this work, prior measurements were conducted to select suitable feedback error signals in the closed-loop. As pointed out by Min *et al.* [1], the pressure fluctuations near the HDD cover may not be good feedback error signals for the active control in this work because of the weak coherence between the pressure fluctuations and HGA vibrations. To examine this, the spectral coherence between the pressure fluctuations near the HDD cover and the HGA off-plate vibrations were measured. The pressure fluctuation was measured by a pressure sensor mounted onto the HDD cover [10], and the HGA vibration was measured by the LDV. Fig. 3 presents the measured results of the spectral coherence as well as the HGA off-plate vibration spectrum. The results show that, within the frequency band from 1 to 4 kHz concerned in this work, there are five principal non-repeatable runout (NRRO) peaks in the HGA off-plate vibration spectrum, around 1256, 1428, 2141, 2519, and 3469 Hz, respectively. It is also shown that the spectral coherence between the pressure fluctuations near the cover and the HGA off-plate vibration are lower than 0.4 at most frequencies around the principal NRRO peaks in the HGA off-plate vibration spectrum. These results confirm weak causality relationship between these two signals. In this experimental demonstration, the HGA vibration signal detected by the LDV was used as feedback error signals in the closed-loop.

III. RESULTS AND DISCUSSIONS

In this experiment, the feedback closed-loop can be tuned to perform active control on an individual frequency peak by setting the center frequency of the narrow band filter. The experiments have been conducted by focusing the active control sepa-

Fig. 4. Spectra of the HGA off-plate vibration before and under active control focused on the principal peak around 1256 Hz. The analog filter in the feedback loop was set at center frequency of 1256 Hz with a bandpass width of 50 Hz.

rately on the five principal peaks in the HGA off-plate vibration spectrum shown in Fig. 3. For the control on the principal peak around 1256 Hz in the HGA vibration spectrum, the filter in the feedback control closed-loop was set at 1256 Hz with a 50 Hz band-pass. The control effect was observed from real-time spectrum results shown in the FFT analyzer monitoring the HGA vibration signal, and the phase and gain on the feedback signals were adjusted until a maximum reduction of the peak was obtained. The control results on the principal peak around 1256 Hz are presented in Fig. 4. It is shown that positive suppression up to 13 dB has been achieved at the principal peak around 1256 Hz. It is interesting to see that, from Fig. 4, the control also has effect (6 dB reduction) on the peak around 1428 Hz, though this peak is outside the filter band-pass in this feedback setting. By turning the frequency filter to the peak around 1428 Hz, similar control effects have been observed and these results are presented in Fig. 5. It is observed, from Fig. 5, that a distinct suppression of up to 16 dB has been achieved on the objective principal peak around 1428 Hz, and simultaneously, a 12 dB reduction is also obtained to the peak at 1256 Hz, even though it lies outside the control frequency band. Meanwhile, a control-induced peak occurs around 1359 Hz in the HGA vibration spectrum this time, probably due to the “water bed” effect [12] inherent in the feedback control. From results shown in Figs. 4 and 5, it is clear that if one of the principal peaks around 1256 and 1428 Hz in the HGA off-plate vibration spectrum is actively controlled, the other can be suppressed simultaneously.

By applying the feedback control to the rest of principal peaks at 2141, 2591, and 3469 Hz, respectively, the simultaneous control effects are also observed and the results presented in Figs. 6–8 correspondingly. In each case, the narrowband filter is focused on one peak and the reductions by the control are obtained simultaneously on all three peaks. This was especially so for the control focused on the peak at 2591 Hz—the reduction is 8.5 dB on the focused peak, while the reduction of

Fig. 5. Spectra of the HGA off-plate vibration before and under active control focused on the principal peak around 1428 Hz. The analog filter in the feedback loop was set at center frequency of 1428 Hz with a bandpass width of 50 Hz.

Fig. 6. Spectra of the HGA off-plate vibration before and under active control focused on the principal peak around 2141 Hz. The analog filter in the feedback loop was set at center frequency of 2141 Hz with a bandpass width of 100 Hz.

15.5 and 8 dB are obtained on the peak at 2141 Hz and 3469, respectively. The corresponding results are shown in Fig. 7.

The experimental results presented in Figs. 4–8 show a successful narrowband active control using the HGA off-plate vibration signal as the feedback error signal to generate acoustic pressure to suppress the HGA flow-induced vibration. The results demonstrate the physical validity of this active control strategy on the HGA flow-induced vibration by acoustic pressure. The control mechanism on the successful active control in this work is not completely clear yet. One possible mechanism is the suppression of turbulent fluctuations closely surrounding the HGA by the active acoustic pressure, which was proposed by Min *et al.* [1]. The simultaneous effects among the principal peaks in response to the narrowband control indicate a kind of correlation between these vibration peaks, and the corresponding mechanism requires further examination through a structure dynamic study on the HGA.

Fig. 7. Spectra of the HGA off-plate vibration before and under active control focused on the principal peak around 2519 Hz. The analog filter in the feedback loop was set at center frequency of 2519 Hz with a bandpass width of 100 Hz.

Fig. 8. Spectra of the HGA off-plate vibration before and under active control focused on the principal peak around 3469 Hz. The analog filter in the feedback loop was set at center frequency of 3469 Hz with a bandpass width of 100 Hz.

IV. CONCLUSION

Experimental active control has been successfully implemented on the HGA flow-induced vibration in a working HDD with a feedback control closed-loop. In the closed-loop, the HGA off-plate vibration detected by a LDV was used as the feedback error signal; a combination of an analog filter, a signal conditioner and an in-house made phase shifter was used as a simple narrowband controller, and a PZT disk on the HDD cover inner surface was used as actuator to generate feedback pressure to suppress the HGA flow-induced vibration. Experiments have been conducted by focusing active control on

five principal peaks in the HGA off-plate vibration spectrum, around 1256, 1428, 2141, 2519, and 3469 Hz, respectively. The results show that distinct active suppression can be achieved in all the narrow bands around the principal peaks in the HGA off-plate vibration spectrum. The maximum suppression is 16 dB at the peak around 1428 Hz. It is also shown that the control has simultaneous effects on the principal peaks around 1256 and 1428 Hz, as well as among principal peaks around 2141, 2519, and 3469 Hz. The experimental results demonstrate the feasibility of an active control strategy proposed by Min *et al.* [1] to suppress the HGA flow-induced vibration by acoustic pressure. The present work serves as the first step for actual implementation of this active control strategy on the HGA flow-induced vibration in working HDDs, and provides useful guidance for the implementation of future broadband active control.

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