FEEDBACK CONTROL OF THE FLOW-INDUCED VIBRATIONS ON THE MAGNETIC HEAD IN HARD DISK DRIVES: DESIGN AND IMPLEMENTATION

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The flow-induced vibration of the head gimbals assembly (HGA) in hard disk drives (HDDs) limits the positioning accuracy of the HDD magnetic head on the tip of HGA for future magnetic recording density. In this work, a digital feedback control close-loop is presented for active suppression of the HGA flow-induced vibrations in working HDDs. The close-loop includes a laser Doppler vibrometer (LDV), a digital feedback controller, and a piezoelectric disk mounted on the inner surface of the HDD cover. The HGA off-plate vibration detected through the LDV was used as feedback error signals, which were then filtered by the digital controller to generate feedback signals with proper phase and gain to drive the piezoelectric disk. The latter then actuated feedback air pressure around the HGA to exert control on the HGA flow-induced vibrations. The digital controller was designed to enable the close-loop with capabilities of single- or simultaneous multi-narrowband control on the HGA flow-induced vibrations. Experiments have been conducted for single- or multi-narrowband active suppression on five principal peaks around 1256Hz, 1428Hz, 2141Hz, 2519Hz and 3469Hz in the HGA off-plate vibration spectrum. For single-narrowband active controls, it is shown that distinct vibration suppression of up to 15 dB can be achieved around those principal peaks respectively. For multi-narrowband active controls, it is shown that distinct suppression can be achieved simultaneously on all five principal peaks in one control with the close-loop.

1. Introduction

The continually increasing demand on the storage capacity of hard disk drives (HDDs) has pushed the storage capacity increasing 60%-100% every year. Such rapid increase of areal density results in a combination of higher track density, higher disk rotation speed and lower flying height of the magnetic head on the tip of head gimbals assembly (HGA). High speed circumferential airflows driven by the disk rotation in working HDDs inevitably induce vibrations on the HGA, and then lead to track mis-registration errors on the magnetic head. The integrated HDD industrial tendencies mentioned above make the HGA flow-induced vibration be one of the challenging problems for achieving high magnetic storage density in future HDDs.
Passive methods were used to control such flow-induced vibrations on the HGA but were far from enough for further fine control in HDDs with areal density towards 10 Tb/in². In usual active controls on this issue, notch filters are applied in servo controller design in HDDs. Evans et al. utilized a suspension actuated by a piezoelectric transducer (PZT) to build a dual-stage servo system to enable active vibration control on the actuator arm in HDDs to help reduce the HGA flow-induced vibrations. The work of Huang et al. suggests one alternative active control strategy in this situation. They successfully controlled the rotation disk flutter through picking up and processing the disk vibration signal to actuate feedback acoustic pressure into the inner space of an HDD. The acoustic pressure then suppressed the aerodynamic instabilities to avoid the flutter. Other researchers also observed in experiments the instability stabilization effect from active acoustic pressure on vortex shedding from circular cylinders, or on shear layer past a cavity in a pipeline. Based on these previous studies and their preliminary experimental and numerical investigations, Min et al. conducted experimental demonstration on the possible control of HGA flow-induced vibrations in a working HDD through active acoustic pressure. Their experimental results show that, distinct suppression of HGA vibrations can be achieved on single principal peaks in HGA off-plane vibration spectrum with the introduced active acoustic pressure. In their experiments, an analogy closed-loop was built for demonstration, which however has only the capability of single-narrowband control then is hard for broadband control in actual applications.

In this paper, we present a progress of digital feedback close-loop implementation for active suppression of HGA flow-induced vibrations in working HDDs through acoustic pressure. This work is following that of Min et al. and is expected to build a further step towards practical active control systems for HGA flow-induced vibrations in working HDDs.

2. Experimental setup

A schematic diagram of the digital feedback close-loop is shown in Fig. 1. This close-loop consisted of a 1-D LDV (Polytec PSV300), a digital controller (AntySound TigerANC-II, whose image is shown in Fig. 2), a piezoelectric transducer (PZT) amplifier (Trek 2210) and a PZT disk (RS 516-7669) mounted on the inner surface of the HDD cover. The HDD was a Seagate 3.5-inch model ST3160215A with one disk and driven by a motor driver (HC6250B-PT) at its default rotation speed of 7200 rpm. During 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. The HGA off-plate vibration was detected with the LDV as feedback error signals in the close-loop. The laser beam from the LDV head went vertically into the HDD through a hole drilled on the HDD cover and was focused on the tip of the HGA, as shown in Fig. 2 of Ref. 14. The LDV output was split into two ways, one was input to a fast Fourier transfer (FFT) analyser (ONO SOKKI CF-5220Z) as data acquisition, and the other was filtered by the digital controller to generate actuation signals with proper phase and gain to drive the PZT disk for feedback acoustic pressure. The digital controller included two parts, a DSP board hardware (TMS320C6747) and a sequence of digital filter coefficients stored in the DSP board to customize the controller frequency response. The digital filter coefficient sequence was designed in simulations before the implementation and then off-line uploaded onto the DSP hardware. The PZT actuator was a thin disk with a diameter of 35 mm and thickness of 1.7 mm, and was glued on the inner surface of the HDD cover through its outer damper ring, as shown in Fig. 3(b). The damper ring could isolate vibration transmission from the PZT disk onto the HDD cover.
Figure 1. Schematic diagram of the experimental setup, including a Seagate hard disk drive (HDD) with a motor driver and a digital feedback control close-loop for the HGA flow-induced vibration. In the close-loop, a laser Doppler vibrometer (LDV) detects the HGA off-plate vibration as feedback error signal, a piezoelectronic transducer (PZT) stuck on the inner surface of the HDD cover actuates feedback acoustic pressure, and a digital controller is used to produce the feedback actuation signals.

Figure 2. Front panel image of the digital controller (AntySound TigerANC-II) used in the feedback close-loop, including a DSP board hardware (TMS320C6747) and a sequence of digital filter coefficients stored in the DSP board to customize the controller frequency response that can be shown and checked on the touch screen on the front panel.

3. Controller design and implementation

A signal diagram of this close-loop is illustrated in Fig. 3, where $D(s)$ denotes the primary disturbance signal that is the HGA off-plate vibration signal before control in experiments. $S$ equals $j\omega$ for the signal Laplace transform and $\omega$ is the angel frequency of the signal. $e(s)$ denotes the error signal (HGA off-plate vibration) under control. $G(s)$ represents the system secondary path transfer function, which is the open-loop transfer function from the input of the controller to the output of the LDV in the setup shown in Fig. 1. $H(s)$ represents the frequency response function of the controller, which actually acts as a digital filter on the signals passing through. In active control experiments, $G(s)$ was pre-measured for system modelling and the following controller design. The Laplace transform of the error signal can be written as

$$e(s) = D(s) - G(s)H(s)e(s).$$  

(1)

From this, the transfer function from disturbance to control error can be

$$e(s) / D(s) = 1/[1 + G(s)H(s)],$$  

(2)

which is also known as the sensitivity function of the system. The objective in classic feedback control systems is to achieve good reduction of the disturbance, which can be translated into minimizing the sensitivity function $S(j\omega)$, with letting $s=j\omega$ in (2),

$$S(j\omega) = 1/[1 + G(j\omega)H(j\omega)],$$  

(3)
where the combination $G(j\omega)H(j\omega)$ is defined as the open-loop frequency response of the control system in classic feedback control theory \(^2\). Control performance can be predicted in controller design stage with a parameter, $\Delta$,

$$\Delta(j\omega) = 20 \log |1 + G(j\omega)H(j\omega)|, \quad (4)$$

which represents disturbance reduction spectrum due to control. Then it is clear that the control system has disturbance attenuation if $|S(j\omega)|<1$ or disturbance amplification if $|S(j\omega)|>1$.

![Schematic signal diagram of the feedback close-loop shown in Fig. 1, where $D(s)$ denotes the primary disturbance signal that is the HGA vibration signal before control in the experiments, $e(s)$ denotes the error signal (HGA off-plate vibration) under control, $G(s)$ represents the system secondary path transfer function, and $H(s)$ represents the frequency response function of the controller.](image)

Prior measurements were conducted on the HGA off-plate vibration spectrum before control, whose results are available in figures in section 4 below. It is shown that, within the frequency band from 1 kHz to 4 kHz concerned in this work, there are five principal non-repeatable runout (NRRO) peaks having much higher outstanding energy level (at least 25 dB) in the HGA off-plate vibration spectrum, around 1256 Hz, 1432 Hz, 2144 Hz, 2524 Hz and 3474 Hz, respectively. For broadband active control, one strategy is to suppress the disturbance all over the objective frequency band \(^2\), and another is to focus suppression on the outstanding principal peaks inside the objective frequency band. For current application, it is more practical and efficiency to take the latter. In this work, single-narrowband controller filters were firstly designed for single suppression on those five principal peaks mentioned above one by one. Then a method was proposed to combine the single-narrowband controller filters into a multi-narrowband one to enable simultaneous suppression on all those principal peaks in the objective control band.

The open-loop transfer function in the system, $G(j\omega)$, was measured to enable the system modelling in controller design stage. Figure 4 shows the measured bode plot of $G(j\omega)$ in experiments. For single-narrowband controls, a standard two-order digital band pass filter, $H_0$, was applied to build the controller,

$$H_0(j\omega) = \frac{[j\omega A_p\omega_p / Q_p]}{[(j\omega)^2 + j\omega \omega_p / Q_p + \omega_p^2]}, \quad (5)$$

where $\omega_p$ denotes the angle frequency of the filter centre, $A_p$ is the filter amplitude at the centre frequency, $Q_p=\omega_p/(2\pi B_w)$ is the quality factor of the filter in which $B_w$ denotes the band pass bandwidth. Then, the single-narrowband controller, $H$, was designed as

$$H(j\omega) = A_0 e^{i\alpha} H_0(j\omega), \quad (6)$$

where $H$ is the frequency response function of the controller. $A_0$ and $\alpha$ are extra amplitude and angle, respectively, to manipulate the standard filter $H_0$. By this way, we can “fine-tune” the magnitude and phase of the controller through performance simulations with (4) to enable the single peak suppression on the HGA vibration with robustness, like tuning the phase shifter in the previous analogue close-loop \(^1\).
For multi-narrowband controls, we defined the single-narrowband controllers determined through (6) for single suppression on those five principal peaks as $H_n$ respectively, where $n=1, 2, \ldots, 5$. Then, one controller $H_S$ through summation combination of single-narrowband controllers $H_n$, was built in frequency domain as

$$H_S(j\omega) = \sum_{n=1}^{5} H_n(j\omega),$$

where $H_n(j\omega) = A_{n,0}e^{\text{j}\omega_n}H_{n,0}(j\omega)$, in which $A_{n,0}$, $\alpha_n$ and $H_{n,0}(j\omega)$ correspond to parameters of $A_p$, $\alpha$ and $H_0$ in (6) for each principal peak, respectively. Given that the center frequencies of principal peaks are defined as $\omega_n$, around frequency $\omega_1$, $H_1$ has a much larger amplitude than those from $H_2$ to $H_5$. Accordingly, in frequency response, $H_S$ can almost work as $H_1$ around frequency $\omega_1$ in spite of the little influence from $H_2$ to $H_5$. Thus $H_S$ has a narrowband suppression on the HGA off-plate vibration around frequency $\omega_1$ due to $H_1$ functioning, and so on around frequencies from $\omega_2$ to $\omega_5$. That is, in theory $H_S$ has a capability of simultaneous multi-narrowband suppression on those five principal peaks in the objective frequency band of the HGA off-plate vibration spectrum.

After the controller design stage, the controllers $H_n$ or $H_S$ were fitted with 256-order finite impulse response filters whose coefficients were later uploaded onto the DSP board for controller implementation in close-loop experiments.

![Bode plot](image)

Figure 4. Bode plot of the measured transfer function $G(j\omega)$ for control system modelling, which is the open-loop transfer function from the input of the controller to the output of the LDV in the setup shown in Fig. 1.

4. Results and discussion

4.1 Single-narrowband control

Single-narrowband controls were conducted focusing on the five principal peaks around 1256 Hz, 1432 Hz, 2144 Hz, 2524 Hz and 3474 Hz in HGA off-plate vibration spectrum one by one. Since results of single-narrowband controls on these peaks were similar to those reported in Ref. 14, we do not present the single-narrowband controls in details here for simplicity. For narrowband control on the single peaks, the controller was designed with Eqs. (4) and (5) on the basis of measured $G(j\omega)$. The determined controller frequency response is similar to that of a band-pass filter. The control results show that distinct suppression about 15 dB was achieved in experiments on the peak of 2144 Hz. It is also shown that the simulation control results can agree reasonably with the experimental results, which demonstrates the validity of simulation methods employed in the con-
controller design stage. These single-narrowband control results show the good working of the implemented digital feedback close-loop for active suppression of the HGA off-plate vibrations.

4.2 Multi-narrowband control

Based on the operational single-narrowband controllers for separate suppression on each principal peaks, a multi-narrowband controller was designed through (7) for simultaneous suppression on all the five principal peaks concerned in this work. Figure 5 shows the frequency response of the multi-narrowband controller uploaded onto the DSP board, which had a capability of multiple narrow bandpass corresponding to the frequency bands of the focused five principal peaks. The corresponding close-loop control results in experiments are presented in Fig. 6. It is shown that, with the digital close-loop, distinct simultaneous suppression was achieved on all the focused principal peaks in the HGA off-plate vibration spectrum in one control. The minimum suppression was 3 dB on the peak of 2524 Hz and the maximum was 17 dB was on the peak of 1432 Hz. Although these control results may be optimised in future work, such as suppression improvement on the peak of 2524 Hz, current results demonstrate a successful design and implementation of the digital feedback close-loop for simultaneous suppression on all the principal peaks focused in the HGA off-plate vibration spectrum.

Experimental control results presented above show successful implementation of the digital feedback close-loop for active suppression on the HGA flow-induced vibration, where the controller can be designed to enable the close-loop have capabilities of single- or multi-narrowband suppression in objective frequency band. The mechanism inside these controls is not completely clear yet. One possible mechanism is the suppression of turbulent fluctuations closely around the HGA through the active acoustic pressure actuated by the PZT disk, as proposed by the authors in previous numerical simulations. But further fine measurements are necessary on the secondary control path in this system for identification, which will be reported and discussed in another paper.

![Figure 5. Bode plot of frequency response of controller designed for multi-narrowband simultaneous suppression on the peaks around 1256 Hz, 1432 Hz, 2144 Hz, 2524 Hz and 3474 Hz.](image-url)
Figure 6. Measured spectra of the HGA off-plate vibration before and under multi-narrowband control focused on the peaks around 1256 Hz, 1432 Hz, 2144 Hz, 2524 Hz and 3474 Hz simultaneously. The peak suppression levels are shown in brackets corresponding to each peak.

5. Conclusion

A digital feedback control close-loop was successfully implemented in experiments for active suppression on the HGA flow-induced vibrations in working HDDs. In this close-loop, the HGA off-plate vibration detected by a LDV was used as the feedback error signals, a digital controller designed with single- and multi-narrowband filter capabilities was employed to generate the feedback actuation signals, and a PZT disk on the HDD cover inner surface was used to actuate feedback acoustic pressure to suppress the HGA flow-induced vibrations. Two sets of experiments have been conducted, in single- or multi-narrowband active controls on five principal peaks around 1256 Hz, 1432 Hz, 2144 Hz, 2524 Hz and 3474 Hz in the HGA off-plate vibration spectrum. In single-narrowband controls, results show that distinct single suppression of up to 15 dB was achieved on those principal peaks respectively. And in multi-narrowband controls, it is shown that simultaneous distinct suppression of up to 17 dB can be achieved on all those focused principal peaks in one control with the digital feedback close-loop. This work provides an important step towards the future diverse active control on the HGA flow-induced vibrations with digital controllers.

Acknowledgment

This work was supported by the Agency for Science Technology and Research (A*STAR), Singapore, under Project 092-156-0128.

REFERENCES


