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ON THE AERODYNAMIC PRESSURE FLUCTUATION AROUND THE HEAD GIMBALS ASSEMBLY INDUCING THE SLIDER VIBRATION IN A HARD DISK DRIVE

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The spectrum-spatio characteristics of the pressure fluctuation around the head gimbals assembly (HGA) in an actual HDD is studied experimentally to understand the excitation of the flow-induced vibration (FIV) of the HGA in HDDs. Aerodynamic excitation around the HGA is detected by a proposed method of measuring pressure fluctuation on the cover inner-surface of an HDD. The results show that the principal non-repeatable run out (NRRO) peaks in the off-track vibration spectra of the HGA are in narrow bands around 1.83 kHz and 2.54 kHz and are dominated by the aerodynamic pressure fluctuation around the HGA. In addition, aerodynamic pressure disturbance in the narrow space of the HDD is found to remain highly coherent at frequencies around the principle peaks. The proposed method for detecting the aerodynamic pressure disturbance around the HGA is shown to be feasible and can be used for signal sensing in future active control on pressure fluctuation in HDDs.

1. Introduction

The flow-induced vibration (FIV) of the slider in hard disk drives (HDDs) limits the positioning accuracy of the magnetic head in HDDs with much higher track density in the future. The temporal pressure fluctuation around the head gimbals assembly (HGA) in an HDD is the direct excitation for FIV of the HGA and slider. Many passive methods have been applied to suppress FIV in HDDs, such as the geometry modifications on HDD interior construction, but they appear not enough for the ultra-high storage density objective in future HDDs. An active control technique has been used to control the disk flutter in an HDD by Huang et al., which promotes an idea of employing actively controlled pressure oscillation (sound pressure) to suppress the aerodynamic disturbance in FIV of the HGA and slider, so as to limit the total mis-registration (TMR) of the slider in a working HDD with high rotation speed and high storage density. The present study is to preliminarily understand the spectrum-spatio characteristics of the aerodynamic disturbance around the HGA for the future active control.

There are some researchers having paid attention to aerodynamic mechanism of FIV inside HDDs. Takada et al. conducted experimental study on the disk flutter in an actual 2.5-inch HDD to...
know the mechanism of the unsteady disk vibration with different working status of operating sliders. Cheng et al.\textsuperscript{10} studied how the shape of the drive top cover influences the flow and the disk vibration inside an optical disk drive. Additionally Nakamura et al.\textsuperscript{11} examined experimentally the FIV characteristics of an HGA in HDDs, where the vibration on the tip of an HGA was detected with a laser Doppler vibrometer with various operation conditions of the HGA. However no investigation has been carried out on the flow fluctuation characteristics around the HGA in their work.

Furthermore, there are some numerical studies on aerodynamic disturbance in HDDs. Shimizu et al.\textsuperscript{8} employed a large eddy simulation (LES) technique to investigate the unsteady flow behaviour and disk flutter in an HDD. Zhang et al.\textsuperscript{5} numerically investigated the flow pattern and FIV inside an actual HDD with a more reliable LES turbulent model. Tsuda et al.\textsuperscript{12} numerically examined the unsteady flow pattern around the actuator arms with weight saving holes or not and studied the power spectra of arm torque coming from the turbulent disturbance around the arm. Focused on the influence on the HGA vibration from flow disturbance generated by the slider, Kazemi et al.\textsuperscript{13} built numerical models to investigate the flow field around the arm and afterwards calculated the HGA vibration with the obtained aerodynamic forces. Nonetheless they neglected the investigation on the spectrum-spatio characteristics of the fluid disturbance around the HGA also.

Shimizu et al.\textsuperscript{14} numerically investigated the unsteady flow in a real HDD with LES models to evaluate the aerodynamic forces acting on the HGA and arm in both time and frequency domains. In their study, the spectra of the slider vibration was compared to the vibration modes of the arm to understand the aerodynamic contribution in FIV of the slider. Unfortunately they paid no attention to the spatial characteristics of the temporal pressure fluctuation from turbulence around the HGA, which is the aerodynamic source for FIV of the HGA and could be important for future fluid control to suppress the FIV.

Despite these widespread interests on the FIV in HDDs, so far there is no study on the spectrum-spatio characteristics of the aerodynamic pressure disturbance around the HGA yet, especially the experimental studies on their contribution to FIV spectra of the HGA and slider head. This paper reports an experimental study on how the aerodynamic pressure around the HGA fluctuates in a working HDD and how such temporal pressure disturbance contributes to FIV of the slider head.

2. **Experiments**

The experimental setup is shown in Fig. 1 to measure the temporal pressure fluctuation inside an actual 3.5-inch Seagate HDD. The HDD has one disk and two HGA headers and operates at a speed of 7200 rpm driven by a HC6250B-PT motor driver from Hokuto Control Incorporation. The dynamic pressure fluctuation is detected with two PCB 103B12 pressure transducers connected to a PCB 483A signal preamplifier, then the signal is analyzed with a FFT analyzer typed ONO SOKKI CF-5220Z.

As inserting the pressure probes into the narrow space inside the HDD is not practical for remarkable obstruction into the original interior flow field, a detection scheme is proposed to monitor the temporal pressure fluctuation around the HGA through measuring that on the inner-surface of the HDD top cover. Although there is some distance (about 3 mm) from the top cover inner-surface to the HGA, the experimental results and numerical analysis below show that in the frequency domain the pressure fluctuation around the principle power peaks at the two places remains coherent always.
Figure 1. Schematic diagram of the experimental setup, where a 3.5-inch Seagate 7200 rpm hard disk drive with one disk and two HGAs is driven by a motor driver at a speed of 7200 rpm.

We have drilled 5 holes with diameter of 3 mm at the cover to enable the interior pressure detection, whose positions are illustrated in Fig. 2. Among them, three ones correspond to the upper projections of three typical track following positions of the HGA, which are inner, middle and outer track respectively. The other two are located separately at 10 mm up-stream and 10 mm down-stream from the middle track following position of the HGA along the arm spanwise direction. The HDD with two transducers adhered on selected holes is shown in Fig. 3. In the measurements, two channel signals of pressure fluctuation are detected and analyzed simultaneously. One probe is located at the hole directly above the HGA track following position always, whose signal is defined as Channel I hereafter. The other probe with signal defined as Channel II is located at the other holes one by one to enable the comparison of the pressure fluctuation at these locations with that directly above the HGA. The sensitivity of the transducer signals after the PCB preamplifier is 75 mV/kPa, which can be used to transfer the FFT analyzer output signal from the voltage level to the sound pressure level (SPL). The SPL is obtained by

\[ L_p = L_v - 20 \lg (S_n) - 20 \lg (p_0). \]  

where \( L_p \) denotes the SPL with unit of decibel (dB) and \( L_v \) is the voltage level from the FFT analyzer with unit dBV in which 1V is used as the reference voltage. \( S_n \) represents the transducer sensitivity of the analyzer input signal, \( 7.5 \times 10^{-6} \) V/Pa. And \( p_0 \) is the reference sound pressure \( 2 \times 10^{-5} \) Pa. In this paper, pressure spectra results are all presented in SPL to order to be physically meaningful.

Figure 2. Locations of 5 holes drilled on the HDD cover for pressure fluctuation detection with three typical track following modes of HGA, which correspond to inner, middle and outer track positions separately. The holes are marked from A to E and the unit in the figure is mm.
3. Results and discussion

In the experiments, corresponding to each operating mode of the HGA, the spectra of Channel I and II are measured by comparison to the pre-measured positioning error signal (PES) from the HDD servo system, to understand the spectrum contribution from the pressure fluctuation to the TMR of the slider. The coherence between the two channel signals is analyzed as well, to explore the coherence of the pressure fluctuation around the HGA in a working HDD.

Three sets of measurements are carried out, corresponding to three typical track following positions of the HGA. In the first set of measurements, the HGA is operating at the inner track following mode, and the Channel I probe is fixed at the hole A and Channel II probe is located at the holes B to E one by one. Only the measurement results of pressure fluctuation with Channel II probe at the hole B that is exactly the closest to the Channel I probe position are selected for analysis and shown in Fig. 4, since the results with Channel II probe at other holes are similar. At the same time, Figure 4 shows the PES spectrum in this set of measurements with the repeatable run-out (RRO) errors deleted, which can be used to identify the FIV spectrum of the slider in non-repeatable run-out (NRRO) errors. In these results, the frequencies of the RRO errors are multiples of rotating frequency (120 Hz) of the 7200 rpm disk. If not specified, the result analysis is focused on the NRRO errors hereafter. From Fig. 4, it is shown that there are four principle peaks in the PES spectrum, which are in narrow bands around 1.83 kHz, 2.54 kHz, 7.15 kHz and 8.5 kHz. And the former two contain much more NRRO energy than the latter ones. It is also shown from Fig. 4 that the spectra of pressure fluctuation in the HDD have remarkable characteristics in NRRO peaks in measurement frequency range. As marked in Fig. 4, distinct NRRO peaks in the SPL spectra of measured pressure fluctuation can be identified around the principle peaks in PES spectrum mentioned above, especially around 1.83 kHz and 2.54 kHz. This indicates that in the measurements the aerodynamic pressure excitation in the HDD is dominant in these principle peaks in the PES spectrum.

Figures 5 presents the corresponding results of measured coherence between two channel signals in this set, where Channel II probe is placed on the hole B. It is shown in Fig. 5 that when two probes are about 14.5 mm (distance between holes A and B) apart in this measurement set, the coherence of measured pressure fluctuation is larger than 0.4 around the frequencies of the principle peaks mentioned above, and in particular is more than 0.8 around 1.83 kHz and more than 0.9 around 2.54 kHz. This fact may implies that the pressure fluctuation at different positions in the narrow space of an HDD could be highly coherent at these frequencies, especially in the height direction whose dimension is only 4 mm. This also suggests the feasibility of the idea of placing
probes on the cover inner-surface to detect the pressure fluctuation at places with small distance apart, for example closely around the HGA, whereas the interior pressure fluctuation is actually hard to be measured for obvious obstruction to airflow by inserting probes into such narrow space. Additionally, the pressure fluctuation amplitude in time domain is averaged to be 5.53 Pa determined by the total SPL 108.8 dB in Channel I from Fig. 4, which indicates that the aerodynamic pressure disturbance in the airflow is linear.

**Figure 4.** The sound pressure level (SPL) spectra of measured pressure fluctuation of two channels (Channel I and Channel II in the upper chart) with inner track following mode of HGA, by comparison to the pre-measured PES spectrum (in the lower chart) in the same HDD working mode. Channel I probe is placed on the hole A and Channel II probe on the hole B.

**Figure 5.** Measured coherence results of two channels with inner track following mode of HGA, where Channel I probe is placed on the hole A and Channel II probe on the hole B.

The results of SPL spectra and PES spectrum when HGA in middle track following mode are presented in Fig. 6, where Channel I probe is placed on the hole B above the HGA and Channel II probe on the hole D. The results with Channel II probe at other holes are not shown here for their similarity also. In Fig. 6, it is shown that the PES spectrum in the middle track mode also has four principal peaks in the narrow bands around 1.83 kHz, 2.54 kHz, 7.15 kHz and 8 kHz, but the peak
around 8 kHz becomes extended and higher than that in the inner track following mode shown in Fig. 4. Distinct NRRO peaks in measured pressure fluctuation spectra of two channels can be identified at frequencies of these principle peaks in PES spectrum again, which indicates the domination from aerodynamic pressure excitation in FIV of the HGA and the feasibility of monitoring the aerodynamic disturbance around the HGA via placing probes on the cover inner-surface in the middle track following mode of the HGA.

![Sound pressure level (SPL) spectra](image)

**Figure 6.** The sound pressure level (SPL) spectra of measured pressure fluctuation of two channels (Channel I and Channel II in the upper chart) with middle track following mode of HGA, by comparison to the pre-measured PES spectrum (in the lower chart) in the same HDD working mode. Channel I probe is placed on the hole B and Channel II probe on the hole D.

Figure 7 shows the results in the third set of measurements, where the HGA is in the outer track following mode, Channel I probe is located at the hole C and Channel II probe at the hole B. The results with Channel II probe at other holes are not shown here for similarity also. In Fig. 7, the PES spectrum in the outer track following mode appears some different from those in the former two sets, where the peaks around 7 kHz and 8 kHz almost disappear in the NRRO errors. And the peak around 1.83 kHz replaces the one around 2.54 kHz to be the largest NRRO peak in the PES spectrum. There are also NRRO peaks that can be identified in the pressure fluctuation spectra of two channels corresponding to these principle NRRO peaks in PES spectrum, but they become indistinct in spectra results of Channel I. Additionally the SPL spectrum of Channel I signal shown in Fig. 7 appears different from those measured in Channel I in other sets, where the windage at lower frequencies becomes much larger and makes the peaks around 1.83 kHz and 2.5 kHz almost indistinct. The reason may be that there is interflow between the circumferential stream inside the disk zone and the stream returning from the outer region of the disk zone in the vicinity of hole C. Such interflow pattern was paid attention to in some published results. The interflow pattern could make the aerodynamic behaviour of the pressure below the hole C much different from other detection positions where the circumferential flow patterns are principle.

As indicated in Fig. 7, coherence between the pressure fluctuation spectra of two channels is lower than those in the former two sets, especially at frequencies below 3 kHz. The reason may be due to the interflow around the hole C. However the measured coherence of two channel signals can
still reach 0.6 around 1.83 kHz and 2.54 kHz corresponding to those two principal NRRO peaks in the PES spectrum, where the distance between two channel probes is 10 mm (holes B and C). This further suggests the feasibility of monitoring the pressure disturbance around the HGA exciting the FIV via detecting the pressure fluctuation on the inner-surface of the HDD top cover.

![Graph 1](image1.png)

**Figure 7.** The sound pressure level (SPL) spectra of measured pressure fluctuation of two channels (Channel I and Channel II in the upper chart) with outer track following mode of HGA, by comparison to the pre-measured PES spectrum (in the lower chart) in the same HDD working mode. Channel I probe is placed on the hole C and Channel II probe on the hole B.

From the results presented above, the principal NRRO peaks in the PES spectrum of the commercial HDD in experiments can be identified at the narrow bands around 1.83 kHz and 2.54 kHz in three typical track following modes of the HGA. It is observed that distinct peaks at these frequencies can be identified also in pressure fluctuation spectra measured on the inner-surface of the HDD cover. Additionally in these two narrow bands, the coherence between the pressure fluctuation at different locations on the HDD cover appears high enough (always exceeding 0.6 within 10 mm distance), which shows that the aerodynamic pressure disturbance in the narrow space of the HDD remains high coherent at these frequencies. This indicates that the principal NRRO peaks in the PES spectrum at the narrow bands around 1.83 kHz and 2.54 kHz are contributed mainly from the aerodynamic pressure disturbance around the HGA and can be monitored by detecting that on the inner-surface of the HDD cover, to avoid the obstruction to the interior airflow in the narrow space in HDDs. And the hole B that is directly above the HGA in middle track position is shown to be a good location on the HDD cover for monitoring the aerodynamic pressure disturbance around the HGA. The amplitude of the measured pressure fluctuation is shown to be around 5.5 Pa over the average gauge pressure, which indicates that the behaviour of pressure fluctuation there is mainly linear. Although further numerical investigation may help understanding the interior pressure fluctuation that is hardly measured in details, the current results are useful for the physical limitation analysis and control strategy determination of the further active pressure fluctuation control system to suppress the FIV of the HGA.
4. Conclusion

In this paper, three sets of measurements have been carried out to detect the pressure fluctuation on the cover inner-surface of a commercial 3.5-inch 7200rpm HDD. The results show that the principal NRRO peaks in the PES spectrum of the HGA are in narrow bands around 1.83 kHz and 2.54 kHz in all track following modes, and they are dominated by the aerodynamic pressure disturbance around the HGA. It is found that the proposed method for monitoring the aerodynamic pressure disturbance around the HGA is feasible and can avoid the obstruction to the interior airflow in HDDs and the location on the cover directly above the middle track following position of the HGA can be a good fixed probe location for interior pressure detection. It is also found that pressure fluctuation behaves linearly inside the HDD. The current results reported in this paper are useful for the future active control of the aerodynamic pressure disturbance in the HDD for suppressing FIV of the HGA.

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