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Aerodynamic Pressure Fluctuations Associated with Flow-Induced Vibration of the Head Gimbals Assembly inside a Hard Disk Drive

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This paper presents an experimental investigation and numerical simulation on the spectrum-spatial characteristics of aerodynamic pressure fluctuations around the head gimbals assembly (HGA) in a working hard disk drive (HDD). The pressure fluctuations are measured through tiny holes on the HDD top cover above the HGA. The positioning error signal and servo system sensitivity in the working HDD are measured as well to evaluate the slider off-track vibration. Comparisons between the spectra of pressure fluctuations and the slider off-track vibration show that, the pressure fluctuations around the HGA are highly associated with the slider off-track vibration in terms of principal peaks in the spectra, especially at 1.83 kHz and 2.54 kHz. The results also show that the spatial coherence of pressure fluctuation around the HGA remains high at frequencies around the principal peaks in the spectra, which has been further confirmed by the numerical simulation based on a two-dimensional large eddy simulation model. It is concluded that the flow-induced HGA vibrations in an HDD can be detected and evaluated through the pressure fluctuations by a sensor around the HGA.

***Index Terms*—pressure fluctuation, flow-induced vibration, turbulence, active control.**

I. INTRODUCTION

THE FLOW-INDUCED vibration (FIV) of the slider in hard disk drives (HDDs) limits the positioning accuracy of the magnetic head in HDDs for future 10 Tb/in^2 magnetic recording density [1]. Aerodynamic pressure fluctuation around the head gimbals assembly (HGA) in an HDD plays an important role in FIV of the HGA and slider [2]. Many passive methods, such as HDD interior geometry modifications, have been applied to suppress the FIV in HDDs [3]-[5], but seem far from enough for the super-high slider positioning accuracy demand in swift growth of storage density [6]. An active control technique has been applied to control the disk flutter in an HDD by Huang *et al.* [7,8], in which the disk vibrations are detected and processed to drive actuators so as to suppress the original disk vibrations. For the control of flow-induced HGA vibrations, the spectrum-spatial characteristics of aerodynamic pressure fluctuation around the HGA are needed to be detected and fully understood.

Among a few studies on aerodynamically induced vibration inside disk drives, experiments have been conducted on the unsteady disk vibration with different working status of sliders in an actual 2.5-inch HDD [9] and on the interaction between the flow and the disk vibration inside an optical disk drive [10]. The FIV characteristics of an HGA with different operation modes in an HDD has been investigated experimentally with a laser Doppler vibrometer in vibration detection [11]. Furthermore, large eddy simulation (LES) [6], [12], [13] or direct numerical simulation [14] technique has been employed for detailed investigation on the unsteady flow behavior and FIV mechanism inside an HDD. In these studies, however, not much results have been reported on the turbulent flow fluctuations inside HDDs, which shall be the direct aerodynamic excitation for the FIV in HDDs.

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Focused on the influence on the HGA vibration from flow disturbance generated by the slider, Kazemi *et al.* [15], [16] built numerical models to investigate the flow field around the HGA and arm and afterwards calculated the HGA vibration with the obtained aerodynamic forces. Shimizu *et al.* [17] investigated numerically the unsteady flow in a real HDD with LES models to evaluate the aerodynamic forces acting on the HGA in both time and frequency domains. Although in their studies the aerodynamic disturbance contribution can be understood somehow by comparison between the slider vibration spectra and the HGA vibration modes, there is no straightforward information in more details on the characteristics of turbulent pressure fluctuation around the HGA yet.

Review of research above shows a lack of studies on the spectrum-spatial characteristics of aerodynamic pressure fluctuations around the HGA so far, especially experimental studies on their effects in the off-track FIV (OT-FIV) spectrum of the slider. This is probably due to the difficulties of the direct measurement inside the HDDs. The present study is an attempt to look into the pressure fluctuations around the HGA and their correlations with the slider OT-FIV leading to the track-misregistration of the magnetic head.

II. EXPERIMENTS AND RESULTS

A. Experimental setup

The experimental setup for measuring the pressure fluctuation inside a 3.5-inch Seagate HDD is illustrated in Fig. 1(a). The HDD had one disk and two HGA heads and operated at a speed of 7200 rpm driven by a HC6250B-PT motor driver. The HGA heads inside the HDD were in the inner, middle and outer track following positions respectively. Since inserting pressure probes into the narrow space inside an HDD could introduce obstructions into the original interior flow field and was therefore impractical, we tried in the present study to detect the aerodynamic pressure fluctuations around the HGA through measuring pressures from tiny holes on the inner-surface of the HDD top cover. Two PCB 103B12 pressure transducers were used in pressure fluctuation measurements and were mounted right above the tiny holes on the top cover. After amplified by a PCB 483A signal preamplifier, the signals from the pressure transducers were analyzed with a fast Fourier transfer (FFT) analyzer (ONO SOKKI CF-5220Z). Fig. 1(b) shows the setup for the positioning error signal (PES) and the servo system sensitivity function (SSSF) in the HDD. The PES and SSSF were measured following a standard method [4], [18] before the modification of the HDD for pressure measurements. The slider OT-FIV spectra were computed by dividing the non-repeatable run-out error spectra [4], [18] in the PES by the SSSF spectra and were compared with the pressure fluctuation spectra.

FIG. 1 HERE

Four holes with diameter of 3 mm were drilled on the cover to enable the interior pressure detection, whose positions are illustrated in Fig. 2. Among them, holes A, B and C corresponded to the upper projections of inner, middle and outer track following positions of the HGA respectively. The hole D was located at 10 mm down-stream from the hole B along the arm spanwise direction. When two holes were used by the transducers, other holes were properly sealed. Fig. 3 shows the HDD with two transducers adhered on selected holes in experiments.

FIG. 2 HERE

FIG. 3 HERE

Two channels of pressure fluctuation signals were collected simultaneously. One signal was from the hole directly above the HGA and was defined as Channel I hereafter. The other one was collected from other holes one by one and was defined as Channel II to enable comparisons with Channel I. The pressure signal outputs in decibel-voltage (dBV) scale were corrected by the transducer sensitivity of 75 mV/kPa and then were transferred into pressure levels in decibel (dB) scale based on a reference pressure p_0 of 2×10^{-5} Pa for spectrum results. The equation for pressure data processing is

$$L_p = L_v - 20\lg(S_{tt}) - 20\lg(p_0)\,, \qquad (1)$$

where L_p denotes the pressure level in dB, L_v is the signal output from the FFT analyzer in dBV based on reference voltage of 1 V. S_{tt} represents the transducer sensitivity of 75 mV/kPa.

B. Results and discussion

The measured pressure fluctuation spectra from Channel I and II are compared with the calculated slider OT-FIV spectra to investigate correspondence between them. Spatial coherence results between these two channels of pressure fluctuation signals are collected as well to investigate the spatial characteristics of pressure fluctuation around the HGA in a working HDD.

Three sets of measurements were carried out, corresponding to three typical track following positions (inner, middle and outer track) of the HGA. In the first set, the HDD was working in the inner track following mode and Channel I transducer was placed on the hole A exactly above the HGA. Measured pressure fluctuation spectra from Channel I and II are shown in Fig. 4 (a), where Channel II transducer was placed on the hole B and results of Channel II from other positions are found to be similar. Fig. 4(b) shows the slider OT-FIV spectrum in this HDD working mode for comparison, where four principal peaks can be found in narrow frequency bands around 1.83 kHz, 2.54 kHz, 7.15 kHz and 8.5 kHz separately and the former two contain much more energy (more than 10 dB) than the latter two. Correspondingly, distinct peaks can be identified in pressure fluctuation spectra shown in Fig. 4 (a) in narrow frequency bands of these four peaks, particularly those around 1.83 kHz and 2.54 kHz containing much more energy than the other two also. This shows a good correspondence of spectrum characteristics between the measured pressure fluctuation and the slider OT-FIV, namely that principal spectrum peaks from aerodynamic excitation in the latter can be identified through those in the former, including the peak frequencies and the relative energy amplitudes corresponding to these peaks. This suggests success of the proposed measurement method, in which the spectrum characteristics of the pressure fluctuation measured on the inner-surface of top cover are used to understand those of aerodynamic excitation in the slider OT-FIV. Fig. 4(c) presents the results of spatial coherence between two channels of pressure signals in this set, and Channel I and II transducers are about 14.5 mm apart at this moment. It is shown that coherence is larger than 0.5 in narrow frequency bands of principal peaks in the slider OT-FIV spectrum, particularly being more than 0.8 around 1.83 kHz and more than 0.9 around 2.54 kHz. This reveals the high spatial coherence of turbulent pressure fluctuation around the HGA in this HDD working mode.

FIG. 4 HERE

In the second measurement set, the HDD was working in the middle track following mode. Corresponding spectra of measured pressure fluctuation are shown in Fig. 5(a) where Channel I and II transducers were placed on the hole B and D respectively. Fig. 5(b) shows the slider OT-FIV spectrum in this track following mode, whose principal peaks can be observed in the narrow frequency bands around 1.83 kHz, 2.54 kHz , 7.15 kHz and 8 kHz as marked out. By comparison, distinct peaks can be identified in pressure fluctuation spectra in Fig. 5(a) in narrow frequency bands of these OT-FIV principal peaks again, especially the two ones around 1.83 kHz and 2.54 kHz containing much more energy than the others. This good spectrum correspondence shows that the principal characteristics of the slider OT-FIV spectrum mainly come from the aerodynamic excitation of turbulent flow around the HGA and can be identified through those of the pressure fluctuation measured on the inner-surface of top cover. The results of spatial coherence between these two channels of pressure fluctuation signals are presented in Fig.

5(c), where distance between Channel I and II transducers is about 10 mm. High spatial coherence of pressure fluctuation around the HGA is observed in narrow frequency bands of principal peaks in the slider OT-FIV spectrum again, particularly up to 0.96 around 2.54 kHz. This fact may explain the success of measurement method for aerodynamic pressure fluctuation inside the HDD. Moreover, it is found that spatial coherence results in this set are higher than those shown in Fig. 4(c) from the first measurement set. The first reason may be due to the shorter distance of 10 mm between the two transducers in this set. The second may be that in this set the holes B and D are almost in a same circumferential stream where the flow patterns could be much similar.

FIG. 5 HERE

Fig. 6(a) presents the pressure fluctuation results in the third set of measurements, where the HDD was working in outer track following mode and Channel I and II transducers were placed on the hole C and B respectively. The corresponding slider OT-FIV spectrum is shown in Fig. 6(b), where principal peaks can be observed around 1.83 kHz, 2.54 kHz, 5.38 kHz and 7.15 kHz as marked out and the peak around 1.83 kHz contains much more energy than the others. Comparisons show that in this set good spectrum correspondence can be observed between the slider OT-FIV and pressure fluctuation spectra again, particularly on the peaks around 1.83 kHz and 2.54 kHz that have much higher energy amplitude than the other peaks. It is worth noting that the pressure fluctuation measured from Channel I in this set shows different spectrum from those in former two sets, where much higher aerodynamic energy is contained below 3 kHz. This may be due to the 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 the hole C. Such interflow pattern has been paid attention to in some previous studies [3], [6], [12] and it could make the aerodynamic pressure behavior under the hole C much different from those under other detection positions where the circumferential flow patterns are dominant. Nevertheless it can still be shown that in this set spectrum characteristics of aerodynamic excitation dominate those in the slider OT-FIV and can be detected through those of the pressure fluctuation measured near the top cover. The corresponding coherence results between two channels of pressure fluctuation are shown in Fig. 6(c) and the transducer positions are about 14.5 mm apart. By comparisons to those in the former two sets, spatial coherence results of pressure fluctuation in this set become smaller on the whole. The reason may be the interflow in the vicinity of the hole C discussed above, which makes the flow patterns under the holes B and C much different and disrupts remarkably the linearity between the pressure fluctuation under these two holes. Nevertheless, in this set spatial coherence higher than 0.5 can be still observed in narrow frequency bands of principal peaks in the slider OT-FIV spectrum.

FIG. 6 HERE

From experimental results presented above, it is shown that the most principal spectrum peaks in the slider OT-FIV are around 1.83 kHz and 2.54 kHz and are dominated by the aerodynamic pressure fluctuation around the HGA. A good correspondence of spectrum characteristics including principal peak frequencies and their relative amplitudes can be always observed between the measured pressure fluctuation and the aerodynamic excitation in the slider OT-FIV, no matter what track following position of the HGA is. High spatial coherence of pressure fluctuation around the HGA is also observed in narrow frequency bands of principal peaks in the slider OT-FIV spectra. These results suggest the success of the proposed measurement method of measuring aerodynamic pressure fluctuations around the HGA to detect the characteristics of the slider OT-FIV.

III. Numerical Validation

Numerical computations are conducted to enable more detailed investigation on the pressure fluctuation inside the HDD, in order to provide further validation on the reliability of the measurement method for characteristics of turbulent pressure fluctuation around the HGA. Since what concerns us most in the validation is the spectrum correspondence between the turbulent pressure fluctuation around the HGA and that near the top cover, a simplified turbulent model of two-dimensional channel flow around a rectangular block is employed for investigation based on the LES [6]. Fig. 7 illustrates the geometry applied to simulate the unsteady airflow around the HGA in middle track following position and the dimensions are in accord with those inside the measured HDD. A rectangular block with 0.3 mm thickness and 8 mm width is used to represent the cross section of the HGA along circumferential direction. In simulations, parabolic velocities with maximum value of 20.7 m/s that equals the circumferential velocity of disk rotation at middle track are defined on the channel inlet and zero pressure is used on the outlet. Other boundaries are considered as no-sliding walls for fluid field. Platform of FLUENT software is employed to perform the computations. In the flow, results from three point positions (P_1, P_2 and P_3) are collected for investigation, where P_1 (15.7 mm, 1.05 mm) and P_2 (24.3 mm, 1.05 mm) are in exactly the upstream and downstream region of the HGA respectively and P_3 (15.7 mm, 3.9 mm) is close to the top wall (namely HDD top cover) above the HGA position. The time step size in simulations is defined as 10 μs based on LES parameters discussed in [6] and more than 3000 time steps have been evaluated. Transient pressure results at points P_1, P_2 and P_3 have been collected for 15 ms after the airflow becomes statistically steady and then the spectra of pressure fluctuation are calculated with FFT algorithm. A quantity of drag pressure, P_d, which leads to drag force on the HGA to yield off-track vibration, can be obtained by subtracting the collected transient pressure at P_2 from that at P_1. The calculated spectra results of pressure fluctuation at P_3 and drag pressure P_d are presented in Figs. 8(a) and (b) respectively, as well as the spatial coherence results between them in Fig. 8(c). It is shown that the principal peak positions from 2 kHz to 8 kHz in pressure fluctuation near the cover can correspond well with those in the drag pressure spectrum, the direct aerodynamic excitation for the HGA OT-FIV. The spatial coherence results higher than 0.8 in this frequency range further demonstrate the good correspondence of characteristics between these two pressure fluctuation spectra. This further validates the reliability of the measurement method for spectrum characteristics of the aerodynamic pressure fluctuation around the HGA. The corresponding explanation for this may be that, the sound wavelengths at frequencies around the principal peaks in the slider OT-FIV spectra are much larger than the narrow space dimensions inside HDDs, for example 43 mm wavelength at 8 kHz compared to 4 mm height in measured HDD. This causes that the air space in the HDD is incompressible for propagation of such turbulent pressure fluctuation, so that the spatial distribution of the pressure fluctuation becomes nearly uniform in the HDD, especially in the off-plate direction. Based on the high spatial coherence of pressure fluctuations, it can be further suggested that one single sensor may be sufficient in detecting the pressure fluctuation characteristics around one HGA inside the HDDs.

FIG. 7 HERE

FIG. 8 HERE

IV. Conclusions

Three sets of measurements and a two-dimensional LES model have been conducted to investigate the spectrum-spatial characteristics of aerodynamic pressure fluctuations around the HGA inside the narrow space of an actual HDD. Good correspondence of spectrum characteristics of not only principal peak frequencies but also their relative amplitudes has been observed between the measured pressure fluctuation and the aerodynamic excitation in the slider OT-FIV for three track following positions of the HGA. This shows that aerodynamic pressure fluctuations around the HGA are highly related to the slider OT-FIV in terms of the principal spectrum peaks, especially at 1.83 kHz and 2.54 kHz. The spatial coherences of pressure fluctuations around the HGA, which are measured by the pressure transducers at several positions, are shown to remain high at frequencies about the principal peaks in the slider OT-FIV spectra. The numerical simulation results provide further validations on the measurement method in the experiments, showing that the air flow and pressure fluctuations around the HGA can be treated as being incompressible due to the narrow space in HDDs that is much smaller than the sound wavelengths corresponding to the frequencies about the principle peaks in the slider OT-FIV spectra. These results also indicate possibility of extending the proposed measurement method into applications in the multi-disk HDDs, provided that proper tiny sensors are available to be inserted into the separate space between disks to measure pressure fluctuations around each HGA [19]. The method for pressure fluctuation measurement and the results presented in this work will be useful for the control on the OT-FIV of the slider in hard disk drives.

Acknowledgment

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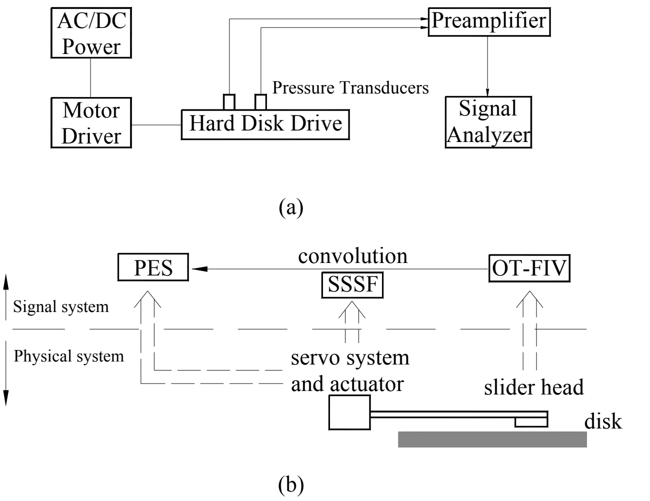

Fig. 1. Schematic illustration of the experimental setup. (a) The experimental setup for the pressure fluctuation measurement, where a 3.5-inch Seagate hard disk drive with one disk and two HGAs is driven by a motor driver at a speed of 7200 rpm, and (b) the time domain signal transmission from the slider OT-FIV to the positioning error signal (PES) via convolution with the servo system sensitivity function (SSSF) in an HDD.

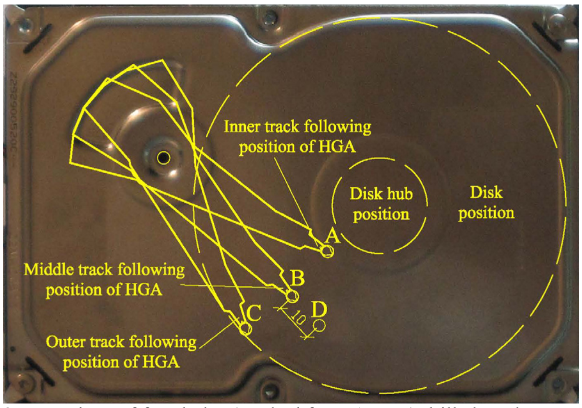

Fig. 2. Locations of four holes (marked from A to D) drilled on the HDD top cover for the pressure fluctuation measurements. Three HGA working positions in inner, middle and outer track following are indicated respectively. The unit in the figure is mm.

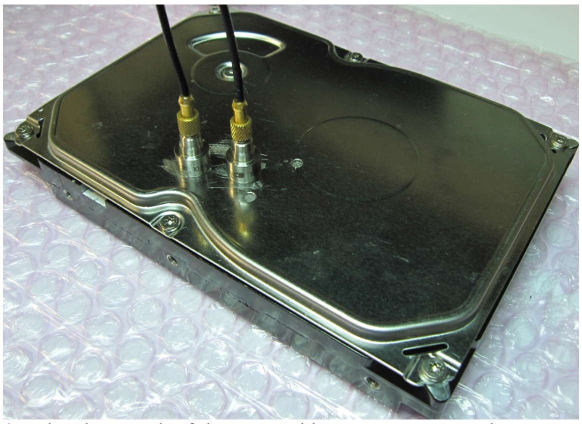

Fig. 3. The photograph of the HDD with two pressure transducers mounted on two selected holes on the cover, while the other two holes are sealed with adhesive tape.

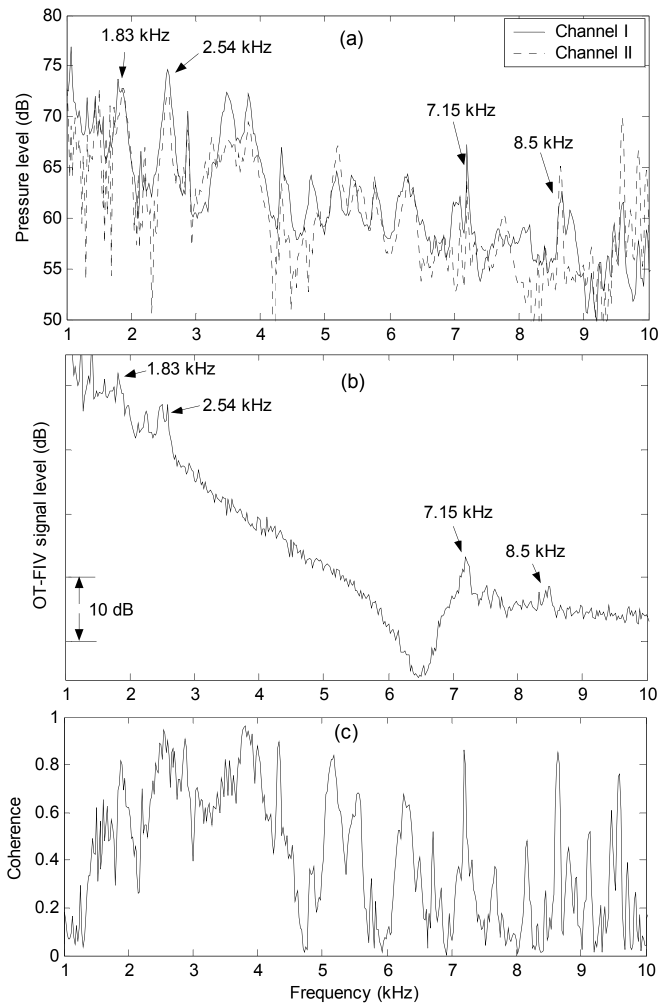

Fig. 4. The HGA heads are in the inner track following position. (a) Spectra of measured pressure fluctuation level from two channels (Channel I and Channel II), (b) spectra of the off-track flow-induced vibration (OT-FIV) of the slider and (c) measured spatial coherence between two channels of pressure fluctuation, where Channel I and II transducers are placed on the hole A and B respectively.

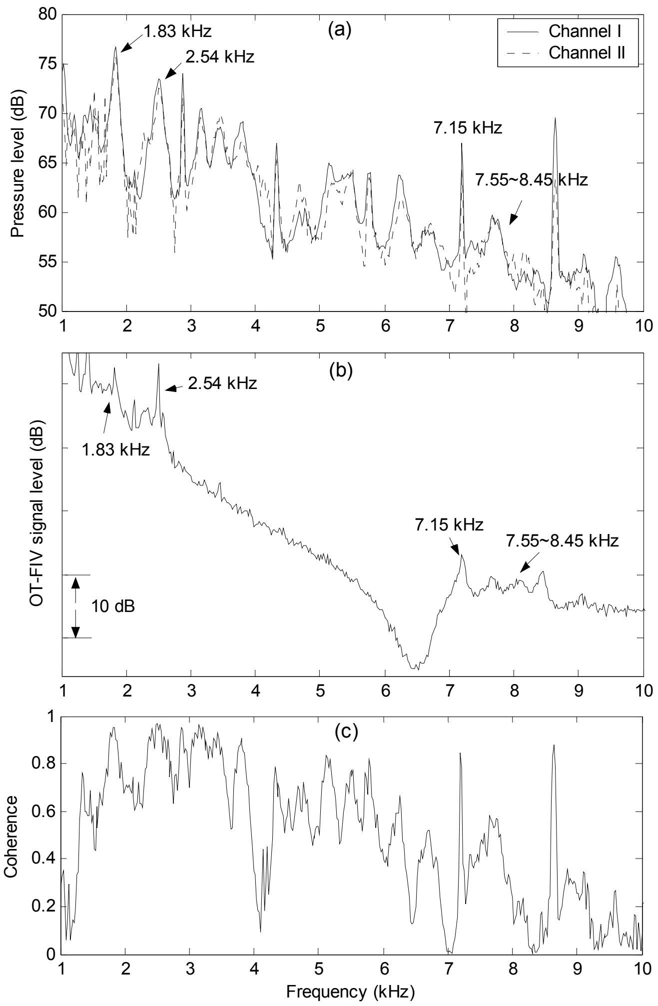

Fig. 5. The HGA heads are in the middle track following position (a) Spectra of measured pressure fluctuation level from two channels (Channel I and Channel II), (b) the spectra of the off-track flow-induced vibration (OT-FIV) of the slider and (c) measured spatial coherence between two channels of pressure fluctuation, where Channel I and II transducers are placed on the hole B and D respectively.

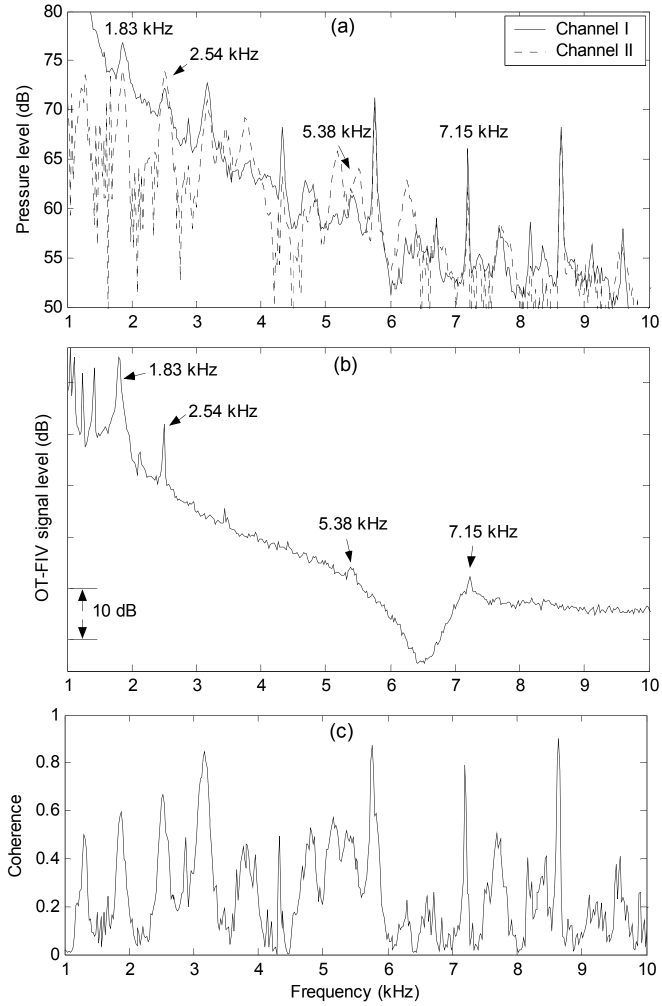

Fig. 6. The HGA heads are in the outer track following position. (a) Spectra of measured pressure fluctuation level from two channels (Channel I and Channel II), (b) the spectra of the off-track flow-induced vibration (OT-FIV) of the slider and (c) measured spatial coherence between two channels of pressure fluctuation, where Channel I and II transducers are placed on the hole C and B respectively.

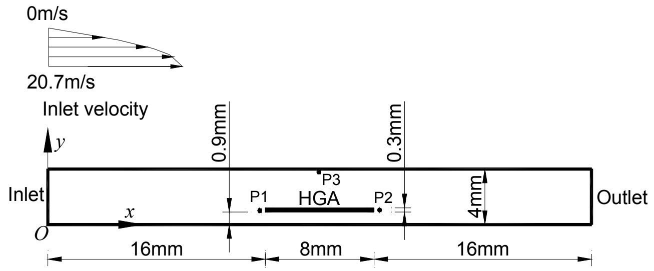

Fig. 7. Geometry of two-dimensional channel flow around a rectangular block to simplify the large eddy simulation on turbulent airflow around the HGA in the middle track following mode. The HGA is simplified as a rectangular block in the flow and dimensions are in accord with those inside the actual HDD in experiments.

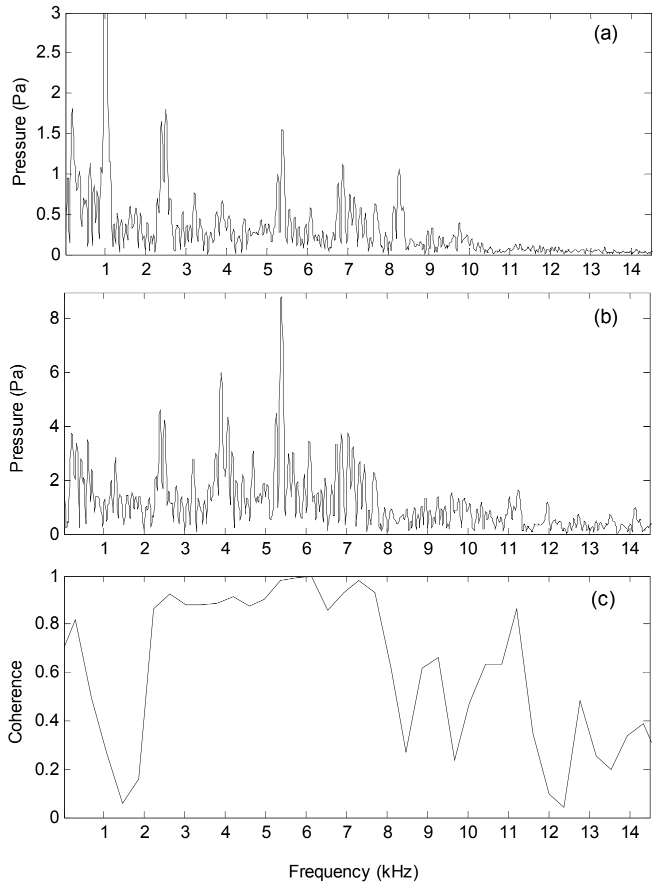

Fig. 8. (a) Calculated spectra of pressure fluctuation at the point P_3 indicated in Fig. 7, (b) calculated spectra of drag pressure P_d on the HGA that is from subtracting the collected transient pressure at point P_2 from that at P_1 in Fig. 7, and (c) spatial coherence between the drag pressure P_d and the pressure fluctuation at the point P_3.