EXPERIMENTAL STUDY OF TURBULENT FLOW BETWEEN SHROUDED CO-ROTATING DISKS

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1 Introduction

The air flow in a hard disk drive (HDD) is characterized by turbulent flow at relatively high disk-Reynolds numbers ($Re_d = RdV_d/v = \Omega^2R^2d/v \approx 10^5$) and one of the big issues in further development of a HDD is the flow-induced vibration (FIV) of disks and read/write head-arm system. Therefore, the detailed investigation of the flow itself and its relationship with FIV, as well as its reduction, are of great engineering importance.

There are numerous studies in the past that considered the turbulent flow in a system of multiple disks rotating in a cylindrical enclosure, a simplified model of a HDD. In an earlier experimental study performed by Abrahamson et al. (1989), it is found that the boundary layer developing on the shroud wall induce a flow instability in the region between disks. Fukaya et al. (2002) performed simultaneous measurements of the disk vibration and the fluid flow to characterize the disk FIV. The attempt by Suzuki et al. (2005) to remove shroud boundary layer away from disks, by introducing a ribbed shroud, indicated a possibility to reduce the disk FIV. The study by Kurashima et al. (2011) to directly measure the pressure on both sides of a disk indicated the difficulty due to the inevitable, invasive nature of the pressure probe. The recent LES study by Washizu et al. (2013) indicated that the pressure fluctuation developing on the surface of disks can be remarkably reduced when the inner wall the shroud is replaced by a ribbed wall.

The present study is primarily planned to provide experimental information to support the above-mentioned LES results by Washizu et al. (2013). In particular, the effect of the shroud wall configuration is investigated by comparing two cases, i.e., flat shroud and ribbed shroud (cf. Figs. 1 and 2), in terms of both disk vibration and pressure fluctuation on the shroud wall.

First, the effect of rib to reduce the disk vibration is confirmed. The rib is found to destroy the large-scale vortices between disks, and at the same time, to block the exchange of fluids between upper and lower disk (Washizu et al., 2013). To this end, two identical test rigs except for the rib on the inner wall of the enclosure are used where the pressure on the disk and the disk vibration are measured.

Second, in order to understand the characteristic pressure distribution which indicates the existence of the large-scale vortex system, the pressure fluctuation and its two-point correlations are measured. Based on the auto-correlation and two-point correlations from various configurations, the rotational speed of the vortices and the number of cells are evaluated. To this end, a new enclosure system is introduced, which makes the simultaneous measurements at two points which are separated by arbitrary circumferential distance possible. The results will be compared with former experiments (e.g., Kanagai et al., 2007).

2 Experiment

Test Rig

The experiments were performed in the disk system which was equivalent to the one used in the experimental study by Kurashima et al. (2011), as shown in Fig. 1. The five disks of radius of 47.5 mm were stacked coaxially at 2.45 mm interval in a cylindrical enclosure. The disks were driven by a DC servo-motor which was connected to the hub of 17.5 mm in radius. The inner wall of the enclosure was made flat, and the disk-top clearance was 0.5 mm. The enclosure had a slit of 10 mm width to provide an access to the probe of displacement sensor for disk-flutter measurement. For the measurement of the pressure on the inner shroud wall, a pair of pressure tap was opened above and below the third disk.

Another set of the experiments were performed in the enclosure which had the inner wall with ribbed surface, as illustrated in Fig. 2. The pitch of the rib was set equal to the distance between the rotating disks, so that the tip of each disk was facing to the rib with 0.5 mm clearance. This configuration was selected to be compared with the preceding computational study (Washizu et al., 2013).

The two-point correlation of the pressure on the shroud wall was measured in a separate test rig which had pressure taps at different locations, so that the pressure at any two positions could be measured simultaneously, cf. Fig. 3. The pressure taps were located at four different circumferential positions ($\theta = 0, \pi/4, \pi/2, \pi$) but on the same axial location.
the other hand, a pair of pressure taps were opened at a distance of 1.225 mm above and below the third disk, so that the pressure above the disk, $+0.5\Delta z$, and below, $-0.5\Delta z$, were measured simultaneously. The enclosure was composed of two pieces, separated at the plane of the third disk, and the upper- and lower-part could be rotated at arbitrary angle; the pressure at two locations which were separated by $\Delta z$ in the axial direction and arbitrary separation in the circumferential direction $\Delta \theta$ could be measured simultaneously, as shown in Fig. 4.

**Instruments**

The fluctuating pressure at the pressure tap was sensed by the condenser microphone (UC-29, RION). The sensor had the diameter of 7.0 mm and length of 10.0 mm. The microphone was connected to the pressure tap by a flexible tube. As depicted in Fig. 5, a stainless pipe $A$, made with aluminum, and the microphone $D$ was connected by a flexible, plastic tube $B$ and a connecting part $C$ which was made of brass and screwed on the microphone.

The microphone had a sensitivity of about $4.0 \text{ mV/Pa}$, and the two microphones were used simultaneously, as illustrated in Fig. 6. A common amplifier was used for the two microphones, so that the phase-lag due to the electronic circuit could be avoided.

As a microphone was not able to measure the absolute pressure but only senses the fluctuation, the instantaneous pressure difference $\Delta p$ between two points could be obtained by simply subtracting one from another:

$$\Delta p = p_1 - p_2,$$

with $p_1$ and $p_2$ being fluctuating pressures measured at upper- and lower side of the disk, respectively. Their time-average should be zero per definition; however, in the practice, there was a slight off-set in the signal measured by two different microphones such that

$$p_1 = \bar{p} + p'_1,$$

$$p_2 = \bar{p} + p'_2.$$

Although the magnitude of the pseudo mean pressure denoted by the over-bar, $\bar{p}$, was small compared with the fluctuating component, it was necessary to introduce the corrected instantaneous pressure fluctuation

![Figure 1: Co-rotating disk system. Top: planer view, Bottom: cross section.](image1)

![Figure 2: Enclosure with ribbed inner wall.](image2)

![Figure 3: Model for measurement of two-point pressure correlation.](image3)

![Figure 4: Detailed view of the test rig for measuring the two-point-correlation of the fluctuating pressure on the shroud wall.](image4)
p\textsuperscript{*}, in order to evaluate the instantaneous pressure difference, namely,

\[ p_{1,2}^* = p_{1,2} - \overline{p}_{1,2}. \]

The corrected pressure fluctuation \( p^* \) was used for the subsequent calculations including the correlation functions.

The disk vibration was measured by an electrostatic capacitance type displacement meter (ST-3512, Iwatsu). The measurement range extended from 25 \( \mu\)m to 75 \( \mu\)m, and its resolution was 10 nm. The probe diameter was 1.5 mm, and its tip was cut at 45 degrees for convenience to access the disk top through the slit of the shroud. All these configurations were common with preceding studies (e.g., Kurashima et al., 2011).

### Experimental Details

The measurements were undertaken for a range of disk rotation speed from 1,000 rpm to 10,000 rpm by the interval of 1,000 rpm. The sampling rate was set to 20 kHz and the data were sampled for 120 seconds at every point.

The electrical signals from the condenser microphones and the displacement meter were acquired by a 16-bit AD board into a personal computer, cf. Fig. 6, and a low-pass filter was applied at the cut frequency of 5 kHz.

### Result

#### Overall Feature of the Vibration

Figure 7 illustrates the spectrum of fluctuating pressure difference \( \Delta p \) in the form of water-fall plot, obtained from the simultaneous measurement of pressure at upper- and lower-surface of the third disk in the flat enclosure, Fig. 1. The \( x \)- and \( y \)-axes indicate the frequency and the disk rotation speed, respectively, so that and the spectrum of the pressure fluctuation at every disk rotation speed are directly related with each other. In accordance with the previous studies, the frequency range of 0 Hz to 2,000 Hz is shown.

It is indicated that the peak column marked by (1) to (8) extend from the origin of the axes. They are called RRO (Repeatable Run Out) which occur at the frequencies proportional to the disk rotation frequency, as a result of the roughness and/or distortion of the disk surface. The other peaks are called NRRO (Non-Repeatable Run Out) which are related to other causes such as the elastic vibration of the disk and flow turbulence.

The result of disk vibration measurement under the equivalent condition is presented also in the waterfall plot in Fig. 8. In comparison with the pressure fluctuation, NRRO components marked by (a) to (j) are more pronounced. It is inferred from the comparison of these two figures that the NRRO components from (a) to (j) are imposed on the broad peak in the pressure fluctuation at the corresponding frequencies, and it grows as the rotating speed increases.

Figures 9 and 10 present the pressure fluctuation and disk vibration measures in the ribbed shroud (cf. Fig. 2). By comparing their counterpart in the flat shroud experiment, one can see that the frequency characteristics are nearly the same, though the magnitude are reduced both in \( \Delta p \) and disk vibration. Some details will be investigated next by inspecting auto- and cross-correlation of the pressure fluctuation.

#### Circumferential Correlation of Fluctuating Pressure

Figure 11 shows the auto-correlation of pressure fluctuation measured at \( \theta = 0 \) and the cross-correlation \( R \) of pressure fluctuation measured at two points separated by \( \Delta \theta = \pi/4 \) on the same \( z \)-plane. Here, the cross-correlation \( R \) is defined by

\[
R = \frac{\overline{p(z, \theta)p(z + \Delta z, \theta + \Delta \theta)}}{\sqrt{\overline{p^2(z, \theta)}\overline{p^2(z + \Delta z, \theta + \Delta \theta)}}}, \tag{1}
\]

hence \( \Delta z \) is zero in this case.

The \( x \)-axis is the non-dimensional time relative to the disk rotation. The auto-correlation signal indicates that there are about 6 small peaks within one disk rotation, which corresponds to (6) of RRO in Fig. 7. On the other hand, the cross-correlation shows a similar wavy pattern but with slight off-set. This off-set is interpreted to be a consequence that the same structure
is captured at the two locations with delay corresponding to 1/8 rotation (=θ/4). In the figure, the off-set is seen to be 0.192, hence there is a discrepancy of 0.125/0.192 ≃ 0.65. We consider this discrepancy is due to the difference in the rotating speed of the disk and the vortex pattern.

The two-point correlations at Δθ=π/2 and π are compared in Figs. 12 and 13, respectively. The auto-correlation is compared in each graph, and it is seen that the cross-correlation is off-set from the auto-correlation by 0.383 for Δθ = π/2 and 0.75 for Δθ = π. If we calculate the discrepancy in the same manner as is for the case of Δθ = π/4, 0.25/0.383 ≃ 0.65, and 0.5/0.75 ≃ 0.67.

These values are in good accordance with each other, and it fair to suppose that the system of six vortices are rotating at about 65% of the disk rotating speed. This is in good agreement with previous research by e.g. Kurashima et al. (2011), where vortices are found to rotate at about 60 ~ 70 % of the disk rotation speed.

**Axial Correlation of Fluctuating Pressure**

Figure 14 compares the auto-correlation and the cross-correlation with axial separation, Δz: The correlation of the pressure at the upper- and lower-side of a disk is calculated at the disk rotation speed of 10,000 rpm and 5,000 rpm. It is seen that both auto- and cross-correlation indicate peaks at the interval of about 0.17, but they are off-set by half the wave length, resulting in the opposite sign to each other. The situation is similar for both rotating speeds. In reference to the previous discussion, it is considered that the system of six vortices is rotating on each side of the disk, at the same speed, but off the phase at the top- and bottom-side. This agrees well with the findings by the numerical simulation by Washizu et al. (2013).
To further investigate the structure on each side of the disk, the cross-correlation measurements are conducted for $\Delta z = 2.45$ mm and $\Delta \theta = 0, \pi/60, 2\pi/60$, and $3\pi/60$, i.e., increment of $\theta$ by 3 degrees. The results at the disk rotation speed of 10,000 rpm are presented in Fig. 15. It is obvious that nearly the same patterns are off-set from each other by a constant difference in time. This is an indication that a fairly firm structure is rotating at a constant speed as the disk rotates.

From the above described difference in the correlation $R$ at different $\Delta \theta$, it is considered that a system of six vortices are rotating on each side of the disk, again in good agreement with the numerical simulation. The situation is found similar in both 10,000 rpm and 5,000 rpm cases. On the other hand, the results of the measurement in the ribbed shroud show a quite different tendency. The peaks in auto- and cross-correlations at the disk rotation speed of 10,000 rpm, Fig. 16, indicates that there are fairly large peaks in opposite sign on each side of the disk but the number of peaks is four over one disk rotation. This structure has completely disappeared when the disk rotation speed was reduced down to 5,000 rpm. It should be noted that the strong correlation does not indicate a strong pressure difference itself, as it is already seen in the waterfall plot of the pressure difference.

**Disk Vibration and Pressure Fluctuation**

The difference due to the configuration of the shroud is now compared in Fig. 17 in terms of the disk vibration, the pressure difference in the same test rig, and the pressure difference in the test rig in the absence of the slit. All plots show the ratio of individual quantities measured in the ribbed shroud against those measured in the flat wall shroud. It is obvious that the ribbed shroud has effectively reduced the disk vibration and the pressure fluctuations over the wide range of the disk rotation speed. In particular, the reduction rate reaches about 50% for the case of the enclosure without slit. The reduction rate was found to be about 40% in the corresponding numerical simulation (Washizu et al. 2013) where the disk vibration is not taken into account.

4 Conclusions

The simultaneous measurement of fluctuating pressure at two points is performed and compared with the disk vibration measurement in a simplified hard-disk drive model. The cross-correlation of fluctuating pressure measured at two locations which are separated in the circumferential direction suggests the existence of a system of six rotating vortices which travels at a speed of about 65% of the disk rotation. The system of rotating vortices is weakened when the rib-shroud is introduced; the circumferential correlation of fluctuating pressure almost completely disappeared at the disk rotation speed of 5,000 rpm. It is further
confirmed that the ribbed shroud is effective to reduce the disk vibration and pressure over a wide range of the disk rotation speed, and its reduction rate is about 50% at maximum.

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References


