An experimental study of three-dimensional vortical structures between co-rotating disks

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Abstract. In this study, we experimentally investigate the flow between co-rotating disks in a stationary cylindrical enclosure. Here, the gap between disks is much narrower than disk radius. This flow is often non-axisymmetrical and complicated. This flow sometimes induces magnetic-head oscillations in disk storage devices of PCs. We carry out flow visualisations using a high-speed camera, and time-successive three-dimensional PIV (Particle Image Velocimetry) analyses of visualised pictures. We focus on the relation and combination of axial modes with circumferencial modes. Tested cases are two, that is, A (\(Re = 1.2 \times 10^4\) and \(\delta = 0.12\)) and B (\(Re = 1.0 \times 10^5\) and \(\delta = 0.20\)). Here, \(Re\) is the rotating Reynolds number, and \(\delta\) is a non-dimensional gap. Case A is in axial mode \(Ⅱ\) and circumferencial mode 8-9, and case B is in axial mode \(Ⅲ\) and circumferencial mode 4. Axial modes are related with the symmetry of a pair of toroidal-vortical structures and circumferencial modes are related with the radial fluctuation of these structures as well as the solid-body-rotation core. As a result, in case A, the vortical structures are mainly influenced by axial mode \(Ⅱ\) in the \(z\) direction, but not influenced by both axial mode \(Ⅱ\) and circumferencial mode \(8-9\) in the \(r\) direction. In case B, the vortical structures are mainly influenced by axial mode \(Ⅲ\), but influenced by circumferencial mode \(4\) in the \(r\) direction.

1. Introduction

Our present interest is the flow between two disks. Namely, we consider a pair of disks of the same radius in a stationary cylindrical enclosure. The gap between disks is much narrower than the disk’s radius. The disks are connected with a common shaft and co-rotate. Such a flow is often seen in hard-disk drives, the most popular storage devices in modern PCs. This flow is often complicated and non-axisymmetrical, consisting of two regions, that is, the core region in solid-body rotation and the outer turbulent region. The flow causes pressure and velocity fluctuations, and yields read/write errors of hard-disk drives due to magnetic-head oscillation. Therefore, for the accurate positioning operation of read/write magnetic heads in high-speed and high-capacity hard-disk drives, we are required to understand the flow.

Until now, various researches have been carried out in order to know the flow. Lennemann (1974) observed some non-axisymmetric circumferencial modes [1]. Recently, Herrero et al. (1999) performed three-dimensional numerical simulations for the flow between co-rotating disks, and classified the flow into three axial modes \(Ⅰ\), \(Ⅱ\) and \(Ⅲ\) [2]. But there has been a need to comprehended the flow field between co-rotating disks from a three-dimensional point of view.
Incidentally, Rabaud and Couder [3] have studied similar flow at low Reynolds numbers, and revealed the instability of a circular shear-layer between two annular laminar flows.

In this study, we carry out flow visualisations by a high-speed camera, and a time-successive three-dimensional PIV (Particle Image Velocimetry) analyses. We use a geometrically-simplified model made by acrylic resin. Our purpose is to research the related and combined effect between axial modes and circumferential modes.

2. Experimental method

2.1. Apparatus

Figure 1 shows a schematic diagram of our experimental apparatus. Gray areas are rotary parts. The experimental apparatus is a geometrically-simplified model of hard-disk drives. Two disks with the same radius are connected with a common shaft. Variable-speed motor makes the shaft rotate. The working fluid is water with which we fill the stationary cylindrical enclosure including two disks. Disks are attached to the rotating centre with error less than 0.01[rad]. Here, we confirmed that, when disks are inclined at 0.2[rad], there is no influence on the flow. Disk-rotation speed is varied from 1.5[rpm] to 150[rpm] by variable-speed motor with several gear heads. The gap between disks is controlled by inserting acrylic pipes between disks as a spacer. Pipes are painted black in order to prevent the reflection of a YAG Laser.

2.2 Governing parameters

The present coordination system is cylindrical \((r, \theta, z)\). Important parameters are as follows (see Figure 2). Disk radius \(R_d (=153[mm])\), acrylic-pipe radius \(R_s (=34[mm])\) and stationary-cylindrical-enclosure radius \(R_w (=154[mm])\) is fixed to be constant. The gap between disks is \(G\).

Rotating Reynolds number based on the disk radius is

\[
Re = \frac{\omega R_d^2}{\nu}.
\]

Here, \(\nu\) is the coefficient of kinematic viscosity. \(\omega\) is disk-rotation speed, and is fixed to 5[rpm] or 40[rpm]. Corresponding \(Re\) is \(4102.1 \times 10^5\) or \(5100.1 \times 10^5\).

The aspect ratio of disk gap to the disk radius is

\[
\delta = \frac{G}{R_d}.
\]

\(\delta\) is equal to 0.12 or 0.20. Non-Dimensional radius of the stationary cylindrical enclosure is

\[
\lambda = \frac{R_w}{R_d}.
\]

As the gap is sufficiently narrow \((0.0065R_d)\) between disk tips and a stationary cylindrical enclosure, \(\lambda\) is approximately 1.0.
Table 1. Experimental parameters.

| Case          | A          | B          |
|---------------|------------|------------|
| Axial mode    | II         | III        |
| Circumferencial mode | 8 - 9     | 4          |
| $Re$          | $1.2\times10^4$ | $1.0\times10^5$ |
| $\delta$      | 0.12       | 0.20       |
| $\lambda$     | 1.0        | 1.0        |
| $t_s/t_d$     | 1.13       | 1.37       |

Table 1 shows the details of our experimental parameters. We performed experiments for two cases A and B, which are in axial mode II and circumferencial mode 8-9, and in axial mode III and circumferencial mode 4, respectively. The period of the core-shape rotation is $t_s$, and the period of the disk rotation is $t_d$ (for “the core-shape rotation,” see below).

2.3 Classification of axial mode and circumferencial mode

2.3.1 Circumferencial mode

We can usually observe that there are two flow regions, namely, the core region in solid-body rotation near the centre shaft, and the outer turbulent region. These regions are well characterized by radial profiles of circumferential velocity (see [4]). We can confirm almost rigid-body-rotational flow in the core region, and much larger velocity fluctuation in outer turbulent region.

The core region has a polygonally-shaped boundary, and the polygonal shape rotates slower than disks. Lennemann [1] defined the circumferencial mode with the number of core apices. For example, in mode 3, we see a triangle of the solid-body rotation core region. In addition, in the outer turbulent region, flow is not completely turbulent, but has a lager structures mentioned below with fluctuating turbulent components.

2.3.2 Axial mode

We can usually observe a pair of toroidal-vortical structures near the stationary cylindrical enclosure in the outer turbulent region. On the basis of the vortical structure’s stability, Herrero et al. [2] classified the flow into three, namely, axial modes I, II and III. In mode I, the vortical structures are steady and keep symmetry with respect to the interdisk midplane. In mode II, the symmetry is broken with a periodic fluctuation. In mode III, the symmetry is broken in a random manner without periodicity.

2.4 Flow visualisation and PIV analysis

We conducted two kinds of flow visualisations, namely, conventional and PIV-oriented ones. Conventional flow visualisation is performed using chemically-bridged polyethylene-resin particles. PIV-oriented flow visualisation is performed using chemically-bridged polyethylene-resin particles with fluorescent paint. For PIV analysis, we use two consecutive pictures, which are cross-correlated. A laser sheet from a YAG laser with optical fiber lightens up the $r$-$\theta$ plane or the $r$-$z$ plane between two disks. Both flow visualisations are recorded by a high-speed camera. Camera frame rates are 500[frame/s] at $Re = 1.2\times10^4$, and 1000[frame/s] at $Re = 1.0\times10^5$. Light inflection through the stationary cylindrical enclosure induces the distortion of images. In order to remove the distortion, we put a square-prism container surrounding the cylindrical enclosure, and fill up water between the cylindrical enclosure and the square-prism container.
3. Results and discussion

As mentioned before, we will show the results for two cases A and B, alternatively.

3.1 PIV analysis

3.1.1 $r-\theta$ plane

- Case A (mode II and 8-9)

Figure 3 shows a conventional flow visualisation on the $r-\theta$ plane. We can see the core, a solid-body rotation region, and the outer-turbulent region. The shape of the core region is an unstable polygon with 8 or 9 apices. Therefore, circumferential modal number is 8 or 9. Figure 4 shows a PIV-oriented flow visualisation on the $r-\theta$ plane. More precisely, in the figure, we see velocity vectors and the denseness of vorticity $\omega_z$ on the midplane between disks. We are able to confirm a nearly solid-body-rotation part in the core region. More specifically, $\omega_z$ in the core region is nearly twice the disk rotation speed. On the other hand, $\omega_z$ is nearly zero in the turbulent region.

The period $t_s$ of the core-shape rotation is about 13.7[s], and the period $t_d$ of the disk rotation is 12.0[s] (the disk-rotation speed is 5[rpm]). Therefore, the core-shape rotates about 88 percent of the disk-rotation speed.

- Case B (mode III and 4)

Figure 5 shows a conventional flow visualisation on the $r-\theta$ plane. The shape of the core region is a polygon with 4 apices. Therefore, circumferential modal number is 4. Figure 6 shows PIV-oriented flow visualisations on the $r-\theta$ plane. As well as in Figure 4, we can see velocity vectors and the denseness of vorticity $\omega_z$ on the midplane between disks. Four figures (a)-(d) are successive with the same interval. We are able to confirm a solid-body-rotation part in the core region. On the other hand, $\omega_z$ is very small in the turbulent region, as well as Figure 4.

The period $t_s$ is 2.05[s], and the period $t_d$ is 1.5[s] (the disk rotation speed is 40[rpm]). Therefore, the core-shape rotates about 75 percent of the disk rotation speed.
3.1.2 r-z plane

- **Case A (mode II and 8-9)**

Figure 7 shows PIV-oriented flow visualisations on the r-z plane. Five successive figures (a)-(e) are taken with a regular interval of the same non-dimensional time \( t/t_d \) of 0.093/4. We can see a pair of toroidal-vortical structures near the cylindrical enclosure. It is interesting that the maximum values of \( \omega_\theta \) are almost twice of the \( \omega_z \) of rotation disks.

The structures fluctuate periodically in the z direction. Then we can classify the flow into mode II. The period of the fluctuation is about 0.093\( t_d \). That period is smaller than the period of circumferential mode of 0.125\( t_d \)-0.141 \( t_d \). Note that there exists only small fluctuation of the structures in the r direction.

- **Case B (mode III and 4)**

Figure 8 shows PIV-oriented flow visualisation on the r-z plane as well as Figure 7. The interval time \( t/t_d \) equals 0.32/4. We also see a pair of vortical structures near the cylindrical enclosure. However, the vortical structures fluctuate irregularly in the z direction. Then we can classify the flow into mode III. We can observe the periodic fluctuations in the r direction, on both vortical structures and the core boundary, which are synchronous with the circumferencial mode. In addition, we can see obvious centrifugal and centripetal flows in the circumferencial mode in figures (b) and (d), respectively. These flows are also synchronous with the circumferencial mode.

![Figure 7](image1.png)  
**Figure 7.** Velocity vectors and vorticity \( \omega_\theta \) on the r-z plane (Case A).

![Figure 8](image2.png)  
**Figure 8.** Velocity vectors and vorticity \( \omega_\theta \) on the r-z plane (Case B).

3.2 Three-dimensional vortical structures (by time-series PIV analysis)

Figures 9 and 10 show flow structures in space-time diagrams, more precisely, time-successive quasi-three-dimensional vortical structures, of case A and case B, respectively. These are ensembles of the r-z plane diagrams such as Figures 7 and 8. Here, iso-vorticity surface of \( \omega_\theta \) can be visualised on the r-z-t space. So we can quasi-three-dimensionally observe the toroidal vortical structures in both figures. In addition, white lines are outer boundaries of the core region.

In Figure 9, we can easily see the outstanding feature described in Figure 7; namely, larger fluctuation in the z direction and smaller fluctuation in the r direction. The effect of the
circumferential mode is small, because the circumferential mode is unstable to fluctuate modal number with time, and because the modal number is large.

In Figure 10, contrary to Figure 9, the axial mode is unstable (Ⅲ) and only the circumferential mode (4) is dominant. More specifically, we can see non-periodic fluctuation on the toroidal structures in the $z$ direction, and periodic fluctuation in the $r$ direction. It is interesting that large-valued vorticity parts leave toward the centre from the downstream of the toroidal-vortical structures.

4. Conclusions
We successfully conducted time-successive PIV analyses for two cases A and B. Case A is in mode II and 8-9 ($Re = 1.2 \times 10^4$, $\delta = 0.12$). Case B is in mode III and 4 ($Re = 1.0 \times 10^5$, $\delta = 0.20$). On the $r$-$\theta$ plane, we confirm solid-body rotation in the core region, and very small $\omega_z$ in the outer turbulent region. On the $r$-$z$ plane, we confirm the periodic fluctuation (mode II) of the toroidal vortical structures, experimentally, as well as the non-periodic fluctuation (mode III). It is interesting that $\omega_{\theta}$ sometimes becomes much larger than the $\omega_z$ of rotating disks. In mode II, $z$-direction fluctuation of the vortical structures is larger than $r$-direction one. The period of the fluctuation in mode II is not related with the period of mode 8-9. In mode III, the vortical structures fluctuate in the $r$-direction according to the circumferential mode, but almost random in the $z$-direction. We can successively show the vortical structures, quasi-three-dimensionally. In mode III, there is a pair of inward branches of toroidal-vortical structures from downstream, and centrifugal and centripetal flows in the outer turbulent region. As a result, in case A, the vortical structures are mainly influenced by axial mode (II) in the $z$-direction, but not influenced by both axial mode (II) and circumferential mode (8-9) in the $r$ direction. In case B, the vortical structures are mainly influenced by axial mode (III), but influenced by circumferential mode (4) in the $r$ direction.
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