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INVESTIGATION OF COMPLEX FLOW BEHAVIORS IN A HARD DISK DRIVE MODEL WITH READ-AND-WRITE ARM AND SHROUD OPENING

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Summary

Flow inside a hard-disk drive (HDD) is investigated using a simplified 3.5” HDD model with read-and-write arm (RWA) and shroud opening. The model was designed to serve as a benchmark of HDD flow investigation both in experiments and in numerical simulations. In the present study, complex flow behaviors in the narrow disk-to-disk space are focused with the RWA inserted into the space. Especially, the flow behavior near the RWA is of great interest. The velocity statistics are acquired at four different locations using a velocity profile sensor with a spatial resolution of 5 µm along the axial direction. The measurement was carried out at the disk Reynolds number Re_D=2.4×10^5, which corresponds to the rotation speed of 7700 rpm at a real 3.5” HDD for desktop computers. The velocity statistics are presented along lines at four different radial locations near the shroud opening with the RWA placed at the disk edge. The velocity profile sensor successfully resolved the velocities between the narrow areas without disturbing the flow. The resulting mean velocities and Reynolds stress components exhibit somewhat different features compared to the ones observed at the flow in an axisymmetric model without shroud opening. Further results of the flow near the RWA will be presented at the conference.

Introduction

The recent development of a hard disk drive (HDD) requires optimum mechanical design in every aspect. The aerodynamic performance inside a HDD is not an exception. A HDD system consists of high-speed rotating magnetic disks (platters) and read-and-write arms (RWAs). The arms are located to the desired radial positions floating over an air film above the disk surface for reading and writing data. The development of HDDs goes toward higher data densities with faster rotation speeds in accordance with ever growing demands for larger storage capacity and faster data access speed. Nowadays, HDDs with a rotation speed up to 15000 rpm are commercially available for enterprise purpose. The floating height of the read-and-write head above the disk surface has reached into the range of 10 nm. The fast rotation of the disks induces a high speed rotating flow, exhibiting highly three-dimensional complex structures in the small dimensions together with the complex geometry. The mechanical problem occurs as the arms are exposed to the high speed rotating flow, causing difficulties in precise control of their positions above the desired tracks. Therefore, the characterization of flow induced vibration (FIV) and hence the detailed investigations of the flow field are desired for the optimum design of the next-generation HDDs.

Many investigations in the past have focused on the complex flow behaviors inside HDDs with their relevance to the disk vibrations. In most of the investigations, simplified models have been used in order to gain general physical insights of the flow and vibrations. Axisymmetric models consisting of corotating disks inside a cylindrical shroud enclosure have typically been employed without the RWAs and shroud openings (Lennemann, 1974; Abrahamson et al., 1989; Schuler et al., 1990; Herrero et al., 1999; Fukaya et al., 2002; Kanagai et al., 2007; Wu, 2009; Shirai et al., 2011).

Flow investigations with non-axisymmetric geometry and/or with simplified flow obstacles have also been made in order to investigate more realistic flow occurring in real HDDs (Lennemann, 1974; Abrahamson et al., 1988; Tzeng et al., 1991; Humphrey et al., 1993; Ursy et al., 1993; Gor et al., 1994; Barbier et al., 2005). The non-axisymmetric geometry simulated the shroud openings for placing the control unit of the RWA assembly. Simplified obstacles were inserted into the flow between the disks for imitating the RWA of real HDDs. Most of the investigations have focused on the influence of the flow obstacles on the wake structures, which exhibited highly three-dimensional features. The insertion of the obstacles suppresses the large-scale vortex structures developing in the outer region. Recent simultaneous measurement of disk vibration and pressure fluctuation has confirmed the same tendency with the existence of a simplified RWA (Kurashima et al., 2011).

Numerical simulations have also been performed using large eddy simulation (LES) (Tatewaki et al., 2001; Al-Shannag et al., 2002; Kazemi, 2008; Kirpekar and Bogy 2008; Kazemi, 2009; Ikegawa et al., 2009; Hendriks, 2010). Nowadays, three-dimensional simulations of the complete flow field are feasible with the detailed geometries of HDDs based on their design data. The simulations have revealed instantaneous complex flow structures, which are not accessible in experiments. Although the simulations with real HDD geometries exhibit specific features of certain geometry, they do not provide sufficient information on the general flow physics of HDDs. Computational costs remain still so high that they do not resolve the details of the flow and not easily provide adequate amount of statistically independent samples for reliable discussions.

The present work was planned as a series of experimental studies in a model HDD to explore the detailed flow characteristics. Velocity measurements in an axisymmetric HDD model were performed without arm by means of a laser Doppler velocity profile sensor providing a high spatial resolution (Shirai et al., 2011). They demonstrated the excellent capability of the measurement technique that could reveal the complex features of the flow inside a narrow tip-clearance region between the disk and the shroud. The present work aims at the flow measurements in a more complex configuration, i.e., the flow around the RWA. For this purpose, a new experimental flow model has been designed and manufactured. The model has a simplified geometry, with which the flow can be investigated systematically both in experiments and in numerical simulations. It has a shroud opening with a simplified RWA, which can be inserted into the flow at different angles for simulating the read-and-write process along the different tracks. Measurement data will serve as benchmark of the computational fluid dynamics (CFD) studies which is undertaken in one of the authors' groups.

Flow Apparatus

The HDD model used in the present study is schematically shown in Fig. 1. The model consists of a pair of corotating disks and a simplified RWA unit accommodated in a shroud with an opening. The dimensions of the model were equivalent to a 3.5" HDD for desktop computers for consumer use. The model was designed to a simplified geometry without the details but still could be used for simulating the main features of a typical HDD. The model comprised several different parts made of different materials. The shroud and the base were made of aluminum. Two sets of shrouds with different opening angles were prepared. They were simplified in order to facilitate the comparison with CFD studies. The disks are fixed to the rotating axis that is driven by a DC motor at a constant speed, see Fig. 2.

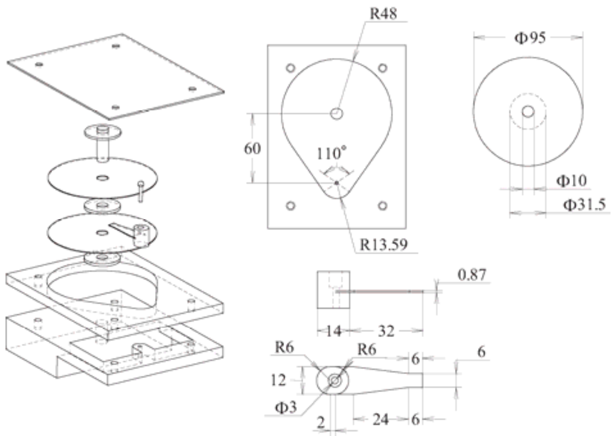

Fig. 1: Simple three-dimensional sketch of the HDD model with dimensions. (a) Whole, (b) RWA, (c) disk, (d) shroud.

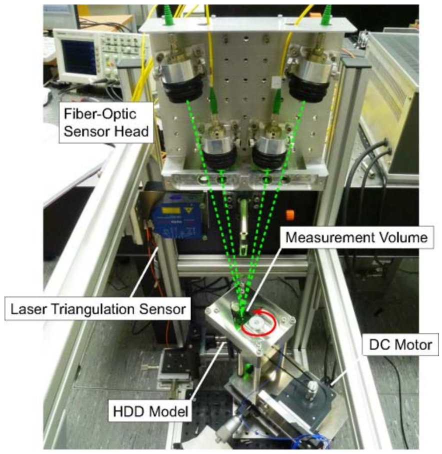

Fig. 2: Picture of the HDD model with the velocity profile sensor at the flow experiment.

The disks, RWA, and top- and bottom-plate were all made of polymethyl methacrylate (PMMA), which allowed optical access for the velocity measurement through them. Their dimensions are shown in Fig. 1. The disks were t_d=0.8 mm thick with the radius R_2=47.5 mm, which were exchangeable to a calibration disk with a pinhole attached on it. The calibration of the sensor was performed in situ at a similar rotation frequency of the disks with the same working fluid for the flow measurement. The spacer made of acrylonitrile butadiene styrene (ABS) had an outer radius of R_1=15.75 mm. As shown in Fig. 3, the RWA was attached to the pivot so that the angle of the arm φ could be set at different angles with respect to the tangential direction of the disk. Due to the finite size of the RWA unit, the smallest angle possible to be set was down to φ=3.5°. The angle increases counter-clockwise direction starting from the centerline connecting the RWA pivot to the disk peripheral edge. The angle of φ=55.8° corresponds to the y-axis. The RWA had a tapered shape toward the edge. The shape was rather simplified compared to the one used in a real HDD. The aluminum shroud with an opening shown in Fig. 3 was prepared for the present experiment. The shroud radius was R_3=48 mm with the tip clearance of 0.5 mm. The origin of the coordinate was set in the middle plane of the disks along the rotation axis. Cartesian coordinates were used with x and y for the disk in-plane and z for the disk out-of-disk coordinates. The model was designed water-tight and filled up with distilled water functioning as the working fluid. The top- and bottom plates were 1 mm thick and provide optical access for the measurements through them. The disks were attached to a rotating shaft, which was further connected to a motor through belt mechanism with 1:2 gear ratio. The rotation of the motor was regulated with an uncertainty of 0.2 % by an encoder built in the motor.

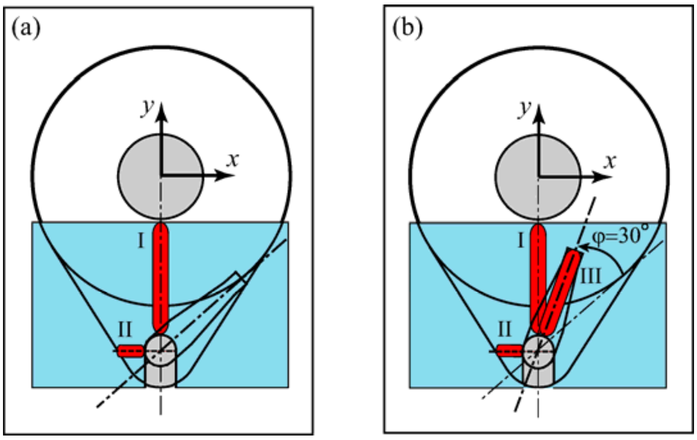

Fig. 3: Definitions of the coordinates and the measurement regions. (a) configuration 1, (b) configuration 2. The hatched area with light blue and red colors corresponds to the optical window at the model bottom and the measurement area of interest, respectively.

Velocity Profile Sensor

Flow measurements were performed with a laser Doppler velocity profile sensor. The details of the sensor can be found elsewhere on the principle (Czarske et al., 2002) and its measurement uncertainties (Czarske et al., 2002; Bayer et al., 2008). The sensor provides spatially high resolved velocity profile $v(z)$ of single tracer particles inside the measurement volume without strongly reducing its size. The sensor system employed in the present study was based on a frequency-division-multiplexing (FDM) technique which distinguishes the two fringe systems with two different carrier frequencies (Pfister et al., 2005). The fiber-optic measurement head had a working distance of about 400 mm in air. The dimensions of the measurement volume were approximately 100 µm and 570 µm in diameter and length in water, respectively. The scattering signals were detected in the forward direction slightly tilted with respect to the plane spanned by the laser beams. The detection volume was adapted to the length of the measurement volume using a proper set of lenses and a multi-mode fiber used guiding the optical signal to a photo-detector. The electrical signals from the photodetector were lead through electric circuits. The signals were down-mixed and separated into two channels corresponding to the two fringe systems. The resulting signals were fed through a hardware signal processor (FSA3500, TSI Inc.), which was used for filtering out the noise and for the amplification of the down-mixed signals. The output signals were digitized with a fast analogue/digital converter card built in a standard PC. Self-made software written in Matlab was used for controlling the data acquisition and further signal processing.

Measurement Conditions

The flow measurements were performed at the disk Reynolds number $Re_D=\Omega R_2^2/\nu=2.4\times10^5$ (Ω: angular velocity of the disk rotation), corresponding to 7700 rpm at a real 3.5” HDD throughout the experiment. At this Reynolds number, the flow should already be in fully turbulence state even without an RWA in an axisymmetric model (Herrero et al., 1999). The velocity measurement was undertaken in the region between the pair of disks (distance: D=2.45 mm). The spatial resolution of an LDV is not sufficient to resolve the boundary layer developing on the disk. The regions of interest in the x-y plane are depicted in Fig. 3. From the regions, we chose several radial locations listed in Tab. 1 and the measurements were performed at these locations along the axial direction. The coordinates are nondimensionalized in the way proposed by Schuler et al. (1990) using the radii of the spacer and the disk with $x^*=(x-R_1)/(R_2-R_1)$ and $y^*=\text{sign}(y)\cdot(\text{abs}(y)-R_1)/(R_2-R_1)$ respectively. The region I is along the line between the disk center and the RWA pivot, through which most of the fluid rotates with the disk rotation. The region II is in the bypass area along the line parallel to the *x*-axis passing through the RWA pivot. Small part of the fluid goes through this narrow region outside of the pivot. The region III is the one between the disks and the RWA inserted deep into the flow at φ=30°. The regions I and II are investigated at the two RWA angles φ=3.5° and 30°, which simulates two read-and-write positions of a real HDD. The measurement volume was traversed 6 or 7 times with partial overlaps of neighboring measurement volumes in order to cover the whole line without discontinuities. The traverse was done with a manual linear stage whose axial position being always monitored with a laser triangulation sensor (resolution: 0.5 µm). A typical configuration of the measurement is shown in Fig. 2. The laser beams went through the model perpendicular to the disks. Mono-dispersed particles made of polystyrene-polystyrol (density: ρ=1050 kg/m^3) were seeded into the model for the flow measurement. The mean diameter was 244 nm, which was measured with a dynamic light scattering technique. This diameter ensures the particle tractability to the flow up to a cut-off frequency at f_c=2.1 MHz with 0.1 % slippage at 20 °C. Typical validated data rate was around 20 Hz with an online processing method. It was not limited by the seeding concentration and can be increased further more.

Tab. 1: The list of measurement locations in the present experiment.

location	region	*x* [mm]	*y* [mm]	x^*	y^*	φ
1	I	0	-27.5	-0.496	-0.370	3.5°
2	I	0	-32.5	-0.496	-0.528	3.5°
3	I	0	-37.5	-0.496	-0.685	3.5°
4	I	0	-42.5	-0.496	-0.843	3.5°

The statistical measurement uncertainty of the sensor depends on the SNR (Bayer et al., 2008). The lower threshold of the SNR value was set at least 5 dB throughout the experiment for keeping the signal quality sufficiently high. The spatial resolution equivalent to the uncertainty of the position determination was 5.4 µm along 570 µm long measurement volume in the *z* axis in water at the typical SNR of 10 dB in the flow experiment. The resolutions in the other two directions are defined by the size of the volume, which is the beam diameter at the measurement volume. The relative uncertainty of velocity measurements was 0.1 % at the experiments. These values are theoretical estimate based on the method proposed by Bayer et al. (2008). The velocity statistics were calculated with an extended slot technique based on Shirai et al. (2006). Sufficient amount of the velocity-position pairs were acquired so that at least 2500 samples were contained in each slot with the width of 30 µm, which ensured the statistical convergence of the data in the slots. The statistical parameters of interest were the mean velocities *U*, *V*, their variances $\overline{uu}$, $\overline{vv}$ and Reynolds shear stress $\overline{uv}$. The flow velocities were measured with the beam plane aligned at three different rotating angles with respect to the *x* direction at the respective measurement locations. The rotating angles were set to α=0°, ±45°. From the measurement, the velocity statistics were calculated with an indirect method proposed by Tropea (1983).

Results and Discussions

The non-dimensional velocity statistics measured at the configuration 1 depicted in Fig. 3 (a) are plotted in Figs.4–6. They are shown along the axial direction at the four radial locations listed in Tab. 1. The axial positions are normalized with the local disk spacing *H* with zero set to the disk-to-disk middle plane. The mean velocities are normalized with the tangential velocity at the disk edge ΩR_2. The Reynolds stress components are normalized with the square of the disk edge velocity $(\Omega R_2)^2$. The statistical measurement uncertainties corresponding to standard deviation or variance are also plotted in the figures.

The normalized mean velocity U^* in Fig. 4 (a) exhibits a linear increase with the radial positions near the disk surfaces, which corresponds to the solid body rotation of the disk. The disk velocities at the corresponding locations are shown as the broken lines with the matched colors in Fig. 4 (a). The gradients of the mean velocities exhibit gradual decrease toward the disk surfaces, which is not consistent to the expectation of linear velocity gradient near the wall. The decrease of the velocity gradients was attributed to the signals originating from the disks. Such signals could not easily be separated from the ones from the tracers in the fluid. With the further increase of the radial position, the velocity in the central area of the disk spacing starts to deviate from the linear increase between the radial locations 2 and 3, and it even exhibits smaller values at the location 4. This is consistent with the existence of the large-scale vortex structures rotating with smaller velocities with the disk rotation in the marginal region. The mean velocity V^* in the y-direction in Fig. 4 (b) shows some scatters possibly due to the reconstruction of the measurement data acquired at the two different angles. The velocities exhibit negative values at all the locations. This is different from the case of an axisymmetric model, where the component exhibits radially inward flow in the central region between the disks. The difference was likely caused by the shroud opening, which allows the fluid to flow outward in the shroud opening region with the centrifugal force. Two velocity peaks are observed at each of the measurement locations and the velocity decreases nearer to the disks. The decrease corresponds to the boundary layers developing over the disk surfaces toward the disk edges, which is consistent to the case of an axisymmetric model.

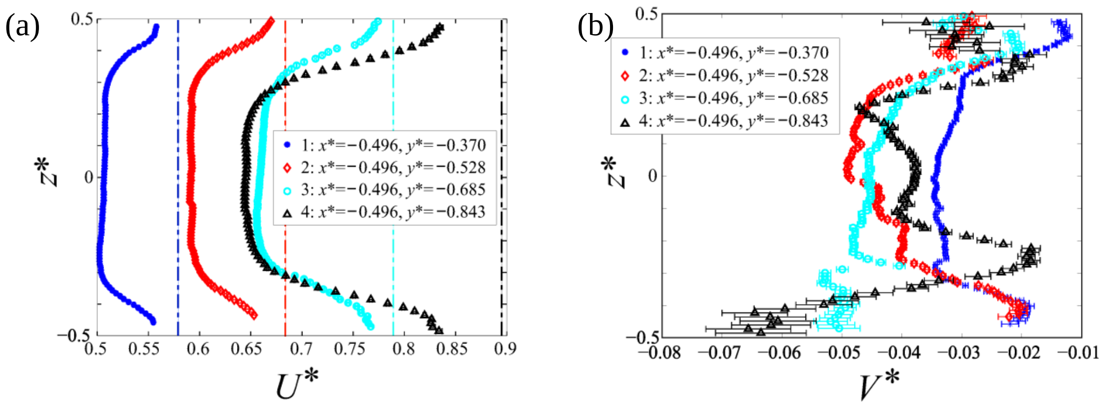

Fig. 4: Non-dimensionalized distributions of the mean velocities (a) U^* *and (b)* V^* along the four measurement locations at the configuration 1. The broken lines with the matched color in the (a) indicate the disk surface velocities at the respective measurement locations.

The Reynolds normal shear stress components $\overline{uu}^*$ and $\overline{vv}^*$ exhibit two peaks near the disks (Fig. 5). These peaks correspond to the high velocity gradients of the mean velocities near the disks shown in Figs. 4. The magnitude of $\overline{uu}^*$ shows good agreement with those measured with an LDV for an axisymmetric model (Schuler et al., 1990). The Reynolds shear stress $\overline{uv}^*$ in Fig. 6 also exhibits similar behaviors to the normal stress components. The shear stress has two peaks corresponding to the high velocity gradients in the mean velocities near the disks. The Reynolds stress components exhibit consistently higher values as the locations moves outward to the disk edge with the present non-dimensionalization method. The Reynolds stresses $\overline{vv}^*$ and $\overline{uv}^*$ reconstructed from the three single measurements have secondary outer peaks. This seems to be artifacts, which are likely caused by the non-perfect coincidence of the measurement locations at the three angles (α=0°, ±45°). The Reynolds stress components exhibit large uncertainty values near the disk surface, which should also be taken into account for interpreting the measurement results near the disk.

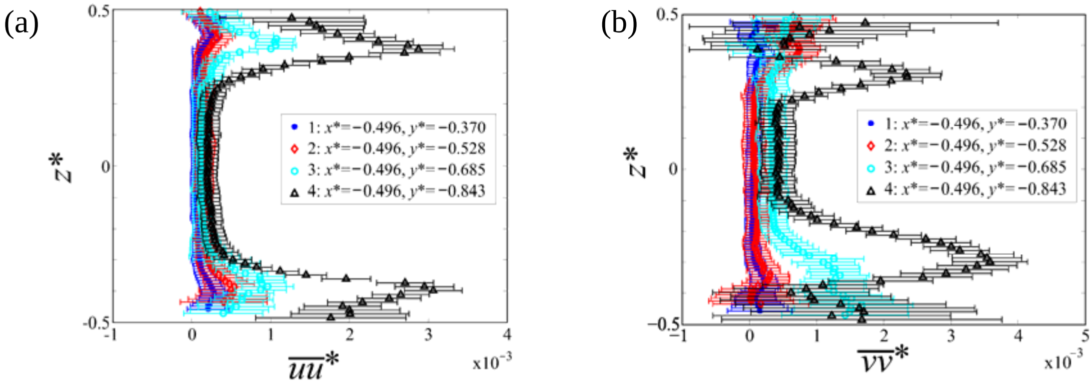

Fig. 5: Non-dimensionalized distributions of the velocity variances (a) $\overline{uu}^*$ and (b) $\overline{vv}^*$ along the four measurement locations at the configuration 1.

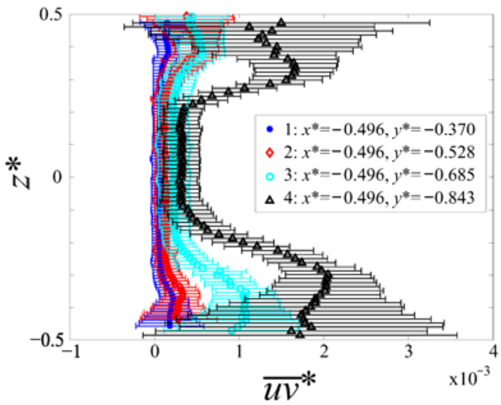

Fig. 6: Non-dimensionalized distribution of the Reynolds shear stress $\overline{uv}^*$ along the four measurement locations at the configuration 1.

Conclusions

The flow inside a HDD was investigated with a simplified experimental model with the shroud opening and the RWA. The model serves as a benchmark for both experimental and numerical investigations of a HDD. The complex behaviors of the flow near the RWA with the shroud opening were focused in the present investigation. We applied the laser Doppler velocity profile sensor in order to achieve the high spatial resolution required to resolve the highly sheared flow in the small dimensions in the region. The sensor had typically a physical spatial resolution of 5 µm in the direction perpendicular to the disk, which was necessary to resolve the highly sheared flow in the small dimensions. The velocity statistics including the mean velocities and Reynolds stress components were obtained with the resulting spatial resolution of 30 µm x 100 µm x 100 µm using the slot technique.

We presented the first results in one of the three regions of interest in the model. The results exhibited large velocity gradients near the disk surface. The velocities measured in the model with the shroud opening exhibited the different behaviors in the radial direction from those observed in an axisymmetric model.

Currently the remaining two regions in the flow bypass and in the region around the RWA are under study. The investigation of the flow velocities between the RWA and the disks, where measurement remains difficult with any other measurement technique, is of special interest. The axial displacement of the disks and its influence on the flow behaviors are also under examination with a chromatic confocal sensor. The emphasis is placed on the acquisition of quality data with the known boundary condition including the disk deflection. The data would serve as benchmark for the numerical simulations undergoing with the experiment.

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