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Aerodynamic Aspects of Disk Files

Abstract: Airflows between centrally clamped, rotating, rigid disks are investigated with respect to the type of flow pattern, the parameters that influence nonuniform flow, and the effects of various flow patterns on disk stability. The experimental method uses a waterflow modeling technique for the airflow. The observed flow patterns are highly unsteady. The configuration and position of the shroud and slider arm are found to be the major parameters that influence flow characteristics. A reduction of disk flutter by a factor of 12 can be achieved when the unsteady flow pattern is changed to a steady flow pattern.

Introduction

Read-write operations in random access disk storage devices are performed by transducers mounted on hydrodynamic slider bearings. High linear bit densities, high track densities, and reliability of operation require not only an extremely low slider flying height but also a good compliance between disk and slider axial motions.

Disk surface finish, flatness, and dynamic stability are usually considered to be the most critical mechanical parameters. However, aerodynamic influences are also critical, and airflow is responsible for two separate effects:

1. *The flow around spinning disks creates mechanical problems.* Any kind of large-scale unsteady flow or pressure fluctuation is a random excitation source for the vibration of disk and slider-arm suspension. An excited disk or a fluttering slider arm causes nonrepeatable relative motions between the read-write head and the recorded data tracks, thereby introducing off-track errors. Severe disk flutter causes data losses that are due to slider-disk interference or slider crashes.
2. *The flow around spinning disks creates thermodynamic problems.* Any nonuniform flow characteristic in the gap between disks represents a nonuniform transfer of friction-generated heat along the disk radius and the disk-pack axis. Thermal expansion gradients cause data losses that are due to inaccuracies of head position.

The flow characteristic, then, is a common cause of both mechanical and thermodynamic effects. Detailed knowledge of the parameters that influence nonuniform flow is required for an adequate understanding of those effects. Unsteady flows are of particular interest.

An experimental investigation is reported in this paper to provide a qualitative description of the basic flow patterns. In addition, quantitative measurements of axial disk motion show the influence of the various flow patterns on rotation stability of a rigid disk.

Basic disk configurations

Basic configurations of interest for various applications can be categorized in the three groups illustrated in Fig. 1: single disks, corotating disks, and centrally clamped disks.

The applications usually require a stationary shroud around the spinning disks for air ducting purposes. Turbomachinery designers have a particular interest in the aerodynamic aspects of disks. Therefore torque losses, reduced efficiency and heat transfer have been the major concerns in the literature on disk aerodynamics. A number of papers have been devoted to these characteristics of both single and multiple disks [1-26].

• *Flow pattern: single disk*

The basic flow around a single disk is symmetric, as illustrated in Fig. 2. The laminar and turbulent flow regimes are characterized by a dimensionless Reynolds number for the disk, $R_d = \omega r^2/\nu$, where ω is the angular velocity, r the disk radius, and ν the kinematic viscosity. Previous investigators [1-15] have extensively analyzed the single-disk system with respect to torque characteristics and heat transfer. Because of the symmetry of the problem, a complete solution of the three-dimensional Navier-Stokes equations is possible for the laminar case. A numerical approximation of the set of differential equations has been carried out by von Karman [7]. The computed torques agreed well with experimental data up

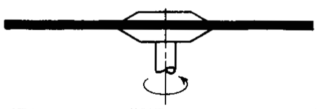
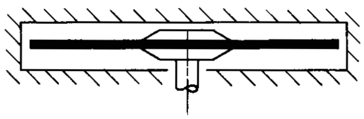
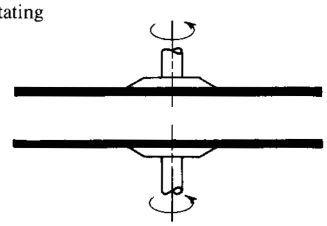
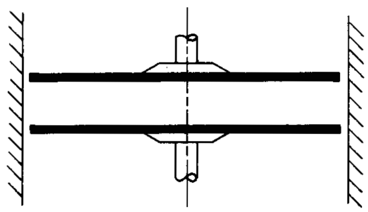
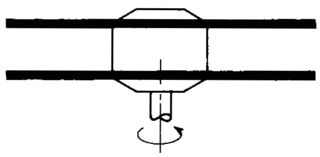
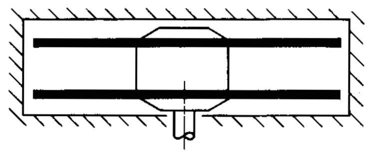
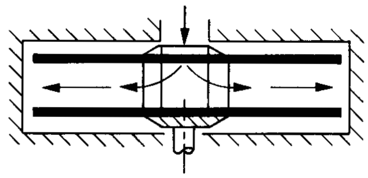
Free disks	Shrouds	Applications	Refs.
Single 		Single disk DASD Axial compressors Axial turbines	[1-15] [27-34]
Corotating 		Axial compressors Axial turbines	[17-26]
Centrally clamped 		DASD disk pack	
		Disk pump/turbines vaneless, radial diffusor	[35-39]

Figure 1 Basic configurations of single, corotating, and centrally clamped disks.

to a disk Reynolds number of 3×10^5. For the turbulent case a 1/7 power law was assumed for the boundary layer and gave good experimental agreement. Approximate methods for computing the heat transfer of the disks are available [1, 8]. Except for the case where sidewalls extend beyond the disk rim [16], no unsteady flow phenomena have been reported.

• *Flow pattern: multiple disks*
The flow around multiple disks has to be divided into two separate areas, as shown in Fig. 3: the flow over the outer disk surfaces and the gap flow.

The flow over the outer disk surfaces is similar to that for the single disk. The gap flow has a zone of recirculation, and fluid moves out of the gap along the disk because of angular acceleration and centrifugal forces. The outflow generates a radial pressure gradient. Fluid moves from near the disk into the gap. For double disks the Reynolds number is defined in a manner such that the disk spacing is taken into account by

$$R_s = \omega r s/\nu,$$

where s is the disk spacing.

There are two aerodynamic differences between corotating and centrally clamped multiple disks: 1) There is additional momentum transfer from the spacing ring to the fluid, and 2) there is no pressure gradient balance across the axis of rotation. Corotating disks have been studied by several authors [17-26]. The major feature of the flow between two disks is the formation of a central core of fluid rotating at a slightly lower speed than the disks. The measured torque agrees well with computations from the single-disk theory for high-spacing Reynolds numbers only (e.g., 5×10^5), i.e., for large disk spacings. Unsteady flow patterns have not been reported.

Centrally clamped disks with or without a shroud and a narrow spacing have not yet been analyzed. This configuration, however, is of particular interest to designers of direct-access disk storage devices. In Table 1 the comparison of characteristic values of reported corotating and centrally clamped disks shows that the disk Reynolds numbers are of the same order of magnitude. The spacing Reynolds numbers, as well as the spacing-to-diameter ratios, however, are one order of magnitude lower in the case of centrally clamped disks for disk-file applications.

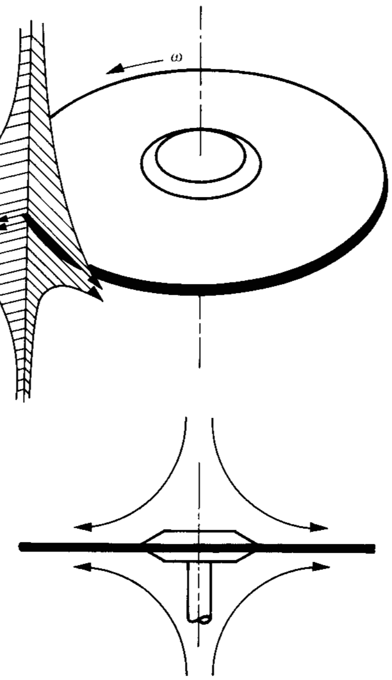
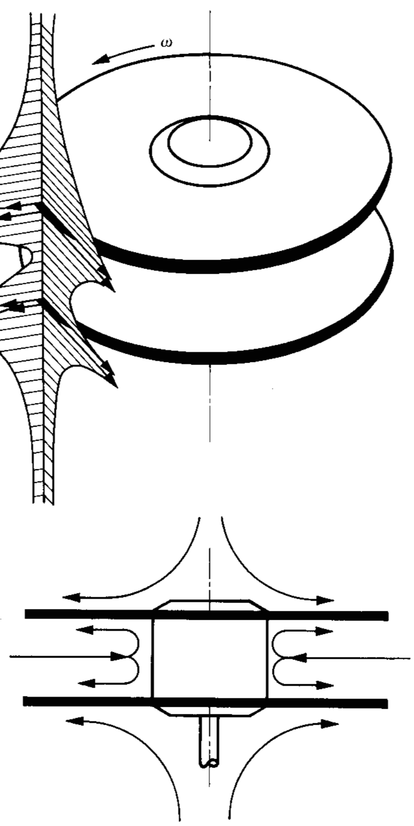


Figure 2 General configuration of flow patterns around a single disk.

Figure 3 General configuration of flow patterns around a double disk, showing the flow over the outer surface and the flow within the gap.



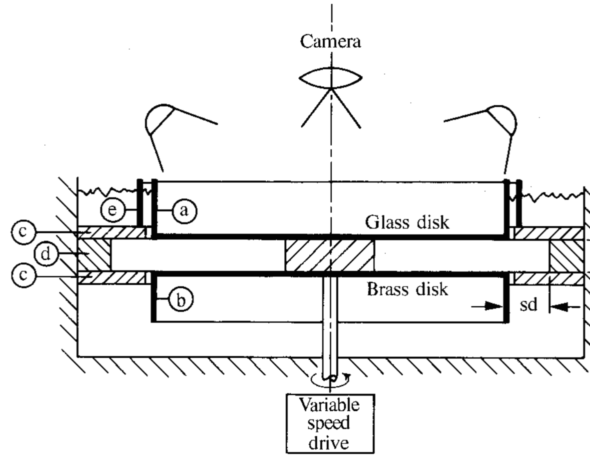


Figure 4 Experimental apparatus for water tank simulation of airflow patterns.

Experimental technique

Laminar and macroscale or microscale turbulent flows require distinctly different analysis methods to obtain a reliable physical interpretation of the flow characteristic. The type of flow has to be known before any quantitative analysis can be undertaken. The objective of this part of the investigation is to determine qualitatively the type of flow and the geometric boundary conditions for steady and unsteady flows.

Common experimental techniques for airflow visualization include wool tufts, smoke tracers, and electric arc tracers. These techniques have the disadvantage that they do not easily provide detailed information about macroscale flow patterns, i.e., separated flows. Response time and/or space resolution are not sufficient. This resolution, however, is achieved when the airflow is simulated by an aerodynamically equivalent water-flow model. The equivalence is obtained by maintaining the same spacing Reynolds number for both flows. Compressibility effects can be neglected because the disk Mach number in air is 0.19 and in water 0.03, both very low.

The flow pattern can be made visible and recorded either by the hydrogen bubble technique or by the use of neutral-density beads or suspended aluminum powder particles. Ease of operation and simplicity of test configuration led to the choice of aluminum powder.

The experimental setup consists of a brass disk clamped to a glass disk and submerged in a water tank, as shown in Fig. 4. A sheet metal retaining ring (a) is fitted to the glass disk to keep water away from the surface and therefore to provide an undisturbed view. To achieve symmetric boundary conditions at the disk rims, a retaining ring (b) is fitted to the bottom disk as well. Two acrylic glass plates (c), spaced by a ring (d), form

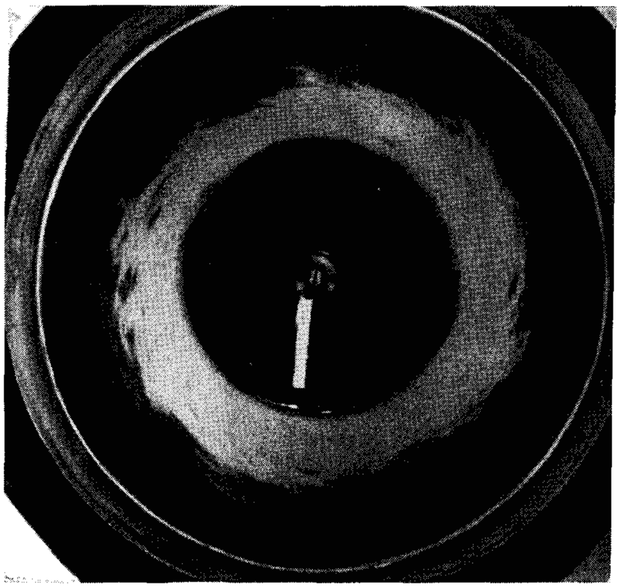


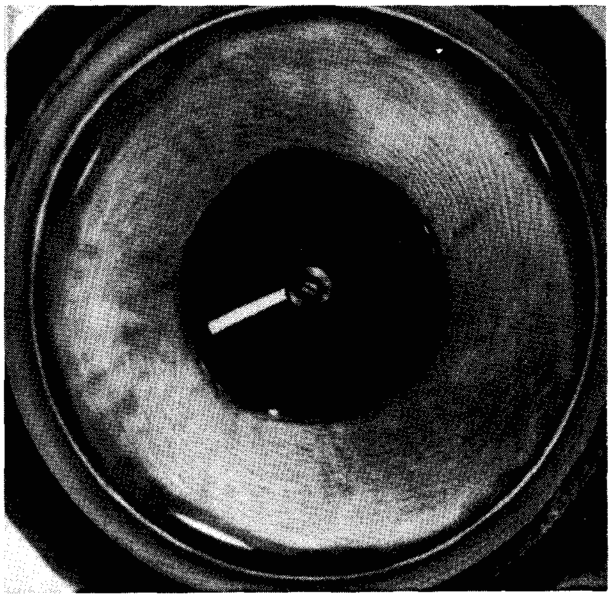
Figure 5 Flow pattern as the disk starts to rotate.

a shroud around the disks. A stationary retaining ring (e) stabilizes the water surface in the tank and prevents air from being sucked into the shroud region. The events are recorded by a medium-speed movie camera. The parameters that are varied are disk spacing, shroud spacing, and simulated type of slider arm.

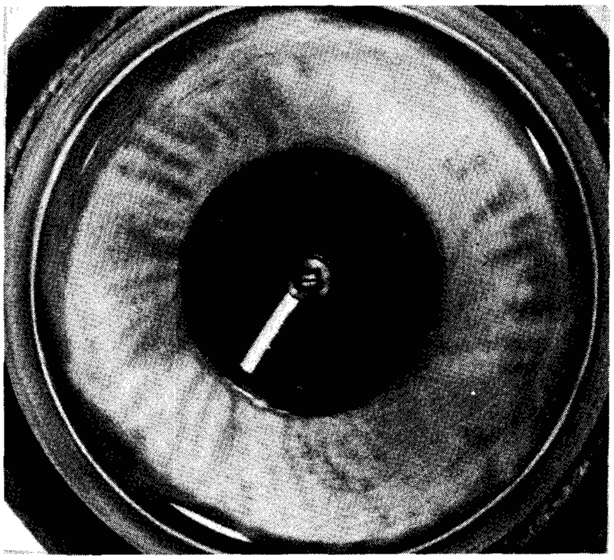
Results and discussion

• *Disk startup*

While the disks are at rest, the aluminum particles settle on the lower disk. When the disk starts to rotate, the aluminum particles in the boundary layer disperse because of increasing shear stress. Disturbances occur at the outer diameter and move rapidly, as a disturbance front, toward the center of the disk. Local instabilities can be observed ahead of the disturbance front, as shown in Fig. 5.



(a)



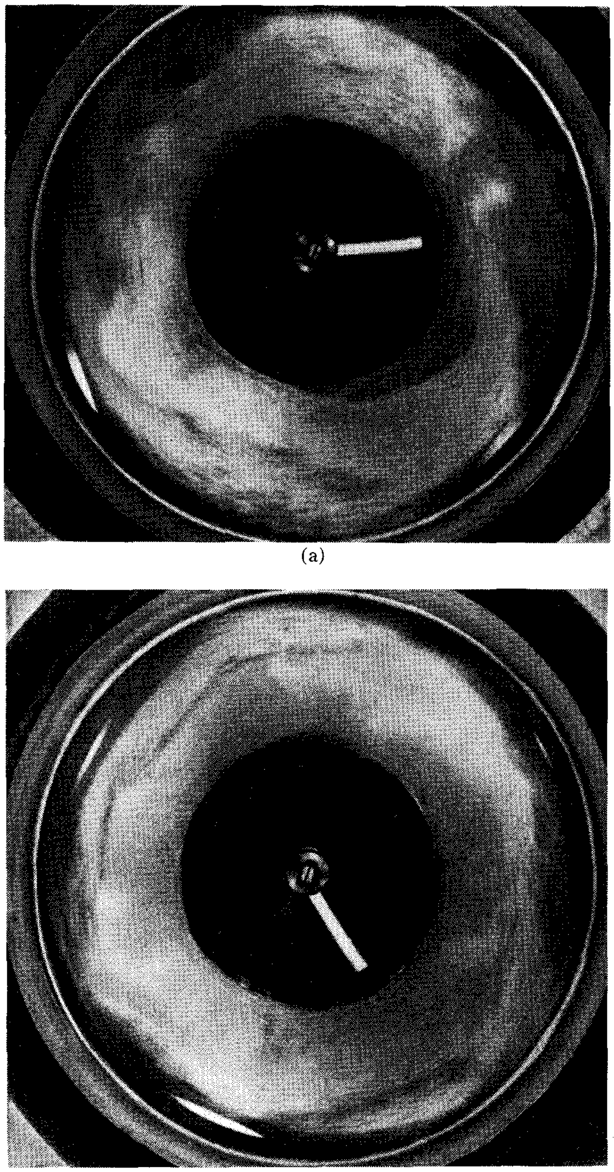
(b)

Figure 6 Flow transitions. (a) Laminar to turbulent; (b) turbulent to laminar.

Table 1. Comparison of characteristic published values of corotating and centrally clamped disks.

Rpm	*Diameter d (mm)*	*Spacing s (mm)*	*s/d*	*Disk Reynolds number* ($R_d = \omega r^2/\nu$)	*Spacing Reynolds number* ($R_s = \omega rs/\nu$)
*710	457.0	101	0.221	2.49×10^5	1.19×10^5
*2040	457.0	203	0.441	7.31×10^5	6.44×10^5
†3600	355.6	7.62	0.0214	7.89×10^5	3.39×10^4

*Corotating disk. See reference [26]
†Clamped disk. Direct access storage device



(a)

(b)

Figure 7 Flow patterns as affected by shroud spacing. (a) Large spacing; (b) small spacing.

At a disk Reynolds number of approximately 8.1×10^5, a flow pattern is generated that can be characterized by streaks in the form of the equiangular spirals illustrated in Fig. 6(a). The flow pattern extends over the whole disk surface.

Gregory, et al. [5] observed a similar pattern when using the china clay method for analyzing the boundary layer of a free-spinning single disk. The flow pattern represents the transition region from laminar to turbulent flow when stationary rows of vortices lie in the boundary layer. A mathematical analysis explained the vortex generation as being a result of three-dimensional instabilities.

With increasing rotational speed the equiangular spirals are interrupted by radial streaks as in Fig. 6(b), which may represent a flow transition from turbulent to laminar flow.

The flow patterns at the design speed depend on the shroud-to-disk spacing. With a large spacing, typical in the design of current disk files, the gap flow pattern can be described by an egg-shaped rotating central core with highly turbulent outer regions. The central core is intermittently interrupted by large vortices which are shed from the spacing ring [Fig. 7(a)]. With decreasing shroud distance the core shape changes to a "dented" circle [Fig. 7(b)].

The observed flow pattern development during startup differs in some aspects from the previously reported single-disk results:

1. The flow patterns can not be held constant with time. They are transient phenomema.
2. The transition from laminar to turbulent flow takes place at a higher disk Reynolds number, i.e., 8×10^5 compared with 2.8×10^5.

The differences can be explained qualitatively in the following way: At the start, the flow between the disks is laminar. With increasing rotation and shear stress, the flow becomes unstable in the vicinity of the wall. At the same time the fluid body gains rotational momentum. The shear stress is reduced and the boundary layer reverts to laminar flow. The start of the solid body rotation of the gap flow increases the transition Reynolds number.

• *Disks at design speed*

The flow patterns shown in Fig. 8 are the result of an interaction between gap flow and surrounding fluid. The interaction is twofold:

1. There is a shear stress because of rotational velocity difference.
2. A pressure balance exists, due to a radial pressure gradient.

The radial pressure balancing occurs in a strong pulsating mode, thus generating an indented shape of the corotating center core, as shown in Fig. 8. The core rotates at approximately 0.8 times the disk speed. In the absolute reference frame, the indented core flow represents an unsteady flow and therefore a source of aerodynamic excitation of the disk and slider arm flutter. The existence of such a flow pattern immediately identifies a cooling problem for rotating multiple disks: Because there is very little mass transfer out of the rotating core, there is also very little convective heat transfer.

Parametric modeling for disks at constant design speed shows that the number of dents increases with decreasing disk-edge-to-shroud spacing. The average core diameter increases with decreasing disk-to-disk and disk-to-shroud spacing.

• *Influence of slider arm*

The influence of the slider arm on the flow pattern is simulated by inserting a beam with rectangular cross section between the disks, as indicated in Fig. 9. The flow pattern changes completely, depending on the radial position of the arm. The dents of the center core disappear when the arm is positioned in the outer gap flow region. A strong vortex sheet is shed from the arm tip, which represents an excitation source for slider-arm flutter. The core still rotates with approximately the disk speed.

Four different flow regions can be distinguished in Fig. 10:

1. Turbulent wake region behind the arm (a).
2. Relaminarized region downstream of the arm as the gap flow returns to solid body rotation (b).
3. Turbulent region upstream of the arm due to direction change of flow (c).
4. Vortex sheet shed from the arm tip (d).

The vortex sheet and the rotating central core disappear when the arm is positioned close to the spacing ring. The flow pattern becomes steady and homogeneous.

The flow visualization results show that quite a variety of flow patterns exists between centrally clamped disks. The disk-to-shroud spacing and radial position of the slider arm are the major geometric parameters.

Influence of flow patterns on disk vibration excitation

Disk vibration excitation, or disk flutter amplitude, is defined as the amount of axial dynamic runout noise that is superimposed on the axial disk runout because of disk flatness and clamping. It is measured with an inductance transducer at the disk rim and integrated over 90 revolutions.

Natural frequencies and corresponding vibration modes of the rotating disk were determined beforehand to ensure resonance-free test conditions and to detect the possibility of resonance excitation due to periodic frequencies. Axial disk runout frequency and harmonics did not coincide with any resonance mode. Periodic frequencies could not be detected in the disk flutter signals. Hence the unsteady flow patterns have to be considered as a nonperiodic excitation for disk flutter.

Figure 11 shows the axial dynamic runout noise as a function of various geometric parameters. The runout noise is made dimensionless by the disk radius.

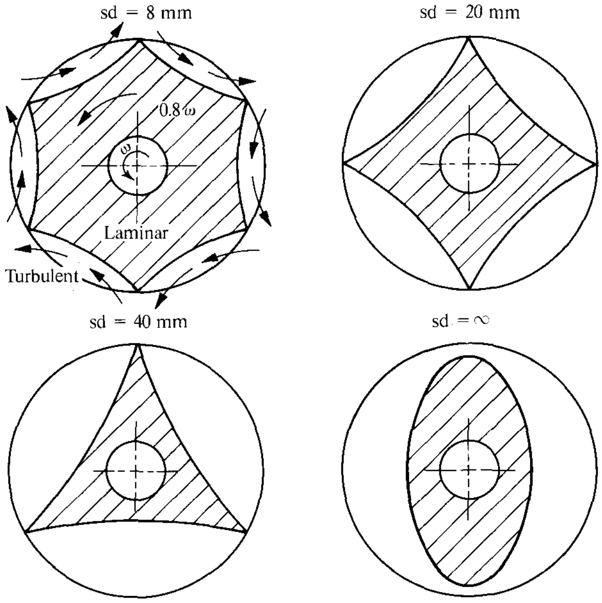
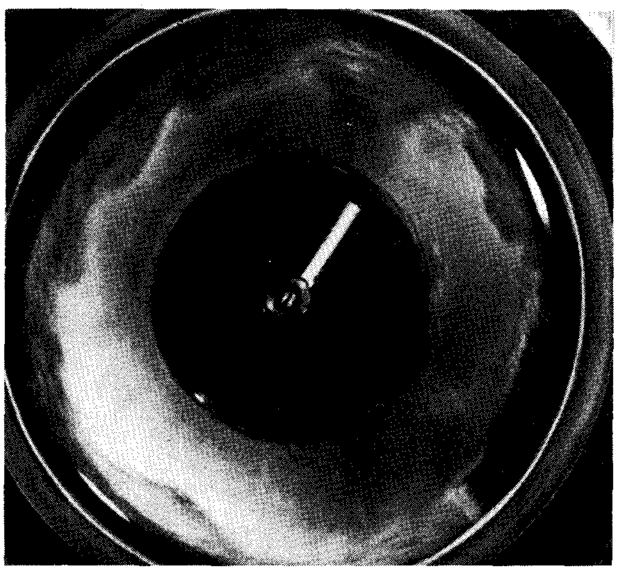


Figure 8 Basic flow patterns showing how the central core varies in shape according to shroud-to-disk spacing sd.



Arm

Figure 9 Effect of simulated slider arm on flow pattern.

Disk flutter increases by a factor of five when two single disks are mounted in a disk pack. The increase at (a), Fig. 11, is caused by unsteady flows generated between two disks. This configuration does not constitute the worst-case condition, because each disk is excited only from one side. However, the double-disk configuration provides a good understanding of the effect of an isolated gap when various gap conditions are compared with the observed flow patterns.

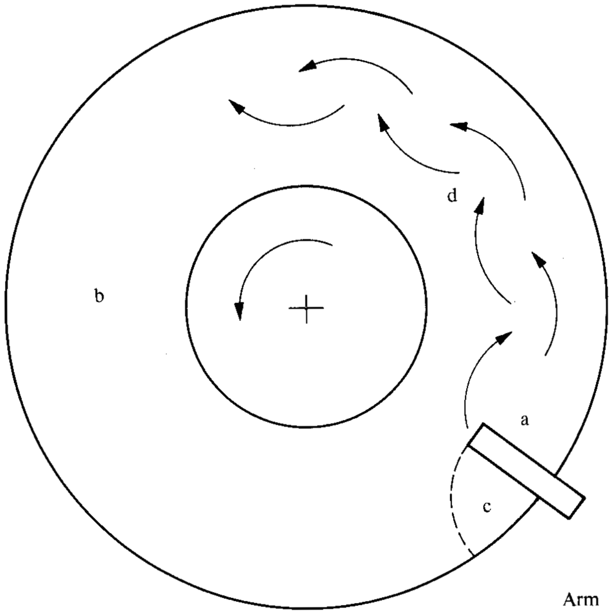
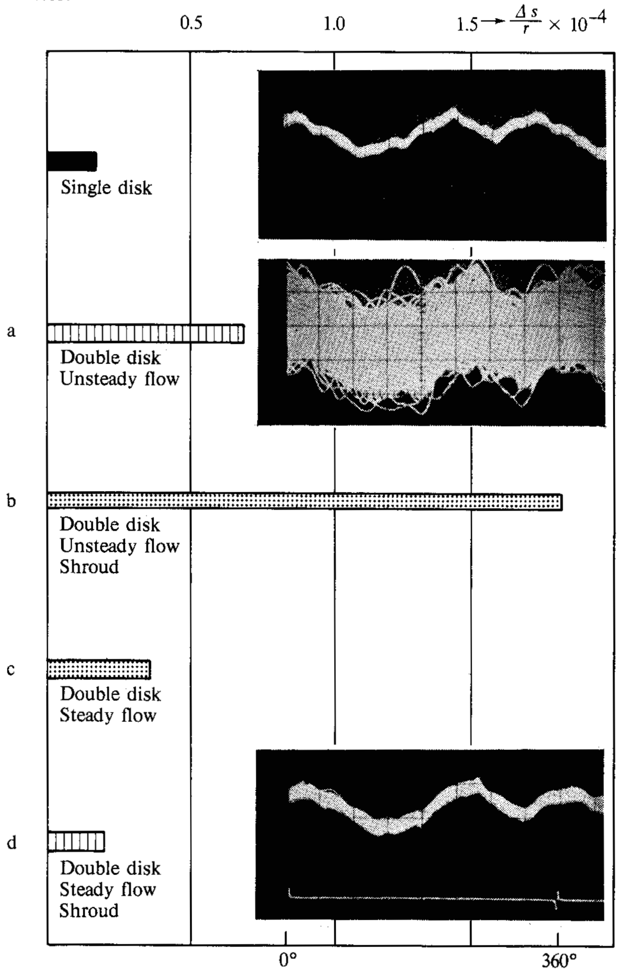


Figure 10 Basic change in flow pattern due to presence of slider arm.

Figure 11 Effects of geometric parameter variations on disk flutter.



A very large increase in disk flutter by a factor of 12 occurs when the disk pack is partially covered by a narrowly spaced coaxial shroud (b). (The space between disk and shroud is 1 mm.) When this rather unexpected effect of the shroud is correlated with the observations made in the watertank simulation, the following physical explanation is obtained.

When a shroud is not used, the velocity differences between outflowing and surrounding fluids cause a rapid turbulent mixing associated with energy dissipation. The rest of the kinetic energy is changed to potential energy: the static pressure increases. Because the gap flow is unsteady, the static pressure must fluctuate, and hence the disks flutter. When the disks are partially covered by a narrowly spaced coaxial shroud, the mixing losses are significantly reduced and the static pressure increases. Since unsteady flows are present, the shroud attenuates disk flutter because of larger pressure fluctuations concentrated at the outer diameter of the disk.

Flutter of a double disk is reduced from a factor of 5 to 2.5 as compared to that of single disks when the simulated slider arm is positioned close to the spacing ring (c). The slider arm acts as a spoiler, which forces the fluid out of the gap area and prevents development of unsteady flows. A further reduction to a factor of 1.25 is experienced when a combination of spoiler and narrow shroud is used (d). In the absence of unsteady flows a shroud reduces disk flutter by reducing the generation of large-scale turbulence at the disk rim, known as the edge effect.

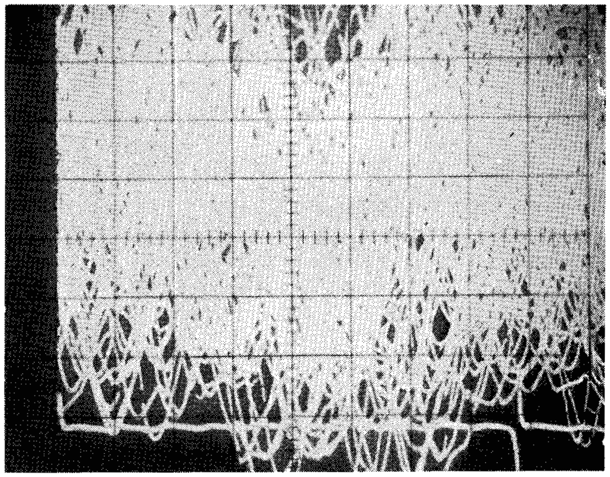
When more than two disks are mounted in a disk pack, the disk flutter increases by a factor of 22 for those disks that are excited from both sides, as illustrated in Fig. 12. The significant influence of the gap flow characteristic on disk stability is demonstrated when the unsteady flow pattern is changed to a steady flow pattern by the action of the spoiler and the shroud. Disk flutter then is reduced by a factor of 12.

Conclusions

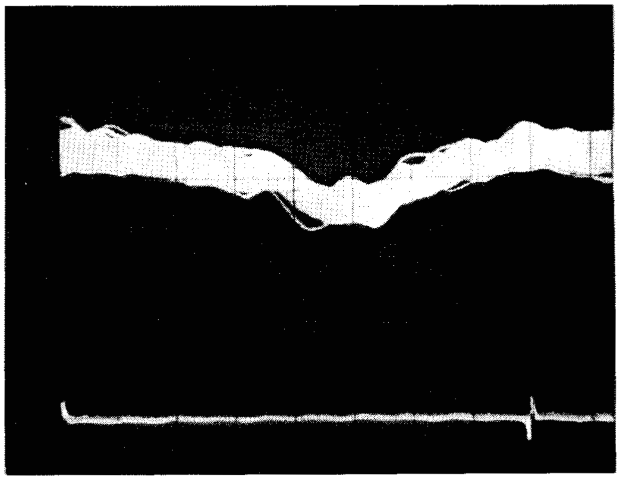
This experimental study of the airflow between centrally clamped rotating disks, using a waterflow modeling method, has identified flow patterns and the main physical parameters that influence turbulent flow. The findings may be summarized as follows.

1. The flow characteristic between centrally clamped and narrowly spaced disks can be described by a laminar, dented central core that is symmetrical about the axis of rotation. The outer regions are highly turbulent.
2. The core rotates at a slightly lower speed than the disks and represents an unsteady flow in the absolute reference frame.

3. Unsteady flow is an excitation source for disk flutter: when single disks are mounted in a disk pack, disk flutter increases by a factor of five for two disks, up to 22 for more than two disks.
4. The flow characteristic is strongly influenced by disk-pack-to-shroud distance and by slider arm position.
5. When an unsteady flow pattern is present, a narrow shroud increases disk flutter.
6. When a steady flow pattern is present, a narrow shroud reduces disk flutter.
7. Disk flutter in a disk pack can be reduced by a factor of 12 when steady flow patterns are achieved.
8. A spoiler between disks prevents development of unsteady flows. The stabilized and homogeneous flow reduces disk flutter and improves cooling of the disks.



Unsteady flow



Steady flow

Figure 12 Measurements of disk flutter in a disk pack, showing stabilizing influence of spoiler and shroud.

Acknowledgment

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Single disks

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Double disks

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• *Enclosed disks*

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