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Study on the Structures of Fluid Flows in the Annular Space Formed by a Submerged Tilting Pad Journal Bearing

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Abstract : In this study, the Taylor vortices of the film flow in the bearing clearance and so-called cavity flow between pads in a submerged tilting pad journal bearing were visualized by means of a tracer method. The effects of pad arc extent and pad inclination (from leading to trailing edges) on fluid flows, especially on the structures of Taylor vortices and cavity flow were investigated. The critical Taylor number of the film flow increased with an increase in pad inclination slightly. The pitch of array of the Taylor vortex rings at the critical Taylor number was, however, scarcely influenced by the pad inclination. The pitch was likely fixed by the mean clearance over the pad. Two-dimensional cavity flow field (in the central section perpendicular to the rotation axis) between pads was measured by a Particle Image Velocimetry to investigate the interaction of film flow and cavity flow between pads. The Taylor vortices out of the preceding pad were almost carried over the cavity region into succeeding pad, and hardly mixed with the cavity flow. This phenomenon is important in relation to the oil exchange between the film and cavity flows.

Keywords : Tilting pad journal bearing, Taylor vortex, Film flow, Cavity flow, Particle Image Velocimetry.

Nomenclature :

C	nominal bearing clearance, Fig. 1
L	axial length of the pad
P	pitch of array of vortex rings (axial height of one vortex ring)
P^*	pitch of array of vortex rings for the corresponding fully circular bearing
R	radius of the shaft (journal), Fig. 1
Re	Reynolds number of the film flow, $Re = R\omega C/\nu$
Ta	Taylor number of the film flow, $Ta = Re\sqrt{C/R}$
Ta_c	critical Taylor number of the film flow
Ta_c^*	critical Taylor number of the film flow for the corresponding full circular bearing
h_{in}	bearing clearance at the leading edge of the pad, Fig. 1
h_{out}	bearing clearance at the trailing edge of the pad, Fig. 1
r_p	radius of curvature of the bearing pad, Fig. 1

α	pad inclination, h_{in} / h_{out}
θ_p	angular extent of the pad, Fig. 1
θ_s	angular extent of the cavity portion, Fig. 1
ν	kinematic viscosity of the lubricating fluid
ω	angular speed of the shaft (journal) rotation, Fig. 1

1. Introduction

Taylor vortices between two rotating cylinders have been discussed by many researchers, originated by Taylor (Taylor, 1923), as one of interesting problems of flow stability in hydrodynamics. These vortices have been also investigated for high-speed applications of hydrodynamic journal bearings (e.g., Short and Jackson, 1975). It will, in such applications, also be interesting to suppress the vortices with some agent in the lubricating fluid such as a surfactant (e. g., Watanabe, Takayama and Ogata, 2004). In many cases, however, both of inner and outer cylinders subjected to the study are fully circular and plain without any axial grooves or cavities.

The present authors are interested in the effect of discontinuity in the cylinder surface just like multi-pad or partial arc journal bearings and/or axially grooved bearings on the appearance of Taylor vortices. They have already investigated the cases in which inner cylinder is plain and rotating and outer cylinder is at rest and has deep cavities just like a multi-pad journal bearing and/or a partial arc journal bearing, and have observed some interesting phenomena, for example the Taylor vortices originated in the pad clearance space were carried over the cavity region as if the bearing surface was fully circular without any grooves or cavities (Noma and Mori, 2001).

In the previous study (Noma and Mori, 2003), for the flow between rotating shaft and padded cylinder like a partial arc journal bearing accompanying a very wide cavity region, the critical Taylor numbers of the film flow in the (pad) bearing clearance space and of the cavity flow were evaluated with changing the angular extent of the cavity portion and the angular extent of the pad. When the angular extent of the cavity portion became large and that of the pad became small, three types of phenomena were found. In the first type, the Taylor vortices of large pitch which were originated in the cavity region were held throughout both regions of cavity and bearing clearance space. In the second type, the vortices of large pitch in the cavity region changed into vortices of small pitch corresponded to the bearing clearance when flowing through the bearing clearance space, and downstream the pad the latter returned to the former. In the third type, the vortices of small pitch corresponded to the bearing clearance were held throughout both regions.

In the cases mentioned above, the shaft and pad surfaces were parallel and did not form so-called converging wedge, so that no pressure might be generated in the bearing clearance space of the pad. On the contrary to those cases, from a practical viewpoint, the present study is focused on the flow field in the multi-pad journal bearing, each pad of which is inclined to form a converging wedge yielding the pressure generation.

To simplify the flow field, the inner cylinder i.e., the shaft (journal) is supported vertically by equally spaced, inclined four pads without any external load, just like a tilting pad guide bearing used for a big vertical water turbine. The pressure is, of course, generated in the bearing clearance space of each pad to yield the bearing stiffness resulting stable operation of the system. In the bearing clearance space, therefore, Poiseuille flow coexists with Couette flow. Around the leading edge of each pad, reverse flow region appears with an increase in pressure generation when the pad inclination becomes large. The axes of Taylor vortices in the film flow which rotate in alternately opposite directions are located along the circumference of the shaft surface, whereas the axis of circulation of so-called cavity flow is located in each cavity portion parallel to the shaft axis.

It is very important to clarify the effect of Taylor vortices on the interaction of film flow within the bearing clearance space and cavity flow between pads, in relation to carry over of lubricating oil sheared and heated in the bearing clearance of the preceding pad (Kimura, 2006). This will be examined experimentally. First of all, the experiment will be carried out to clarify the structures of Taylor vortices by means of a tracer method under the condition of pressure generation with regard to the effects of pad inclination and pad arc extent on the critical Taylor number at which the Taylor vortices appear first in the bearing clearance space and also on the structure of vortices. Secondly, two-dimensional cavity flow field (in the central section perpendicular to the rotation axis) between pads will be measured by a Particle Image Velocimetry (PIV) to investigate the interaction of film and cavity flows between pads in relation to the effects of pad inclination and pad angular extent on the interaction.

2. Experimental Apparatus and Procedure

Basic constitution of the experimental apparatus is the same as the previous study (Noma and Mori, 2001). The top view of the pad arrangement is shown in Fig. 1. Four transparent acrylic circular arc pads are equally spaced around the aluminum rotary shaft in the transparent acrylic cylindrical housing. Radius of curvature, r_p, of the bearing surface of each pad is machined just equal to the sum of shaft radius, R, and nominal bearing clearance, C. The aluminum shaft is rotated by an electric motor of variable speed.

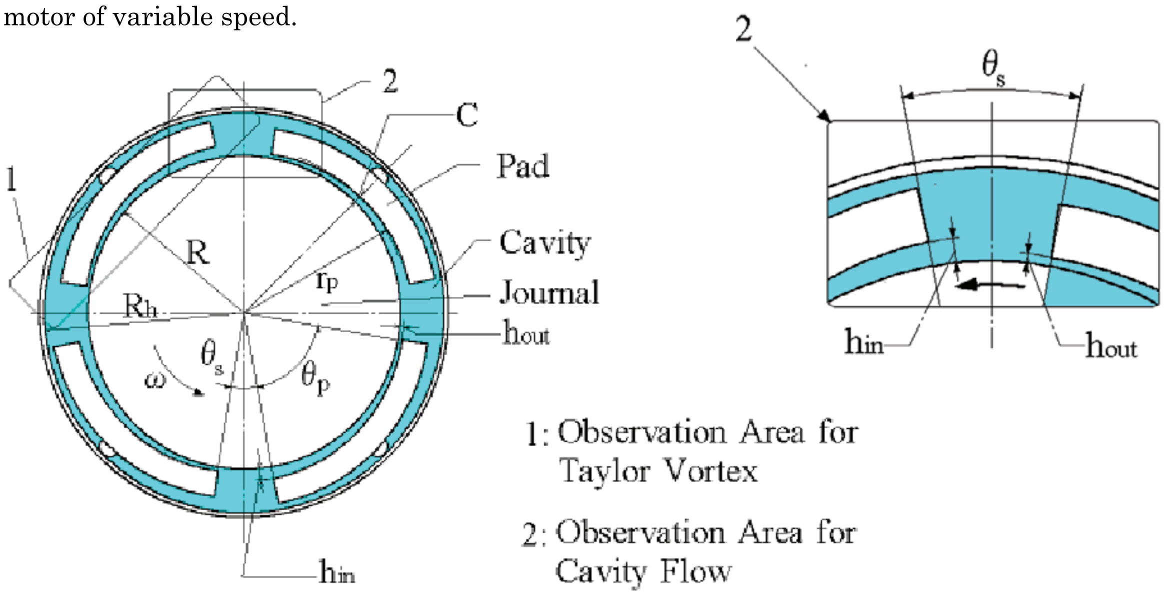


Fig. 1. Experimental apparatus.

Main dimensions and experimental conditions are shown in Table 1. The nominal bearing clearance, C, is set at the pad center, so that $C = r_p - R$. The value of C becomes 4.5 mm, and the clearance ratio, C/R, becomes 0.047. This is ten times larger than actual journal bearings even for a high speed application where the clearance ratio may be set much larger than that of a low speed application. The reason why such a large clearance ratio is set in the present study is to realize visualization of Taylor vortices at very low rotational speeds, restricting the pressure and heat generation small enough not to yield unfavorable distortions both in the pads and housing which are made of transparent acrylic resin. Though the smaller clearance ratio than the present study can narrow down the range of Taylor vortex flow regime, similarity could be held for an actual high speed bearing of somewhat large clearance ratio, unless its clearance ratio is set so small that the shear flow may suddenly be plunged into the turbulent regime without Taylor vortices.

In the case of actual tilting pad journal bearings accompanying high pressure generation, the inclination of each pad, h_{in} / h_{out}, is automatically held correspond to the pivot location. However, in the present study, it is fixed to a certain value a prior to ensure stable operation at low speeds.

Tap water is used as the lubricating fluid and aluminum powder (particle diameter is less than 43 μm) is used as the tracer. The top end plate made of transparent acrylic resin is set to avoid end effects due to the free surface and also to visualize the cavity flow from the top. The experiment is performed at room temperature. Because of very low frictional heating, variation of temperature of the lubricant water was found to be within ±0.1 K during one test run.

The observation areas are shown in Fig. 1. The visualized section in the observation area (1) is a partial cylinder along the shaft surface and the visualized section in the observation area (2) is a mid-plane perpendicular to the shaft axis. Visualization in those sections is realized by two kinds of halogen light sheets, cylindrical and flat. Visualized images are recorded in a digital VCR (30 frames/sec) and transferred to an image processing board on PC. Mean velocity vectors are calculated by means of a commercial PIV software, Flow-vec32.

Origination and change of the structure of Taylor vortices are observed in the observation area (1). The structure of the cavity flow and the interaction between this and Taylor vortices are visualized in the observation area (2).

Table 1. Main dimensions and experimental conditions.

Radius of the shaft, R [mm]		95.5
Speed of the shaft rotation, N [rpm]		0.7 ～ 40.0
Nominal bearing clearance, C [mm]		4.5
Pad	Angular arc extent, θ_p [degree]	70, 80
	Axial length, L [mm]	110.0
	Radius of curvature, r_p [mm]	100.0
	Inclination, $\alpha = h_{in}/h_{out}$	2.0 ～ 3.0
Inner radius of the housing, R_h [mm]		122.0
Lubricating fluid		Tap water
Tracer		Aluminum powder

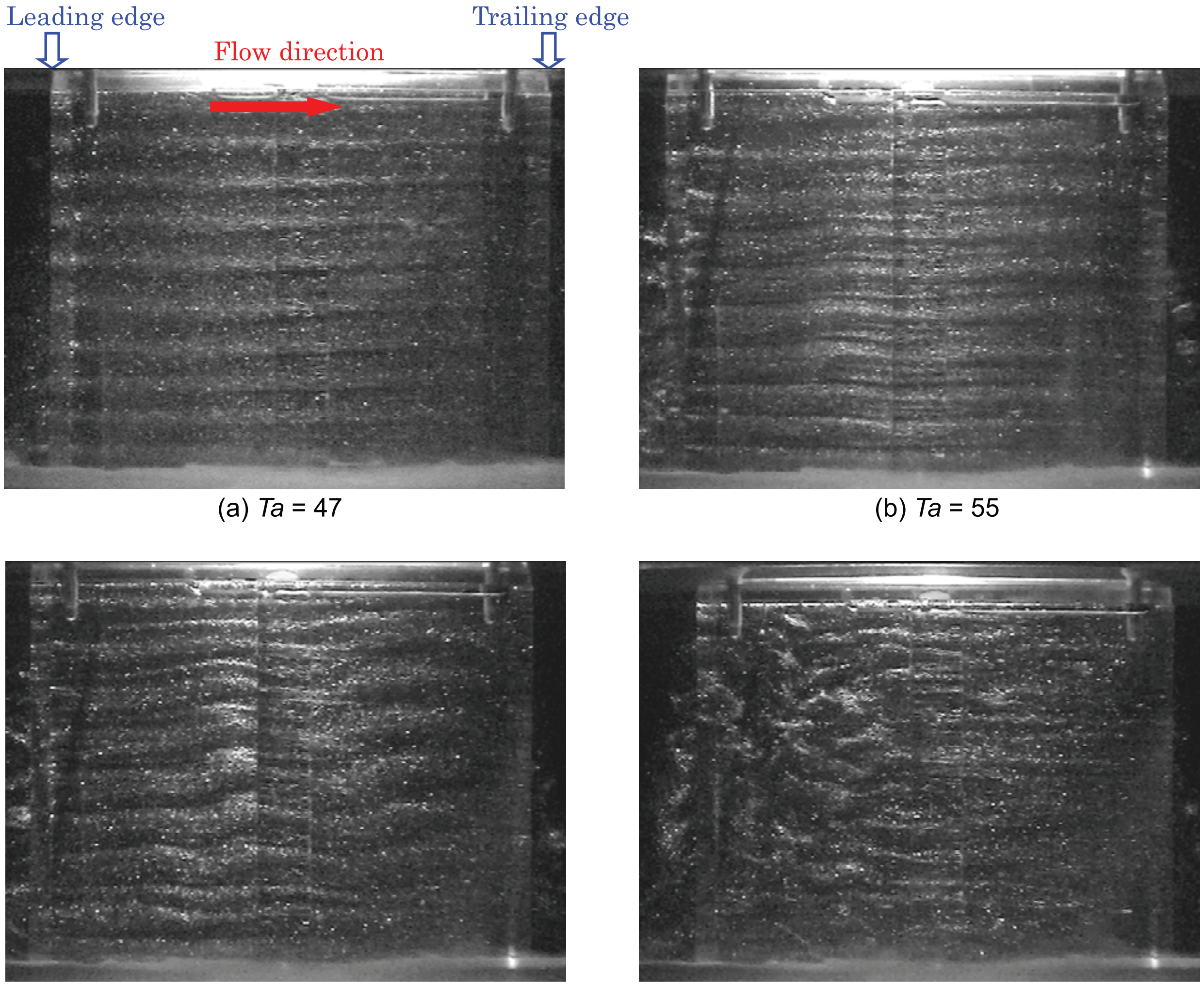
3. Experimental Results and Discussions

In the previous paper dealing with the case of concentric pads fixed parallel to the shaft surface (Noma and Mori, 2001), the authors pointed out that the critical Taylor number decreased and the cross section of the vortex ring became somewhat oblong along the shaft surface compared with the case of fully circular plain cylinder. In that experiment, the fluid was allowed to flow through the channel behind each pad. If this flow was stopped by some pad supporting elements, the cavity flow could be changed, and then the Taylor vortices in the film flow within the bearing clearance space might be influenced to some extent. After publication of the paper, the authors were interested in this problem, and performed supplementary experiments. As the result, it was found that the flow behind the pads gave almost no influence on the Taylor vortices in the film flow, whereas it changed the cavity flow a little. Considering such a fact, in the present study, the flow behind each pad is stopped at the pad center as shown in Fig. 1.

Figure 2 shows a typical example of variation in the Taylor vortices when the Taylor number was increased. The Taylor number in the present study dealing with inclined pads was defined by using the bearing clearance at the pad center as the representative. Those photographs were taken in the observation area (1). The inner cylinder surface, i.e., the shaft surface, was moving from the left hand side to the right hand side in each figure. The 70° pads were used and the inclination of each pad was set to 2.5.

Figure 2(a) was taken at *Ta* = 47, just after the Taylor vortices appeared. Under this condition, the vortex rings were in almost parallel throughout the bearing clearance space, though the leading edge clearance was 2.5 times larger than the trailing edge clearance. The pitch of array of vortex rings was about 2.6 times of the clearance at the pad center. Those seem to be implying that radial height of the cross section of the vortex ring should be continuously varied from the leading edge clearance to the trailing edge clearance. Considering the flow pattern shown in Figs. 5 and 6, however, one can realize that, just down stream the leading edge, the vortex rings could not fill up the clearance space, so that the radial height might be shorter than the clearance there.

When the Taylor number was increased up to 55, it can be found, on closer inspection to the video pictures, that some vortex ring was branching into three rings around the center line of the pad, and that this branching became vague toward the trailing edge of the pad where the clearance is much smaller. It may be signed in Figs. 2(b) and (c). When the Taylor number was increased up to 61, the vortex rings became wavy (Fig. 2(c)), i.e., the flow was brought into the wavy vortex flow regime. The wave grew gradually with the increase in the Taylor number, and at *Ta* = 98, as found in Fig. 2(d), the vortex rings fell into disorder upstream the center line where the clearance is large. Downstream the center line where the clearance is small, the flow was still in the wavy vortex regime. The Taylor number higher than this value might lead the flow into so-called turbulent regime partially. The value of *Ta* = 98 for the onset of turbulence is much lower than the value for the case of concentric fully circular cylinders (*Ta* ≈ 330). This may be attributable to the effect of cavity flow developed and also to the effects of reverse flow and higher local Taylor number in the bearing clearance due to the pad inclination.



(a) *Ta* = 47

(b) *Ta* = 55

(c) *Ta* = 61

(d) *Ta* = 98

Fig. 2. Typical example of variation in the Taylor vortices.

In Fig. 3, the critical Taylor number normalized by that of the concentric fully circular case, Ta_c / Ta_c^*, is plotted against the pad inclination, α. Circles represent the data for the 70° pads and squares represent the data for the 80° pads. For both cases, the effect of pad inclination on the critical Taylor number appears when α exceeds 2.0. For $\alpha > 2.0$, the critical Taylor number generally increases with the increase in α, though the data are up and down a little. The inclination of $\alpha = 2.0$ is nearly corresponding to the condition of an appearance of reverse flow region in the film flow within the bearing clearance just downstream the leading edge of the pad. The reverse flow region can grow to spread into the bearing clearance space from the leading edge to the center as the inclination is increased. Therefore, the results imply that growth of the reverse flow region can delay the onset of Taylor vortices in the film flow. This corresponds to the effect of eccentricity in a fully circular case (e.g., Vohr, 1967).

Looking at the data more precisely, it can be found that the critical Taylor number slightly decreases with decrease in the angular extent of the pad which means increase in the angular extent of the cavity, irrespective of the pad inclination, or irrespective of the reverse flow. This might be implying that the critical Taylor number is slightly influenced by the development of the cavity flow.

In Fig. 4, the pitch of array of vortex rings at the critical Taylor number normalized by that for concentric fully circular cylinders, P / P^*, is plotted against the pad inclination, α. The vortex rings were almost parallel from the leading edge to the trailing edge of the pad as shown in Fig. 2(a). Since, however, the pitch was, strictly speaking, not constant along the pad circumferentially and also axially, the values plotted in this figure were measured at the pad center. The pitch of array of vortex rings evaluated in such a manner is about 1.2 times of P^* ($\approx 2.1C$) for concentric fully circular cylinders irrespective of the pad inclination. On the contrary to the critical Taylor number, the pitch is scarcely affected by the pad inclination, i.e., by the reverse flow. The effect of angular extent of the pad on the pitch is undetectably small.

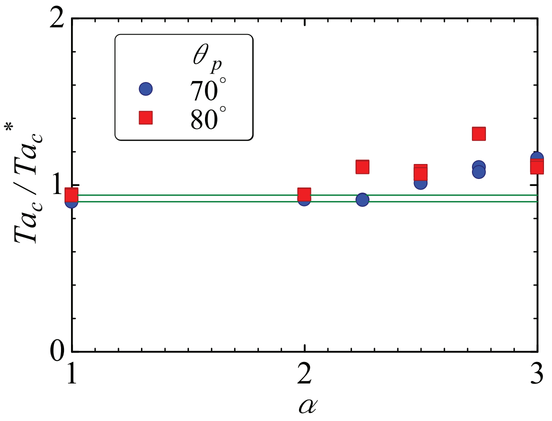


Fig. 3. Relationship between α and Ta_c / Ta_c^*.

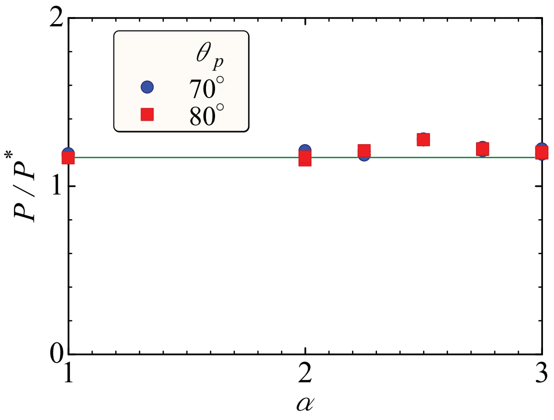
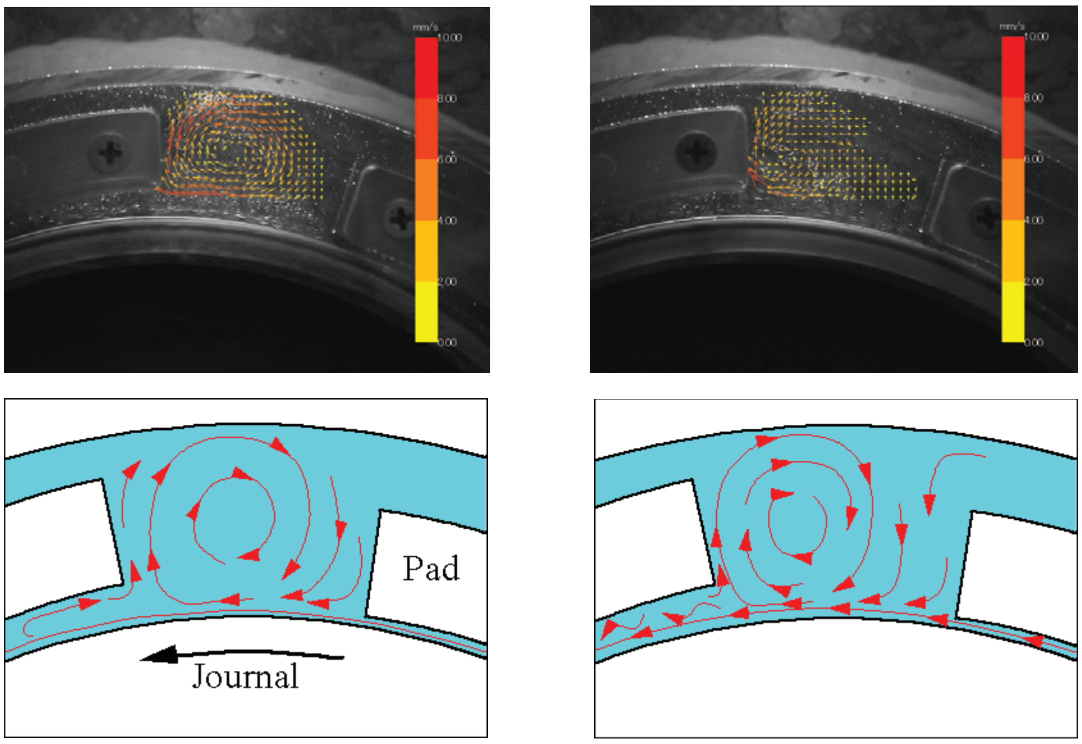


Fig. 4. Relationship between α and P / P^*.

Figure 5 shows the photographs of the cavity flow field corresponding to Fig. 2 which were taken in the observation area (2) In each photograph, mean flow vectors calculated by means of the PIV are shown. Just below each photograph, flow patterns transcribed from the video shooting are added.

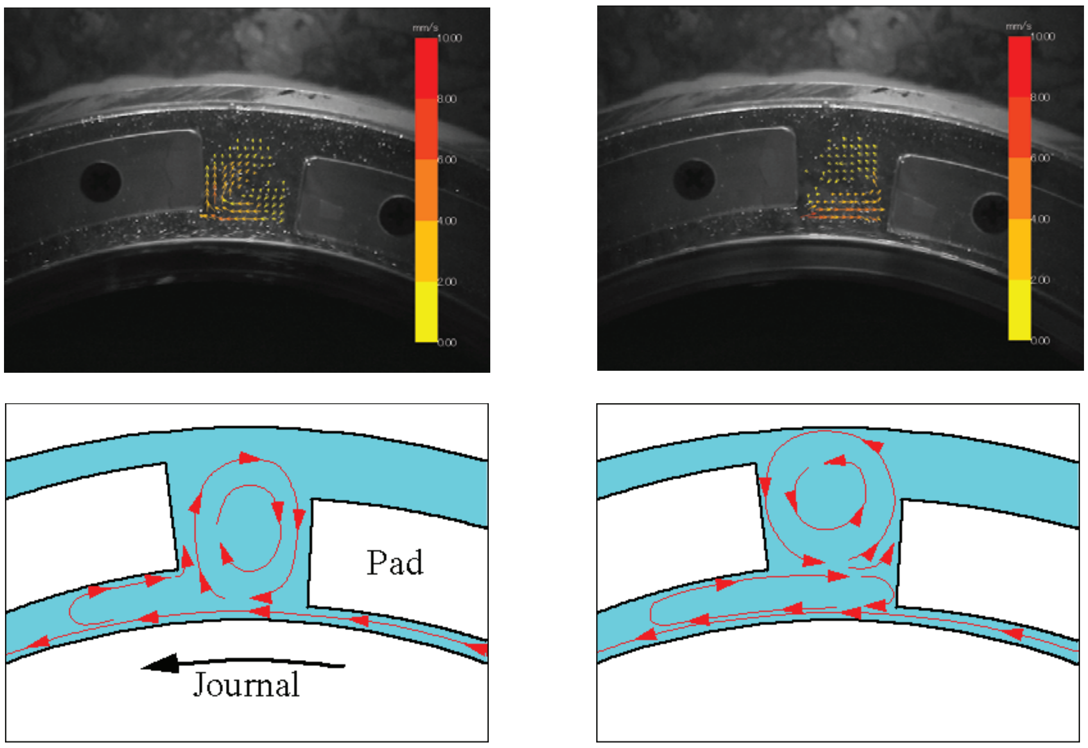
When the rotational speed was much lower than that for Ta_c, the reverse flow was not observed clearly because of too small pressure generation within the bearing clearance space. The film flow out of the trailing edge of the preceding pad was carried over the cavity region into the leading edge of the following pad. The cavity flow dragged by this film flow seemed to merely circulate clockwise within the cavity. Looking at the video pictures with possible care, however, the cavity flow adjacent the film flow was also dragged into the bearing clearance space of the following pad, but a certain part of this flow was forced back by the pressure generation there. These flows were too small to be recorded and analyzed by the present method.

When the rotational speed was increased up to $Ta = 46$, a little higher than the critical Taylor number, the pressure generation in the bearing clearance space became large enough to yield detectable reverse flows near the leading edge of the following pad. This is shown in Fig. 5(a). In this



(a) *Ta* = 46 (b) *Ta* = 106

Fig. 5. Cavity flow between pads [$\theta_p = 70°$, $\alpha = 2.5$].



(a) *Ta* = 45 (b) *Ta* = 111

Fig. 6. Cavity flow between pads [$\theta_p = 80°$, $\alpha = 2.5$].

case, the Taylor vortices developed in the film flow within the preceding pad were, without notable changes in the pattern, carried over the cavity region into the following pad as if there was no cavity. A part of the cavity flow dragged by such a film flow was forced into the following pad once, but it was, detectably, forced back along the pad surface by the pressure which was sufficiently generated within the bearing clearance of the pad. The film flow accompanying the Taylor vortices and the cavity flow circulating clockwise were observed as if they existed independently over the cavity, though the latter was induced by the former. Such a flow pattern was observed up to the Taylor number at which the Taylor vortices fell into disorder. As already shown in Fig. 2(d), this was occurred at about Ta = 100. In Fig. 5(b) for Ta = 106, the reverse flow is not sketched in the bearing clearance as if there was no reverse flow. This may be the trick of disordered vortices. The reverse flow could be observed in the adjacent section. When the Taylor number was increased much higher than this and the flow became turbulent, not only the film flow but also the cavity flow became three dimensional and mixing of the film and cavity flows became significant.

Figure 6 shows the photographs and illustrations of the cavity flow field for the 80° pads. The results shown in Figs. 6(a) and (b) are similar to those in Figs. 5(a) and (b).

As shown in Fig. 6(b), however, an interesting phenomenon was observed when the rotational speed was increased up to $Ta \approx 110$ where the Taylor vortices became wavy but not disordered yet. This was never observed in the case of 70° pads. The operating condition for Ta = 111 yielded higher pressure in the bearing clearance space, so that the reverse flow accompanying large momentum was discharged from the leading edge of the following pad into the cavity. This reverse flow was directed to the trailing edge of the preceding pad, and then this was turned downward to the shaft surface and dragged by the film flow into the bearing clearance space of the following pad. In such a manner, the stable clockwise circulation was generated over the film flow. On the other hand, the cavity fluid just outside the reverse flow was dragged to the right, and this dragged flow was turned upward along the side wall of trailing edge of the preceding pad. This flow yielded a large counterclockwise circulation in the cavity. As the result, a stable clockwise circulation adjacent the film flow and a stable counterclockwise circulation coexisted within the cavity at the same time. This phenomenon seems to have been yielded by moderate growth in the cavity flow to the left which was dragged by the film flow, because of smaller angular extent of the cavity region. In this case, the film flow accompanying the Taylor vortices was also carried over the cavity region, and the cavity flow dragged by this film flow seems to have been merely circulated clockwise almost not to be mixed with the outside cavity flow with counterclockwise circulation. This was kept up to Ta = 166, at which the Taylor vortices were notably disturbed. Such phenomena were commonly observed for the condition of $\alpha > 2$. Due to such a phenomenon, in this case, mixing of the film and cavity flows seems to have been very weak. The reason why a stable clockwise circulation was not induced in the case of 70° pads may be attributable to the fact that, due to larger angular extent of the cavity, the flow dragged to the left was developed enough to deflect the whole of discharged reverse flow as if it turned the corner of the leading edge.

When the rotational speed was increased up to Ta = 220, the flow accompanying the vortex rings was broken into turbulent one. This could weaken the momentum of the reverse flow and strengthen the momentum of the cavity flow to the left through strong mixing effects. Under such a condition, the clockwise circulation could not be formed even in the case of 80° pads. When the film flow in the bearing clearance space became turbulent, the cavity flow seems to have been changed from two dimensional to three dimensional irrespective of the angular extent of the pads, and thus mixing of the film and cavity flows seems to have been promoted.

4. Conclusion

In the present study, the Taylor vortices of the film flow in the bearing clearance space and the cavity flow between pads in a submerged tilting pad journal bearing were visualized by means of a tracer method. The results obtained can be summarized as follows;

The critical Taylor number of the film flow is scarcely influenced by the pad inclination unless this exceeds the critical value yielding a reverse flow region in the bearing clearance space. When the pad inclination exceeds this critical value, the critical Taylor number increases with the inclination.

The pitch of array of vortex rings at the critical Taylor number is almost constant along the pad irrespective of the pad inclination whether the reverse flow appears or not. It is likely fixed by the bearing clearance at the pad center.

The film flow accompanying the Taylor vortices is, irrespective of the pad inclination, carried over the cavity region without notable changes in the pattern. In the cavity, so-called cavity flow accompanying a two dimensional circulation is induced by the film flow discharged from the preceding pad. Those flows coexist stably unless the Taylor vortex rings are strongly disturbed.

For the pad of large angular extent, the cavity region between pads becomes narrow. In this case, a counter circulation appears outside the depressed regular circulation when the Taylor number increases up to a certain value. This may be caused by a strong reverse flow discharged from the leading edge of the following pad into the cavity and moderate development of the flow dragged by the film flow between pads. Those two circulations can coexist stably unless the Taylor vortex rings are strongly disturbed.

Those phenomena imply that the lubricant working in the bearing clearance and the lubricant staying in the cavity are hardly mixed with each other unless the film flow becomes turbulent. This effect is more notable if two circulations appear in the cavity region. This means that the lubricant sheared and heated, in other words, used many times in the bearing clearance can scarcely be mixed with a fresh lubricant of a large amount which remains in the cavities not to be used. This will be undesirable problem in a large scaled fluid bearing.

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