Article

Effects of the Recess Geometry on Flow Characteristics of Cryogenic Hybrid Journal Bearings for Rocket Turbopumps

Mamoru Oike^{1)*}, Masataka Kikuchi²⁾, Satoshi Takada²⁾, Takayuki Sudo²⁾ and Tomoyuki Takano³⁾

¹⁾Department of Mechanical Engineering, Ishinomaki Senshu University, 1 Shinmito, Minamisakai, Ishinomaki, Miyagi 986-8580, Japan

²⁾Kakuda Space Center, Japan Aerospace Exploration Agency, 1 Koganezawa, Kimigaya, Kakuda, Miyagi 981-1525, Japan

³⁾Japan Aerospace Technology, 1 Koganezawa, Kimigaya, Kakuda, Miyagi 981-1525, Japan

*Corresponding author: Mamoru Oike (oike@isenshu-u.ac.jp)

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Abstract

In the present study, a flow visualization experiment in the clearance between a clear floating-ring and a rotating journal was carried out in order to clarify the effects of the recess geometry on the flow characteristics. Five types of the floating-rings with different recess geometries, i.e., the plane rhombus, the plane circle, the revise circular Young Leaf Mark, the dome and the revise dome geometries, were operated at a rotational speed of up to 40,000 rpm using liquid nitrogen as the working fluid to observe the interaction between source flow from the recess and rotating flow induced by the journal rotation in the clearance. The cavitation cloud inside the clearance was induced by viscous frictional heating and the pressure drop. The influence of the sweepback angle (θ_s) of the recess leading edge on the flow characteristics was investigated by comparing flow coefficient (C_f) and the cavitation cloud area ratio (A_c) obtained from the visual image. Based on the experimental results, it may be confirmed that the effects of the recess geometry on the flow characteristics of the cryogenic hybrid journal bearings are mainly caused by the influence of the θ_s value on the flow condition.

Keywords

journal bearing, cryogenic turbopump, flow visualization, recess geometry, recess sweepback angle, cavitating flow, liquid nitrogen

1 Introduction

The lifetime of a rocket engine depends mainly on the durability of bearings and seals in a cryogenic turbopump. Almost all cryogenic turbopumps of rocket engines have a rotor system supported by self-lubricating ball bearings operated in liquid hydrogen or liquid oxygen. Since a differential slip and Hertz stress act in the rolling contact area between a ball and a raceway, it is difficult to avoid the lifetime shortening wear of material inside the contact area. Moreover, the polytetrafluoroethylene (PTFE) solid lubricant film on the contact area has a limitation of the SV value, which is the value of Hertzian stress (S) times the differential slip speed (V), to maintain a good lubricating condition in the cryogenic fluid [1]. Therefore, the rotational speed of the cryogenic turbopump must be restricted to avoid critical damage such as seizing. A hybrid journal bearing (HJB) is a fluid-film journal bearing with characteristics of both hydrostatic and hydrodynamic bearings. The main advantage of HJBs are small size, good load capacity, a quasi-unlimited life (no observed wear), and the use of process fluid for lubrication [2]. By replacement of the

self-lubricating ball bearings in the cryogenic turbopumps by HJBs, a significantly higher lifetime can be obtained and the inherent limitation of the rotational speed of the turbopumps can be greatly extended in cryogenic rocket engines for future reusable launch vehicles (RLVs), where the lifetime of mechanical components is a critical issue. Although many experimental studies on HJBs have been carried out to develop high performance HJBs for cryogenic turbopumps [3-7], it has not yet been completely realized because there is little demand for development of a launch vehicle capable of being reused over hundred times. However, detailed reference data based on experimental results will be required to develop high performance cryogenic HJBs in the near future.

In a previous study [8], two types of hybrid journal bearings (HJBs) with different recess geometries, i.e., the Young Leaf Mark (YLM, Types Ca and D in Fig. 1) and the square (Type Ba), were operated at a rotational speed of up to 67,000 rpm using liquid nitrogen as the working fluid in order to clarify the influences of the journal rotating direction on performance of the cryogenic HJBs. The dependence of the rotor vibration on the rotational speed was confirmed to be affected by the

Fig. 1 Photos of test HJB inner surfaces with Young Leaf Mark recess (Journal rotating direction: counterclockwise for Type Ca, $\theta_s = -45$ deg., clockwise for Type D, $\theta_s = 45$ deg.) and square recess (Type Ba, $\theta_s = 0$ deg.) [8]

Fig. 2 Comparisons of the horizontal and vertical amplitudes (ΔH and ΔV) of the rotor vibration for Types D, Ca and Ba of HJBs [8]

direction of journal rotation. As shown in Fig. 2, the test HJB (Type D) with the positive sweepback angle (θ_s) of the recess leading edge showed the smallest rotor vibration in the high-rotational-speed operation where the hydrodynamic effect was predominant. A flow visualization experiment in the clearance between a clear floating-ring (CFR) and a rotating journal was carried out to clarify the effect of the θ_s value on the flow characteristics. Four types of CFR with different recess geometries, i.e., the YLM (Type D), the revise YLM (Type C),

the square (Type B) and the non-recessed (Type FR) geometries, were operated at a rotational speed of up to 45,000 rpm using liquid nitrogen (LN_2) to observe the interaction between a source flow from the recess and rotating flow induced by the journal rotation in the clearance [9]. The dependence of the flow characteristics on the rotational speed was confirmed to be affected by the θ_s value.

In the present study, five types of the CFR with different recess geometries, i.e., the plane rhombus, the plane circle, the circular Young Leaf Mark, the dome and the revise dome geometries, were newly operated at a rotational speed of up to 40,000 rpm using liquid nitrogen as the working fluid to compare with the results obtained for Types B, C, D and FR in the previous study [9]. The effects of the recess geometry on the flow characteristics were investigated by comparing the flow coefficient (C_f) and the cavitation cloud area ratio (A_c) obtained from the visual image.

2 Experimental procedure

2.1 Clear floating-ring

Flow visualization experiments were conducted to clarify the flow pattern of cryogenic fluid within the clearance between the CFR and the journal. Figure 3 is a photograph of the test CFR (Type D) section [9]. The test CFR made of polycarbonate is a floating-ring which has four orifice-compensated recesses on the inner surface to simulate the interaction between a source flow from the recess and a rotating flow induced by the journal rotation in the clearance of the HJB, as shown in Fig. 3. Five types of the CFRs have different recess geometries, i.e., the

Fig. 3 Photograph of the test CFR (Type D) section [9]

Fig. 4 Recess geometries of Types E, F, G, K and M

plane rhombus (Type E), the plane circle (Type F), the circular Young Leaf Mark (Type G), the dome (Type K) and the revise dome (Type M) geometries, as shown in Fig. 4. The geometry parameters of the test CFRs including the recess geometry, the static radial clearance (C_0) in LN_2 and the sweepback angle of the recess leading edge (θ_s) are listed in Tables 1 and 2. The recess geometries of Types B, C, D and FR are also shown in Fig. 4 and listed in Table 2. The journal surface is coated with Cr_2O_3 plasma spray film so that its surface seems to be black.

Table 1 Geometry parameters of a test CFR

Diameter of CFR, d (mm)	40
Axial length of CFR, L (mm)	30
Recess orifice diameter, d_o (mm)	1.0
Number of recesses, Nr	4
Maximum axial length of recess, L_r (mm)	10
Maximum recess depth, h (mm)	1.0
Recess area ratio, Ar	0.106

Table 2 Recess geometries of test CFRs

Type of CFR	Static radial clearance, C_0 (mm)	Recess geometry	Mean recess sweepback angle, θ_s (degree)
Type E	0.046	Plane rhombus	45
Type F	0.042	Plane circle	45
Type G	0.042	Revise circular YLM	-45
Type K	0.044	Dome	45
Type M	0.046	Revise dome	0
Type B	0.050	Square	0
Type C	0.044	Revise YLM	-45
Type D	0.041	Yung Leaf Mark (YLM)	45
Type FR	0.047	None	-

2.2 Test procedure

The test CFRs were operated at a rotational speed of up to 40,000 rpm using the cryogenic flow visualization test apparatus [10] at the JAXA Kakuda Space Center. Figure 5 shows a photograph of the test apparatus, which is constructed with a visualization section, a rotor support section and a compact electric motor. The rotor is supported by a pair of self-lubricated ball bearings cooled by cryogenic liquid and driven by the electric motor connected with one end of the rotor. The cryogenic liquid is sealed by a face contact metal-bellows mechanical seal and the test CFR. The clear case of the test CFR is also made of polycarbonate and the outer case of the test apparatus in the test CFR section is composed of a transparent plastic, acrylic acid resin. The cavity between the clear case and the clear outer case is evacuated by a vacuum pump to create a heat insulation layer. The flow pattern in the CFR clearance was observed by three video cameras and a high-speed video camera installed in four radial directions, as shown in Fig. 5. Liquid nitrogen (LN_2) was supplied to the test CFR with a pressure of up to 1.7 MPa to achieve a safe, easy operation. The main test conditions are listed in Table 3. Test conditions

Fig. 5 Photograph of the test apparatus

Table 3 Main test conditions

LN ₂ supply pressure, P_1 (MPa)	0.7 – 1.7
Pressure difference of CFP, ΔP_{12} (MPa)	0.6 – 1.6
LN ₂ supply temperature, T_1 (K)	85 – 105
LN ₂ supply flow rate, Q (l/s)	0.050 – 0.140
Steady rotational speed, N (rpm)	20,000 – 40,000
Sommerfeld number, S	0.46 – 1.03

such as LN₂ supply pressure were established to operate the test CFR at over 40,000 rpm based on a previous study [9]. The static pressure and the fluid temperature were measured at major points in the test CFR and the apparatus. The pressure fluctuations upstream and downstream of the CFR were also measured by a piezoelectric pressure sensor. Volumetric flow rate of LN₂ was measured by a turbine flowmeter installed in the supply line leading to the test CFR. In the experiment, the rotational speed firstly increases and then decreases by stages.

The flow coefficient (C_f) defined by Eq. (1) is introduced to evaluate the flow condition in the CFR clearance.

$$C_f = \frac{Q}{\pi d C_0 \sqrt{\frac{\rho_{sat}}{2 \Delta P_{12}}}} \quad (1)$$

Here, ρ_{sat} is the saturated density of LN₂ at the upstream temperature (T_1). Thus, the flow coefficient expresses the ratio of the axial flow speed at the outlet of the CFR clearance based on the measured volumetric flow rate (Q) to the axial flow speed of saturated LN₂ calculated from the pressure difference of the CFR (ΔP_{12}). The value of C_f is considered to be an index to evaluate a synergy effect of the inlet and outlet losses, and the two-phase flow on the flow condition through the clearance [8, 9]. The cavitation area ratio (Ac) obtained by Eq. (2) is also introduced to evaluate the two-phase flow condition in the CFR clearance.

$$Ac = \frac{4 a_c}{\pi d L} \quad (2)$$

Here, a_c is the cavitation cloud area within the clearance on the fourth of the CFR inner surface obtained from the snapshot

of the video image captured by the video camera 1 [9]. The flow coefficient and the cavitation area ratio were obtained for various values of the cavitation number (σ_{ps}) defined by Eq. (3).

$$\sigma_{ps} = \frac{P_1 - P_{sat}}{\Delta P_{12} + (1/2) \rho_{sat} V_\theta^2} \quad (3)$$

Here, P_{sat} is the saturated pressure at T_1 , and V_θ is the circumferential velocity of the journal outer surface. Thus, the value of σ_{ps} takes into account the pressure drop and the flow speed of saturated LN₂ induced by the journal rotation through the CFR clearance [9].

3 Experimental results

Five test series were newly carried out in the present study. An example of the state and properties of liquid nitrogen obtained for Type F is listed in Table 4. Liquid nitrogen is found to be in the saturated condition downstream of the test CFR. The standard deviations of the measured static pressure and temperature were less than 1% of their average values under the steady rotating condition.

Figure 6 shows the variations of the C_f , the Ac and the T_1 vs the rotational speed obtained for Type E. Flow visualization images obtained at (a) to (d) denoted in the Fig. 6 are shown in Fig. 7. The variations and the images for Type F, Type G and Type K are also shown in Figs. 8 to 13. Since the journal surface is coated with Cr₂O₃ plasma spay film, it looks black in the image. When the cavitation occurs in the CFR clearance, it looks like a white cloud, i.e., a cavitation cloud, as shown in Figs. 7, 9, 11 and 13. According to the high-speed video image (20,000

Table 4 State and properties of liquid nitrogen (LN₂) obtained for Type F ($N = 37.3$ krpm, $Ac = 0.867$)

Location	Upstream	Downstream
Pressure (MPa)	1.60	0.12
Temperature (K)	89.5	78.8
Density, ρ (kg/m ³)	753.4	802.0
Viscosity, μ (μPa-s)	102.9	143.8

fps), the flow pattern of the cavitation cloud is considered to be an unstable turbulent flow. Furthermore, it was confirmed that LN_2 flowed out of the CFR clearance in the two-phase state independent of the rotational speed. The experimental results indicate that the value of Ac tends to increase with increasing

rotational speed, and that the value of C_f then tends to decrease with an increase in the rotational speed for each type of the CFR because of viscous frictional heating. However, a sudden change of T_1 seems to induce large variations of Ac and C_f in the moderate speed operation independent of the CFR type.

Fig. 6 Variations of the cavitation area ratio (Ac), the flow coefficient (C_f) and the upstream temperature (T_1) vs the rotational speed obtained for Type E

Fig. 7 Visualization images obtained at the (a) to (d) denoted in Fig. 6 for Type E, captured by the video camera 1

- (a) $N = 38.5$ krpm, $T_1 = 88.2$ K, $\sigma_{ps} = 0.328$, $C_f = 0.213$, $Ac = 0.640$
 (b) $N = 40.3$ krpm, $T_1 = 88.1$ K, $\sigma_{ps} = 0.311$, $C_f = 0.212$, $Ac = 0.810$
 (c) $N = 35.2$ krpm, $T_1 = 91.7$ K, $\sigma_{ps} = 0.345$, $C_f = 0.238$, $Ac = 0.338$
 (d) $N = 35.1$ krpm, $T_1 = 99.8$ K, $\sigma_{ps} = 0.217$, $C_f = 0.179$, $Ac = 0.736$

Fig. 8 Variations of the cavitation area ratio (Ac), the flow coefficient (C_f) and the upstream temperature (T_1) vs the rotational speed obtained for Type F

Fig. 9 Visualization images obtained at the (a) to (d) denoted in Fig. 8 for Type F, captured by the video camera 1

- (a) $N = 35.2$ krpm, $T_1 = 89.7$ K, $\sigma_{ps} = 0.354$, $C_f = 0.196$, $Ac = 0.743$
 (b) $N = 37.3$ krpm, $T_1 = 89.5$ K, $\sigma_{ps} = 0.333$, $C_f = 0.196$, $Ac = 0.867$
 (c) $N = 28.3$ krpm, $T_1 = 92.6$ K, $\sigma_{ps} = 0.408$, $C_f = 0.232$, $Ac = 0.283$
 (d) $N = 30.1$ krpm, $T_1 = 102.3$ K, $\sigma_{ps} = 0.251$, $C_f = 0.144$, $Ac = 0.593$

Fig. 10 Variations of the cavitation area ratio (A_c), the flow coefficient (C_f) and the upstream temperature (T_1) vs the rotational speed obtained for Type G

(a) $N=36.4$ krpm, $T_1=90.3$ K, $\sigma_{ps}=0.330$, $C_f=0.206$, $A_c=0.681$

(b) $N=38.4$ krpm, $T_1=88.6$ K, $\sigma_{ps}=0.322$, $C_f=0.200$, $A_c=0.810$

(c) $N=33.2$ krpm, $T_1=90.4$ K, $\sigma_{ps}=0.371$, $C_f=0.245$, $A_c=0.371$

(d) $N=33.9$ krpm, $T_1=101.9$ K, $\sigma_{ps}=0.221$, $C_f=0.197$, $A_c=0.594$

Fig. 11 Visualization images obtained at the (a) to (d) denoted in Fig. 10 for Type G, captured by the video camera 1

- (a) $N = 36.4$ krpm, $T_1 = 90.3$ K, $\sigma_{ps} = 0.330$, $C_f = 0.206$, $A_c = 0.681$
 (b) $N = 38.4$ krpm, $T_1 = 88.6$ K, $\sigma_{ps} = 0.322$, $C_f = 0.200$, $A_c = 0.810$
 (c) $N = 33.2$ krpm, $T_1 = 90.4$ K, $\sigma_{ps} = 0.371$, $C_f = 0.245$, $A_c = 0.371$
 (d) $N = 33.9$ krpm, $T_1 = 101.9$ K, $\sigma_{ps} = 0.221$, $C_f = 0.197$, $A_c = 0.594$

Fig. 12 Variations of the cavitation area ratio (A_c), the flow coefficient (C_f) and the upstream temperature (T_l) vs the rotational speed obtained for Type K

Fig. 13 Visualization images obtained at the (a) to (d) denoted in Fig. 12 for Type K, captured by the video camera 1

- (a) $N = 35.1$ krpm, $T_l = 90.4$ K, $\sigma_{ps} = 0.330$, $C_f = 0.207$, $A_c = 0.713$
 (b) $N = 38.0$ krpm, $T_l = 90.8$ K, $\sigma_{ps} = 0.299$, $C_f = 0.194$, $A_c = 0.952$
 (c) $N = 29.8$ krpm, $T_l = 90.5$ K, $\sigma_{ps} = 0.356$, $C_f = 0.253$, $A_c = 0.255$
 (d) $N = 29.9$ krpm, $T_l = 101.0$ K, $\sigma_{ps} = 0.245$, $C_f = 0.154$, $A_c = 0.667$

Fig. 14 Effect of the recess geometry on the cavitation area ratio (Ac) and the flow coefficient (C_f) obtained for $T_i = 87 - 91$ K in the high-rotational-speed operation

(a) Variations of the cavitation area ratio (Ac) and the flow coefficient (C_f) vs the rotational speed

(b) Variations of the cavitation area ratio (Ac) and the flow coefficient (C_f) vs the cavitation number (σ_{ps})

3.1 Steady state

Firstly, the steady-state results obtained for $T_i = 87$ to 91 K in the high-rotational-speed operation are described. The effects of the recess geometry on the values of Ac and C_f are shown in Fig. 14. Figure 14 (a) shows the relationships between Ac and the rotational speed, and C_f obtained for each type of the CFR. The relationships to the value of σ_{ps} are also shown in Fig. 14 (b). The results of Types B, C, D and FR obtained in the previous study [9] are also plotted in Fig. 14. Each line represents a fitting curve. The value of Ac obtained for each type of CFR tends to increase with increasing rotational speed, i.e., decreasing σ_{ps} for up to $Ac = 1$, while the value of C_f tends to decrease. The values of C_f obtained for Type FR without a recess are much smaller than those for the other types of the CFR because of no source flow from the recess. Comparison of Ac at the same value of σ_{ps} indicates that the average values of Types C and G having $\theta_s = -45$ deg. are smaller than those of the other types of CFR, and that the difference between them tends to be smaller as the cavitation number decreases. On the other hand, the average values of C_f for Types C and G are larger than those of the other types of CFR in the high σ_{ps} condition where the average value of C_f obtained for Type B is located in the middle range between those of Types C and G, and the other types of CFR. However, distinct differences among them are found to disappear in the low σ_{ps} condition. These facts indicate that the flow characteristics in the CFR clearance was affected by the recess geometry even at the same value of σ_{ps} in the relatively high σ_{ps} condition.

Figure 15 shows the relationships between Ac and C_f for each type of the CFR. Since two-phase flow of LN_2 occurred at the clearance outlet independent of the rotational speed, the C_f showed a considerably low value even if $Ac = 0$ [9]. The values of C_f basically tend to decrease with the increase in Ac . The C_f values obtained for $T_i = 87$ to 91 K in the high-rotational-speed operation are plotted against the Ac values for each type of the CFR in Fig. 15. Each solid line represents a fitting curve. According to the fitting curves, the value of C_f obtained for each type of CFR tends to decrease with increasing Ac , and the C_f value of Type FR without the recess is confirmed to be much smaller than those of the CFRs with the recess independent of the Ac value. Since the sonic speed of the cavitating flow drastically decreases, the cavitating flow is considered to be choked at the clearance outlet. Therefore, the flow coefficient (C_f) is denoted by Eq. (4).

Fig. 15 Variations of the flow coefficient (C_f) vs the cavitation area ratio (Ac) obtained for $T_i = 87 - 91$ K in the high-rotational-speed operation

$$C_f = \frac{\rho_m a_m}{\rho_0} \sqrt{\frac{\rho_{sat}}{2\Delta P_{12}}} \quad (4)$$

Here, ρ_m is the mixture density of vapor and liquid two-phase flow at the clearance outlet, a_m is the sonic speed of the cavitating flow at the outlet, and ρ_0 is the density of LN_2 at the turbine flowmeter. When the isothermal process without the thermodynamic effect of cavitation is assumed, the values of ρ_m and a_m are obtained from a void fraction (α) of the cavitating flow at the clearance outlet by using Eqs. (5) and (6) [11]:

$$\rho_m = \alpha \rho_v + (1 - \alpha) \rho_l \quad (5)$$

$$a_m = a_v \left[\kappa \left\{ \alpha^2 + \alpha (1 - \alpha) \frac{\rho_l}{\rho_v} \right\} \right]^{-0.5} \quad (6)$$

where ρ_v and ρ_l are nitrogen saturated densities of vapor and liquid phases at the clearance outlet, and κ is the specific heat ratio of nitrogen. Thus, the value of C_f can be considered to depend mainly on the void fraction and the saturated temperature (T_{out}) or pressure of nitrogen at the outlet plane of the CFR clearance. Figure 16 shows the relationships between the void fraction and the sonic speed at the outlet and those between the C_f value obtained for $\Delta P_{12} = 1.5$ MPa and the outlet saturated temperature range of $T_{out} = 78 - 86$ K by using Eqs.

Fig. 16 Relationships between the void fraction and the sonic speed at the outlet plane of the clearance, and the C_f value obtained for $\Delta P_{12} = 1.5$ MPa and the outlet saturated temperature range of $T_{out} = 78 - 86$ K by using Eqs. (4) – (6) [9]

(4) – (6) based on the experimental results [9]. The average value of C_f obtained for the CFRs with the recess is about 0.21 at $Ac = 0.8$ and that of Type FR is about 0.16, as shown in Fig. 15. According to the results shown in Fig. 16, if the difference of T_{out} between them is less than 2 K, the α value of Type FR at the outlet is found to be about 0.1 larger than those of the CFRs with the recess. Furthermore, the maximum difference of C_f between Type C and Type F near $\sigma_{ps} = 0.36$ is found to be about 0.04 (= 0.24-0.20) in Fig. 14 (b), which indicates that the recess geometry difference caused an increase of about 0.063 in the void fraction at the clearance outlet.

3.2 Transient state

The influence of the sudden change of the upstream temperature (T_1) of LN_2 on the flow condition in the clearance of the CFR was investigated under the condition of a nearly constant rotational speed. As shown by (c) and (d) denoted in Figs. 6, 8, 10 and 12, a sudden rise in the upstream temperature (ΔT_1) occurred in the moderate speed operation independent of the CFR type, which induced a drop in the cavitation number

(σ_{ps}) and consequently induced a rise in the cavitation area ratio (ΔAc) and a drop in the flow coefficient (ΔC_f). Figure 17 shows visualization images obtained before and after the sudden rise in the upstream temperature (ΔT_1) for Type M. Figure 18 shows the effect of the sudden rise in the upstream temperature on the cavitation area ratio and the flow coefficient for each type of the CFR including Type M. Figure 18 (a) shows the relationships between ΔT_1 normalized by the Stepanoff's factor $B(T^*)$ [12] and ΔAc , and ΔC_f divided by the average (C_{fm}) of those before and after ΔT_1 . The normalized ΔT_1^* is defined by Eq. (7):

$$\Delta T_1^* = \frac{\Delta T_1}{T^*} = \Delta T_1 \frac{\rho_l C_{pl}}{\rho_v L_h} \quad (7)$$

where ρ_v and ρ_l are saturated densities of vapor and liquid phases, C_{pl} is the specific heat at constant pressure, and L_h is the latent heat at T_1 before the rise. The values of ΔAc and $\Delta C_f / C_{fm}$ are also plotted against the drop in the cavitation number ($\Delta \sigma_{ps}$) induced by ΔT_1 in Fig. 18 (b). Figure 18 shows that the values of ΔAc and $\Delta C_f / C_{fm}$ depend on the recess configuration including no recess. The sweepback angle of the recess leading edge (θ_s) shown in Fig. 4 is introduced to express the differences between test CFRs, i.e., $\theta_s = -45$ deg. for Types C and G, $\theta_s = 0$ deg. for Types B and M, and $\theta_s = 45$ deg. for Types D, E, F and K. Each bold solid line represents a linear fitting curve obtained for the CFRs with $\theta_s = 45$ deg. Each bold dashed line represents that for the CFRs with $\theta_s = 0$ deg., and each bold dotted line represents that for the CFRs with $\theta_s = -45$ deg. Comparison between them at the same value of ΔT_1^* or $\Delta \sigma_{ps}$ indicates that both the ΔAc and $\Delta C_f / C_{fm}$ values obtained for the CFRs with $\theta_s = 45$ deg. are considerably larger than those for the CFRs with $\theta_s = -45$ degree. On the other hand, the values of ΔAc and $\Delta C_f / C_{fm}$ obtained for the CFRs with $\theta_s = 0$ deg. are located in the middle range between those for the CFRs with $\theta_s = 45$ deg. and the CFRs with $\theta_s = -45$ degree. Therefore, the pressure distributions within the clearances of the CFRs with $\theta_s = -45$ deg. can be considered to be higher than those of the CFRs with $\theta_s = 45$ deg., which is basically correspondent with the steady-state results shown in Fig. 14.

4 Discussion

Five types of the CFRs with different recess geometries,

(a) $N=31.2$ krpm, $T_1=90.8$ K, $\sigma_{ps}=0.374$, $C_f=0.256$, $Ac=0.227$

(b) $N=31.0$ krpm, $T_1=102.5$ K, $\sigma_{ps}=0.226$, $C_f=0.186$, $Ac=0.589$

Fig. 17 Visualization images obtained before and after the sudden rise in the upstream temperature (ΔT_1) for Type M, captured by the video camera 1

(a) $N = 31.2$ krpm, $T_1 = 90.8$ K, $\sigma_{ps} = 0.374$, $C_f = 0.256$, $Ac = 0.227$

(b) $N = 31.0$ krpm, $T_1 = 102.5$ K, $\sigma_{ps} = 0.226$, $C_f = 0.186$, $Ac = 0.589$

Fig. 18 Effect of the sudden rise in the upstream temperature (ΔT_i) on the cavitation area ratio and the flow coefficient
 (a) Relationships between ΔT_i normalized by the Stepanoff's factor $B(T^*)$ and ΔAc , and ΔC_f divided by the average (C_{fm}) of those before and after ΔT_i
 (b) Relationships between drop in the cavitation number ($\Delta \sigma_{ps}$) induced by ΔT_i and ΔAc , and ΔC_f divided by the average (C_{fm}) of those before and after ΔT_i

i.e., the plane rhombus, the plane circle, the revise circular Young Leaf Mark, the dome and the revise dome geometries, were newly operated at a rotational speed of up to 40,000 rpm using liquid nitrogen as the working fluid to compare with the results obtained for four types of the CFRs presented in the previous study [9]. Figure 19 shows the relationships between the sweepback angle of the recess leading edge (θ_s) and the rise in the cavitation area ratio (ΔAc), and the drop ratio of the flow coefficient ($\Delta C_f / C_{fm}$) induced by the sudden rise in the upstream temperature (ΔT_i). Data obtained in a narrow range of $\Delta \sigma_{ps} = 0.13 - 0.17$ are plotted in Fig. 19 to focus on the effect of the sweepback angle of the recess leading edge. Each solid line represents a fitting curve. The average values of ΔAc and $\Delta C_f / C_{fm}$ are found to increase monotonically with the increase in θ_s , which demonstrates that the flow condition depends strongly on the sweepback angle of the recess leading edge.

The upstream boundary between the liquid phase and the cavitation cloud within the clearance may be considered to

Fig. 19 Effect of the sweepback angle of the recess leading edge (θ_s) on the rise in the cavitation area ratio (ΔAc), and the drop ratio of the flow coefficient ($\Delta C_f / C_{fm}$) induced by the sudden rise in the upstream temperature (ΔT_i), obtained for drop in the cavitation number of $\Delta \sigma_{ps} = 0.13 - 0.17$

present a kind of contour line of the highest saturated pressure. According to the visualization images in Figs. 7, 9, 11, 13 and 17, the rise in the cavitation area ratio induced by ΔT_i is found to be caused by the growth of the cavitation area from downstream to upstream of the recess area, which indicates that the value of ΔAc depends on the pumping effect of the recess. Therefore, the ΔAc values of the CFRs with $\theta_s = -45$ deg. are basically smaller than those of the CFRs with $\theta_s = 45$ deg., which means that the recess pumping effect of the CFR with $\theta_s = -45$ deg. is stronger than that of the CFR with $\theta_s = 45$ degree. These results can be considered to demonstrate that the pumping effect of the recess induced by the interaction between the source flow from the recess and the rotating flow caused by the journal rotation is stronger in the CFR with $\theta_s = -45$ deg. than in the CFR with $\theta_s = 45$ degree. In general, this feature would be easily predicted by the results obtained for the herringbone grooved journal bearings [13]. Therefore, it may be confirmed that the effects of the recess geometry on the flow characteristics of the cryogenic hybrid journal bearings are mainly caused by the influence of the θ_s value on the flow condition.

However, the strong pumping effect induced by the recess leading edge of the HJB with $\theta_s = -45$ deg. may produce a large pressure fluctuation in the circumferential direction on the bearing inner surface, which seems to excite journal vibration for the cryogenic HJB. The average values of ΔH and ΔV obtained for over 60,000 rpm in Fig. 2 are plotted against the sweepback angle of the recess leading edge in Fig. 20 [8]. An error bar of the average represents the standard deviation ($\pm \sigma$), and the average rotational speed of each type is about $N = 64,000$ rpm, respectively. Each line represents the fitting curve. The amplitudes of rotor vibration obtained for $N > 60,000$ rpm are found to decrease monotonically with the increase in θ_s , which indicates that the rotor vibration depends strongly on the sweepback angle of the recess leading edge in the high-rotational-speed operation. Since a source flow from the recess interferes with the rotating flow induced by the journal rotation in the bearing clearance, $\theta_s = -45$ deg. is considered to cause a stronger disturbance flow than that of $\theta_s = 45$ deg. in the high-rotational-speed operation where the hydrodynamic effect is predominant. This may be one of the main reasons why the

Fig. 20 Comparisons of the horizontal and vertical amplitudes (ΔH and ΔV) of the rotor vibration for Types D, Ca and Ba of HJBs in the high-rotational-speed operation [8]

dependence of the rotor vibration on the rotational speed was affected by the sweepback angle of the recess leading edge.

5 Conclusions

A flow visualization experiment in the clearance between a clear floating-ring (CFR) and a rotating journal was carried out in order to clarify the effects of the recess geometry on the flow characteristics. Five types of the CFRs with different recess geometries, i.e., the plane rhombus, the plane circle, the revise circular Young Leaf Mark, the dome and the revise dome geometries, were operated at a rotational speed of up to 40,000 rpm using liquid nitrogen as the working fluid to observe the interaction between source flow from the recess and rotating flow induced by the journal rotation in the clearance. The influence of the sweepback angle of the recess leading edge (θ_s) on the flow characteristics was investigated by the comparing flow coefficient (C_f) and the cavitation cloud area ratio (A_c) obtained from the visual image.

Based on the experimental results obtained for nine types of the CFRs with different recess geometries, the dependence of the flow characteristics on the rotational speed was verified to be affected by the sweepback angle of the recess leading edge. The results obtained in the steady-state and the transient-state demonstrated that the pumping effect of the recess induced by the interaction between the source flow from the recess and the rotating flow caused by the journal rotation is stronger in the CFR with $\theta_s = -45$ deg. than in the CFR with $\theta_s = 45$ deg., independent of the recess edge geometry.

Therefore, it may be considered that the effects of the recess geometry on the cryogenic HJBs are mainly caused by the influence of the sweepback angle of the recess leading edge on

the flow condition in the high-rotational-speed operation where the hydrodynamic effect is predominant.

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