



## Experimental Modeling of a Long Orifice-type Restrictor of High Speed Turbine Hybrid Bearing

F. Ji<sup>a</sup>, Y. M. Wang<sup>\*b,c</sup>, J. Tian<sup>a</sup>, Y. Y. Zhang<sup>a</sup>

<sup>a</sup> Xi'an Aerospace Propulsion Institute, Xi'an, China

<sup>b</sup> School of Automation, Xi'an University of Posts and Telecommunications, Xi'an, China

<sup>c</sup> State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, China

### PAPER INFO

#### Paper history:

Received 28 September 2014

Received in revised form 20 January 2016

Accepted 03 March 2016

#### Keywords:

Hybrid Bearing

Long Orifice-type Restrictor

Experimental Model

Liquid Nitrogen

### ABSTRACT

To overcome the space limitation of orifice-type and capillary restrictors in hybrid bearings, a kind of atypical long orifice-type restrictor is proposed and its experimental model is established. Through the analysis of the structure and flow rate of orifice-type restrictor and capillary restrictor, a long orifice-type restrictor and a feasible experimental modeling method are presented by use of orifice plate instead of the whole bearing. The flow rate of water film restrictors are tested under the aspect ratio of 4-10 and the pressure difference of 1.5-5.5 MPa and the experimental model of long orifice-type restrictor is established. The result shows that the restrictor of atypical structures needs to be modeled by experiment. The flow discipline of atypical restrictor is approximate to typical orifice-type restrictor and the throttling model is a nearly turbulent model.

doi: 10.5829/idosi.ije.2016.29.03c.12

### NOMENCLATURE

$\bar{Q}$	Dimensionless flow	$h_0$	Bearing clearance ( $\mu\text{m}$ )
$\bar{C}_d$	Restrictor's design coefficient	$B$	Flow dimension
$p_r$	Oil chamber pressure (MPa)	$m$	Constant value of 1 or 0
$p_s$	Inlet pressure (MPa)	$Q_{m2}$	Flow of orifice-type restrictor (g/s)
$\bar{p}_r = p_r / p_s$	Dimensionless form of pressure	$\bar{Q}_{m2}$	Dimensionless form of flow
$Q_{m1}$	Flow of capillary restrictor (g/s)	$v_c$	Outlet velocity (m/s)
$\bar{Q}_{m1}$	Dimensionless form of flow	$A_c$	Area of systolic section
$v_y$	Velocity of flow (m/s)	$C_q$	Flow coefficient between 0.6 and 0.7
$A$	Area of orifice section	$d_0$	Orifice diameter (mm)
$\Delta p$	Pressure difference	$\alpha_q$	Coefficient between 0 and 1
$d$	Diameter (mm)	<b>Greek Symbols</b>	
$l$	Length (mm)	$\eta$	Kinematic viscosity ( $\text{cm}^2/\text{s}$ )
$d_c$	Capillary pipe throttling diameter (mm)	$\delta$	Capillary throttling coefficient
$l_c$	Capillary pipe length (mm)	$\lambda$	Orifice-type throttling coefficient
$R$	Outer diameter of capillary (mm)	$\rho$	Density of lubrication medium ( $\text{kg}/\text{m}^3$ )
$r$	Inside diameter of capillary (mm)		

## 1. INTRODUCTION

Rolling bearings are significantly abraded when rocket engine is in the environment of low temperature, low

viscosity and heavy load. They have to be replaced after each flight and are hard to meet the requirements of new generation of turbine pump [1]. Hybrid bearing has become the first choice of new supporting component of turbine pump due to its excellent performance. The research on replacing rolling bearing with hybrid bearing

\*Corresponding Author's Email: xautroland@163.com (Y.M. Wang)

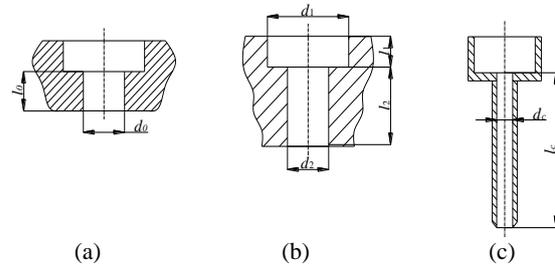
was developed very early in foreign countries and it is still in the stage of test and demonstration. The laminar, transition and turbulent models for different kinds of restrictors have been investigated by many researchers. Dwivedi et al. [2] studied the effect of different flow regimes including laminar, transition and turbulent flow condition on the static and dynamic performance parameter of hydrodynamic bearing. Manshoor et al. [3] investigated the performance characteristics of a thin film lubricated journal bearing based on three kinds of turbulent models. Shenoy and Pai [4] did much research on the stability characteristics of an externally adjustable fluid film bearing in the laminar and turbulent regimes. Bouard et al. [5] presented the influence of the flow regime on tilting-pad journal bearing performance by the use of three turbulent models. Khalil et al. [6] studied the effect of laminar and turbulent lubrication on the performance of externally pressurized circular and conical thrust bearings based on Reynolds stress model. Philippe and Antunes [7] proposed theoretical model and experiments on the nonlinear dynamics of parallel plates subjected to laminar/turbulent squeeze-film forces. Maneshian and Gandjalikhan Nassab [8] presented a thermohydrodynamic analysis of turbulent flow in journal bearings based on the computational fluid dynamic techniques. Deylami et al. [9] investigated heat transfer and pressure drop in a corrugated channel based on a RNG turbulence model. Renn and Hsiao [10] described the experimental and CFD study on the mass flow-rate characteristic through an orifice-type restrictor in aerostatic bearings. Chang et al. [11] investigated the influences of geometry and flow parameters on the discharge coefficients in aerostatic bearings with orifice-type restrictors.

Recently, China has verified the replacement possibility in the preliminary project and implemented a great number of theoretical and test researches including medium [12], complex three-dimensional field [13] and test [14-16]. However, the restrictor models in hybrid bearing are orifice-type restrictor and capillary restrictor model with certain constraint conditions [17], such as orifice jet condition, very long throttle pipe, etc. Due to the special property of lubrication medium, spatial environment of turbine pump as well as limitation of technological level, there is much difficulty in the computation of liquor inlet flow of liquid oxygen or hydrogen lubricating hybrid bearing using the present two models.

Moreover, the use of two models will result in the calculation errors of the bearing performance. To solve this problem, Dai et al. [12] established one kind of short capillary restrictor model. However, this model is only a simulation model and has not been verified by tests.

Based on the above analysis, this paper proposes long orifice-type restrictor structure base on hybrid bearing orifice-type and capillary restrictor structure analysis and mathematical model of flow. An orifice plate flow test is

designed and the flow of water lubricant under different pressures is tested. A long orifice-type restrictor experimental model is also constructed. The flow under liquid nitrogen lubricant is also measured and the proposed model is verified.



**Figure 1.** Restrictor: (a) orifice-type, (b) long orifice-type, (c) capillary.

## 2. THEORETICAL MODEL OF RESTRICTOR

**2. 1. Structure Type of Fixed Restrictor** Although the operating principle of hybrid bearing is similar to cylindrical bearing, cavity, hybrid bearing has its own distinct features because of the existence of fluid. In bearing operation, dynamic pressure effect appears at the boundary of fluid cavity and fluid cavity region has static pressure effect. Figure 1 shows three kinds of restrictors' structure; Figure 1 (a) and (c) show common orifice-type restrictor and capillary restrictor and Figure 1 (b) shows new type of atypical long orifice-type restrictor structure between common restrictor structures on the basis of national project research in earlier stages.

### 2. 2. Theoretical Model of Atypical Long Orifice-type Restrictor

The distinction between orifice-type restrictor ( $l/d < 4$ ) and capillary restrictor ( $l/d > 10$ ) is the value of aspect ratio. This paper presents a long orifice-type restrictor when aspect ratio is between 4 and 10. Dimensionless Equation of the flow passing through restrictor (capillary, orifice-type) is [18]:

$$\bar{Q} = \bar{C}_d (1 - \bar{p}_r)^m \quad (1)$$

In Equation (1), when  $m=1$ , it is capillary restrictor; when  $m=0.5$ , it is orifice-type restrictor;  $\bar{p}_r = p_r / p_s$  ( $p_r$  is oil chamber pressure,  $p_s$  is inlet pressure),  $\bar{C}_d$  is restrictor's design parameter. The flow of capillary restrictor ( $l/d > 10$ ) is:

$$Q_{m1} = \int_A v_y dA = \frac{\pi \Delta p d^4}{128 \eta l} \quad (2)$$

where  $A$  is the area of orifice section,  $v_y = \frac{\Delta p}{4 \eta l} (R^2 - r^2)$ ,  $\Delta p = p_s - p_r$  is the pressure difference,  $\eta$  is kinematic

viscosity. When flow dimension is  $B = \left( \frac{p_s h_0^3}{12\eta} \right)$ , the dimensionless form of the flow is:

$$\bar{Q}_{in1} = \frac{Q_{in1}}{B} = \frac{3\pi d_c^4}{32h_0^3 l_c} (1 - \bar{p}_r) \quad (3)$$

$$\bar{C}_d = \delta = \frac{3\pi d_c^4}{32h_0^3 l_c} \quad (4)$$

where  $d_c$  is capillary pipe throttling diameter,  $h_0$  is bearing clearance,  $l_c$  is capillary pipe length,  $\bar{p}_r = p_r/p_s$  is dimensionless form of pressure,  $h_0$  is bearing clearance.

When aspect ratio was less than 4 ( $l/d < 4$ ), the flow model performed like orifice outflow form model. The flow value can be calculated using Bernoulli's equation in the form:

$$Q_{in2} = A_c v_c = C_q \frac{\pi d_0^2}{4} \sqrt{\frac{2\Delta p}{\rho}} \quad (5)$$

where  $A_c$  is the area of systolic section,  $v_c$  is outlet velocity,  $C_q$  is flow coefficient (0.6~0.7),  $d_0$  is orifice diameter and  $\rho$  is density of lubrication medium. The dimensionless form of Equation (5) is:

$$\bar{Q}_{in2} = \frac{C_q \frac{\pi d_0^2}{4} \sqrt{\frac{2\Delta p}{\rho}}}{B} = \frac{3\sqrt{2}\pi C_q d_0^2 \eta}{h_0^3 \sqrt{\rho p_s}} \sqrt{1 - \bar{p}_r} \quad (6)$$

$$\bar{C}_d = \lambda = \frac{3\sqrt{2}\pi d_0^2 \eta}{h_0^3 \sqrt{\rho p_s}} \quad (7)$$

According to incompressibility of fluid, the flow through restrictor  $\bar{Q}_{in}$  must be equal to the flow out of the controlled oil chamber  $\bar{Q}_{out}$ , i.e.

$$\bar{Q}_{in} = \bar{Q}_{out} \quad (8)$$

Because of the limit of spatial dimension of turbine pump, inner and outer diameter of hybrid bearing is very small, causing the length of liquor inlet hole on the bearing to be very small. In the meantime, the diameter of liquor inlet hole cannot be too small due to technological reason. So the applied restrictor device can neither really meet the condition of capillary restrictor nor meet the condition of orifice-type restrictor, resulting in the difficulty in flow calculation when using this liquor inlet hole to perform throttling. In order to simplify the design of bearing, the liquor inlet hole on the bearing will be directly used for throttling instead of the additional restrictor, and the precise calculation of flow passing through liquor inlet hole during throttling will become particularly important. This paper proposed a model with explicit

physical significance solving particular flow problem. The following flow model named long orifice-type restrictor model has dimensionless form as:

$$\bar{Q}_{in} = \alpha_q \bar{Q}_{in1} + (1 - \alpha_q) \bar{Q}_{in2} \quad (9)$$

where  $0 \leq \alpha_q \leq 1$  and it is the correlation coefficient that describes the connection between long orifice-type restrictor and the other two restrictors including the orifice-type and capillary restrictors. In particular, when  $\alpha_q = 0$ , it is orifice-type restrictor model; when  $\alpha_q = 1$ , it is capillary restrictor model. The dimension of liquor inlet hole is between dimension of capillary and orifice-type restrictor and the proposed model has the features of two typical kinds of restrictor. The coefficient  $\alpha_q$  can be determined based on the experiment and the conservation law of fluid flow. From Equations (1) ~ (9), we can infer:

$$\alpha_q \cdot \delta (1 - \bar{p}_r) + (1 - \alpha_q) \cdot \lambda (1 - \bar{p}_r)^{\frac{1}{2}} = \bar{Q}_{out} \quad (10)$$

where  $\alpha_q$  is the coefficient between 0 and 1,  $\delta$  is capillary throttling coefficient,  $\lambda$  is orifice-type throttling coefficient. It can be seen from Equation (10) that the influencing factors of bearing flow in long orifice-type restrictor model includes capillary restrictor coefficient and orifice-type restrictor coefficient, as well as long orifice-type restrictor coefficient.

### 3. TEST DESIGN AND EXPERIMENT RESULTS

#### 3. 1. Test Design and Results

According to restrictor's evolution mechanism and flow calculation equation, the design adopts throttling orifice plate for flow test and test sketch is shown in Figure 2. Thickness of orifice plate is fixed value. As the aperture and pressure of both sides of orifice plate changes, the flow passing through throttling hole is measured and the relationship between flow and aspect ratio and pressure difference of throttling hole is analyzed. The throttling hole flow with water medium is tested. The test parameters includes throttling aperture  $d(0.5-4\text{mm})$  and different pressures  $P(1.5-5.5\text{MPa})$ , and the known orifice plate length  $l=5\text{mm}$ . Table 1 shows experiment values and Table 2 shows the flow values calculated with orifice-type restrictor and capillary restrictor equations, respectively. Letter "O" denotes Orifice-type Restrictor and letter "C" denotes Capillary Restrictor in Table 2.

#### 3. 2. Error Analysis and Construction of Long Orifice-type Restrictor Experimental Model

It can be seen from Table 1 and Table 2 that the flow test value is similar to calculated results of orifice-type restrictor model, but far away from calculated results with capillary restrictor model. According to flow

calculation equation, restrictor flow will increase as pressure difference and aperture increases. Figure 3

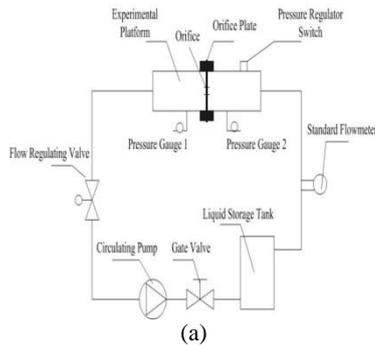
shows the curve of orifice plate flow of different aspect ratios with pressure difference.

**TABLE 1.** Aqueous medium restrictor flow test data (pressure units MPa, flow units  $g \cdot s^{-1}$ )

$P_1$	$P_2$	$\Delta P$	$Q_1 (l/d=10)$	$Q_2 (l/d=5)$	$Q_3 (l/d=2.5)$	$Q_4 (l/d=1.67)$	$Q_5 (l/d=1.25)$
1.5	0	1.5	12	40	123	285	497
2.5	0	2.5	15.5	51.4	158.4	365	640
3.5	0	3.5	18.4	61.1	187	428	758
4.4	0	4.4	21.3	68	209	484	851
5.5	0	5.5	24.5	76.5	236	539	944

**TABLE 2.** Aqueous medium restrictor calculated flow data (pressure unit MPa , flow units  $g \cdot s^{-1}$ )

$\Delta P$	flow $Q_1 (l/d=10)$		flow $Q_2 (l/d=5)$		flow $Q_3 (l/d=2.5)$		flow $Q_4 (l/d=1.67)$		flow $Q_5 (l/d=1.25)$	
	OR	CR	OR	CR	OR	CR	OR	CR	OR	CR
1.5	8	4.6	30	7.3	120	117.2	271	593.1	482	1874.6
2.5	10	7.6	39	12.2	156	195.3	350	988.6	622	3124.4
3.5	12	10.7	46	17.1	184	273.4	414	1384.0	736	4374.1
4.4	13	13.4	52	21.5	206	343.7	464	1739.9	825	5498.9
5.5	14	16.8	58	26.9	231	429.6	519	2174.9	923	6873.6



**Figure 2.** Orifice plate flow test system sketch

When the throttling aperture with the same length has difference of more than two times, the flow passing through restrictor has the difference of an order of magnitude. The curve shows influence law of restrictor's geometrical parameter on the performance of hybrid bearing. Figure 4(a) and Figure 4(b) show the error ratio between measured value and calculated value of orifice plate flow under different restrictor models as inlet and outlet pressure difference changes, where ratio  $l/d$  is 2.5 and 10 respectively, and outlet pressure  $P_2$  is 0. It can be known from the figure: when restrictor's aspect ratio  $l/d < 4$ , flow measured value is close to the calculated value using orifice-type restrictor model, the error between them changes not much as inlet and outlet pressure difference increases about 2%; measured flow value is very different from the calculated value using capillary restrictor model, the error between appears

linear variation as inlet and outlet pressure difference increases. The pressure difference is 5.5MPa especially, the error increases to 80%. When restrictor's aspect ratio  $4 < l/d < 10$ , no matter what kind of typical restrictor model is used, flow measured value is very different from calculated value and orifice-type restrictor error curve appears in rising trend. As inlet and outlet pressure difference increases, the capillary restrictor error curve appears in rapid descending trend.

According to the above analysis, orifice-type restrictor model can be used for flow calculation when aspect ratio is within (0, 4). When aspect ratio is within (4, 10), there is not proper restrictor model. In this paper, the measured data can be fitted on the interval to obtain experimental equation of long orifice-type restrictor model under water lubrication medium in the form:

$$Q = (0.042 \frac{l}{d} + 0.7) \frac{\pi d^2}{4} \sqrt{\frac{2(p_s - p_r)}{\rho}}, \quad 4 \leq \frac{l}{d} \leq 10$$

$$Q = 0.7 \frac{\pi d^2}{4} \sqrt{\frac{2(p_s - p_r)}{\rho}}, \quad 0 \leq \frac{l}{d} < 4 \quad (11)$$

The meaning of Equation (11) is that we can obtain complete model of restrictor with  $0 < l/d \leq 10$  by experiment.

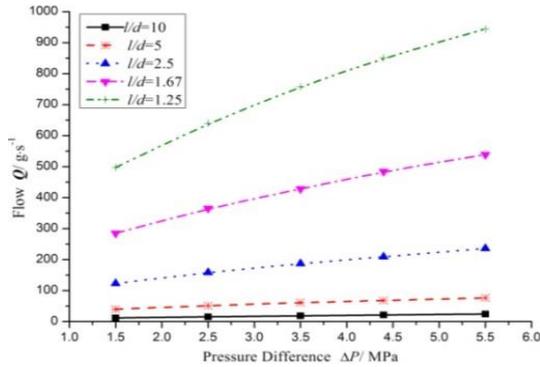


Figure 3. Orifice plate flow of different aspect ratios with pressure difference

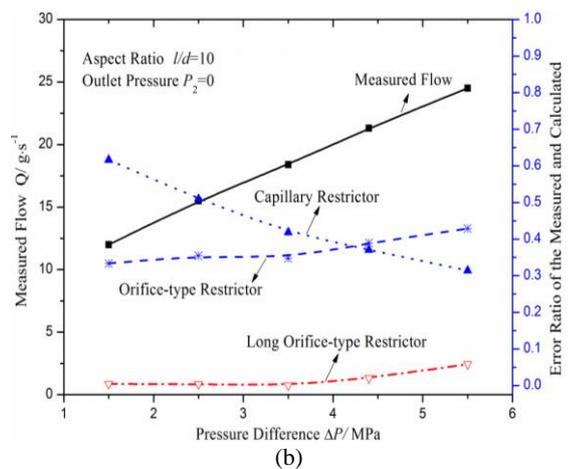
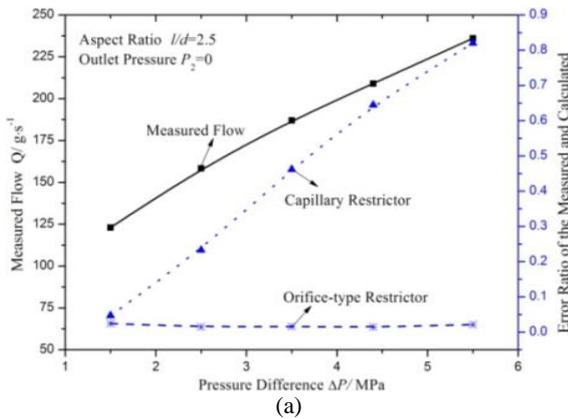


Figure 4. Error ratio between flow measured value and calculated value

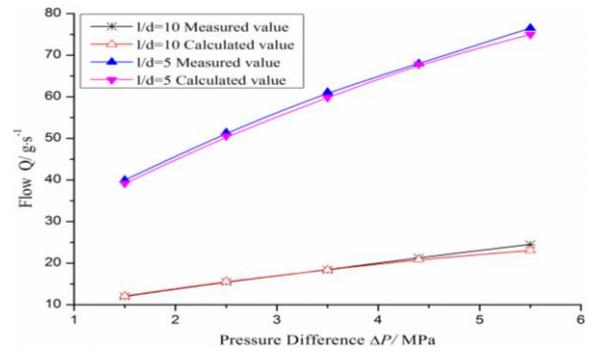


Figure 5. Comparison of flow measured and calculated values with  $l/d=10$  and  $l/d=5$

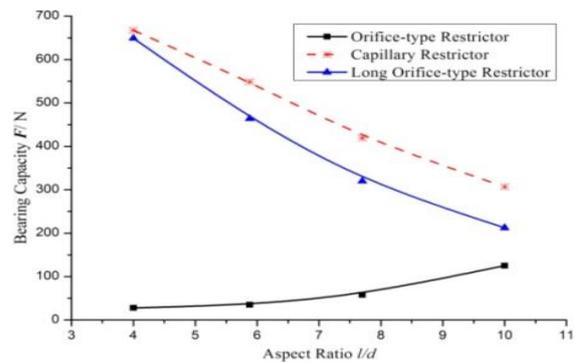


Figure 6. Bearing capacity and aspect ratio under different restrictor models

But we should also understand that this type of test is not easy. Especially, the medium of test is liquid nitrogen. We have drawn the flow curve of calculated and experiment values for long orifice type restrictor in the range  $l/d = 10$  and  $l/d = 5$  in Figure 5 to verify the proposed model.

The long orifice-type restrictor model constructed from the experimental results conjecture that the flow state of lubrication medium is transition state from laminar state to turbulent state. The Reynolds number can be calculated by:

$$Re = \frac{\rho v d}{\mu} = \frac{998 \text{ kg/m}^3 \times 9.4 \text{ m/s} \times 0.0005 \text{ m}}{1.01 \times 10^{-3} \text{ Pa}\cdot\text{s}} = 4645$$

when  $Re < 2000$ , the flow state of lubrication medium is laminar; when  $Re > 4000$ , the flow state of lubrication medium is turbulent. Therefore, the flow state of lubrication medium is transition state from laminar to turbulent state and long orifice type model in this paper is roughly turbulent model.

On the basis of hybrid bearing performance simulation procedure programmed by our project team, the bearing capacity of certain type of hybrid bearing with capillary restrictor model, orifice-type restrictor model and long orifice-type restrictor model are calculated respectively. Basic parameters of

computational examples: four oil chambers, inner diameter of bearing 30 mm, outer diameter 62 mm, width 16 mm, oil chamber depth 1.5 mm, oil chamber length 7.85 mm, and oil chamber width 8 mm; oil supply pressure is 10 MPa, bearing radius clearance 30  $\mu\text{m}$ , rotating speed 29000  $\text{r}\cdot\text{min}^{-1}$ , and eccentricity 0.2, water lubrication, medium density is 998.22  $\text{kg}\cdot\text{m}^{-3}$ . Restrictor aspect ratio  $l/d$  respectively takes 4, 5.9, 7.7 and 10, length  $l=5\text{mm}$ .

Figure 6 shows the change of bearing capacity and aspect ratio under different restrictor models. Data analysis indicates that bearing capacity under different restrictor models is much different. As mentioned in the literature and the experimental results indicate, the load capacity cannot be determined by the flow rate. For the orifice restrictor, the change of diameter can lead to the change of oil chamber pressure and the change of load capacity. It means that when the diameter decreases and  $l/d$  remains, the oil chamber pressure will increase, the hydrostatic effect will be strengthened and the load capacity will increase. The hydrostatic effect of oil inlet hole is not strong in the experiment of capillary pipe and long orifice type restrictor models. As increasing the diameter of restrictors, the oil chamber pressure and the load capacity will decrease. Typical orifice-type restrictor model and capillary restrictor model cannot meet restrictor's bearing performance simulation analysis when aspect ratio  $4 \leq l/d \leq 10$  and the atypical long orifice-type restrictor model provides technical support for this type of restrictor and design of bearing in the high-speed turbo pump. In other words, when aspect ratio  $4 \leq l/d \leq 10$  the long orifice-type restrictor model can be applied for design of bearing in the high-speed turbo pump to overcome the space limit of orifice-type and capillary restrictors in hybrid bearings. The long orifice-type restrictor model can be only used at the condition of aspect ratio  $4 \leq l/d \leq 10$ .

### 3.3. Experimental Verification of the Long Orifice-type Restrictor Model with Liquid Nitrogen

The long orifice-type restrictor model was obtained by test with water lubricant in previous section. In order to verify the correctness of the model, the flow of liquid nitrogen was measured in this section. In liquid nitrogen experiment, when the aspect ratio of orifice plate is respectively 2.5 and 1.67 ( $0 < l/d < 4$ ), theoretical value of flow was calculated using Equation (11) in long orifice-type restrictor model. The model has been validated through comparison of measured and calculated values. Figure 7(a) and Figure 7(b) show the measured and calculation values of liquid nitrogen flow along with pressure difference when restrictor aspect ratio is 2.5 and 1.67, respectively. It shows that it is a certain deviation between the calculated value and measured value of liquid nitrogen flow. It was also found that the error ratio is about 0.2, namely the measured value of

liquid nitrogen flow is about 80% of the calculated value. The phenomenon of aerosol and cavitation were founded in the experiment. Accordingly, the problem of two-phase (liquid-vapor) lubrication existed in the experiment.

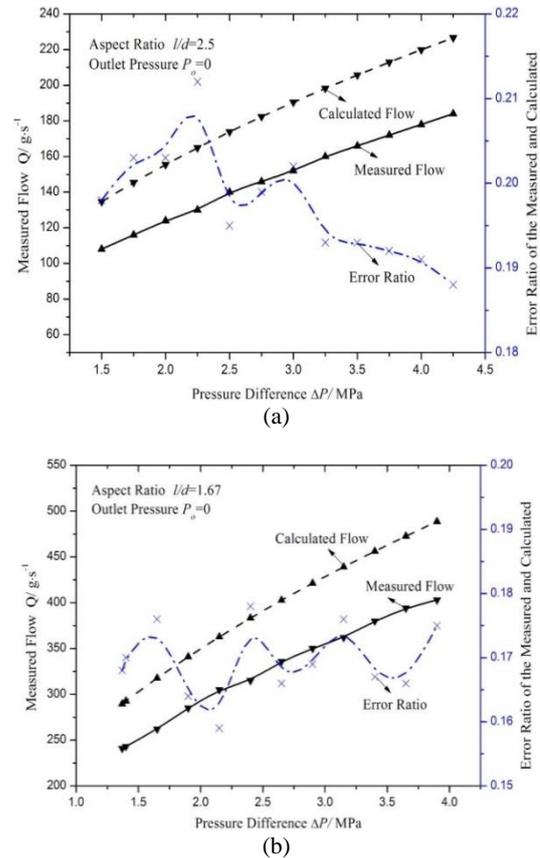


Figure 7. Error ratio between flow measured value and calculated value

In summary, the proposed long orifice-type restrictor model under the respective water and liquid nitrogen lubricants are tested and verified. Equation (11) gives a complete flow rate model with  $0 < l/d \leq 10$ , where the orifice-type restrictor model can be used at the condition  $0 < l/d < 4$  and the long orifice-type restrictor model can be used at the condition  $4 \leq l/d \leq 10$ . The appropriate models can be selected according to restrictor's  $l/d$  in the engineering. The research results can provide first-hand test data support for hybrid bearing of high-speed rocket engine turbo pump.

### 4. CONCLUDING REMARKS

The restrictor model is needed for the performance calculation or simulation of high-speed hybrid bearing. The practice of this paper indicates that restrictor with

atypical structure needs test modeling and one feasible program of test modeling is given using orifice plate instead of the whole bearing. Considering one kind of long orifice-type restrictor similar to typical orifice-type restrictor, the experimental work was to measure the flow of such atypical restrictor with water as lubrication medium; the restrictor aspect ratio (4-10) and pressure difference (1.5-5.5 MPa), indicated the flow law is similar to typical orifice-type model.

Based on the test modeling method of short capillary restrictor model in the literature [8], one analytic express that combines the typical capillary and orifice-type models was used to simulate or fit the experimental data published in this paper. The test model of such atypical restrictor was also obtained. Because the nature is inclined to typical orifice-type model, it is named as long orifice-type restrictor model.

Traditionally, the establishing models are divided into four types of jet flow, laminar flow, turbulence and transition region; jet flow and laminar flow models respectively correspond to restrictor with typical orifice-type and capillary structure, and long orifice-type restrictor model in this paper is roughly turbulence model.

## 5. ACKNOWLEDGMENT

This work was supported by National Natural Science Foundation of China (No. 51575418), Natural Science Foundation of Shaanxi Province of China (No. 2014JQ7252), Open Fund of State Key Laboratory for Strength and Vibration of Mechanical Structures (SV2015-KF-04), and New Star Team of Xi'an University of Posts and Telecommunications.

## 6. REFERENCES

1. Yang, Z., San Andres, L. and Childs, D.W., "Thermal effects in liquid oxygen hydrostatic journal bearings", *Tribology Transactions*, Vol. 39, No. 3, (1996), 654-662.
2. Dwivedi, V.K., Chand, S. and Pandey, K., "Effect of different flow regime on the static and dynamic performance parameter of hydrodynamic bearing", *Procedia Engineering*, Vol. 51, (2013), 520-528.
3. Manshoor, B., Jaat, M., Izzuddin, Z. and Amir, K., "CFD analysis of thin film lubricated journal bearing", *Procedia Engineering*, Vol. 68, (2013), 56-62.
4. Shenoy, B. and Pai, R., "Stability characteristics of an externally adjustable fluid film bearing in the laminar and turbulent regimes", *Tribology International*, Vol. 43, No. 9, (2010), 1751-1759.
5. Bouard, L., Fillon, M. and Frene, J., "Comparison between three turbulent models—application to thermohydrodynamic performances of tilting-pad journal bearings", *Tribology International*, Vol. 29, No. 1, (1996), 11-18.
6. Khalil, M., Kassab, S. and Ismail, A., "Performance of externally pressurized conical thrust bearing under laminar and turbulent flow conditions", *Wear*, Vol. 166, No. 2, (1993), 147-154.
7. Piteau, P. and Antunes, J., "A theoretical model and experiments on the nonlinear dynamics of parallel plates subjected to laminar/turbulent squeeze-film forces", *Journal of Fluids and Structures*, Vol. 33, (2012), 1-18.
8. Maneshian, B. and Gandjalikhan Nassab, S., "Thermohydrodynamic characteristics of journal bearings running under turbulent condition", *International Journal of Engineering Transcatons A: Basics*, Vol. 22, (2009), 181-194.
9. Deylami, H.M., Amanifard, N., Sanaei, M. and Kouhikamali, R., "Numerical investigation of heat transfer and pressure drop in a corrugated channel", *International Journal of Engineering Transcatons A: Basics*, Vol. 26, No. 7, (2013), 771-780.
10. Renn, J.-C. and Hsiao, C.-H., "Experimental and CFD study on the mass flow-rate characteristic of gas through orifice-type restrictor in aerostatic bearings", *Tribology International*, Vol. 37, No. 4, (2004), 309-315.
11. Chang, S., Chan, C. and Jeng, Y., "Numerical analysis of discharge coefficients in aerostatic bearings with orifice-type restrictors", *Tribology International*, Vol. 90, (2015), 157-163.
12. Dai X.Y., Yuan X.Y. and Miao X.S., "Analysis of a hybrid bearing with several low-viscosity fluids", *Lubrication Engineering*, Vol., No. 39, (2004), 10 - 13.
13. Xiaoyang, Z.G.Y., "A theoretical study on three-dimensional pressure distributions and temperature field of water-lubricated hydrostatic journal bearings [j]", *Lubrication Engineering*, Vol. 8, (2006).
14. Zhang, G., Yuan, X., Zhou, M. and Liu, S., "Hybrid journal bearings for cryogenic liquid rocket engine turbopumps", in Proceedings of ICMEM2005 (International Conference on Mechanical Engineering and Mechanics), (2005), 210-215.
15. Yuan, X., Zhang, G., Li, B. and Miao, X., "Theoretical and experimental results of water-lubricated, high-speed, short-capillary-compensated hybrid journal bearings", in STLE/ASME International Joint Tribology Conference, *American Society of Mechanical Engineers*, (2006), 391-398.
16. Zhang G.Y., Yuan X.Y. and Miao X.S., "Experiment for water-lubricated high-speed hydrostatic journal bearings", *Tribology International*, Vol. 26, No. 3, (2006), 73-80.
17. Zhang, G. and Liu, Z., "Performance analysis of membrane restrictor hybrid journal gas bearings", *Jixie Gongcheng Xuebao (Chinese Journal of Mechanical Engineering)*, Vol. 47, No. 3, (2011), 73-80.
18. Sharma, S.C., Jain, S. and Mohan Reddy, N.M., "A study of non-recessed hybrid flexible journal bearing with different restrictors", *Tribology Transactions*, Vol. 44, No. 2, (2001), 310-317.

## Experimental Modeling of a Long Orifice-type Restrictor of High Speed Turbine Hybrid Bearing

F. Ji<sup>a</sup>, Y. M. Wang<sup>b,c</sup>, J. Tian<sup>a</sup>, Y. Y. Zhang<sup>a</sup>

<sup>a</sup>*Xi'an Aerospace Propulsion Institute, Xi'an, China*

<sup>b</sup>*School of Automation, Xi'an University of Posts and Telecommunications, Xi'an, China*

<sup>c</sup>*State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, China*

---

### PAPER INFO

چکیده

---

#### Paper history:

Received 28 September 2014

Received in revised form 20 January 2016

Accepted 03 March 2016

---

#### Keywords:

Hybrid Bearing

Long orifice-type Restrictor

Experimental Model

Liquid Nitrogen

برای غلبه بر محدودیت فضای محدودسازهای نوع اریفیس و مویرگی در یاطاقان های ترکیبی، یک نوع محدود ساز آتیپیک بلند از نوع اریفیس پیشنهاد شده است و مدل تجربی آن ایجاد شده است. از طریق تجزیه و تحلیل ساختار و نرخ جریان در محدودساز نوع اریفیس و مویرگی، یک محدودساز نوع اریفیس بلند و یک روش مدل سازی تجربی با استفاده از صفحه ارفیس به جای تمام بلبرینگ ارائه شده است. نرخ جریان محدودسازهای فیلم آب در نسبت ابعاد ۱۰-۴ و اختلاف فشار از ۱/۵-۵/۵ مگاپاسکال تست شده است و مدل تجربی محدودساز نوع اریفیس بلند ایجاد شده است. نتیجه نشان می دهد که محدود ساز آتیپیک باید توسط آزمایش مدل سازی شود. نظم و انضباط جریان محدود ساز آتیپیک تقریباً مشابه محدودساز نوع اریفیس معمولی است و مدل گلوگاه یک مدل تقریباً آشفته است.

**doi:** 10.5829/idosi.ije.2016.29.03c.12

---