CFD Investigation on the Performance of Aerostatic Thrust Bearing With Exhaust Slots Used in Low-vacuum Condition

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***Abstract*—This paper analyzes the performance of aerostatic thrust bearing working in low-vacuum condition using Computational Fluid Dynamics (CFD) software Fluent. Load Carrying Capacity (LCC), stiffness, gas leakage of the bearings with different geometrical structures are calculated and the results indicate that gas leakage can be reduced greatly by double exhaust slots, smaller film thickness, wider exhaust slot and larger slot distribution radius. The conclusions of the paper can be used for the designing of aerostatic thrust bearing used in vacuum condition.**

Keywords-Aerostatic thrust bearing; Exhaust slot; Low-vacuum condition

I. INTRODUCTION

Aerostatic bearing has been widely used in ultra-precision measuring instruments, machine tools and computer peripheral devices for its minimal friction, low heat generation and high precision. With the development of vacuum technology and Micro Electro Mechanical Systems (MEMS), more and more devices, like EUV exposure, interferometric measurement, high precision semiconductor inspection and IC manufacturing will be operated in vacuum condition. Therefore, many scholars researched the vacuum compatible aerostatic bearing numerically and theoretically in recent years.

Devitt and Kirkpatrick [1] designed a precision air bearing stage with a moving vacuum chamber. The main feature was that the stage is part of the vacuum chamber. All motion elements were outside the chamber. Furthermore, chamber volume was very small and the cost was significantly reduced. Nils developed a contact-free exhaust system for vacuum compatible gas bearing guides and a vacuum of 10^{-4} Pa was achieved [2]. Trost designed a hydrostatic bearing for vacuum application and mathematics model of the bearing was constructed for calculating the flow characteristics in the passage between the first and second groove [3]. Schenk [4] analyzed the performance of aerostatic bearing working in high-vacuum environment or ambient condition Results indicated that stiffness and gas load of the bearing pads are significantly degraded. Moreover, the operating point of the orifice-bearing pad is shifted to larger gap height at vacuum conditions. Gyungho [5] investigated the pressure rising characteristics of vacuum chamber induced by air bearing stage moving at different velocities. Also, additional leakage resulting from the feeding motion was researched.

Actually, the influence of slot distribution radius and slot width on the performance of condition has not been studied. In this paper, the influence of above parameters on gas leakage and LCC of the bearing is analyzed and some conclusions are obtained for the parameters determination.

II. BEARING STRUCTURE

Flat aerostatic circular orifice-bearing pads used in vacuum condition with single-exhaust slot and double-exhaust slot are investigated. Because the structure model is symmetric and the flow speed is only relevant with radial distance, having nothing to do with rotation angle. In order to save calculation time, the model can be simplified as two-dimensional profile model through symmetry axis. Geometrical structure of bearings with single-exhaust slot and double-exhaust slot are shown in Fig.1(a) and Fig.1(b) respectively, where D=60 mm, d=0.1 mm, u=0.5 mm, v=0.5 mm, other parameters vary with different need in simulation. (shown in Table.1)

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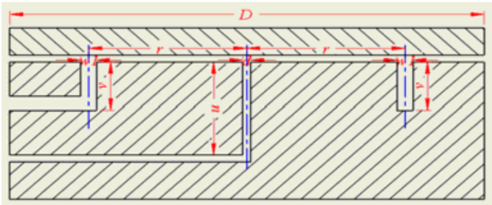
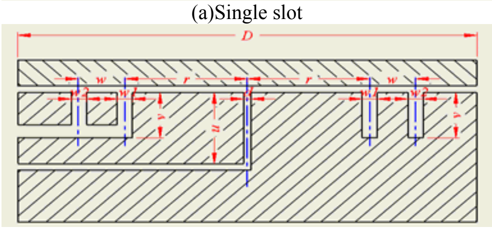


(a)Single slot



(b) Double slot

Fig.1 The bearing model using in vacuum condition

Table 1. THE BEARING PARAMETERS TO BE CALCULATED

No.	*r*(mm)	*w*1(mm)	*w*2(mm)	*h*(μm)
1	20	2	2	2~20
2	20	2	0	2~20
3	20	1~6	0	8
4	16~24	2	0	8

h=2, 4, 6, 8, 10, 12, 14, 16, 18 and 20μm; *w*1=1, 2, 3, 4, 5 and 6mm; *r* =16, 18, 20, 22 and 24mm.

Using Gambit, the preprocessor of Fluent, we construct the grid model. As is shown in Fig.2, there are five wall boundaries for the mode with double slots: inlet, outlet1, outlet2, outlet3, axis and walls. To improve mesh quality and calculation accuracy, quadrilateral elements are adopted and there are 100 nodes/mm on ordinary walls. Critical sections need increase the nodes number properly, hence the nodes on inlet and outlet3 are 500 and 1000/mm respectively, 200 nodes per millimeter are set on outlet1 and outlet2.

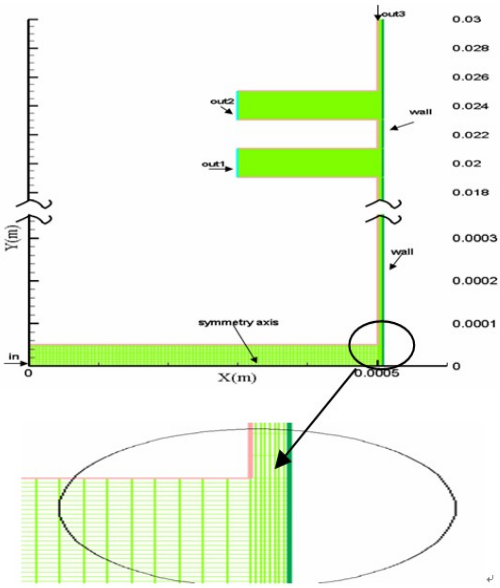


Fig.2 Grids of model with double-slot

In the simulations, implicit solver is selected and k-epsilon turbulence model is selected to calculate the pressure distribution inside the bearing. The gas is considered to be ideal-compressible and the pressure boundaries are as following: inlet pressure 0.5 MPa, the pressure of outlet1, outlet2 and outlet 3 is all 0Pa. It's notable that operation pressure is 0.001MPa and its position coordinate is at (0.3, 20). Moreover, residual curves, outlet mass flow rate and pressure are monitored to ensure a reliable convergence.

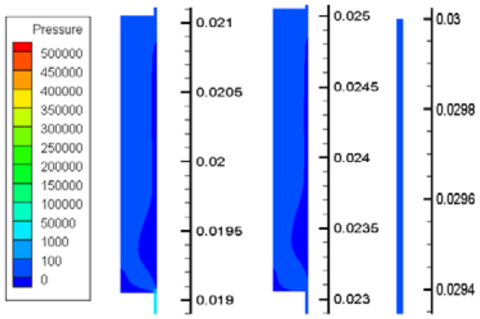


Fig.3 Pressure contours

Fig.3 is the contours of Pressure in the first slot, second slot and outlet3, in the bearing, pressurized gas through the orifice gets into bearing clearance, and continuously vented to vacuum chamber from bearing outlet after pumped by first and second exhaust tank. In order to maintain the vacuum pressure in vacuum chamber, low gas leakage is needed. From the Figure.3, we can see, gas pressure in exhaust slot is small enough especially after the second slot. It means the leakage flow is little, therefore, exhaust slot is very effective and plays a main role in the vacuum maintaining, of course, numerical results will be analyzed in the following discussion.

III. PERFORMANCE ANALYSIS OF THE BEARING WITH SINGLE-SLOT OR DOUBLE-SLOT EXHAUST GROOVE

As is mentioned above, for vacuum compatible gas bearing, the first factor we should consider is the leakage flow, it determined directly the vacuum quality. Generally, most of the gas is exhausted to outside by vacuum pump, so in this paper, the gas flux in outlet3 is used as a variation to study the gas leakage flow.

Table 2. GAS LEAKAGE IN DIFFERENT FILM THICKNESS

film thickness (μm)	Single (kg/s)	Double (kg/s)	magnitude difference
2	1.4e-19	1.9e-30	10
4	2.5e-18	7.42e-29	10
6	1.63e-17	1.42e-27	10
8	6.0e-17	6.36e-27	9
10	1.66e-16	4.76e-26	9
12	6.14e-16	1.31e-25	9
14	8.6e-16	5.58e-25	9
16	1.85e-15	7.7e-25	9
18	2.66e-15	2.4e-24	9
20	3.99e-15	6.0e-24	8

It can be seen from table.2 that the gas leakage flow increases with film thickness for both single-slot and double-slot bearings. And gas leakage can be reduced by eight orders of magnitude at least if a second slot is added. The calculation results coincide with that of Schenk in reference [4].Therefore, double or more exhaust slots are recommended for bearings working in high-vacuum.

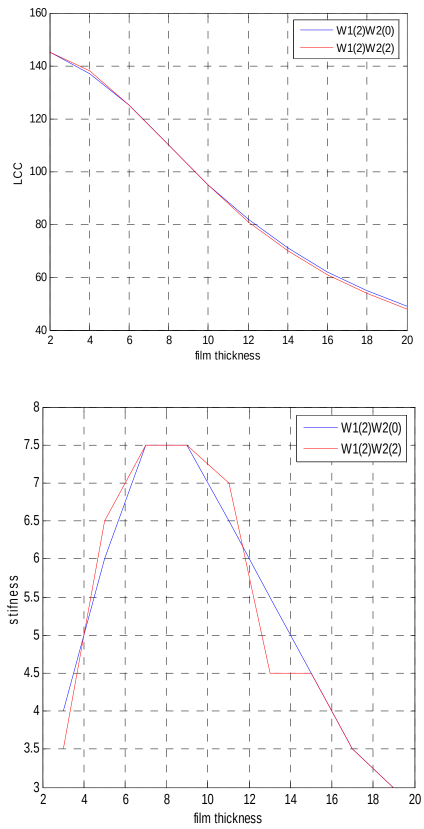


Fig.4 LCC and stiffness of single-slot and double-slot

Fig.4 shows that LCC decreases with film thickness, while stiffness first increases and then decreases. Furthermore, stiffness reaches the maximum value when film thickness is 8μm. There is less difference for LCC of bearings with one slot or two slots. From above analysis, it can be concluded that double-slot bearings can reduce gas leakage greatly and maintain LCC and stiffness at the same time.

IV. Influence of Exhaust Slot Width and Distribution Radius on Bearing's Performance

Table 3. Gas leakage flow, LCC in different slot width

slot width(mm)	Out3（kg/s）	LCC(N)
1	1.33e-14	115
2	5.8e-17	109.5
3	4.6e-19	104
4	1.6e-21	98.5
5	2.1e-23	93.3
6	4.9e-26	88

In order to analyze the influence of exhaust slot width on gas leakage flow and LCC, bearing model with the third geometric data in Table.1 is calculated. And results are as follows(Table.3), gas leakage flow and LCC decreases with the exhaust slot width if film thickness is constant

In the next, bearing model (NO.4 in table.1) is established to research the influence of exhaust slot position on the gas leakage and LCC. The simulation results are shown in Fig.5, with the same film thickness, as the slot distribution radius *r* increases, gas leakage and LCC increase.

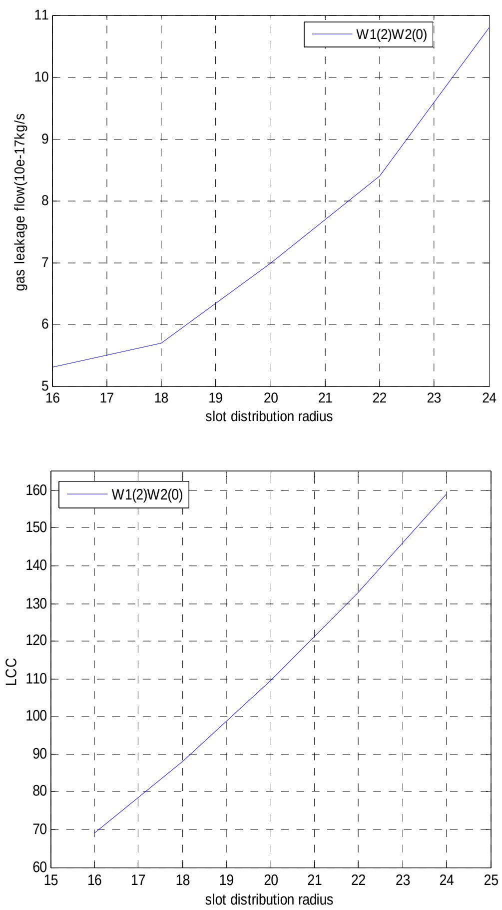


Fig.5 gas leakage, LCC with different distribution radius

V. Conclusion

In the paper, the effect of four variation (exhaust slot numbers, film thickness, exhaust slot width, slot distribution radius) on the performance of the bearing (gas leakage flow, LCC, stiffness) working in low vacuum condition is analyzed using CFD software Fluent. And the following conclusions can be obtained according to the calculation results.

(1) The bearing with double-slot can reduce gas leakage without decreasing LCC and stiffness. Therefore, it is desirable in the bearing working in high vacuum condition.

(2) For a certain value of film thickness, as the exhaust

slot width increases, gas leakage decreases, and LCC decreases linearly. So in order to improve bearing performance, larger exhaust slot width is needed.

(3) In the premise of gas leakage flow meeting the conditions, choosing larger distribution radius can achieve larger LCC.

Appendix. Nomenclature

D bearing diameter
d orifice diameter
u orifice depth
r distribution radius of the first exhaust slot
w1 the first exhaust slot width
w2 the second exhaust slot width
v slot depth
h film thickness

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