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Influence of flow parameters on static characteristics of porous aerostatic bearing

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Abstract: There is a wide variety of applications of aerostatic bearings in manufacturing such as those in precision machine tools and metrology equipment. As a specific type of aerostatic bearings, porous aerostatic bearings are more stable and stronger due to the use of porous materials. There is still not much research on the static characteristics influenced by flow-related parameters. In this paper, a mathematic model is proposed to simulate the static properties of porous aerostatic thrust bearings, including load-carrying capacity, mass flow rate and stiffness. The pressure distribution inside the bearing is analyzed by calculation based on Navier-Stokes equations. The flow factors and their effect on bearing static properties are then investigated. The findings indicate that, an increase in film thickness of the bearing shall cause load-carrying capacity decrease and also stiffness decrease. However, by increasing the thickness of porous layer the stiffness of the bearing can be effectively increased. In addition, the increased film thickness shall result in an increased mass flow rate into the bearing. These findings can be used to help design porous aerostatic bearings that are more efficient and able to handle higher loads.

Key words: porous aerostatic thrust bearing; film thickness; load-carrying capacity; static characteristics; mass flow rate

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1 Introduction

Aerostatic bearings are widely used in precision machinery and equipment due to their low friction, high precision, and high load-carrying capacity (LCC). The use of aerostatic bearings has significantly improved the

performance of machinery and equipment. In the past decade, the use of porous materials, thus porous aerostatic bearings, has attracted more and more attentions. This specific type of bearing has several benefits such as great precision and reduced friction^[1], and the load-carrying capacity as well as other characteristics are also significantly enhanced^[2]. The

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performance of porous aerostatic bearing is strongly influenced by various flow-related parameters, including film thickness, bearing thickness (which is the thickness of porous material, hence is also referred to as porous thickness), supply pressure (the pressure at the inlet), and so on. Therefore, understanding the influence of flow parameters on bearing characteristics is essential for the aerostatic bearing to deliver the desired performances.

Until present, there have been some studies on the characteristics of the porous aerostatic bearings. Sahto et al^[3] compared the various types of aerostatic porous restrictors and improved the load-carrying capacity with an increasing in the supply of air pressure. A finite difference approach has been used to numerically determine the co-efficient of discharge based on computational fluid dynamics (CFD)^[4]. The study on the pressure distribution of film and how manufacturing flaws affect porous aerostatic bearings has also been carried out^[5]. However, when disturbance like inertial effects or machining forces are present, the comparatively low stiffness of the bearings shall reduce the accuracy of the machine where such bearings are used^[6].

On the other hand, there are also some researches that are relevant to the study of porous bearings. For example, the distortions of the porous plates, sleeve and shaft were properly considered to compute the axial stiffness of an aerostatic spindle by using the transient FEM structure analysis, transient CFD fluid analysis, and mesh technology^[7]. The resultant quasi-static solutions, however, do not sufficiently describe the physics of the effects of gas lubrication films, despite being highly suitable for incompressible lubrications^[8]. The fluid-structure interaction (FSI) analysis of the porous aerostatic bearing is often based on the CFD approach. It takes longer to solve the governing equation of the air film based on FEM than it would be to analyze the pressure distribution of the air film using CFD simulation^[9]. Wang et al^[10] studied how manufacturing errors can affect the bearing's load-carrying capacity. They found that static performance is greatly affected by the film thickness and the pressure distribution. And, the

transient and steady state performances of porous bearings are still being investigated extensively due to the complexity of irregular structure of porous materials.

In this paper, we take the thrust bearing as the research object. The influence of supply pressure on the LCC of porous aerostatic thrust bearing is investigated first. Also studied is the influence of the bearing thickness on the LCC of the porous aerostatic thrust bearing. The Fluent CFD software is used for determination of the internal pressure distribution in the clearance of the bearing. Lastly, the impacts of supply pressure, film thickness and other parameters of the porous material on the stiffness of the porous aerostatic thrust bearing are investigated. The aim of this work is to understand the static characteristics of the porous aerostatic bearings so as to improve their performance, and to help ensure that they can support the required load without excessive deformation or wear.

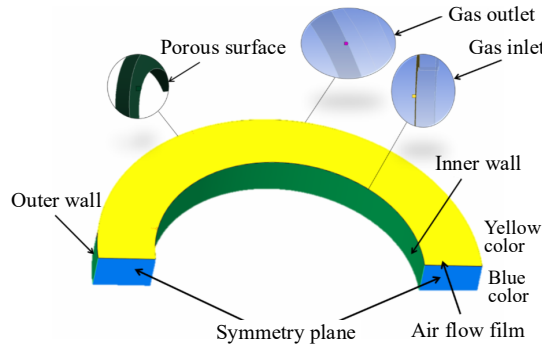
2 Modeling of porous aerostatic bearing

2.1 Structure of porous restrictor

Different from ordinary aerostatic thrust bearings, a porous thrust bearing consists of an important component called porous restrictor, which is used to generate air film between the bearing body and the shaft or any other mechanical structure that is to be supported by the bearing. Besides, the porous restrictor also has the strength of producing a more even pressure distribution of air, as compared with other mechanisms that are also capable of generating air film^[11]. At the working mode, air flows into the bearing body through inlet, which is then blown into the porous material of the restrictor at a specified pressure called supply pressure. Through this porous material, the outflow of air shall then produce the required air film, which shall determine the load-carrying capacity of the bearing.

It is necessary to build up a model of a restrictor and an air film for studying the static characteristics of porous bearing. For simplicity of elaboration, we refer

to the modeling of porous restrictor and air film as the modeling of porous aerostatic bearing itself. In this paper, ANSYS workbench is used to establish the finite element model of the bearing. Fig. 1 shows the geometric construction of the restrictor, where half of the geometry is shown as this is to be used to generate the corresponding mesh model. The geometric parameters of the restrictor, together with other essential data used in this study, are shown in Table 1.



Remarks: yellow color shows where the air film is located and bearing thickness refers to height of the blue part.

Fig. 1 Geometric construction of a porous bearing

Table 1 Design parameters and computational conditions for porous bearing

Parameters	Units	Values
Inside diameter	μm	56 000
Outside diameter	μm	80 000
Outlet pressure	MPa	0
Supply pressure	MPa	0.4~0.6
Atmospheric pressure	kPa	101.325
Temperature	K	291.143
Inertial resistance		2.5×10^7
Fluid	Laminar	
Solution method	SIMPLEC	
Standardization solution	Standard initialization	
Co-efficient of viscous resistance	m^{-2}	1.27×10^{14}
Porosity		0.3
Density	$\text{kg} \cdot \text{m}^{-3}$	Ideal gas
Bearing thickness	mm	4~8
Film thickness	μm	4~21
Specific heat (C_p)	$\text{J} \cdot (\text{kg} \cdot \text{K})^{-1}$	1 006.43
Thermal conductivity	$\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$	202.4
Viscosity	$\text{kg} \cdot (\text{m} \cdot \text{s})^{-1}$	$1.789 4 \times 10^{-5}$
Weight of molecular	$\text{g} \cdot \text{mol}^{-1}$	28.966

2.2 Governing equation

As mentioned above, the flow of air is slowed down by the resistance it faces as it passes through the porous medium^[12]. Fig. 2 illustrates the diagram of the porous aerostatic thrust bearing, where d_1 and d_2 indicate the outside and inside diameters respectively, H and h refer to the size of air chamber and air film thickness respectively, p_s and p_o indicate initial supply pressure and out air pressure respectively.

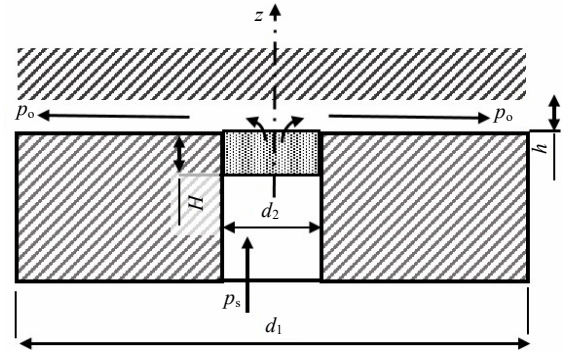


Fig. 2 Diagram of the porous aerostatic bearing

The equation for Darcy's law governs the flow of air through porous materials (Eq. 1). The air flow of air film is also controlled by Reynolds equation^[13].

$$u_z = -\frac{\varphi}{\mu} \frac{dp_i}{dz}, \quad (1)$$

where u_z is the axial velocity of air inside the porous material; φ is the coefficient of viscous resistance of the substance; μ is dynamic viscosity coefficient; p_i is the air pressure in the porous material. Eq. (2) can be used to find the continuity equation in a porous mass.

$$\frac{\partial(\rho u_z)}{\partial z} = 0. \quad (2)$$

Substitute u_z from Eq. (1) and then unify the equation, it will give

$$-\frac{\varphi \rho_a}{2\mu p_a} \frac{\partial}{\partial z} \left(p_i \frac{\partial p_i^2}{\partial z} \right) = 0. \quad (3)$$

In external environment the air pressure and density are p_a and ρ_a respectively, affecting how easily the air flows and is released from the container.

In Eq. (3), substitute $p_i = p_s$ at $z = -H$ and $p_i = p_d$ at $z = 0$, then

$$\frac{\partial p_i^2}{\partial z} = \frac{p_s^2 - p_d^2}{H}. \quad (4)$$

Eq. (5) determines the clearance of bearing flowing by the mass of air.

$$Q_1 = \frac{\rho u_z \pi d_1^3}{8} = \frac{d_1^3 \varphi \rho_a}{16 \mu p_a} \frac{\pi (p_s^2 - p_d^2)}{H}. \quad (5)$$

Q_1 is the amount of air exiting the bearing, from which Eq. (6) is derived.

$$Q_2 = \int_{d_1/2}^{d_2/2} 2\pi r \int_0^h \rho v_r dz dr, \quad (6)$$

where Q_2 is the air mass flow out of the porous bearing, v_r is the velocity of air in the air film and follows the Reynolds equations:

$$\frac{\partial p}{\partial r} = \frac{\partial}{\partial z} \left(\mu \frac{\partial v_r}{\partial z} \right), \quad (7)$$

where p is the pressure in the air film.

If bearing speed is slow then, we can get desired boundary conditions. If $v_r = 0$ at $z = 0$ and $z = h$, $p = p_a$ at $r = d_2/2$, then by using Eq. (6) and (7), we get

$$Q_2 = -\frac{\pi r \rho h^3}{6 \mu} \frac{\partial p}{\partial r}. \quad (8)$$

With the principle of mass conservation, i.e. $Q_1 = Q_2$, the pressure expression may be determined:

$$p = \sqrt{p_d^2 - (p_d^2 - p_a^2) \frac{\ln(2r/d_1)}{\ln(2d_2/d_1)}}, \quad d_1/2 \leq r \leq d_2/2. \quad (9)$$

2.3 Simulation model

Based on the above analytical results, the static characteristics of porous aerostatic bearings are calculated by using the methods of both FDM (Finite Difference Method) and FEM. In this article, Fluent 20.0 is used to resolve Navier-Stroke equations, and the equations for viscous laminar are also calculated. To minimize the consumption of time for simulation, an axisymmetric model is also used^[14].

With Fluent 20.0, the mesh model of the porous restrictor is generated. Since this is a symmetrical part, the mesh model is given in half, as shown in Fig. 3. Normally, numerical simulation can take a long time, depending on the quality of the grids and the accuracy of the results. In order to shorten the time required to run the simulation and produce accurate results, it is

important to keep the grid quality high, while limiting the number of grids used. The data of the mesh model including bounding box size, numbers of nodes and elements etc. are shown in Table 2. Fig. 4 shows the flowchart of analysis for determining the bearing static properties.

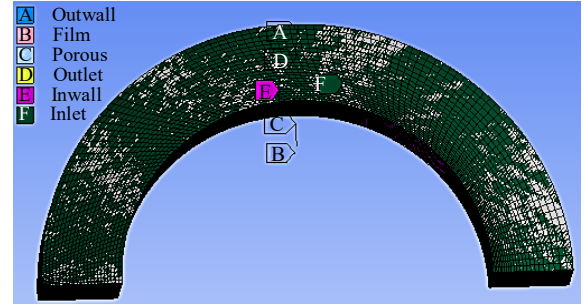


Fig. 3 Mesh model of the porous restrictor

Table 2 Mesh data of porous aerostatic bearing

Items	Names	Units	Values
Bounding Box	Length X axis	m	8×10^{-2}
	Length Y axis	m	4×10^{-2}
	Length Z axis	m	8×10^{-2}
Properties	Volume	m ³	1.026×10^{-5}
	Factor value		1
Statistics	Model bodies		2
	Active model bodies		2
	Number of meshed nodes		287 472
	Number of meshed elements		270 480
Mesh metric		None	

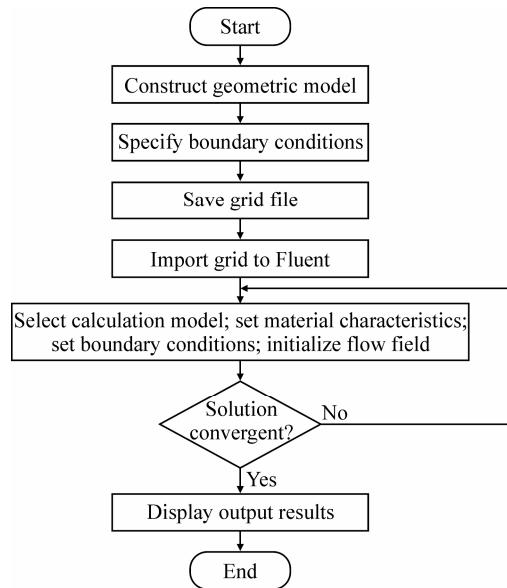


Fig. 4 The flow chart for model preparation and simulation

3 Results

3.1 Pressure distribution based on bearing thickness and supply pressure

The pressure contour in the air film can be acquired by CFD. It can be seen in Fig. 5, where the high pressure area within the air film is concentrated near the equalizing pressure of porous bearing and the pressure goes out the atmospheric pressure through the edge of the bearing.

In Fig. 5(a), the distribution of pressure at supply

pressure 0.4 MPa is presented first, with bearing thickness being 4 mm. The inlet pressure of the bearing was equal to the supply pressure. The outlet pressure due to atmospheric pressure condition lowers the magnitude to 0.096 8 MPa. Due to outlet atmospheric condition the minimum value of pressure was 0.126 MPa at the outer boundary of the porous bearing. The outlet pressure has been raised to 0.126 MPa because of an increase in the inlet pressure from 0.4 to 0.5 MPa. This increase in the inlet pressure causes the outlet pressure to increase till 0.156 MPa. However, the distribution of pressure on the surface of the air bearing

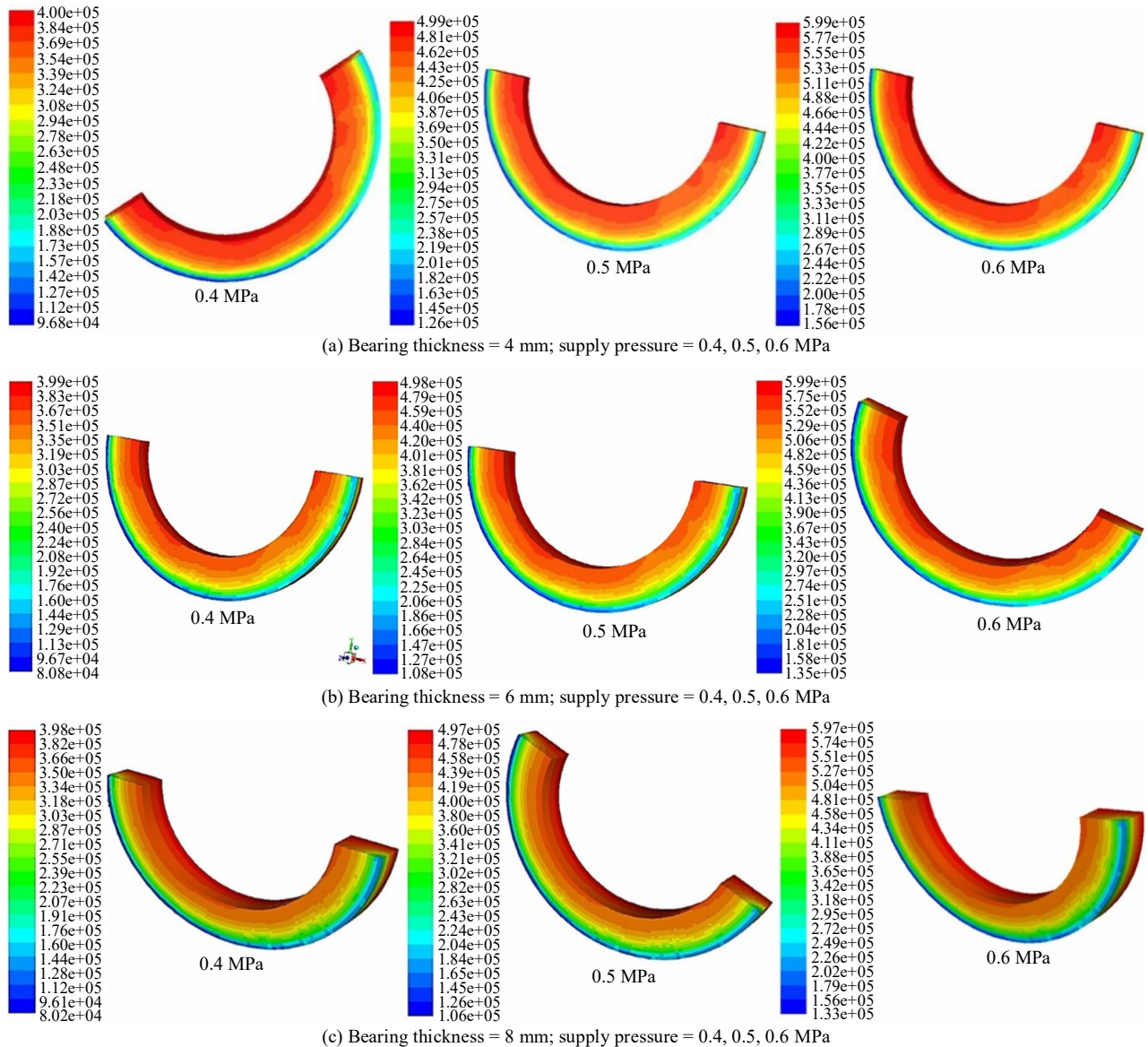


Fig. 5 Distribution of pressure based on bearing thickness and supply pressure

remains the same. The increase in inlet pressure from 0.4 till 0.6 MPa shows that this has resulted in overall increase in outlet pressure even at the boundary of the bearing. This homogenous distribution causes the bearing to become more stable for given operating conditions.

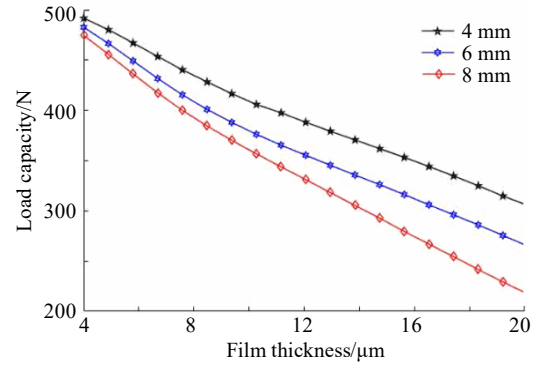
Fig. 5(b) shows the results when bearing thickness is 6 mm. Comparing with the above results, the increase in bearing thickness causes the pressure distribution beginning at inlet toward outlet vary significantly. For supply pressure 0.4 MPa, the max pressure was 0.4 MPa at the inlet while the outlet was 0.080 8 MPa. Similarly, the curve of pressure distribution for the supply pressure 0.5 MPa indicates that the outlet pressure was changed to be at 0.108 MPa. Lastly, the effect of pressure distribution along the bearing surface at inlet pressure 0.6 MPa was determined. It reflects that the lowest pressure of 0.136 MPa was determined at the boundary of the bearing, where the difference in pressure from inlet to outlet is the highest.

The thickness of bearing, as indicated in Fig. 5(c), further increases to 8 mm, where the pressure distribution along the radii of bearing was presented. It was observed that as the distance of the bearing was increased from inside radius (inlet) to outside radius (outlet), magnitude of the supply pressure was found decreased. This decrease in magnitude was observed from 0.398 till 0.090 2 MPa when supply pressure is 0.4 MPa. The difference in pressure magnitude shows the direction of flow from inlet to the outlet. Furthermore, the pressure distribution at 0.5 MPa supply pressure indicates that the pressure variation was 0.497 to 0.106 MPa. This variation with axial direction in pressure along the bearing was distinguished. Lastly, distribution of pressure along the axial route of bearing was observed and minimum pressure was found to be 0.133 MPa. The difference in pressure allows the flow direction to move from inlet to outlet surface.

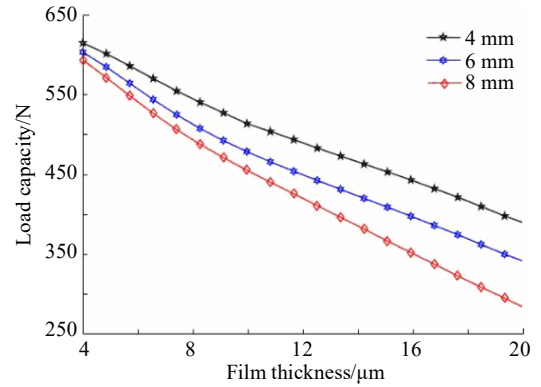
3.2 Effects of film and bearing thickness on load-carrying capacity

In the study, the impacts of film thickness and bearing thickness over the load-carrying capacity are

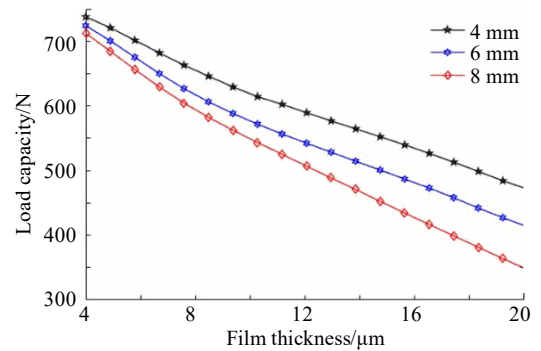
visualized in Fig. 6. With the increasing of the thickness of film, the load-carrying capacity is gradually decreased at a supply pressure 0.4, 0.5 and 0.6 MPa separately.



(a) Supply pressure = 0.4 MPa; bearing thickness = 4, 6, 8 mm



(b) Supply pressure = 0.5 MPa; bearing thickness = 4, 6, 8 mm



(c) Supply pressure = 0.6 MPa; bearing thickness = 4, 6, 8 mm

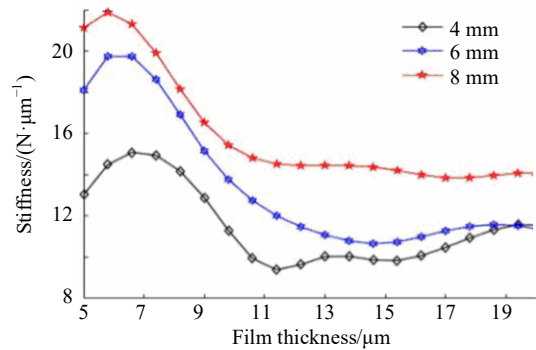
Fig. 6 Load-carrying capacity vs film thickness

Similarly, with the increase of bearing thickness, the load-carrying capacity also decreases at a specified supply pressure, such as the first one (Fig. 6(a)) that is with 0.4 MPa supply pressure and the bearing thickness increases from 4 to 8 mm. In porous aerostatic bearing, the flow of fluid is handled by both flow geometry and flow pressure. There is a clear relationship between the

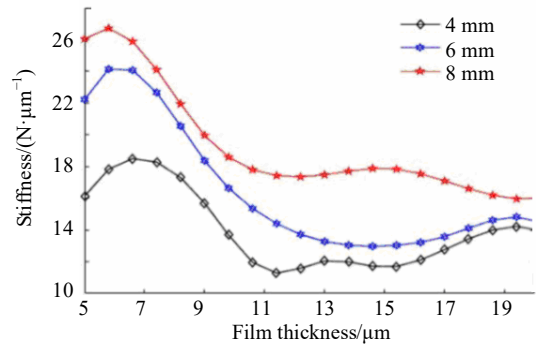
film thickness, bearing thickness and the load-carrying capacity of the bearing. This has been attributed to the fact that more load can be carried due to the increased contact area between the bearing and the shaft.

3.3 Effects of film and bearing thickness on stiffness

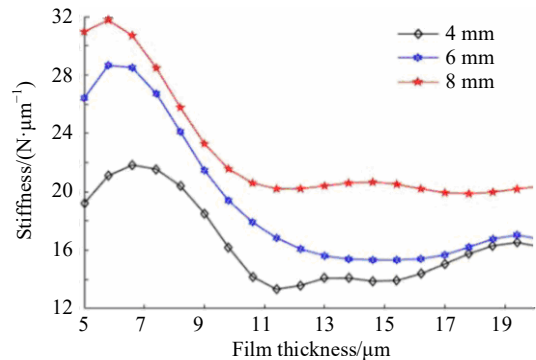
In principle, the change in stiffness of aerostatic bearing is associated with both film thickness and bearing thickness, as reflected in Fig. 7.



(a) Supply pressure = 0.4 MPa; bearing thickness = 4, 6, 8 mm



(b) Supply pressure = 0.5 MPa; bearing thickness = 4, 6, 8 mm



(c) Supply pressure = 0.6 MPa; bearing thickness = 4, 6, 8 mm

Fig. 7 Stiffness vs film thickness

It has been observed that the minimum and maximum stiffness are $9 \text{ N} \cdot \mu\text{m}^{-1}$ and $15 \text{ N} \cdot \mu\text{m}^{-1}$ respectively at 4 mm bearing thickness. If the bearing thickness is 6 mm, then maximum and minimum stiffness

change to $19 \text{ N} \cdot \mu\text{m}^{-1}$ and $10 \text{ N} \cdot \mu\text{m}^{-1}$ respectively. Similarly, if bearing thickness is 8 mm, then maximum stiffness sets to $21 \text{ N} \cdot \mu\text{m}^{-1}$ and minimum stiffness sets to $13 \text{ N} \cdot \mu\text{m}^{-1}$.

The above results show that, the porous bearing stiffness decreases if film thickness increases and simultaneously porous bearing stiffness increases as the bearing thickness increases. The highest stiffness is only attained when the value is large in bearing thickness. The result confirms that there exists inverse relationship between stiffness of the bearing and film thickness.

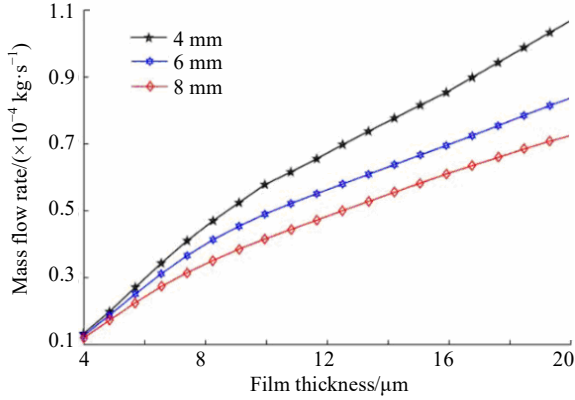
In fact, the increase in film thickness shall lead to the pressure gradient reduce across the bearing, resulting in a decrease in the stiffness of the bearing. When film thickness increases, the fluid flow in the porous material becomes more viscous due to the increased resistance to flow. Such changes reduce the pressure gradient across the bearing, as the fluid pressure at the inlet is reduced. According to Darcy's law, the fluid flow rate via the porous channel is found directly proportional to the observed pressure gradient, thus it decreases pressure gradient, which leads to decrease in stiffness.

3.4 Effects of film and bearing thickness on mass flow rate

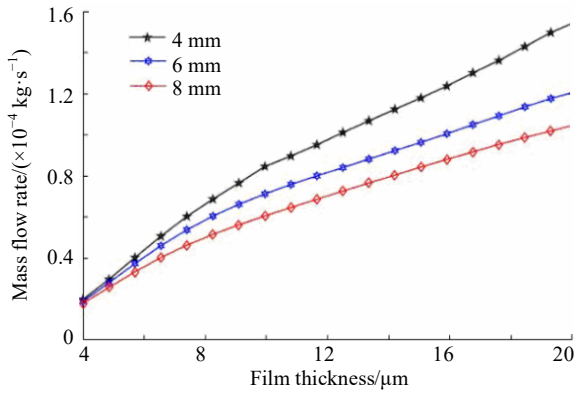
As shown in Fig. 8, when the bearing thickness is 4 mm, the minimum mass flow rate is $1.34 \times 10^{-5} \text{ kg} \cdot \text{s}^{-1}$ and the maximum mass flow rate is $1.07 \times 10^{-4} \text{ kg} \cdot \text{s}^{-1}$. At a bearing thickness of 6 mm, the maximum mass flow rate is $8.37 \times 10^{-5} \text{ kg} \cdot \text{s}^{-1}$ and the minimum mass flow rate is $1.28 \times 10^{-5} \text{ kg} \cdot \text{s}^{-1}$. Further, at a bearing thickness of 8 mm, the maximum mass flow rate is $7.25 \times 10^{-5} \text{ kg} \cdot \text{s}^{-1}$ and the minimum mass flow rate $1.21 \times 10^{-5} \text{ kg} \cdot \text{s}^{-1}$.

Fig. 8 also shows that, as the thickness of the film increases, the mass flow rate also is raised. With a decrease in the thickness of the porous layer, the pressure and mass flow rates are increased at different supply rates. When the bearing thickness increases, higher flow rate of the mass also rises. The result identifies that there is direct observed relationship between film thickness and mass flow rate. As the film

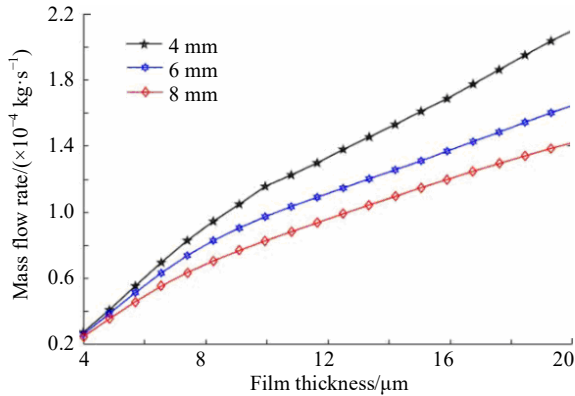
thickness increases, the mass flow rate of the bearing also increases.



(a) Supply pressure = 0.4 MPa; bearing thickness = 4, 6, 8 mm



(b) Supply pressure = 0.5 MPa; bearing thickness = 4, 6, 8 mm



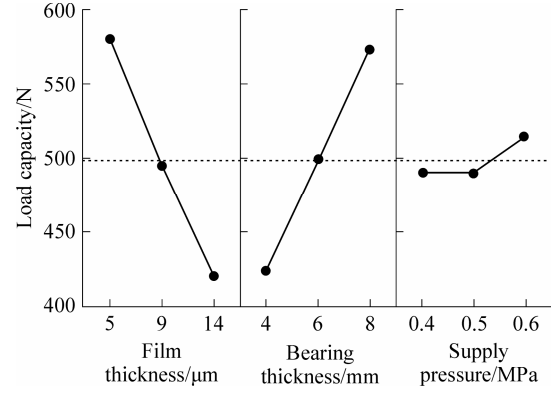
(c) Supply pressure = 0.6 MPa; bearing thickness = 4, 6, 8 mm

Fig.8 Mass flow rate vs film thickness

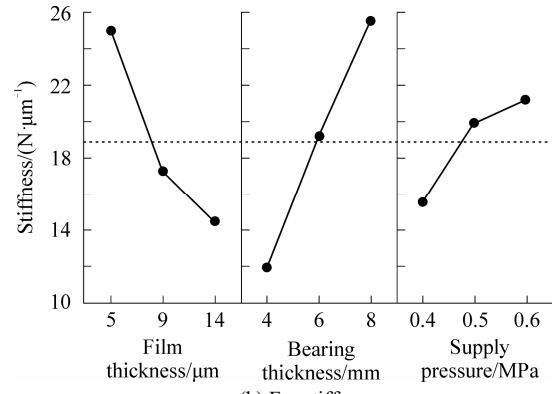
4 Sensitivity analysis of influences

The performance of an aerostatic porous bearing is influenced by the static characteristics such as load-carrying capacity, stiffness and mass flow rate, which in turn are determined by several influencing factors, including film thickness, bearing thickness, and supply

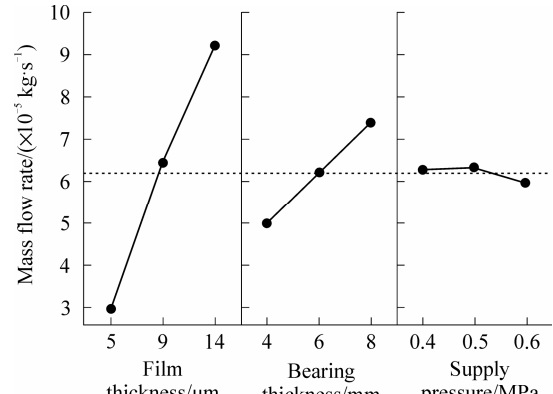
pressure. A sensitive study of these influencing factors would be beneficial to the design of high-performance aerostatic porous bearings. Fig. 9 shows the sensitivity curves to be explained below.



(a) For load capacity



(b) For stiffness



(c) For mass flow rate

Fig. 9 Sensitivity of film thickness, bearing thickness and supply pressure on load-carrying capacity, stiffness and mass flow rate

Take the load-carrying capacity as an example. The load-carrying capacity is influenced by both film thickness and bearing thickness monotonously, with the former being negative and the latter positive. These

characteristics make it easy for the designers to assign values to the film thickness and bearing thickness. Conversely, the load-carrying capacity is influenced by supply pressure in a more complex way, hence it is necessary to find optimal supply pressure value so as to maximize the load-carrying capacity.

Additionally, let's calculate the sensitive values for load-carrying capacity shown in Fig. 9(a), which are:

Sensitivity of film thickness on load-carrying capacity:

$$\frac{165}{9} = 18.33 ;$$

Sensitivity of bearing thickness on load-carrying capacity:

$$\frac{150}{4} = 37.5 ;$$

Sensitivity of supply pressure on load-carrying capacity:

$$\frac{80}{0.2} = 400 .$$

The above values show that the influence of supply pressure on load-carrying capacity is the most sensitive, while the other two are much less sensitive. Hence, when we need to make a relative big change to the load-carrying capacity of the bearing, variation of supply pressure would be the preferred option. This, however, need to be exploited by paying attention to the varied sensitivity values over the range of supply pressure change.

Similar analysis can be done for sensitivity of stiffness and mass flow rate. For space constraint, this is not to be elaborated here.

5 Conclusions

The above sections presented our study on the influence of flow-related parameters on the static characteristics of porous aerostatic thrust bearings. The findings are summarized as follows.

(1) LCC of aerostatic porous bearings decreases by the rise in both film thickness and bearing thickness, and if the supply pressure increases LCC shall increase

further more.

(2) The joint influence of supply pressure with film thickness and bearing thickness over stiffness is complex and varies with the specific values of these variables. At first, the stiffness of the aerostatic porous bearing rises, and it then decreases due to the difference in load. As the bearing thickness increases, the stiffness also increases. The highest value of stiffness is attained with a large value of bearing thickness. If the supply pressure increases, the stiffness also upsurges.

(3) It is observed that when bearing thickness decreases, the rate of mass flow increases; and if film thickness increases, the mass flow rate increases correspondingly.

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气流参数对多孔质空气静压轴承静态特性及性能影响研究

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摘要: 空气静压轴承在精密机床和计量设备等制造业领域应用广泛。多孔质空气静压轴承是一种特殊类型的空气静压轴承, 其由于使用了多孔质材料, 因此更加稳定和坚固。目前针对这类轴承有关气流参数对轴承静态特性及性能影响的研究还较为欠缺。为此, 本文提出了一个数学模型用于模拟多孔质空气静压推力轴承的静态特性, 包括承载能力、刚度及质量流率等。通过使用基于 Navier-Stokes 方程的计算, 对轴承内部的压力分布进行了分析。随后, 研究了对轴承静态特性可能产生影响的相关气流参数及其影响情况。研究结果表明, 轴承气膜层厚度的增加会导致轴承承载能力和刚度的下降, 但增加多孔质层的厚度可以提高轴承刚度。此外, 增加气膜层厚度会使得进入轴承的空气质量流率得以提升。这些结果可用于帮助设计更为高效且能够承担更高负载的多孔质空气静压轴承。

关键词: 多孔质静压推力轴承; 气膜厚度; 承载能力; 静态特性; 质量流率

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