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Analysis of flexible air bearing and design of testing machine

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Analysis of flexible air bearing and design of testing machine

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Abstract—The paper takes a type of flexible air bearing as the research object, and the bearing structure is analyzed in detail. Combined with the traditional analysis method of tilting pad bearing and the fluid-solid coupling theory, a new analysis model for performance prediction of the bearing was established. The performance of air bearing with inner diameter of 70mm was calculated by changing the input pressure or the inlet capillary diameter. The structure of the bearing was optimized by analyzing the calculation results, and the structure of the separate inlet nozzle was added. A bearing testing machine is designed for the flexible air bearing test to verify the improvement of bearing performance.

1. Introduction

Rotary machinery is widely used in petrochemical, aerospace, energy and other industries. Bearing is a key component of rotating machinery and plays a vital role in its performance. Traditional oil-lubricated bearings have high power loss, high requirements for sealing and great pollution to the environment. The air bearings can overcome these shortcomings of oil-lubricated bearings very well, and it has some advantages of high speed, large rotation accuracy and wide application space. However, air has the characteristics of low viscosity and compressibility, which makes traditional air bearings have low stiffness and poor damping characteristics, so the load capacity of the bearing and the rotational stability of the rotor are limited.

Since air bearing was proposed, how to improve the load capacity of bearing and the rotary stability of bearing rotor system has been the research goal of the majority of scholars. In 2009, Ertas proposed a new type of hybrid radial air bearing (HGB), and carried out bearing take-off test, load capacity test and rotor dynamic characteristic test for the bearing, which proved the feasibility of this new structure. And based on the experimental results, an analytical model of the flexible bearing system is established. But this model is obtained after a lot of simplification, and its calculation accuracy is poor[1]. In 2015, Adolfo Delgado conducted dynamic tests on the air bearing based on the research by Ertas, and proved that HGB has the characteristics of large load capacity and appropriate damping, which can be used in large turbomachinery[2]. In 2018, Hunan University proposed another high-damping flexible support tilting pad air bearing structure based on the research of HGB, and conducted in-depth theoretical and experimental research on the wire mesh structure. It is proved that the introduction of wire mesh material can effectively improve the damping and stability of the bearing[3].

This paper mainly conducts in-depth research on the HGB proposed by Ertas, and an effective flexible bearing performance prediction model was established, and the bearing structural parameters were optimized according to the results of the model, so as to improve the applicability of the bearing to different working conditions. At the same time, a high-speed rotary testing machine is designed for air bearing performance test to verify the bearing optimization results.

2. Bearing optimization design

The optimized structure of the bearing is shown in Fig. 1. The bearing consists of four parts: (1) the bearing body composed of four separate inner rings, S-shaped springs, and outer rings fixedly connected; (2) the steel mesh dampers on both sides of the S-shaped spring; (3) the bearing end plate; (4) the detachable intake nozzle.

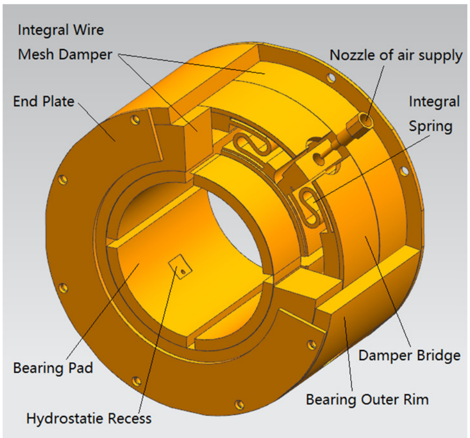


Fig.1 3D structure drawing of bearing

The unique structural design of HGB has the following four characteristics, which play an important role in improving the load of the bearing and the rotational stability of the bearing rotor system.

(1) Integrated S-spring structure: A pair of asymmetrically arranged S-springs are integrated connected between each pad and the outer ring of this type of bearing. The integrated connection can effectively improve the centering ability of the bearing, and the design of the asymmetric S-spring can realize the radial movement of the rotor and the deflection of the pad.

(2) Wire mesh damper structure: Due to the extremely low viscosity of the gas, the damping characteristics of traditional air bearings are poor, and the use of wire mesh dampers can effectively improve the damping characteristics of HGB. The stiffness of the steel mesh damper is small, which can ensure that the stiffness of the bearing is controlled by the S-spring. The end plates on both sides of the bearing can change the damping by changing the axial compression of the wire mesh damper, and the high temperature resistance and corrosion resistance of the wire mesh damper make its application range wider.

(3) Eccentric design: The structure of HGB adopts the design concept of multiple eccentricity in the design. It is beneficial to the deflection of the pad by the asymmetrical design of the two S-springs on each pad. The hydrostatic recess on the pad is designed to be closer to the leading edge of the pad is also to improve the deflection capacity of the pad. Many researches suggest that the deflection capacity of bearing pad can effectively improve the load and compliance of bearing.

(4) Separate air intake nozzle structure: The HGB was originally designed as an unchangeable air intake structure fixed on the bearing pad. Considering that the air intake requirements of the bearing work under different working conditions are different, and it is also difficult to process the capillary holes on the bearing body, the bearing studied in this paper adds a replaceable external intake nozzle structure, which makes the application of the bearing more flexible and the manufacturing cost is lower.

3. Bearing analysis model

3.1. Construction of performance prediction mode

At present, the research on the analysis model of traditional tilting pad bearing is relatively mature, but the research on the analysis model of flexible tilting pad air bearing is still less. Based on existing bearing analysis methods and fluid-solid coupling theory, a new analysis model suitable for the bearing is established in this paper, as shown in Figure 2. In the figure, O is the bearing center, O_R is the center of the shaft, O_P is the center of a single bearing pad, O'_P is the center of a single pad when the bearing system is running stably,R is the rotor radius, R_b is the inner diameter of the bearing pad, S_1 and S_2 are the simplified support points of the S-spring, and C is the midpoint of the pad.

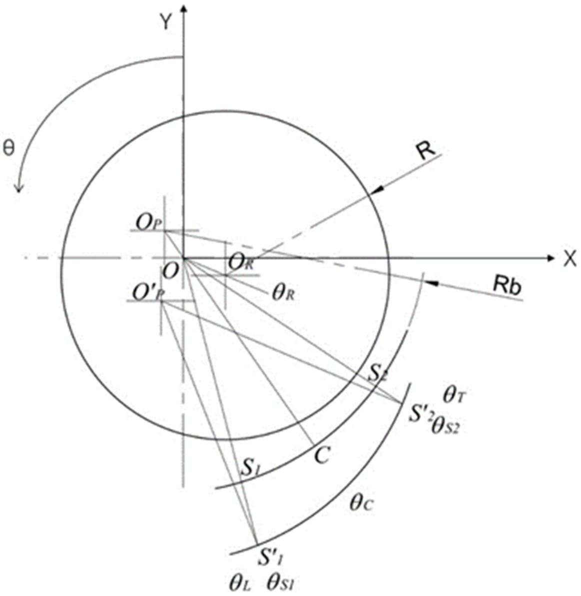


Fig.2 Bearing analysis model

According to the bearing analysis model, when the bearing runs stably, the flow balance of each pad, the force balance of each pad and the overall force balance of the bearing should be satisfied. According to these equilibrium conditions, equations are established and Matlab software is used to program and calculate the relationship between the pressure distribution of the pad, the thickness of the gas film, the gas consumption and other related quantities during the stable operation of the bearing.

The analytical model simplifies the support of the asymmetrically arranged S-spring to the support of the bearing at two different points S1 and S2 on the pad. From the analysis of the geometric relationship, the expression of the gas film thickness h can be obtained (Eq. 1).

$$h = r_p\,cos(\theta - \theta_p) + \sqrt{{R_b}^2 - {r_p}^2\,sin^2(\theta - \theta_p)}$$
$$-e\,cos(\theta - \theta_R) - \sqrt{R^2 - e^2\,sin^2(\theta - \theta_R)} \quad (1)$$

The compressible gas Reynolds equation (Eq. 2) can be obtained from the gas continuity equation, gas state equation, simplified gas motion equation, combined with the velocity boundary condition, pressure boundary condition and symmetric boundary condition.

$$\frac{1}{R^2}\frac{\partial}{\partial\theta}\left(\left(h^k\right)^3 P^k\frac{\partial P^k}{\partial\theta}\right) + \frac{\partial}{\partial y}\left(\left(h^k\right)^3 P^k\frac{\partial P^k}{\partial y}\right) = 6\mu\omega\frac{\partial}{\partial\theta}\left(h^k P^k\right) \quad (2)$$

Combined with the flow balance equation (Eq. 3), force balance equation (Eq. 4) and overall bearing force balance equation (Eq. 5), the finite difference method and numerical iteration method are used to solve the Reynolds equation of compressible gas. The pressure distribution of each pad, the thickness of gas film and the gas consumption can be calculated. The calculation flow chart is shown in Fig. 3.

$$\frac{\pi d^4}{256\mu lRT}(P_1^2 - P_2^2) = q_m = q_{mL} = \oint_S \rho h\bar{U}dS \quad (3)$$

$$\begin{bmatrix} F_{PX} \\ F_{PY} \end{bmatrix} = F_P = F_S = \begin{bmatrix} F_{SX} \\ F_{SX} \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} F_{RX} \\ F_{RY} \end{bmatrix} = \sum_{k=1}^{x} \begin{bmatrix} F_{PX}^{k} \\ F_{PY}^{k} \end{bmatrix} \tag{5}$$

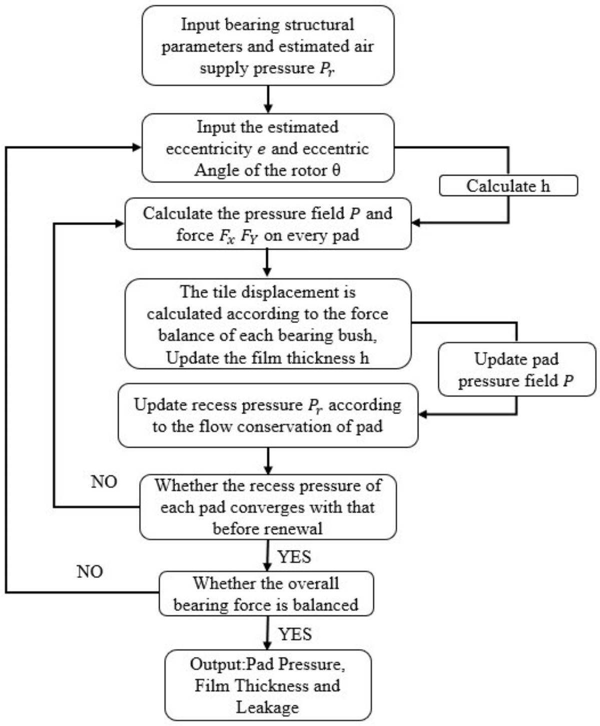
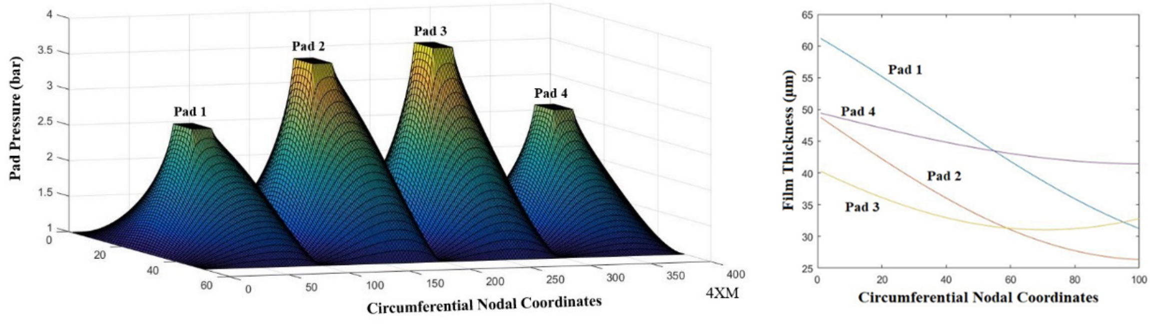


Fig.3 Flow chart of bearing performance prediction calculation

3.2. *Calculation results*

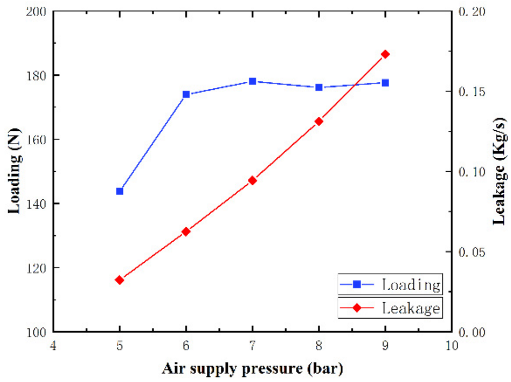
Using the established calculation model, the performance of a bearing with an inner diameter of 70mm is calculated. The detailed parameters of the bearing are input to calculate, and the calculation results are obtained when the bearing runs stably at a speed of 30000r /min. Fig.4 shows the calculation results of pad pressure distribution and film thickness distribution of the sample bearing



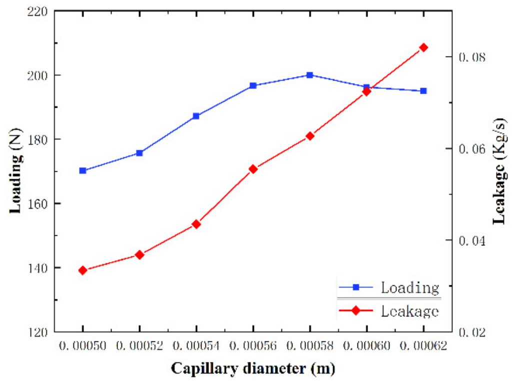
(a) Pad pressure distribution (b) The film thickness

Fig.4 Sample calculation results

The influence of different inlet pressure and capillary diameter of inlet nozzle on bearing performance was further calculated by using this calculation model, and the calculation results are shown in Figure 5.



(a) Effect of intake pressure



(b) Effect of inlet nozzle diameter

Fig.5 Bearing performance prediction results

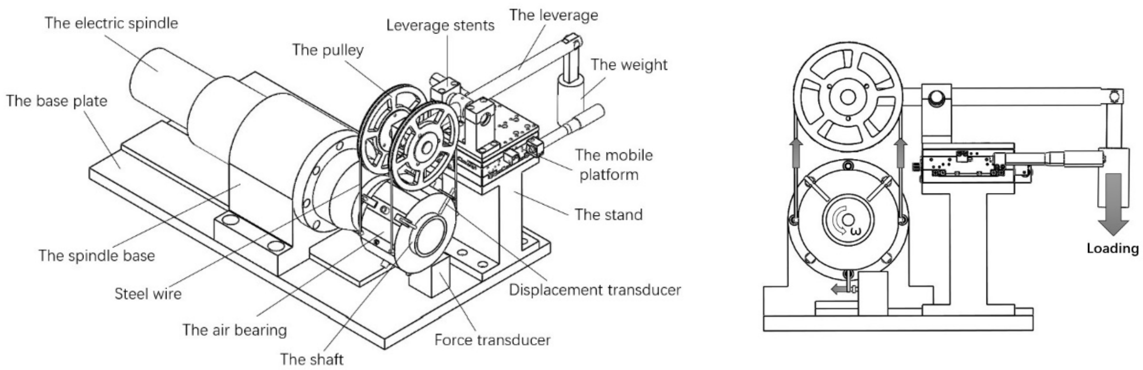
According to the calculation results, when only the intake pressure is changed, with the increase of the intake pressure, the load capacity increases rapidly below 6 bar and slowly above 6 bar. And the air consumption increases with the increase of the intake pressure. When only the capillary diameter is changed, the load increases first and then decreases with the increase of capillary diameter in a certain range. But the gas consumption increases all the time, which is undesirable. Therefore, when optimizing the structural parameters of bearings of this size, the intake pressure of bearings can be set at about 6 bar, and the diameter of capillary tubes can be set at about 0.58mm. However, because there are some coupling relations between bearing parameters, in order to make the optimization results more accurate, specific experimental results should be added into the optimization process of structural parameters.

4. Design of bearing testing machine

At present, there are few researches on high-speed bearing rotary testing machines. Most of the existing high-speed testing machines have problems such as insufficient speed, insufficient bearing capacity, poor stability, single test bearing size and inconvenient installation. In view of the test requirements of flexible air bearings, a bearing high-speed test machine is designed and a complete bearing test scheme is summarized to prepare for the subsequent bearing experimental research.

The designed air bearing high-speed test bench mainly includes three parts: rotating drive system, experimental bearing system and experimental loading and testing system. The structure of the test bed is shown in Fig 6(a). The maximum speed of the test machine is 30000 r/min, and the static circular runout of the bearing end of the test machine is not more than 10um. The design of the testing machine adopts the modular design concept, which can design different loading and testing systems with different experimental schemes.

The rotary driving system of the testing machine adopts the design structure of high-precision high-speed motorized spindle with special tool handle, and the tool handle part is used as the rotating shaft of the test bearing. The high-speed motorized spindle supported by two sets of angular contact ball bearings installed back-to-back was selected to improve the rotation accuracy of the rotary drive system. HSK tool holder interface is used to directly connect the rotary shaft with the motorized spindle, which eliminates the coupling structure and is beneficial to improve the dynamic balance characteristics of the rotary drive system. In addition, the quick conversion of bearing test of different sizes can be realized by quickly changing the handle of different sizes. In the experimental bearing system part, a universal test sensor mounting hole is designed on the experimental bearing shell, and the air inlet is designed with the structure of fast air connection port and separated air inlet nozzle, which can realize the compatibility and rapid conversion of different experimental test systems. The pulley lever loading system is adopted in the experiment and loading system. One end of the lever is connected with two pulleys, and four steel wires from the two pulleys are connected with the experimental bearing. The other end is loaded with heavy objects. When the bearing is running, the pulley loading system minimizes the impact on the torque of the experimental bearing while loading. The lower end of the bearing can measure the bearing torque by extending the torque measuring rod fixed on the bearing to push the high-precision force sensor. The force analysis of the testing machine is shown in Fig 6(b).



(a) Bearing testing machine structure (b) Force analysis of testing machine
Fig.6 Bearing testing machine

The experimental loading test system can carry out static loading test and force hammer impact test of bearings. The ultimate load and rotational stability of the bearing can be judged by measuring the shaft trajectory and working torque of the rotor subjected to a certain impact under different rotational speeds and loads. Subsequently, the dynamic characteristics of bearings can be further studied by changing the design of the experimental loading test part on this test machine.

5. Conclusion

In this paper, a new flexible air bearing (HGB) structure is studied deeply, and an analysis model suitable for this type of bearing is established, and the performance prediction of this type of bearing is realized. According to the analysis of the performance calculation results of the bearing with inner diameter of 70mm, the inlet pressure and inlet capillary diameter parameters of the bearing are optimized, and the structure of the separated inlet nozzle is added, which greatly improves the bearing capacity and rotary stability of the bearing and improves the flexibility of the bearing. The optimal design of HGB can no longer rely on experiments, which greatly reduces the cost of optimal design of bearing. The high-speed bearing test bed designed in this paper has the advantages of high rotation accuracy, strong load capacity and high modular structure, which is ready for all kinds of bearing test in the future.

In the future, the established bearing performance prediction model needs to be continuously improved to improve the calculation accuracy. The testing machine designed at present can only test the static loading of bearings, and the dynamic performance test module of bearings should be added later to further study the performance of bearings.

Acknowledgments

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