Research on the design and load bearing characteristics of air bearings based on micro-groove structure and reverse fixation

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Abstract. In this study, a novel air bearing design based on a microgroove structure with a reverse fixed configuration is proposed to improve the bearing load carrying capacity, stability, and operating efficiency, while reducing the frictional torque and micromotion wear during startup. First, this paper proposes a novel air bearing design to optimize the pressure distribution of the air film by opening circumferential microgrooves on the flat foil, improve the gas flow by channeling the air flow, increase the stiffness of the air film and reduce the leakage rate, so as to enhance the bearing load carrying capacity. Secondly, to address the micromotion wear caused by small sliding between the foils due to the dynamic phase difference in the traditional design, the reverse fixation configuration of the flat foil and wave foil is proposed. On the basis of the above, it is verified by MATLAB numerical simulation and experiment. The results show that the improved air bearing exhibits higher load carrying capacity, significantly lower friction torque, good start-stop performance, and improved stress distribution and thermal expansion stability of the system. This indicates that the design has significant advantages in improving bearing load carrying characteristics, reducing friction loss and extending service life, and has a wide range of application prospects, especially suitable for high load and high speed equipment.

Keywords: Air Bearings, Reverse Fixation, Circumferential Microgroove, Load Carrying Characteristics, Friction Losses.

1. Introduction

The aerodynamic foil bearing is a bearing that does not require oil lubrication. By rotating the rotor with the foil forming a wedge structure thus forming an air film. Using air as the medium, a fluid film is formed to lubricate the bearing [1]. In recent years, air dynamic pressure foil bearings have been increasingly used in the fields of aviation, space exploration, high-speed rotating machinery and medical equipment [2]. With the continuous updating and iteration of mechanical equipment, high rotational speeds and high loads require more and more bearing capacity. The current gas foil bearings have limited load carrying capacity, excessive friction during startup, and high energy consumption, which limits their promotion and application to more high load fields [3]. Now there is an urgent need to develop a new type of gas-foil bearing and design a more effective foil structure to optimize the distribution and stability of the gas film to further improve the load carrying capacity and reduce energy consumption.

In this study, circumferential micro-slots are cut in the flat foil to facilitate the air to enter the diversion slots and make the air film distribution more uniform. During startup, the air in the high-pressure region is influenced by the flow channel, which makes it easier to form an air film and reduces the overall friction torque. In the fixing method, the fixing configuration of flat foil and wave foil with opposite rotation direction is adopted. Since the dynamic deformation tendency is the same, the dynamic friction in operation is reduced. The improved air dynamic pressure foil bearing further increases the bearing capacity. With the advantages of low friction resistance, good starting and stopping performance, long service life and oil-free lubrication, they will be widely used in the future in many fields such as high speed machinery.

2. Research on the circumferential microgroove structure of flat foils

2.1. Parameterized circumferential microgroove

The corrugated gas radial foil bearing mainly consists of a flat foil, a wave foil and a sleeve, and the flat foil and the wave foil are mounted in such a way that one end is fixed and the other end is free, and the circumferential ends of the flat foil are not connected [4]. As shown in Fig. 1. Its working principle is that when the bearing and rotor relative movement, the gas due to its viscous effect, is dragged and pressed into the wedge gap, while the gas film is compressed and pressure is generated, and the pressure generated by the gas film increases with the increase in rotational speed until the rotor shaft is separated from the flat foil, constituting a dynamic pressure suspension. In order to improve the bearing capacity of the gas radial foil bearing, a new type of flat foil with circumferential micro-slots on the surface is proposed. As shown in Fig. 2.

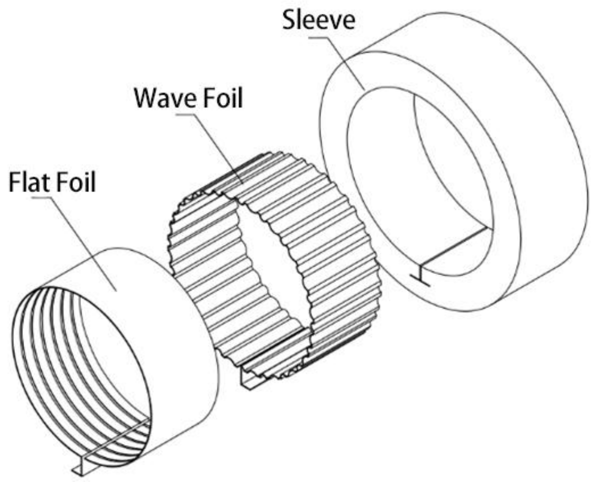


Figure 1. Air Foil Radial Bearing Structure

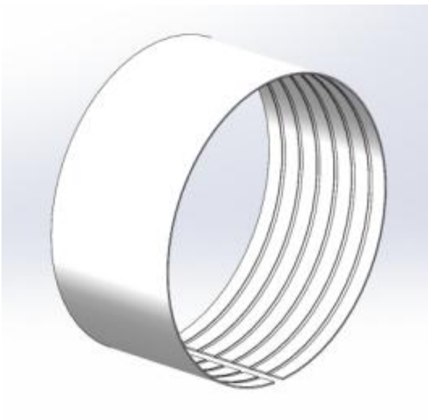


Figure 2. Flat foil with circumferential microgrooves

A schematic diagram of the geometrical parameters of the circumferential microgrooves on the surface of the flat foil is given in Fig. 3. Where D denotes the depth of the micro-slot and W denotes the width of the micro-slot.

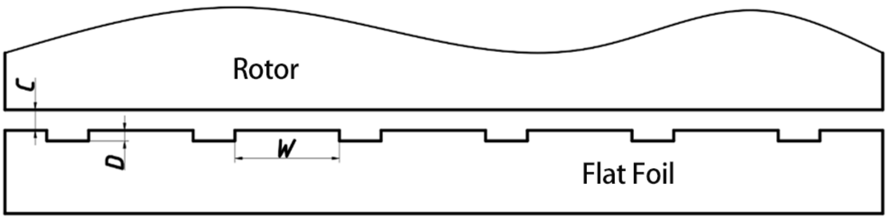


Figure 3. Schematic diagram of microgroove geometry parameters

Compared to conventional gas radial foil bearings, microgroove gas radial foil bearings have a groove depth component added to the gas film thickness equation.

Eq. (1) is the equation of the air mold without the micro-slotted part and Eq. (2) is the equation of the air mold with the micro-slotted part:

$$h = C + e\cos(\theta) + w_z \tag{1}$$

$$h = C + e\cos(\theta) + w_z + D \tag{2}$$

Where θ is the circumferential coordinate; C is the nominal clearance; e is the eccentricity; ω_z is the foil deformation; D denotes the slot depth

In this paper, corrugated gas radial foil bearings are studied and the specific parameters of the bearings are shown in Table 1.

Table 1. Structural parameters of gas radial foil bearing

parameters	numerical value
Shaft diameter D/m	21×10^{-3}
Bearing length L/m	15.5×10^{-3}
Nominal *clearance* C/m	30×10^{-6}
Wave foil thickness t_b/m Flat foil thickness t_p/m	100×10^{-6} 200×10^{-6}
Wave foil corrugated unit length s/m	3.75×10^{-3}
Wave foil corrugated half-sine length 2l/m	3×10^{-3}
Foil modulus of elasticity E_b/Pa	2.14×10^{11}
Foil Poisson's ratio	0.3
Lubricant Gas Power Viscosity $\mu/(P_a \cdot s)$	1.932×10^{-5}
Trough depth D/m	5×10^{-6}
Slot width W/m	1.5×10^{-3}
Number of circumferential microgrooves n	6

In this study, the sensitivity of each parameter to the air film stiffness, leakage rate, and temperature rise is analyzed through simulation and experimentation, and the dynamic pressure effect is enhanced when the groove depth is increased, but the leakage rate may increase nonlinearly [5]. It has also been shown that finer weave texture design can improve the performance of foil bearings [6]. Appropriately increasing the foil thickness can effectively increase the load carrying capacity of the foil, but it also reduces the adaptive capability of the foil bearing [7]. In order to further improve the load carrying capacity of gas radial bearings, in this study, the number of microgrooves was opened as 6 evenly distributed, the depth of the microgrooves was 5×10-6 m, and the width of the microgrooves was 1.5×10-3 m. The effect of rotational speed, eccentricity, and geometric parameter of circumferential microgrooves on the static characteristics of the bearings was investigated by comparing them with the conventional foil bearings.

2.2. Research on the regulation mechanism of air film pressure by microtanks

By opening a drainage groove on the inner wall of the flat foil, it plays a certain role in guiding the airflow and can effectively improve the pressure distribution of the air film. During operation, the air film is more easily formed by the structure of the drainage groove, which lifts up the inner ring and improves the load bearing capacity. After air enters the guide groove, it will make the pressure distribution of the air film more reasonable, and compared with the flat foil without guide groove, it can produce more load bearing pressure. When the bearing is subjected to external loads, the air film is better able to resist deformation, thereby increasing the load carrying capacity.

The micro-slot structure destroys the formation of vortices, reduces the turbulent kinetic energy, and inhibits the formation of turbulence. Moreover, the sealing effect between the microgrooves can make the leakage rate of the air bearing lower. Especially during the start-up phase, the micro-slots produce a local pressurization effect. The inlet of the groove is low pressure and the outlet is high pressure, which makes it easier to form a high-pressure air film according to Bernoulli's principle. Therefore, the stiffness of the air film is increased, the bearing capacity is increased, the friction torque during startup is reduced, and the speed of the air bearing is increased.

2.3. Improved static feature solving

In this paper, the numerical solution of gas radial foil bearing is carried out without considering journal tilting and simulated by MATLAB. The foil bearing is first meshed and then the lubrication equations are solved for the air bearing. Boundary conditions and convergence conditions are introduced. The air film pressure is equal to the ambient pressure because the flat foil is not fixed circumferentially and endwise and is connected to the environment. It is set as dimensionless pressure $P=1$. Since the bearing is a circumferentially closed annulus, the periodicity condition $P(0,z)=P(2\pi,z)$ is satisfied by default, which is implicitly realized by mesh head-to-tail in the code.

The static characteristics of gas radial foil bearings mainly include load carrying capacity, deflection angle, friction moment and gas film thickness. Generally, by solving the pressure-controlled Reynolds equation, the gas film pressure and gas film thickness are obtained and then the other static characteristics are solved.

The load bearing force is determined by first finding the component in the direction of eccentricity in the direction of perpendicular eccentricity, respectively, and then finally finding the combined force.

$$F_X=\int(P-P_a)\cos\theta dA \tag{3}$$

$$F_y=\int(P-P_a)\sin\theta dA \tag{4}$$

$$W_0=\sqrt{F_x^2+F_y^2} \tag{5}$$

The friction moment is an integral of the shear stress:

$$T=\int\tau RdA \tag{6}$$

$$\tau=\frac{\mu U}{h}+\frac{h}{2R}\frac{\partial P}{\partial\theta} \tag{7}$$

Offset angle:

$$\phi=-\arctan\left(\frac{F_y}{F_x}\right) \tag{8}$$

The simulation results show that with the increase of rotational speed, the load carrying capacity will rise accordingly. However, the micro-groove is too deep which will increase the friction, so the micro-groove is not easy to be more than $10\mu m$. And the increase of the eccentricity e will increase the corresponding load carrying capacity, but the friction torque will also increase, so the suitable eccentricity e is around 0.7. Figure 4 below shows the distribution of air film thickness:

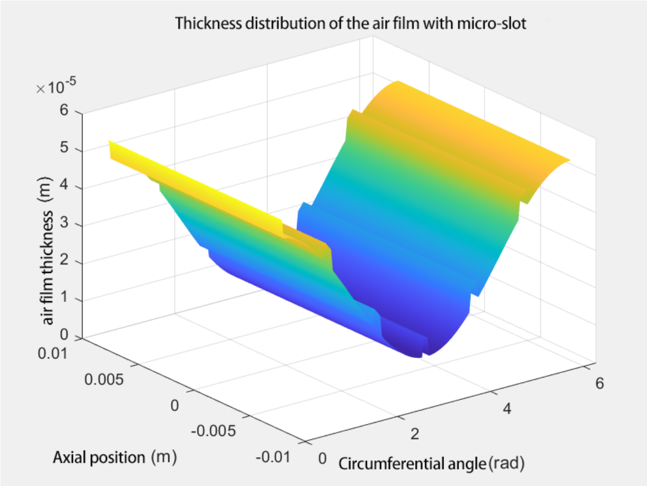


Figure 4. Distribution of air film thickness

With the improved flat foil, the eccentricity angle will be smaller in operation, the load direction will be close to coincide with the eccentricity direction, and the stability of the bearing will be higher. When the rotational speed of the gas foil bearing with circumferential micro-groove structure is 60,000 rpm and the eccentricity is 0.7, the load carrying capacity obtained is 142.7564N, the angle of misalignment -14.23, and frictional torque of 0.0875 N-m. The load carrying capacity is further improved and the frictional torque during start-up transient is reduced compared with the conventional bearings.

3. Research on flat foil and wave foil reverse fixation configurations

3.1. Mechanical advantages of the reverse fixed configuration

In the reverse fixation configuration, the flat and wave foils move in opposite directions. The flat foil expands under the pressure of the air film, the expansion tendency. The wave foil itself has a waveform structure, and when subjected to the pressure of the air film and the action of the flat foil, the wave foil is squeezed so that the waveform tends to flatten and has a tendency to lengthen. The reverse fixation schematic is shown in Figure 5.

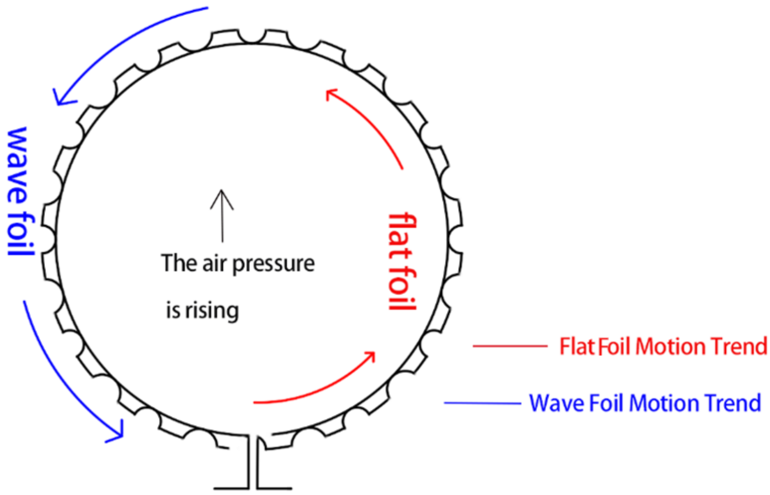


Figure 5. Reverse fixation

The inverse fixation of the flat foil and wave foil enables the two to maintain the same dynamic movement trend under force, thus effectively avoiding the interference of the reverse force between them. This reverse fixation design converts the relative displacement between the two foils into an overall elastic deformation by means of mechanical constraints, which significantly reduces the relative motion and friction loss between the two foils. In particular, in conventional fixation designs, micro-slip (less than 10 μm) usually occurs due to the dynamic phase difference between the foils, which is the main cause of micromotion wear [8]. By optimizing the structure, the reverse fixation reduces the relative displacement by more than 80%, which greatly inhibits the occurrence of adhesive wear and abrasive wear, effectively reduces friction and wear, and enhances the long-term reliability and lifetime of the system.

In addition, the reverse fixation design significantly improves the stability and durability of the system. As the relative motion of the two is effectively reduced, the vibration and uneven stresses of the system are also effectively suppressed, thus enhancing the overall load resistance and improving the stability of the system. This reverse-fixed configuration effectively extends the service life of the equipment and enhances its long-term stability under high-load, high-speed conditions, significantly improving overall performance. The reverse-fixed foil is shown in Figure 6.

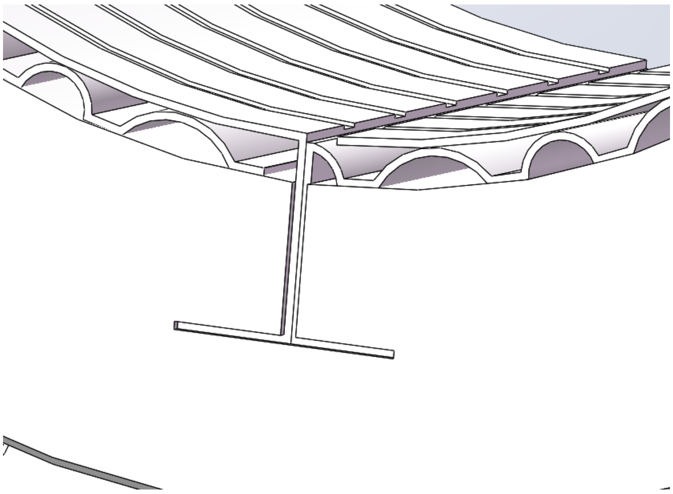


Figure 6. Reverse Fixed Foil

3.2. Comparison with conventional fixation

In conventional fixing methods, fixing or restraining methods are usually used to secure the position of the foils. Flat and wave foils are fixed directly or connected by means of a support structure, and the fixing snap angle is the same as the foil rotation. The conventional fixed foils are shown in Figure 7.

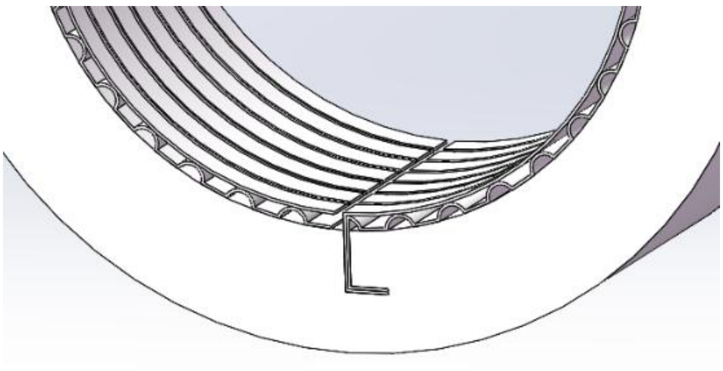


Figure 7. Conventional fixed foil

The reverse-fixed configuration demonstrates excellent performance in friction loss control due to its superior dynamics. The configuration utilizes a reverse-constrained design to create a more symmetrical hysteresis loop during the compression-rebound cycle of the wave foil, which effectively reduces energy loss by approximately 25% and significantly reduces friction loss. This advantage is especially critical for improving system energy efficiency under high-speed start-stop conditions, resulting in superior start-stop performance. In contrast, the lack of a reverse fixation design in traditional fixation methods results in greater relative motion, leading to increased friction losses and easier heat buildup in the system.

The reverse-fixed configuration also offers significant advantages in terms of system stability and load-carrying capacity. Under high loads and high speeds, this configuration provides more balanced pressure sharing, higher load carrying capacity, and ensures long-term stable system operation. In addition, the flat foil and wave foil adopt a reverse thermal expansion structure, and its unique thermal expansion compatibility design makes the expansion tendency of the flat foil and the wave foil constrain each other. Experimentally, it is proved that the design can control the gap change due to thermal deformation within ±3 μm at 200°C, which is much better than the ±15 μm of the isotropic design [9]. In contrast, the traditional fixed method has a weaker load-bearing capacity at high rotational speeds and high loads, and is prone to vibration, imbalance or damage, which leads to higher maintenance costs [10].

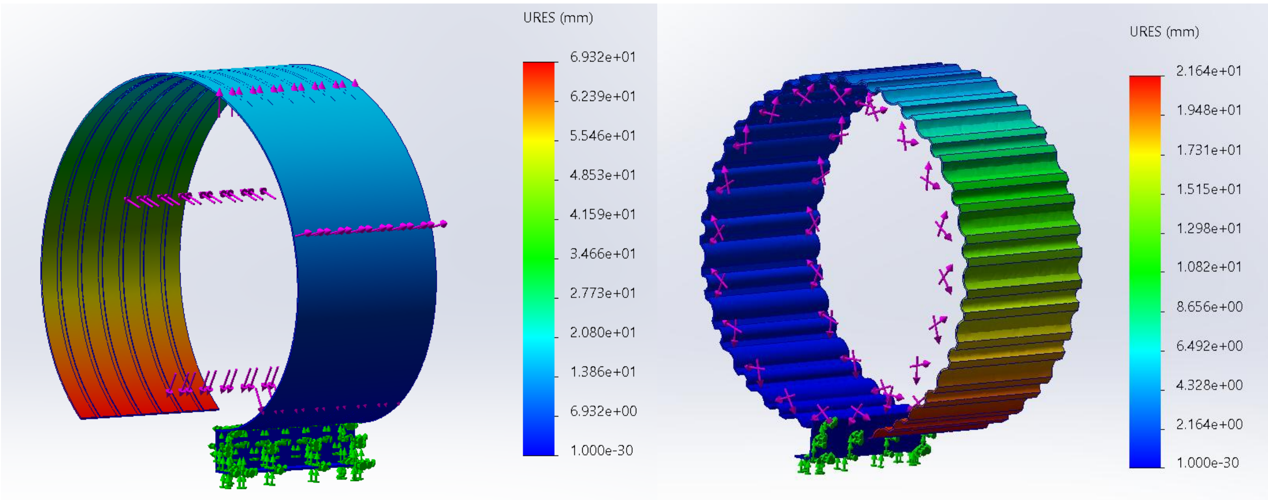
3.3. Numerical simulation and parameter optimization

The design parameters of the flat foil and wave foil are the same, as shown in Table 2.

Table 2. Design parameters for flat and wave foils

makings	Speed/rpm	eccentricity	Load capacity/N
304 steel	60,000	0.7	11.247

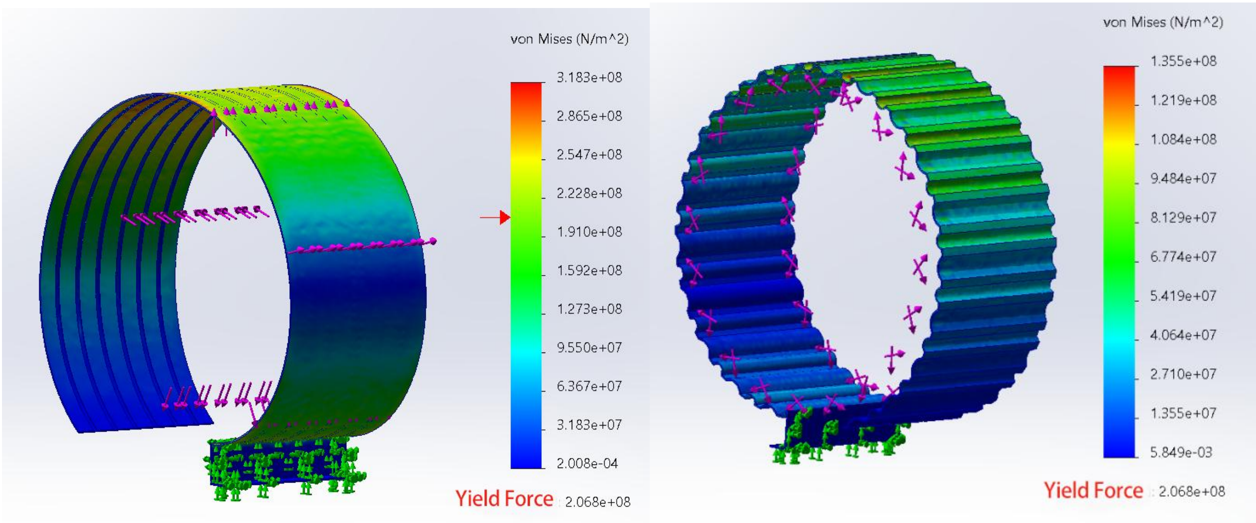
Based on the parameters in Table 2, the flat foil and wave foil are simulated under conventional operating conditions and the displacement, stress and strain simulation plots are obtained as shown in Fig. 8, Fig. 9 and Fig. 10, respectively.



(a) Flat foils (b) Wave foils

Figure 8. Displacement simulation diagram

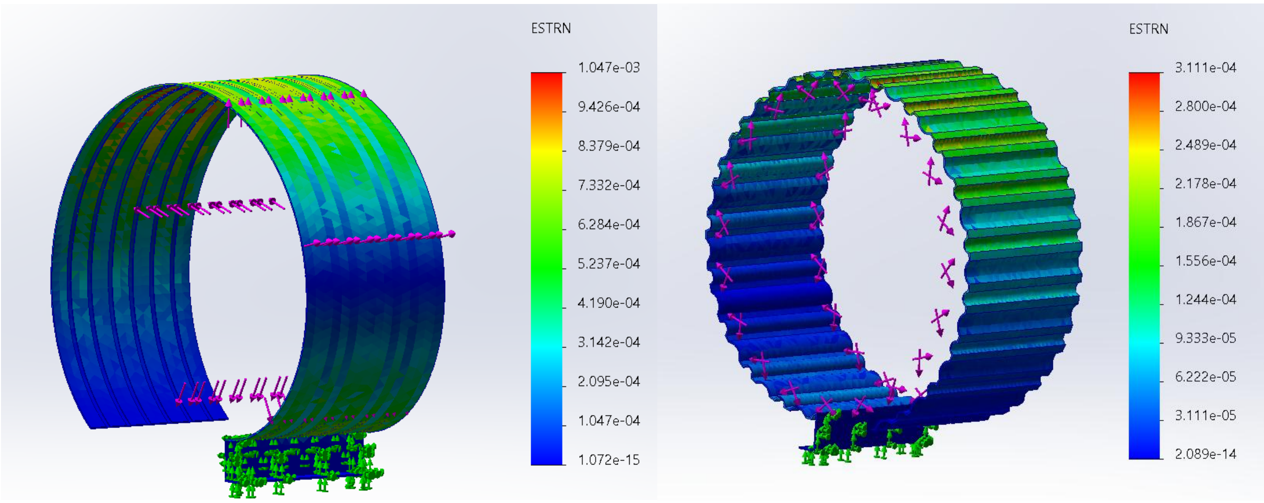
As can be seen in Fig. 8, the relative slip between the flat foil and the wave foil is significantly reduced in the reverse fixation configuration. Since the flat foil and wave foil move in opposite directions in the reverse fixation design, their relative motion tendencies cancel each other out, which effectively reduces the friction loss due to slippage. Unlike conventional designs, which cause the relative slip between the foils to add up, the conventional fixation method increases friction losses. With the reverse fixation design, the displacement of the two foils is much smaller and the friction loss is effectively controlled, reducing heat buildup in the system.



(a) Flat foils (b) Wave foils

Figure 9. Stress simulation diagram

It can be noticed from Fig. 9 that in the reverse-fixed configuration, the area of the high-stress region of the flat foil is reduced by about 10%, while the stress gradient of the wave foil becomes flatter. This optimization results in a more uniform stress distribution throughout the system and reduces the risk of local overloading. Through simulation results, it is shown that the stresses in the reverse-fixed configuration are all within safe limits, ensuring the long-term stable operation of the system, whereas the conventional fixing method may have an increased risk of vibration, imbalance, or damage due to uneven stresses.



(a) Flat foils (b) Wave foils

Figure 10. Strain simulation diagram

From Fig. 10, it can be concluded that the strains of the flat foil and the wave foil are complementary and the stiffness is enhanced in both. The reverse-fixed design achieves strain complementarity through the expansion of the flat foil and the compression of the wave foil, thus transforming the antagonistic deformation in the conventional design into a synergistic energy dissipation. This transformation not only contributes to stress redistribution, but also significantly enhances stiffness. The reverse-fixed configuration enhances the load carrying capacity of the system by working in concert and reduces friction losses through effective energy dissipation. Secondly, the thermal expansion behaviors of the flat and wave foils are optimized. With the reverse thermal expansion design, the stability of the system under temperature change is significantly improved, and the gap changes due to thermal deformation are effectively controlled.

4. Conclusions

For flat foils there is a circumferential micro-groove structure, which improves the air bearing's evacuation of airflow and enhances the air film stiffness. The presence of micro-slots reduces the leakage rate. And it also reduces the turbulent kinetic energy and inhibits the formation of turbulence. According to Bernoulli's principle, the microgrooves produce a localized high-pressure effect, which increases the bearing capacity of the air bearing and reduces the friction torque at startup. The flat foil and wave foil reverse fixed configuration effectively reduces the relative sliding displacement of the two foils during operation. The friction loss can be controlled and the heat accumulation can be reduced. With the complementary strains, the energy dissipation is optimized and the stability of the system is significantly improved.

In the future, it can be applied to construction machinery, air compressors, aerospace, medical equipment and many other equipment and fields. It helps to improve the stability of system operation and solve the problems of short service life and high maintenance cost. Air bearing oil-free lubrication, clean and pollution-free, the protection of the environment and green sustainable development, play a vital role.

The present study does not exclude the effect of errors introduced by the simulation on the accuracy of the test results. Various aspects of the parameters of the microgroove structure need to be further improved. For example, although the micro-groove structure can effectively increase the bearing capacity significantly, the friction moment during operation is large. Subsequent studies will continue to refine and improve such issues.

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