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MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

Numerical analysis of seal force in contacting finger seal

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Abstract. A finger seal is a flexible sealing device widely used in high-temperature and high-pressure environments such as gas turbines. Its force analysis is the key to the design and optimization of finger seal performance. At present, most of the research on force analysis of finger seals is focused on the whole seal ring, but each finger beam has a different contact performance with the shaft. In this paper, a new force analysis method for contacting finger seals is proposed, as well as the model of finger seals with or without eccentricity is established to analyze the force of a single finger beam. The curved flexible finger beam is transformed into a straight one loaded with a certain moment at the end of it. The force acting on the finger beam is studied and compared with the existing reference to demonstrate the feasibility of the analysis method. By changing each parameter of the finger seal, the relationship between seal force and structural parameter is investigated. It shows that this method is meaningful to the calculation results of seal force for single finger beam and can promote the development of finger seal and make it further in engineering application.

Keywords: bending flexible beam; contacting finger seal; seal force; eccentricity; numerical analysis.

1. INTRODUCTION

Gas turbines are extensively used in aerospace, shipping, and other fields because of their high power [1, 2]. To make the gas turbine work normally, it is necessary to ensure that its internal structure is intact, so reducing wear and leakage has become the focus of the research. As an important part of this kind of turbine, seal equipment needs to be stable and dependable to ensure its normal operation [3–5]. Seal technology has become the key point of the growth of gas turbines with high efficiency, low consumption, and reliable operation. As a new type of seal, finger seals have been widely researched. According to whether the finger and rotor are in contact or not, there are two types of seal: contact type and noncontact type. In these two types, the contacting one is that the rubber seal on the beam comes into connection with the rotor, and the force of this kind of seal will change when the rotor condition changes as well. According to Arora *et al.* [6], the seal effect of this kind of innovative technology has much better performance than that of traditional labyrinth seal, with its leakage amounting to 80% of that of the labyrinth seal. When there exists a similar seal effect, the cost of a finger seal is exceptionally low, about half of that of a brush seal. Because of its excellent characteristics, research on this kind of seal is significant.

Over the years, researchers and scholars have conducted in-depth research on finger seals. Braun *et al.* [7, 8] studied the seal impact of noncontact finger seals, determined the relationship, and performed numerical calculations by CFD. Chen *et al.* [9, 10] applied dynamic analysis and proposed a comparable dynamical model for the reason of the distributed mass method. The dynamic efficiency of finger seals was analyzed by employing such models, and the seal of C/C composite materials was also studied. Wang *et al.* [11, 12] conducted a dynamic analysis of finger seals of composite materials to study the seal performance of finger seals from the point of view of mechanics. The authors considered the finger seal when it is under operating conditions to find out its dynamic performance and temperature variation to promote the development of this kind of seal towards engineering applications. On this basis, the relationship between impact and fingertip seal was analyzed [13], and it was found that impact has a remarkable impact on the dynamic behavior of this sealant. Wang *et al.* [14] established the finger seal comparable dynamical framework based on the complex working conditions. Furthermore, this author analyzed its dynamic performance and found out that its accuracy in the framework had been confirmed by testing. Li *et al.* [15] used a high-speed seal testbed to study leaks as well as wear features of finger-sealing devices during different temperatures and rotational speeds. Zhao [16] considered the tilt and impact of the rotor, and modified parameters of the comparable dynamical framework. Through the porous approach, Zhao *et al.* [17] established a model and considered both sides of the leaking movement, exploring the leakage of finger seals, and laying the foundation for the analysis of its seal characteristics. Zhang *et al.* [18] investigated a variable stiffness finger seal and then compared it with a finger seal of a conventional profile to demonstrate the superiority of the performance of such a new seal. Zhao *et al.* [19] proposed a secondary finger seal and made a detailed study of the sealing characteristics of this type. Zhang *et al.* [20] proposed a multi-objective optimization model to in-

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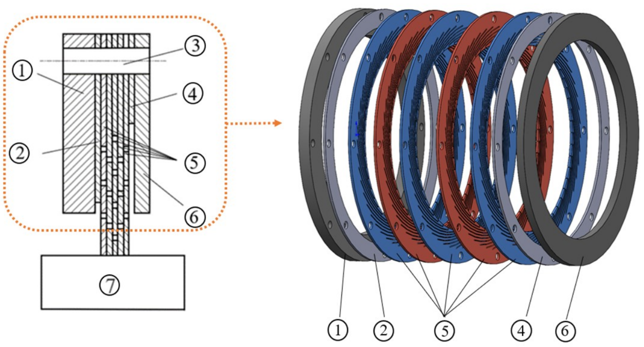
vestigate the structural parameters of finger seals. Zhang [21,22] analyzed the performance associated with the noncontact finger seal during contact and noncontact, as well as the dynamic characteristics. Boudreau and Picard [23] adopted the finger seal for the engine combustion chamber. In summary, many studies on the seal performance of finger seals have been conducted by scholars, but little work can be found on the analysis of seal force, especially for a single finger beam.

Currently, most of the literature addresses the seal force during the whole cover piece. However, the structure is composed of multiple finger beams, and the seal force is calculated based on the pulling force functioning in the entire piece. In the course of the functioning with a rotor-finger seal system, as there exist many thin metal beam arrangements, each beam has a different contacting performance with the shaft. Its angle and contacting area are different from each other. Thus, the seal force on each beam will be not the same. When the force is analyzed, the results are not accurate enough if only the seal force during the whole cover piece is considered. This paper proposes a method for calculating finger seal force to study the specific force of a single finger beam when it is in a contact situation. The models of the finger beam without eccentricity and with eccentricity are established, and the curved flexible finger beam is regarded as the straight one with an added certain loading moment at the end of it. The seal force loaded on the end is studied and compared with the literature. When the friction factor, finger beam length, and other structural coefficients change, the change of seal force is explored. Compared with the results of the literature and considering the actual situation, the result obtained by using this method is more practical and makes a certain contribution to promoting the engineering application of finger seals.

2. FINGER SEAL-ROTOR FORCE MODEL

A finger seal is a multi-layer superimposed seal device, which is composed of cover plates, spacers, and seal pieces, and is combined with rivets. The seals are evenly cut into thin flexible metal beams by wire cutting, which are called finger beams. The two adjacent seal pieces are arranged staggered, covering the gap between the finger beams [24]. The overall structure of contacting finger seal can be seen in Fig. 1.



① Forward cover plate, ② Forward spacer, ③ Rivet, ④ Aft spacer, ⑤ Finger elements, ⑥ Aft cover plate, ⑦ Rotor

Fig. 1. Structure of finger seal

In practical engineering applications, a finger seal is often installed on the shaft in a state of multi-layer overlay. Therefore, the force of the single finger piece is analyzed, and the overall force condition can be obtained after the combination. Considering that the finger sealing becomes cyclical symmetrical, just one finger beam has been selected to analyze seal force. Because the finger beam of involute finger sealing is longer and its curve is larger, it has better follow-up performance than other types of finger beams. In this work, the involute finger seal is taken as the research object.

2.1. Bending flexible beam

In the natural state, the finger beam bends to the side of the shaft. Since it is a new kind of flexible seal technology, when studying the force of a single finger beam, it must ensure that it is a certain elastic metal sheet. Therefore, when analyzing a single-finger beam, it can be regarded as a flexible beam with initial bending.

In the analysis of the initially bending flexible beam, to simplify the calculation, according to the "1R pseudo-rigid body model" [25], the curved finger beam can be assumed as a straight beam with a certain moment Mi at the end of it, as shown in Fig. 2. According to this "1R pseudo-rigid body model", the characteristics associated with the adaptive mechanism can be analyzed using the theory of rigid bodies. The finger beams are very thin metal beams, which are flexible mechanisms due to their inherent bending properties. The deformation of the finger beam when the force acts can be studied by using the analysis method of rigid beam. It is assumed to be a straight beam of equal length but subjected to a certain moment at the end, and this straight beam will bend to the starting point of a finger beam under the action at the moment.

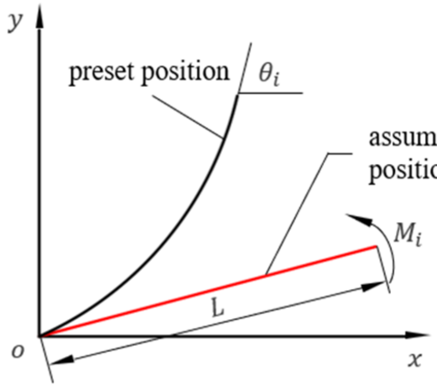


Fig. 2. Straight beam with a certain moment at the end

As observed, the preset position refers to the initial position of the finger beam that is in no contact with the rotor, with the beam capable of being deemed a cantilevered beam alongside radians. The angle between the ultimate point of the beam and the horizontal direction is expressed as θ_i. The assumed position means that a finger beam with initial radians is presumed to function as a straight beam alongside a point at its ultimate point. Torque is expressed in terms of M_i. The straight beam is now in the assumed position.

According to the Bernoulli-Euler equation, the connection that exists between the deformation angles as well as the moment at the end of a beam can be seen from the following equation

$$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \frac{M_i}{EI}\,. \tag{1}$$

Separate variables and integrate

$$\int_0^{\theta_i} \mathrm{d}\theta = \int_0^{L} \frac{M_i}{EI}\,\mathrm{d}s, \tag{2}$$

$$M_i = \frac{EI\theta_i}{L}, \tag{3}$$

where E represents the modulus of elasticity associated with the finger beam material; I remains the point of finger beam inertia; θ_i represents a deformation angle at the finger beam end; M_i remains the loaded moment assumed at the end of the straight beam.

Using the above method, the moment at the end of the beam can be obtained.

2.2. Force model of the rotor without eccentricity

When the rotor is stationary or the speed is low, and the rotor is not eccentric, the single-finger force model is established, it can be seen in Fig. 3. The single-finger beam is regarded as a straight one that has an end loading moment M_i. Since the multi-layer seals work together during operation, and the rotor is stable, it is assumed that the torsion acting on the beam as well as the deformation that occurs in the radial direction are ignored. As the tensile deformation of the finger beam throughout the circumferential direction remains significantly lower when compared to the radial direction, the tensile deformation is ignored.

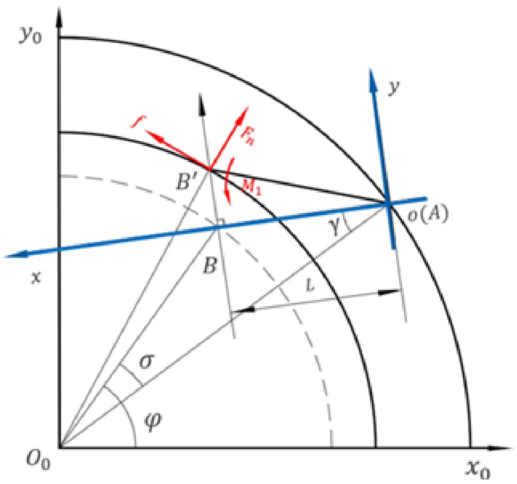


Fig. 3. Single finger beam stress model

Taking the center of the rotor and the middle point on the root of the finger beam to be the collaborate origin, the collaborate systems $x_0O_0y_0$ and xOy are established regarding the power source traverse section of the spindle, where $x_0O_0y_0$ remains the absolute coordinate system and xOy is the relative coordinate system. The rotor rotates counterclockwise, the exterior circle radius of the finger seal emerges as R, and r represents the rotor radius. OB represents the finger beam in the natural state, and its length is L. σ is the angle between O_0O and O_0B in the coordinate system $x_0O_0y_0$ and γ is the original preference during the finger beam.

For the reason that the finger seal acts as a touching seal, to ensure that the finger beam and the rotating shaft are interference fit so it can ensure its good seal performance at rest, a certain amount of interference is required when installing the seal piece so that the finger beam is slightly raised. At the same time, the final portion of the finger beam B will be bent upward to B' position.

The pulling force functioning upon the finger beam which contacts the rotor is shown in Fig. 3, when the finger beam is forced to support force F_n and interaction f is generated by the rotor, along with torque M_1 in a counterclockwise direction. The stress point of the finger beam reaches a state of force balance. In accordance with both the notion of stretching deformations as well as the theory of plane hypothesis, the following can be obtained

$$\theta_{B_1} = \frac{FL^2}{2EI} = \frac{(F_n\cos\theta_B + \mu F_n \sin\theta_B)\,L^2}{2EI}, \tag{4}$$

$$\theta_{B_2} = \frac{M_1 L}{EI}, \tag{5}$$

where θ_B is the final bending angle of the tip beam, θ_{B1} the deformation angle due to the support force F_n, and θ_{B2} the deformation angle due to the moment M_1.

According to the principle of superposition

$$\theta_{B_1} = \theta_{B_2} - \theta_B\,. \tag{6}$$

By combining equation (3), equation (4), and equation (5), we can obtain

$$F_n = \frac{2EI\theta_B + 2M_1 L}{L^2\left(\cos\theta_{B_1} + \mu\sin\theta_{B_1}\right)}, \tag{7}$$

where μ remains the contact factor among a finger beam along with the spindle.

It is evident from equation (6) that the seal force F_n is connected to both θ_B and the moment M_1. Figure 3 illustrates the analysis of the geometric relationship in the diagram.

$$\sigma = \angle BO_0O = \arcsin\frac{l_{AB}\sin\gamma}{lO_0B} = \arcsin\frac{L\sin\gamma}{\sqrt{L^2+R^2-2LR\cos\gamma}}\,. \tag{8}$$

So θ_B can be expressed as

$$\theta_B = \angle O_0B'B = \arcsin\frac{l_{O_0B}\sin\angle O_0B'B}{r} = \arcsin\frac{(r-\delta)\cos(r+\delta)}{r}, \tag{9}$$

where δ is the radial displacement resulting from the deformations of the fingertip beam.

Seal force of the finger when the rotor is not eccentric can be obtained by simultaneous equation (4), equation (6), and equation (7).

2.3. Force model of a rotor with eccentricity

During the rotating part is eccentric, the shaft squeezes the finger beam towards the axial direction, which further aggravates the lifting of the finger beam. The pulling force framework for a single finger beam is determined as can be seen in Fig. 4.

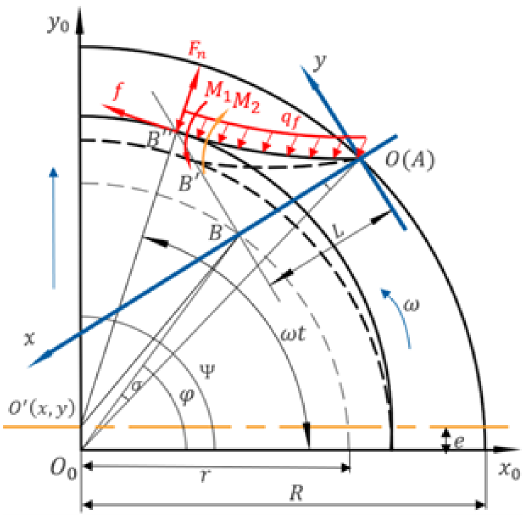


Fig. 4. Single finger beam stress model with eccentricity

While the elongated orientation is assumed to be upwards vertically together with y direction, two coordinate systems, $x_0O_0y_0$ and xOy, are created that are exactly the same as those in Fig. 3. All other aspects of the geometrical connections as well as finger beam parameters are unchanged. φ remains the location angle of finger beam with respect to the absolute system of coordinates. An irregular separation e is present when the longitudinal center rises to the point O' and can be expressed as follows

$$e = \sqrt{x^2 + y^2}\,. \tag{10}$$

The rotating part is unconventional and the twisted finger beam is assumed to be a straight beam alongside the conclusion adding time M_1. The final portion attached to the finger beam is raised to the starting stretching location B' to B'' because of the spindle eccentricities as additional bending occurs. The stretching happens through the momentum M_2 functioning on the ultimate point of the finger beam, within a counterclockwise motion. Additionally, owing to the elongated shape of the rotor, it is not smooth in the axial direction and there is eddy current movement. Consequently, when using several placed finger fragments, there currently needs to be reciprocal disarray among finger pieces. The investigation demonstrates that every finger beam gets subjected to a frictional force generated by adjacent finger beams. In accordance with the research, this frictional force has become equivalent to a constant load q_f operating upon one finger beam according to the same direction as F_n, which means

$$q_f = \beta F_n\,, \tag{11}$$

where β represents the evenly distributed loading friction coefficient of the finger beam in equation (11).

In addition indicated by Fig. 4, during this point, the finger beam undergoes exposure to the supporting force F_n and friction force f generated by the spindle, along with frictional uniform load q_f as well as final adding M_1 along with M_2. Within the moment the finger beam reaches equilibrium with forces during the exact location. By applying the concept of stretching deformations along with the plane presumption theory, what occurs is

$$\theta_{B_1} = \frac{FL^2}{2EI} = \frac{(F_n \cos\theta_B + \mu F_n \sin\theta_B)\, L^2}{2EI}\,, \tag{12}$$

$$\theta_{B_2} = \frac{ML}{EI} = \frac{(M_1 - M_2)\, L}{EI}\,, \tag{13}$$

$$\theta_{B_3} = \frac{q_f L^3}{6EI}\,. \tag{14}$$

According to the principle of superposition

$$\theta_B = \theta_{B_2} - \theta_{B_1} - \theta_{B_3}\,. \tag{15}$$

Through integrating equations (11)–(14), it is possible to obtain

$$F_n = \frac{6ML - 6EI\theta_B}{3L^2\left(\cos\theta_{B_1} - \mu \sin\theta_{B_1}\right) + \beta L^3}\,, \tag{16}$$

where M is equal to $M_1 - M_2$.

According to equation (16), μ remains the frictional factor among the finger beam and the rotating part. Because the objective about gain θ_B, the geometrical relationships within the representation undergo examination, and these are easily observed in Fig. 4

$$l_{O'B} = \sqrt{e^2 + (r-\delta)^2 - 2e(r-\delta)\cos(\psi - \varphi)}\,, \tag{17}$$

$$\angle O_0BO' = \arcsin\left[e \sin(|\psi - \varphi|) \times \frac{1}{\sqrt{e^2 + (r-\delta)^2 - 2e(r-\delta)\cos(\psi-\varphi)}}\right], \tag{18}$$

$$\begin{aligned}\angle O'BB' &= \frac{3}{2}\pi - \angle O_0BO' - \angle O_0BA \\ &= \frac{\pi}{2} + \gamma + \sigma \\ &\quad - \arcsin \frac{e\sin(|\psi-\varphi|)}{\sqrt{e^2+(r-\delta)^2-2e(r-\delta)\cos(\psi-\varphi)}}\,,\end{aligned} \tag{19}$$

Thus, θ_B may be expressed as follows

$$\theta_B = \arcsin \frac{\sqrt{e^2 + (r-\delta)^2 - 2e(r-\delta)\cos(\psi-\varphi)}}{r} \times \cos\left[r+\delta-\arcsin \frac{e\sin(|\psi-\varphi|)}{\sqrt{e^2+(r-\delta)^2-2e(r-\delta)\cos(\psi-\varphi)}}\right]. \tag{20}$$

According to the above, the total amount of θ_B can be gathered, and F_n at eccentric indicates it is achievable through carrying it back.

From the two equations for the rotor without eccentricity and the rotor with eccentricity, this is easily determined that the primary variables affecting the finger seal force are parameters inside the finger seal-rotor system, including E, I, the finger beam length L, as well as the friction factors of the finger seal μ and θ_B. By varying those parameters, the connection between the parameters of the finger seal and its seal force can be obtained, as well as the relationship between the seal force in the noneccentric and variations about seal force within noneccentric and eccentric conditions.

2.4. Verification of seal force model

When the rotating part is eccentric, the rotor moves within an identified radial orientation. Due to its elasticity, the finger beam in the other direction of the rotor motion compresses and the single finger beam contacts the rotor. There is no contact between the finger beam on the opposite side of the motion direction and the rotor. It can be seen that not all of the finger beams are in contact. The whole area is capable of being separated into interaction as well as noncontact zones.

From the axial direction, the whole finger sealing piece can be divided into two zones. The contact area is approximated as 180°. Since the finger seal piece is a circular structure, a quarter of the seal piece is taken for analysis, as shown in Fig. 5. Due to the characteristics of the finger beam, it is possible to obtain

$$F_x = F_n \cos(\tau), \tag{21}$$

$$F_y = F_n \sin(\tau), \tag{22}$$

$$\tau = bm, \tag{23}$$

where b is the angular difference between the τ angles about both finger beams along m remains the total amount of finger beams in a certain region. Since the seal piece is a symmetrical structure, a quarter of the region is taken here for calculation. In this work, the number of one seal piece is 60 for the overall structure, the maximum value of m in the region is 15, and $b = 6$. The partial forces in the x-axis along with the y-axis directions of the seal piece were calculated using the method in this work and compared with the results in reference [26] for analysis. The comparison result is shown in Fig. 6.

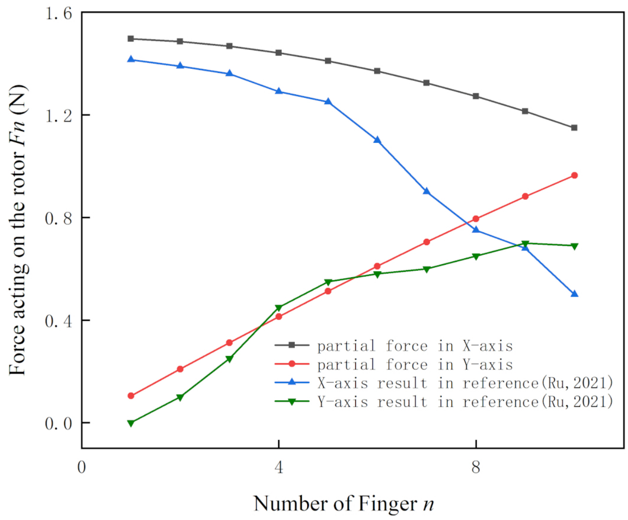


Fig. 6. Differences in two calculation results

In Fig. 6, the lines show that the partial force in the x-axis direction is in a smooth decreasing trend, while the partial force in the y-axis keeps rising. This is because the force point keeps approaching the y-axis in the calculation process. Meanwhile, the variation trend of the partial forces in both directions is similar to the results in the reference. The result shows that partial force in the x-axis direction decreases uniformly using the calculation method in this paper, while the trend of the partial force on the first four finger beams in the reference is similar to the results in this paper and then decreases rapidly. The partial force on the y-axis increases, which matches the results in the reference. However, the result shows that as the number of beams increases, partial force in the y-axis direction in the reference rises slower. According to the actual situation, combined with the analysis in Fig. 3, it can be found that the partial forces on the x-axis and y-axis are uniformly varied. In contrast, the computation results obtained from [26] exhibit that this seal partial force changes too fast with the increase of the number of finger beams. The data shows that the calculation method presented in the paper more accurately reflects the actual situation and yields superior results.

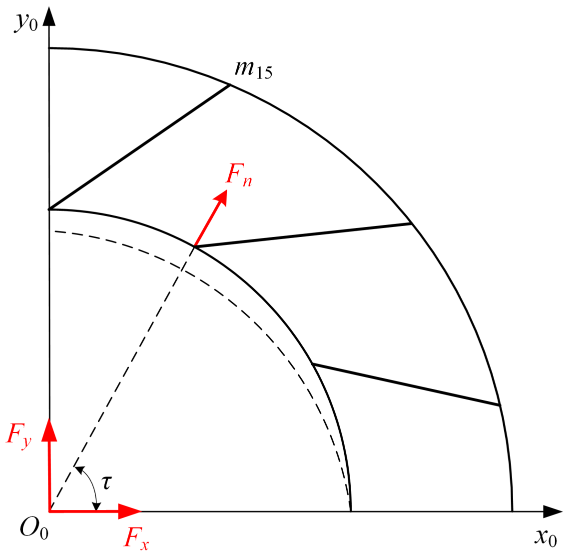


Fig. 5. Stress condition of finger seal finger beam in contact area

3. RESULTS AND DISCUSSION

3.1. Seal force of rotor without eccentricity

In accordance with the structural features presented by the finger seal, the seal force variation is obtained when the length of the finger beam is changed with different friction factors at an initial interference of 0.15 mm, as shown in Fig. 7. There is also an effect on the seal force caused by the change of friction factor for different length of beam, as shown in Fig. 8.

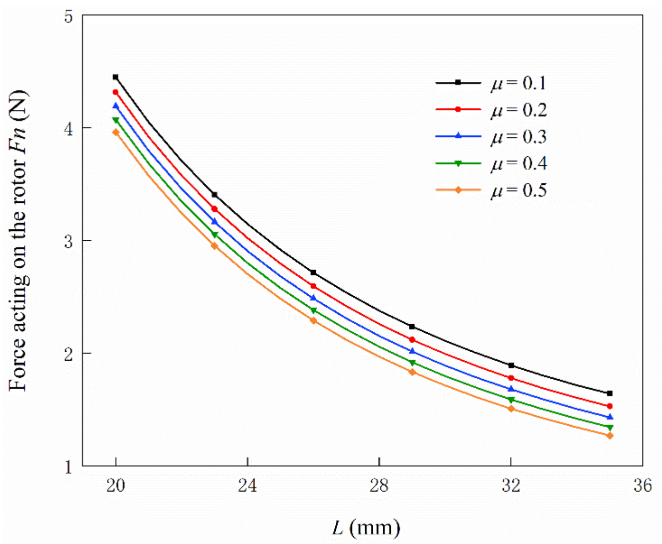


Fig. 7. Effect of finger beam length on seal force without eccentricity

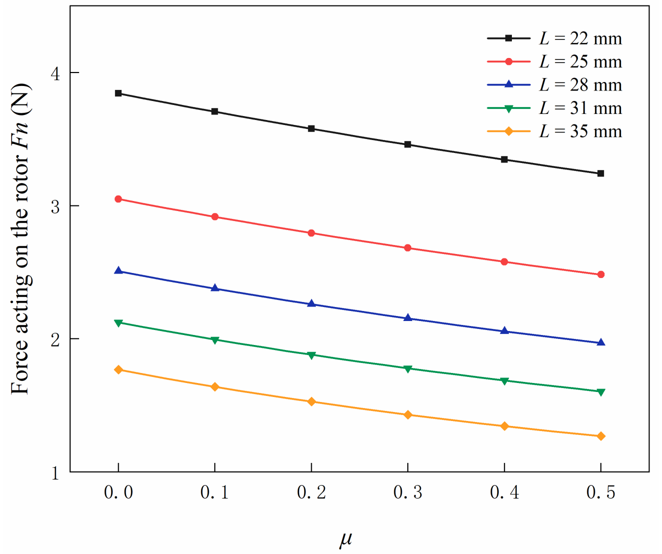


Fig. 8. Effect of friction factor on seal force without eccentricity

No eccentricity occurs when the rotor is running at a low speed. Due to the amount of interference among the rotating part along with the seal device, the finger beam must be exposed to frictional force generated by the rotor, and the seal force is bound to change when the friction factor of the contact surface changes. It can be seen from the figure that when the length that contains the finger beam is the same, the larger the friction factor is, the smaller the seal force becomes. And when all the friction factors are the same, the seal force diminishes as the length increases.

When the length is the same, the direction of the friction force is contrary to the direction of the finger beam movement. Since there is an initial inclination angle among the finger beam and the rotor surface, along with a certain friction force stretch on the finger beam, there is a tendency to break away from the rotor. When this friction force increases, this tendency becomes increasingly significant, which is expressed numerically as a reduction in the seal force.

When the friction factor is constant, the finger beam is flexible and deformed in the operating condition. Therefore, when all other parameters are constant, the shorter the finger beam, the greater its stiffness, and the more difficult it is to produce deformation under the same amount of interference. Thus, an enhancement within the seal force is demonstrated. When the length associated with the finger beam increases, its stiffness decreases, and deformation is more likely to occur. Good followability reduces the hysteresis phenomenon, but it will make the seal performance decrease.

There is some information shown in Figs. 7 and 8, single beam seal force also changes significantly when the friction factor and finger beam length are varied together. Both an increase in the friction factor and finger length result in an overall reduction in the seal force. However, the comparison of the two figures shows that the change in seal force is not significant when the friction factor alters, while the change is significant when the length of the finger beam is amended. Accordingly, it can be concluded that the change of length can yield a more remarkable effect on seal performance within the finger seal than the friction factor μ.

3.2. Seal force when the rotor is eccentric

Based on the structural characteristics of the finger seal, when initial interference is 0.15 mm and the rotating part is unconventional, the change of finger beam seal force with different parameters is explored by changing the eccentricity. When the finger beam length L, friction factor μ, friction factor β between finger plates as well as the inclination angle γ of the finger beam change, the single beam seal force produced by the finger beam to the rotor also changes, as shown in the following figure.

When the speed of the rotor is fast, the whirl will occur, and the rotor will be eccentric in the system. When the finger beam length is 25 mm and the eccentricity changes, with the increase of the finger beam length, the seal force still shows a downward trend, as shown in Fig. 9. The reason this phenomenon occurs is that when the length associated with the single finger beam increases, stiffness decreases, the follow-up of the seal device is improved, as well as the seal functioning decreases.

Also, it can be inferred from Fig. 9 that the effect of eccentricity on seal force decreases as finger beam length rises. The change in seal force caused by a change in eccentricity is more significant when the length is 22 mm, while when the length increases to 35 mm, it is difficult for the change in eccentricity to affect the seal force. This is due to the longer finger beam, which reduces the range of variation throughout the radial orientation, and the good followership associated with the finger

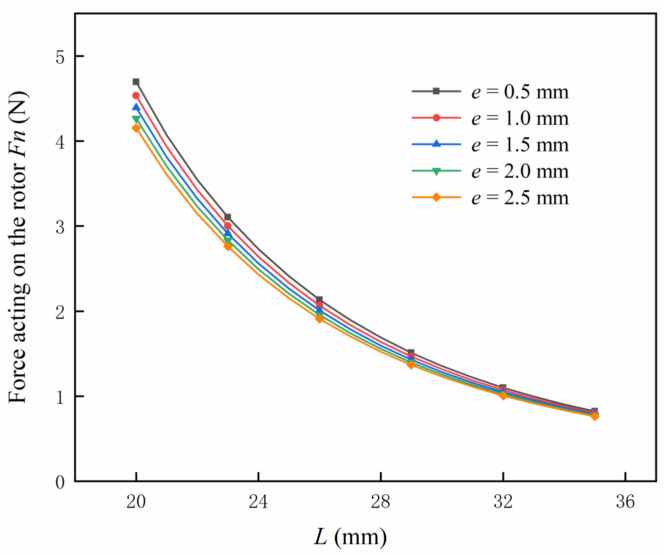


Fig. 9. Effect of finger beam length on seal force with eccentricity

beam, which is less prone to the hysteresis effect, so the impact on seal force is minimal.

The change associated with the seal force can be observed in Fig. 10 when the amount of friction μ among the finger beam along with the rotating part is changed. According to the figure, the seal force increases as the friction factor increases. This is due to the rotor eccentricity, which lifts the finger beam within the direction of radiance as well as stretches it in the circumferential direction, increasing the contact area among the finger beam along with the rotating part, making uncontacted piece smaller when eccentric, and therefore increasing the seal force. Meanwhile, the seal force associated with finger seal decreases as the eccentricity increases. This phenomenon occurs because when the rotor is eccentric, a contact area and a noncontact area will be formed on the rotor surface. When the eccentricity is larger, the contact area will be smaller and the noncontact area is bigger, which negatively affects the seal force.

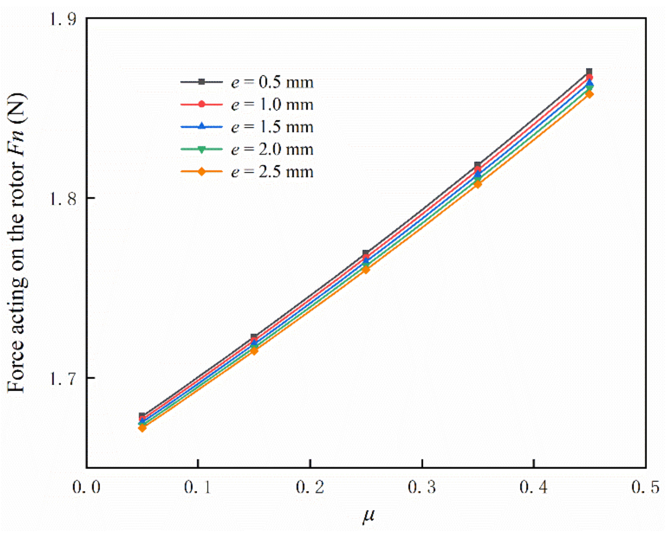


Fig. 10. Effect of friction factor on seal force with eccentricity

Similarly, as the finger beam length increases with a fixed eccentricity, the higher the friction factor, the higher the seal force regarding finger beam on rotor, as shown in Fig. 11. Seal force decreases as the length of the finger beam elongates. This phenomenon occurs because as the finger beam elongates, its stiffness decreases and the force on the rotor drops.

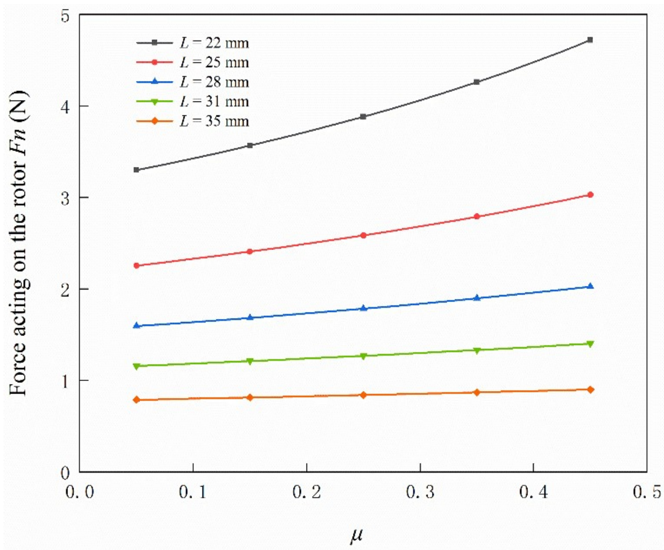


Fig. 11. Influence of friction factor and finger beam length on seal force

At the same time, in the case of eccentricity, the change in the friction factor has an upward trend on the seal force. The greater the friction factor, the more pronounced the degree of change in the seal force when the finger length changes by the same amount. When the rotating part is unconventional, the interaction position among the finger beam along with the rotor changes, and this time when the friction factor is larger, the deformation caused by the friction is increased. Because of tensile deformation, the force among the finger beam along with the rotating part is closely related to the beam stiffness itself. Therefore, as the finger gets longer, its stiffness decreases, which has an impact on the seal force.

Figure 12 shows the force change of changing the friction factor β on seal force at different eccentricities. The figure demonstrates that the seal force tends to decrease while the friction factor grows.

The reason for this phenomenon is that when the friction factor β increases, the finger beam can be affected by forces of friction generated by the adjacent finger piece. Within the procedure regarding rotor eccentricities, the finger beam is prone to the hysteresis effect. The higher the friction force, the worse the beam follower performance, which will be manifested as a decrease in seal force. It can be seen that the force decreases rapidly between 0.1 and 0.2 as the friction force increases. From 0.2 to 0.3, the decreasing tendency of the seal force slows down. That is probably due to the limited degree of influence on the seal force while the friction factor rises to a certain level. During the change in eccentricity, the seal force remains unchanged, and the change of seal force can hardly be seen in the figure.

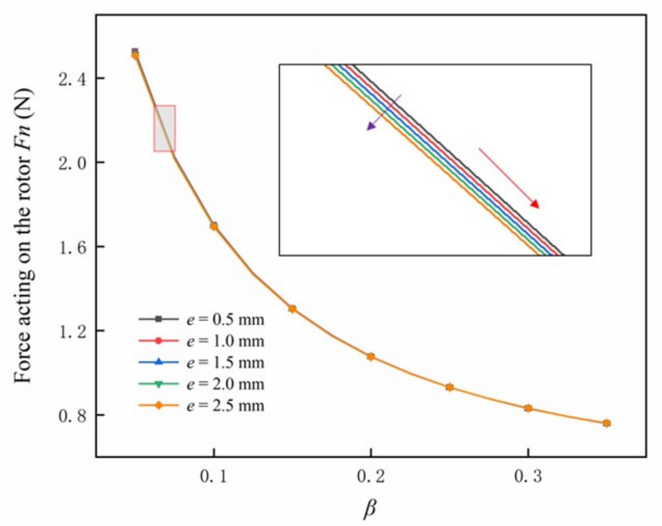


Fig. 12. Effect of friction factor between fingers on seal force

When the beam position angle keeps changing, the modification associated with the seal force is shown on Fig. 13. This pronounced change proves that the variance in the seal force shows a certain pattern with the change of the inclination angle. In the interval from 37° to 43°, the seal force associated with the finger seal shows a complete cycle change, and in the middle of 37° to 40°, the seal force first decreases and then rises back and returns to the original level. This indicates that there is an exceedingly small value point of the seal force in this interval, while there is an exceptionally large value point of the seal force between 40° and 43°.

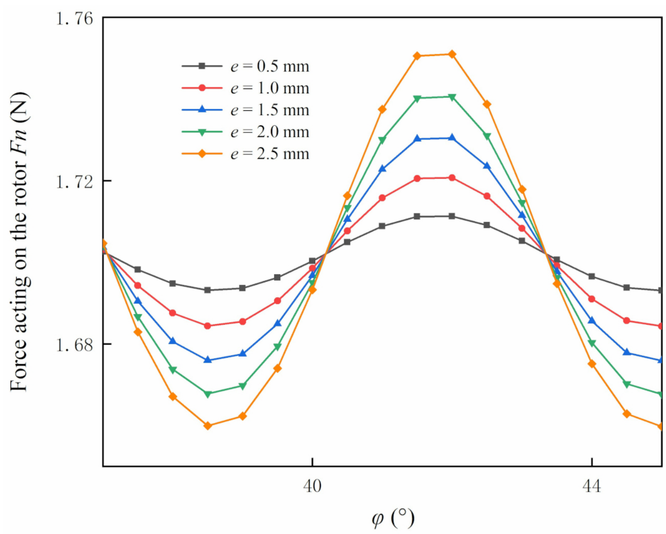


Fig. 13. Influence of position angle on seal force

This phenomenon is closely related to the finger beam structural dimensions. At rotor eccentricity, the contacting angle among the finger beams along with the rotating part in various positions becomes continuously smaller while the rotor keeps rising. When the rotating part moves upward, as can be seen from Fig. 4, the angle of the beam bending upward grows, with a stronger lifting effect on the finger beam. During the motion, the seal force falls. And while the position angle becomes larger, the deformation caused by the beam bending upward decreases and the seal force keeps increasing. Meanwhile, it can be found that the seal force is affected by the position angle with the increase of the eccentricity showing an upward trend. As the rotor eccentricity increases, the influence on the position angle grows and the deformation of the finger beam increases, for this reason, the seal force also grows.

4. CONCLUSIONS

This work investigates the forces at the end of the finger beam contacting with the rotor when the finger seal piece is in operation. The analysis is conducted on a single finger beam and no longer on the whole seal piece. A new analysis method is proposed, where the bending finger beam is considered a flexible beam with a certain moment at the end. The variation of the seal force is discussed separately for the two cases of the rotor with and without eccentricity. The main conclusions of this work can be seen as follows:

1. When there is no eccentricity, the seal force of finger seal decreases with the increase of finger beam length besides friction coefficient, and the influence of finger beam length on seal force is more obvious.
2. When the rotor is eccentric, the seal force is constantly changing with the change of eccentricity. The length of the finger beam and the friction factor have a conspicuous effect on seal force. When the position angle of the finger beam changes, the seal force changes periodically, and force varies uniformly with the change of the position angle in the interval.
3. The eccentricity influence on seal force is nonlinear. When the finger beam length changes, the influence of eccentricity on seal force weakens. When the friction factor changes, the influence of eccentricity is more obvious.

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