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Numerical analysis of seal force in contacting finger seal

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Abstract. Finger seal is a flexible sealing device widely used in high-temperature and high-pressure environments such as gas turbine. Its force analysis is the key to design and optimize the performance of finger seal. At present most of the research on force analysis of finger seal are focused on the whole seal ring, but each finger beam has a different contacting performance with the shaft. In this work, a new force analysis method for contacting finger seal is proposed, as well as the model of finger seal 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.

Key words: bending flexible beam; contacting finger seal; seal force; eccentricity; numerical analysis

1. INTRODUCTION

Gas turbine has been extensively used in aerospace, shipping and other fields because of the high power [1,2]. In order 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 reliable 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 seal has been widely concerned by researchers. According to whether the finger and rotor is contact or not, there are two types of seal: contacting type and non-contacting 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 new technology has much better performance than that of traditional labyrinth seal, as well as its leakage is 80% of that of labyrinth seal. When there exists a similar seal effecting, the cost of finger seal is very low, about half of that of brush seal. Because of its excellent characteristics, it is very meaningful to research this kind of seal.

Among these years, researchers and scholars have conducted in-depth research on finger seal. Braun *et al.* [7,8] studied the seal impact of non-contact finger seal, determined the relationship and performed numerical calculation 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 dynamical efficiency about finger seal was analyzed by employing such model, as well as the seal of C/C composite materials was also studied. Wang *et al.* [11,12] have set up a dynamic analysis of finger seal of composite materials to study the seal performance of finger seals from 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 re-markable impact upon 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 about 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] took into account the tilt and impact of the rotor, and modified parameters of the comparable dynamical framework. Though

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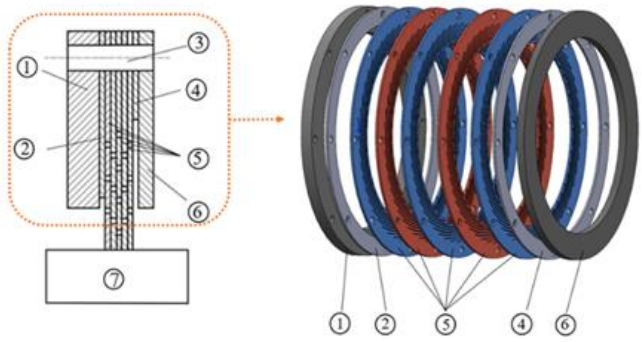
the porous approach, then Zhao *et al.* [17] established a model and considered both sides leaking movement, as well as explored the leakage of finger seal, and this established a groundwork to stay the analysis of its seal characteristics. Zhang *et al.* [18] investigated a variable stiffness finger seal 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 on the sealing characteristics of this type. Zhang *et al.* [20] proposed a multi-objective optimization model in an effort for investigating the structural parameters of finger seal. 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 engine combustion chamber. In summary, many studies on the seal performance of finger seal have been conducted by scholars, but relatively little work can be found on the analysis of seal force, especially for single finger beam.

At present stage, 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 situation of the pulling force functioning on the entire piece. In the course of the functioning with a rotor-finger seal system, as there exists many thin metal beam arrangements, each beam has a different contacting performance with the shaft. It's 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 single finger beam when it is in contacting 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 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 considered 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 seal.

2. FINGER SEAL-ROTOR FORCE MODEL

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 Figure 1.



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

Fig.1. Structure of finger seal

In practical engineering applications, 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 over-all force condition can be obtained after the combination. Considering that the finger sealing gets the cyclical symmetrical, and 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 beam. 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, it has to make sure when studying the force of a single finger beam, 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, with the aim of simplifying 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 Figure 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. So the deformation of the finger beam when the force acting 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 finger beam under the action at the moment.

As observed, the preset position refers to the initial position of the finger beam which has been none-contact with the rotor, the beam is capable of being deemed a cantilevered beam alongside radians. As well as the angle between the final 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 final point. Torque is expressed in terms of M_i. The straight beam is now in the assumed position.

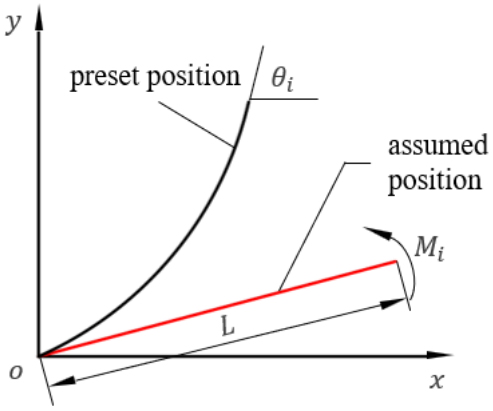


Fig.2. Straight beam with a certain moment at the end

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:

$$\frac{d\theta}{ds} = \frac{M_i}{EI} \tag{1}$$

Separate variables and integrate:

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

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

where E represents the modulus of elasticity associated with the finger beam material; as well as 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 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 Figure 3. The single finger beam is regarded as a straight one which 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 finger beam throughout the circumferential direction remains significantly lesser when compared to the radial direction, the tensile deformation is ignored.

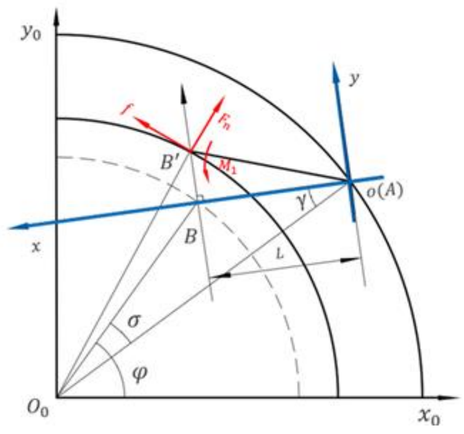


Fig.3. Single finger beam stress model

Taking the center of the rotor and the middle point on the root of the finger beam to be the collaborate origin, the collaborate system $x_0O_0y_0$ 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. Suppose the rotor rotates counterclockwise and the exterior circle radius of the finger seal has emerged as R, as well as r represents the rotor's 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 coordinate system $x_0O_0y_0$. 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 finger beam which is contacting with rotor is shown in Fig. 3, when the finger beam gets forced to supporting force F_n as well as interaction f generated by the rotor, along with torque M_1 in a counterclockwise direction. The stress point of the finger beam has reached a state of force balance. In accordance to both the notion of stretching deformations as well as the theory of plane hypothesis, the following can be obtained.

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

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

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 the Eq. (3), Eq. (4) and Eq. (5), we can get:

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

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

It is evident from Eq. (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 Eq. (4), Eq. (6), and Eq. (7).

2.3. Force model of rotor with eccentricity.

During the rotating part is eccentric, the shaft will squeeze the finger beam towards the axial direction, which will further aggravate the lifting of the finger beam. The pulling force framework for a single finger beam has been determined as well as could be seen in Figure 4.

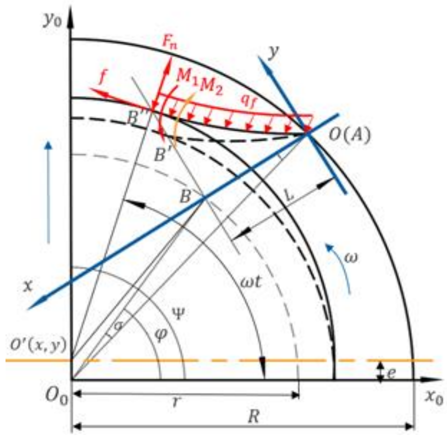


Fig.4. Single finger beam stress model with eccentricity

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 Figure 3. All other aspects of the geometrical connections as well as finger beam parameters have been the same. 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' as well as is capable of being written as follows:

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

During the rotating part is unconventional, the twisted finger beam is assumed that it's a straight beam alongside the conclusion adding time M_1. The final portion attached to the finger beam is going to be 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 final 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 fingertip beam gets subjected with 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's beam according to the same direction as F_n, which means:

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

β represents the finger beam's evenly distributed loading friction coefficient in Eq. (11).

In addition indicated by Fig. 4, during this point the finger beam undergoes exposure to the supporting force F_n as well as 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 has reached equilibrium with forces during the exact location. By applying the concept of stretching deformations along with the plane presumption theory, this happens that:

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

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

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

According to the principle of superposition:

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

Through integrating Eq. (11)-Eq. (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 Eq. (16), μ remains the frictional factor among the finger beam as well as 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:

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

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

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

Thus, θ_B may be expressed as follows:

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

According to the above, the total amount of θ_B is able to gathered, as well as the F_n at eccentric indicates 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 as well as θ_B. By varying those parameters, the connection among the parameters of the finger seal and its seal force can be obtained, as well as the relationship between the seal force in the non-eccentric and variations about seal force within non-eccentric and eccentric conditions.

2.4. Verification of seal force model.

When the rotating part has been eccentric, the rotor moves within an identified radial orientation. Due to its elasticity, the finger beam at the other direction of rotor motion gets compressed as well as single finger beam is contacting with the rotor. There is no contacting relationship between 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 non-contact zones.

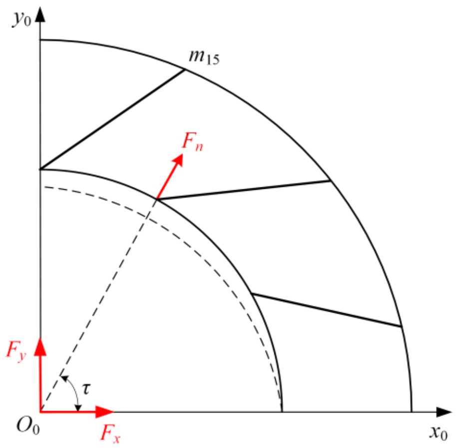


Fig.5. Stress condition of finger seal finger beam in contact area

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 that:

$$F_x = F_n \cos(\tau) \quad (21)$$

$$F_y = F_n \sin(\tau) \quad (22)$$

$$\tau = bm \quad (23)$$

where b is the angular difference between the τ angles about both finger beams along with m remains the total amount of finger beams in certain region. For the reason that 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 overall structure, the maximum value of m in the region is 15, and b=6. The partial forces in the x-axis along with y-axis directions of the seal piece have been calculated using the method in this work and compared with the results in the reference [26] for analysis. The comparison result is shown in Fig. 6.

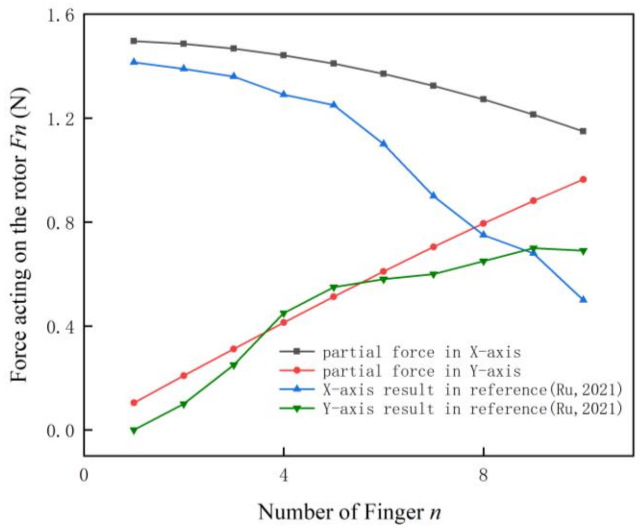


Fig.6. Differences in two calculation results

In Figure 6, what lines show can be seen that the partial force in x-axis direction is in a smooth decreasing trend, while the partial force in the y-axis keeps rising. This is due to the fact that the force point keeps approaching to 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 thereafter. The partial force on the y-axis is increasing, which is a good fit with the results in the reference. However, the result shows that as 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 varying. In contrast, the computation results obtained from Ref. [26] exhibit that this seal partial force changes too fast with the increase of the number of finger beams. As the data shows that this calculation method in the paper is much closer to the actual situation and has better results.

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 about the finger beam is changed with different friction factors at an initial interference of 0.15 mm, as shown in Figure 7. As well as the effect on the seal force caused by the change of friction factor for different length of beam, as shown in Figure 8.

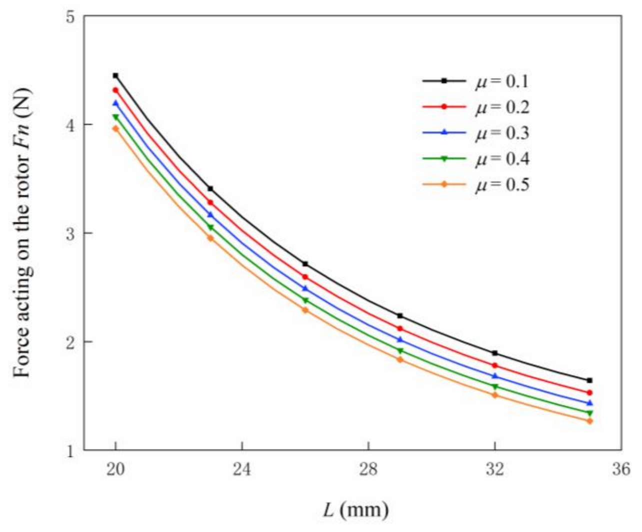


Fig.7. Effect of finger beam length on seal force without eccentricity

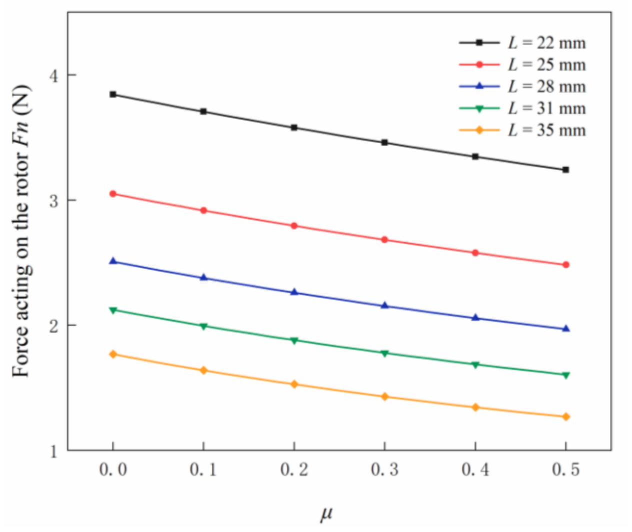


Fig.8. Effect of friction factor on seal force without eccentricity

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 has to 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 the larger friction factor is, the smaller the seal force is when the length that contains the finger beam is the same. And when all the friction factors are the same, the seal force becomes smaller as length increases.

When the length is the same, the direction of friction force is on the contrary to the direction of finger beam's movement. Since there is an initial inclination angle among the finger beam as well as the rotor surface, along with a certain friction force stretch on the finger beam, causing a tendency to break away from the rotor. When this friction force increases, this tendency becomes more and more 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 is, the greater its stiffness, the more difficult it is to produce deformation under the same amount of interference, so it shows an enhancement within the seal force. When the length associated with the finger beam increases, its stiffness becomes smaller 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 Figure 7 and Figure 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 about the two figures shows that the change in seal force is not significant when the friction factor is changed, while the change is significant when the length of finger beam is changed. Accordingly, it can be concluded that the change of length can get more remarkable effect on seal performance within the finger seal than the friction factor μ.

3.2. Seal force when the rotor is eccentric.

On the basis of structural characteristics of finger seal, when initial interference is 0.15mm 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 is also changing, 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 finger beam length is 25 mm, as well as the eccentricity changes, with the increase of the finger beam length, the seal force still shows a downward trend, as shown in Figure 9. The reason for why this phenomenon occurs is that when length associated with the single finger beam increases, stiffness decreases, the follow-up about the seal device has been better, as well as the seal functioning decreases.

What is the information can also be told is that from Figure 9, the effect of eccentricity on seal force decreases as finger beam length rises. The design has been seen that 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 fin-ger beam, which reduces the range of variation throughout the radial orientation, and the good followership associated with the finger beam, which is less prone to hysteresis effect, so the effect on seal force is minimal.

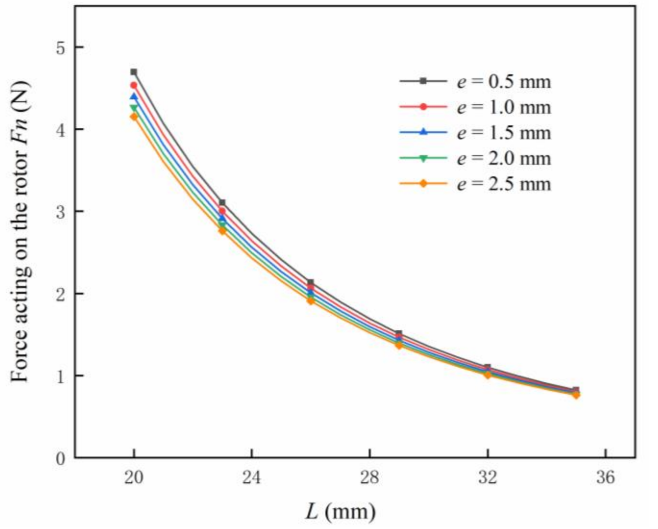


Fig.9. Effect of finger beam length on seal force with eccentricity

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, it could be found the fact that 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 non-contact 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 has a negative impact on the seal force.

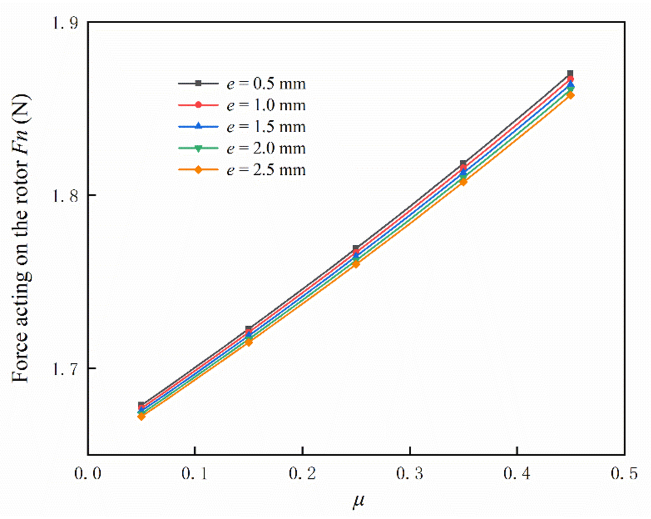


Fig.10. Effect of friction factor on seal force with eccentricity

Similarly, as finger beam length increasing with a fixed eccentricity, the higher friction factor, the higher the seal force regarding finger beam on rotor, as shown in Figure 11. Seal force is decreasing as the length of the finger beam gets longer. This phenomenon occurs because the fact that as the finger beam gets longer, its stiffness decreases and the force on the rotor decreases.

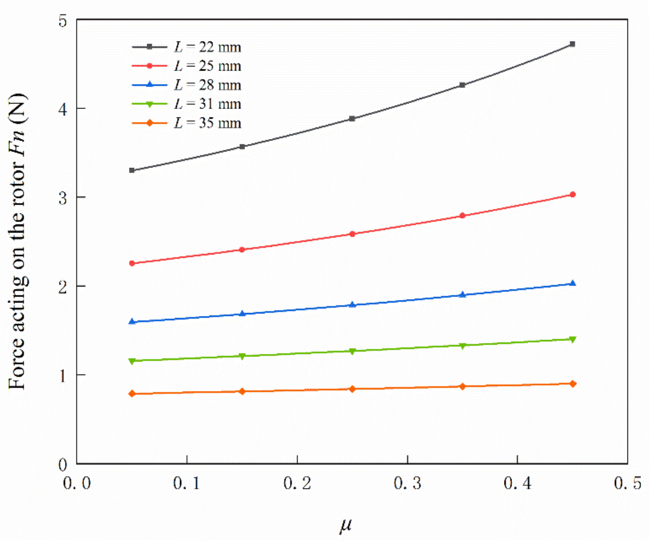


Fig.11. Influence of friction factor and finger beam length on seal force

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. This is because 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 larger. 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 is increasing.

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

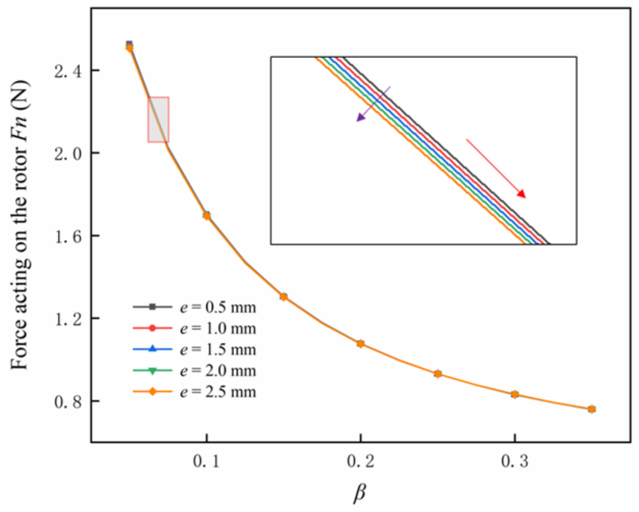


Fig.12. Effect of friction factor between fingers on seal force

When the beam position angle keeps changing, the modification associated with the seal force is shown in Figure 13. This pronounced change demonstrates that the variance about 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 a very small value point of the seal force in this interval, while there is a very large value point of the seal force between 40° and 43°.

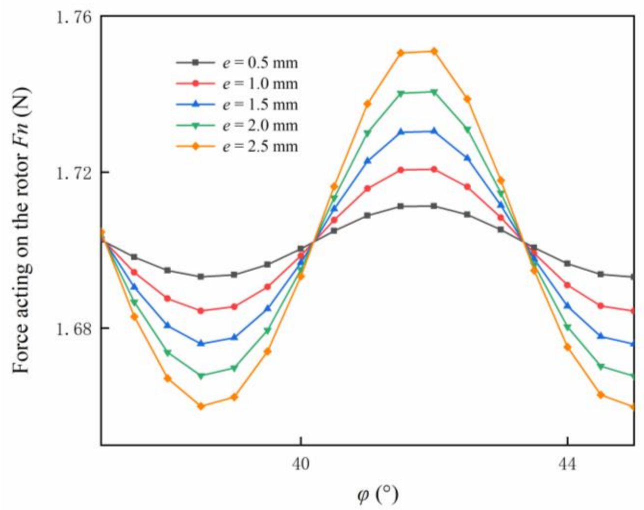


Fig.13. Influence of position angle on seal force

This phenomenon is closely related to the finger beam structural dimensions. At rotor eccentricity, the contacting angle among the finger beam along with the rotating part in different positions becomes continuously smaller while the rotor keeps going to rise. When the rotating part moves upward, as can be seen from Figure 4, the angle of the beam bending upward becomes larger, and the stronger its lifting effect on the finger beam. During the motion, the seal force goes down. 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 the seal force is affected by position angle with the increase of the eccentricity showing an upward trend. This is due to the fact that as the rotor eccentricity increases, the influence on the position angle becomes larger and the deformation of the finger beam increases, for this reason that the seal force also increases.

4. CONCLUSIONS

This work investigates the forces at the end of finger beam contacting with rotor when finger seal piece is in operation. The analysis is carried out 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 as a flexible beam with certain moment at the end. The variation of the seal force is discussed separately for the two cases of 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 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 finger beam length changes, the influence of eccentricity on seal force is weakening. When friction factor changes, the influence of eccentricity is more obvious.

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