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Effect of working environment on C/C composite finger seal performance

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Abstract. With the development of the technology, the working conditions, which include high temperature, assembly and working state, have important influence on the dynamic performance of finger seal. Therefore, it is necessary to consider above factors together when the finger seal performance is carried out. But so far, the finger seal performance under considering several factors together have not been investigated. Based on this, the material parameters, which are needed in the dynamic performance analysis process of C/C composite finger seal, are obtained by the tribology test of C/C composite. Then the equivalent dynamic model of finger seal based on distributed masses is established under considering the rotor incline, temperature, assembly and impact together. And the dynamic performance of finger seal is analyzed by the model. The results are shown that the above working states have complex influence on the finger seal performance. Meanwhile, the leakage performance of finger seal is compared with those of labyrinth seal in the bearing chamber working environment, and the advantage of finger seal is represented. The dynamic performance analysis of finger seal under considering complex working states is carried out, and the theory research system of finger seal is further improved.

1. Introduction

A seal device as an important component of aero-engine, has decisive influence on the performance of aero-engine. Finger seal as a novel seal device recently attracts many attentions of scholars[1-3].

Many scholars investigated the performance of finger seal under dynamic condition by equivalent dynamic model. Braun et al treated non-contact finger seal as a system of lumped mass-spring-damping, neglecting the frictional resistances between aft cover plate and finger element and among finger elements[4,5]. Marie treated non-contact finger seal as two degrees of freedom equivalent dynamic model based on lumped mass, only considering the frictional resistance between low pressure finger element and aft cover plate[6]. Su et al carried out the hysteresis performance analysis of finger seal by equivalent dynamic model based on lumped mass, and compared the finger seal leakage rates under dynamic condition with those under static condition[7]. Chen et al established equivalent dynamic model of finger seal based on distributed masses[8].

Recently, the performance analysis of C/C composite finger seal begins to attract many attentions of scholars. Chen et al analyzed the dynamic performance of the C/C composite finger seal by equivalent dynamic model based on the distributed masses[9]. Wang et al discussed the effect of temperature on the dynamic performance of C/C composite finger seal based on the distributed masses[10]. Wang et al also analyzed the effect of rotor incline on the dynamic performance of C/C composite finger seal[11], and discussed the effect of impact velocity and impact restitution coefficient on the dynamic performance of C/C composite finger seal[12].

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But finger seal locates in the coupling effect among some working states in fact. Therefore it is necessary to carry out the dynamic performance analysis under complex working states. Based on this, the material parameters, which are needed in the dynamic performance analysis of C/C composite finger seal, are obtained by the tribology test of C/C composite. The equivalent dynamic model of C/C composite finger seal under complex working states is established, and the finger seal performance under single working state is compared with those under complex working states. Then the effect of rotor incline angle and impact velocity on the finger seal performance under complex working states is carried out. Meanwhile the advantage of finger seal is represented by the comparison between the leakage rates of finger seal and labyrinth seal in bearing chamber working environment. The dynamic analysis technology contributes to improve the practicality of finger seal engineering design.

2. Tribology test of C/C composite

Finger seal and rotor or aft cover plate are made of C/C composite and steel, respectively. Therefore the tribology performance analysis between finger seal and aft cover plate or between finger seal and rotor could be transformed for those between C/C composite and steel. Based on this, C/C composite sample and columnar steel dowel are machined, respectively. The tribology test is carried out by the UMT multifunction friction-abrasion testing machine. Then the effect of fiber orientation of C/C composite and working state on the tribology performance between C/C composite and steel is investigated. The experimental results provide some input parameters for the dynamic analysis of finger seal.

2.1. Structure of UMT multifunction friction-abrasion testing machine

The frictional coefficients between C/C composite and steel under different working states and fiber orientation are obtained by the UMT multifunction friction-abrasion testing machine, which is composed by the systems of hydraulic pressure, dynamical force and control.

2.2. Preparation of C/C composite sample

The schematic diagram of C/C composite sample is shown in Figure.1. To guarantee fiber integrality, machining precision and repetition tests of C/C composite sample, the C/C composite is made into a cube, whose length, width and height are 30mm, 20mm and 3mm by wire electrode cutting respectively, that is shown in Figure.2. And then the surface roughness of C/C composite sample is 1.5μm. In addition, columnar steel dowel is made of $45^{\#}$ steel in the test.

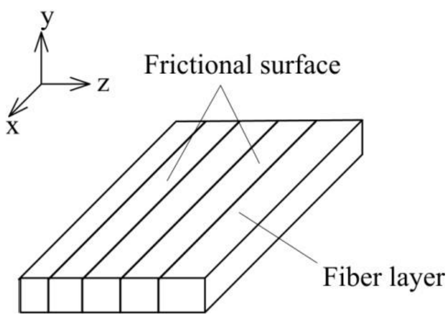

Figure 1. Schematic diagram of C/C composite sample.

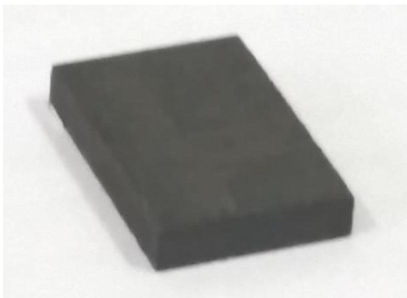

Figure 2. Sample of C/C composite.

2.3. Tribology test principle of C/C composite

The working principle of UMT multifunction friction-abrasion testing machine is shown in Figure.3. The static friction sample or columnar steel dowel is perpendicular to the surface of C/C composite sample, and C/C composite sample begins to move backwards and forwards in a straight line. The friction-abrasion between C/C composite sample and columnar steel dowel is generated in the process. Then frictional coefficient and amount of abrasion could be measured by sensors in test device.

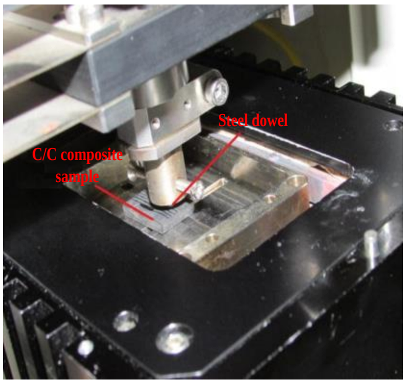

Figure 3. Working principle interpretation of UMT multifunction friction-abrasion testing machine.

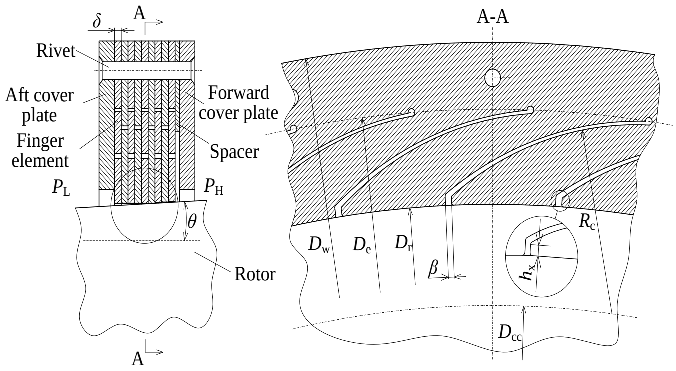

Figure 4. Schematic diagram of finger seal structure.

3. Equivalent dynamic model of finger seal

3.1. Finger seal structure
Finger seal is constituted by multiple finger elements, which are staggered, and every finger element includes some finger sticks (see Figure.4). The structural parameters of finger seal are introduced by the literatures [11] in the manuscript.

3.2. Equivalent dynamic model of finger seal based on distributed masses
When the fingers stick and rotor are in contact state, the forced vibration differential equations can be defined as

$$\begin{cases} m_1\ddot{x}_1 = -k_1x_1 + k_{c1}(y_1 - x_1) + F'_{f1} - F_{f1} \\ m_2\ddot{x}_2 = -k_2x_2 + k_{c2}(y_2 - x_2) + F'_{f2} - F_{f2} \\ \vdots \\ m_{n-1}\ddot{x}_{n-1} = -k_{n-1}x_{n-1} + k_{c(n\text{-}1)}(y_{n-1} - x_{n-1}) + F'_{f(n-1)} - F_{f(n-1)} \\ m_n\ddot{x}_n = -k_nx_n + k_{cn}(y_n - x_n) - F_{fn} \end{cases} \tag{1}$$

When the finger sticks and rotor are in separation state, the forced vibration differential equations can be defined as

$$\begin{cases} m_1\ddot{x}_1 = -k_1x_1 + P_1 + F'_{f1} - F_{f1} \\ m_2\ddot{x}_2 = -k_2x_2 + P_2 + F'_{f2} - F_{f2} \\ \vdots \\ m_{n-1}\ddot{x}_{n-1} = -k_{n-1}x_{n-1} + P_{n-1} + F'_{f(n-1)} - F_{f(n-1)} \\ m_n\ddot{x}_n = -k_nx_n + P_n - F_{fn} \end{cases} \tag{2}$$

where n is number of finger elements, $n \geqslant 2$ and n is an integer.

3.3. Equivalent parameters
The correlative parameters, which include the equivalent mass m_i and structural stiffness k_i of finger stick, contact stiffness coefficient k_{ci} between finger stick and rotor, frictional resistances F_{fi} and F'_{fi}

between finger element and aft cover plate and among finger elements, thermal deformation of finger stick, fluid pressure P_i, leakage rate and contact pressure, are introduced by the literature [11] in the manuscript. In addition, frictional coefficient, which is used to calculate frictional resistance, is obtained by C/C composite tribology test.

3.4. Displacement excitation of rotor

The amount of rotor incline corresponding to random finger element can be defined as[11]

$$\begin{cases} \Delta r_i = -(i_{\mathrm{th}} - i)\delta \tan(\pi + \theta) & 1 \le i < i_{\mathrm{th}} \\ \Delta r_i = 0 & i = i_{\mathrm{th}} \\ \Delta r_i = (n - i)\delta \tan(\theta) & i_{\mathrm{th}} < i < n \end{cases} \tag{3}$$

where i_{th} is serial number of reference finger elements.

The displacement excitation of the rotor under considering complex working states, which include the incline of the rotor, assemble condition, temperature effect and impact effect, can be defined as

$$y_i = a_{\mathrm{c}} \Delta r \sin(\omega t) + \Delta r_i \sin(\omega t) \pm e + l_{\mathrm{c}i} \tag{4}$$

where a_{c} is impact magnification coefficient; ω is angular velocity of rotor; Δr is the radial displacement amplitude of rotor; t is the time; Δr_i is the amount of rotor incline corresponding to finger element; e is the amount of interference or clearance, '+' and '-' express interference fit and clearance fit, respectively; $l_{\mathrm{c}i}$ is the thermal deformation of the finger stick.

3.5. Leakage rate Q

The leakage gap $h_i(t)$ between finger stick in the i_{th} finger element and rotor at time t could be defined as

$$h_i(t) = x_i(t) - y_i(t) \tag{5}$$

where $x_i(t)$ and $y_i(t)$ are displacement response of finger stick in the i_{th} finger element and displacement excitation of rotor at time t, respectively. And the schematic of finger seal leakage gap $h_i(t)$ are shown in Figure. 5.

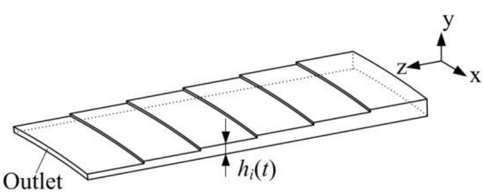

Figure 5. Schematic of finger seal leakage gap.

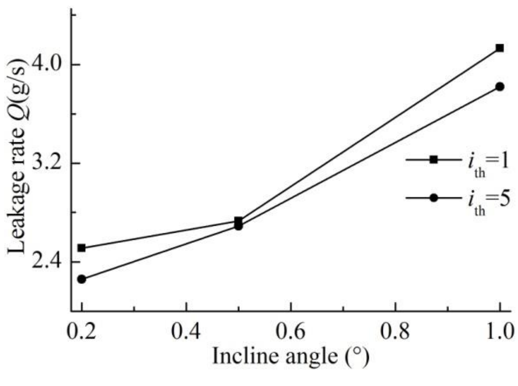

Figure 6. Effect of incline angle on leakage rate of finger seal under complex working states.

The outlet of leakage gap is chosen as the location of leakage rate calculation, and then the leakage rate $q(t)$ of finger seal at time t could be defined as

$$q(t) = \sum_{m=1}^{M} \sum_{k=1}^{K} \left[w_{mk}(t) \rho_{mk}(t) \Delta l_{\mathrm{x}}(t) \Delta l_{\mathrm{y}}(t) \right] \tag{6}$$

where $w_{mk}(t)$ is velocity of arbitrary fluid microunit in z the direction; $\rho_{mk}(t)$ is fluid density of microunit; M and K are total of grids in the x and y directions, respectively; $\Delta l_{\mathrm{x}}(t)$ and $\Delta l_{\mathrm{y}}(t)$ are sizes of fluid microunit in the x and y directions at time t, respectively.

Therefore, the average leakage rate of finger seal in a motion period could be defined as

$$\bar{q} = \frac{1}{f}\sum_{j=1}^{f} q(t + j\Delta t) \tag{7}$$

where f is time steps quantity.

4. Results and discussions

C/C composite finger seal, which is constituted by nine finger elements, is treated as research object, and the effect of complex working states, which include the incline of the rotor, assemble condition, temperature effect and impact effect, on the dynamic performance of finger seal is analyzed.

4.1. Leakage rate of finger seal in bearing chamber

The future application of C/C composite finger seal, which is due to its self-lubricating performance and lower structural stiffness, could be leaned to adopt by interference fit in bearing chamber working environment. Therefore the following analysis is carried out under temperature being 400℃ and interference fit.

4.1.1. Effect of rotor incline angle on finger seal leakage rate under complex working states. Under the conditions of the impact velocity being 0.05m/s, temperature being 400 ℃ and amount of interference fit being 0.01mm between finger seal and rotor, the leakage rates under different incline angles of rotor are calculated, that are shown in Figure.6. The leakage rates under precession incline i_{th}=1 are all larger than those under nutation incline i_{th}=5. It is consistent with the phenomenon of reference [11]. The main reason is that the displacement excitations of rotor acting on finger sticks are different under considering incline of rotor. In addition, the leakage rates of finger seal are all increased with increasing incline angles of rotor under precession incline i_{th}=1 and nutation incline i_{th}=5, that are also shown in Figure.6. It is different from the phenomenon of reference [11]. Therefore the complex working states makes the finger seal performance to become complicated.

4.1.2. Effect of impact velocity on finger seal leakage rate under complex working states. Under the conditions of the incline angle of rotor being 1 º, temperature being 400℃ and amount of interference fit being 0.01mm between finger seal and rotor, the leakage rates under different impact velocities are calculated, that are shown in Figure.7. The leakage rates of finger seal under the complex working states are increased with increasing impact velocities. It is consistent with the phenomenon of reference [12]. The main reason is that the displacement excitation of rotor acting on finger stick is larger under considering impact effect. In addition, the leakage rates of finger seal under precession incline i_{th}=1 are all larger than those under nutation incline i_{th}=5. It is consistent with the phenomenon of reference [12]. The reason is also that the displacement excitations of rotor acting on finger sticks are different under considering incline of rotor

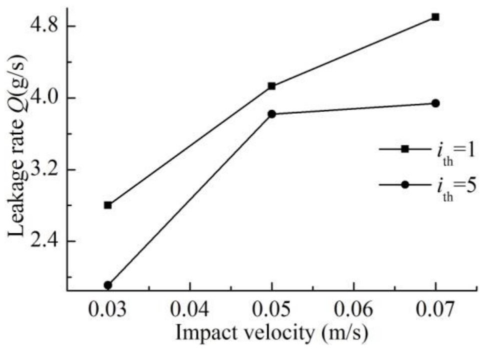

Figure 7. Effect of impact velocity on leakage rate of finger seal under complex working states.

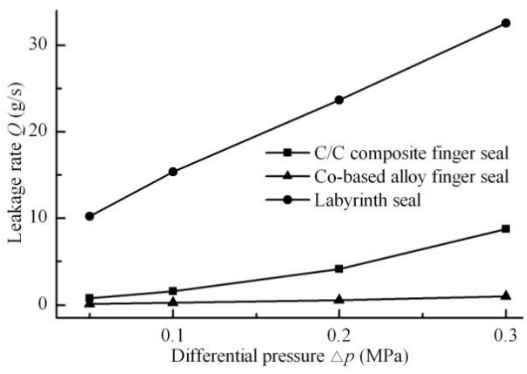

Figure 8. Comparison between leakage rates of finger seal and labyrinth seal with increasing differential pressure.

4.2. *Comparison between leakage rates of finger seal and labyrinth seal in bearing chamber*. Under rotational speed being 9000r/min, the comparison between the leakage rates of finger seal, which are made of C/C composite and Co-based alloy, and labyrinth seal with increasing differential pressure are shown in Figure.8. It is shown that the leakage rates of finger seals, which are made of C/C composite and Co-based alloy, are all remarkably smaller than those of labyrinth seal with increasing differential pressure. The feasibility of finger seal being used in bearing chamber is represented. In addition, it is also shown that the leakage rates of finger seal and labyrinth seal are all increased with increasing differential pressure. It is easy to understand the phenomenon of labyrinth seal. But for finger seal, the frictional resistances between low pressure finger element and aft cover plate and among finger elements are increased with increasing differential pressure, and the hysteresis degree of finger seal is also increased. When the finger stick is separated from rotor, the fluid pressure acting on the finger stick is increased with increasing differential pressure, and then the hysteresis degree is further increased. Therefore the leakage rate of finger seal is increased with increasing differential pressure. The leakage rate of Co-based alloy finger seal is remarkably smaller than those of C/C composite. The results are shown that the seal performance of Co-based alloy is excellent than those of C/C composite, but the shorter abrasion life-span is noticeable disadvantage.

5. Conclusions

The frictional coefficients, which are obtained by C/C composite tribology performance test, are treated as the main material parameters, and they are used to analyze the dynamic performance of C/C composite finger seal. Based on this, the equivalent dynamic model of C/C composite finger seal based on distributed masses is established, and the effect of complex working states on the dynamic performance of finger seal is carried out by the model. The main conclusions are as follow.

The effect of incline angle of rotor and impact velocity on the dynamic performance of finger seal under complex working states is discussed, respectively, and compared with those of references [11] and [12]. The prominent difference among the above results is represented. Meanwhile the complicated effect of complex working states on the finger seal dynamic performance is proved.

The leakage rates of finger seal under considering complex working states are remarkably smaller than those of labyrinth seal in bearing chamber. Therefore the advantage of finger seal is also represented.

6. References

[1] Arora G K, Proctor M P, Steinetz B M and Delgado I R. Pressure balanced, low hysteresis, finger seal test results. NASA TM 1999-209191, June 1999

[2] Arora G K and Glick D L. Pressure balanced finger seal[P]. Patent 6,196,550, USA, 2001

[3] Proctor M P, Kumar A and Delgado I R. High-speed, high-temperature finger seal test results. *J Propul Power*, 2004, **20**: 312-18

[4] Braun M J, Pierson H M, Deng D, Choy F, Proctor M P and Steinetz B M. Structural and dynamic considerations towards the design of a padded finger seal. In: 39th AIAA/ASME/SAE/ASEE joint propulsion conference, Huntsville, Alabama, 20-23 July 2003, paper no. AIAA 2003-4698. Reston: AIAA

[5] Braun M J, Pierson H M and Deng D. Thermofluids considerations and the dynamic behavior of a finger seal assembly. *Tribol Trans*, 2005, **48**: 531-47

[6] Marie H. A study of non-contacting passive-adaptive turbine finger seal performance. PhD Thesis, University of Akron, USA, 2005

[7] Su H and Chen G D. Dynamic behavior analysis of finger seal based on equivalent dynamic model. *Chin J Mech Eng*, 2010, **23**: 590-9

[8] Chen G D, Lu F, Yu Q P and Su H. Dynamic analysis of finger seal using equivalent model based on distributed mass method. *Proc IMechE, Part C: J Mechanical Engineering Science*. 2014, **288**: 2992-3005.

[9] Chen G D, Wang L N, Yu Q P and Su H. Dynamic analysis of C/C composite finger seal. *Chinese J Aeronaut*, 2014, **27**: 745-58.

[10] Wang L N, Chen G D, Su H, Lu F and Zhang Y C. Effect of temperature on the dynamic performance of C/C composite finger seal. *Proc IMechE, Part G: J Aerospace Engineering*. 2016, **230**(12): 2249-64.
[11] Wang L N, Chen G D, Su H, Lu F and Zhang Y C. Effect of work status on leakage and contact pressure of C/C composite finger seal. *Proc IMechE, Part C: J Mechanical Engineering Science*. 2017, **231**(5): 925-40.
[12] Wang L N, Chen G D, Su H, Lu F and Zhao H L. Impact dynamic analysis of C/C composite finger seal. *Proc IMechE, Part G: J Aerospace Engineering*. 2017, **231**(7): 1225-37.

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