Experimental Study on Performances of Carbon Seal and Finger Seal under High-speed and High-pressure Condition

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Abstract. Carbon seal and finger seal are both advanced and used in aero-engine and gas turbine. Compared with the finger seal, the application of carbon seal is longer and its technology is more mature. But the finger seal also has excellent sealing performance, and it is much more economical than carbon seal. Based on a self-developed dynamic sealing test rig, the experimental studies on performances of carbon seal and finger seal under high-speed and high-pressure conditions are carried out in this paper, and the comparison on leakage and durability of the two seals is carried out in-depth to find the possibility that replacing carbon seal with finger seal, which can provide references for the selection of sealing types. The experimental results show that, under the same structural and operating conditions, the durability of carbon seal is better than that of the metal matrix finger seal, but the leakage of finger seal is smaller. Considering the manufacturing costs, the finger seal has potential to replace carbon seal at lower speed. Therefore, developing nonmetallic finger seal is an effective way to promote advanced sealing technology, which combines the flexible structure of finger seal with new material that has high thermal conductivity, low expansion, and low friction.

1. Introduction
Sealing devices are widely used in various mechanical systems, and play an important role in ensuring their stable operation, preventing accidents, and protecting the environment. For some major equipment such as aero-engine, gas turbine and rocket engine, advanced sealing technology also has an important mission to enhance performance and reliability, and reduce consumptions and emissions. Correlative studies show that, it must make great efforts in the design of components to enhance the performance of aero-engine by 0.1%, while it can be enhanced by 1%~2% easily with the application of advanced sealing technology [1]. In recent years, the requirements on speed, load and reliability of modern industry become higher and higher, that makes the operating conditions of seals harsher, but also brings new challenges and opportunities for the development of advanced sealing technology.

Carbon seal is a kind of contact seal, it works by contact between the carbon ring which is assembled in the stator and the rotor (as shown in Figure 1(a) and (b)), and it has been used for the bearing chamber seal of aero-engine such as M88 and F404 [2]. Due to the high strength, high thermal conductivity, low expansion, and low friction of carbon, the carbon seal has the advantages of low leakage and long-life. Correlative studies show that, compared with the labyrinth seal and floating-ring seal, the carbon seal can reduce the leakage by 90%. However, due to the large quantity of heat generation, brittleness of carbon, sensitivity to lubricant and machining accuracy, the carbon seal has
problems of charring and blistering on the friction surface, and leakage increase caused by breakage of carbon ring, which increase the costs of manufacturing and maintenance for carbon seal.

The finger seal is also a kind of contact seal, but with flexible structure, which is shown in Figure 1(c). The finger seal is composed of a stack of finger elements, the forward and aft cover plates, and clamped by some rivets. Each element includes several flexible fingers placed symmetrically along the circumferential direction; it rotates relative to its adjacent elements due to the gaps between fingers are able to be covered. Finger elements contact closely with the rotor to eliminate gas leakage. According to the flexibility of fingers, the finger seal can accommodate the rotor displacement and thermal deformation. Correlative studies show that, the finger seal has lower leakage and power loss than those of the commonly used labyrinth seal, and it has almost similar leakage as brush seal, though its cost only half of that for brush seal; besides, finger seal can avoid possible problems such as breakage of brush wire \cite{2-4}. Due to the low manufacturing cost and high sealing performance, the finger seal attracts many researchers’ attention.

Up to now, many researchers have presented theoretical and experimental studies on the performance of carbon seal and finger seal. For carbon seal, Lin et al. proposed the direction of improving the working ability and durability of circumferential carbon seal \cite{6}; Zhang et al. found that the carbon ring is liable to fracture under shock and wear, which would cause the failure of carbon seal \cite{7}; Yan et al. and Roe et al. studied the friction and wear properties of carbon at high temperature by experiments \cite{8, 9}; Zhu \cite{10} gave a model of mechanical properties for carbon. For finger sealing, Glenn Research Center studied the leakage, power consumption and wear characteristics of finger seal by experiments, and compared the results with these of other seal types to prove the huge application prospect of finger seal \cite{3-5}. Chen et al. analyzed the impact of structural and operating parameters on the performance of finger seal, such as the thickness of finger element, number of fingers and rotating speed \cite{11-13}. Liu and Wang et al. presented some suggestions for the material selection of finger seal and coating by experiments \cite{14-15}.

Compared with carbon seal, the finger seal is a kind of “young” seal type; and its technology and application are not mature enough. But the finger seal also has excellent sealing performance, and it is much more economical than carbon seal. Therefore, in this paper, the experimental studies on performances of carbon seal and finger seal under high-speed and high-pressure conditions are carried out with a self-developed dynamic sealing test rig, and the comparison on leakage and durability of the two seals is carried out in-depth to find the possibility that replacing carbon seal with finger seal, which can provide references for the selection of sealing types.

2. Test rig and Experimental Procedure

2.1. Dynamic Sealing Test rig

In this paper, a self-developed dynamic sealing test rig is used to carry out the performance test of carbon seal and finger seal. The construction of test rig and sealing test unit are shown in Figure 2. The test rig is driven by a three-phase asynchronous motor with a rated speed of 5000rpm, and the motor connected with the rotor of test unit with couplings and a speed increaser, which makes the highest rotating speed (expressed as $n$) of finger sealing test unit reach 30000rpm. A vortex gas
compressor supplies high pressure gas for the experiments, and the pressure of gas (expressed as $\Delta p$) can be adjusted with the pressure regulating valve. In the experiments, the high pressure gas flows into the high pressure chamber of test unit, then leaks into the two adjacent low pressure chambers through the test seals, and exhausts through the two vents at the bottom. The vents connect with two mass flow meters, with which the leakage rates (expressed as $Q$) of carbon seal and finger seal can be measured respectively.

2.2. Dynamic Sealing Test rig
The carbon seal and finger seal used in the experiments are shown in Figure 3, and their materials and structural parameters are shown in Table 1.

![Figure 2. Dynamic sealing test rig and sealing test unit](image)

(a) Dynamic sealing test rig  (b) Sealing test unit

![Figure 3. Carbon seal and finger seal used in the experiments](image)

(a) Carbon seal  (b) Finger seal  (c) Sealing runner

| Types       | Materials | Diameter of runner | Single seal axial width | Total axial width |
|-------------|-----------|--------------------|-------------------------|-------------------|
| Carbon seal | Carbon    | 130mm              | 2.5mm                   | 10mm(4 carbon rings) |
| Finger seal | 1Cr13     | 150mm              | 0.4mm                   | 2.4mm(6 finger elements) |

2.3. Experimental procedure

2.3.1. Static leakage test.
Test the leakage rate of carbon seal and finger seal under four pressures (0.1MPa, 0.2MPa, 0.3MPa and 0.4MPa) when the rotor is in the stationary state.

2.3.2. Dynamic leakage test.
Test the leakage rate of carbon seal and finger seal under four pressures (0.1MPa, 0.2MPa, 0.3MPa and 0.4MPa) when the rotor is rotating. The operating conditions of dynamic leakage test are shown in Table 2. At each pressure, the leakage rates of the two seals are tested under six rotating speeds successively.

| Parameters | Values |
|------------|--------|
| Parameters | Values |
2.3.3. *Durability test.*

After the static and dynamic leakage tests are finished, the durability tests of carbon seal and finger seal are carried out. The durability tests are carried out under the condition that the pressure and rotating speed are 0.15 MPa and 7500 rpm respectively, and last for 74 hours. After the durability tests, the dynamic leakage tests of the two seals are carried out again to compare their durability.

3. Experimental Results and Discussion

Figure 4 shows the static leakage test results of carbon seal and finger seal. It can be seen that, under the static condition, as the increase of pressure strengthens the pressure flow in the leakage clearance, so the leakage rates of the two seals both increase gradually. And due to the inner diameter of finger seal used in experiments is larger than that of carbon seal, while its axial width is much smaller than that of carbon seal, which increase the circumferential leakage area and reduce the flow resistance for the finger seal, so the leakage rate of the finger seal is larger than that of carbon seal. However, even with the structures that weak its sealing performance, the leakage of finger seal is still at the same level with that of carbon seal. According to the hydromechanics theory, it can be predicted that two units of finger seals can reach the sealing effect of four carbon rings, which axial width is still smaller than that of carbon seal.

![Figure 4. Static leakage test results of carbon seal and finger seal](image)

Figure 5 to Figure 7 show the dynamic leakage test results for the carbon seal and finger seal before and after the durability test under different pressures. It can be seen that, due to pressure fluctuations during the experiments, the results also show some fluctuations, and because of the flexible structure of finger seal, its leakage rate show more complex change with operating conditions; but in general, as the pressure increases, the leakage rates of the two seals both increase gradually, and as the increase of rotating speed strengthens the flow resistance in the leakage clearance, the leakage rates of the two seals tend to decrease.

In addition, before and after the durability test, the difference in leakage rate of carbon seal is smaller than that of finger seal, which shows the carbon seal has better durability due to the inherent self-lubricating property of carbon. However, it’s also noticed that the leakage rate of finger seal is always at the same level with that of carbon seal before and after the durability test, even with larger inner diameter and smaller axial width that weak its sealing performance; as same as the analysis of the static leakage test results, it can also be predicted that two units of finger seals can reach the sealing effect of four carbon rings under the conditions of this paper.

The comparison of experimental results between carbon seal and finger seal in this paper shows that, the durability of carbon seal is better than that of metal matrix finger seal due to its inherent self-lubricating property; but according to the experimental results and hydromechanics theory, it can be predicted that the leakage of finger seal would be much less than that of carbon seal under the same structural and operating parameters; and considering the fact that the manufacturing and maintenance costs of finger seal are much less than these of carbon seal, the finger seal has potential to replace...
carbon seal, especially at lower speed; besides, with the combination of flexible structure and new material that has high thermal conductivity, low expansion, and low friction, developing nonmetallic finger seal is an effective way to promote advanced sealing technology.

Figure 5. Dynamic leakage test results before and after durability test ($\Delta p = 0.1\text{MPa}$)
(a) Carbon seal (b) Finger seal.

Figure 6. Dynamic leakage test results before and after durability test ($\Delta p = 0.2\text{MPa}$)
(a) Carbon seal (b) Finger seal.

Figure 7. Dynamic leakage test results before and after durability test ($\Delta p = 0.3\text{MPa}$)
(a) Carbon seal (b) Finger seal.

4. Conclusion
Based on the self-developed dynamic sealing test rig, the experimental studies on performances of carbon seal and finger seal under high-speed and high-pressure conditions are carried out in this paper, and the comparison on leakage and durability of the two seals is carried out in-depth. According to the experimental results, the following conclusions can be presented:

1. Due to the inherent self-lubricating property of carbon, the durability of carbon seal is better than that of metal matrix finger seal.

2. Under the same structural and operating parameters, the leakage of finger seal is much less than that of carbon seal.

3. Based on the above conclusions, and considering the advantage of economy for finger seal, the finger seal has potential to replace carbon seal at lower speed.

4. Developing nonmetallic finger seal is an effective way to promote advanced sealing technology.
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