Chinese Journal of Aeronautics, (2016), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University
Chinese Journal of Aeronautics

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Research on the dynamic performance of a C/C composite finger seal in a tilting mode

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Received 15 July 2016; revised 14 September 2016; accepted 9 October 2016

KEYWORDS

Aero-engine;
C/C composite;
Dynamic performance;
Finger seal;
Nutation tilt;
Precession tilt

Abstract The complex operating state of aero-engines has an impact on the performance of finger seals. However, little work has been focused on the issue and the dynamic performance of finger seals is also rarely studied. Therefore, a distributed mass equivalent model considering working conditions is proposed in this paper for solving the existing problems. The effects of the fiber bundle density and the preparation direction of the fiber bundle of a C/C composite on the dynamic performance of a finger seal are investigated in rotor tilt based on the proposed model. The difference between the C/C composite finger seal performances under the rotor precession and nutation tilt cases is also investigated. The results show that the fiber bundle density and the preparation direction of the fiber bundle have an influence on the dynamic performance of the finger seal as rotor tilt is considered, and the dynamic performance of the finger seal is different in the two kinds of tilting modes. In addition, a novel method for design of finger seals is presented based on the contact pressure between finger boots and the rotor. Finger seals with good leakage rates and low wear can be acquired in this method.

1. Introduction

Continuous improvement of an aero-engine's performance leads to more stringent requirements on the performances of seal devices located in it, and the quality of seals has become one of the important factors that restrict further improvement of the performance of an aero-engine. A finger seal can follow the running rotor compliantly and adapt the shaft offset without any damage to the integrity of the seal for its flexibility, and it also shows the advantages of high performance and low cost when compared to conventional labyrinth and brush seals; therefore, it has a potential application in aero-engine systems. For these reasons, finger seals have received more and more attentions in recent years.[1–4]

A finger seal operates under dynamic conditions and the analysis of its dynamic performance is complicated. To solve this problem, a method in which a finger seal was regarded as a spring-mass equivalent dynamic model was proposed,

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.11.002
1000-9361

which can reduce the complexity of dynamic analysis and obtain the dynamic performance with acceptable accuracy. Braun et al.[5,6] made a padded finger seal equivalent to a lumped mass-spring-damp model, in which the influence of the friction between finger elements (or between the finger element and the aft cover plate) was neglected, and the gas film was equivalent to the gas film stiffness and gas film damping. The authors analyzed the motion of the padded finger seal along with the rotor movement based on the model, and their work revealed the parameters that affected the motion of the finger seal and provided a theoretical foundation for design of finger seals with good performance. Marie[7] developed a two-degree-of-freedom lumped mass model in which only the friction between the low-pressure finger element and the aft cover plate was considered to study the padded finger seal, the structural stiffness of the finger seal related to structural parameters was calculated, and the gas film dynamic stiffness coefficients of the finger seal as a function of the rotor speed, gas film clearance and structural parameters were established theoretically. The author proposed that the gas film clearance could be controlled by varying the pressure differential and rotor speed when the finger seal geometrical parameters were held at constants, in order to achieve good sealing performance and wear behavior for the finger seal. Su and Chen[8] analyzed the hysteresis and contact performance of a finger seal with a lumped mass equivalent dynamic model as well as studied a dynamic design approach for a finger seal with low hysteresis and low wear. The authors also performed a contrast analysis of the dynamic and static hysteresis of the finger seal, and the results showed the necessity of dynamic performance analysis of the finger seal. Chen et al.[9] treated a multiple superimposed Co-base alloy finger seal as an assembly of distributed mass, considered the coupling effect between the finger elements, and built an equivalent dynamic model based on the distributed mass method. They analyzed the dynamic displacement response of the finger seal as well as proposed the calculation methods of the leakage flow rate and the contact pressure between the finger stick and the rotor. The authors also demonstrated the superiority of the equivalent dynamic model based on the distributed mass method compared to that based on the lumped mass method. Du et al.[10,11] carried out a dynamic performance analysis by a semi-analytical method, in which the leakage of a finger seal was obtained by solving the Reynolds equation under the premise that the leakage clearance was acquired, and the main factors affecting the leakage performance were also analyzed.

Considering the excellent self-lubricating property of C/C composites, they are applied in finger seal component preparation to improve the seal performance, which may be a most feasible solution to reduce the hysteresis effect of a finger seal when the wear life is ensured; therefore, many efforts have been made on researching the application of C/C composites in finger seals in recent years. Lu et al.[12] evaluated the macroscopic elastic properties of a 2.5D C/C composite by calculating its stiffness matrix with the constituent material properties, and established a finite model for the dynamic performance analysis of a C/C composite finger seal. The authors also studied the impacts of yarn density and yarn braided patterns on the dynamic performance of the finger seal, and their work supported the possibility of applying C/C composites in preparation of finger seals. Chen et al.[13] analyzed the dynamic performance of a 2.5D composite finger seal based on the equivalent model of distributed mass, and compared the performance with that of a Co-base alloy finger seal. Their research indicated that the leakage rate of the Co-base alloy finger seal is smaller than that of the 2.5D C/C composite finger seal, but the contact pressure is greater for its structural stiffness being greater; therefore, the wear life of the 2.5D C/C composite finger seal is much longer compared to that of the Co-base alloy finger seal.

For an aero-engine, the complicated and hostile operating environment of the rotor can reflect the harsh working conditions of seal devices, including the influence of rotor tilt. However, the effect of rotor tilt was not taken into account in previous works, so it may be too complicated to consider the impact. Note that an inclination of the aero-engine rotor is inevitable, so it is necessary to conduct dynamic analysis considering rotor tilt, which not only extends the research on dynamic performance of finger seals, but also provides necessary technical reserves for the application of finger seals in engineering.

This paper develops a distributed mass equivalent dynamic model considering precession tilt and nutation tilt of the rotor. The influences of the fiber bundle density and the preparation direction of the fiber bundle on the dynamic performance of a finger seal are studied based on the model, and the difference between the dynamic performances of the finger seal in both tilt modes is also analyzed. The work in this article contributes to the practical application of the finger seal dynamic analysis technology in engineering analysis design, and also perfects the theoretical system and method of dynamics of finger seals to a certain extent.

2. Distributed equivalent model

2.1. Structure of the finger seal

A finger seal is composed of several finger elements and each finger element is shaped by a series of flexible finger sticks arranged at a regular space in the circumferential direction. Multiple staggered and superimposed finger elements are held by a forward cover plate and an aft cover plate, all of which are fixed by rivets. As shown in Fig. 1, D_w is the outside diameter of the finger seal; D_e is the base diameter of the finger seal; R_c is the seal finger stick arc radius; D_{cc} is the central diameter of the stick circle; D_r is the rotor diameter; a finger boot is a part of a finger stick which is in contact with the rotor, and h' is the height of finger boots; β is the repeat angle; and δ is the thickness of finger elements.

2.2. Equivalent model of the finger seal

The mechanical behavior between the multiple superimposed finger seal and the rotor can be described by the distributed mass equivalent dynamic model shown in Fig. 2. Due to the cyclic symmetrical structure of the finger seal, a single finger stick in each finger element is selected as the research issue. In Fig. 2, m_i and k_i are the equivalent mass and equivalent structural stiffness of one finger stick in the ith finger element, respectively; F_{fi} and F'_{fi} are the friction forces between adjacent finger elements or between the finger element and the aft cover plate; x_i is the displacement response of one finger stick in the ith finger element. The state when finger sticks