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Leakage and wear characteristics of finger seal in hot/cold state for aero-engine

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ABSTRACT

Experimental investigation has been done to approach the leakage and wear characteristics of finger seal in hot/cold state. The High-speed Sealing Test Rig was used in the study. Leakage measurements were done in terms of different working parameters. The pressure ratio changed from 1.1 to 1.8 and the rotating speed varied from 0 to 5000 rpm. The temperature altered from 283 K to 433 K to achieve the cold state and hot state, respectively. Two groups of durability tests were carried out in hot/cold state, separately. Each durability test lasted 300 h with two finger seals. An accurate optical measuring instrument was applied to record the wear growth of the finger seals. Results showed that the flow factor monotonously increases with the pressure ratio and decreases with the rotating speed. An attractive feature is firstly captured that the finger seal with double-laminate achieves lower leakage in cold state while the finger seal with triple-laminate behaves better in hot state. Full life-cycle theory was applied to analyse the wear of the finger seal. The wear growth curve exhibits a rule of SPSP (Sharp Wear, Progressive Wear, Stable Wear and Permanent Wear). Of particular interest is the wear comparison between hot state and cold state, which is firstly discussed in the study and shows that finger seals operating in hot state generate obviously more wear than those in cold state.

1. Introduction

Finger seal is a novel and revolutionary innovation in sealing technology [1]. The typical characteristics of finger seal are high speed, pressure and temperature capability, low leakage, low cost and long life-time, which can greatly reduce overall engine specific fuel consumption, production cost and maintenance cost for aero-engines. Comparing with the commonly used labyrinth seal, finger seal has demonstrated spectacular lower leakage as mentioned by Arora et al. [2], where as more as 20–70% air leakage is reduced. Comparing with the brush seal, finger seal is considerably cheaper. The cost to fabricate finger seal is estimated to be approximately half of the cost to fabricate brush seals [3]. Proctor et al. [4] systematically compared the leakage characteristics and wear of labyrinth seal, brush seal and finger seal and proved that finger seal exhibits lower leakage and wear again.

The leakage of the finger seal is a critical characteristic for aero-engines. Arora et al. [2] designed a pressure-balanced, low-hysteresis finger seal, which successfully operated at different harsh conditions and the leakage is acceptable. Also in the NASA High Speed, High Temperature Turbine Seal Test Rig, Proctor et al. [4,5] continually carried out static, performance, and endurance test and the maximum condition can reach 366 m/s, 517 kPa, 922 K. In the initial static test, the flow factor of the finger seal increases with the pressure difference first and then tends to be gentle. In rotating test, the power loss of the finger seal and the brush seal is equal. Delgado and Proctor [6] further indicated that leakage decreases with the increase of surface speed which can attributes to the reduced clearances from disk centrifugal growth. In order to foster future compliant seal concepts, Braun et al. [7] experimentally and numerically carried out an investigation to gain a better understanding of finger seal functionality. The finger seal with double-pad yields lower operating temperatures and less leakage at higher pressures. The force analysis was done by Li et al. [8] for a double-laminate single-padded finger seal. The lifting force on the pad bottom, including the hydrodynamic lifting force and the pressure force due to the axial pressure differential, plays an important role in the sealing behavior. The hydrodynamic lifting force must outperform the axial effects to make the finger seal more adaptive. In addition, the leakage increases linearly with the increasing axial pressure differential. In depth, the flow mechanism was indicated by Yue et al. [9] for a triple-laminate single-padded finger seal. A pair of vortices with

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Nomenclature

Symbols

B	thickness of finger seal mm
b	thickness of finger laminate mm
c	finger boot/rotor clearance mm
c_c	finger boot/rotor clearance in cold state mm
c_h	finger boot/rotor clearance in hot state mm
D_f	inner diameter of finger seal mm
D_r	outer diameter of rotor mm
$\dot{m}$	leakage kg/s
$\dot{m}_1$	leakage in #1 low pressure cavity kg/s
$\dot{m}_2$	leakage in #2 low pressure cavity kg/s
N	number of finger laminates
P	pressure MPa
P_0	pressure of high pressure cavity MPa
P_1	pressure of #1 low pressure cavity MPa
P_2	pressure of #2 low pressure cavity MPa
T	temperature K
T_0	temperature of high pressure cavity K
T_1	temperature of #1 low pressure cavity K
T_2	temperature of #2 low pressure cavity K
T_c	temperature in cold state for wear test K
T_h	temperature in hot state for wear test K
s	finger gap mm
t	accumulative run time h
V_a	horizontal vibration g
V_b	vertical vibration g

Greek symbols

δ	wear extent mm
π	pressure ratio
ϕ	flow factor kg·K$^{0.5}$/(MPa·m·s)
Ω	rotating speed rpm

Subscripts

0	high pressure cavity
1	#1 low pressure cavity
2	#2 low pressure cavity
a	horizontal direction
b	vertical direction
c	cold state
f	finger seal
h	hot state
r	rotor

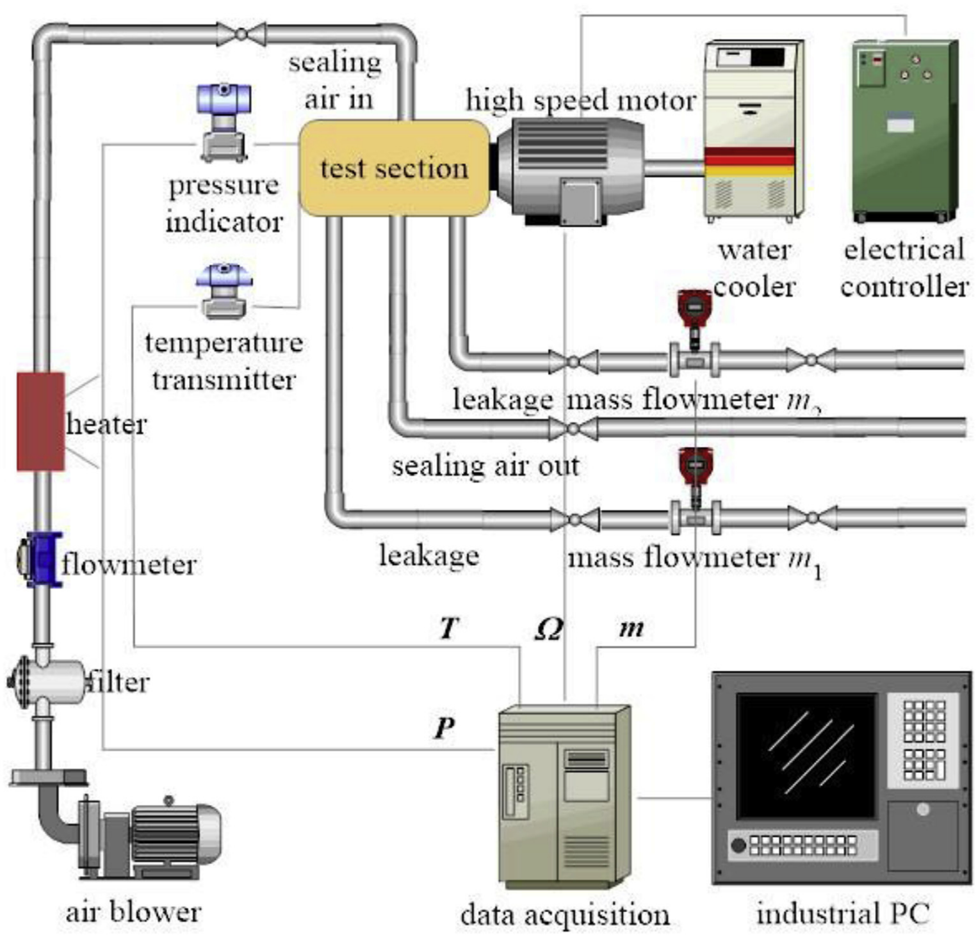

Fig. 1. Layout of High-speed Sealing Test Rig.