

Development of Advanced Carbon Face Seals for Aircraft Engines

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Abstract. Abstract. Modern aircraft gas turbine engines require the development of seals which can operate for a long time with low leakages. The basic type of seals applied for gas turbine engine rotor supports is face seal. To meet the modern requirements of reliability, leak-tightness and weight, low-leakage gas-static and hydrodynamic seals have to be developed. Dry gas seals use both gas-static and hydrodynamic principles. In dry gas seals microgrooves are often used, which ensure the reverse injection of leakages in the sealed cavity. Authors have developed a calculation technique including the concept of coupled hydrodynamic, thermal and structural calculations. This technique allows to calculate the seal performance taking into account the forces of inertia, rupture of the lubricant layer and the real form of the gap. Authors have compared the efficiency of seals with different forms of microgrooves. Results of calculations show that seal with rectangular form of microgrooves has a little gap leading to both the contact of seal surfaces and the wear. Reversible microgrooves have a higher oil mass flow rate, whereas HST microgrooves have good performance, but they are difficult to produce. Spiral microgrooves have both an acceptable leakages and a high stiffness of liquid layer that is important in terms of ensuring of sealing performance at vibration conditions. Therefore, the spiral grooves were chosen for the developed seal. Based on calculation results, geometric dimensions were chosen to ensure the reliability of the seal operation by creating a guaranteed liquid film, which eliminates the wear of the sealing surfaces. Seals designed were tested both at the test rig and in the engine.

1. Introduction

Engines with advanced parameters require seals operating for a long time with low leakages [1-5]. The basic type of seals applied for gas turbine engine rotor supports is face seal. To meet the modern requirements of reliability, leak-tightness and weight, low-leakage gas-static and hydrodynamic seals have to be developed [6,7]. Dry gas seals use both gas-static and hydrodynamic principles. In dry gas seals microgrooves are often used, which ensure the reverse injection of leakages in the sealed cavity.

The operating principle of such type of seals is based on the balance of axial forces, acting on axially-movable and rotating rings. Complex-shaped microgrooves are produced on the face area [1-2]. At operational conditions pressure rises up in the gap that leads to the displacement of axial-movable ring and minimum positive clearance of 1...3 μm in friction couple is formed. It allows seal to operate with low leakages without the wear for the wide range of operating parameters.

Application of modern materials, complex-shaped microstructures and improvement in manufacturing technology allow to broaden their functional possibilities. Therefore, authors have decided to apply the low leakage seals technology in order to improve existing face seals and to develop advanced face seal constructions applied for aircraft engine.



To develop the seal, the hydrodynamic performance of lubrication layer in the gap with microgrooves has to be determined [8, 9] and the required thermal state has to be achieved [10].

2. Methodology of flow calculation in the seal gap

To design a face seal the following factors have to be taken into account: inertial forces effect on the lubrication layer, possible liquid evaporation in the gap, thermal and force deformation of the seal rings.

The main problem in the calculating of the seal characteristics is to find pressure field on the working surface of seal rings. There are some analytical equations, which allow to calculate the pressure distribution in the ring gap for the seals without microgrooves. These equations were derived from Navier-Stokes equation taking into account averaging the inertial terms for the layer thickness by the Slezkin-Targ method. However, due to the complexity of differential equations these formulas were obtained for particular cases only. To calculate flow parameters of the hydrodynamic seals, the complex forms of microgrooves and deformed gap (figure 1) have to be taken into account (here r_1 and r_2 – inner and outer radius of seal; p_1 and p_2 are pressure inside and outside respectively). In order to calculate these tasks the finite volume method has been used. [8]. The pressure at each point of finite volume was obtained from the condition of flow equality through the control volume in the radial and circumferential directions (figure 2).

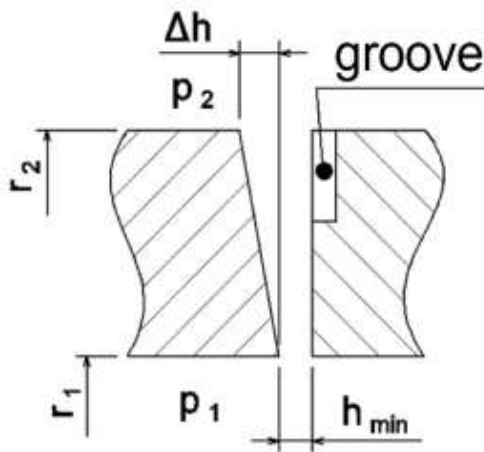


Figure 1. Simplified scheme of complex-shaped clearance

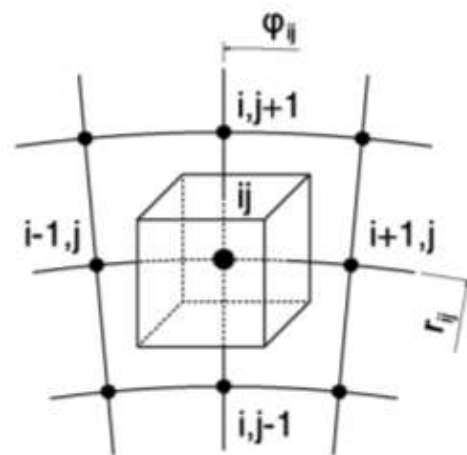


Figure 2. Finite volume

The equation for the pressure calculation at the point ij taking into account the inertial forces is following

$$p_{ij} = (B_{ij}p_{i-1,j} + C_{ij}p_{i+1,j} + D_{ij}p_{i,j-1} + E_{ij}p_{i,j+1} + F_{ij} + G_{ij}) / A_{i,j}, \quad (1)$$

where coefficients are

$$A_{ij} = \frac{\Delta r}{24\mu\Delta\phi} \left[2\left(\frac{h^3}{r}\right)_{ij} + \left(\frac{h^3}{r}\right)_{i-1,j} + \left(\frac{h^3}{r}\right)_{i+1,j} \right] + \frac{\Delta\phi}{24\mu\Delta r} \left[2(h^3r)_{ij} + (h^3r)_{i,j-1} + (h^3r)_{i,j+1} \right] \quad (2)$$

$$B_{ij} = \frac{\Delta r}{24\mu\Delta\phi} \left[\left(\frac{h^3}{r}\right)_{ij} + \left(\frac{h^3}{r}\right)_{i-1,j} \right] \quad (3)$$

$$C_{ij} = \frac{\Delta r}{24\mu\Delta\varphi} \left[\left(\frac{h^3}{r} \right)_{ij} + \left(\frac{h^3}{r} \right)_{i+1,j} \right] \quad (4)$$

$$D_{ij} = \frac{\Delta\varphi}{24\mu\Delta r} \left[(h^3 r)_{ij} + (h^3 r)_{i,j-1} \right] \quad (5)$$

$$E_{ij} = \frac{\Delta\varphi}{24\mu\Delta r} \left[(h^3 r)_{ij} + (h^3 r)_{i,j+1} \right] \quad (6)$$

$$F_{ij} = r_{ij} \frac{\omega\Delta r}{4} (h_{i-1,j} - h_{i+1,j}) \quad (7)$$

$$G_{ij} = \frac{\rho\omega^2\Delta\varphi}{80\mu} \left[(h^3 r^2)_{i,j+1} - (h^3 r^2)_{i,j-1} \right] \quad (8)$$

h – a current gap value (in the location of microgrooves location h equals the sum of the gap value and the depth of the groove);

r, φ – point coordinates in the polar coordinate system;

μ – dynamic viscosity;

ρ – density;

ω – rotational speed;

G_{ij} – inertial forces coefficient.

The pressures are found using iterative method. After the calculation of pressure distribution in the gap $p=p(r, \varphi)$, the following parameters has to be determined: carrying capacity of layer W that is a force disclosing the sealing joint; bending moment M ; stiffness of lubrication layer C ; windage N in the gap:

$$W = \int_0^{2\pi} \int_{r_1}^{r_2} p r dr d\varphi \quad (9)$$

$$M = \int_0^{2\pi} \int_{r_1}^{r_2} p \cdot r^2 dr d\varphi \quad (10)$$

$$C = -dW / dh \quad (11)$$

$$N = \mu\omega^2 \int_0^{2\pi} \int_{r_1}^{r_2} \frac{r^3}{h(r, \varphi)} d\varphi dr \quad (12)$$

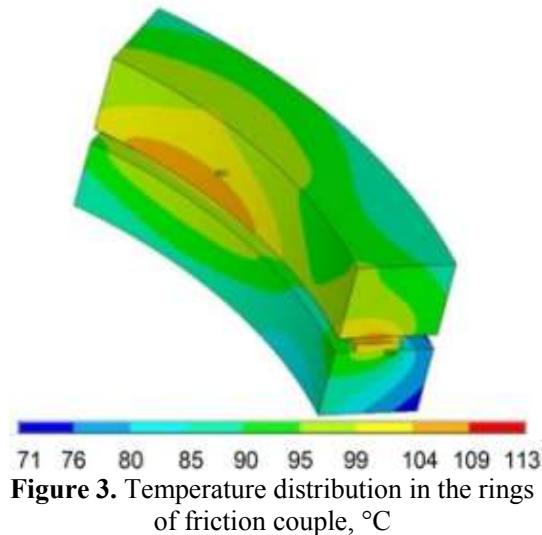
Leakage through the seal gap in the radial direction is

$$Q = \frac{1}{12\mu} \int_0^{2\pi} \left[r h^3(r, \varphi) \frac{dp}{dr} \right]_{r=r_1} \pm \frac{3\rho\omega^2 r^2 h^3(r, \varphi)}{10} d\varphi \quad (13)$$

Here the second term in brackets takes into account the influence of inertia forces. The sign – or + is determined by the direction of the flow.

To consider coupled hydrodynamic, thermal and structural processes, iterative conjugate computation has been performed using developed software based on described methodology and software ANSYS Mechanical. In figure 3 an example of temperature distribution at the rings of friction pair is shown. The

temperature non-uniformity in the circumferential direction is observed. The reason for that is significant difference in friction power in the seal gap and locations of lubrication rupture. For this reason thermal deformation can cause an undulation that can be determined by iterative calculation.



3. Performance comparison of seals with microgrooves of different forms

Calculations were performed for 4 types of microgrooves (figure 4) produced on the ring with an outer diameter of 110 mm. The geometry of microgrooves was optimized. Comparison of seal performance is shown in table 1.

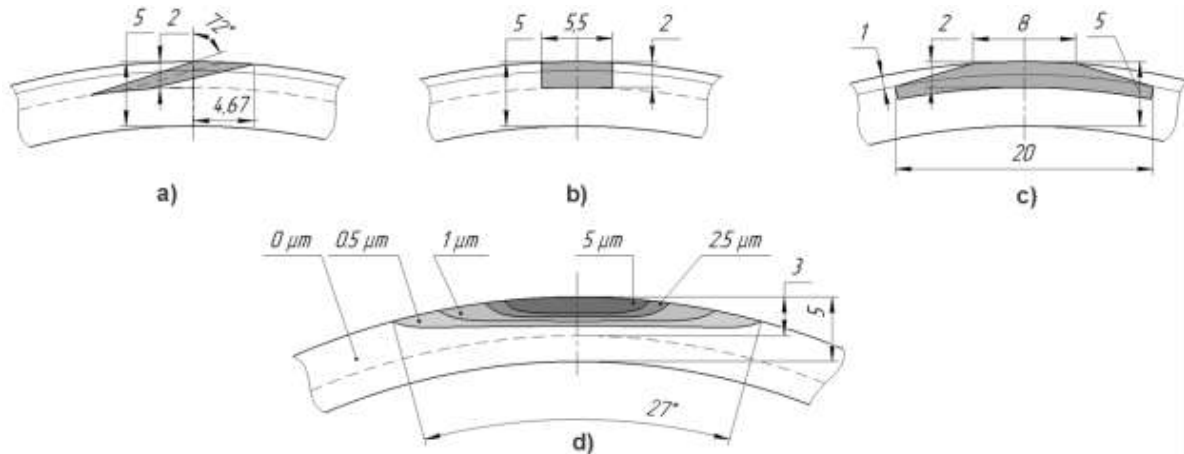


Figure 4. Design of microgrooves:

a) spiral; b) rectangular; c) reversible; d) HST (Hydrodynamic Surface Tension)

Table 1. Performance of seals with different forms of microgrooves

Microgroove type	Gap (μm)	Leakage (g min ⁻¹)	Frictional power (W)	Liquid layer stiffness (N μm ⁻¹)
spiral	1,33	1,65	1214	670
rectangular	0,28	0,02	3221	93
microgrooves HST	0,94	0,60	1613	1323
reversible	1,56	2,54	960	186

Results of calculations show that seal with rectangular form of microgrooves has a little gap leading to both the contact of seal surfaces and the wear. Reversible microgrooves have a higher oil mass flow rate, whereas HST micro-grooves have good performance, but they are difficult to produce. Spiral microgrooves have both an acceptable leakages and a high stiffness of liquid layer that is important in terms of ensuring of sealing performance at vibration conditions. Therefore, the spiral grooves were chosen for the developed seal.

4. Seal design and test

Bearing chamber of compressor supports is traditionally sealed by contact seals because this type of seals can ensure the best tightness. Replacement of face-seals with non-contact seal can significantly increase the seal life with slight reduction in tightness. The work on the installation of seals with gas and liquid lubrication in aircraft engines was carried out in cooperation with PJSC "Kuznetsov". Designed and manufactured prototypes of face seals with microgrooves for the compressor support of the aircraft engine are shown in figure 5 and 6.

The seal separates the air cavity of the compressor and the bearing chamber. Several nozzles supply oil to holes in the sleeve, whereby an oil bath is formed due to the centrifugal forces and the oil under pressure enters the gap. As a result, the contact surface A of the seal is lubricated. The piston ring of the seal is made of pyrographite. The contact surface of the steel sleeve is coated with a chromium-molybdenum coating. To ensure a non-contact operating, a structure of microgrooves is applied to the surface A of the sleeve (figure 5).

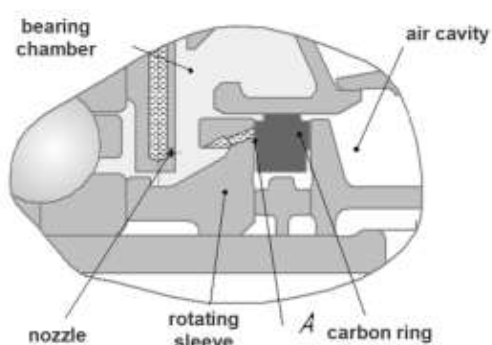


Figure 5. Seal design in compressor support



Figure 6. Sleeve of face seal with microgrooves

The results of calculations have shown that seals operated with the gap of about $2\mu\text{m}$ in all operating points of the engine. The air leakage through the face gap was less than 0.05 g/s .

Authors have developed a manufacturing technology and have produced a prototype at the Samara University. Tests both at the test rig (3 hours) and in the engine (10 hours with 6 starts and 6 shutdowns) have confirmed the operability of the developed seal. No wear of the operating surfaces was detected.

5. Results and discussions

Authors have developed a calculation technique including the concept of coupled hydrodynamic, thermal and structural calculations. This technique allows to calculate the seal performance taking into account the forces of inertia, rupture of the lubricant layer and the real form of the gap. New hydrodynamic seal was designed for the support of GTE compressor. Based on calculation results, geometric dimensions were chosen to ensure the reliability of the seal operation by creating a guaranteed liquid film, which eliminates the wear of the sealing surfaces. The results of tests both at the test rig and in the engine confirmed the low air leakage and reduced frictional power. As a further research, the authors plan to use ceramic materials with wear-resistant DLC (diamond like carbon) coatings with a low friction coefficient.

Acknowledgment

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