# Fluid-Structure Analysis of a Hybrid Brush Seal

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**Abstract.** A multidisciplinary mathematical model of a hybrid brush seal is developed. Gas flow pressure distributions and lifting forces acting on the seal compliant elements depend on current positions of the latter ones and vice versa. Seal operating clearance and leakage are obtained by means of the iterative approach for solving static fluid-structure interaction problem. A model comprising rigid pad attached to elastic support with the equivalent stiffness matrix is used for calculation of seal compliant element displacements. A model of flow in the clearances between the pads and the shaft based on 2D Reynolds equation is used for calculation of gas lifting force acting on pads. Both simplified models are verified by comparing with results obtained by means detailed 3D simulations. It is shown that the circumferential inclination of pads has significant influence on the gas lifting force generated under the pads.

**Keywords:** Hybrid Brush Seal · Fluid-Structure Interaction · Reynolds Equation · Radial Clearance · Mathematical Simulation

## 1 Introduction

Seals using to reduce gas leakage through the gaps between rotating and stationary parts of turbomachines. The most common art labyrinth seal, which due to their shape they create increased hydraulic resistance, which prevents the flow of gas from the high-pressure area to the low-pressure one. The amount of gas leakage through the labyrinth seal is proportional to the clearance, and the installation of a minimum gap allows for a high degree of sealing. However, the deformation of the parts of the sealing unit as part of gas turbine engine under the influence of variable thermal inertial loads can lead to a change in the working gap by up to 1.0 mm [1]. As a result, during the engine's operating cycle, the labyrinth seal can operates with an excessive clearance, which reduces its efficiency. Reduction of parasitic secondary flows in gas turbine engines allows to improving engine performance.

Unlike rigid labyrinth seal, a feature of promising seals is to ensure a guaranteed small gap and small gas leakage at various engine operating modes. In such constructions, the external change in the gap is compensated by the displacement of elastic elements under the action of gas forces. Lately new high-efficient seal technologies have been developed for air-to-air leakage reducing – brush seals, finger seals, foil seals, and etc. [2]. One of the promising contactless seals is a hybrid brush seal [3–5], and all-metal compliant HALO seal [6].

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## 2 Hybrid Brush Seal

Hybrid brush seal consists of a number of elastically supported pads arranged along the shaft circumference (Fig. 1). The pads are attached to the housing by means of an elastic support, which has low rigidity in the radial direction. Axial stiffness of the support is large, which makes it possible to use this seal between areas with a large pressure drop. The brush seal acts like a secondary seal preventing the direct leakage through the stationary seal parts. At the same time, the surfaces between which the brush seal is installed have zero relative rotation speed.

Gas lifting forces acting on the pads are determined by the gas flow pressure and depend on the current positions of the pads and vice versa. That provides a potential for the hybrid brush seal to adjust clearance and maintain its minimal value with respect to an external relative motion of rotor and stator parts. Gas-dynamic balancing of the pads on a thin gas film above the shaft surface is investigated by means of numerical simulations. It is assumed that all pads deflect independently of each other. Then the model of the hybrid brush seal can be built based on the consideration of one supported pad.

The results of bench tests of a combined brush seal are known, for the manufacture of the suspension of which the method of electroerosion treatment was used [3]. The tests carried out confirmed the contactless operation mode and the reduction of gas leakage by two or more times compared to the labyrinth seal.

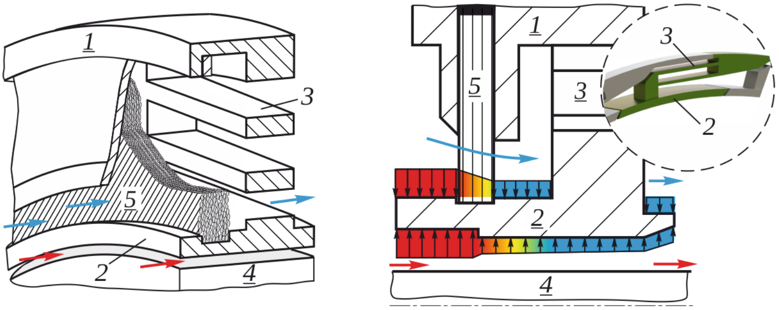

**Fig. 1.** Hybrid brush seal: *1* – housing; *2* – pads; *3* – elastic support; *4* – shaft; *5* – secondary brush seal.

The level of detail of mathematical models should allow considering a large number of design options while maintaining an acceptable complexity of calculations. At the same time, a large number of simplified approaches and calculation methods have already been developed for the brush seal [7–9], which is secondary in the design under consideration. Therefore, the main attention is paid to the construction of a mathematical model for the analysis of balancing pads on an elastic suspension under the action of gas-static and gas-dynamic lifting forces. The brush seal is considered as an elastic porous base, for the calculation of which well-known models can be used [9].

When choosing the design scheme, the following assumptions are made: the main contribution to balancing is made by the flow of gas in the gap between the pads and the rotor; radial movements of the pads do not lead to contact between them; the contact of the pads and the brush seal is considered dense and uniform. The precession of the rotor and the asymmetry of the outer casing were not considered in this work. Under these conditions, all pads will occupy the same deformed position, and circumferential cycling of the working gaps will be performed. Therefore, the main characteristics of the seal (flow rate, the size of the working gap, etc.) can be determined by the results of the calculation of one pad. In case of violation of the rotational symmetry of the arrangement of pads or gas loads, it is necessary to consider a set of pads, each of which can be calculated according to the algorithm given below. Note that the independence of the pad movements allows the seal to correct the asymmetry of the radial gap.

Thus, the design scheme of the seal includes: an arbitrarily selected pad on an elastic suspension cantilevered along the outer diameter (Fig. 2); a thin gas layer in the gap between the rotor surface and the inner surface of the pad; a sector of the brush seal above the pad.

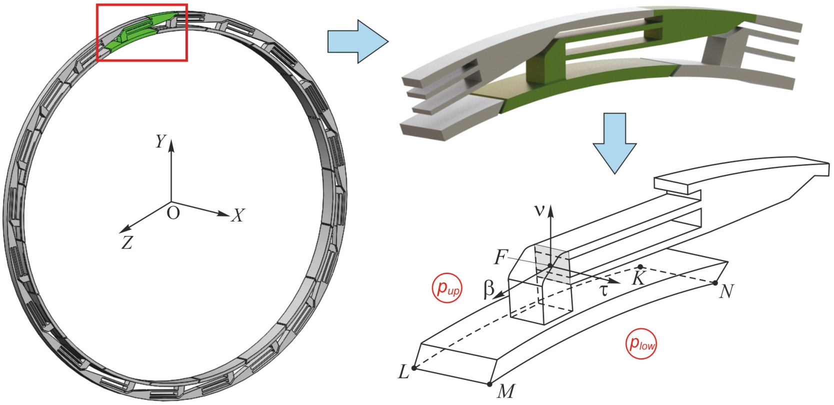

**Fig. 2.** Hybrid brush seal and elastically supported pad.

## 3 Fluid-Structure Interaction Model

The representation of a seal compliant element in the form of a rigid cylindrical pad and an elastic support is applied as results a preliminary analysis. The brush seal is considered as a simple elastic foundation with the certain stiffness and leakage rate. An equivalent fluid-structure interaction (FSI) model based on the spatial motion of the pad-support interface is proposed. To obtain the steady fluid-structure interaction solution iterative approach incorporating simplified time-efficient structure stress-strain and gas flow models is used, see Fig. 3.

The position of the pad is determined by six degrees of freedom (generalized coordinates): displacements $\delta_\tau$, $\delta_\upsilon$, $\delta_\beta$ and rotation angles $\theta_\tau$, $\theta_\upsilon$, $\theta_\beta$ of section *F*, in which the pad is associated with the support, see Fig. 2. The validity of this assumption is confirmed by the results of three-dimensional calculations.

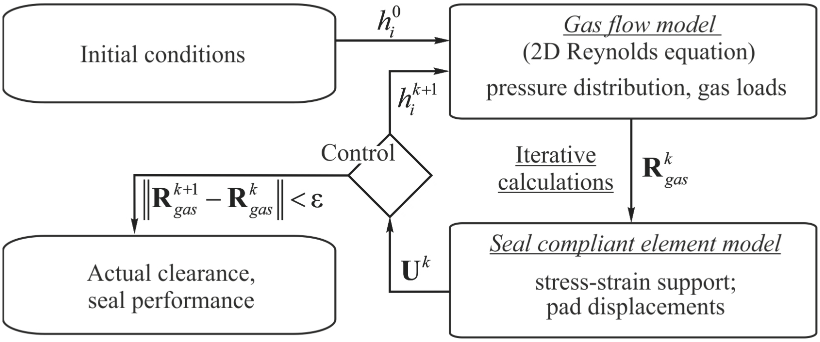

**Fig. 3.** Static fluid-structure interaction model.

The interdependence of the underpad pressure and the pad position leads to the nonlinear equilibrium equations introducing the balance of gas loads and elastic forces of support and brush:

$$\mathbf{K}_{\text{sup}} \cdot \mathbf{U} = \mathbf{R}_{gas}(\mathbf{U}), \tag{1}$$

where $\mathbf{K}_{sup}$ is matrix of the equivalent stiffness of the elastic support (taking into account the stiffness of the secondary brush seal); $\mathbf{U} = \{\delta_\tau, \delta_\upsilon, \delta_\beta, \theta_\tau, \theta_\upsilon, \theta_\beta\}^{\mathrm{T}}$ is vector of generalized coordinates; $\mathbf{R}_{gas}(\mathbf{U})$ is the vector of the equivalent gas load, composed of the components of the summary force and moment, reduced to the center of the section $F$.

The pad displacements are obtained by multiplying the compliancy matrix (inverse to stiffness matrix) of the elastic support with brush and the gas load vector. The corresponding compliances are obtained by applying unit loads with respect to the model DOFs during the initial 3D structural analysis performed only once. Simplified model is verified by comparing with the results of the 3D numerical simulations for complex loading (Fig. 4).

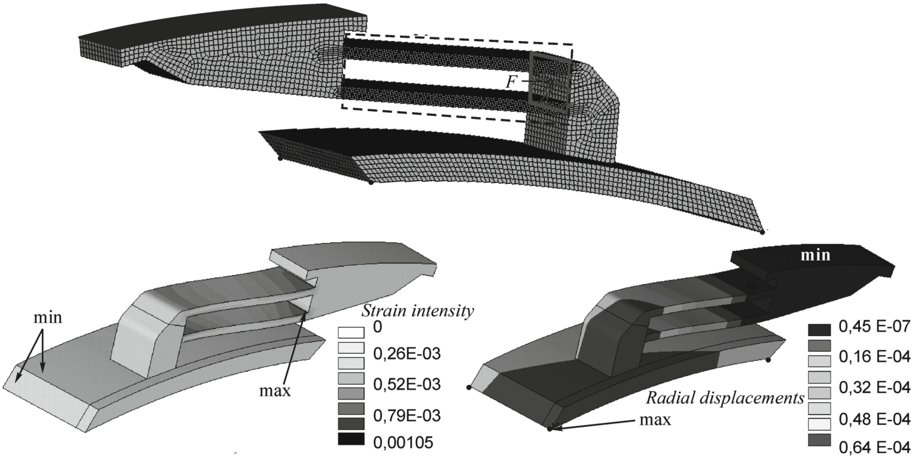

**Fig. 4.** 3D numerical simulations: model, radial displacements.

During the iterations the gas pressure distributions are obtained by solving 2D Reynolds equation for a thin gas layer, which is widely used for hydrodynamic seals and bearings analysis [10]:

$$\frac{\partial}{\partial z}\left(ph^3\frac{\partial p}{\partial z}\right)+\frac{\partial}{\partial s}\left(ph^3\frac{\partial p}{\partial s}\right)=6\mu\omega R_{sh}\frac{\partial(ph)}{\partial s}, \tag{2}$$

where $p(z, s, t)$ is gas flow pressure; $h(z, s, t)$ is the gap thickness (clearance); $\mu$ is dynamic viscosity; $\omega$ and $R_{sh}$ are an angular velocity and a radius of the rotor; $z$ and $s$ are «axial» and «circumferential» local Cartesian coordinates on the gap involute $D_{inv}$. Gas inertia effects are neglected. Flow is treated to be compressible, adiabatic and laminar.

Static pressures values are used as the boundary conditions: $p = p_{up}$ in the inlet; $p = p_{low}$ in the outlet and circumferential sides. In 2D case with accounting circumferential flow solution is found numerically by using the in-house unsteady nonlinear FEA program based on implicit Euler scheme of the in time integration and Newton-Raphson method [11]. The Reynolds equation was made dimensionless to get good convergence of each time step solution.

Developed simplified model based on Reynolds equation is verified by comparing with 3D CFD results for different pressure drops and shaft velocities. Pressure distributions under rigid lift pads for circumferentially convergent and divergent clearances are shown in Fig. 5. It allows us to calculate aerodynamic lifting force, acting on the seal pad. This model has also been previously successfully used to calculate gas flow in the finger seals [11, 12].

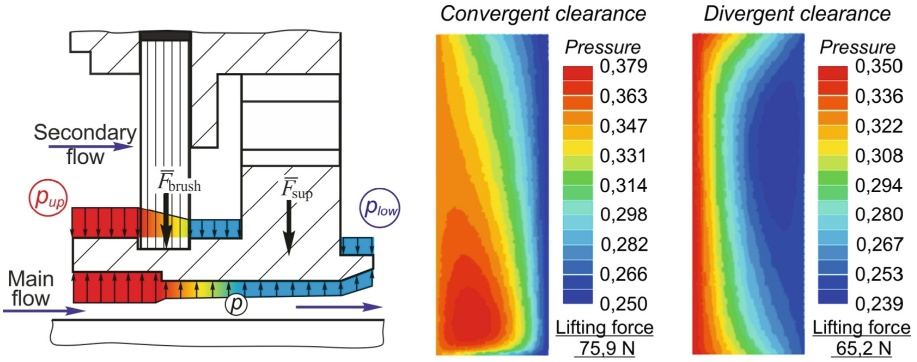

**Fig. 5.** Hybrid brush seal loading and underpad pressure distributions.

The results of solving the fluid-structure interaction problem for the hybrid brush seal with pads initially located concentrically to the rotor surface (installation gap 10 μm) are shown in Fig. 6. The same figure shows the results of the verification 3D simulation.

Such calculations were made for various initial gaps in the seal. It is shown that the circumferential inclination of the pads demonstrate significant influence on the gas lifting force generated under the pads. At small clearances either a gas-dynamic build-up in a circumferentially converging film, or a «suction» force otherwise is developed. Then several design features (e.g. position of the support relatively to the pad) are investigated to assure a converging operating clearance. This is to be the main contributor to the efficient seal operating, i.e. being non-contacting and with low leakage.

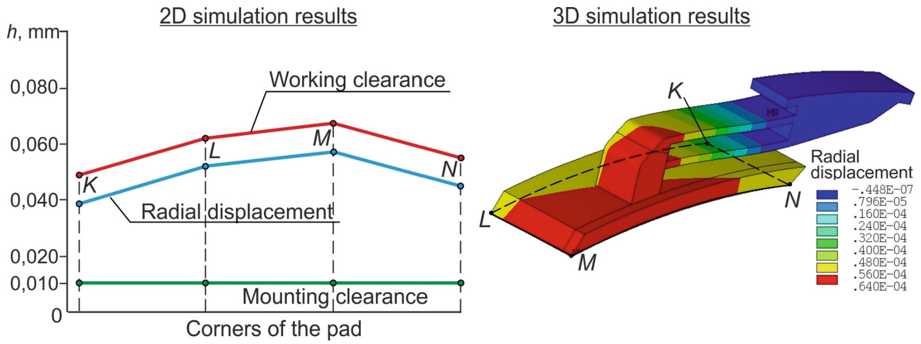

**Fig. 6.** Static fluid-structure interaction results for the hybrid brush seal.

The simplified approaches can be used also for dynamic analysis of the hybrid brush seal. For example, the dynamic response of the pad to modeling radial excursions of the shaft and gas pressures drop changing is shown in Fig. 7 for case with reduced numbers of the DOFs.

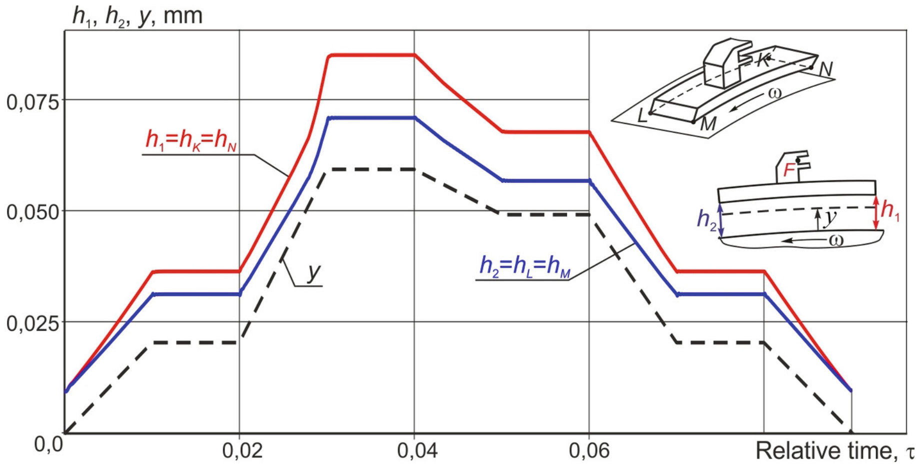

**Fig. 7.** Dynamic response of the pad of hybrid brush seal to modeling radial excursions $y$ of the shaft and gas pressures drop changing.

## 4 Conclusions

Multidisciplinary mathematical simulation technique based on two-way FSI coupling is developed for performance evaluation of the hybrid brush seal. The models are based on the simplified approaches: the model comprising rigid pad attached to elastic support with the equivalent stiffness matrix is used for calculation of seal compliant element displacements; the model of gas flow in the clearance between a pad and the rotor based on the 2D Reynolds equation is used for calculation of gas lifting force. Both simplified models are verified by comparing with the results obtained by means of detailed 3D simulations.

Calculation time for fast models is significantly less than for 3D detailed models meanwhile their accuracy is sufficient for hybrid brush seal design features preliminary investigation. Developed models allow to introduce simple iterative algorithm to solve inverse problem of mathematical simulation and to calculate seal geometric design parameters according to the specified restrictions on the radial displacement of the pads. This result would have been difficult to obtain using time-consuming traditional numerical 3D approaches.

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