770. Aeroelastic self-oscillations of gas seal wall

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Abstract. The channel with a moving wall is considered to describe aeroelastic oscillations induced by gas flow. One of the channel walls has two degrees of freedom and it is supported by springs and dampers. The multi-fields investigation method is based on simulation transient gas flow in the channel to calculate aerodynamic forces acting on the wall. Corresponding rigidity and damping gas flow parameters obtained from these loads are included into the wall oscillations model for the stability analysis.

The models are developed for two channel types: with smooth and finned wall. Aeroelastic stability boundary is shown for both channels. An effect of structural parameters on the realization of convergent oscillation and self-oscillation modes is shown too. A paradox of system destabilization with the increasing damping is observed for a certain parameter set.

Keywords: aeroelastic stability, oscillations, gas flow, seal.

Introduction

Gas flow ducts and channels are the important parts of different technical devices. Non-stationary processes, which take place in these channels, may influence significantly on the device performance and service life. It's true both for simple devices and for extremely complex devices as gas turbine engines. For example modern aircraft engine have more than 100 small channels (seals) between rotor and stator. Some of them have smooth walls (annular seals), other have finned walls (labyrinth seals). The aim of the seal is to reduce gas leakage from high pressure area to low pressure one. Thus we have the flow induced by the pressure drop in the channel. In some cases energy of this flow may lead to seal wall self-oscillations and fatigue failure of the seal. Such problems were fixed in real engines.

Aeroelastic analysis is a generally multi-field problem. To solve this problem we should combine the gas flow model and the wall dynamic model (Fig. 1). In this work we use "local" channel models, but in a general case the seal wall may have some "external" quasi-stationary motion induced by centrifugal or thermal growth of the rotor, rotor deflections and thermal growth of the stator. These external motions lead to a clearance change and thus may have an influence on gas flow and seal stability too. For the real seal initially we need to find the external stator/rotor motions and thereafter use the local models. To solve the external task a whole engine hydraulical net model and modules of thermostressed analysis can be used. These external models are not discussed in this work.

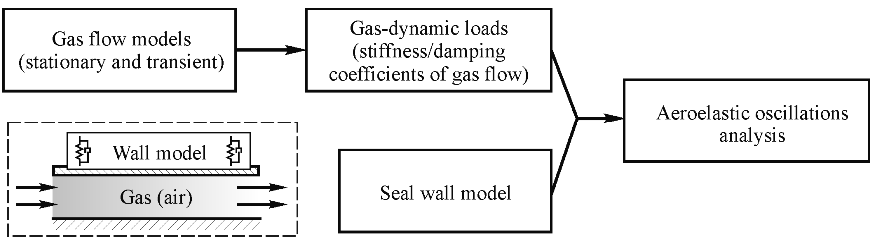


Fig. 1. The aeroelastic analysis algorithm

Fig. 1 shows overall algorithm of aeroelastic analysis. Gas channel with rigid moving wall is considered to describe seal aeroelastic oscillations induced by transient gas-dynamic loads. One of the channel walls has two degrees of freedom and it is supported by springs and dampers. The investigation method is based on simulation transient gas flow in the channel to calculate aerodynamic forces. These forces are included into the wall oscillations model for the analysis of stability.

Obviously this algorithm can be used for various gas ducts and seals, including new high-efficient finger seals with flexible fingers. The finger seal (see Fig. 2) is comprised of a stack of plates with special cuts which form the fingers. The downstream fingers have lift pads on one of their ends and act as cantilever beams, flexing away from the rotor during gap decrease through centrifugal or thermal growth of the rotor or during rotordynamic deflections [1]. The problem of flexible finger self-oscillation, induced by gas loads acting on their pads, may be significant for these seals. Some feature of this analysis will be discussed further.

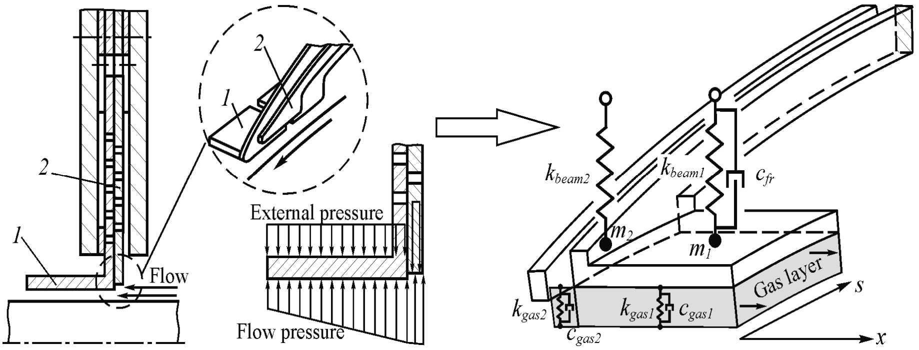


Fig. 2. Compliant finger seal model: 1 – downstream finger with lift pad; 2 – upstream finger

Aeroelastic self-oscillations of plane channel wall

The main generalized models with two degrees of freedom are shown in the Fig. 3. These models are plane and walls are considered to be absolutely rigid. Springs and dampers with stiffness (k_0, k_1) and damping (c_1) coefficients imitate seal structure characteristics. The seal clearance δ is much smaller than its length *L*. The stability analysis for these models can be carried out by standard mathematical methods, but first we must know non-stationary gas flow pressure distribution in the channel. At the same time this pressure distribution is depended on boundary conditions and actual wall position. Thus we have direct correlation between wall position and values of aeroelastic forces.

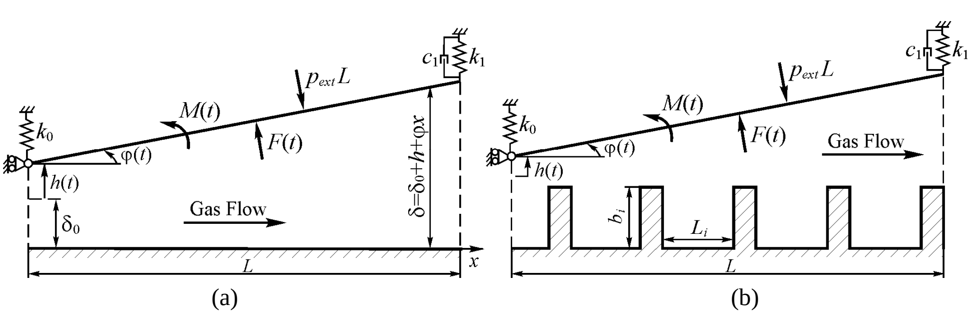


Fig. 3. Plane channel model with (a) smooth and (b) finned wall

If φ is sufficiently small, then wall oscillations (with two degrees of freedom: φ and *h*) are described by equations:

$$\begin{cases} m\ddot{h} + \dfrac{mL}{2}\ddot{\phi} + c_1(\dot{h} + \dot{\phi}L) + k_0 h + k_1(h + \phi L) = \Delta F, \\ \dfrac{mL}{2}\ddot{h} + \dfrac{mL^2}{3}\ddot{\phi} + c_1 L(\dot{h} + \dot{\phi}L) + k_1 L(h + \phi L) = \Delta M, \end{cases} \tag{1}$$

here m is the wall mass; h and ϕ are deviations from the static equilibrium position; ΔF and ΔM are the aeroelastic force and moment deviations from their values at the static equilibrium. These deviations can be represented as follows:

$$\Delta F = \frac{\partial F}{\partial h}h + \frac{\partial F}{\partial \varphi}\varphi + \frac{\partial F}{\partial \dot{h}}\dot{h} + \frac{\partial F}{\partial \dot{\varphi}}\dot{\varphi},\ \Delta M = \frac{\partial M}{\partial h}h + \frac{\partial M}{\partial \varphi}\varphi + \frac{\partial M}{\partial \dot{h}}\dot{h} + \frac{\partial M}{\partial \dot{\varphi}}\dot{\varphi}, \tag{2}$$

and they are called stiffness and damping gas flow coefficients.

The transient gas flow models for smooth and finned channels are developed to obtain pressure distribution $p(x, t)$ and to calculate aerodynamic force F and moment M which are acting on the seal walls:

$$F(t) = \int_0^L p(x,t)dx, \quad M(t) = \int_0^L xp(x,t)dx .$$

In a general case turbulent gas flow is described by a system of partial derivatives differential equations. This system consists of continuity equation, momentum equations, and energy equation. And it also contains some differential equations, used to describe the turbulence model. At the same time, there is a lot of experimental data that allows us to define friction coefficients, depending on Reynolds number for such small gas channels.

Thus, the gas flow model can be built with one dimensional approximation that reduces calculation time. We can write continuity equation (3), momentum equation (4), energy equation (5), and state equation. If wall deviations are small, this gas-dynamic system can be linearized:

$$\frac{\partial(\rho\delta)}{\partial t} + \frac{\partial(\rho u\delta)}{\partial x} = 0, \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{2\tau}{\rho\delta} = 0, \tag{4}$$

$$\frac{\partial T^*}{\partial t} + u\frac{\partial T^*}{\partial x} - \frac{1}{\rho c_p}\frac{\partial p}{\partial t} = 0, \tag{5}$$

here ρ is the gas density, u is the flow velocity, and T^* is the stagnation temperature. The shear stress τ is equal to $\tau = f\,\rho u|u|/2$, where the wall friction factor f for a turbulent flow is equal to $f = 0.187 \cdot \mathrm{Re}_x^{-0.333}$.

One-dimensional transient gas flow simulation is carried out using finite difference method with implicit scheme. And in some cases two-dimensional transient gas flow in the channel with moving wall is simulated also to test 1D model results. The analysis is carried out using commercial software. The difference between 1D and 2D models for aerodynamic force $F(t)$ and moment $M(t)$ is less than 2 %. Therefore our fast 1D model (with linear approximation) can be used for such research.

For the finned channel we add some equations for narrowing/widening flow interaction near the fins (teeth). Gas flow in this case can be described by "one-volume" model [2]:

$$\frac{\partial}{\partial t}\left(p_i S_i\right)+\mu_0\mu_{i+1}\delta_{i+1}\sqrt{RT(p_i^2-p_{i+1}^2)}-\mu_0\mu_i\delta_i\sqrt{RT(p_{i-1}^2-p_i^2)}=0, \qquad i=1..N, \tag{6}$$

where N is the number of cavities between the fins, S_i is the cross-section cavity area, μ_i is the discharge coefficient:

$$\mu_i=\frac{\pi}{\pi+2-5\beta_i+2\beta_i^2}, \text{ where } \beta_i=-1+\left(\frac{p_{i-1}}{p_i}\right)^{(\gamma-1)/\gamma}.$$

For detailed analysis of the finger seal we can use 2D gas flow model with circumferential coordinate s (see Fig. 2). This model is constructed on the Reynolds equation:

$$\frac{\partial}{\partial s}\left(p\frac{\delta^3}{\eta}\frac{\partial p}{\partial s}\right)+\frac{\partial}{\partial x}\left(p\frac{\delta^3}{\eta}\frac{\partial p}{\partial x}\right)=6\left[2\delta\frac{\partial(p\delta)}{\partial t}+\omega R\frac{\partial(p\delta)}{\partial s}\right]. \tag{7}$$

Reynolds approach is more effective for the 2D transient gas flow modeling, but anyway for first approximation can be used 1D gas flow model. Finger stiffness k_{beam} can be evaluated by 3D stress analysis of fingers assembly by using commercial software (ANSYS and etc.). In all other aspects of the research method is similar to represented here.

Stiffness and damping gas layer coefficients obtained from the aerodynamic loads are included into the wall dynamic model Eq. (1) for analysis of the stability of the aeroelastic oscillations. Let us find the solution Eq. (1) in the following form:

$$\begin{cases} h=He^{i\omega t}, \\ \varphi=\Phi e^{i\omega t}, \end{cases} \tag{8}$$

where ω is the self-oscillations frequency, H and Φ are complex amplitudes. Combining Eq. (1), (2), (8) and writing nontrivial solution existence condition, we can determine parameters of self-excitation oscillations.

Fig. 4 represents safe operating area 1, unstable area 2, and boundary of stability 3 (curve of harmonic self-oscillations) for the smooth channel under some operating conditions. It must be noted, that in this case linear damping c_1 increase may cause growth of oscillations and seal instability. This effect is similar to Mansour`s anomaly and can be explained as follows: there is no direct coupling between damping coefficient increase and damping forces work increase for such systems with two degrees of freedom [3].

Let us consider the behavior of characteristic equation roots λ with damping coefficient c_1 vary. As a result of characteristic equation numerical solution, two pairs of complex conjugate roots (λ_1, λ_2) and (λ_3, λ_4) are obtained. Fig. 5a shows λ_1 and λ_3 versus c_1 on the complex plane (increasing c_1 is indicated by arrows). For Re(λ) < 0 oscillations decrease. The intersection points of curves λ with ordinate axis Re(λ) = 0 correspond to harmonic self-oscillations, and the system is unstable in the area Re(λ) > 0.

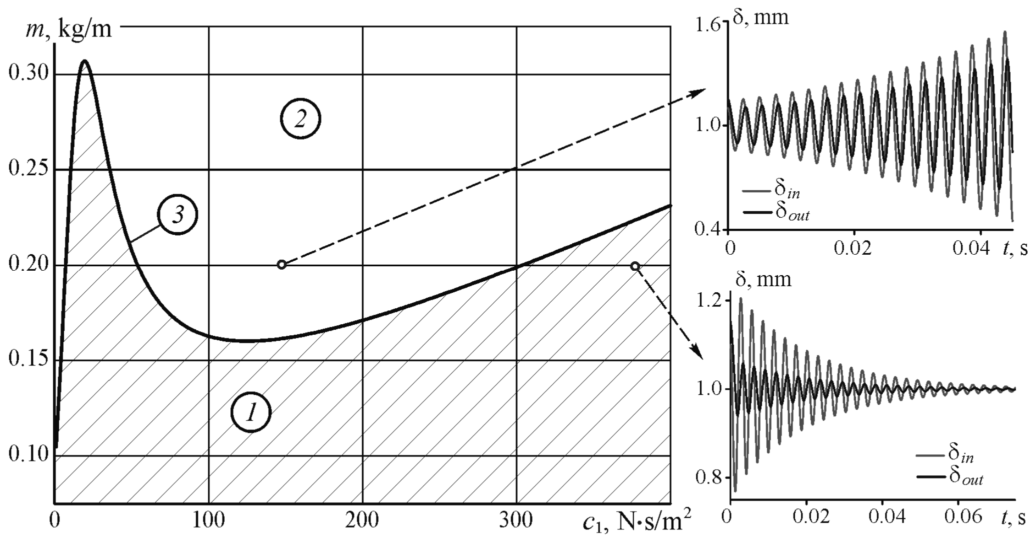


Fig. 4. Smooth channel stability region: 1 – safe operating area, 2 – unstable area, 3 – stability threshold

On the boundary of stability there may be qualitative changes when stiffnesses are varied. If stiffnesses k are “small” values, then with damping increasing, the system turns from oscillations increase to oscillations decrease. With stiffness increasing, nonlinear effects appear – see Fig. 5b.

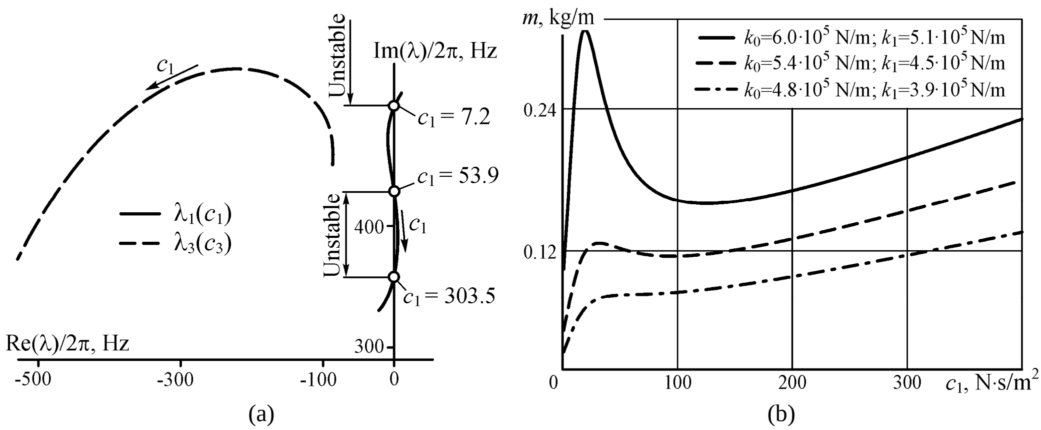
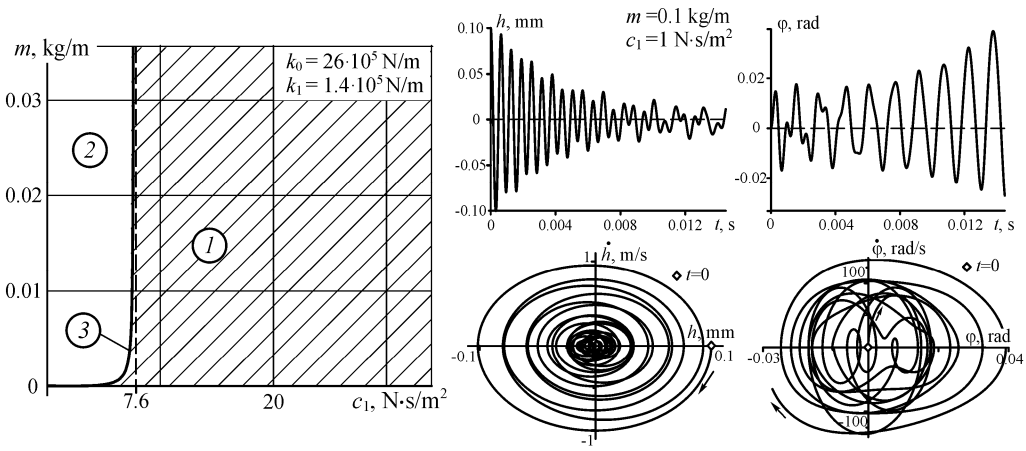


Fig. 5. (a) Characteristic equation roots λ versus c_1; (b) stability threshold for different stiffness

Fig. 6a shows stability region for the finned channel. The effect of seal destabilization with increase of damping coefficient isn’t observed for selected seal parameters.

The Eq.(1) and Eq.(6) can be joining into one nonlinear system, where $\Delta F = \int_0^L p(x,t)dx - F(h_0, \varphi_0)$ and $\Delta M = \int_0^L p(x,t)xdx - M(h_0, \varphi_0)$.

Numerical solutions of this system for different damping coefficient values confirm the boundary of stability. For example Fig. 6b shows $h(t)$ and $\varphi(t)$ behavior for small damping (point from unstable area). More detail gas-dynamic analysis and stability analysis for these channels are represented at the works [4, 5].



(a) (b)

Fig. 6. Finned channel stability region (a) and system behavior for small damping (b): 1 – safe operating area; 2 – unstable area; 3 – stability threshold

Conclusions

This research is first stage of seal/channel aeroelastic stability study. Developed mathematical models allow obtaining initial results on the behavior and stability of such systems. It is shown that the aeroelastic oscillations problem is essentially nonlinear even for our models with two degrees of freedom (for example a paradox of system destabilization with the increasing damping is shown). Obviously such problem should be solved with use of multi-fields investigation method only.

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