MODIFIED SINGLE-CONTROL VOLUME MODEL FOR LABYRINTH SEAL: APPLICATION FOR STABILITY STUDY OF A ROTOR/STATOR INTERACTION

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Abstract: This article focuses on the stability study of a rotor/stator interaction via a labyrinth seal. To predict the destabilizing force exerted by the labyrinth seal, a single-control volume analysis is performed. The main contribution is a new model of the air flow in the control volume of labyrinth seal with temperature as a parameter and a new bladed disk model for study of the coupling phenomenon in the rotor/stator systems.

Keywords: *rotor dynamics, stability study, labyrinth seals, single-control volume model*

Labyrinth seals are commonly found in turbomachinery. They are comprised of one rotating and one fixed component. Together with the annular cavities which are formed by the coaxial rotor-stator cylindrical surfaces and a series of sealing teeth, they keep the high and low pressure cavities separated.

The proposed model for gas flow is based on the single-control volume model defined by two main equations of continuity and moments written for each cavity of labyrinth seal and one additional mass-flow equation for complete seal. The classical approach consists of consideration that the thermal process in the cavity is adiabatic or isothermal. These assumptions often made in the majority of articles on this subject can lead to quite different behaviour. Taken into account these thoughts the proposed model has an additional expression for the temperature variations which is associated to energy equation.

The solution technique consists in deriving the governing equations for each labyrinth cavity similar to that performed by Childs (1993) taken into account the energy equation. The resulting set of partial differential equations is linearised using a perturbation analysis for small motion about a centered rotor position. The resulting set of linear algebraic equations is solved for the pressure, velocity and temperature perturbations about the circumference. The dynamic coefficients characterising the impact of fluid-induced forces on the system stability are determined by integrating the pressure perturbations around the rotor.

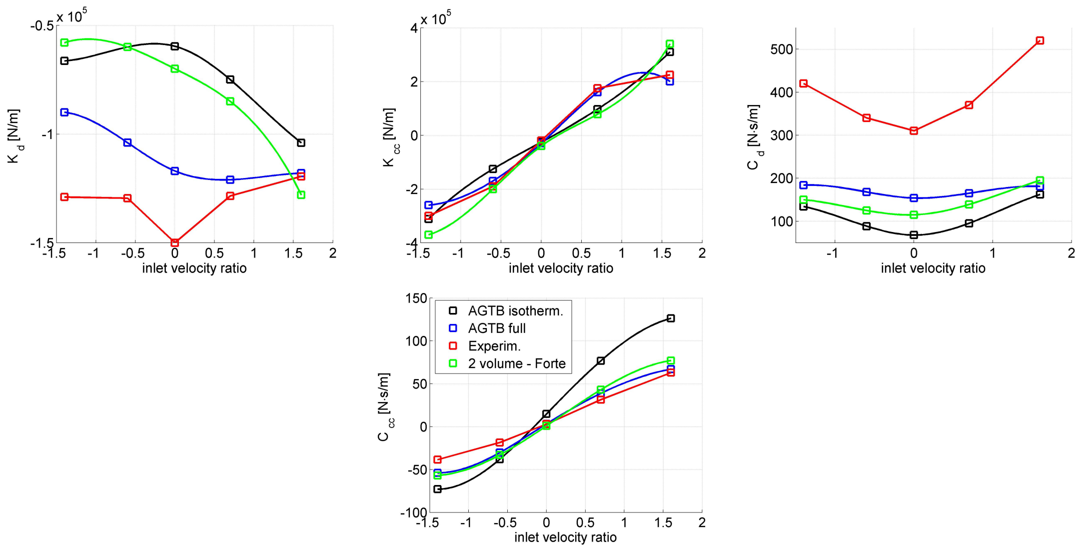

Figure 1: Rotordynamics coefficients

A computer program based on the theoretical model described above was developed. It was tested comparing its results with those of the two-volume model of Forte (1999) and with the only available experimental results taken from Scharrer (1985) report. Figure 1 show theoretical and experimental dynamical coefficients for a teeth-on-stator seal. The main operating quantity is inlet velocity ratio (inlet tangential velocity/rotor speed). The acronym "AGTB isoterm." is used for classical model with isothermal assumption for thermal process in the cavity, "AGTB full" is for model with the energy equation.

The single-control volume model with an energy equation predicts the right trend for the dependence on inlet velocity ratio for the direct stiffness coefficient K_{cc}. The values are much closer than the 2-volume model or model with thermal assumptions. For the damping coefficients C_{cc} the proposed model seems to give better results with respect to the experimental ones than the 2-volume model but the trend of the dependence on the inlet velocity ratio is worse described. For the two cross-coupled coefficients k_{cc} and c_{cc} the complete behaviour is similar to the two-volume model.

Now, the simplified model of a bladed disk with the labyrinth seal on top of the blades with a flexible carter retained for the study of influence of labyrinth seal on the system stability is presented. The proposed model is under a valid basis, an example of such a design can be a spatial turbo-engine (see Fig. 2).

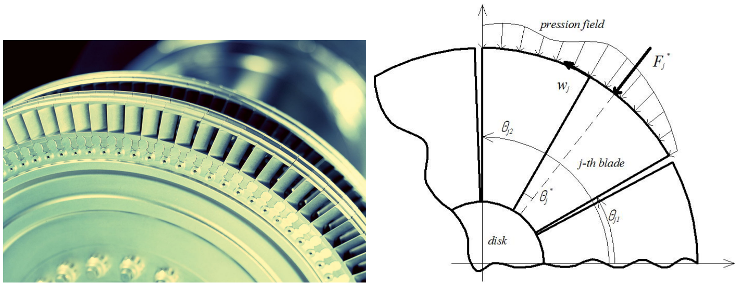

Figure 2: The LOX turbopump bladed disk with labyrinth seal of a spatial turbo-engine(left) and the proposed model for bladed disk(right)

The set of equations for the system described above in the form of Cauchy has the following form:

$$\begin{Bmatrix} \dot{\mathbf{Q}}_\mathbf{1} \\ \dot{\mathbf{Q}}_\mathbf{2} \\ \dot{\mathbf{X}} \end{Bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} & \mathbf{0} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{D} & \mathbf{M}^{-1}\mathbf{Rt} \\ \mathbf{A}_\mathbf{der}^{-1}\mathbf{B} & \mathbf{A}_\mathbf{der}^{-1}\mathbf{C} & -\mathbf{A}_\mathbf{der}^{-1}\mathbf{A} \end{bmatrix} \begin{Bmatrix} \mathbf{Q}_\mathbf{1} \\ \mathbf{Q}_\mathbf{2} \\ \mathbf{X} \end{Bmatrix}, \tag{1}$$

where $\left\{\mathbf{Q_1 Q_2 X}\right\}^T$ - vector of the DoF of the system in discussion (consists from the rotor and stator displacements as well as the pression, circumferential velocity and temperature perturbation in each cavity), $\mathbf{M}, \mathbf{D}, \mathbf{K}$ - mass, damping and stiffness matrix respectively, the terms of $\mathbf{A}$, $\mathbf{A_{der}}$, $\mathbf{B}$ and $\mathbf{C}$ consist from zero-order variables.

As a result, we can see that the presence of the labyrinth seal in a fairly simple autonomous system 1, leads to the instability of the stationary unperturbed motion as depicted on the Fig. 3. But the system stability loss condition depends on the chosen model for inter-cavity process - with the energy equation or with the adiabatic hypothesis.

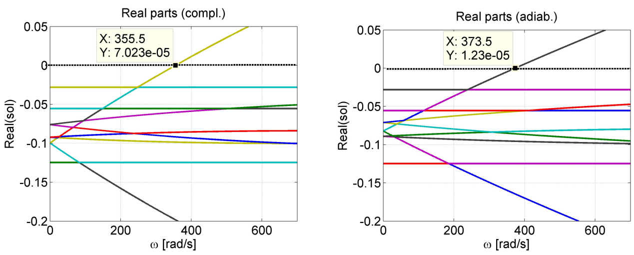

Figure 3: Real parts of the roots of characteristic equation for the proposed system with the energy equation (left) or with the adiabatic hypothesis (right)

In this study an advanced single-control volume model for labyrinth seal was proposed to identify the instability phenomenon in a rotor-stator coupled system. The model with an energy equation make rotordynamic analysis more accurate in the trend prediction of the dependence on the inlet velocity ratio. The proposed model for bladed disk with labyrinth seal and flexible stator is new for the stability study of this sort of system. The obtained results underline the difference between the chosen model for thermal process in the cavity and they gives us a thoughts that the system with an energy equation is better suited for stability study. The proposed model needs a further study and an experimental results for verification. Nevertheless the energy equation have to be taken into account in the sot of a quick thermomechanical analysis of the sealed rotor structures.

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