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[Extended Abstract]

Influence of seal compliance on rotordynamic behavior

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1. Introduction and Modeling

Compliant hybrid seals (e.g. HALO seal [1]) offer a comparatively new approach to reduce leakage in turbo machinery, leading to higher efficiency even under transient operation. These properties are achieved by a reduced sealing gap along with added seal flexibility to minimize the risk of surface rubbing.
In this contribution the steady state stability, the bifurcation behavior and the resulting limit cycles of a compliant seal-rotor system are being discussed. The underlying model consists of a *Laval*-Rotor (*Jeffcott*-Rotor) and a rigid seal ring which is visco-elastically connected to the environment (see left chart in Figure 1). The turbulent, incompressible flow through the seal leads to fluid forces which are described by the non-linear semi-empirical model by *Muszynska* [2]. The dynamics of rotor and seal are given by

$$\mathbf{M}_{\mathrm{R}}\ddot{\mathbf{r}}_{\mathrm{R}} + \mathbf{B}_{\mathrm{R}}(\Delta\mathbf{r})\dot{\mathbf{r}}_{\mathrm{R}} + \mathbf{K}_{\mathrm{R}}(\Delta\mathbf{r})\mathbf{r}_{\mathrm{R}} = \mathbf{F}(\Delta\mathbf{r}) \quad \text{and} \quad \mathbf{M}_{\mathrm{S}}\ddot{\mathbf{r}}_{\mathrm{S}} + \mathbf{B}_{\mathrm{S}}(\Delta\mathbf{r})\dot{\mathbf{r}}_{\mathrm{S}} + \mathbf{K}_{\mathrm{S}}(\Delta\mathbf{r})\mathbf{r}_{\mathrm{S}} = -\mathbf{F}(\Delta\mathbf{r}), \quad \text{where}$$

$$\mathbf{F}(\Delta\mathbf{r}) = -\begin{pmatrix} m_f & 0 \\ 0 & m_f \end{pmatrix}\Delta\ddot{\mathbf{r}} - \begin{pmatrix} \bar{D} & 2\bar{\tau}\Omega m_f \\ -2\bar{\tau}\Omega m_f & \bar{D} \end{pmatrix}\Delta\dot{\mathbf{r}} - \begin{pmatrix} \bar{K} - m_f\bar{\tau}^2\Omega^2 & \bar{\tau}\Omega\bar{D} \\ -\bar{\tau}\Omega\bar{D} & \bar{K} - m_f\bar{\tau}^2\Omega^2 \end{pmatrix}\Delta\mathbf{r}, \quad \text{and}$$

$$\Delta\mathbf{r} = \mathbf{r}_{\mathrm{R}} - \mathbf{r}_{\mathrm{S}}, \quad \bar{K} = K_0(1 - \|\mathbf{r}_{\mathrm{R}} - \mathbf{r}_{\mathrm{S}}\|^2)^{-n}, \quad \bar{D} = D_0(1 - \|\mathbf{r}_{\mathrm{R}} - \mathbf{r}_{\mathrm{S}}\|^2)^{-n}, \quad \bar{\tau} = \tau_0(1 - \|\mathbf{r}_{\mathrm{R}} - \mathbf{r}_{\mathrm{S}}\|^2)^{b}.$$

$\mathbf{M}, \mathbf{D}$, $\mathbf{K}$ and $\mathbf{r}$ are the mass-, damping-, stiffness-matrices and the position vectors respectively. The subscript R indicates rotor-related and the subscript S seal-related variables and parameters. $\mathbf{F}(\Delta\mathbf{r})$ is the fluid force. Furthermore, m_f is the coefficient of the fluid inertia, D_0 is the coefficient of the fluid damping, K_0 is the coefficient of the fluid radial stiffness, Ω is the angular velocity of the rotor, τ_0 is the fluid average circumferential velocity ratio and n and b are empirical parameters [3].

2. Results

Linear Analysis: The right chart in Figure 1 shows the number of unstable eigenvalues for the ratio $\kappa^2 = \frac{c_S}{c_R}$ ($c_{S,R}$: seal support stiffness and rotor stiffness) plotted against a dimensionless rotational rotor speed η and thus indicates the stable and unstable steady states. The dotted black line marks the stability boundary for a stiff seal support. Three interesting conclusions can be drawn: Firstly, the visco-elastic seal support leads to an increased parameter range with stable solutions. Secondly, the mobility of the seal stabilizes the solution: the stability limit for a compliant support converges towards the limit for stiff support with increasing support stiffness and thus less mobility. And thirdly, the solutions become unstable due to different complex conjugated eigenvalue pairs A and B.

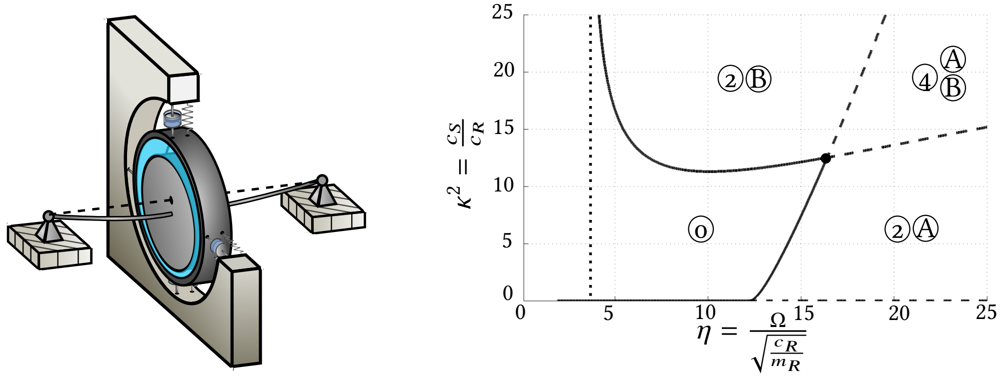

Figure 1. Left: rotor-seal model. Right: stability chart: ratio $\kappa^2 = \frac{c_S}{c_R}$ over dimensionless rotational rotor speed η. Digits: numbers of unstable eigenvalues; letters A and B: specific pairs of eigenvalues; vertical dotted line: stability limit for stiff seal support. Source of right chart [4].

Non-linear Analysis: The solutions display two qualitatively different non-linear behaviors: The first one occurs, if κ^2 is chosen in a way that the eigenvalue pair A becomes unstable first when η is increased. In this case the solution looses its stability via a *Hopf* bifurcation and the seal exhibits medium sized amplitudes whilst the rotor only displays comparatively small ones: a continued operation after the loss of stability might be possible. The second qualitative solution type is shown in figure 2 and occurs if the eigenvalue pair B is the first one to become unstable. Again, the steady state solution looses its stability via a *Hopf* bifurcation but this time rotor and seal display large amplitudes most certainly prohibiting ongoing operation. Raising the bifurcation parameter η further the periodic cycle looses its stability via a *Neimark-Sacker* bifurcation. Crossing the area of the eigenvalue pair A to the area of A and B in the right chart in figure 1, a second (unstable) periodic orbit emerges which gains its stability via a *Neimark-Sacker* bifurcation. The two *Neimark-Sacker* points are connected by a quasi-periodic repellor. In addition, unbalance of the rotor is considered. It leads to a further stabilization. The forced periodic orbits loose their stabilities via *Neimar-Sacker* bifurcations.

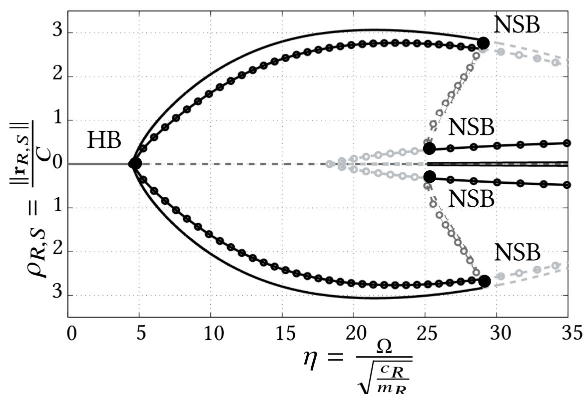

Figure 2. Steady state and circular limit cycles radii $\rho_{R,S}$ over dimensionless rotational rotor speed η fro $\kappa^2 = 20$. Solid black lines: stable seal (dotted) and rotor orbits; dashed light grey lines: unstable seal (dotted) and rotor orbits; (dashed) dark grey line: (un)stable steady states; dark grey dashed line between NSB points: averaged radius of unstable quasi-periodic orbit; HB: *Hopf* bifurcation; NSB: *Neimark-Sacker* bifurcation. Source [4].

References

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