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Simulation of Refrigerant-Lubricated Gas Foil Bearings

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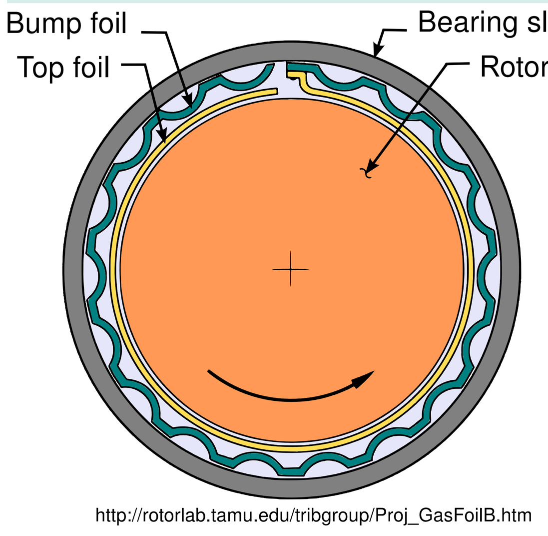
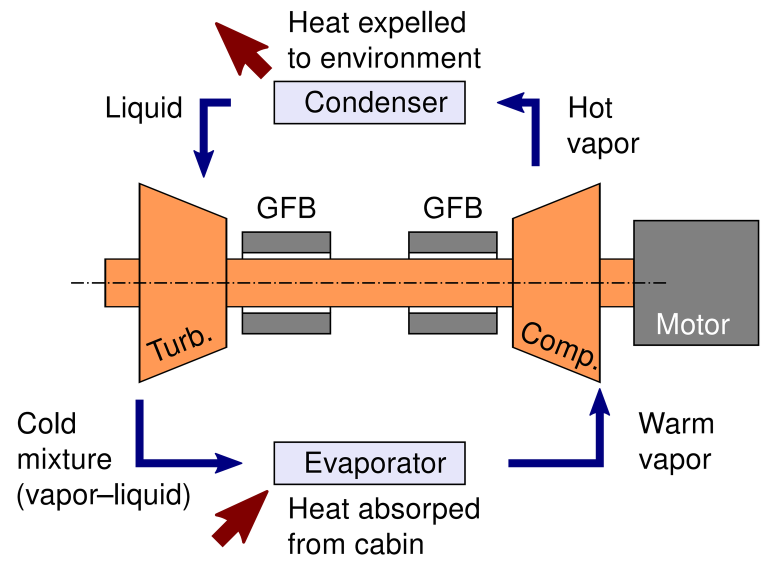
Gas Foil Bearings (GFBs)



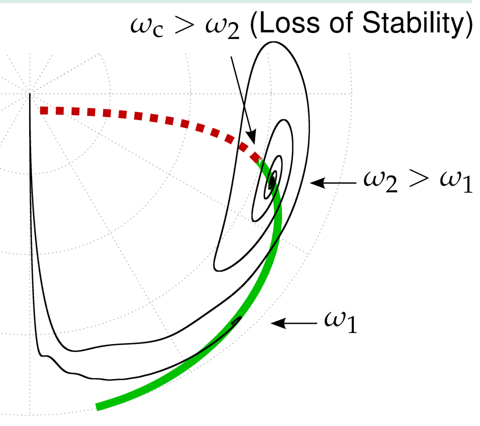
- High-speed rotor supported by aerodynamic lubrication wedge
- Oil-free machinery offers high energy efficiency and low wear

Application: Vapor-Compression Refrigeration



- System optimized by using refrigerant as the lubricating fluid

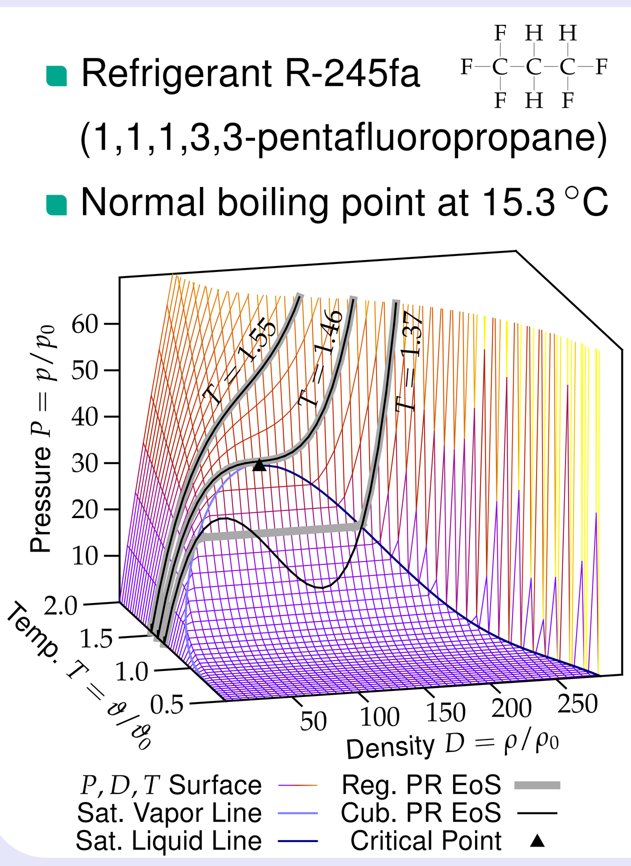
Challenge: Self-Excited Vibrations



- Stationary operating points tend to become unstable at elevated rotational speed
- Occurrence of self-excited rotor vibrations with large amplitudes (fluid whirl)
- Key requirements for simulation of GFB rotor systems
  1. Realistic fluid model accounting for phase transitions
  2. Dissipative foil structure model considering dry friction
  3. Rotor model mutually coupled to nonlinear GFB forces

Fluid Model

- Refrigerant R-245fa (1,1,1,3,3-pentafluoropropane)
- Normal boiling point at 15.3 °C



- Cubic Peng–Robinson equation of state (PR EoS)

$$P_{\mathrm{PR}}(D,T) = \frac{1}{p_0}\left[\frac{R\vartheta_0 T}{\left(\frac{M}{\rho_0 D}\right) - b} - \frac{a(\vartheta_0 T)}{\left(\frac{M}{\rho_0 D}\right)^2 + 2b\left(\frac{M}{\rho_0 D}\right) - b^2}\right]$$

- Equilibrium vapor pressure (coexistence curve) by fitting simplified Clausius–Clapeyron solution

$$P_{\mathrm{sat}}(T) = \exp\left(C_0 - C_1 T^{-1} - C_2 \ln T\right)$$

- Regularization of PR EoS requires algebraic solution of cubic equation $P_{\mathrm{PR}}(D,T) = P_{\mathrm{sat}}(T)$ for roots $D_{\mathrm{v}}(T) < D_{\mathrm{m}}(T) < D_{\mathrm{l}}(T)$
- Mass fraction of liquid

$$W_{\mathrm{l}}(D,T) = \frac{D - D_{\mathrm{v}}(T)}{D_{\mathrm{l}}(T) - D_{\mathrm{v}}(T)}$$

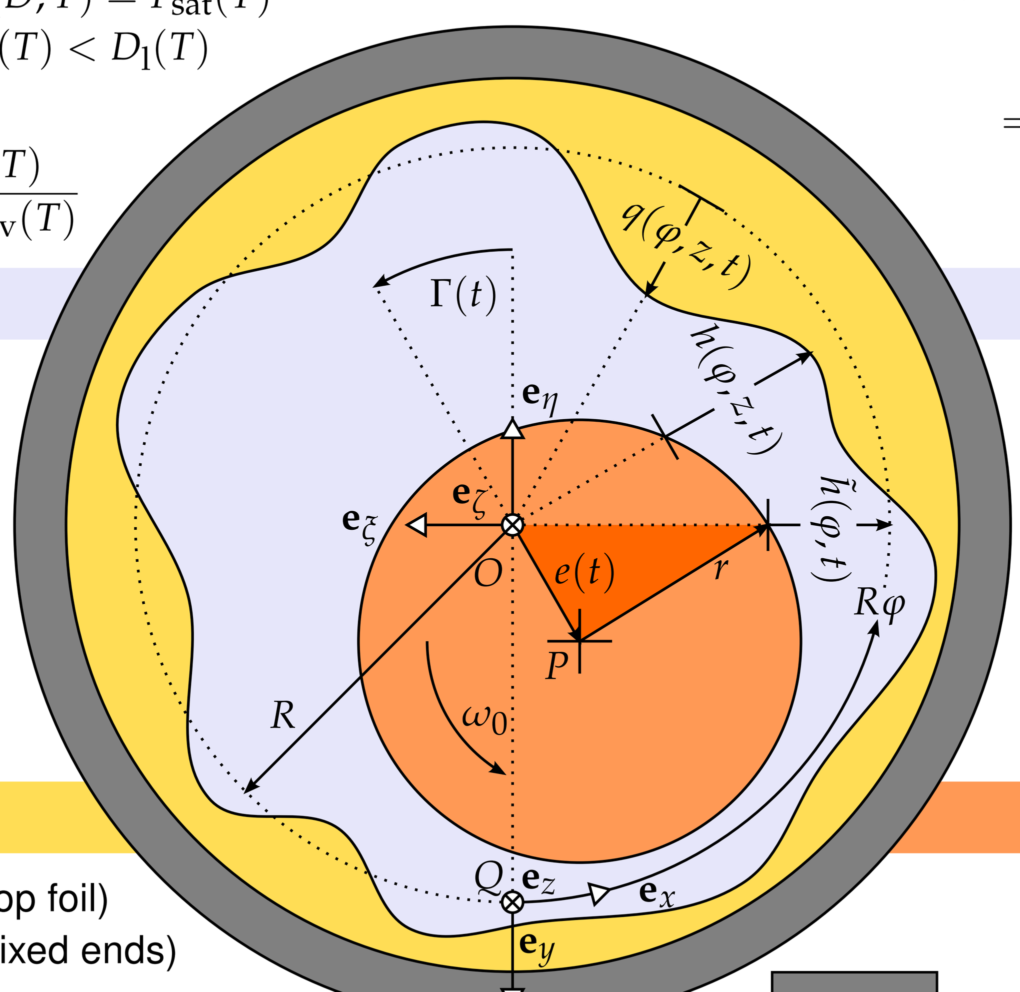
- Fluid film thickness

$$H = \underbrace{1}_{\text{Clearance}} \underbrace{- \varepsilon(\tau)\cos\left[\varphi - \gamma(\tau)\right]}_{\text{Rotor position}} \underbrace{- Q}_{\text{Structure deformation}}$$

- Reynolds equation for compressible fluids (density D, pressure P, viscosity V)

$$\underbrace{\frac{\partial D}{\partial \tau}H}_{\text{Fluid compression}} + D\Big\{\underbrace{-\varepsilon'(\tau)\cos\left[\varphi-\gamma(\tau)\right] - \varepsilon(\tau)\gamma'(\tau)\sin\left[\varphi-\gamma(\tau)\right]}_{\text{Rotor squeeze}} \underbrace{- \frac{\partial Q}{\partial \tau}}_{\text{Structure squeeze}}\Big\}$$

$$= \frac{1}{2}\Big\{\underbrace{\frac{\partial}{\partial\varphi}\left[\frac{DH^3}{V}\frac{\partial P}{\partial \varphi}\right] + \kappa^2\frac{\partial}{\partial Z}\left[\frac{DH^3}{V}\frac{\partial P}{\partial Z}\right]}_{\text{Poiseuille flow}} \underbrace{- \Lambda\frac{\partial}{\partial\varphi}\left[DH\right]}_{\text{Couette flow}}\Big\}$$

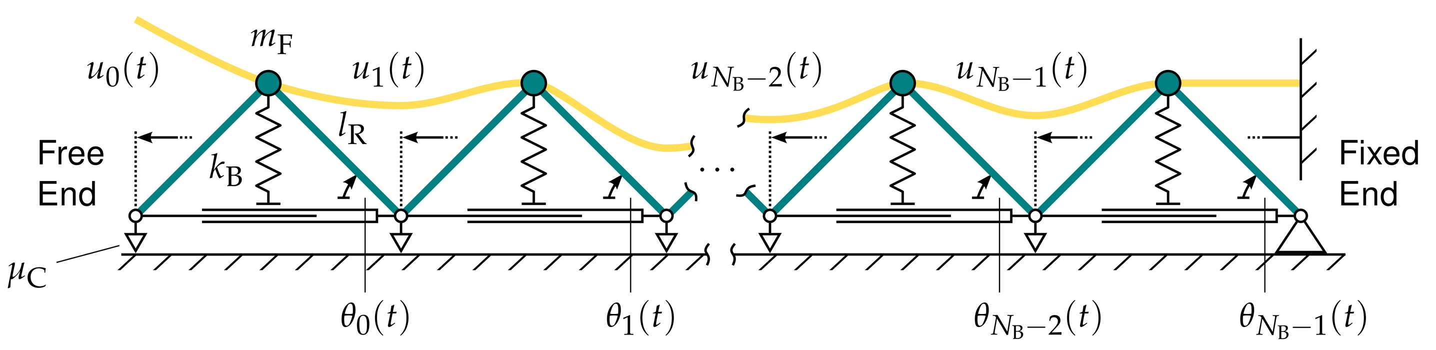


Fluid Dynamics $P(\varphi,Z,\tau)$ → **Structure Dynamics** $Q(\varphi,Z,\tau)$, $Q'(\varphi,Z,\tau)$

Rotor Dynamics $\varepsilon(\tau)$, $\varepsilon'(\tau)$, $\gamma(\tau)$, $\gamma'(\tau)$ → **Fluid Dynamics** $P(\varphi,Z,\tau)$

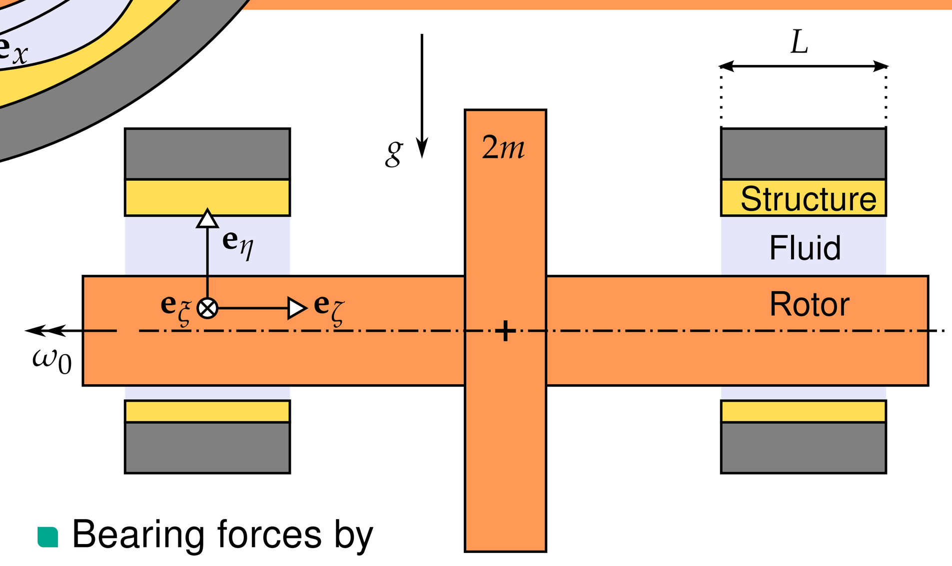
Structure Model

- Deformation field $Q(\varphi,Z,\tau)$ calculated with beam model (top foil) coupled to deflections of N_{B} bumps per foil strip (free and fixed ends)
- Axially averaged pressure load $\overline{P}(\varphi,\tau) = \int_{-0.5}^{+0.5} P(\varphi,Z,\tau)\,\mathrm{d}Z$



- Coulomb friction forces $f_n(\tau) = \mu_{\mathrm{C}}\left[f_{\perp,n}(\tau) + f_{\perp,\mathrm{preload}}\right]\operatorname{sgn} U_n'(\tau)$
- Continuous signum regularization $\operatorname{sgn} U_n'(\tau) \approx \tanh\left[\Xi U_n'(\tau)\right]$ with $\Xi \gg 1$

Rotor Model



- Symmetric horizontal rotor (rigid or elastic)
- Constant vertical load and static unbalance
- Rotational speed (bearing number)

$$\Lambda = \frac{6\mu_0\omega_0}{p_0}\left(\frac{R}{C}\right)^2$$

- Bearing forces by pressure integration

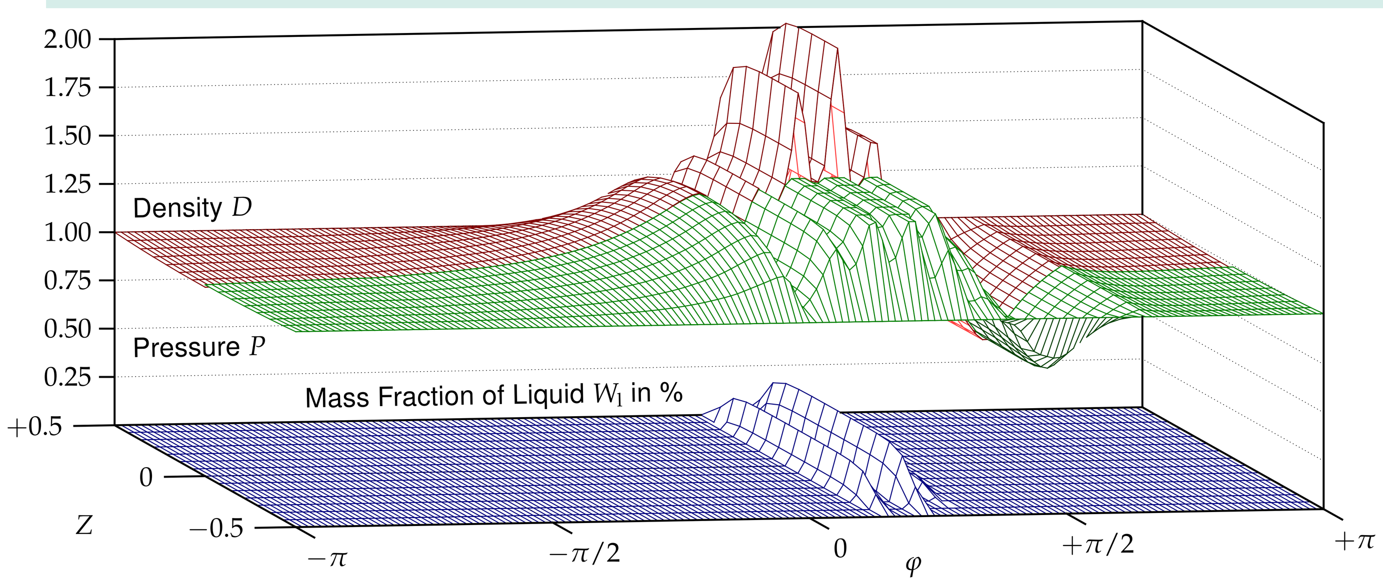
$$\mathbf{f}(\tau) = \begin{bmatrix} f_\xi(\tau) \\ f_\eta(\tau)\end{bmatrix}_{\{\mathbf{e}_\xi,\mathbf{e}_\eta\}} = \int_{-0.5}^{+0.5}\int_0^{2\pi} P(\varphi,Z,\tau)\begin{bmatrix}\sin\varphi \\ \cos\varphi\end{bmatrix}_{\{\mathbf{e}_\xi,\mathbf{e}_\eta\}}\mathrm{d}\varphi\,\mathrm{d}Z$$

Computational Analysis

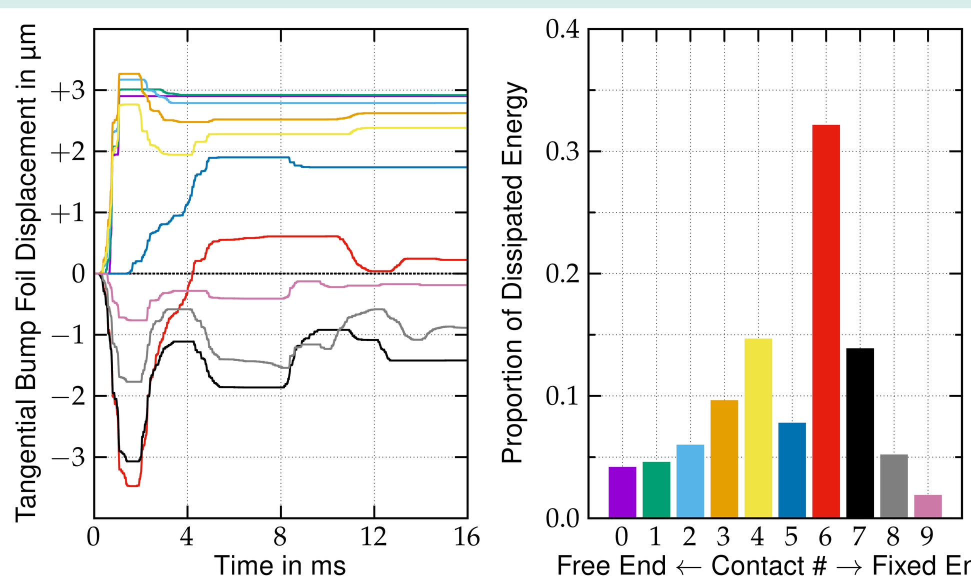
- Finite difference discretization on computational grid $N_\varphi \times N_Z = 469 \times 15$
- Simultaneous subproblem solution by means of collective state vector
- Nonlinear ODE system $\mathbf{s}'(\tau) = \mathbf{k}\left\{\mathbf{s}(\tau),\Lambda\right\}$ with $\mathbf{k}\colon \mathbb{R}^n \times \mathbb{R} \to \mathbb{R}^n$

$$\mathbf{s}(\tau) = \left[\, D_{1,1}(\tau)\ \cdots\ D_{N_\varphi-2,N_Z-2}(\tau)\ \ \Theta_0(\tau)\ \Theta_0'(\tau)\ \cdots\ \Theta_{N_{\mathrm{B}}-1}(\tau)\ \Theta_{N_{\mathrm{B}}-1}'(\tau)\ \ \varepsilon(\tau)\ \varepsilon'(\tau)\ \gamma(\tau)\ \gamma'(\tau)\,\right]^\top \in \mathbb{R}^n$$

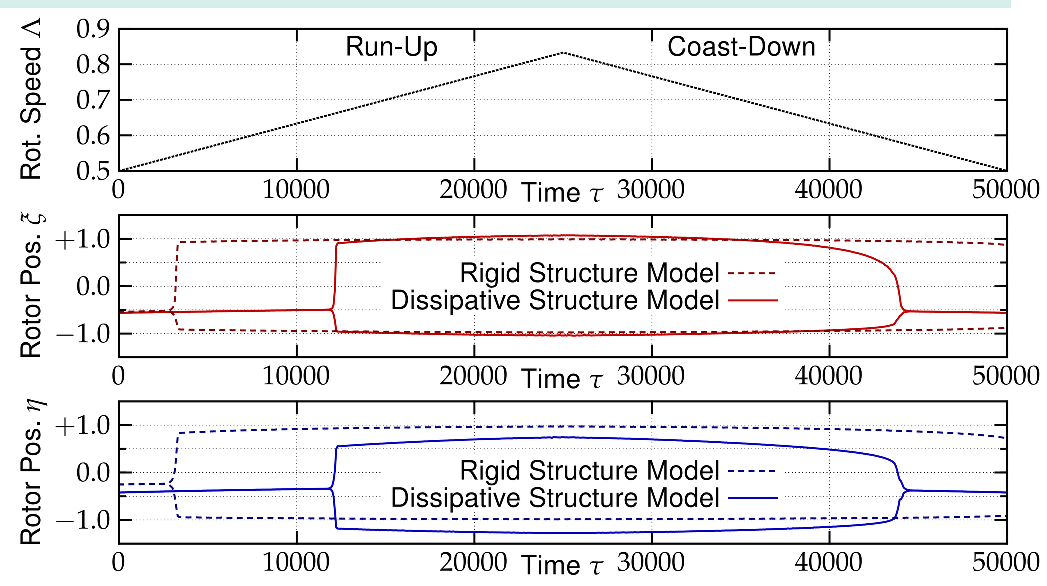
Results and Conclusions



1 Fluid pressure build-up limited by local vapor–liquid phase transitions



2 Important effect of bump–bump interaction mechanisms



3 Undesirable self-excitation vibrations reduced by friction