Karlsruhe Institute of Technology

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

ENSA Marrakech

Université franco-allemande Deutsch-Französische Hochschule

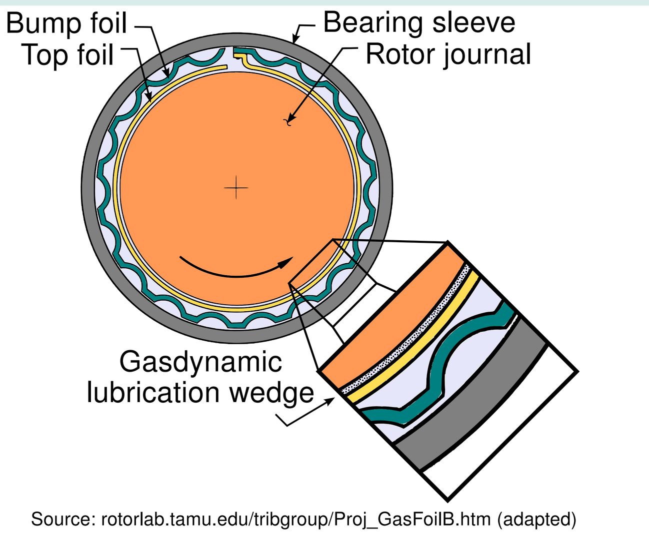
German-French-Moroccan Summer School 2018
TRIBOLOGY TODAY – From Research Labs to Industry

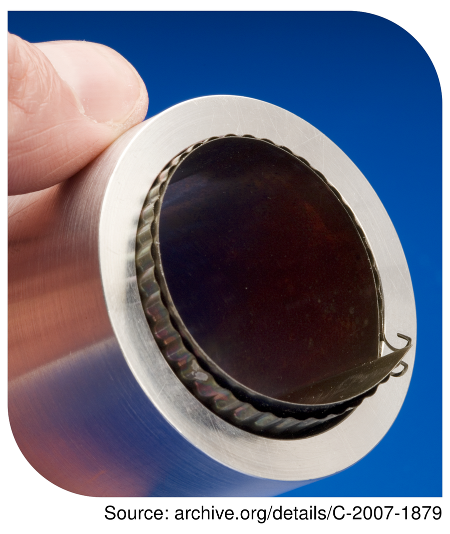
Marrakesh, Morocco
April 8–14, 2018

Modeling and Simulation of Refrigerant-Lubricated Gas Foil Bearings

Tim Leister, Wolfgang Seemann, Benyebka Bou-Saïd

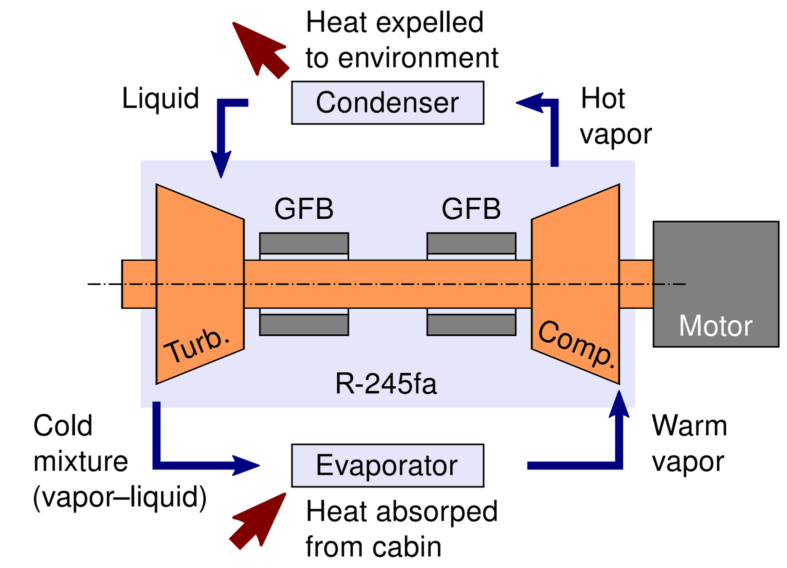
Self-Acting Gas Foil Bearings (GFBs)





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

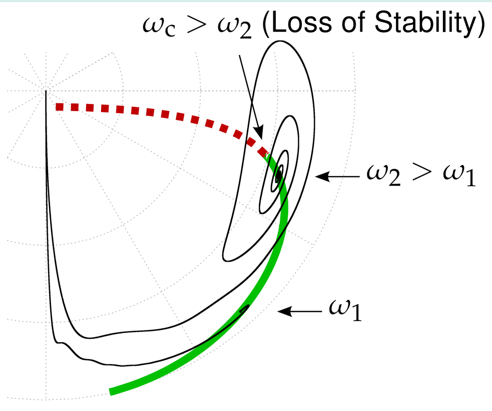
Application: Vapor-Compression Refrigeration



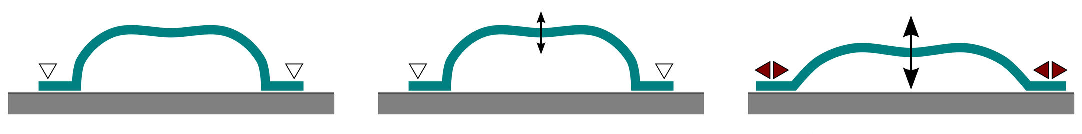
- System optimized by using refrigerant as lubricating fluid

Challenge: Self-Excited Vibrations

- Stationary operating points tend to become unstable at elevated rotational speeds
- Occurrence of self-excited rotor vibrations with large amplitudes (fluid whirl)

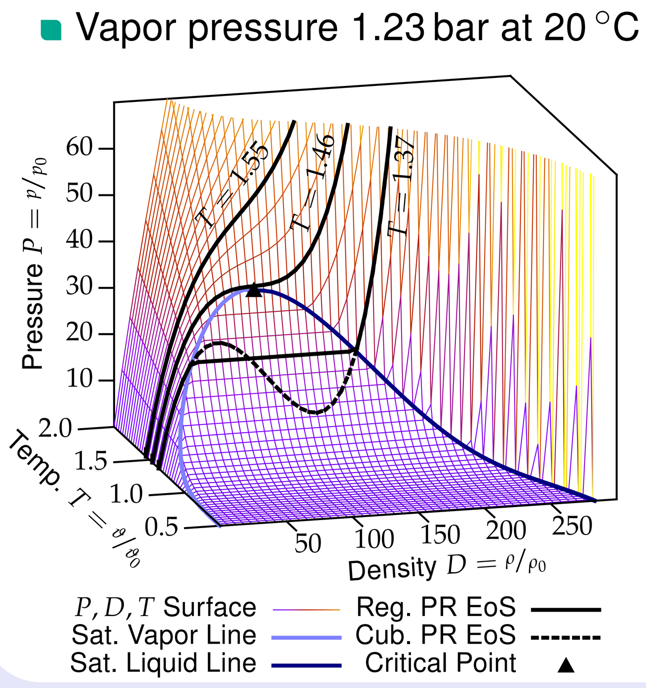


- Vibrations calmed down by deliberately introduced friction?



Fluid Model for Non-Ideal Gases

- Refrigerant R-245fa (1,1,1,3,3-pentafluoropropane)
- Vapor pressure 1.23 bar at 20 °C



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

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

- 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 by algebraic solution of cubic equation $P_{\mathrm{PR}}(D,T) = P_{\mathrm{sat}}(T)$ with roots $D_v(T) < D_m(T) < D_l(T)$
- Mass fraction of liquid

$$W_l(D,T) = \frac{D - D_v(T)}{D_l(T) - D_v(T)}$$

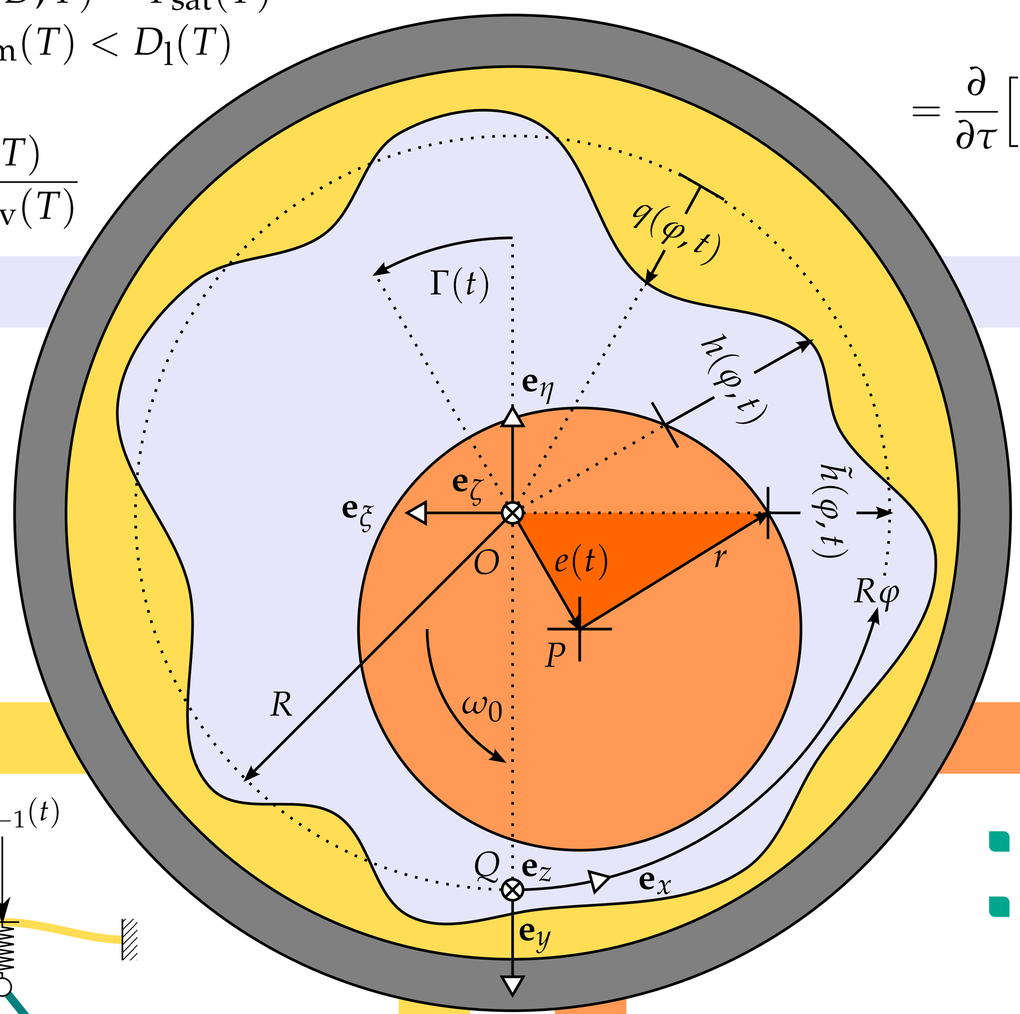
- Fluid film thickness

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

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

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

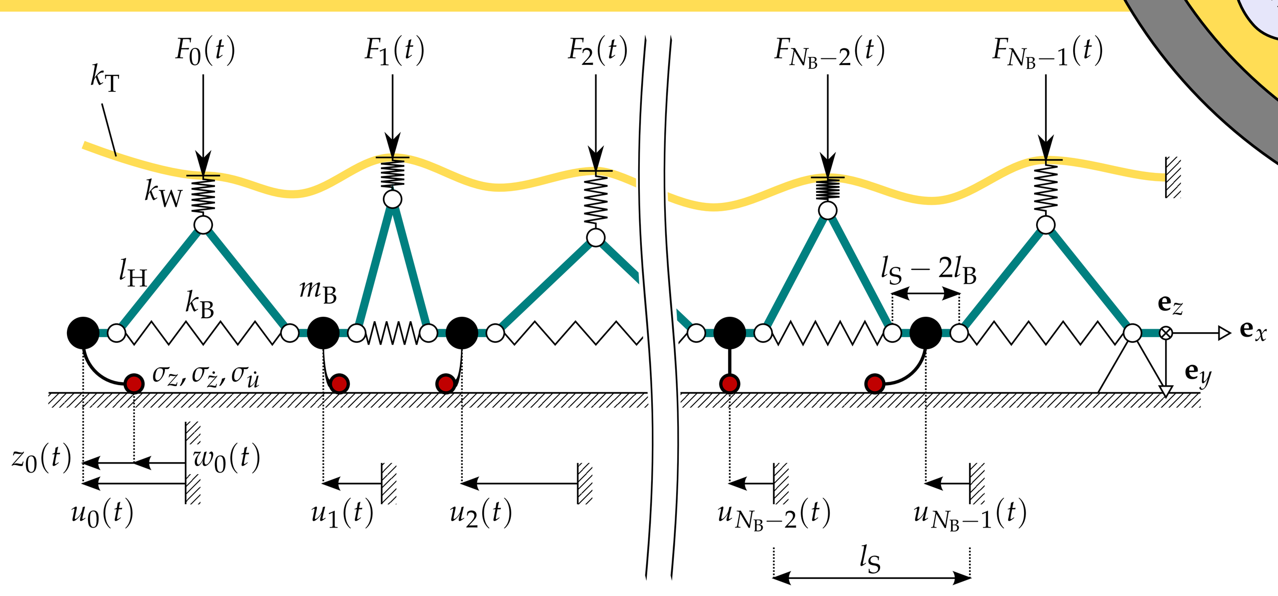
$$= \frac{\partial}{\partial \tau}\left[DH\right] = \frac{1}{2}\left\{\underbrace{\frac{\partial}{\partial \varphi}\left[\frac{DH^3}{V}\frac{\partial P}{\partial \varphi}\right] + \kappa^2 \frac{\partial}{\partial Z}\left[\frac{DH^3}{V}\frac{\partial P}{\partial Z}\right]}_{\text{Poiseuille flow}} \underbrace{-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



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

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

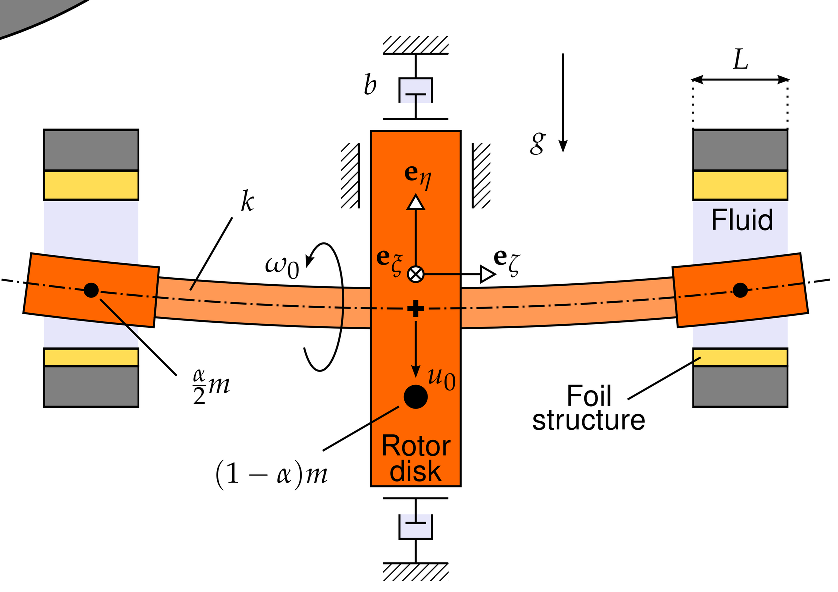
Foil Structure Friction Model



- Triangular spring–mass–rod arrangement with superposed elastic beam model
- Elasto-plastic bristle friction $Z_n'(\tau) = U_n'(\tau) - \alpha_n(\tau)\beta_n(\tau)\left|U_n'(\tau)\right|\dfrac{\sigma_Z Z_n(\tau)}{\mu_n(\tau) f_{\perp,n}(\tau)}$

Jeffcott–Laval Rotor Model

- Elastic horizontal rotor symmetrically mounted on two GFBs
- Small proportion $\alpha/2$ of total mass shifted to each journal



- Constant vertical load and unbalanced disk
- Rotational speed (bearing number)

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

- Coordinate transformation

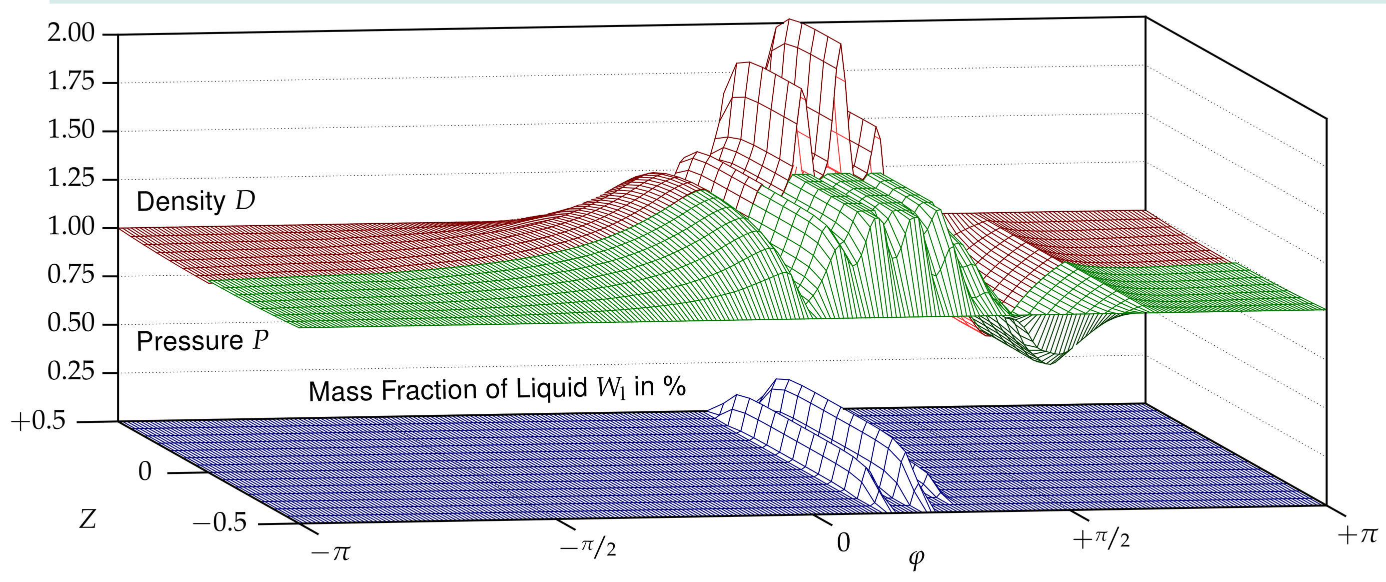
$$\varepsilon(\tau) = \sqrt{X(\tau)^2 + Y(\tau)^2}$$
$$\gamma(\tau) = \operatorname{atan2}\{-X(\tau), -Y(\tau)\}$$

Computational Analysis

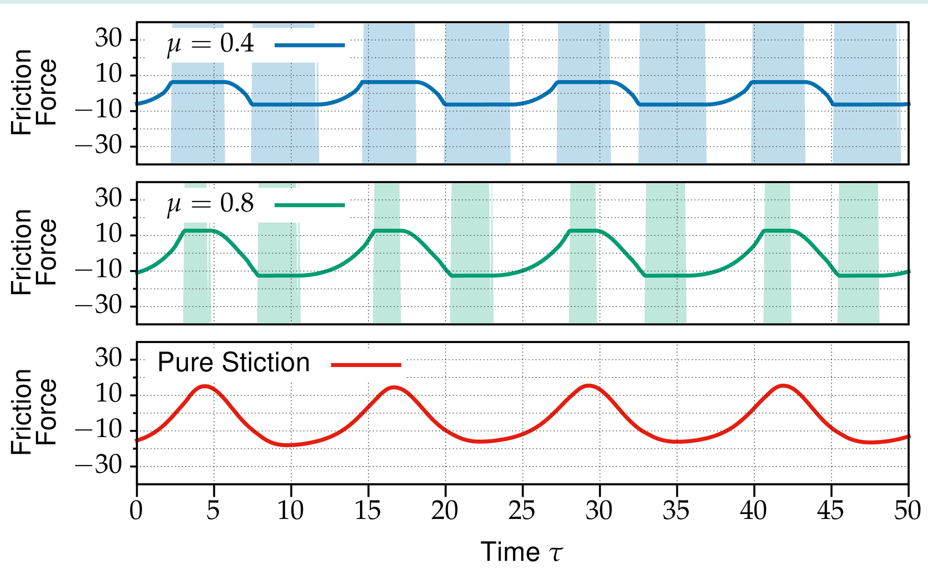
- Finite difference discretization on computational grid $N_\varphi \times N_Z = 469 \times 15$
- Simultaneous subproblem solution by means of collective state vector
- Nonlinear ODE system $\mathbf{s}'(\tau) = \mathbf{k}\{\mathbf{s}(\tau), \Lambda\}$ with $\mathbf{k}\colon \mathbb{R}^n \times \mathbb{R}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

$$\mathbf{s}(\tau) = \left[\;\cdots D_{i,j}(\tau)\cdots \;\middle|\; \cdots U_n(\tau)\; U_n'(\tau)\; Z_n(\tau)\cdots \;\middle|\; X(\tau)\; X'(\tau)\cdots X_D(\tau)\; X_D'(\tau)\cdots\;\right]^\top \in \mathbb{R}^n$$

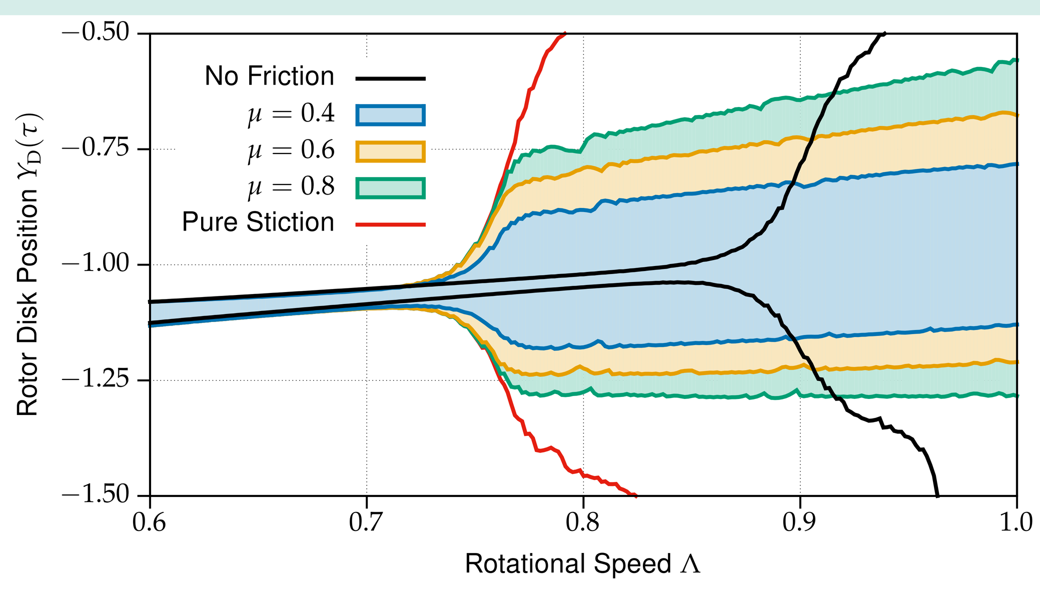
Results and Conclusions



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



2 Characteristic stick–slip transitions in the contacts



3 Vibrations calmed down by deliberately introduced friction