Gas Foil Bearing for Small Scale Turbomachinery

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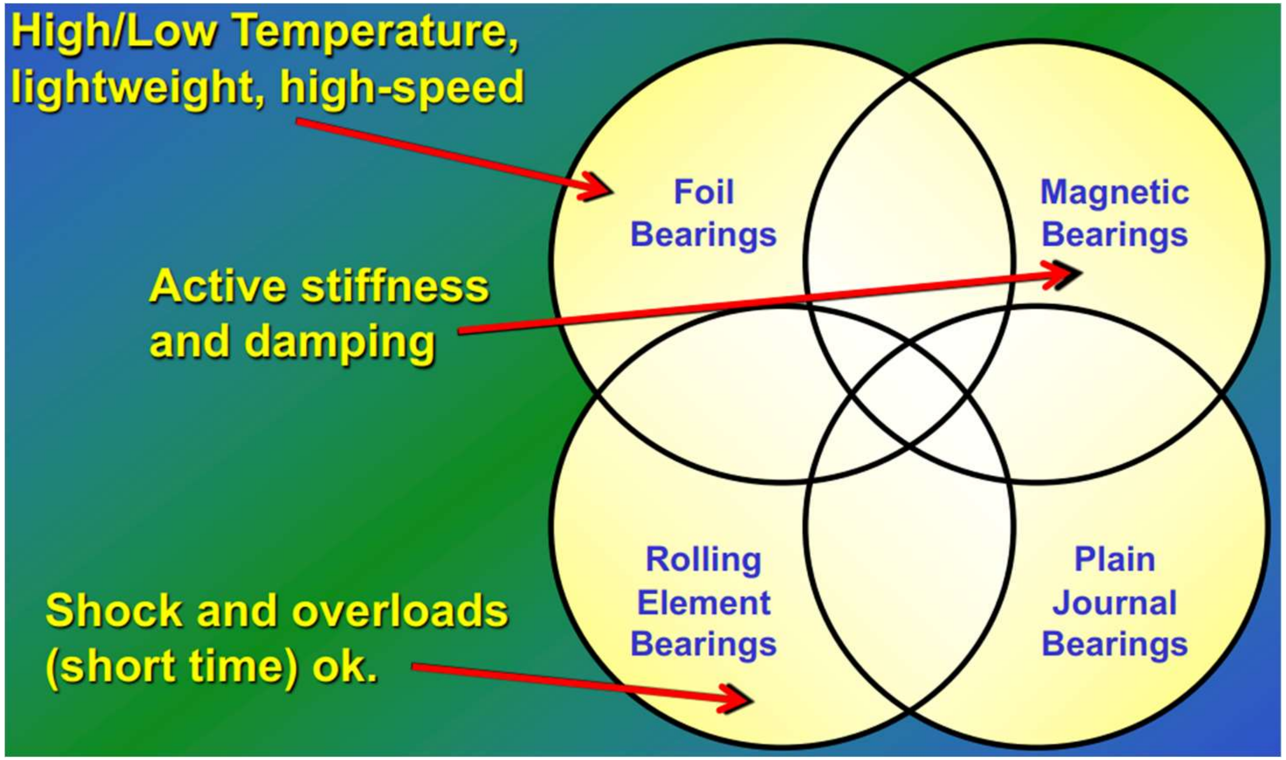
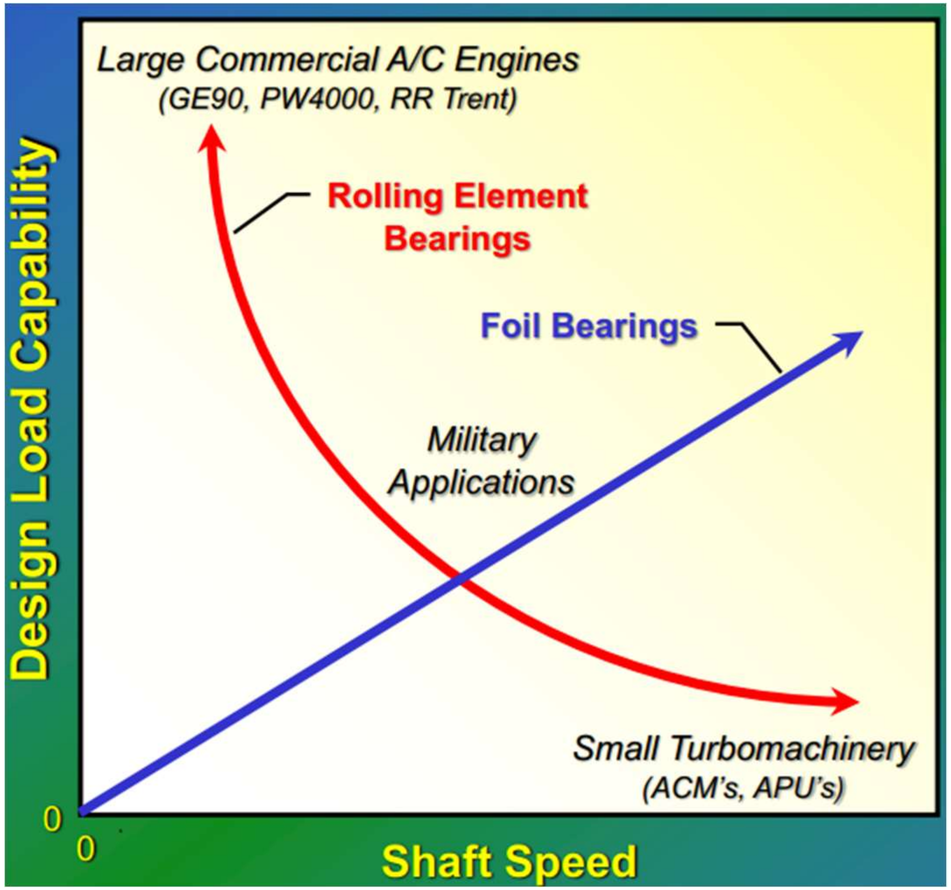
Fit4Micro workshop, 25th September 2024- Aachen

Background

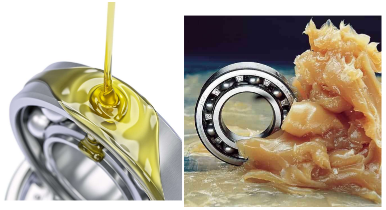


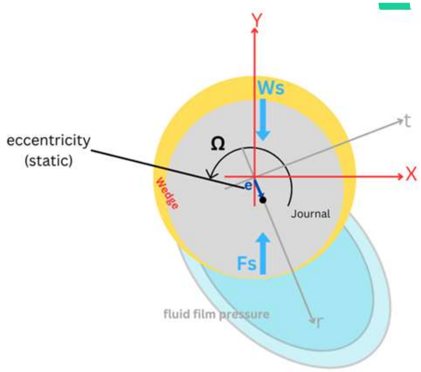


[1] Dellacorte C. Oil-free enabling technology: Gas Foil Bearings (2018,Jan 25th) Schaeffler, A.G., Schweinfurt, Germany. https://ntrs.nasa.gov/api/citations/20180004646/downloads/20180004646.pdf

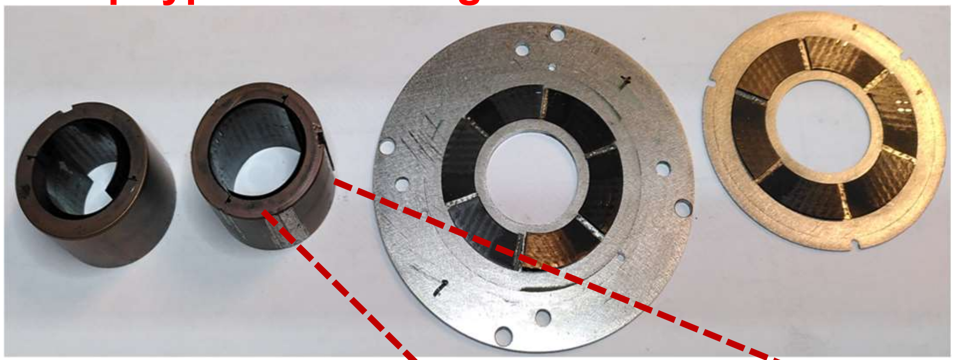
Foil Bearings: Benefits

- Self-lubricating (no external pressurization needed)
- No oil needed
- No maintenance (Reduced operating cost)
- Light-weight
- Misalignment friendly :]
- No restriction of DN number

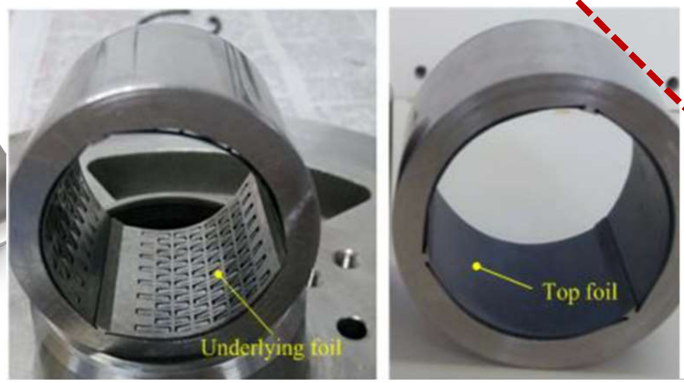


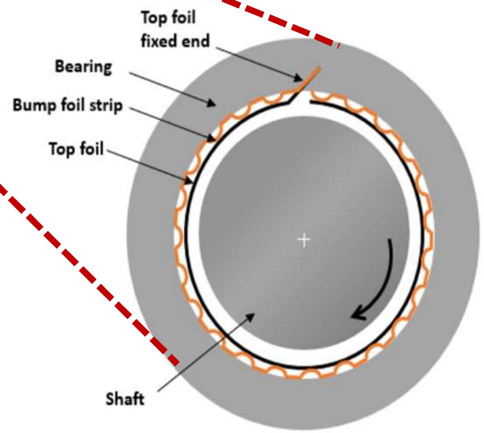


Bump type foil bearings



Cantilever foil bearings



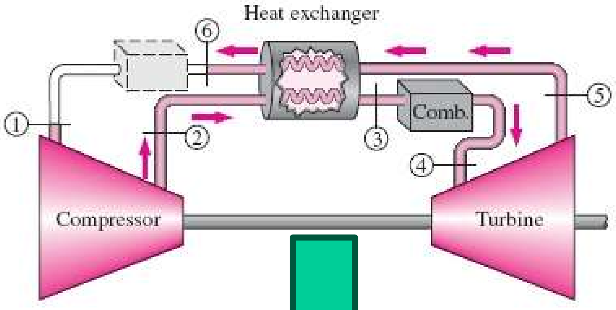


Source: Bosch mobility

Design: Microturbine perspective

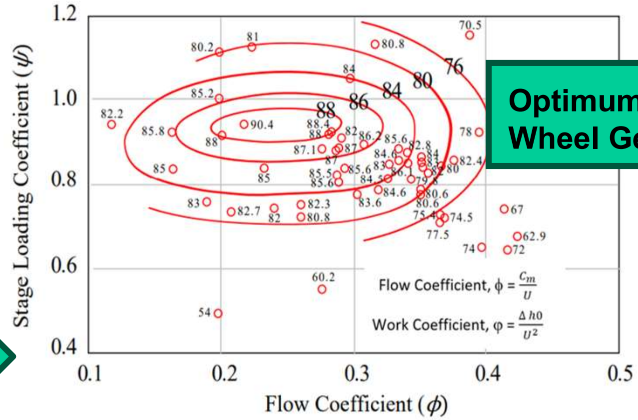
Preliminary sizing

Cycle Analysis



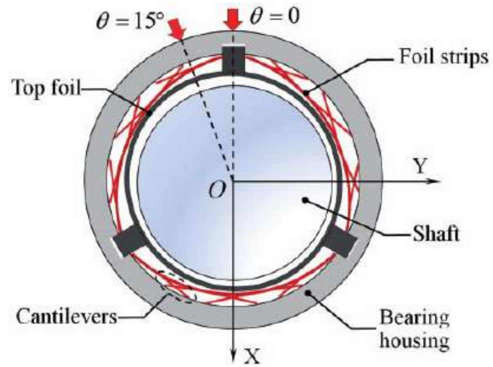
Mass flow & PR

Baines Chart [Psi-Phi]



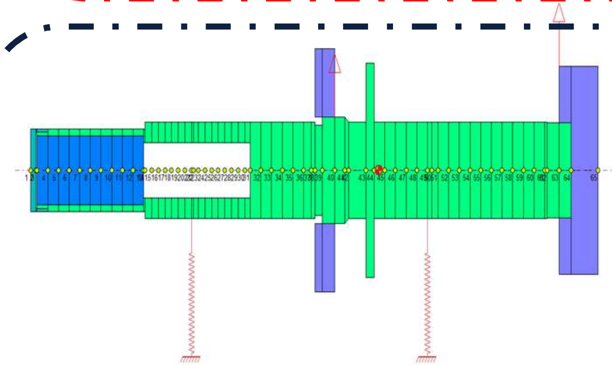
Optimum Speed, Wheel Geometry

Preliminary Bearing Design [DN=3M—3.5M]

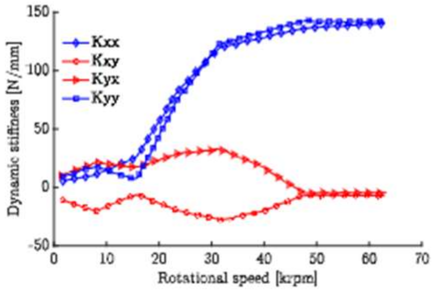


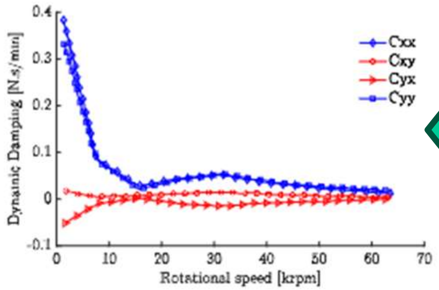
Shaft Diameter

Detailed Analysis



Rotordynamic Analysis





Static & Dynamic Stiffness & Damping

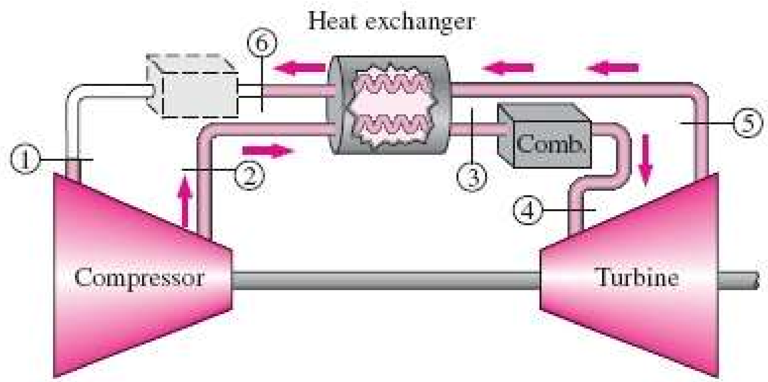
Step-1: Cycle Analysis

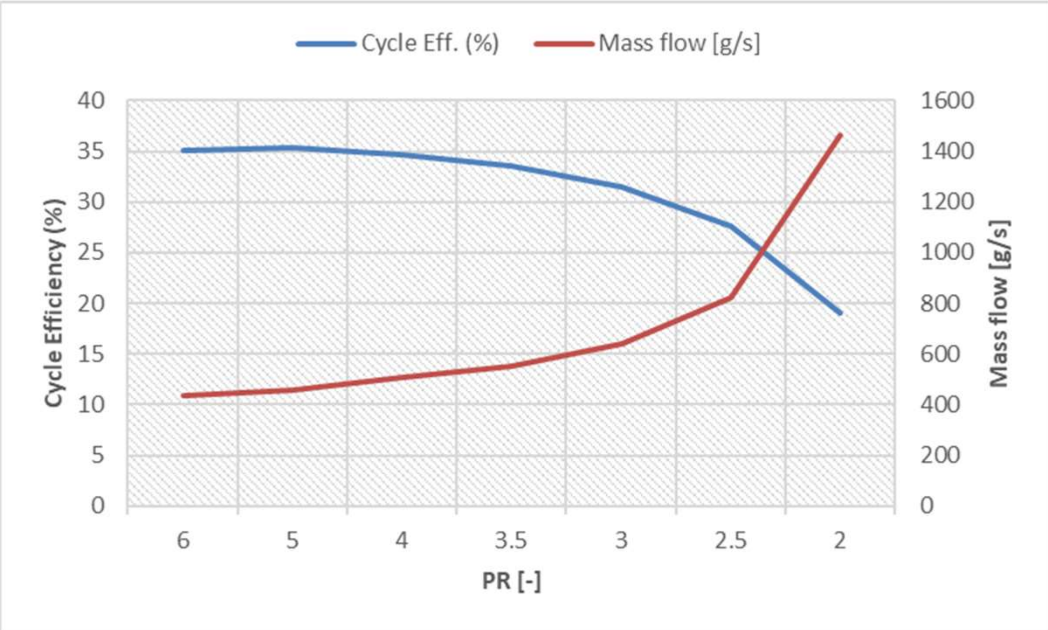
- Cycle Assumptions (**65kW electric power**)

$\eta_c = 75\%$, $\eta_t = 85\%$, $\varepsilon_{hex} = 85\%$

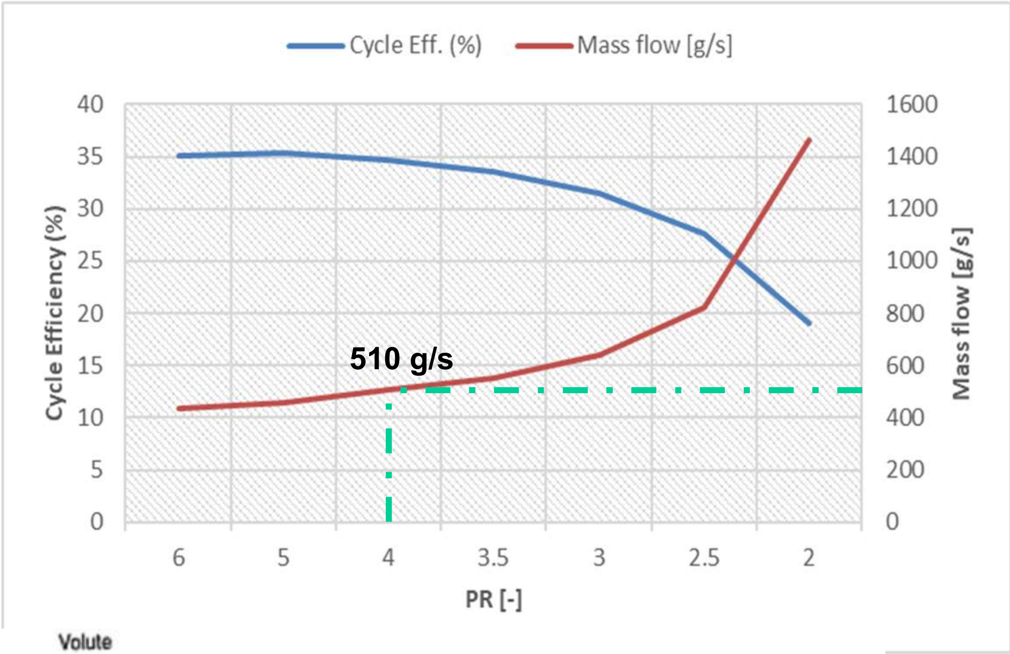
$Q_{el} = 65kW$, $\frac{Q_{loss}}{Q_{el}} = 2\%$, $TIT = 920°C$

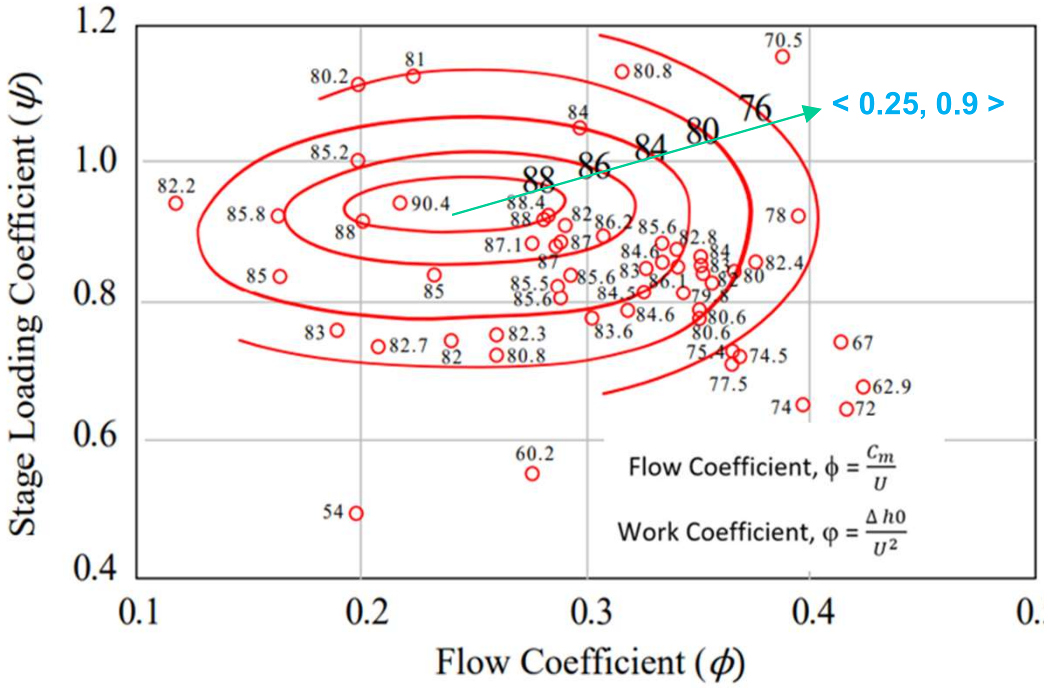
$\frac{\Delta P_{2-3}}{P_2} = 2\%$, $\frac{\Delta P_{3-4}}{P_3} = 2\%$, $\frac{\Delta P_{5-6}}{P_5} = 4\%$

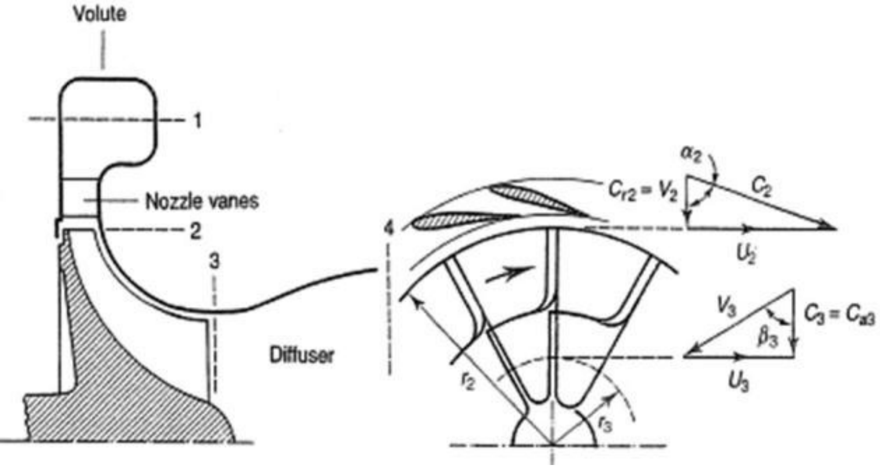




Steps-2,3: Shaft Speed & Bearing Diameter





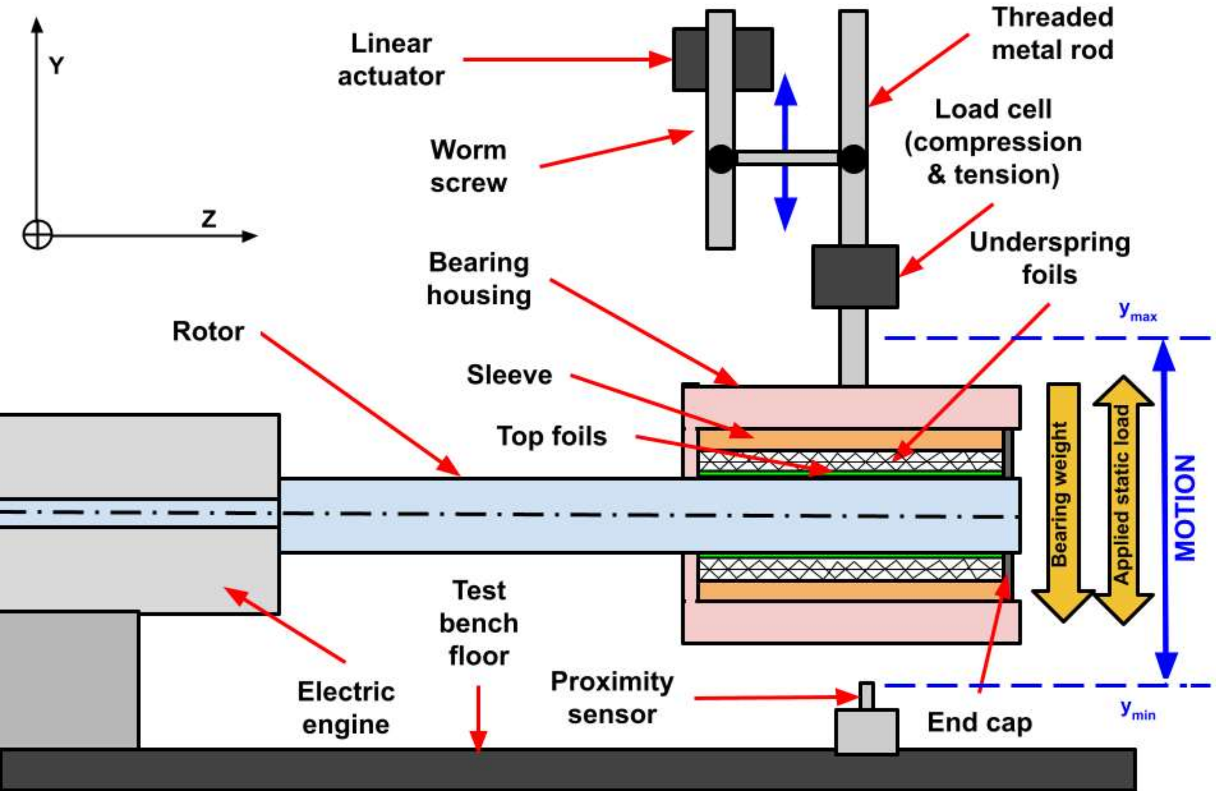


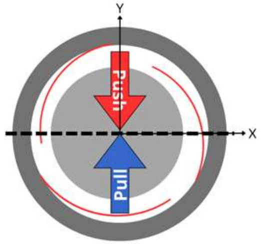
- Dia = 125 mm
- Tip height = 12 mm
- RPM = 96000

ψ=0.21 & φ=0.91

DN = 3M—3.5M
Dia = 31mm—36mm

Step-4: Static/Dynamic Stiffness & Damping



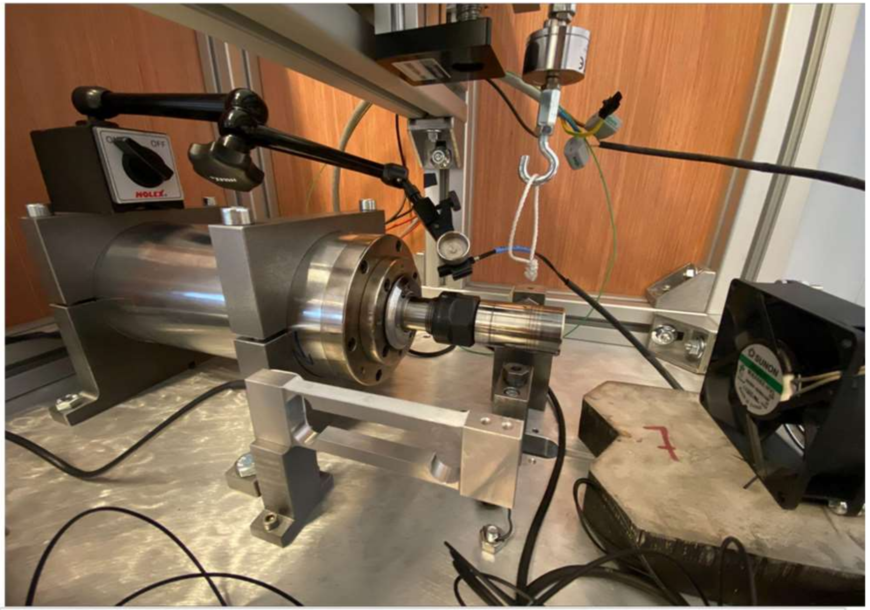


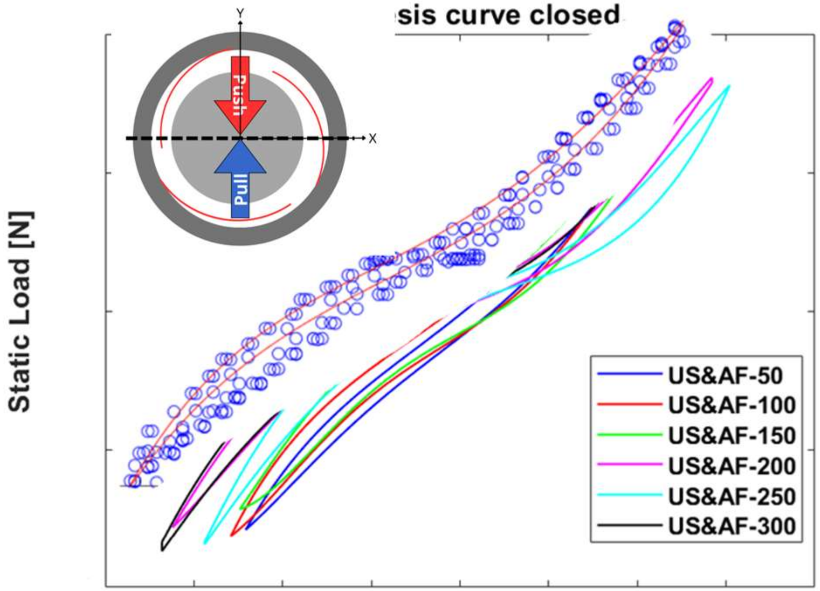
- Rotation speed 0 rpm
- Loading range ≃ -80N → +80N
- 1 cycle = loading phase (-80N → +80N) + unloading phase (+80N → -80N)
- At least 3 cycles for repeatability
- Tested specimen: Different sleeves & combinations of AF & US

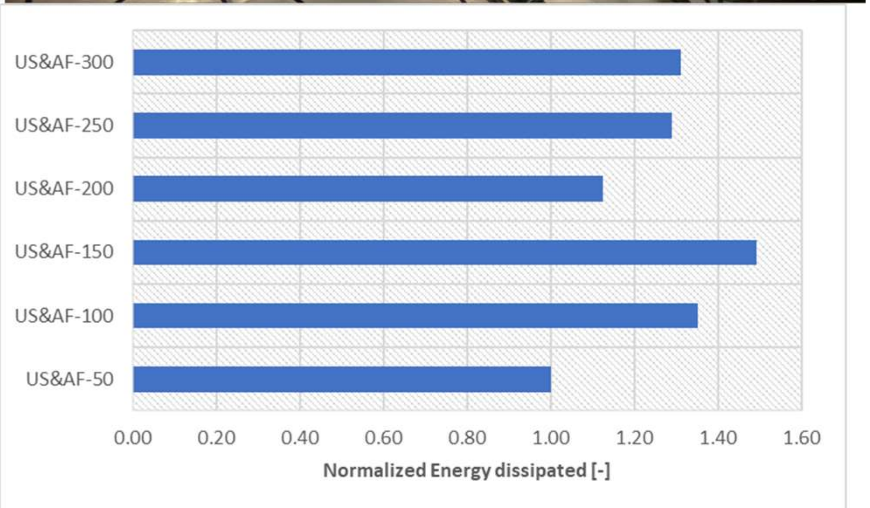
Load cell limit = +/-100N

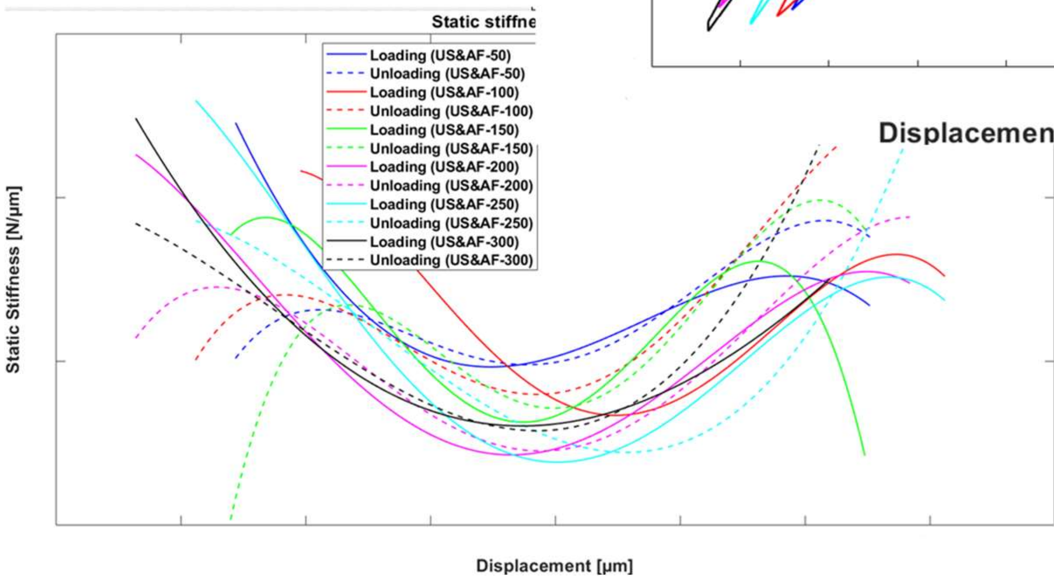
* Marcel Mahner, Marcel Bauer, Andreas Lehn, Bernhard Schweizer. (2019). *An experimental investigation on the influence of an assembly preload on the hysteresis, the drag torque, the lift-off speed and the thermal behavior of three-pad air foil journal bearings*. Tribology Int., 137, https://doi.org/10.1016/j.triboint.2019.02.026.

Step-4: Static Stiffness & Damping

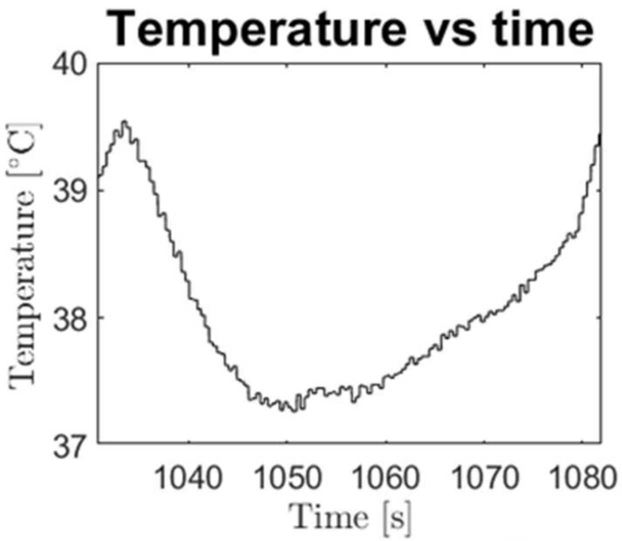


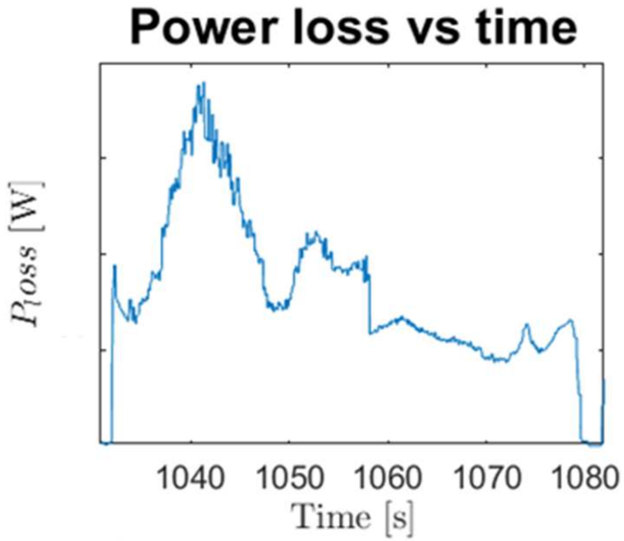


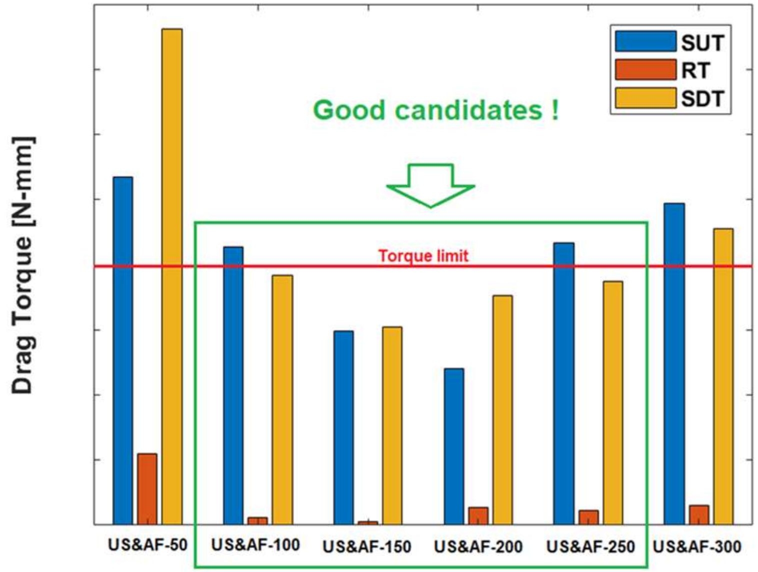


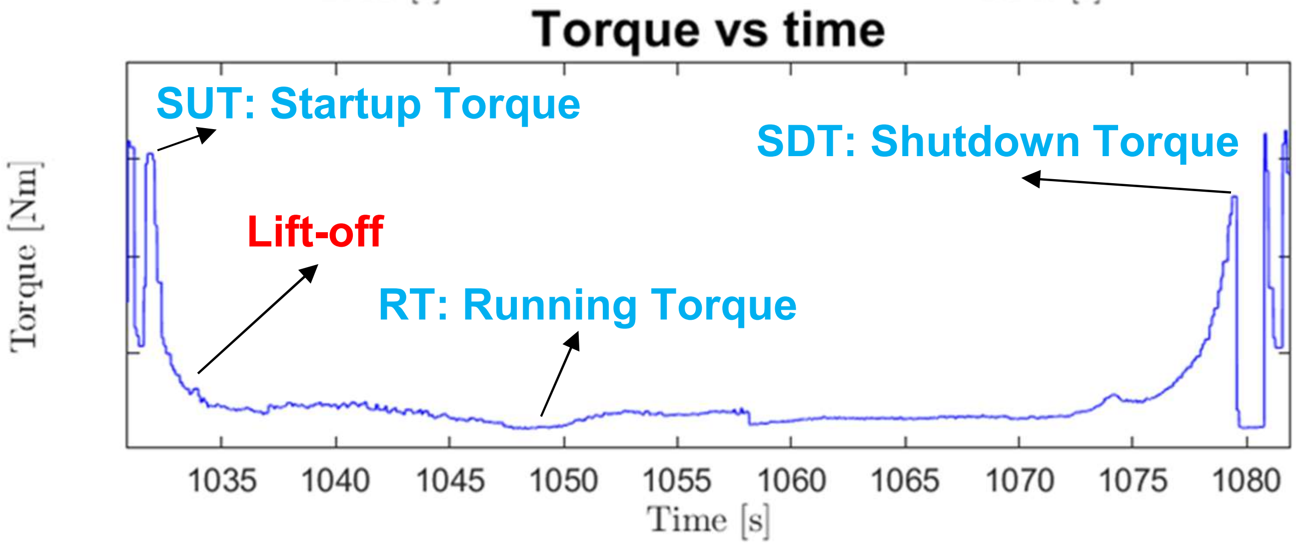


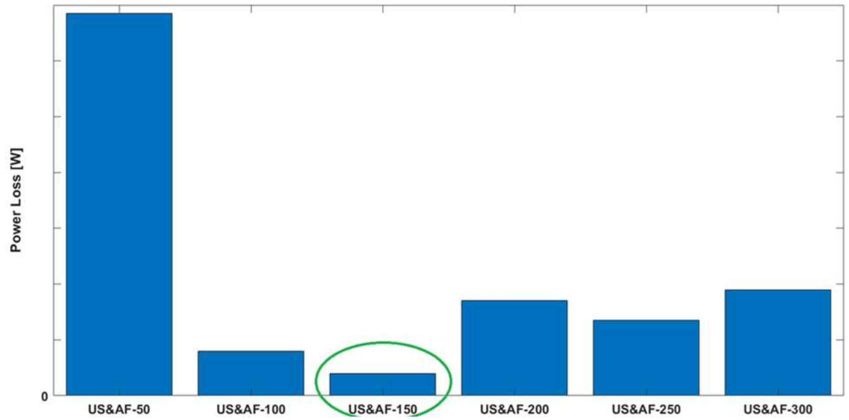
Step4: Lift off & Power Loss









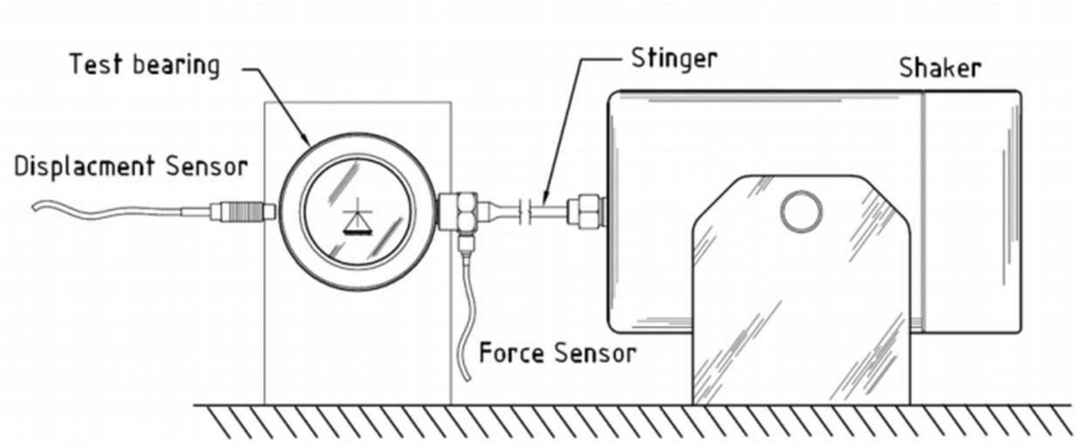


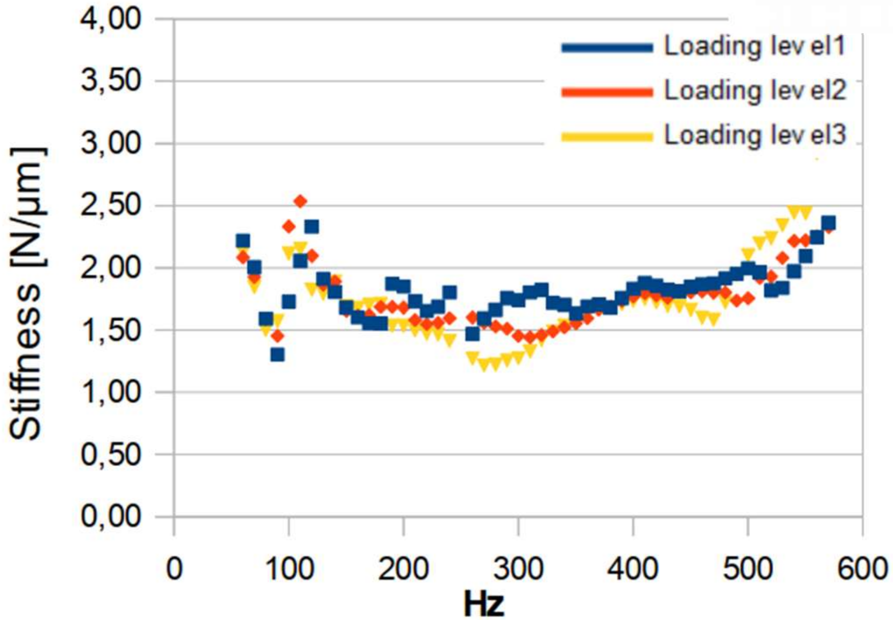
Step-4: Dynamic Stiffness & Damping [Exp.]

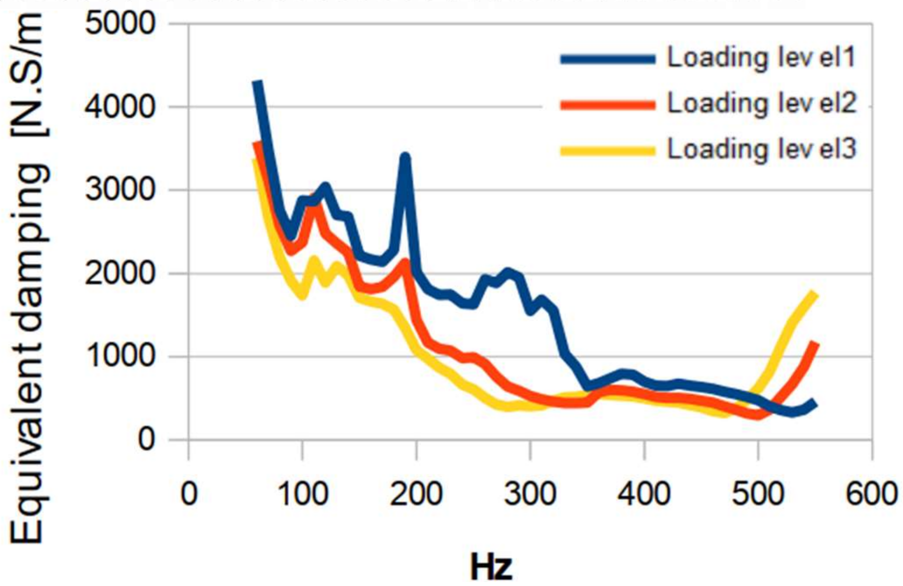
$$\left(K+i\,\omega C_{eq}-M\,\omega^2\right)=\frac{F}{X}$$

$$K=\mathrm{Re}\left(\frac{F}{X}\right)+M\,\omega^2$$

$$C_{eq}=\mathrm{Im}\left(\frac{F}{X}\right)/\omega$$





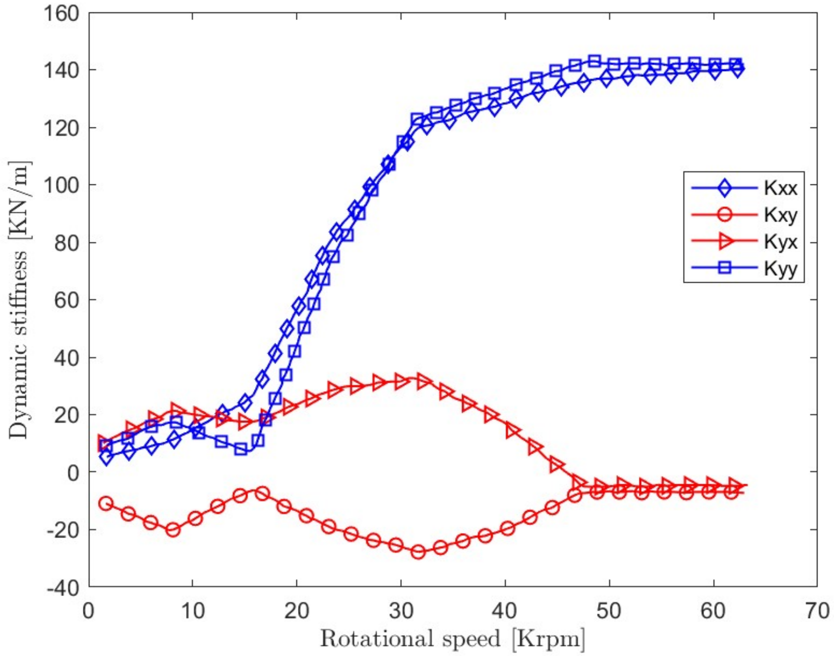


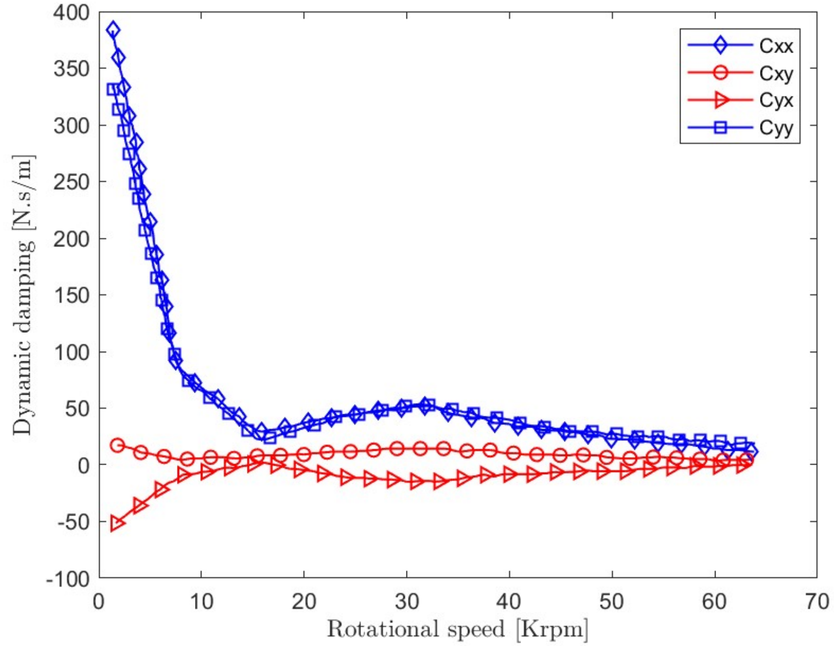
N. Prechavut and H. P. Berg, “An experimental study on structural characteristics of cantilever-type foil bearings,” 2015, Deutscher Luft- und Raumfahrtkongress 2015, DocumentID: 370040.

Step-4: Dynamic Stiffness & Damping [Num.]

- Coupled fluid-structural calculations

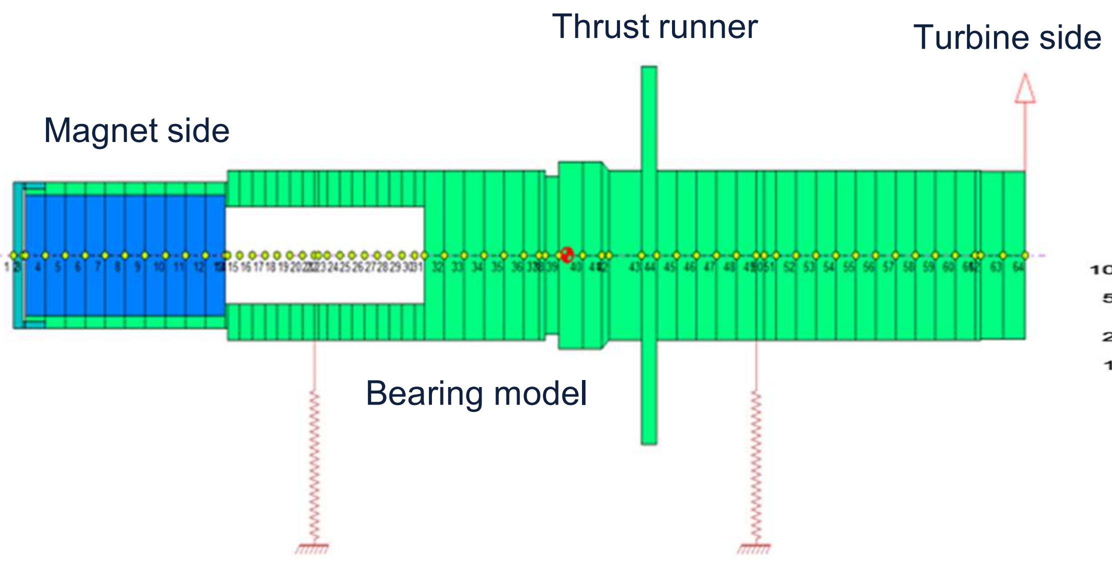
  - Reynold's equation coupled with spring/beam elements

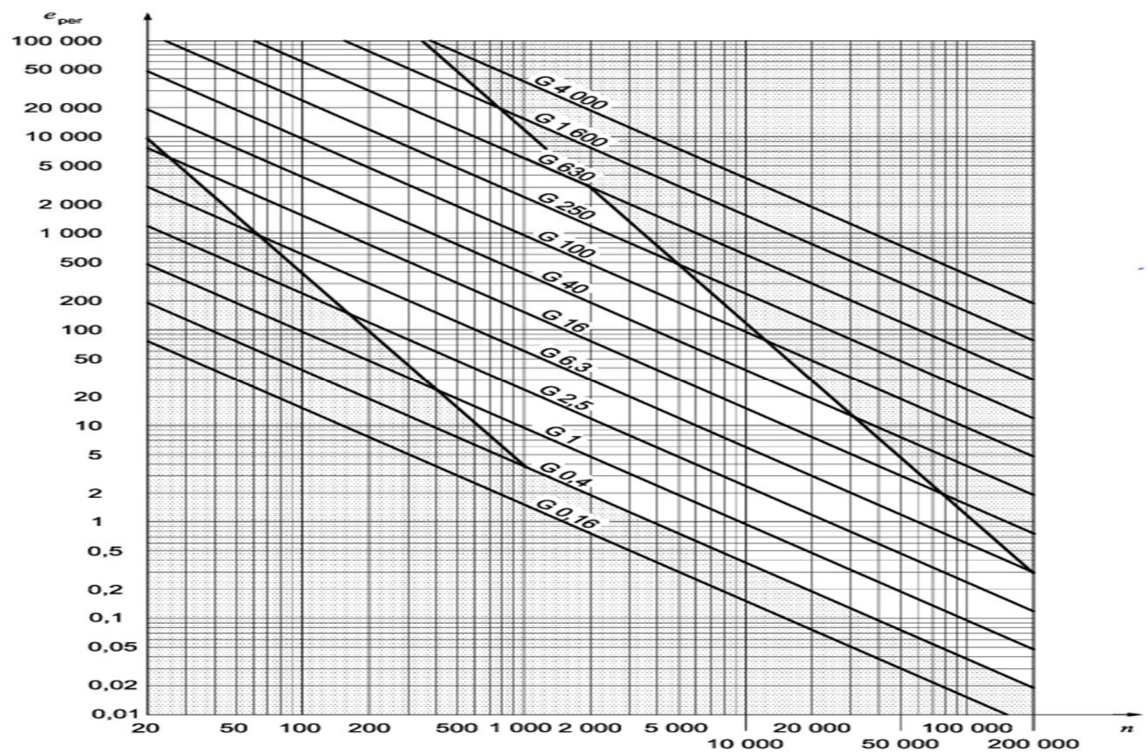




Cheng et al. 'Rotor Dynamic Experimental Investigation of an Ultra-High-Speed Permanent Magnet Synchronous Motor Supported on a Three-Pad Bidirectional Gas Foil Bearing'. https://doi.org/10.1177/1687814019875368

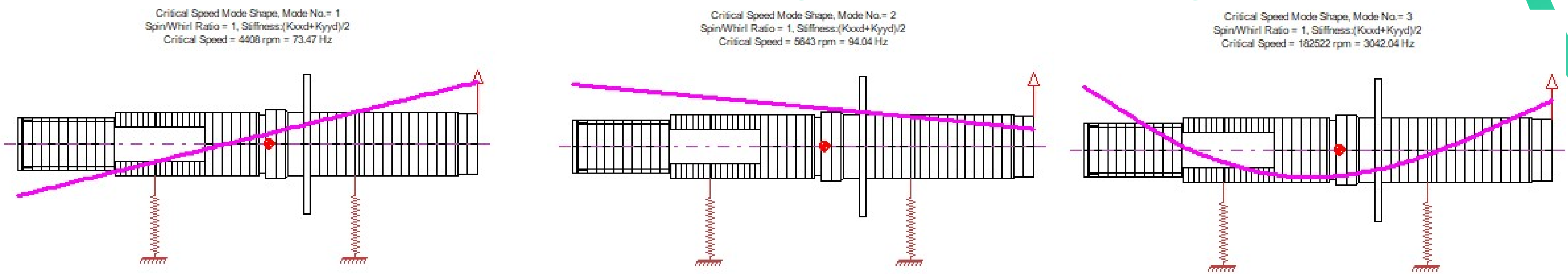
Step- 5: Rotordynamic analysis

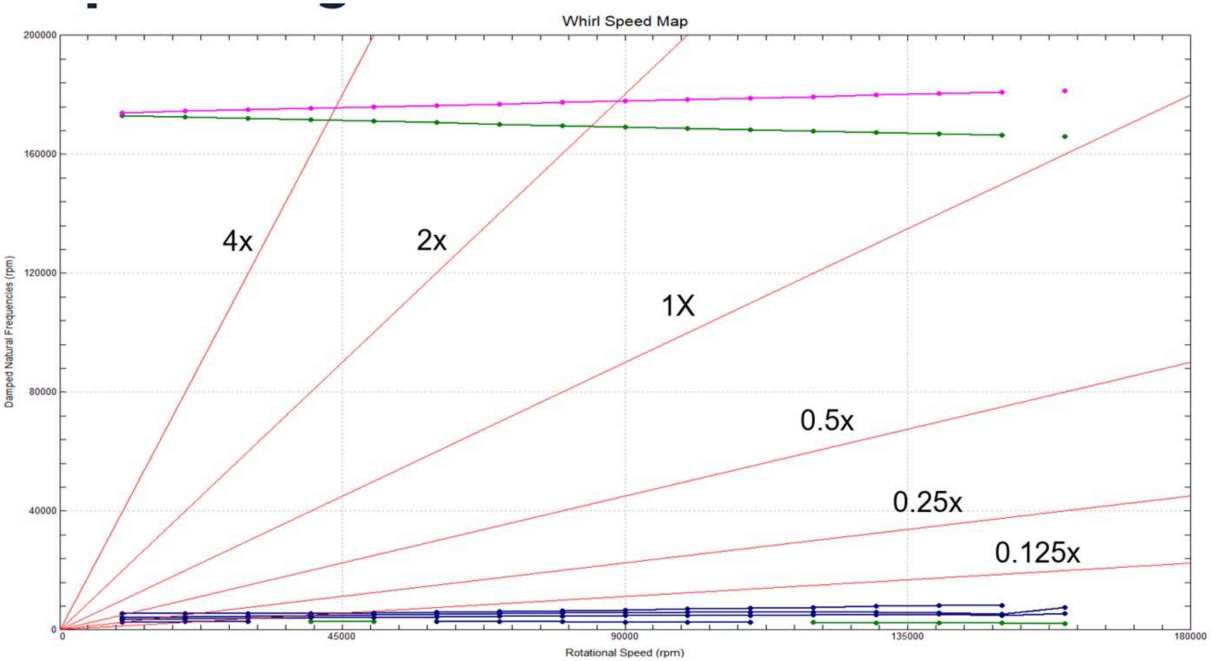


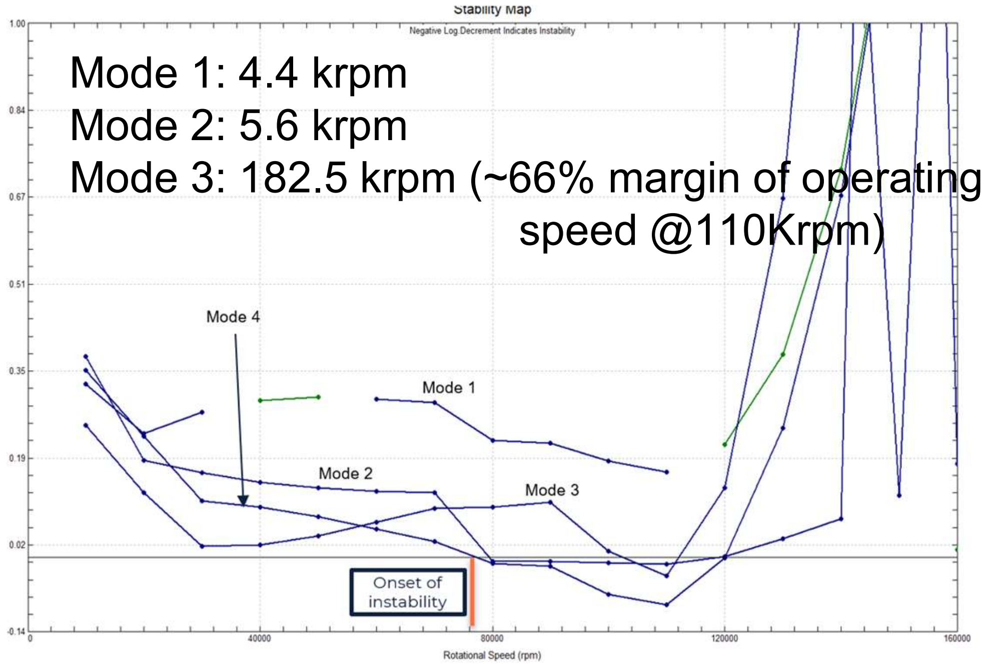


- The turbo bar has a mass. Length and inertia to mimic the real turbomachine.
- The unbalance magnitude is taken as 4*e_{per} @110000rpm from G6.3 ISO21840-11:2016 norm.
- Soft bearing model are used.

Step- 5: Rotordynamic analysis

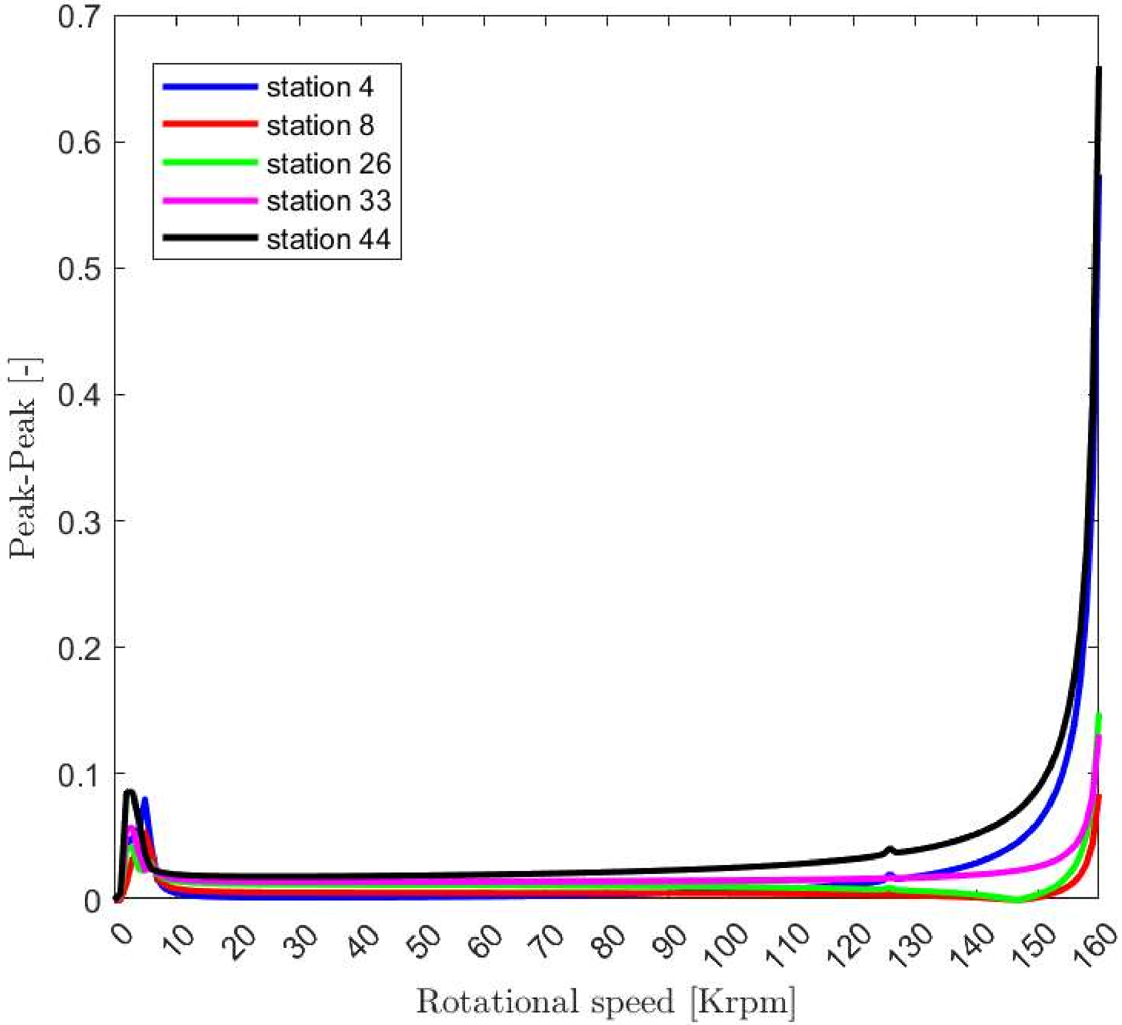


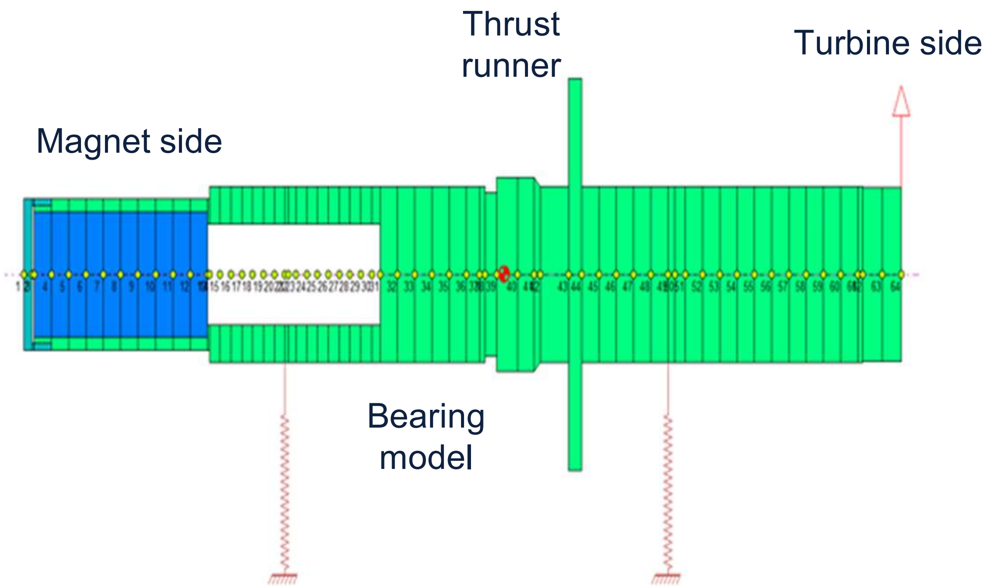




Instability expected from 76 to 120 Krpm

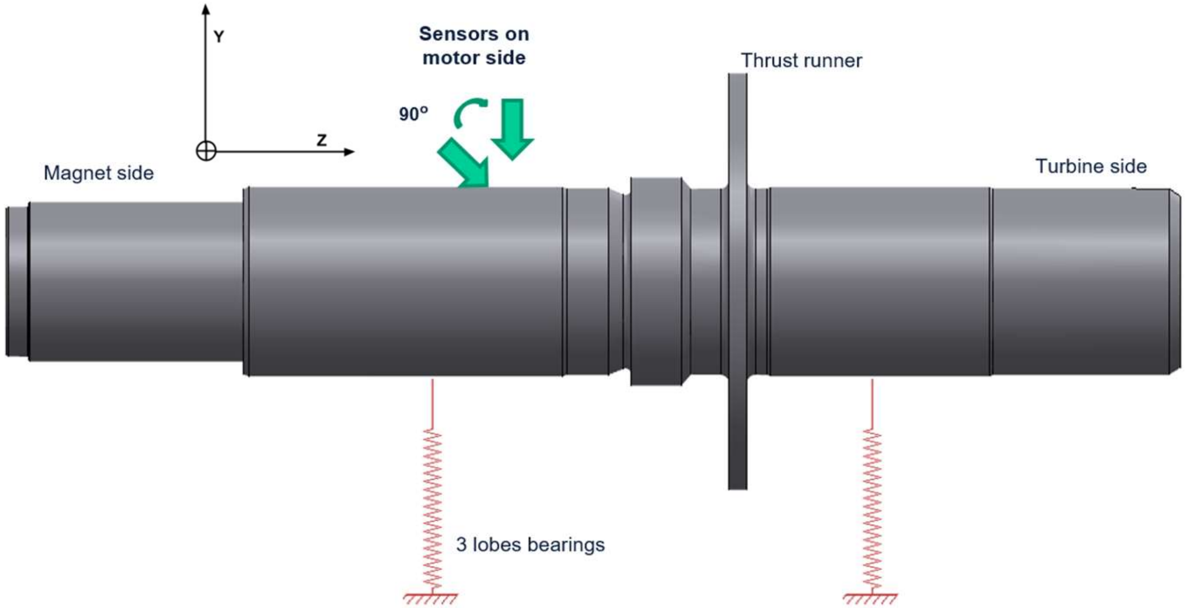
Step- 5: Rotordynamic analysis

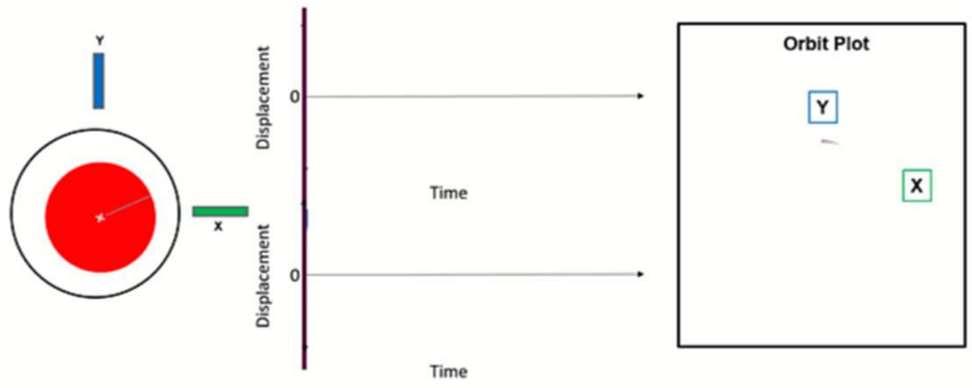




Step-6: Experimental Verification

1. 2x displacement sensors (>25kHz)
2. Speed sensor (zero reference for phase)
3. Displacement in two orthogonal directions is measured
4. Plot X-displacement against Y-displacement gives the orbital plot





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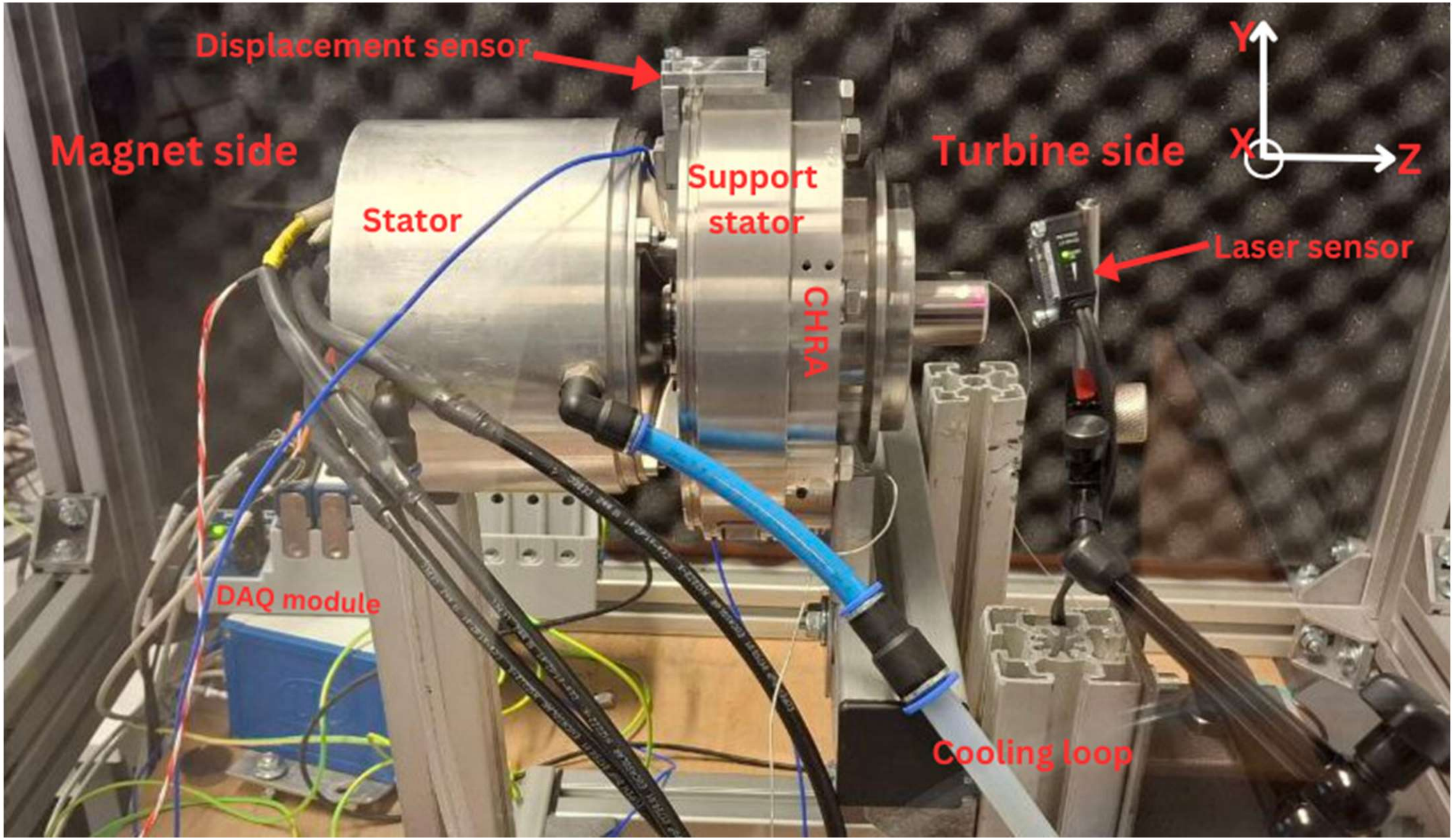

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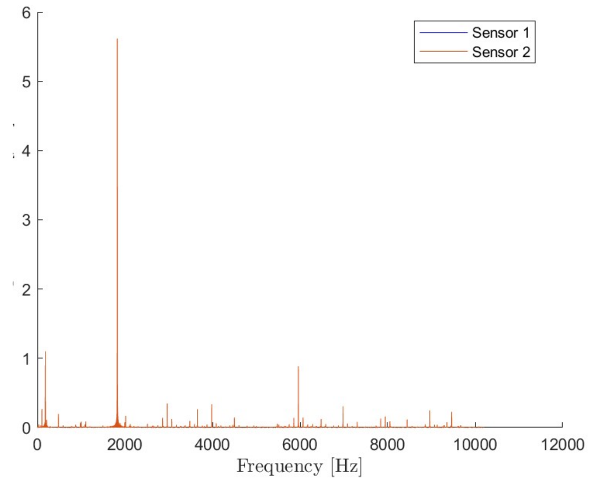
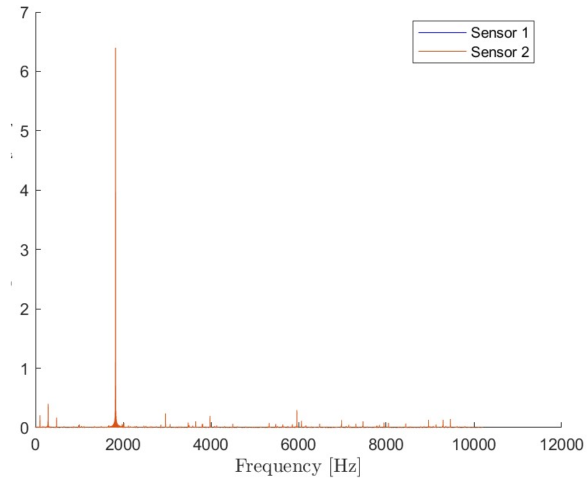
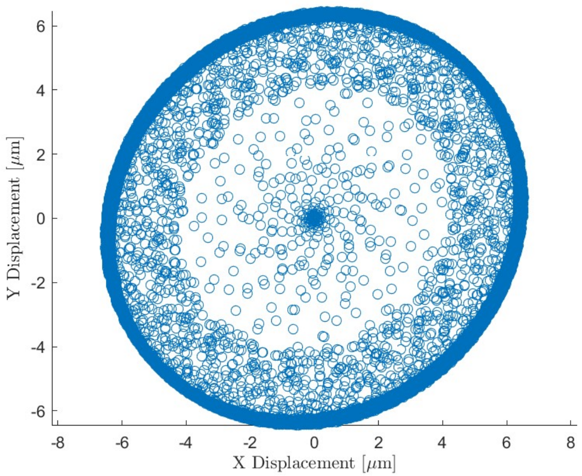


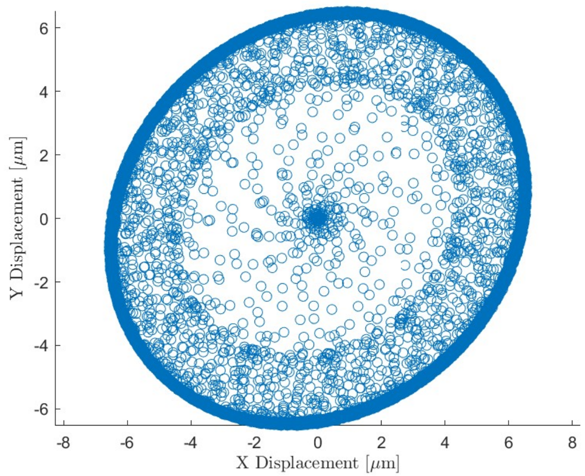
Sub-synchronous Vibrations



Stable structural design



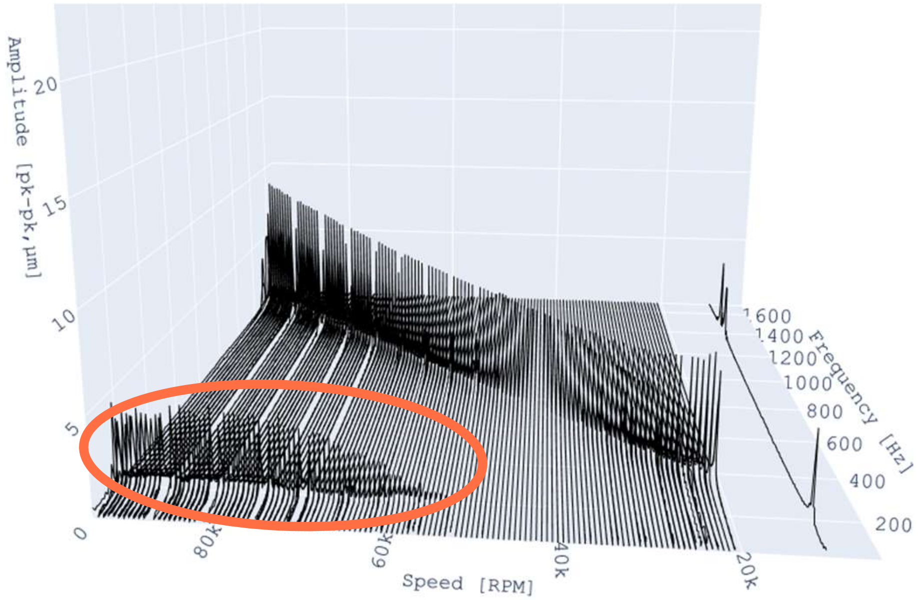
1X- Orbit



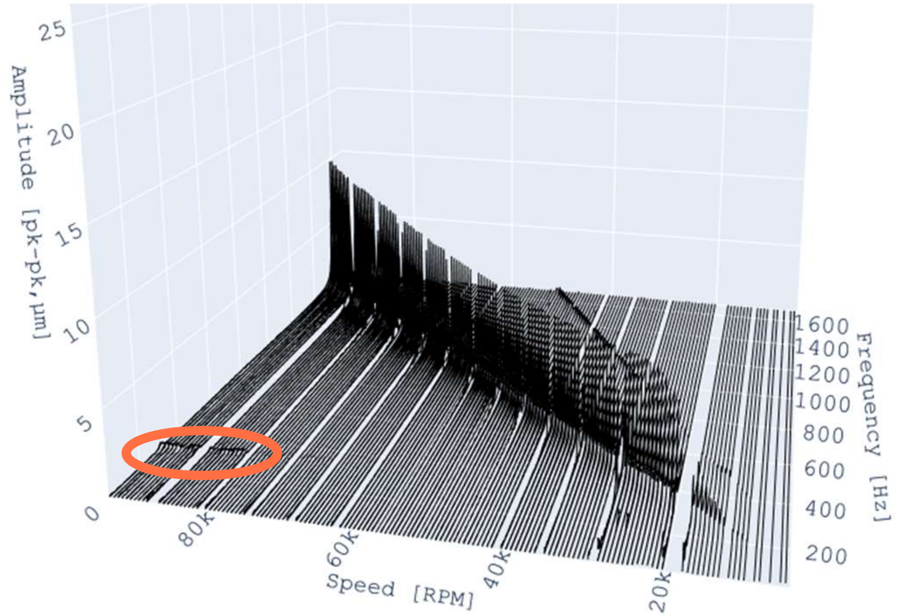
1X- Orbit

Step-6: Experimental Verification

Unstable Bearing Structure



Stable Bearing Structure (Improved design)



Recap & Outlook

1. Details matter (microns)
2. Experimental test rigs are unavoidable to verify design of experiments
3. There is a sweet spot in stiffness & damping of bearing foils
4. Experiments to establish dynamic stiffness and damping are expensive & time consuming. OEMs do the mix of simulations & experiments.
5. There will be additional thermal management challenges when microturbine is fully operational.

Thanks

Do you have questions?
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