Application of Hydrostatic Bearings in sCO_2 Turbomachinery

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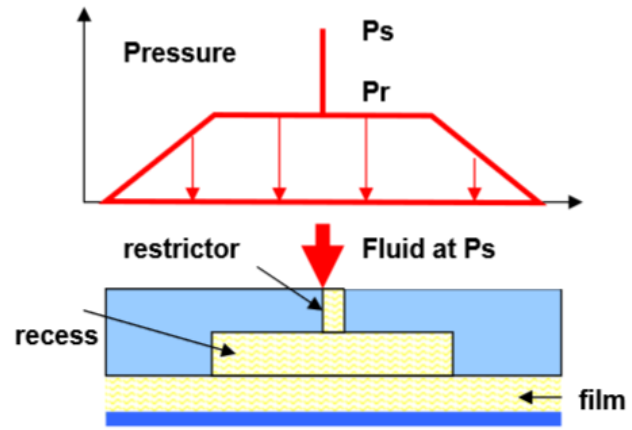
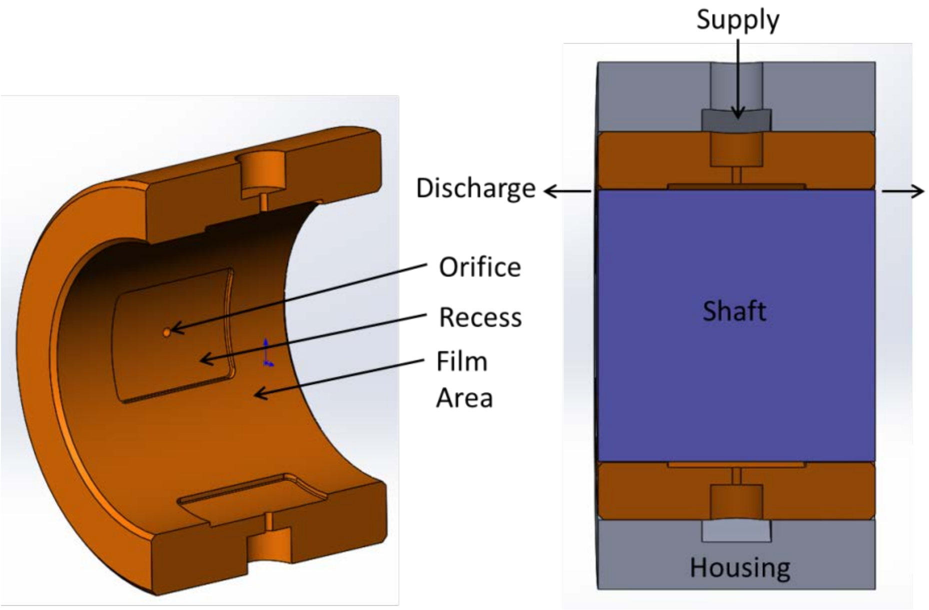
Operating Principle

- Non-contacting, fluid film type
- Fluid is pressurized externally and delivered to bearing clearances.
- Shaft rotation and a viscous fluid are not required
- Flow restriction or control
    - Orifice
    - Capillary tube
    - Control valve
    - Positive displacement pumps





Advantages & Disadvantages

Advantages

- Use with low viscosity process fluids (sCO2)
  - Hermetic designs
  - Thermal management
- Large load capacities
- High damping and stiffness values
- High bearing DN values
- Meets industrial life requirements (Non-contacting)
- Shaft rotation not required (Startup & shutdown)
- Load monitoring (Recess pocket pressure)
- Passive control (Orifice fed)

Disadvantages

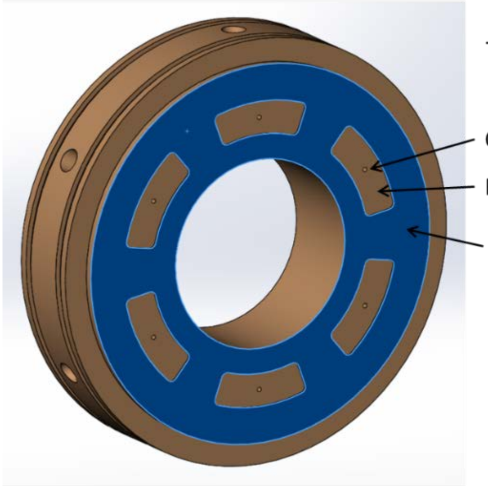
- External supply cost and complexity
- Leakage flow parasitic
- Whirl frequency ratio limitations (Whip)
- Supply considerations during startup and shutdown.

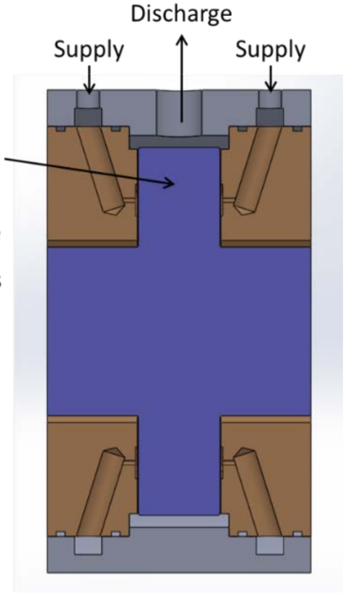
Compressibility

- Traditional hydrostatic design type is ideal when bulk modulus >> bearing pressure differential (Incompressible)
  - Reference 5 gives detailed design parameter
- Traditional hydrostatic designs require supercritical conditions for CO_2.
  - Regulate discharge pressure for Rankine cycles.
  - Avoid two phase flow
- Additional modifications to help mitigate compressibility of sCO_2.
  - Minimize recess / land area (~ 25%)
  - Minimize recess depth (10X min film)

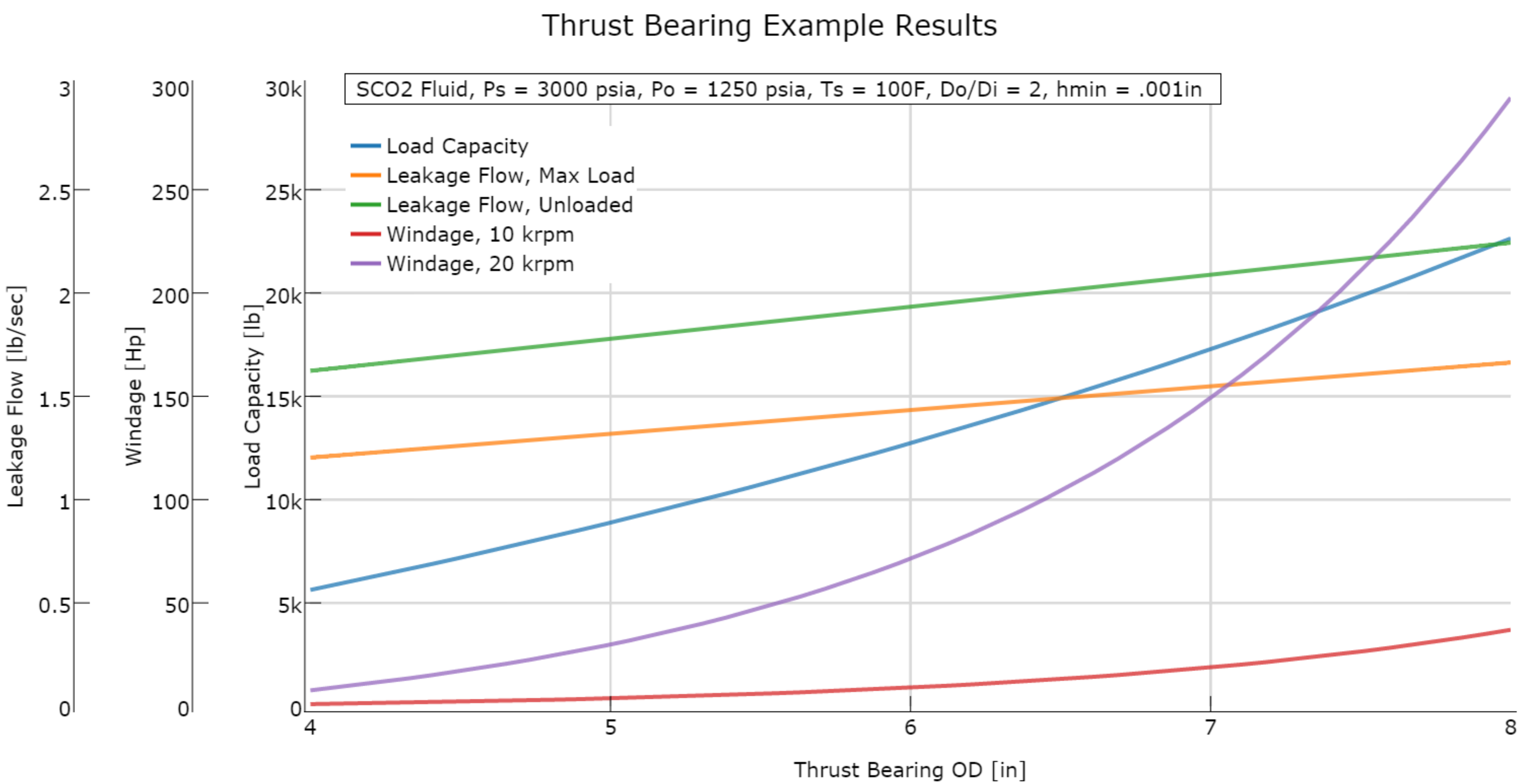
Hydrostatic Thrust Bearings

- Load capacity
  - $\frac{1}{3} \times Pressure\ Differential \times Bearing\ Area = \frac{\pi}{12}(P_s - P_o)(D_0^2 - D_i^2)$
  - Monitor recess pressure to infer bearing loading
- Leakage flow (sCO_2 specific)
  - Compressible orifice flow
  - C_d = .65 - .8
  - $A_O = .0014D_o + .0086\ [in\text{^}2]$
  - $R_{PR} = \frac{P_r - P_o}{P_s - P_o}$ = 0 - .7
- Windage (sCO_2 specific)
  - Based on thrust collar surrounded by fixed clearance (Rough estimate).
  - $W = \frac{k}{1.44E11}\rho_d N^3 {D_o}^4(D_o + 5B)$
  - $k = 18.23Re^{-.644}$+.004
  - $Re = \pi \rho_d {D_o}^2 \frac{N}{60\mu_d}$



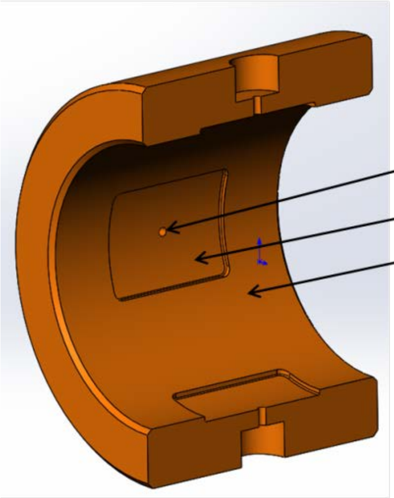


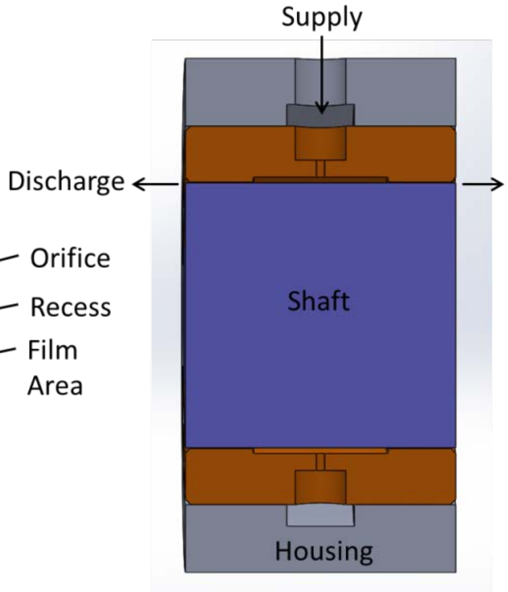
Thrust Bearing Example Results



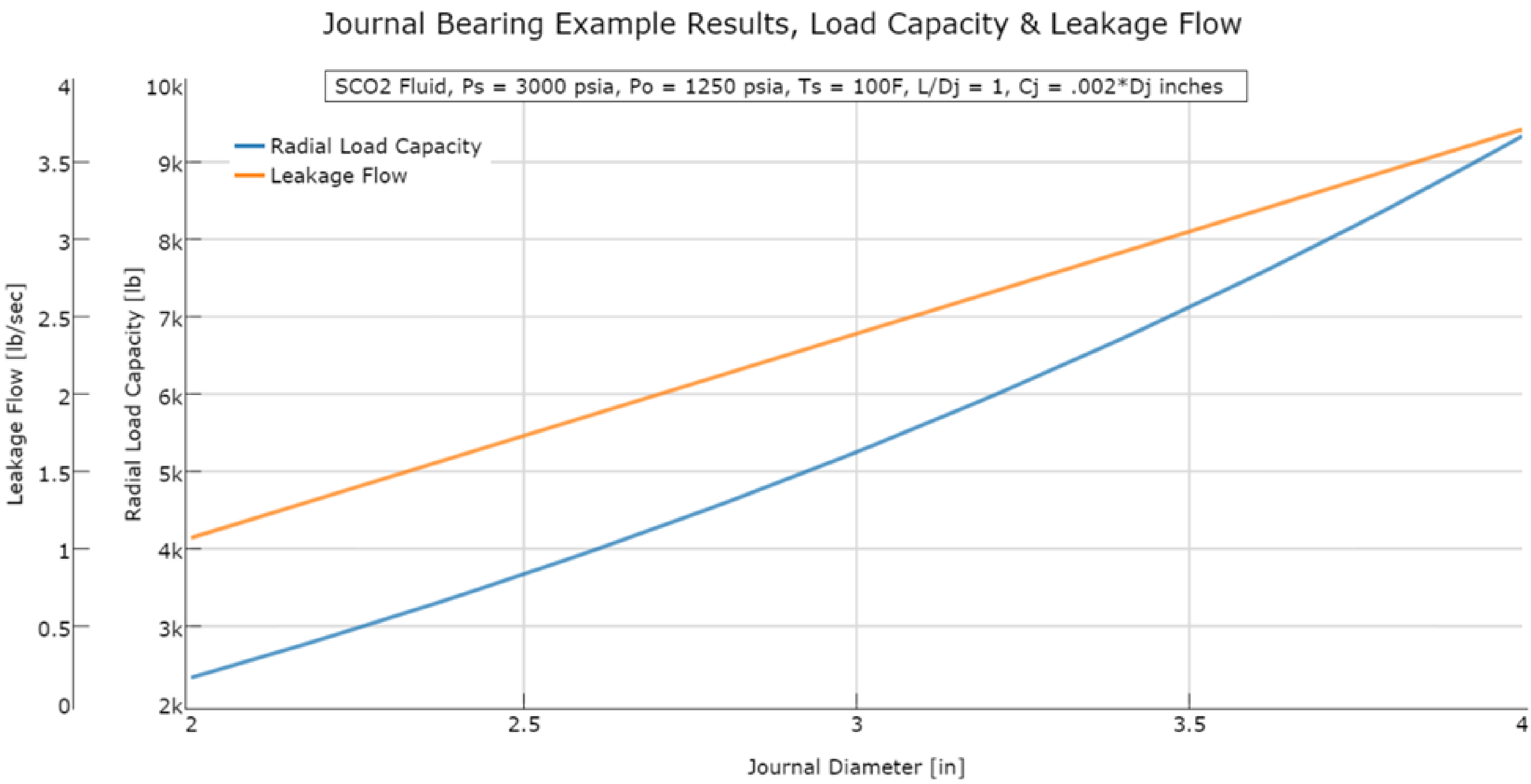
Hydrostatic Journal Bearings

- Load capacity
  - $\frac{1}{3} \times Pressure\ Differential \times Projected\ Area = \frac{1}{3}(P_s - P_o)(D_j L)$
- Leakage flow (sCO2 specific)
  - Compressible orifice flow
  - Cd = .65 - .8
  - $A_0 = .016D_j - .019\ [in^2]$
  - $R_{PR} = \frac{P_r - P_o}{P_s - P_o} = .5$



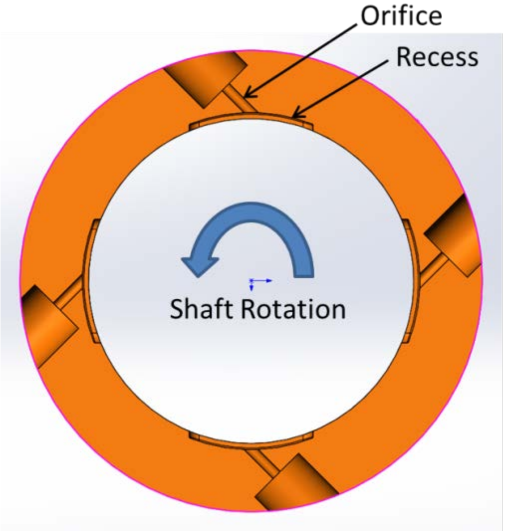


Journal Bearing Example Results – Leakage & Load Capacity



Rotordynamics with SCO2 Hydrostatic Bearings

- Computational analysis typically required for bearing dynamic coefficients (XLHydrojet utilized for results presented herein).
- Critical speeds
  - Large damping typically results in low imbalance response levels.
  - Rigid modes typically very well damped and require no critical speed margin.
- Rotordynamic stability
  - Effective at mitigating large cross coupled forces found in sCO_2 turbines, compressors, pumps, and seals.
  - sCO_2 viscosity is significant enough that whirl frequency ratio limitations exist similar to plain hydrodynamic bearings (whip).
    - First critical can determine speed limitations (WFR ~ .5)
    - Design for maximum bearing stiffness and rotor rigidity.
    - Angled injection can help mitigate limitation



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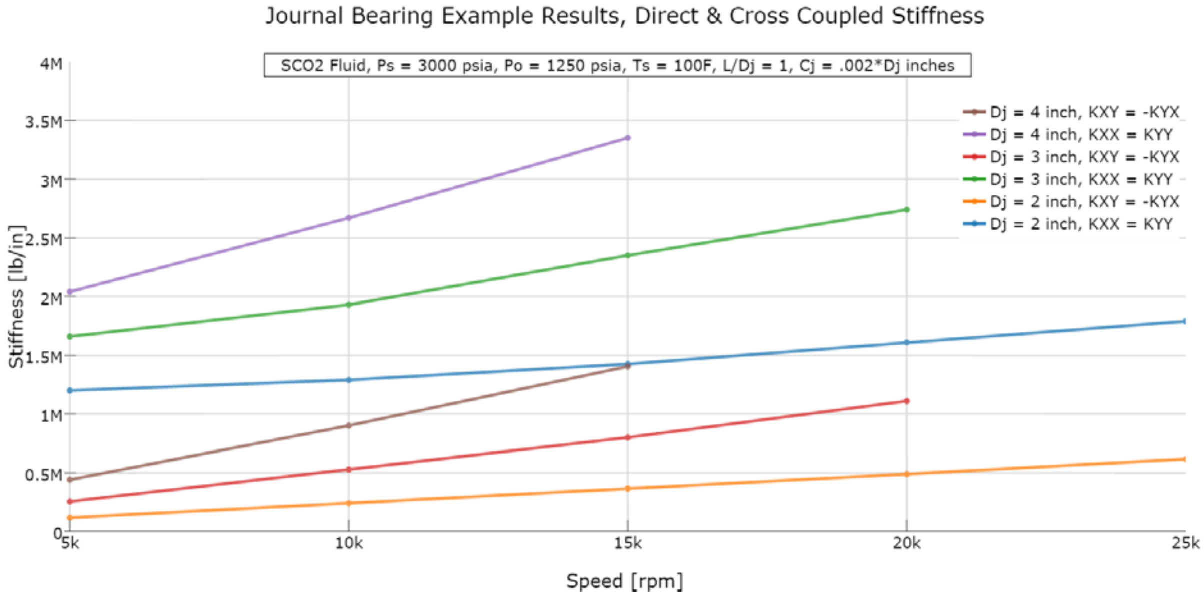
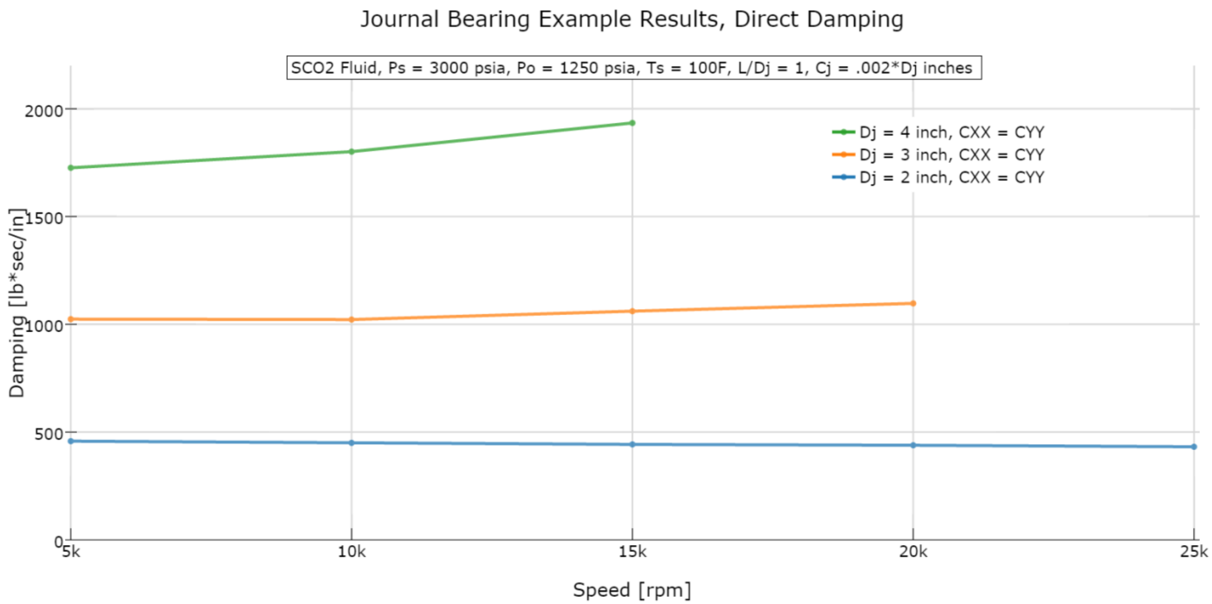
Journal Bearing Example Results – Dynamic Coefficients





Conclusions

- sCO_2 hydrostatic bearings offer exceptional performance (Load capacity, damping, DN, and operational life).
- Suitable for consideration in MW class sCO_2 machines where their parasitic losses may be tolerable.
- Supercritical conditions and reduced recess volumes help mitigate effects of fluid compressibility.
- sCO_2 hydrostatic journal bearings
  - Design generally driven by rotordynamic considerations
  - Large damping yields very good imbalance response and stability margins.
  - Stability limitations exist that are similar to plain hydrodynamic bearings. Angled injection can help mitigate (Reference 4).
- sCO_2 hydrostatic thrust bearings
  - Size generally limited by leakage and windage losses
    - Leakage determined by minimum film clearance. Minimum film clearance depends on alignment capability.
    - Windage of thust collar OD and unloaded face can be significant (D^5).
  - Bearing load can be monitored via pressure measurement in the recess.
- Guidelines presented are intended to help determine feasibility, balance design trades, and proceed to detailed design.

References

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[3] Hamm, H. W. “Determining Fluid Friction or Windage of Rotating Discs”, Allis-Chalmers Electrical Review, Fourth Quarter, 1962

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[5] San Andrés, L., “Fluid Compressibility Effects on the Dynamic Response of Hydrostatic Journal Bearings”, L. San Andrés, WEAR, (1991), 146, pp. 269-283

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[7] San Andrés, L., Phillips, S., and Childs, D., (2016), “A Water Lubricated Hybrid Thrust Bearing: Measurements and Predictions of Static Load Performance”, ASME Turbo-Expo Conference, Seoul, June 13-17, ASME Paper No. GT2016-56349