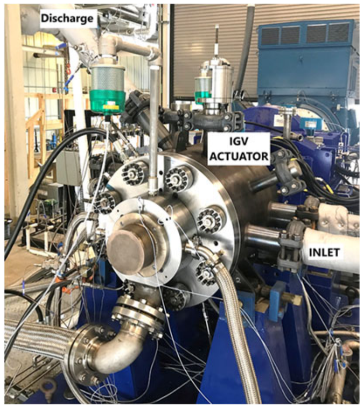
7th International sCO2 Power Cycles Symposium
February 21-24, 2022
San Antonio, TX

Mechanical and Rotordynamic Test Results of a Supercritical CO_2 Compressor Operating Near the Critical Point



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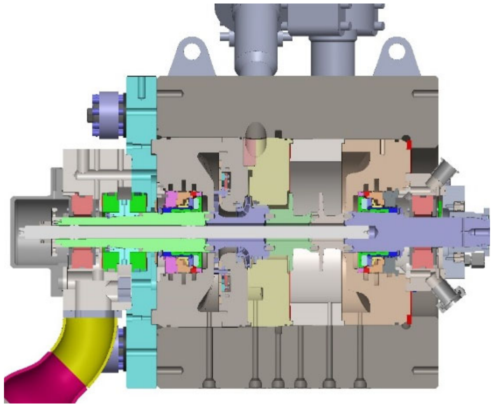
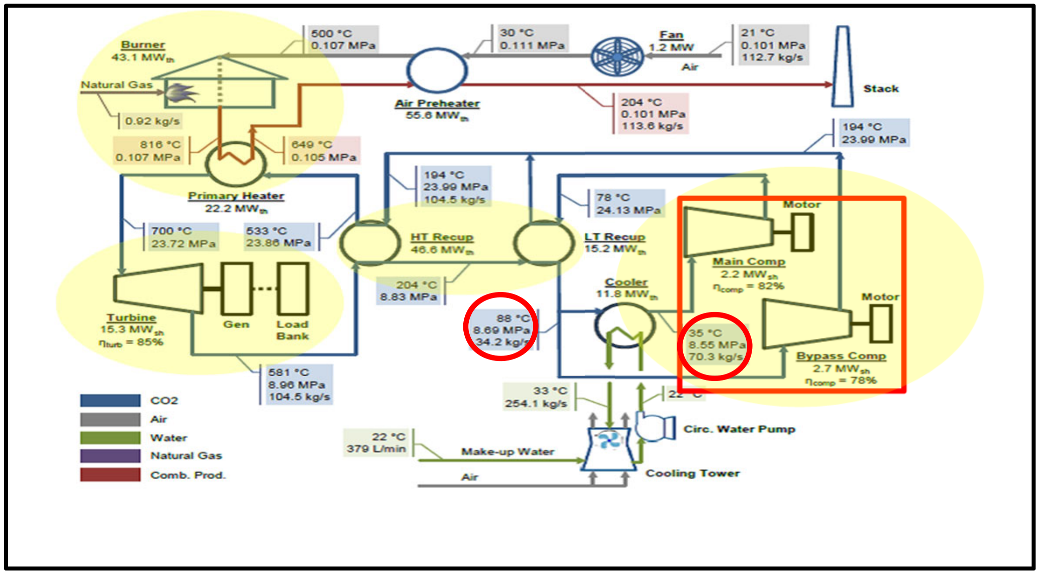
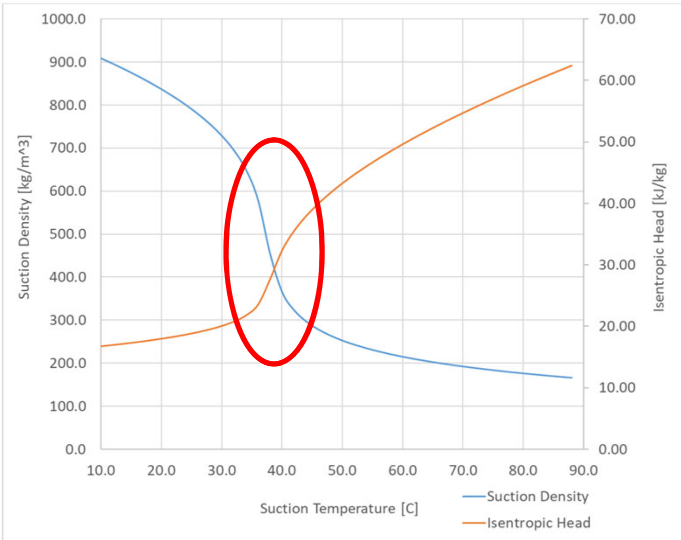


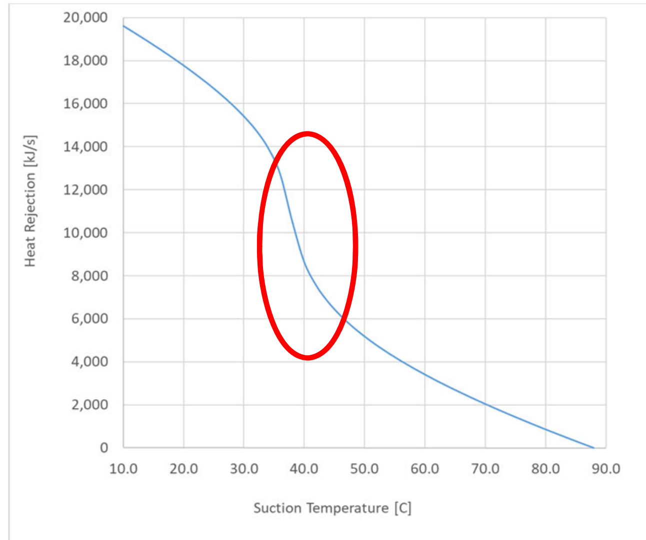
Power Cycle



- 10 MWe, Re-compression Brayton Cycle
- Main Components
  - High and Low Temperature Recuperator
  - Main and Bypass Compressor
  - High Temperature Turbine
- Main Compressor Conditions
  - Inlet: 35°C and 8.5 MPa
  - Exit: 74°C and 27.2 MPa
  - ~70 kg/s
  - Mean Gas Density: 677.3 kg/m^3

Introduction

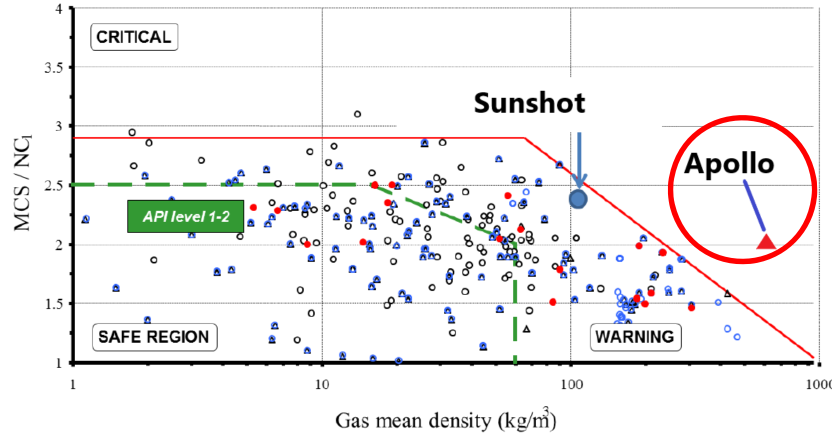


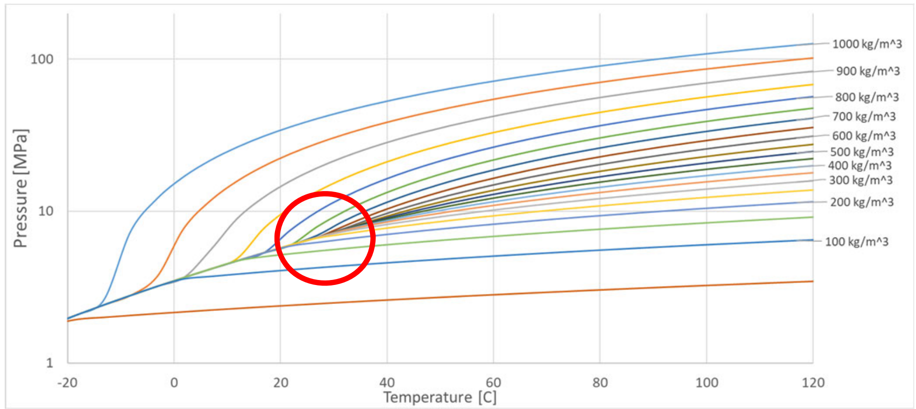


- Design conditions are driven by achievable suction temperatures from water / air cooling
  - While colder suction temperatures (liquid) requires less compression power, chilling coefficient of performance is much greater than water / air cooling
- Inflection point around 35^{o}C at 8.5 MPa

Introduction

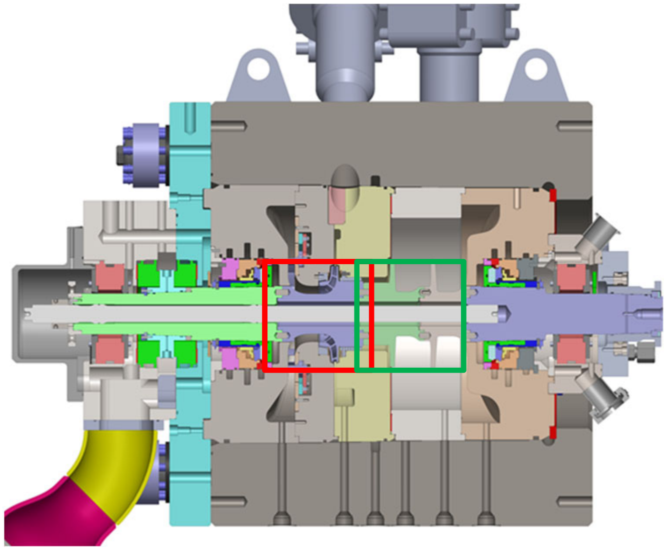
- High density and large density swings are challenging for a compressor to manage
- High density → large fluid forces to could excite lower modes (subsynchronous)
- Large density swings → large changes in mass flow
- Fulton Chart (top right) highlights Critical Speed Ratio (CSR) vs Gas Mean Density along with experience limits and checks for API analysis requirements

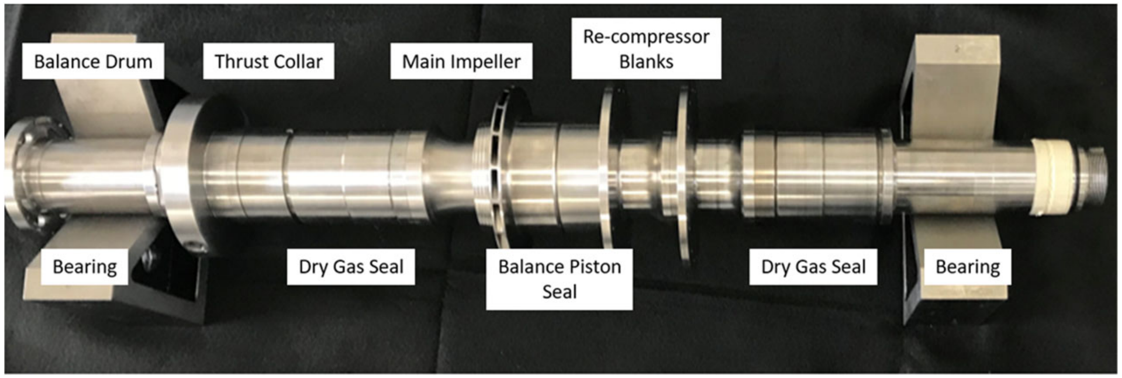




Compressor Details

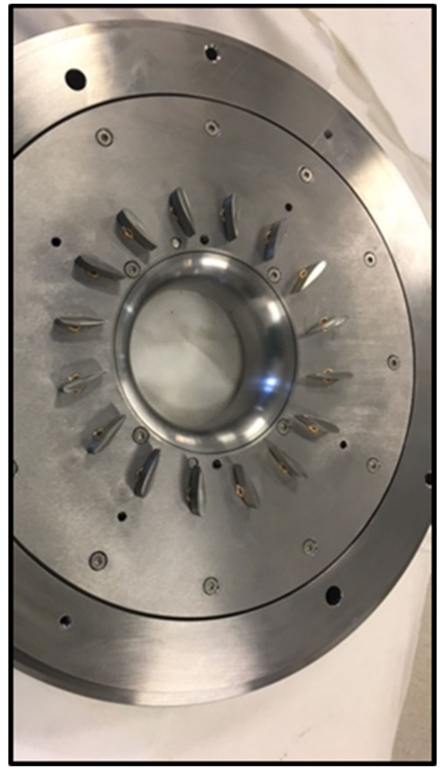
- Smaller bearings → Lower stiffness
- Higher stiffness and larger bearings can lead to reduce vibrations if high density flow becomes an issue
- Current test only looking at main compressor
- Blank discs for bypass compressor



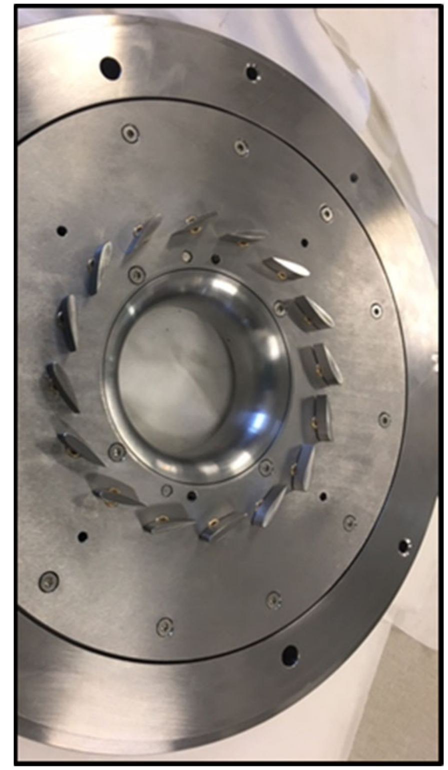


Compressor Details

- To extend flow range with large changes in density, actuated inlet guide vanes
- +10° for Hot Day Flow (50°C and 10.5 MPa)
- -60° for Cold Day Flow (20°C and 7.0 MPa)
- 33% swing in suction density. 3X swing in density at 85 MPa
- Adjust volume flow to maintain constant mass flow supply to the turbine



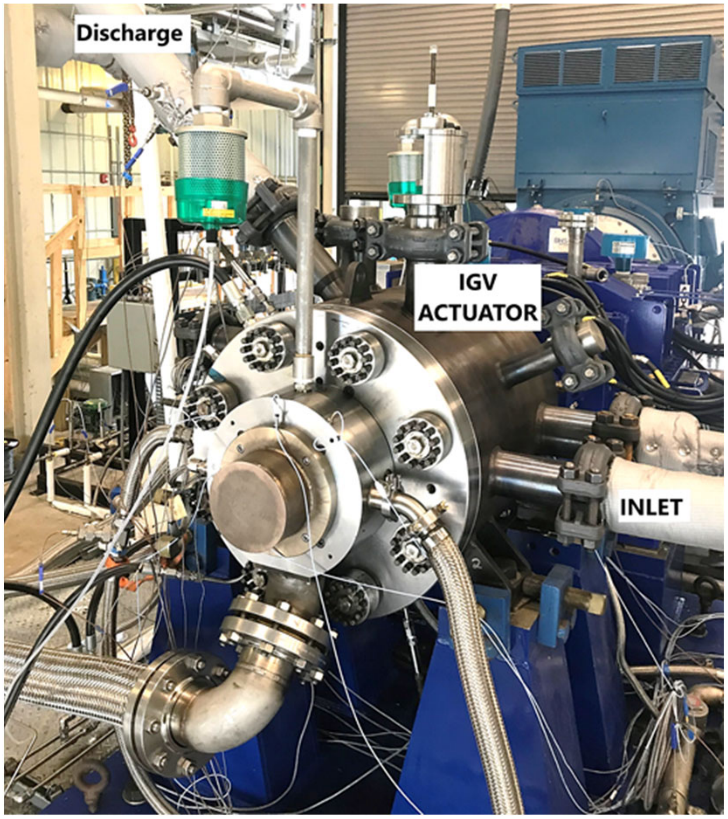
+10°



-60°

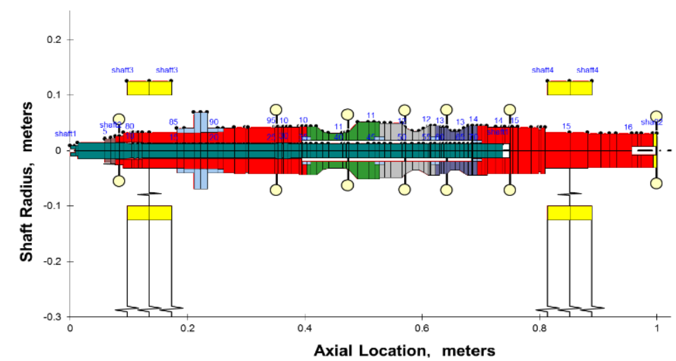
Compressor Details

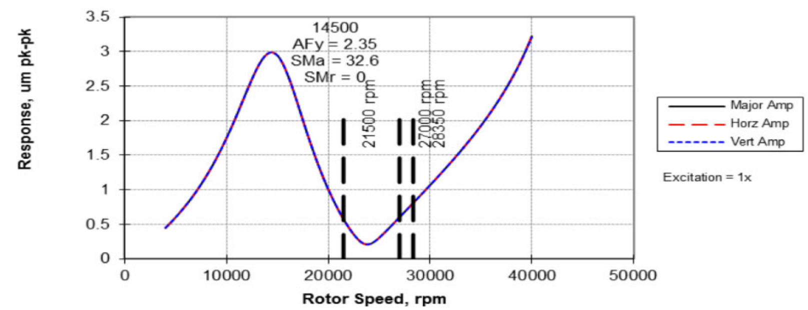
- Final assembly of compressor installed on the stand
- 3 MW motor with 2 gearboxes for modular test capabilities
- Horizontal bundle that can be removed separately from the outer case



Rotordynamic Analysis

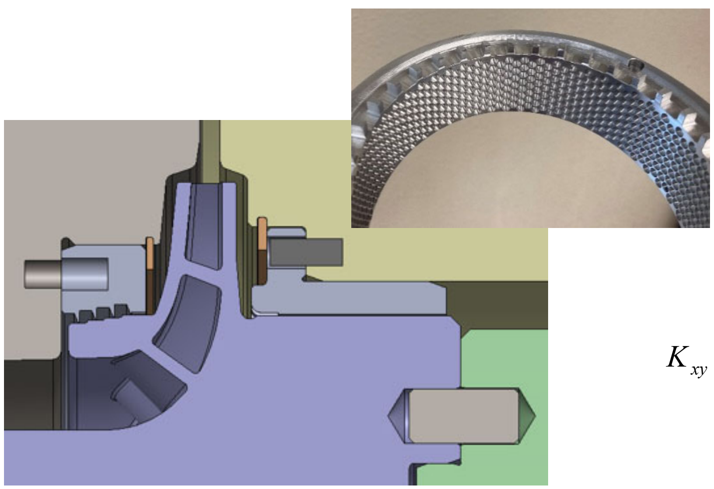
- Final rotor configuration used inboard thrust bearing to provide better control of the bending mode
- Critical speed is well damped with good separation margin from the running speed
- Bending critical well above running speed



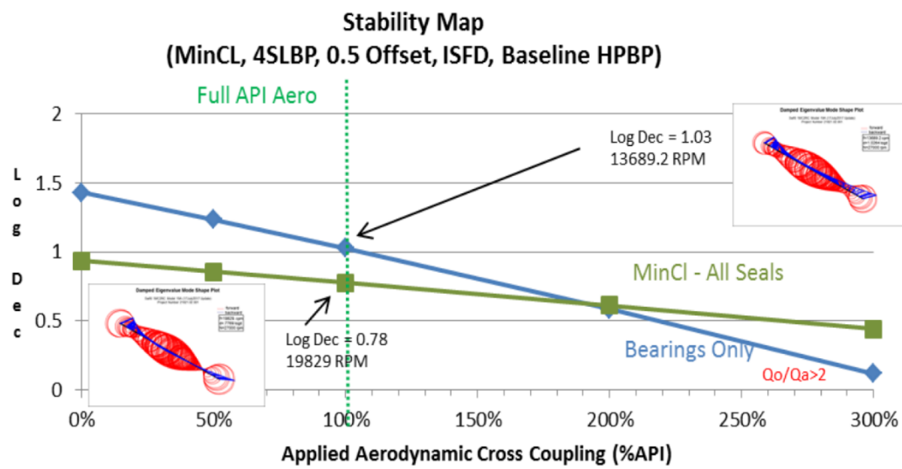


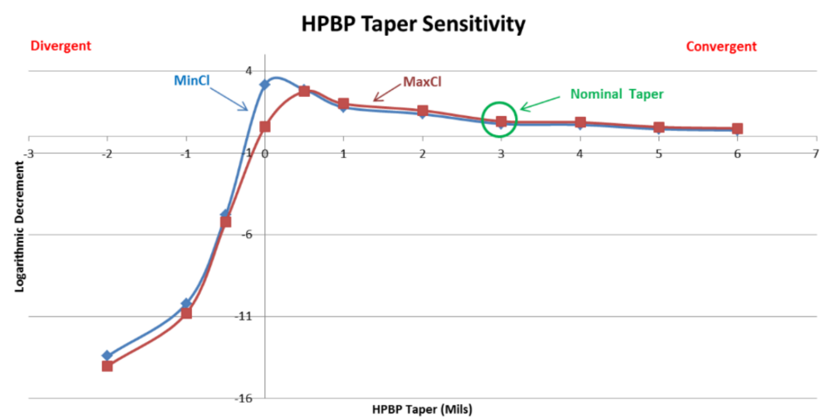
Rotordynamic Analysis

- Rotodynamic forces amplified by high density fluid
- Swirl brakes and damper seals
- Damper seal carrier design to minimize conin of the seal clearance



$$K_{xy} = \frac{C_{mr}\ \rho_{dis}\ U^2\ L_{shr}}{Q / Q_{design}}$$





Test Loop Design

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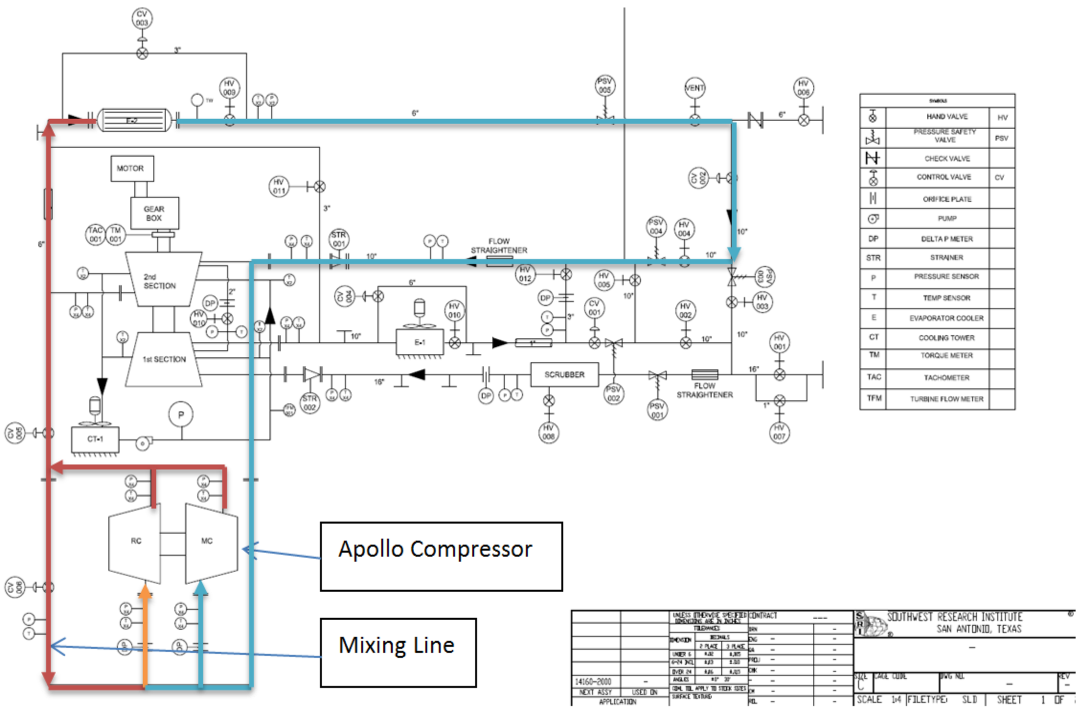
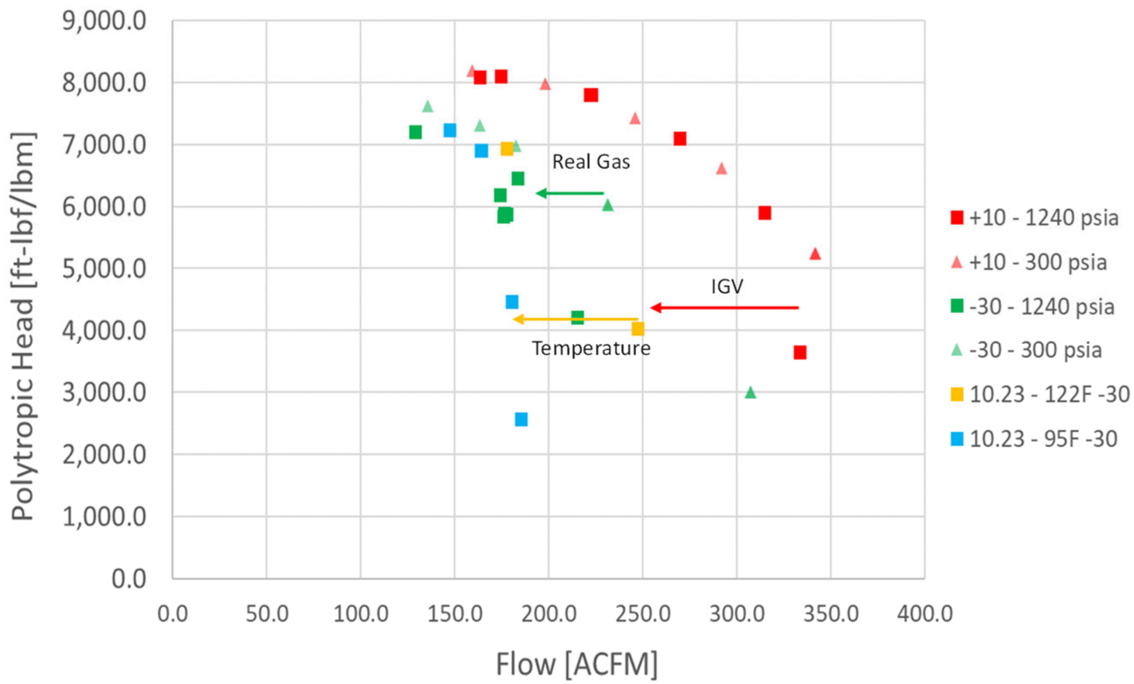
- Modified existing CO2 loop
- Driven by 3 MW electric motor through two step-up gearboxes



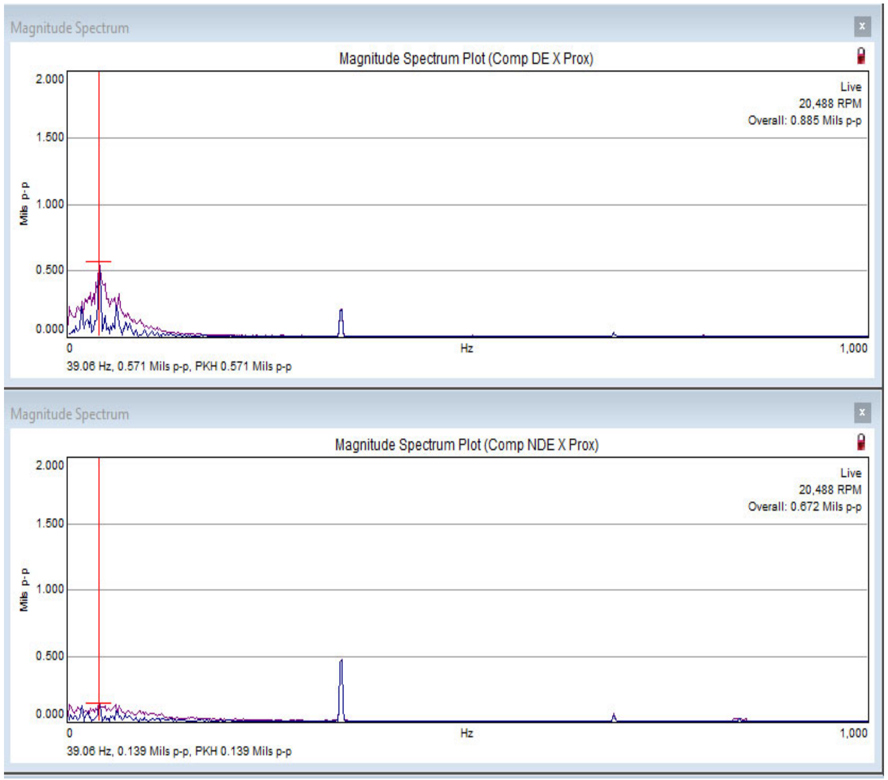
Test Results

- After break-in, testing performed at medium and full pressure
  - 300 and 1240 psi suction pressure
  - +10° and -30° IGV setting angles
  - 95° and 122°F suction temperature
- Both speed of sound and IGV setting has strong effect on the flow capacity of the compressor



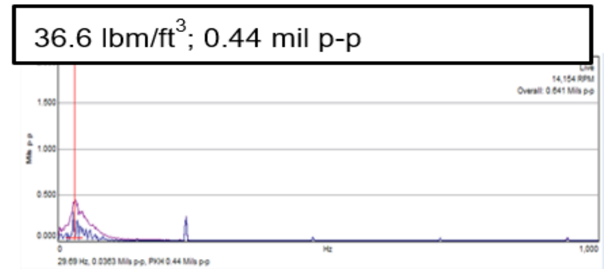
Vibration Results

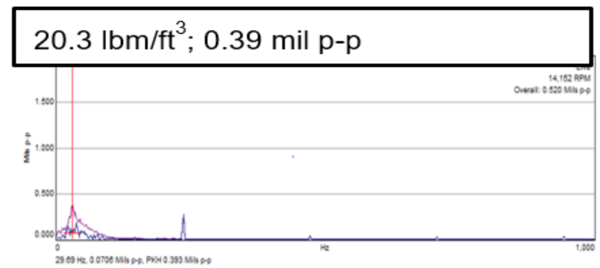
- Compare bearing vibrations at 2.0 MPa and full speed (27,000 rpm) and 8.5 MPa and lower speed (20,500 rpm)
- Around 8X increase in Sub Synchronous vibrations

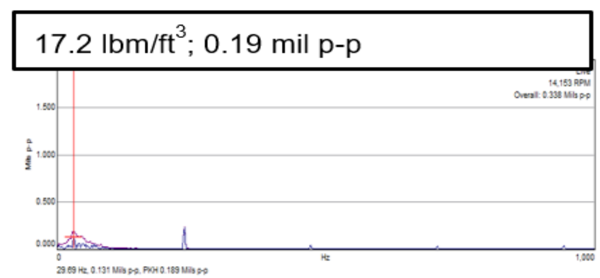


Vibration Results

- Spectra were captured while reducing suction pressures from 85.2 barg (1,236 psia) down to 70.1 barg (1,016 psi)
- Density reduced by factor of 2 and subsynchronous followed
- Indicated Subsynchronous vibration was related to gas density and was broad-band in nature
    - Not from rotordynamic instability or rotating stall

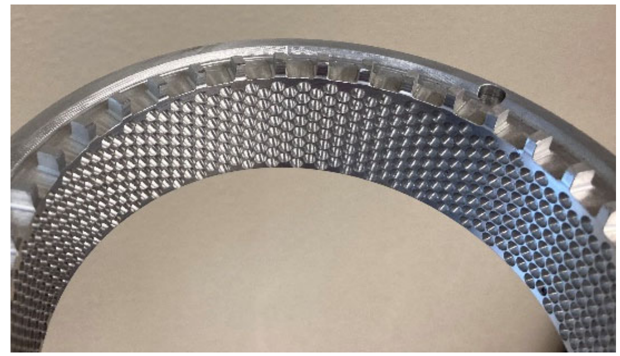


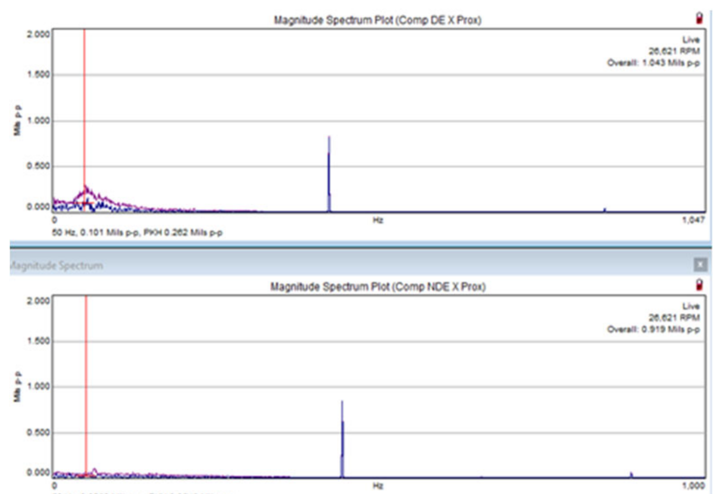




Vibration Results

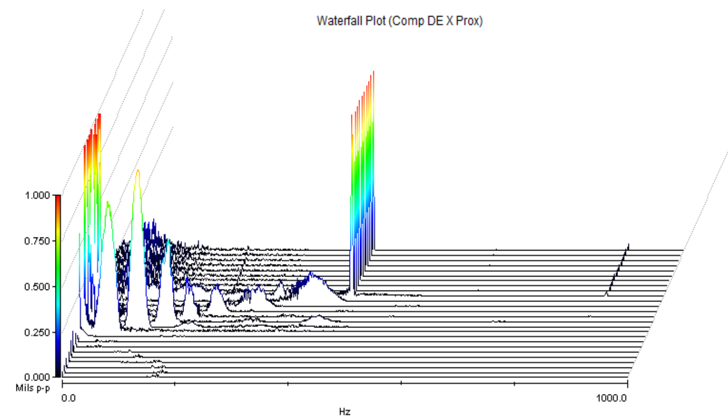
- Following disassembly, it was discovered the balance piston was not machined with converging taper as designed
- A new seal was manufactured with positive taper
- Resulting response improved allowing full speed operation but subsynchronous vibration persisted

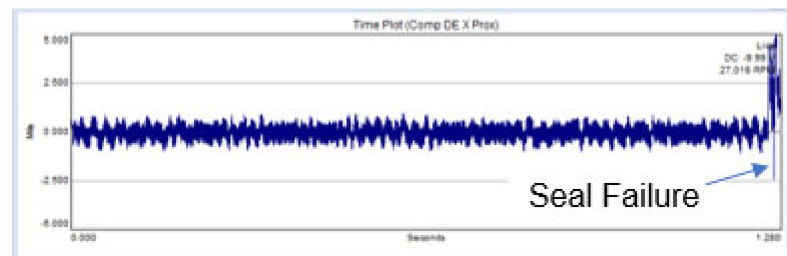




Dry Gas Seal Failure

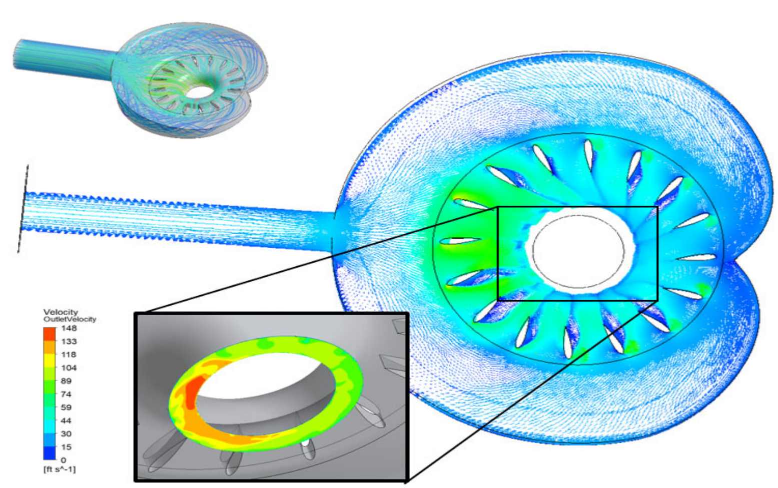
- A dry gas seal failure occurred at around 41.6°C (107°F) inlet temperature
- Temperature was changing slowly and is unlikely the cause of the seal failure
- A root cause failure investigation determined that a bad lot of seal material was obtained from the seal supplier for the silicon carbide seal ring
- A second set of seals for a different vendor was used for subsequent tests

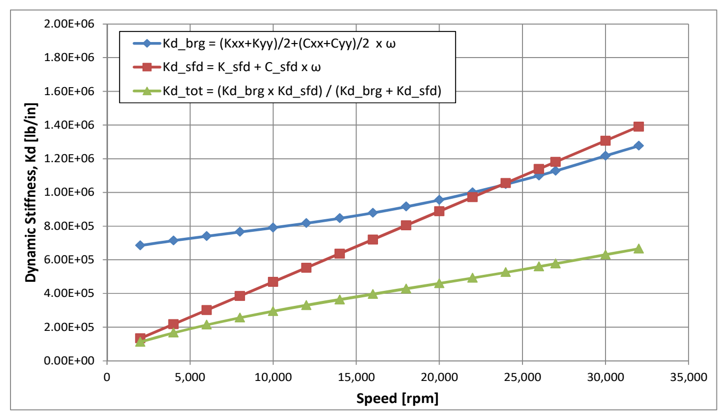




Broadband Subsynchronous Vibration

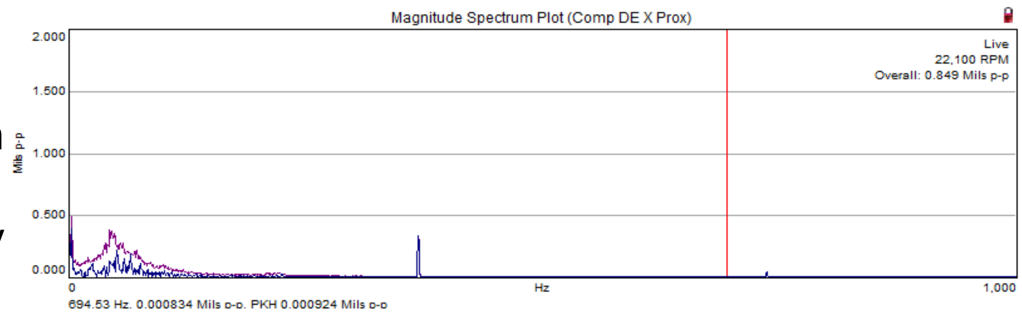
- CFD analysis was performed of the inlet with the +10° IGV setting and the exact operating conditions during the first test
- Due to the compact size of the compressor and the high pressure nozzle case penetration, a relatively small inlet plenum was incorporated resulting in less than ideal flow behavior around the IGVs
- Since redesigning the inlet was not feasible given the space constraints, the bearings were modified to improve their dynamic response at these low frequencies by locking up the damper



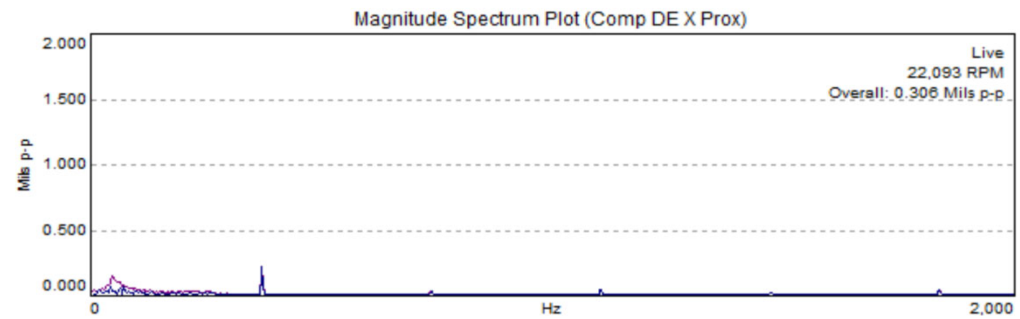


Broadband Subsynchronous Vibration

- Vibration with and without SFD with at nearly identical operating conditions with +10° IGV setting shown
- Subsynchronous vibration is significantly reduced



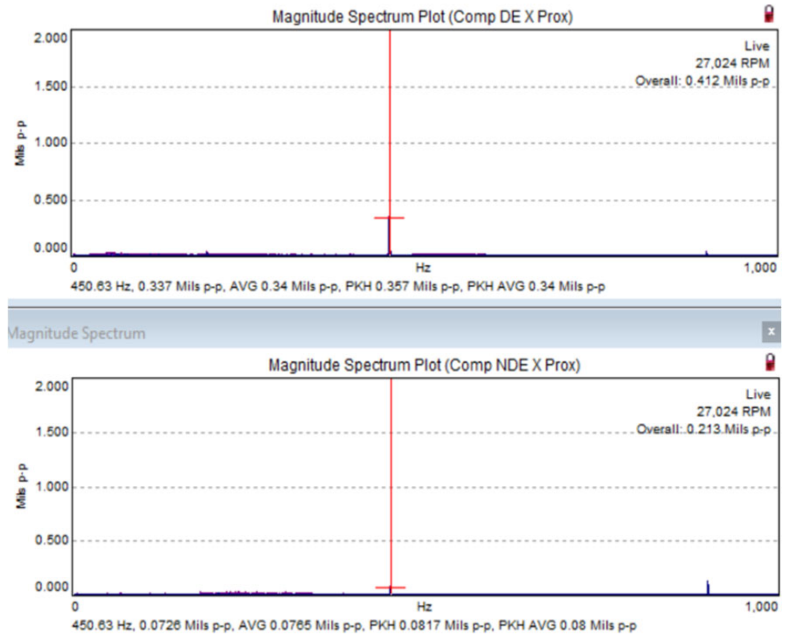
Vibration Spectrum with SFD, Ps=1220psi, Ts=97F, N=22,100 rpm, 70% throttle, +10 IGV



Vibration Spectrum without SFD, Ps=1214psi, Ts=103F, N=22,093 rpm, 68% throttle, +10 IGV

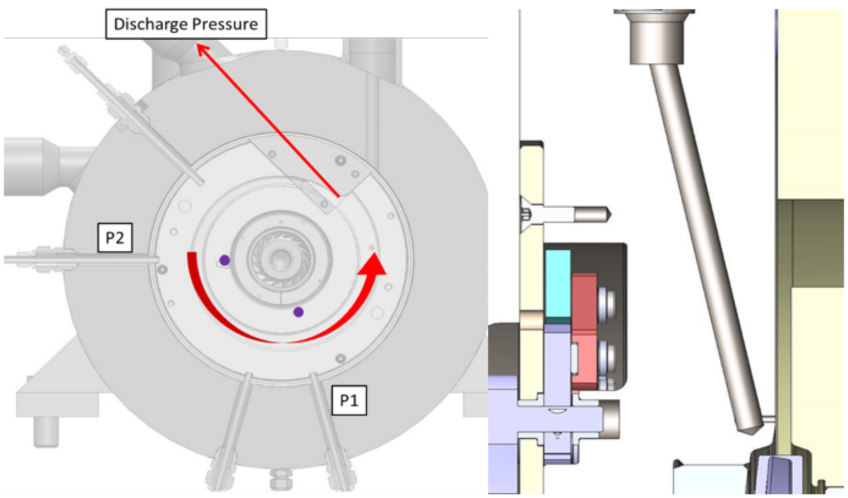
FINAL TEST

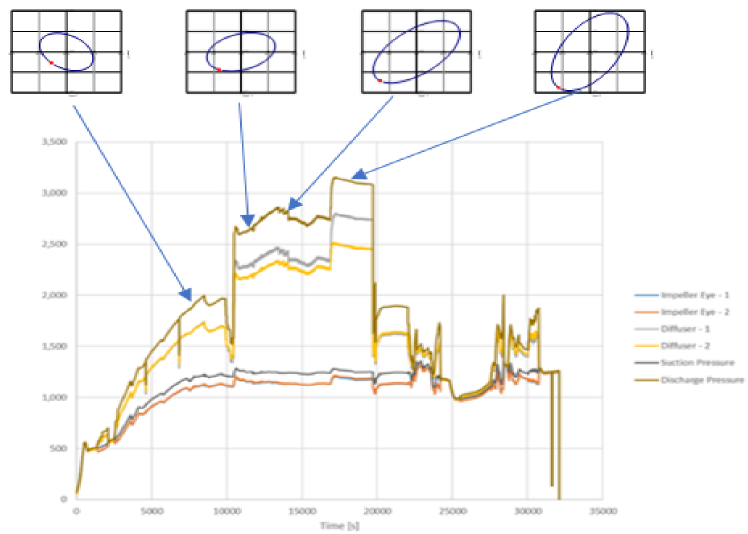
- Final test at full speed and pressure with -30° IGV shows even lower SSV
- P1=1,248 psi, P2=,3341 psi, 27,000 rpm
- discharge density is 710 kg/m3 (44.5 lbm/ft^3), which is 71% of water
- Highest density compressor reported in literature



Volute Forces

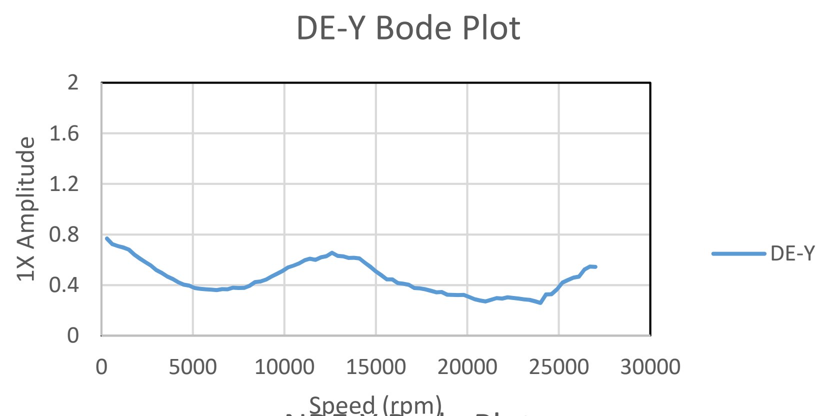
- Internal pressure measurements in the diffuser showed different pressures as compressor is throttled
- The vibration orbits showed a corresponding change in shape
- These are caused by non-uniform velocities in the volute resulting in a static pressure distribution and radial force reacted by the bearings.

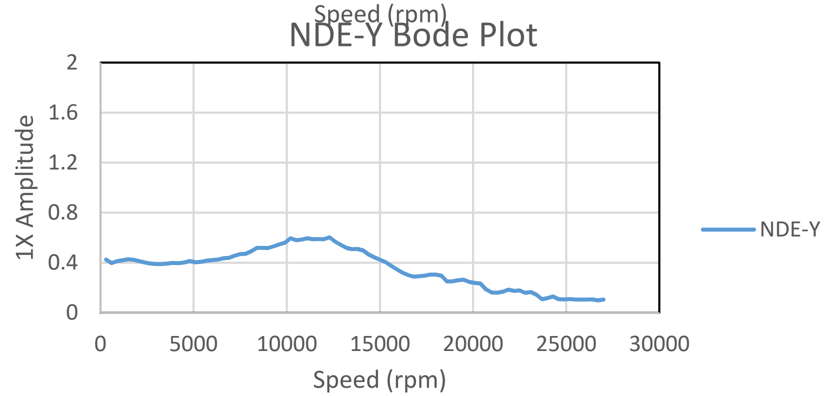




Bode Plots

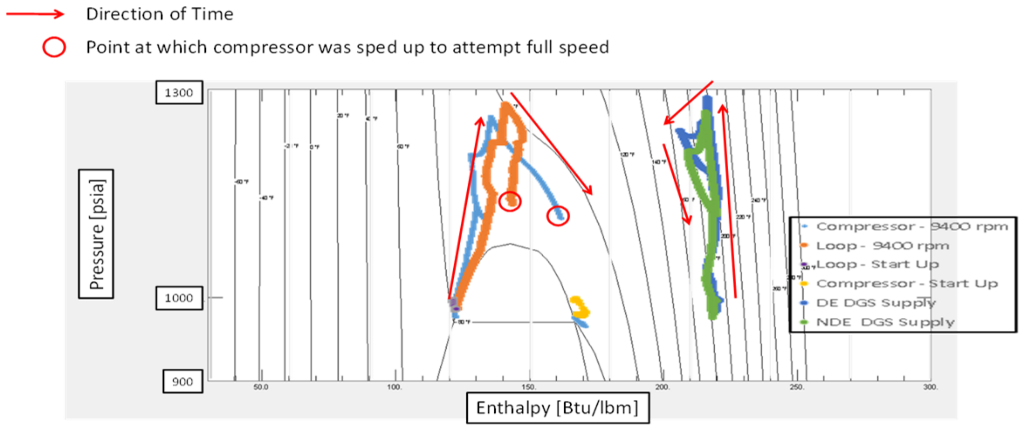
- Bode plots (1X amplitude vs speed) captured during the rundown show smooth vibration and well damped critical speeds even with damper bearings locked up

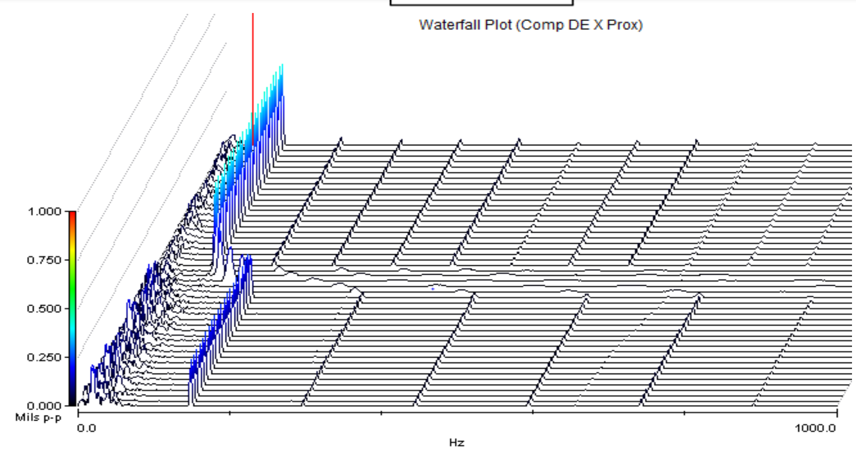




Pressurized Cold Start

- Cold start was initiated where the loop had cooled to 27ºC (80ºF) and the pressure reduced to 68.6 bara (995 psia)
  - Below the critical pressure
  - Inlet conditions were multi-phase
- Compressor was started to 5,000 rpm and then increased to 9,000 rpm
  - Cooling water turned off to warm the loop and pressurize it without having to add mass
- Some subsynchronous vibration occurred but was well controlled
- Once pressure climbed to design point (83 bar, 1200 psi), the rotor was accelerated to full speed





Conclusion

- Apollo sCO2 compressor development was able to achieve all of its mechanical objectives in terms of speed, pressure capability, stable rotordynamic behavior, and variable IGVs
- Fluid induced subsynchronous vibration unlike traditional rotordynamic instabilities and rotating stall
  - Vibration amplitude was observed in test to be proportional to the inlet density
  - High density of supercritical CO2 acts to amplify unsteady aerodynamic forces
- By eliminating the SFDs, good vibration behavior was observed over a range of operating conditions and IGV setting angles and good agreement with predictions was demonstrated
- Dry gas seal failure was encountered which was attributed to a material defect in the seal ring
- The volute forces acting on the rotor had an influence on the vibration orbits but were able to be accommodated by the bearings
- Cold start inside the liquid-vapor dome performed without any operational issues
- Full speed reached and tested at 35oC and 8.5 MPa. Highest density compressor in operation - (618 kg/m3) steady state operation and peaked at 720 kg/m3 during off-design operating conditions
- Total vibrations at 50% of alarm (under API vibration limit) indicating potential for higher pressure and lower temperature operation to increase compressor performance

Acknowledgements

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