Designing Oil Free Screw Compressor Systems for Acoustic Resonance during Shop Testing, Field Startup, and Process Operation

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Case Study Overview

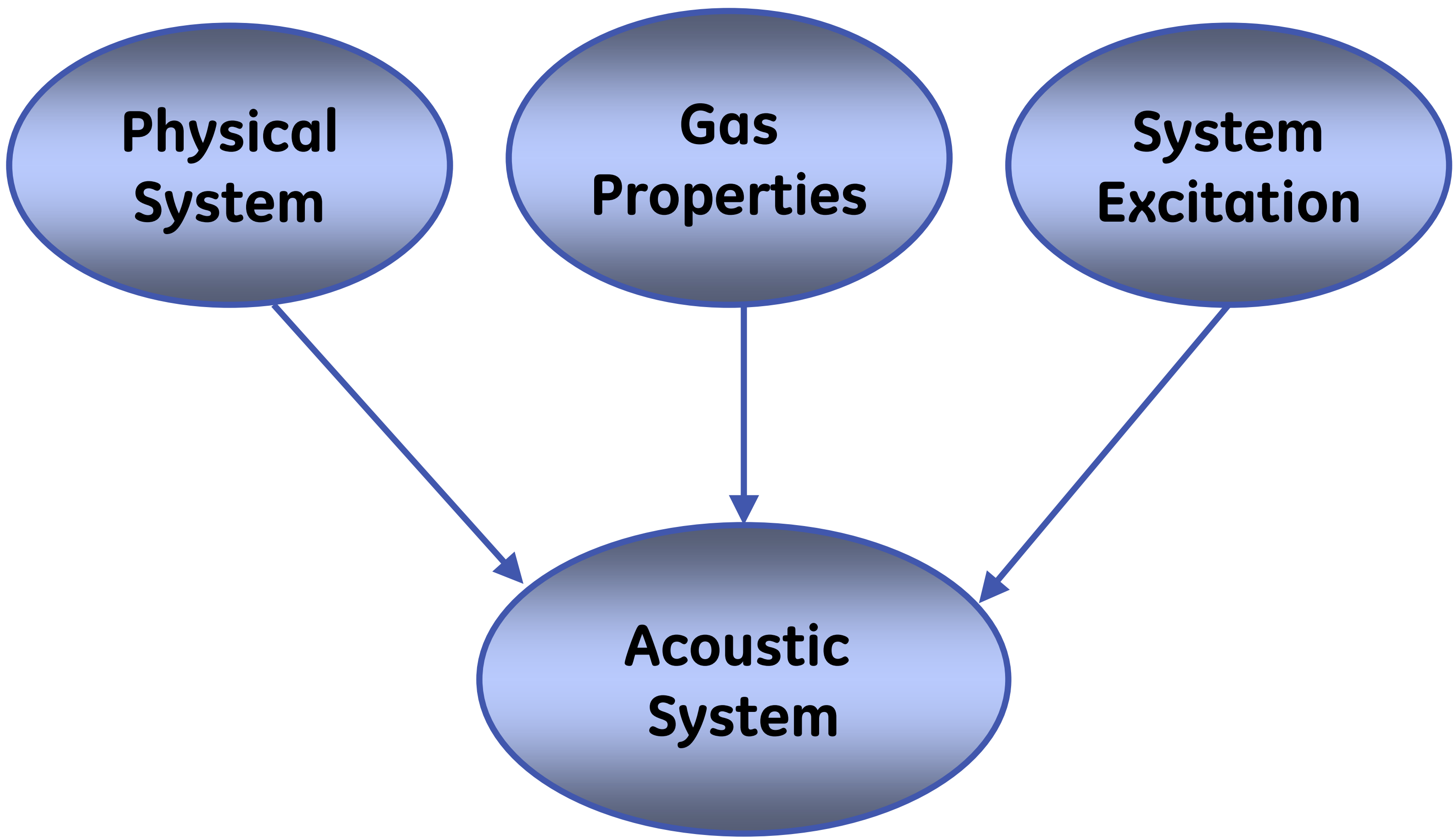
An OFS (Oil Free Screw) compressor experienced problems meeting the API 619 3rd Edition vibration level acceptance criteria during shop testing. Extensive testing identified the primary mechanism that increased the rotor vibration levels was high levels of dynamic pressure pulsations due to acoustic resonance.

This presentation will identify the fundamentals of acoustic resonance and how these frequencies can be affected by the factors which define an acoustic system.

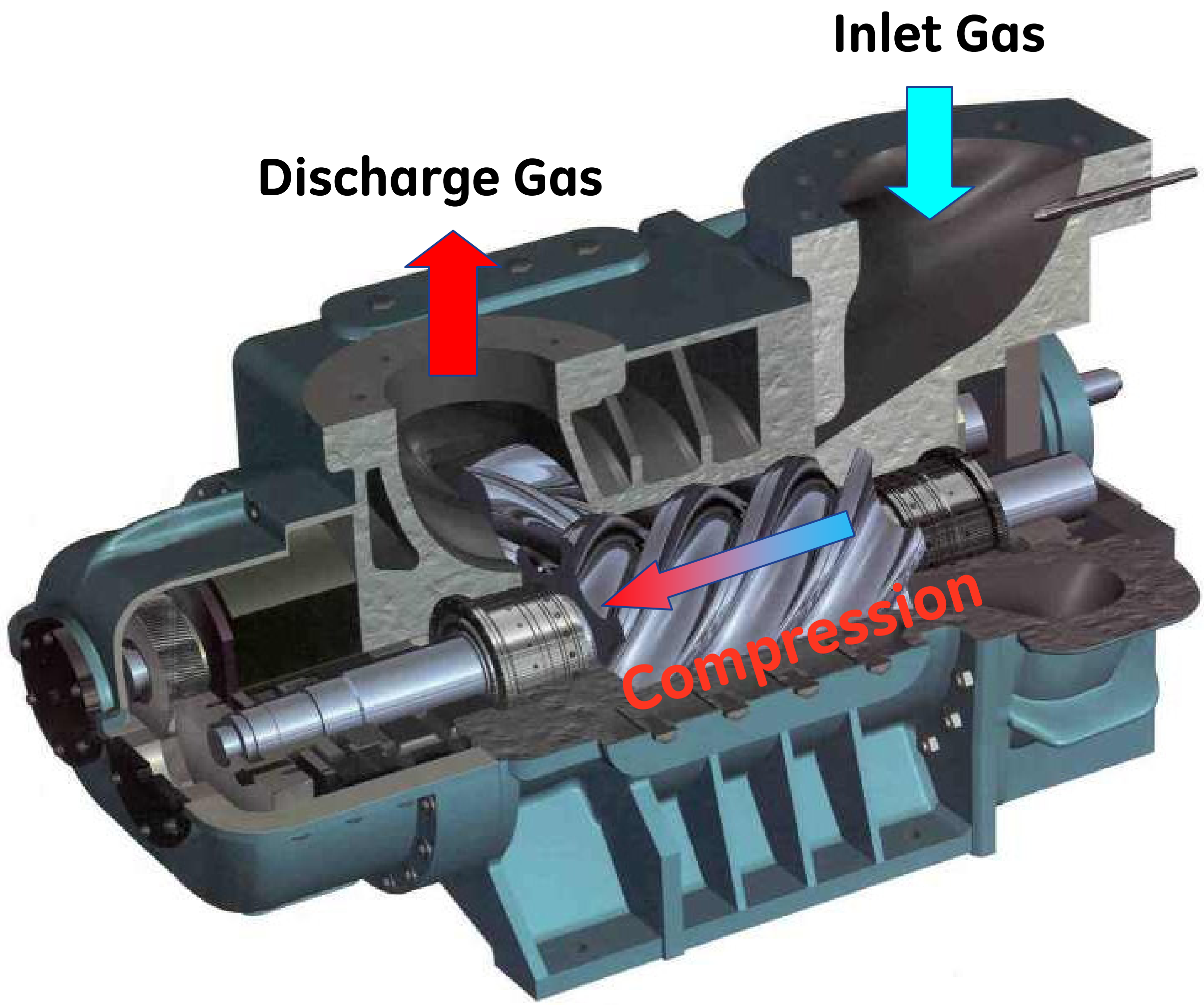
An inherent characteristic of OFS compressor discharge flow is a pulsed flow defined by pocket or lobe passing frequency occurring when the discharge gas from the rotor lobe pocket passes into the discharge porting. Oil free screw compressors can experience high levels of vibration due to acoustic resonance coupling with high dynamic pressure pulsations generated by these positive displacement machines.

When a screw compressor is not volumetrically matched and the gas MW, density or discharge pressure is high, the discharge dynamic pressure pulsations can be high.

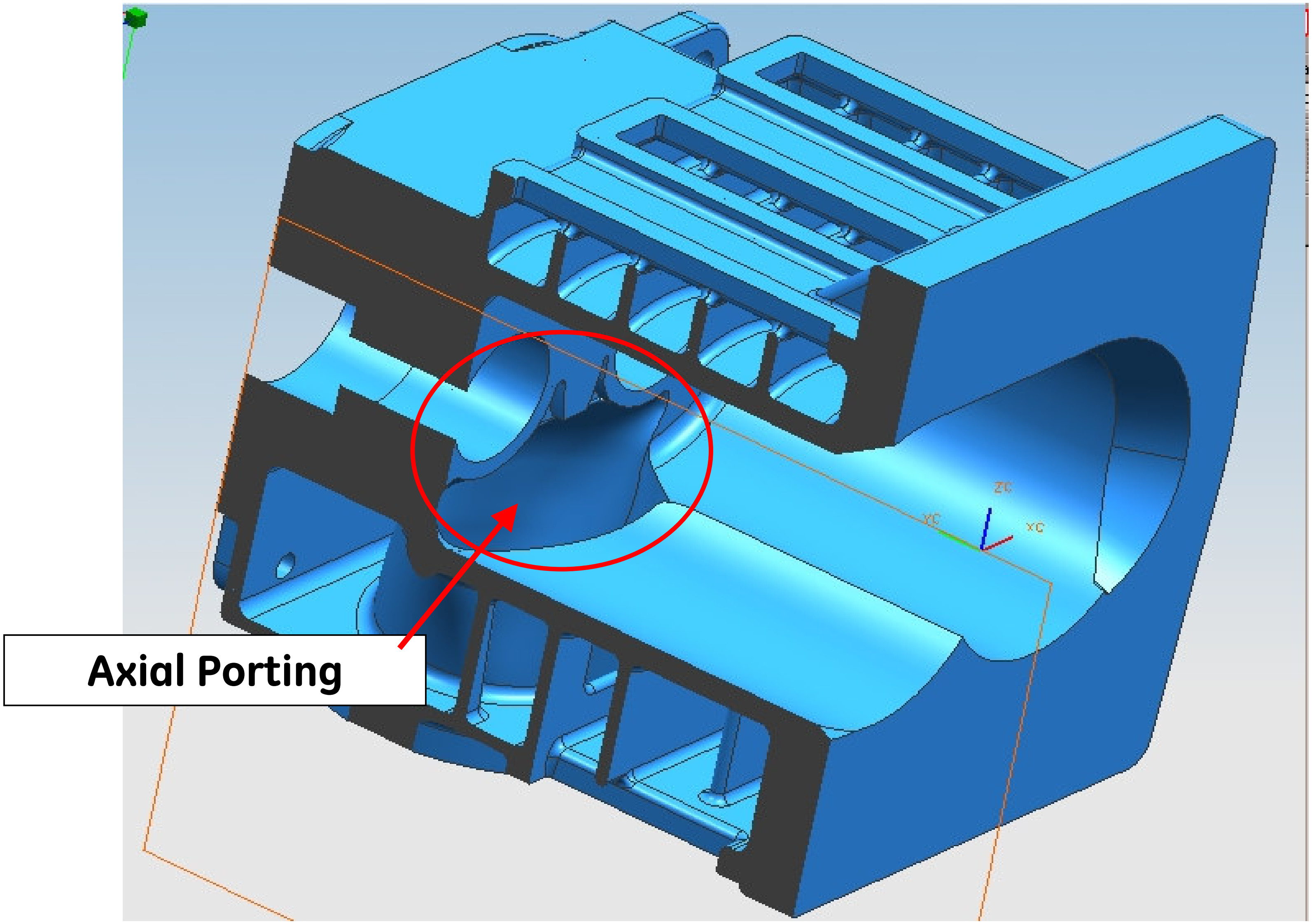
Acoustic System Variables



Physical System - OFS Cross Section



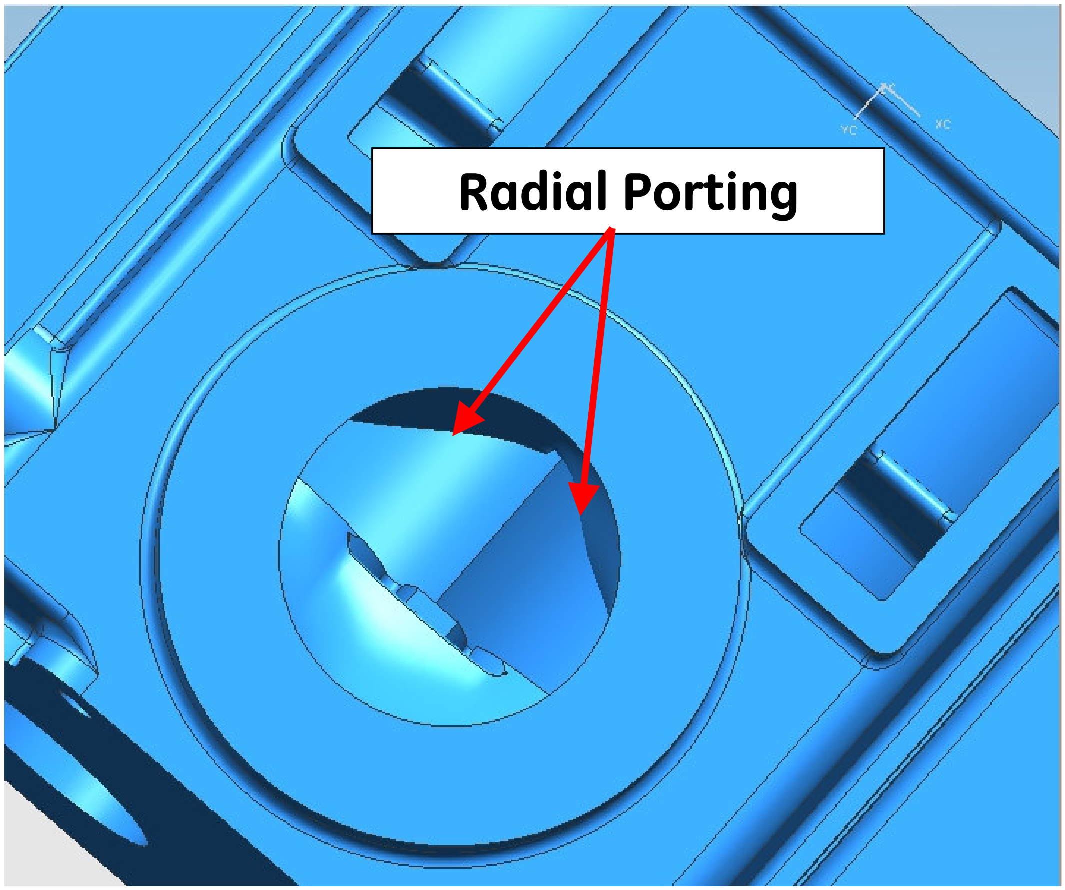
OFS Compressor Axial Discharge Porting



OFS Compressor Axial Discharge Porting

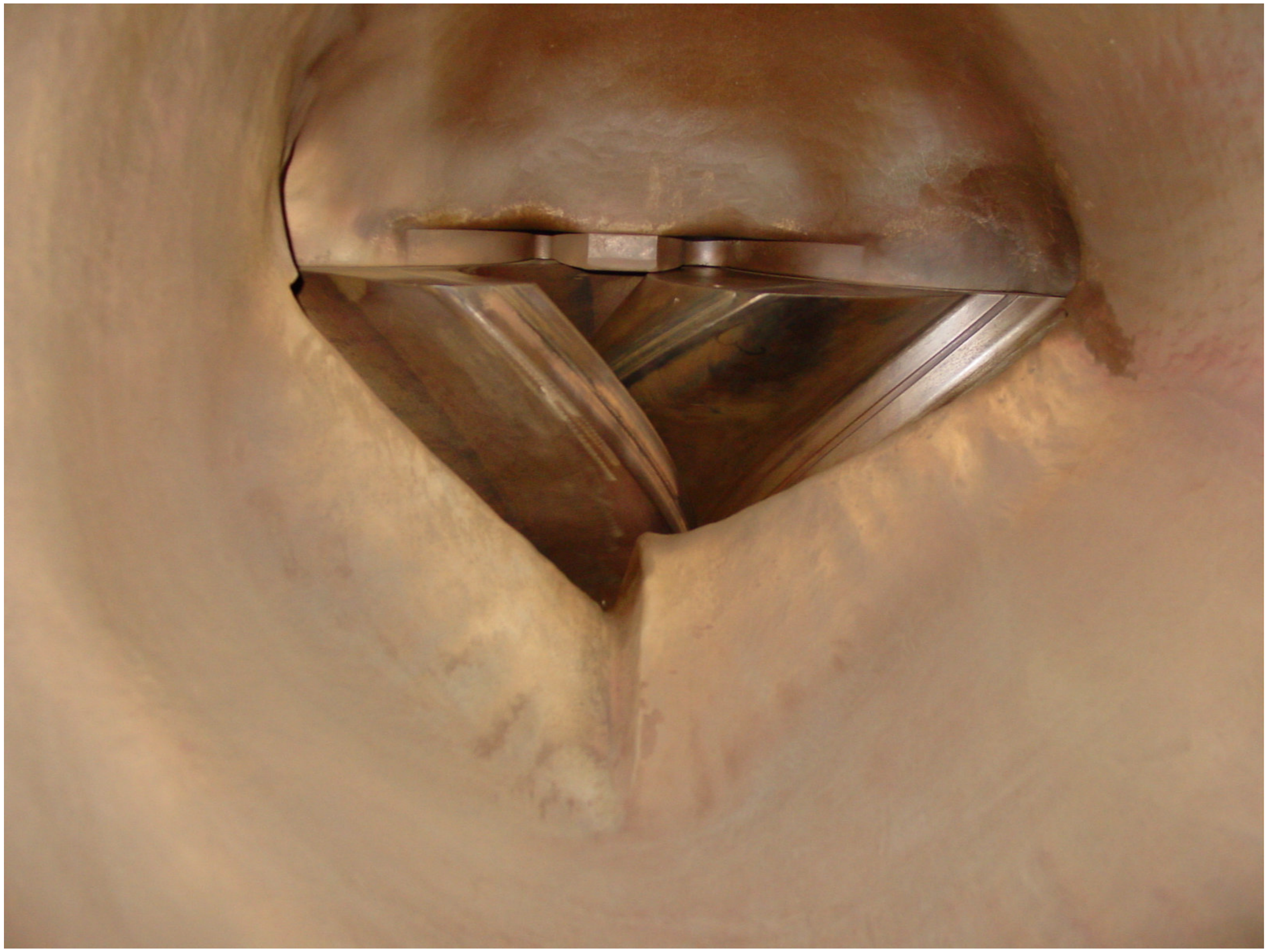
Axial Porting

OFS Compressor Radial Discharge Porting

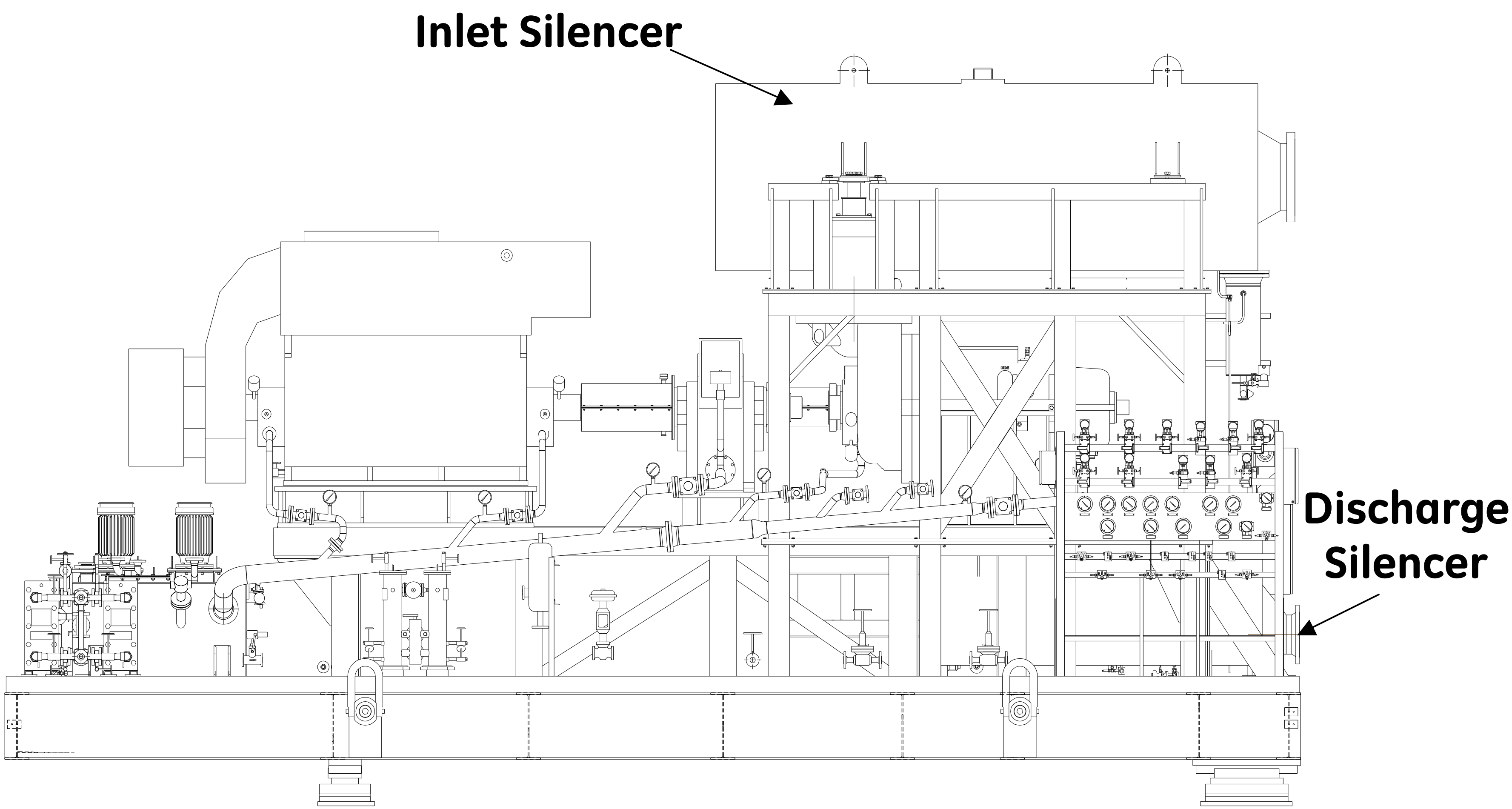


OFS Radial Discharge Porting

Radial Porting



Physical System - General Arrangement

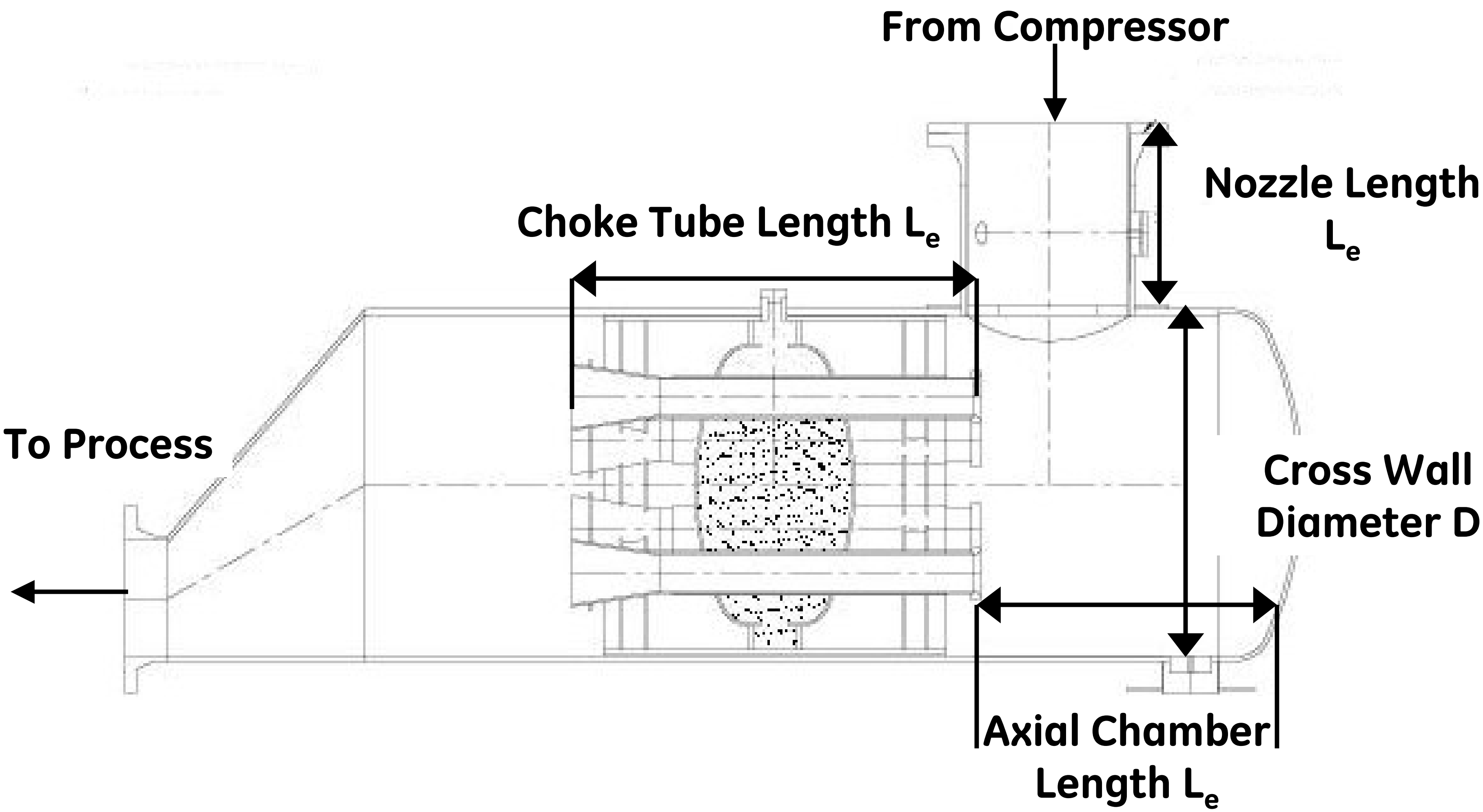


Compressor Package

OFS String Test Arrangement

Physical System - Silencer Cross Section

Patent WO99/11938 (Pulsation Dampener)



Gas Properties

c = acoustic velocity (velocity of sound in a fluid)

$c = SQRT(zkg_cRT)$ for ideal gas

Where: **R = Gas constant (1545.33 / mol weight)**

T = Temperature (Rankine = 459.6 + °F)

k = Ratio of specific heats (c_p/c_v)

g_c = Proportionality constant

$= 32.2\ lb_m\text{–}lb_f / s^2$

z = Compressibility factor

System Excitation

- **Lobe Passing Frequency**

  Number of rotor lobes multiplied by compressor operating speed. (4X running speed for this case)

- **Harmonics of Lobe Pass**

  Fixed speed implies fixed lobe passing frequency and harmonics

  Variable speed implies lobe passing frequency and harmonics will vary with compressor operating speed

1-D Acoustic Frequency Equations

- **Nozzle Modes (Open-Closed System)**

  n = (1,3,5,7,9....) * c/4*L_e where c is acoustic sound speed and Le is nozzle acoustic length

- **Axial Chamber Length Modes (Closed-Closed System)**

  n = (1,2,3,4,...) * c/2*L_e where c is acoustic sound speed and Le is axial chamber acoustic length

1-D Acoustic Frequency Equations (cont)

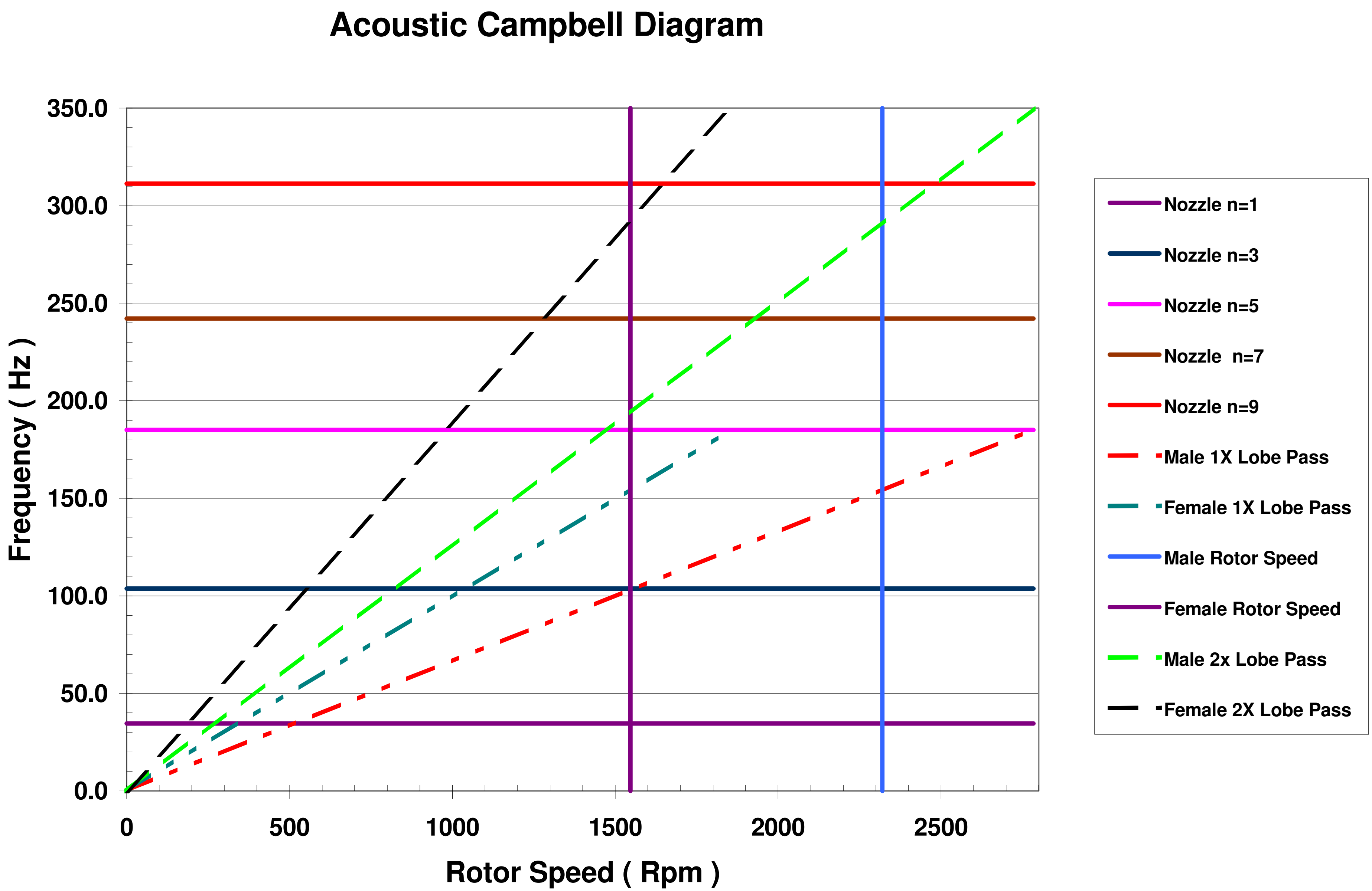
- **Choke Tube "Pass Band" Modes (Open-Open System)**

  n = (1,2,3,4,…) * c/2*L_e where c is acoustic sound speed and Le is choke tube acoustic length

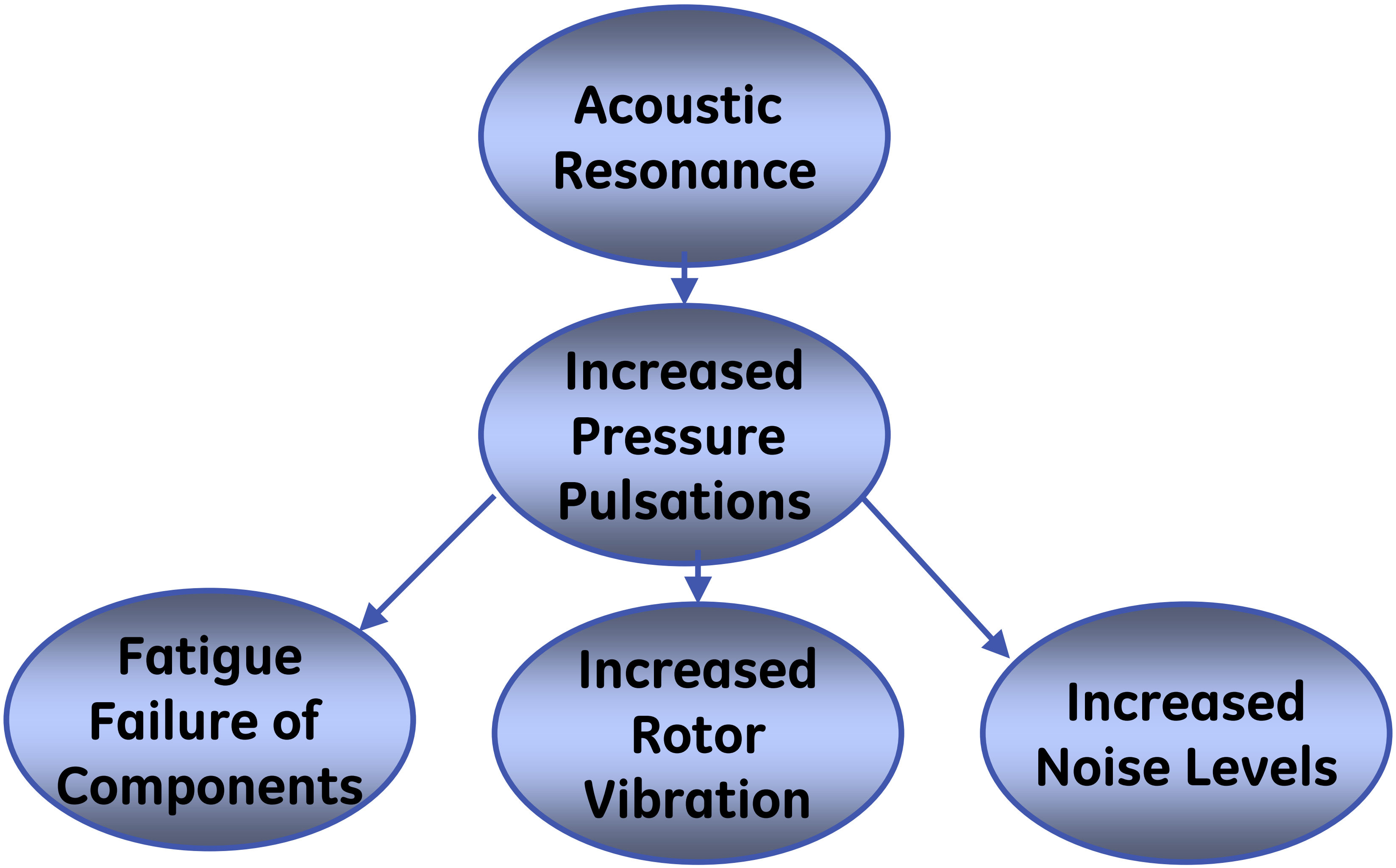
- **Cross Wall "Lamda" Modes (Closed-Closed System)**

  n = λ * c/D where c is acoustic sound speed and λ is (0.586, 0.972, 1.219, 1.337) for the first four λ modes

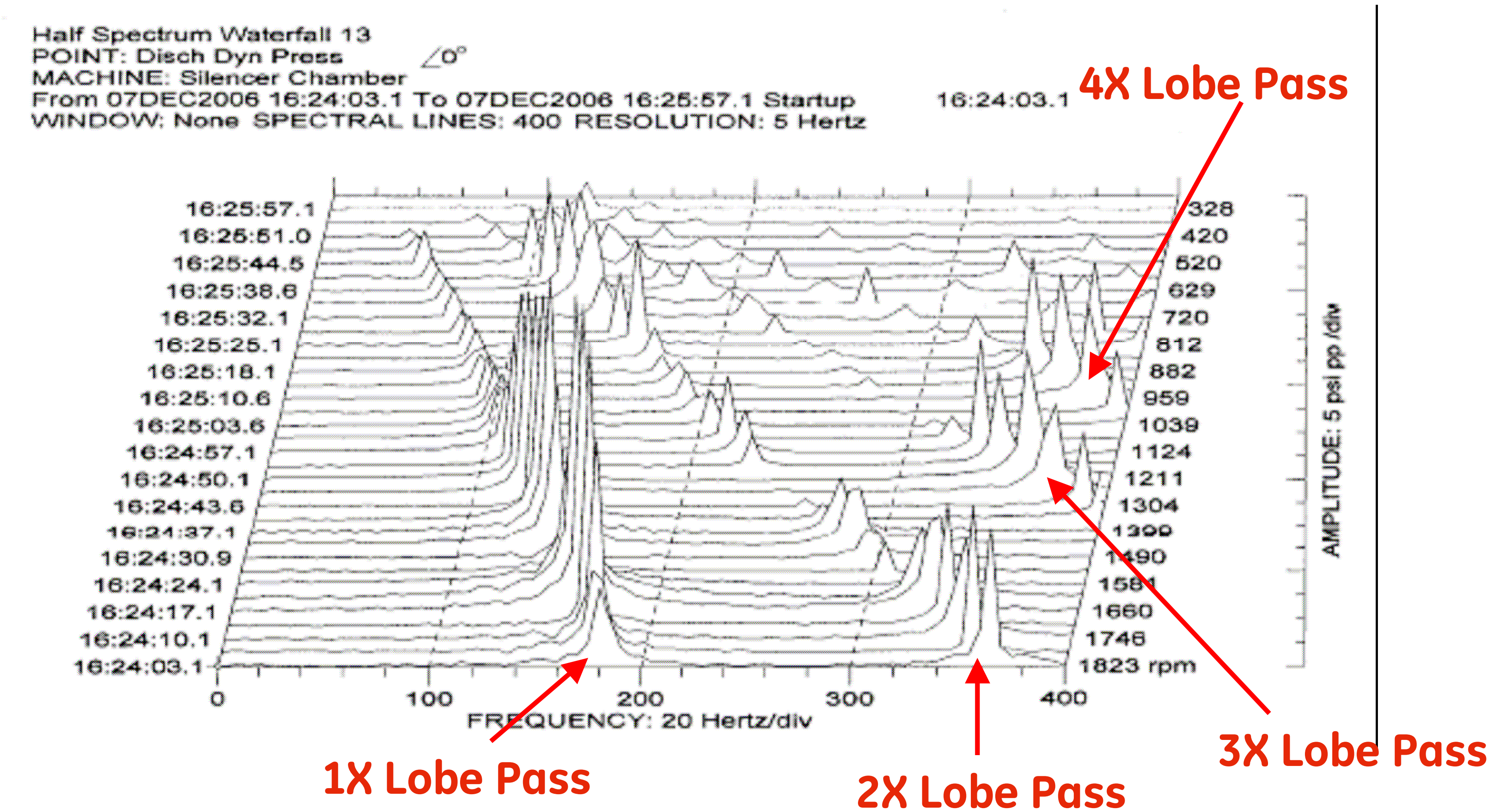
Campbell Diagram



Why do we need to understand the impact of Acoustic Pulsations?



Dynamic Pressure in Discharge Silencer as Function of Lobe Pass Frequency

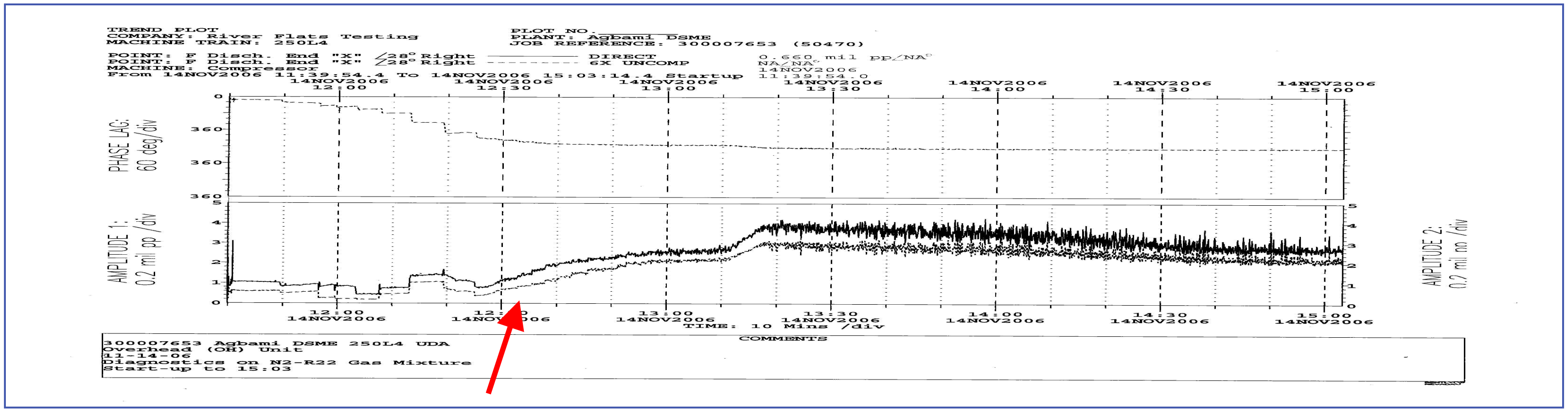


Shop Testing

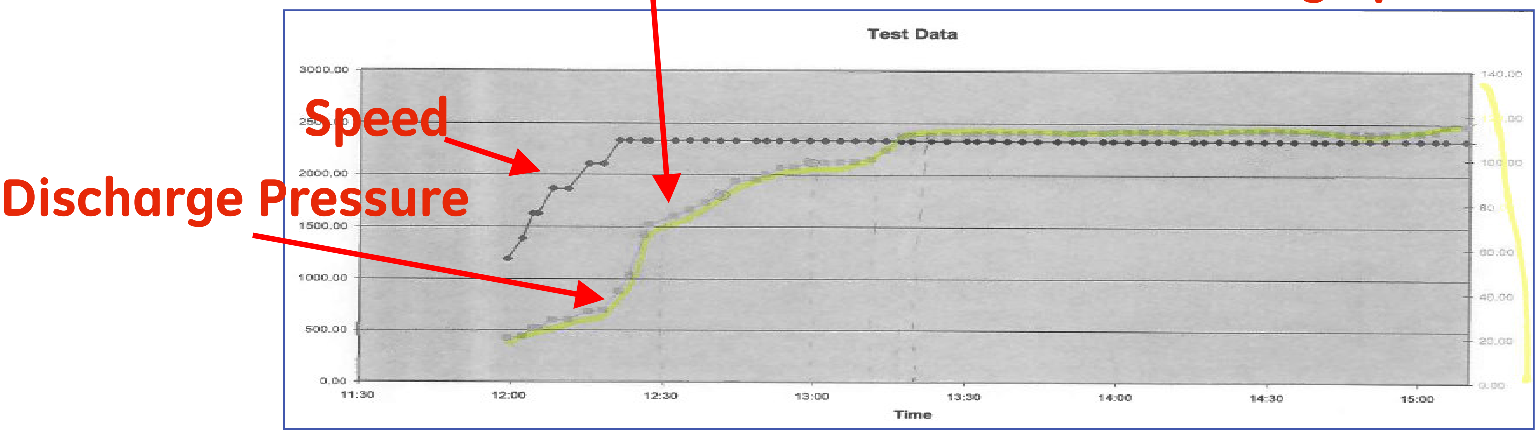
- **Test gas may not match process gas (MW, Z, or k)**
  - **MW affect the speed of sound**
  - **K affects the speed of sound**
  - **K affects the discharge temperature which affects the speed of sound**
- **Test gas may not produce the same compressor internal volume matching as process gas**
  - **Pressure pulsations may be higher with test gas**
- **Test gas discharge pressure may need to be raised to volumetrically match the process**
  - **Higher discharge pressure and/or higher discharge density results in higher pressure pulsations**

250L4 OFS Full Pressure Testing

250L4 OFS Compressor Full Load Test



Vibration increase tracks with discharge pressure increase.



- **Vibration amplitude on female rotor discharge end "X" probe is closely related to the increase in discharge pressure**
- **Is this a pressure pulsation effect or density effect?**

API 619 requirements

Unless otherwise agreed, the pressure drop through the pulsation suppressors/silencers shall not exceed the following values:

a) For suction silencer 1% of the absolute pressure at the pulsation suppressor/silencer inlet.

b) For discharge silencers 2.5% of the absolute pressure at the pulsation suppressor/silencer discharge.

The peak to peak pulsation levels on the process side piping side of the the inlet and discharge silencers shall not exceed 2 percent of the mean line absolute pressure or the value calculated from the following formula, whichever is smaller:

SI Units: $P\% = 28.6 / (P^{1/3})$ or U.S customary units: $P\% = 15/ (P^{1/3})$

Where:

$P\%$ = maximum allowable peak to peak pulsation expressed as a percentage of the mean line absolute pressure.

P = mean line-side pressure in kPa absolute (psia).

Modifications Made to Minimize Pressure Pulsations

Orifice Basket

- Position to be effective (velocity mode shape plot)
- Pressure drop and API performance testing

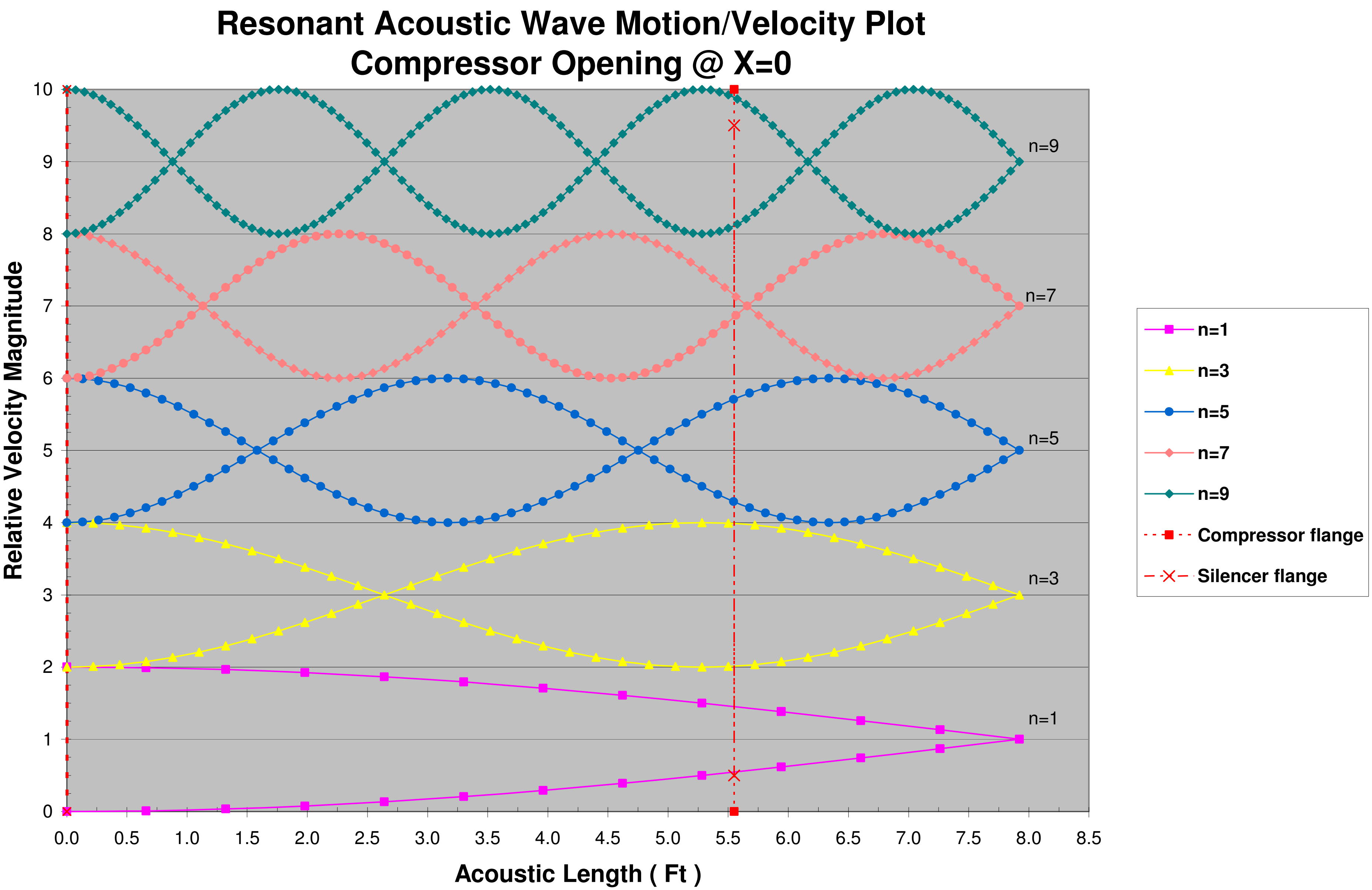
Kotter Plate

- Position to be effective (velocity mode shape plot)
- Pressure drop and API performance testing

Diffuser

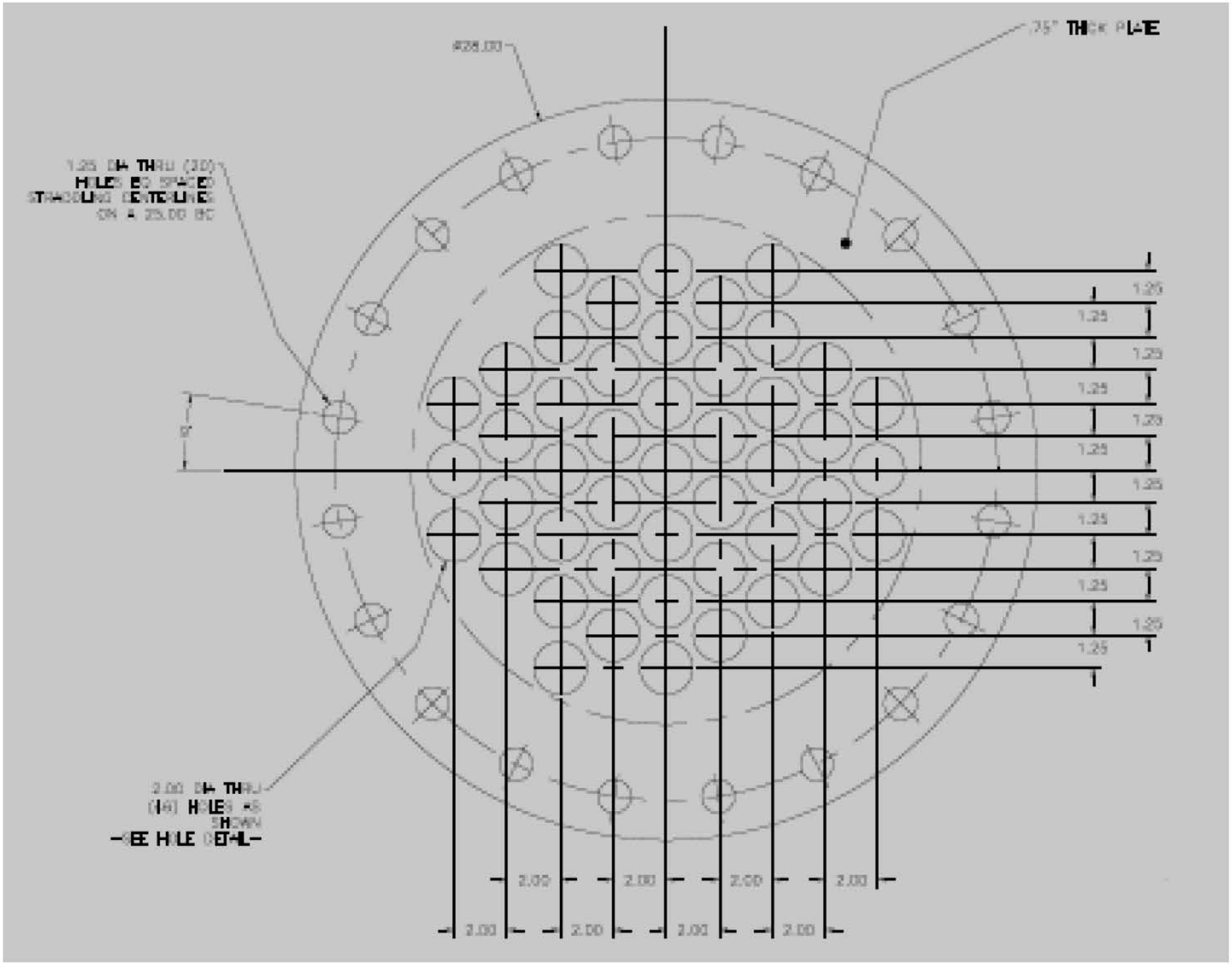
- Changes nozzle and possibly chamber frequencies
- Pressure drop and API performance testing

Velocity Mode Shape Plot

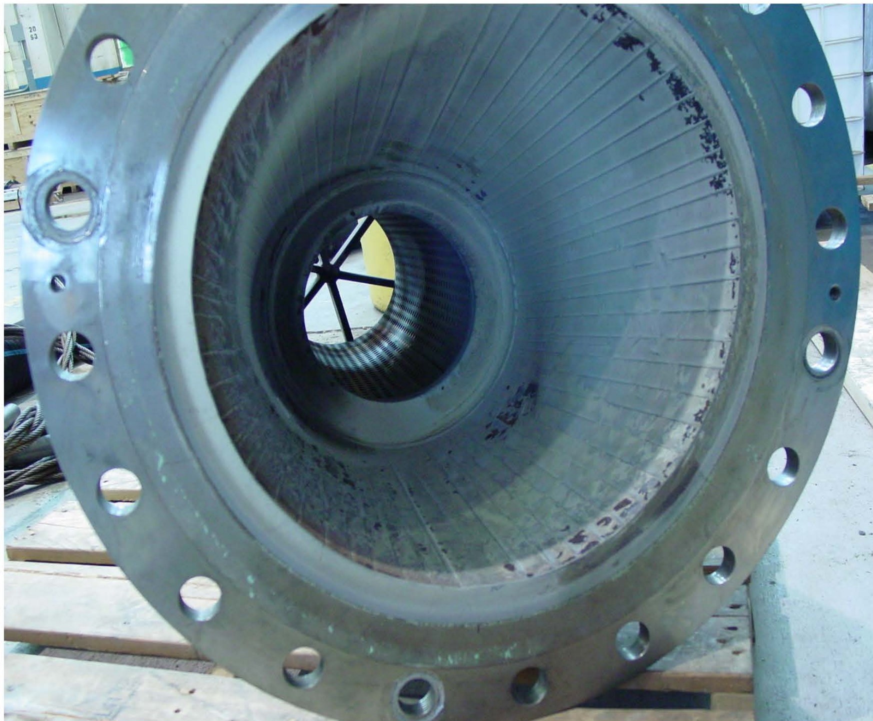


Orifice Basket

Kotter Plate



Diffuser-Patented 09/486478



Field Startup Considerations

- **Startup gas should be specified on Data Sheets**

- **If compressor drive is variable speed, the startup speed range should be specified**

Process Startup Consideration

- **Define transition in gas composition from startup case to operating case (Such as nitrogen purge with introduction of process gas)**

- **Define operating cases with varying MW, z, k, and T2**

- **Define variable speed range**

Questions?

Back-Up

Testing and Results

- **Test speed of sound for 60MW gas at test conditions was 858 ft/sec. For 74MW gas at test conditions was 751 ft/sec**

  (751/858)*2350 = 2057 rpm

  (751/858)*1550 = 1357 rpm

- **Response peaks on male and female rotors for the two gases occur at frequencies related to the ratio of sound speed**

- **Agreement (?) reached on matching discharge acoustic sound speed**

- **Consultant identified results of an analysis commissioned by the end user which was completed in Dec 2005. The results identified that several acoustic modes on the discharge end of the compressor were very close to the lobe passing frequency of the compressor**

- **Conducted speaker testing to confirm compressor acoustic cavity length**

Testing and Results (continued)

- **GE becoming convinced that the high rotor vibration is associated with high dynamic pressure pulsations which are driving a forced response of the rotor**
- **Customer consultant reviewing the test data states that dynamic pressure pulsations are a cause of concern and more detailed investigation into the the system acoustics begins**
- **Calculations made to define the range of acoustic speed of sound for matched acoustic testing**
- **Critical or forced response issue unresolved! Test with extreme range of acoustic sound speed from ~650 ft/sec to ~900 ft/sec at contract pressure and ratio across the compressor**
- **Test at contract acoustic sound speed with varying levels of discharge density at contract ratio across the compressor**
- **Since there was an acoustic response and high dynamic pressure pulsations, then change the gas composition to move the acoustic resonance**

Testing and Results (continued)

- Objective – See if the response peaks of rotor vibration move to establish if forced response and not resonance was cause of high rotor vibration
- Contract discharge acoustic sound speed results in operation on a n=3 mode of a ¼ wave length acoustic resonance
- No way to detune the mode effectively
- Introduce pressure drop to “kill” pressure pulsations
- Kotter plate installed at the compressor discharge flange
- Orifice “basket” installed in the silencer nozzle

Conclusions

- **The test Bode plots identify that most of the amplitude is related to lobe pass frequency**
- **Tests with significant sound speed changes does little to move the speed at which peak response occurs**
- **Acoustic resonance creates conditions of forced response**
- **Density affects the level of vibration at fixed acoustic conditions**