INVESTIGATIONS OF HIGH PRESSURE ACOUSTIC WAVES IN RESONATORS WITH SEAL-LIKE FEATURES

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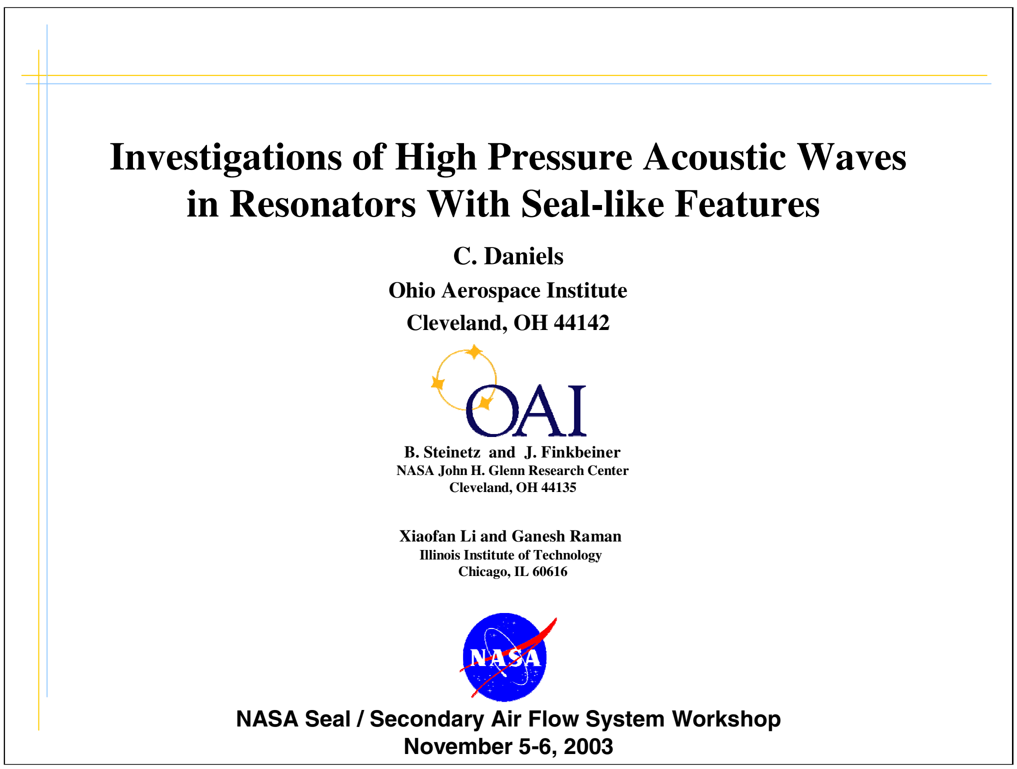

Presentation

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- Program Objective
- Research Objective
- Baseline Configuration
  - Experimental Setup
  - Results
- Closed Configuration with Blockages
  - Experimental Setup
  - Results
- Open Resonator Configuration
  - Experimental Setup
  - Results
- Open Resonator Configuration with Δp
  - Experimental Setup
  - Results
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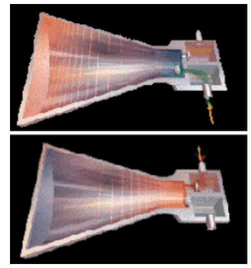
Background

- Linear acoustic theory limits pressure waves to approximately 10% overpressure. Shock formation dissipates any additional wave energy.
- Dr. Timothy Lucas discovered a method to produce high-amplitude pressure waves in acoustic resonators in 1990.
- Using specially shaped resonating cavities, dynamic gas pressures exceeding 500 psi can be generated shock-free.
- Lucas focused on creating refrigeration compressors and formed Macrosonix Corporation to develop the technology.
- Most previously published work focused mainly on using refrigerant as the working fluid.



Mechanical Engineering Magazine "Sound Waves at Work" March, 1998

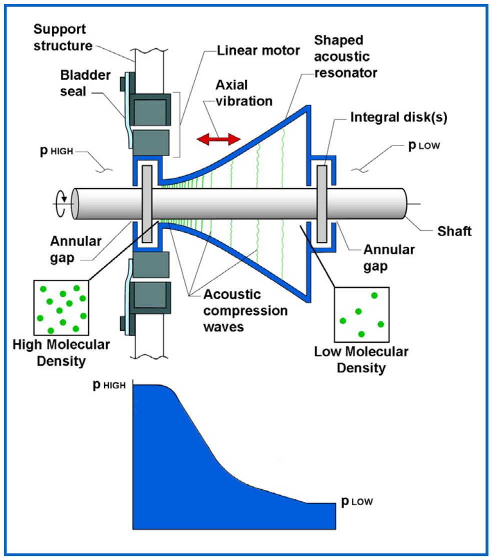
Program Goal

Development of a non-contacting seal that would overcome two fundamental problems of conventional seals:

- Leakage
- Wear

Exploit recent developments in non-linear acoustics

- Specially shaped acoustic resonator is driven at resonance
- Generation of high-amplitude pressures



Research Objective

- Extend the research of non-linear acoustics in resonators:
  - Lawrenson, et al. (1998)
    - **Experimentally generated high overpressure unshocked waveforms**
    - **Peak acoustic pressures of 1446kPa (209 psia)**
  - Ilinskii, et al. (1998)
    - **1-Dimensional numerical prediction**
    - **Non-linear acoustics with shaped resonators**
  - Chun, et al. (2000)
    - **Additional resonator shapes**
- Determine if high-amplitude standing pressure waves can be generated:
  - using air as the working fluid
  - in resonators containing seal-like features
    - **blockages (shaft)**
    - **ventilation holes (annular clearance)**

Dimensionless Variables

Dimensionless **Pressure**

– $\mathbf{p / p_0} = p_{\mathrm{INSTANTANEOUS}} / p_{\mathrm{AVE\ QUIET\ CONDITION}}$

– $\mathbf{p_{MAX} / p_0} = p_{\mathrm{CYCLE\ MAXIMUM}} / p_{\mathrm{AVE\ QUIET\ CONDITION}}$

- Dimensionless **Frequency**
  – $\mathbf{\Omega} = 2 \cdot f \cdot l_{\mathrm{RESONATOR}} / (\gamma \cdot 8314 \cdot T_K / \mathrm{MW})^{1/2}$

- Dimensionless **Time**
  – $\boldsymbol{\tau} = f \cdot t / (2 \cdot \pi)$

Baseline Configuration

Baseline Configuration: Experimental Setup

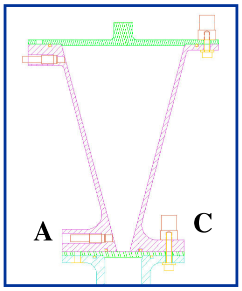
- **Electrodynamic Shaker Table**
  - **500lbf (2220N) capacity**
- **Conical Resonator**
  - **r(z) = 0.0056 + 0.2680·z [m]**
  - **Aluminum 7075T6 with 0.14inch (3.6x10^{-3}m) wall thickness**
  - **Containing air (ambient conditions)**
- **Instrumentation**

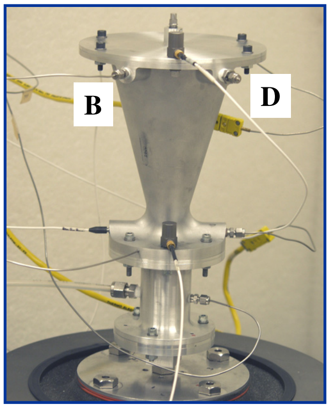
A. Dynamic pressure sensors (2)

B. Static pressure transducers (2)

C. Accelerometer (2)

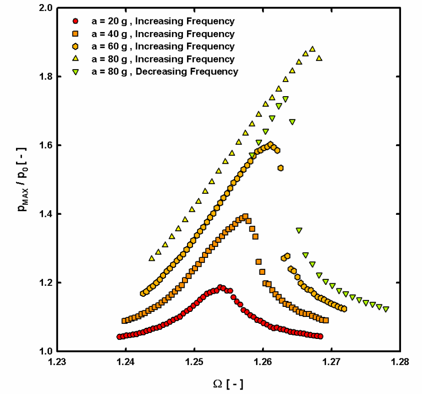
D. Thermocouples (2)





Baseline Configuration: Experimental Results

- Non-linear frequency shift with increasing acceleration amplitude
- Moderate hysteresis evident (hardening)



Cylinder shocks below Pmax/Po < 1.1

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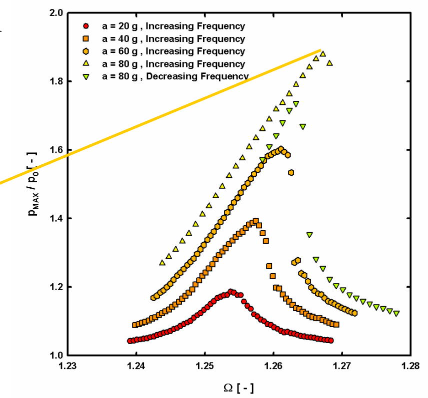
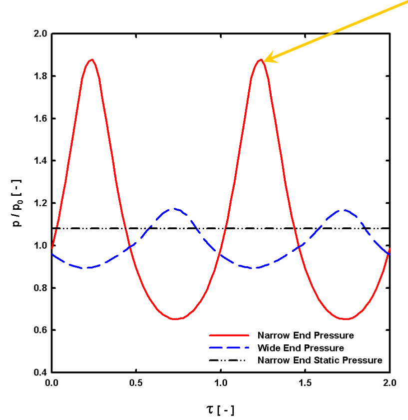




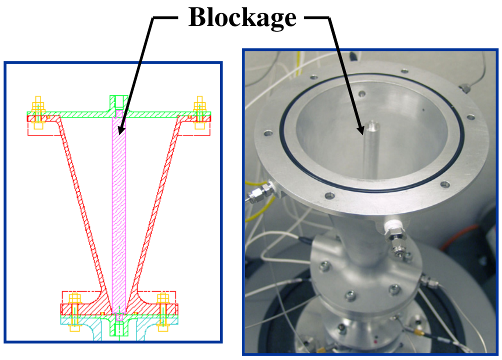
- Constant max acceleration: 80g
- P_o = 100.2 kPa (14.5 psia)
- No microshocks evident
- P_{MAX} / P_0=1.88 (188.3kPa / 27.3psia)
- Static Pressure rise of 8.4 kPa (1.2psi)

Cylinder shocks below Pmax/Po < 1.1

Closed Resonator Configuration With Blockages

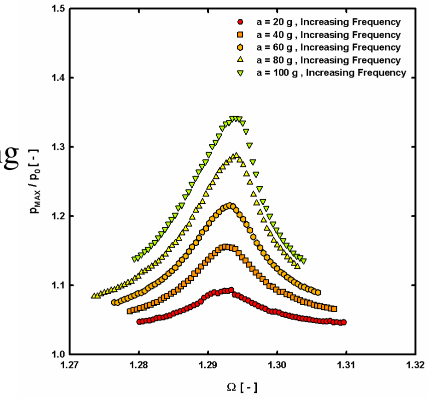
Closed Configuration w/ Blockages: Experimental Setup

- Identical hardware and instrumentation used in Baseline experiments
- Baseline end caps (no ventilation holes)
- Additionally
  - Centrally located cylindrical blockage
    - **ϕ 0.403 inch (1.255 cm)**



Closed Configuration w/Blockages: Experimental Results

- Blockage Diameter: ϕ 0.403 inch (1.255 cm)
- No apparent hysteresis
- No frequency shift with increasing acceleration amplitude



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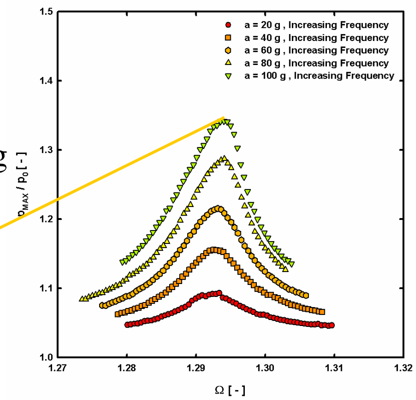
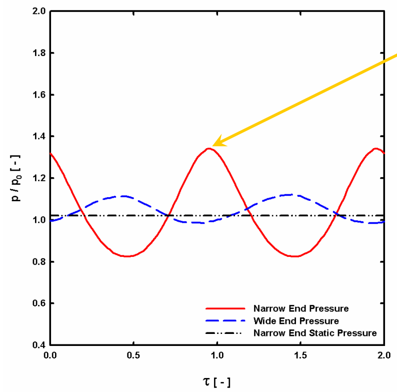


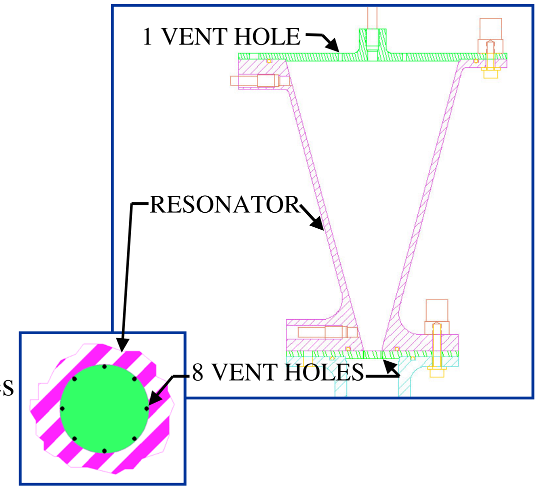


- No microshocks evident
- P_o = 97.6 kPa
- P_{MAX} / P_0 = 1.34 (130.8 kPa)
- Static Pressure rise of 2.1 kPa

Open Resonator Configuration

Open Resonator Configuration: Experimental Setup

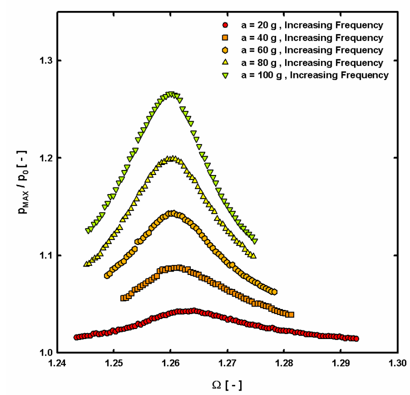
- Identical hardware and instrumentation used in baseline experiments
- End caps
  - Aluminum 7075T6
  - 0.188inch (4.77×10^{-3}m) thickness
- Additionally
  - Wide end cap:
  - one (1) ventilation hole ϕ0.100in ($\phi 2.54 \times 10^{-3}$m)
  - Narrow end cap:
  - eight (8) ventilation holes ϕ0.025in ($\phi 6.35 \times 10^{-4}$m)



Wide and narrow ventilation have similar areas

Open Configuration: Experimental Results

- Max acceleration: 100g
- No apparent hysteresis
- No frequency shift with increasing acceleration amplitude



Open Configuration: Experimental Results

- Max acceleration: 100g
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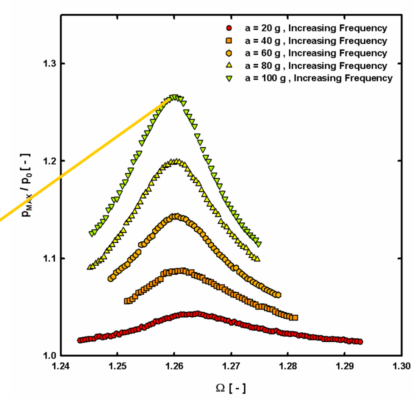
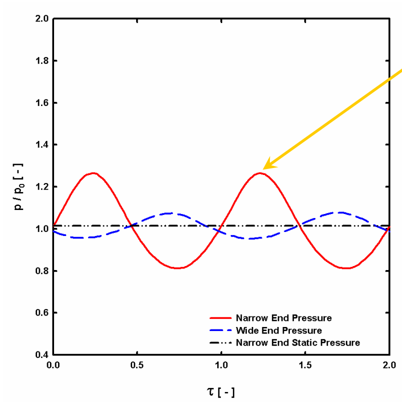
- No frequency shift with increasing acceleration amplitude





- No microshocks evident
- P_o = 99.2 kPa
- P_{MAX} / P_0 = 1.26 (125.5 kPa)
- Static Pressure rise of ~ 0.5 kPa

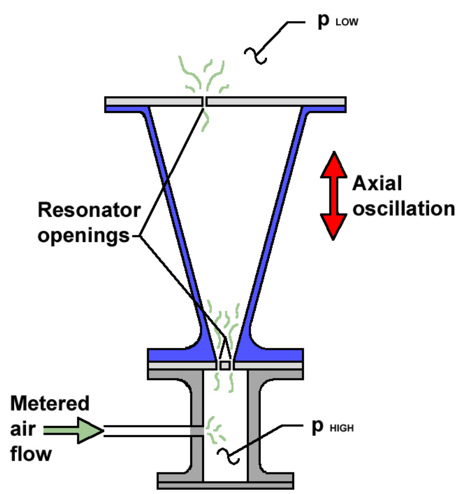
Open Resonator Configuration with Pressure Differential

Open Resonator Configuration: Experimental Setup

- Identical hardware and instrumentation used in open resonator experiments

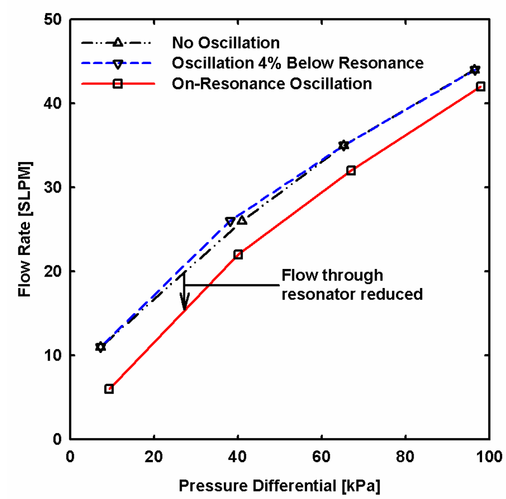
- Additionally
  - Plenum pressurized
  - Air flow metered

- Oscillation conditions:
  - No Oscillation
  - Off Resonance
  - On Resonance



Open Resonator with Differential Pressure Results

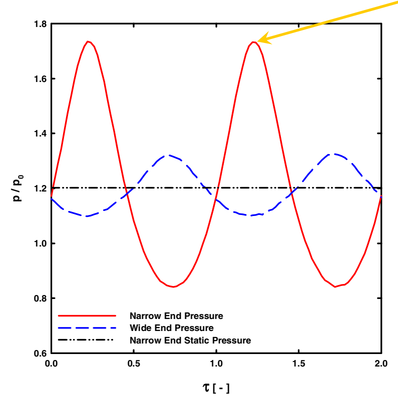
- **No Oscillation**
- **Off Resonance**
- **On Resonance**

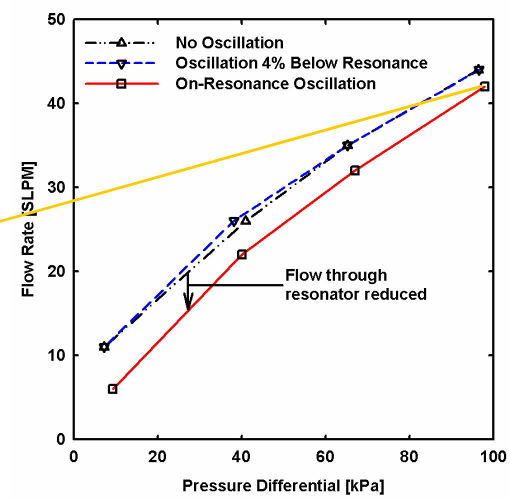


1.5 psi seal

Open Resonator with Differential Pressure Results

- **No Oscillation**
- **Off Resonance**
- **On Resonance**





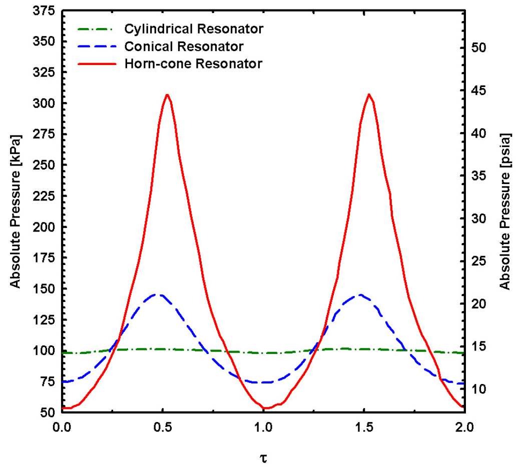
Feasibility of reducing air-flow using acoustic pressurization demonstrated

Summary

1. Standing waves with maximum pressures of 188 kPa have been produced in resonators containing ambient pressure air.
2. Addition of structures inside the resonator shifts the fundamental frequency and decreases the amplitude of the generated pressure waves.
3. Addition of holes to the resonator does reduce the magnitude of the acoustic waves produced, but their addition does not prohibit the generation of large magnitude non-linear standing waves.
4. The feasibility of reducing leakage using non-linear acoustics has been confirmed.

Future Work

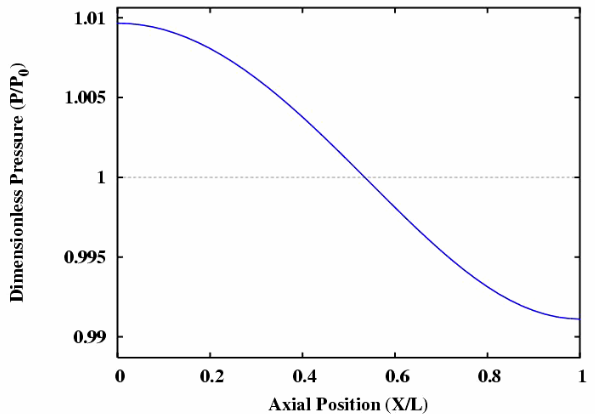
- Other resonator shapes are known to produce higher pressure amplitudes (shown right).
- Other advanced seal concepts have been identified and are expected to have greater pressure blocking ability.

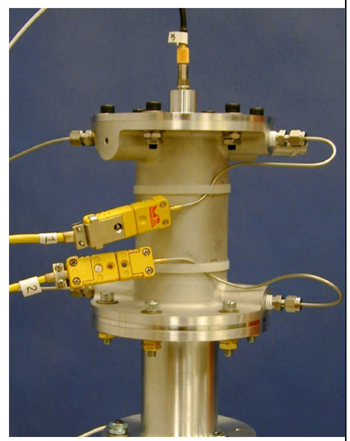


End of Presentation

Appendix

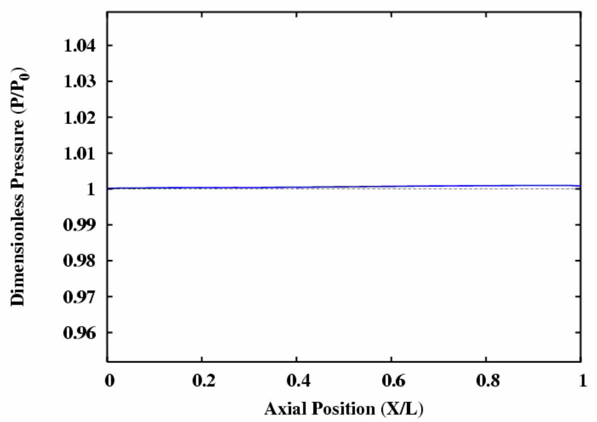
Shock Formation in a Cylindrical Resonator

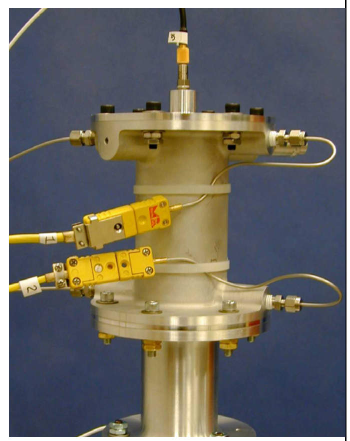




Off Resonant Frequency Oscillation

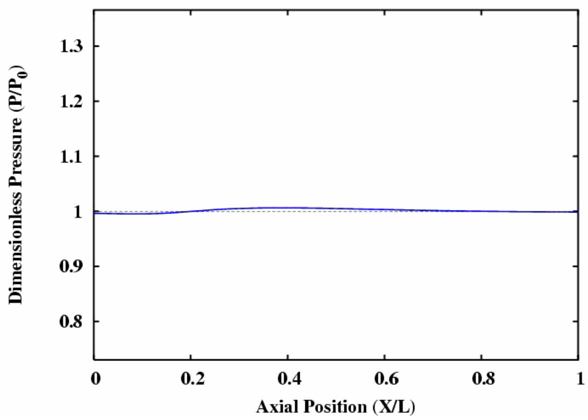
Shock Formation in a Cylindrical Resonator

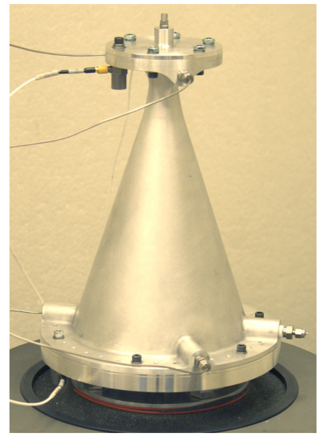




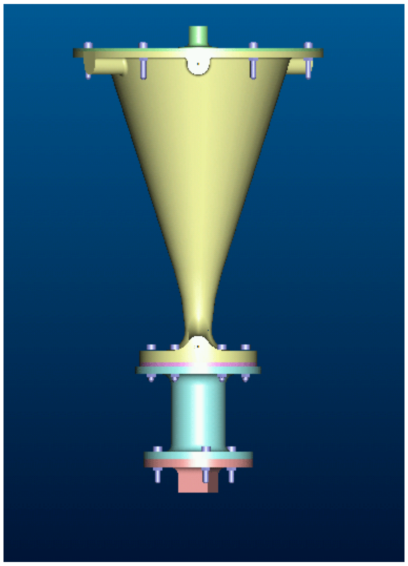
<u>On</u> Resonant Frequency Oscillation

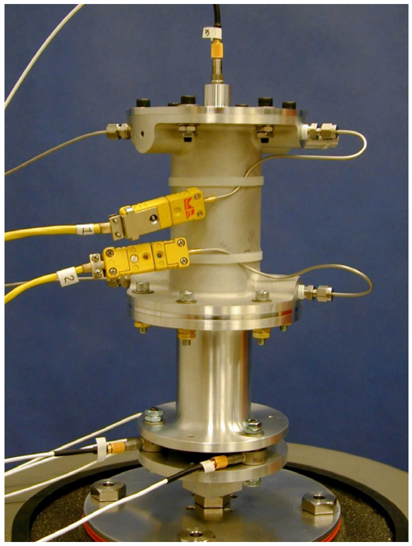
Pressure Waveform in a Horn-cone Resonator





<u>On</u> Resonant Frequency Oscillation

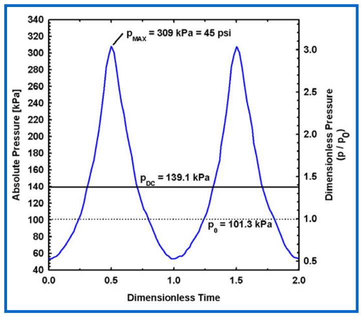


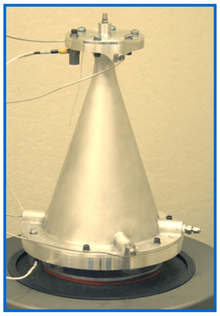


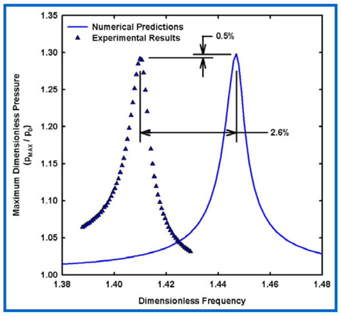
Horn-cone resonator results

Using New Glenn Acoustic Seal Lab:

- Demonstrated high acoustic pressures **(~45psi)** suitable for seals can be generated in closed resonators with **air** as working fluid (Literature: high molecular weight refrigerant)
- Demonstrated high acoustic pressures possible with addition of central shaft blockage





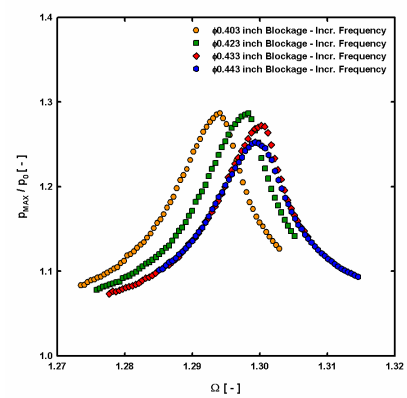


Developed / validated

- 1-Dimensional acoustic resonator analysis/design tool for closed resonators.
  - **Good agreement between experimental and predicted pressure amplitudes and resonant frequency**

Closed Configuration w/Blockages: Experimental Results

- Constant maximum sinusoidal acceleration: 80g
- Increasing blockage diameter:
  - Reduces P_{MAX}
    - **$P_{MAX} / P_0 = 1.65$ (ϕ0.403 inch)**
    - **$P_{MAX} / P_0 = 1.57$ (ϕ0.443 inch)**
  - Increases fundamental resonant frequency
    - **$\Omega_1 = 1.293$ (ϕ0.403 inch)**
    - **$\Omega_1 = 1.299$ (ϕ0.443 inch)**



Comparison of Results

- Maximum Acceleration Amplitude: 80g
- From the baseline configuration:
  - P_{MAX} reduced 31% with addition of openings
  - P_{MAX} reduced 36% with addition of blockages
  - Ω increased 2% with addition of blockages