NUMERICAL INVESTIGATIONS OF HIGH PRESSURE ACOUSTIC WAVES IN RESONATORS

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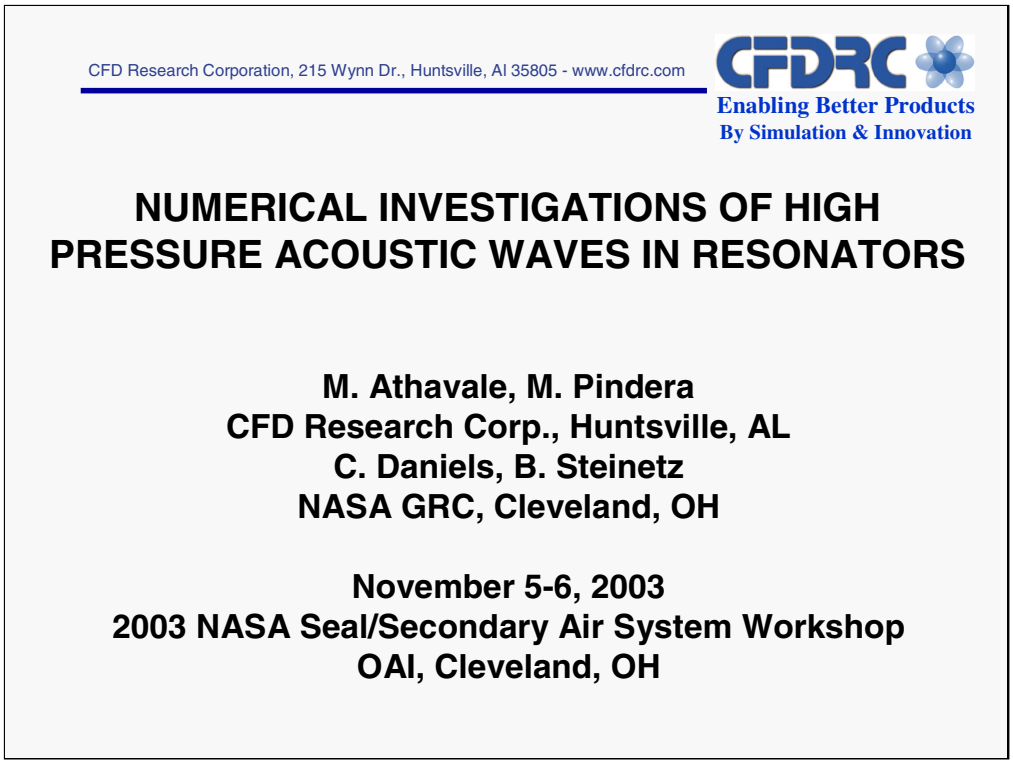


This presentation presents work on numerical investigations of nonlinear acoustic phenomena in resonators that can generate high-pressure waves using acoustic forcing of the flow. Time-accurate simulations of the flow in a closed cone resonator were performed at different oscillation frequencies and amplitudes, and the numerical results for the resonance frequency and fluid pressure increase match the GRC experimental data well. Work on cone resonator assembly simulations has started and will involve calculations of the flow through the resonator assembly with and without acoustic excitation. A new technique for direct calculation of resonance frequency of complex shaped resonators is also being investigated. Script-driven command procedures will also be developed for optimization of the resonator shape for maximum pressure increase.

OUTLINE

- Overview and Objectives
- Description of Methodology
- Closed Cone Resonator, Bomb Tests
- Flow in Cone Resonator Assembly
- Summary

OVERVIEW AND OBJECTIVES

- Acoustic Resonators are Used to Build Large Pressure Changes by Nonlinear Amplification of Small/Acoustic Disturbances
  - acoustic forcing at resonance frequency sets up re-enforcement of pressure waves
  - different resonator shapes for better performance
  - gas compressors, e.g. in refrigeration systems,
  - fluid sealing..
- Current Available Design Tools Consist of 1-D Numerical and/or Analytical Models
  - for estimation of resonance freq., pressurization
  - limited usefulness in complex flow systems+resonators

OVERVIEW AND OBJECTIVES

- **Objectives of this Project is to Test and Adapt a High-Fidelity CFD Code for Analysis and Design Prototyping of Acoustic Resonators**
  - calculation of resonance frequencies of complex-shaped resonators
  - estimation of the pressure performance of resonators
  - optimization of resonator shapes using script-driven automated analysis procedures
  - simulations of full resonator assemblies to predict flow-performance in actual systems

DESCRIPTION OF METHODOLOGY

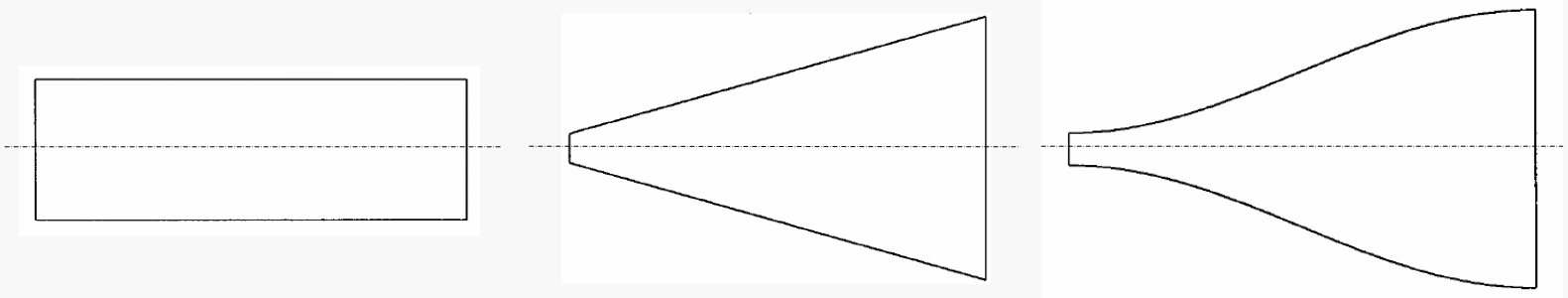
- **Utilize an Advanced CFD Solver CFD-ACE+ for Fully-Resolved Flow Analysis of Resonators;**

  Salient Features are:

  - **finite volume, pressure based**
  - **high-order spatial and temporal resolution**
  - **moving grid formulation for oscillator excitation**
  - **conjugate heat transfer; real gas effects,**
  - **script-based code execution for automated grid generation, code execution, and for optimization of resonator shape**

DESCRIPTION OF RESONATOR SET UP

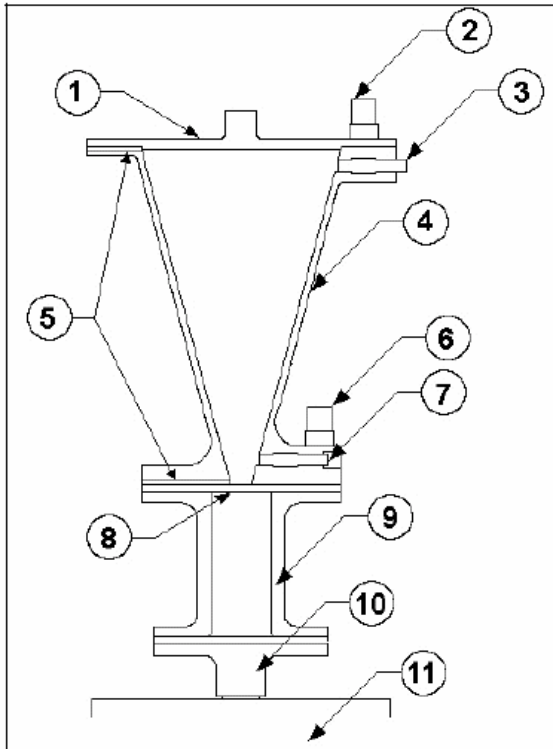
- Acoustic Resonators are Typically Axisymmetric Tubes with Different Shapes
  - cylindrical, conical, half-cosine shaped



- Shape of the Wall and Tube Length are Key Parameters that Decide Pressurization, Resonance Frequency
- Vibrate the Entire Resonator to Input Acoustic Energy
- Cone Resonator Analyzed
  - pressure history at different frequencies
  - numerical results compared with GRC experimental data

CONE RESONATOR SCHEMATIC

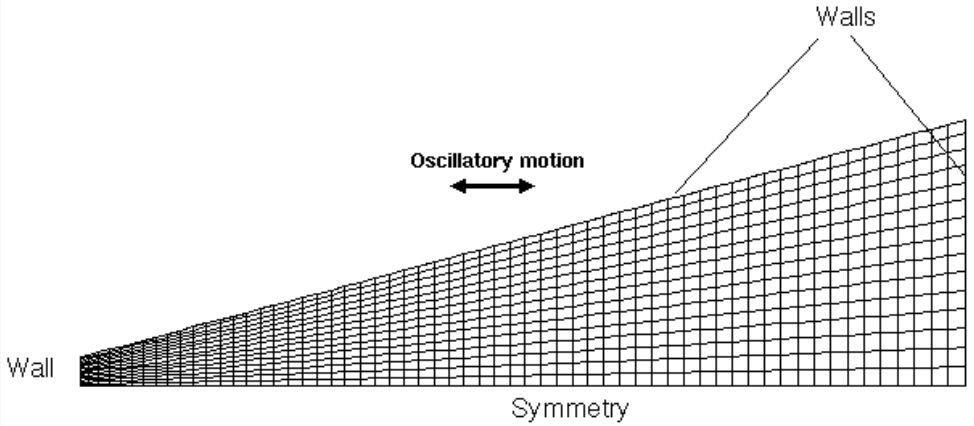
- **The GRC Cone Resonator Setup Was Used in the Simulations, for both Closed Resonator and Resonator with Flow**



1. Sealed wide end cap
2. Wide end accelerometer
3. Wide end dynamic pressure transducer
4. Acoustic resonator
5. Static pressure and thermocouple ports
6. Narrow end accelerometer
7. Narrow end dynamic pressure transducer
8. Sealed narrow end cap
9. Attachment to shaker table
10. Attachment to shaker table
11. Electrodynamic shaker

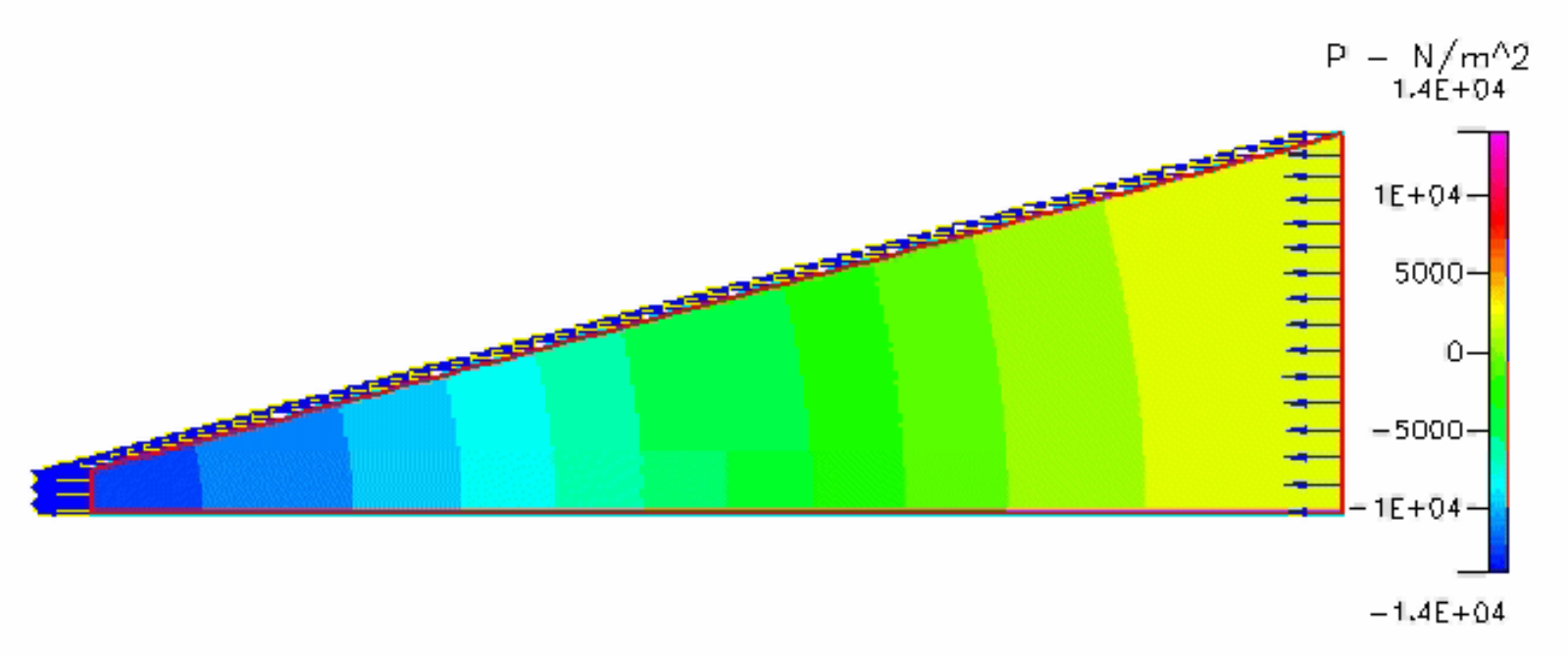
CLOSED CONE RESONATOR MODEL SETUP

- 2-D Axisymmetric Representation of Resonator
- Computational Grid: 50x18 Cells
- Flow and Boundary Parameters:
  - air as compressible working fluid, laminar flow
  - acoustic forcing through a sinusoidal motion imposed on all walls, @ different accelerations
  - 3-rd order convective fluxes, time step @ ~ CFL = 0.5
  - two acceleration amplitudes : 10 and 50g
  - different frequencies: between 1285-1295 Hz



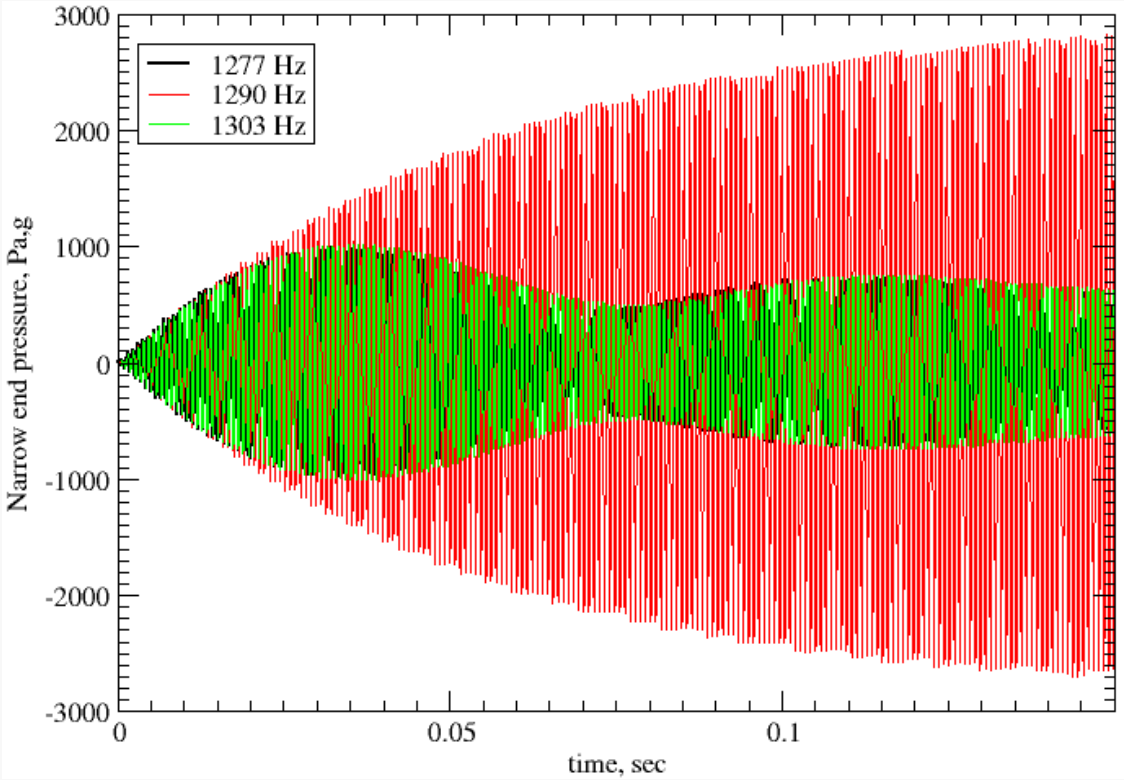
CONE RESONATOR RESULTS

- **Static Pressure Field in the Resonator, at Resonance, Oscillation Frequency = 1288 Hz, Accel. Ampl. = 50g**



CONE RESONATOR RESULTS

- **Static Pressure Trace at the Narrow End; Plotted for Different Frequencies near Resonance, Accel. Ampl. = 10g**



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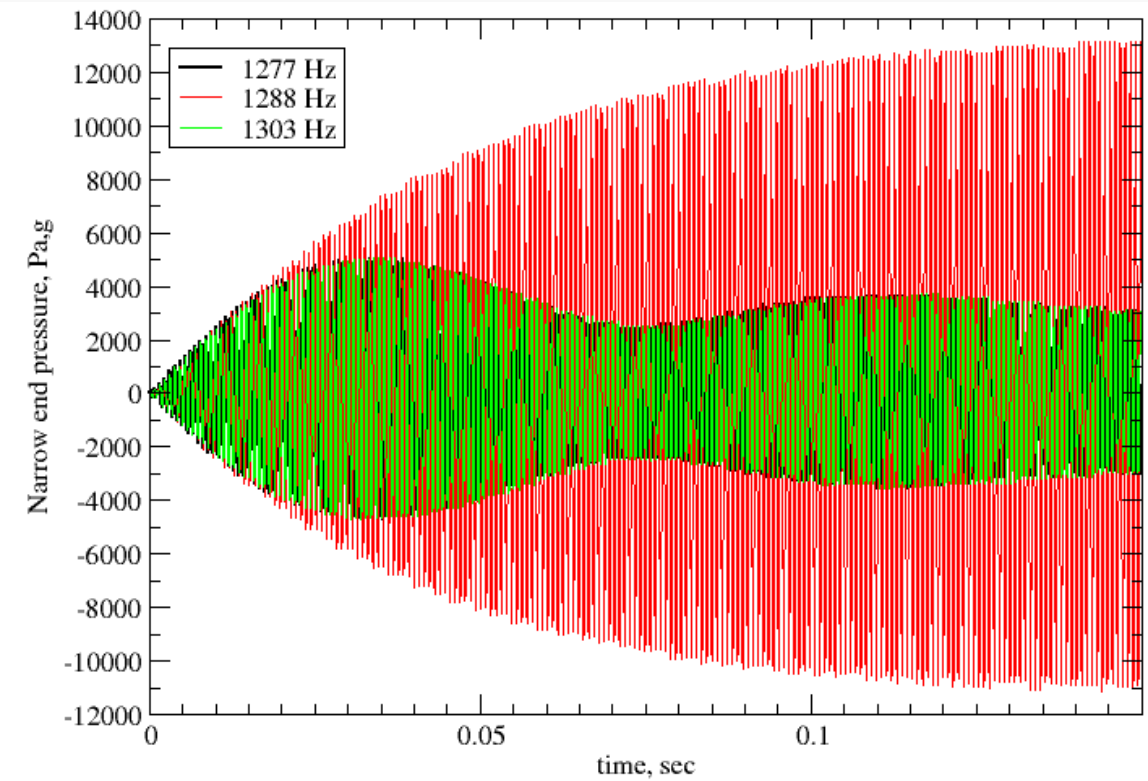


CONE RESONATOR RESULTS

- Calculated and Experimental Results for the Cone Resonator: Pressurization and Resonance Frequencies
  - the experimental and computed resonance frequencies match well
  - pressurization amplitude is also reasonably well predicted

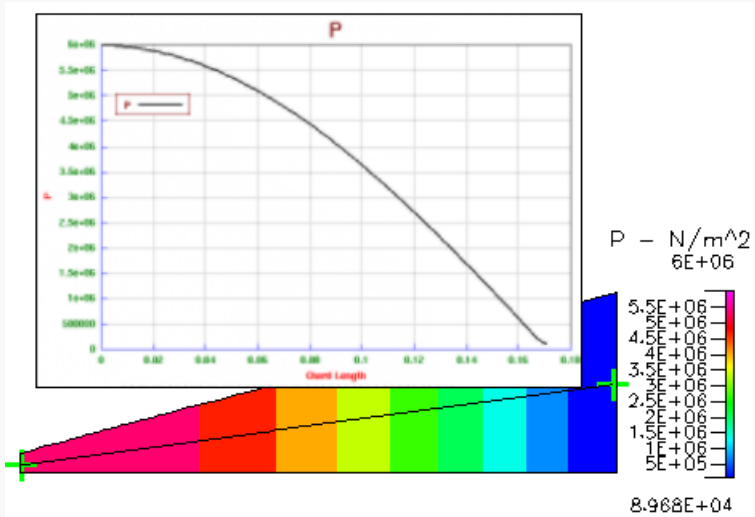
Acceleration Amplitude	Resonance Frequency, Hz Experimental	Resonance Frequency, Hz Numerical	Maximum Pressure, kPa Experimental	Maximum Pressure, kPa Numerical
10 g	1287-1293	1288	118.331	114.5
50 g	1287-1293	1290	104.148	103.28

CONE RESONATOR BOMB TESTS

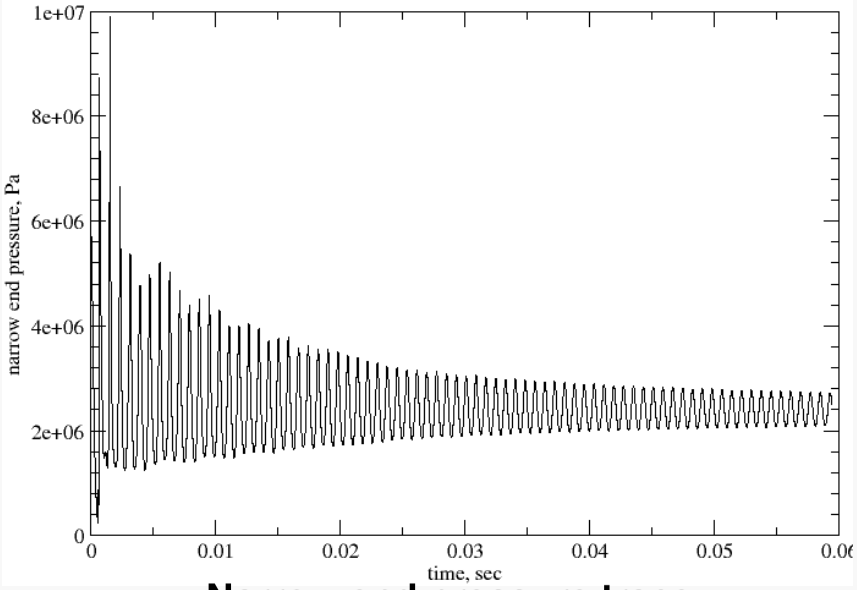
- Resonance Frequency of Resonator is a Key Parameter
  - treatment of complex shaped resonators is difficult
  - frequency-scanning is one approach: calculate pressurization @ different frequencies
- Proposed New Method: Based on Bomb Tests
  - impose an initial pressure distribution in the resonator; typically a half-cosine wave with a large amplitude
  - calculate the time-accurate flow field as the initial pressure wave settles into an oscillatory response at the resonance frequency
- Trial and Error for Resonance Frequencies is Not Needed

BOMB TEST RESULTS

- **Sample Pressure Field and Pressure Trace at the Narrow End of the Resonator, Initial Pressure Amplitude 6 MPa**
  - **Fourier transform of pressure trace → resonance frequency**
  - **no trial and error needed for frequency calculations**
- **Preliminary Results Show Predicted Frequencies Within 3%, Further Refinements in Progress**



Initial pressure distribution



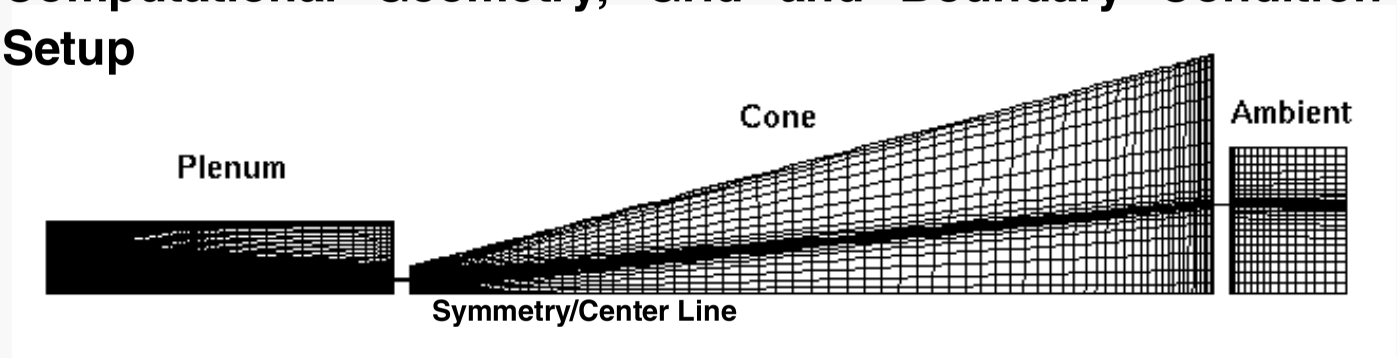
Narrow end pressure trace

RESONATOR ASSEMBLY FLOW SETUP

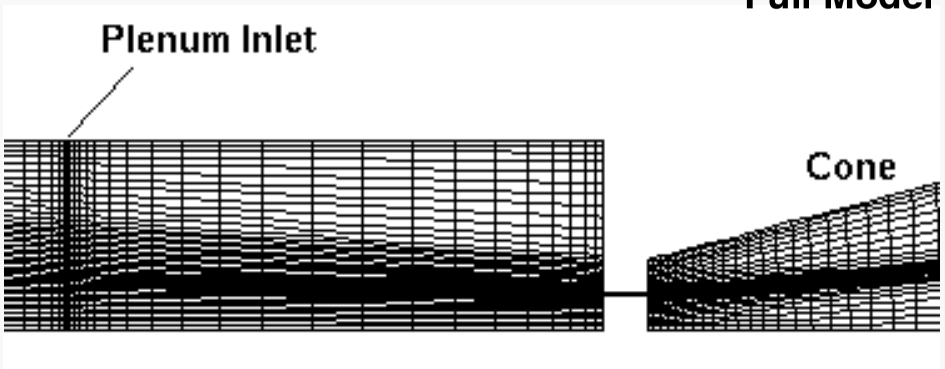
- Work on the GRC Resonator Flow Experimental Setup Was Started and is in Progress
- Schematic of the Computational Model Shown
  - 2-D axisymmetric representation of the assembly used
  - flow passages (holes) represented by 2-d slits
  - slit widths initially matched flow areas, subsequently changed to match steady-state flow rates
  - pressure differential across the assembly generates airflow through the resonator
- Air as Working Fluid, Laminar Flow, Ambient Pressure @ 99 kPa, Plenum Pressurization of 7.3, 41.3, 65.6 kPa and 96.9 kPa above Ambient

RESONATOR ASSEMBLY FLOW SETUP

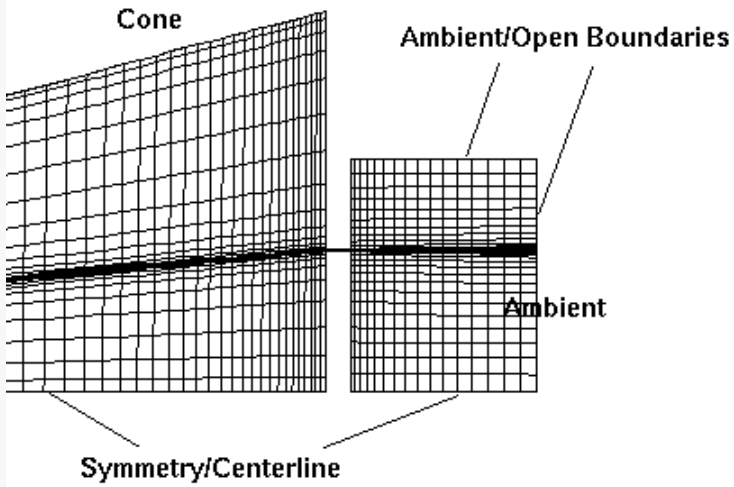
- **Computational Geometry, Grid and Boundary Condition Setup**



Full Model



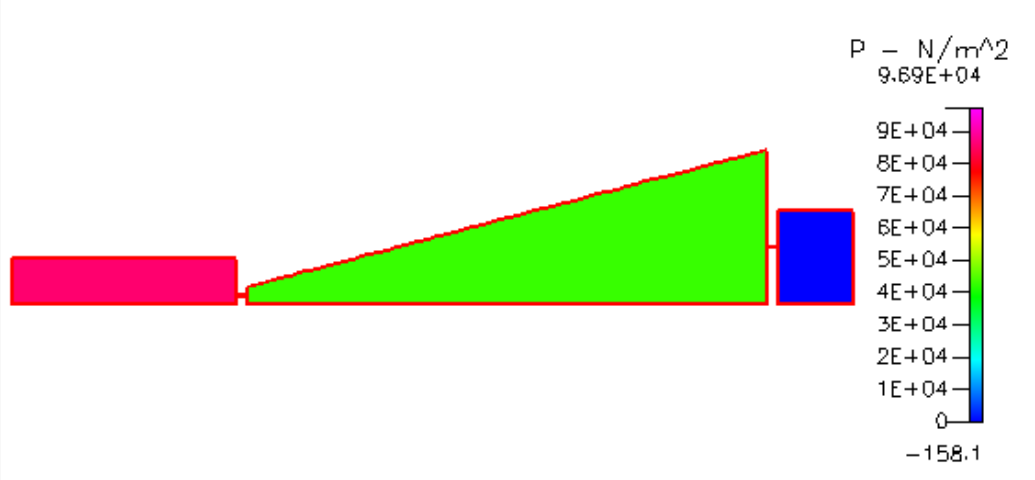
Detail Near Plenum



Detail Near Exhaust

RESONATOR ASSEMBLY STEADY-STATE RESULTS

- **Steady-State Results Obtained at Four Plenum Pressure Levels: 7.3, 41.3, 65.6 and 96.9 kPa**
  - **calculated mass flow rates compared with GRC experiments**
  - **2-D flow slit widths were adjusted to match experimental flow rates**
- **Sample Results for Plenum Pressurization of 97 kPa:**

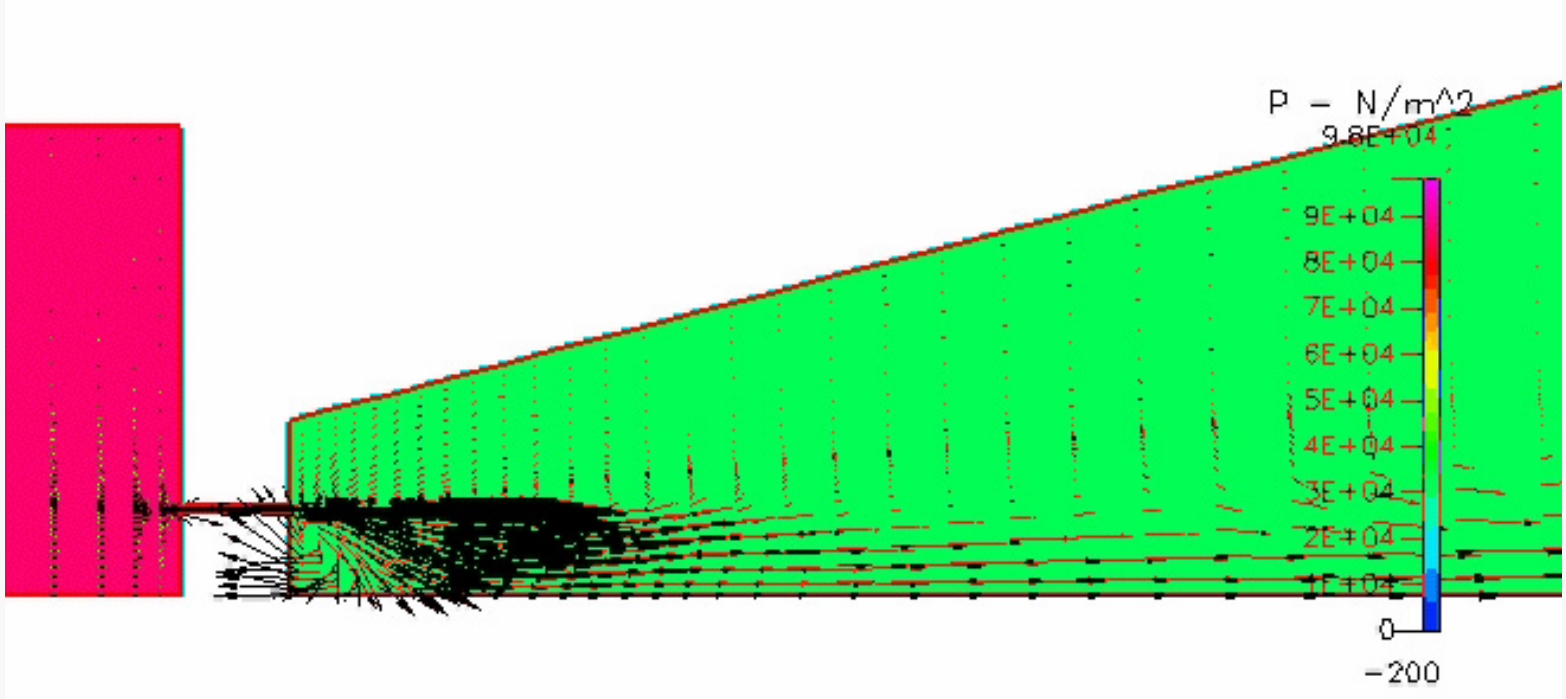


RESONATOR ASSEMBLY TRANSIENT RESULTS

- Starting With the Steady-State Flow Results, Assembly Oscillations were Imposed as Moving Wall Conditions
- Oscillation Frequency Initially Set to 1300 Hz (Experimental value)
  - for initial runs, two plenum pressurization cases were used: lowest (7.3 kPa) and highest (96.9 kPa)
  - static pressure trace at narrow end of the cone used to assess the resonance frequency
  - numerical results showed that the resonance was at a much lower frequency of approximately 1280 Hz

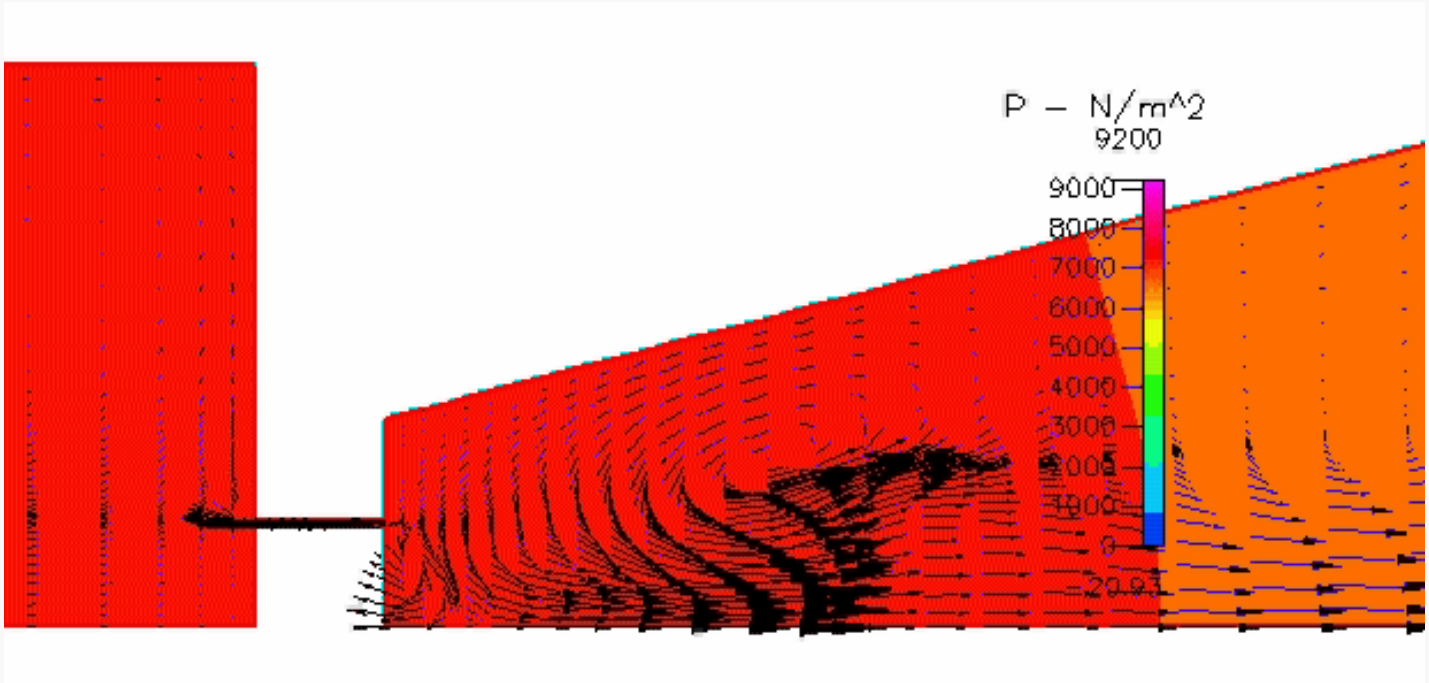
RESONATOR ASSEMBLY VELOCITY FIELDS

- Resonator Oscillations Generate Time-Dependent Pressure Fields in the Plenum and Resonator
- Transient Velocity and Pressure Field @ 96.9 kPa and 1280 Hz



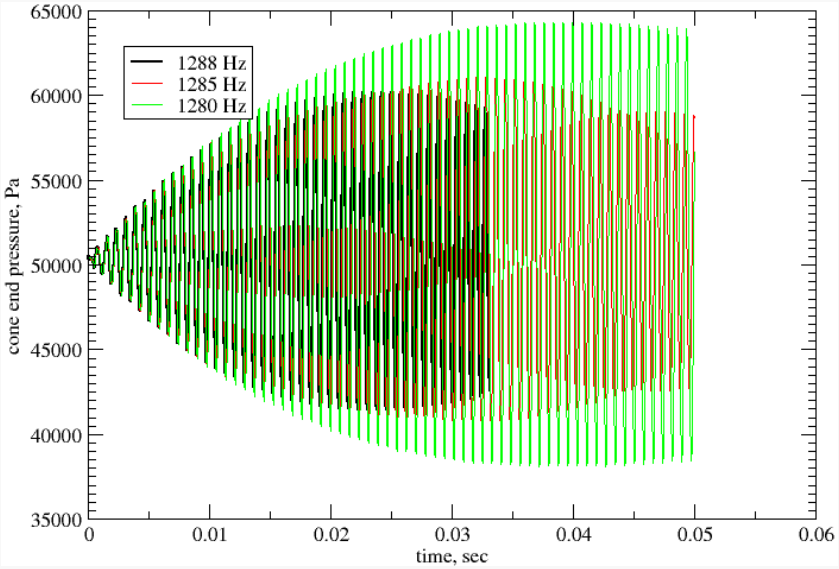
RESONATOR ASSEMBLY VELOCITY FIELDS

- **Transient Velocity and Pressure Fields @7.3 kPa and 1288 Hz**

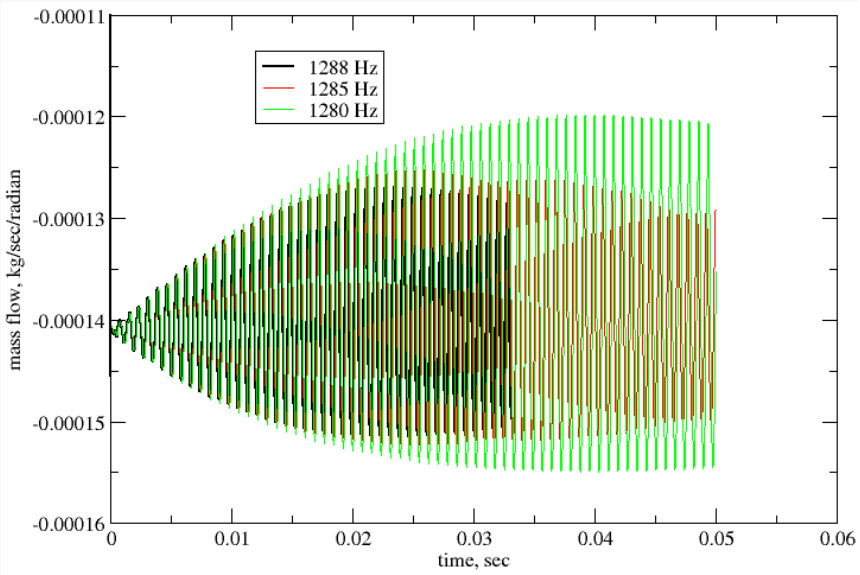


RESONATOR ASSEMBLY TRANSIENT RESULTS

- **Cone Narrow End Pressure Trace for Different Oscillation Frequencies Used to Estimate Resonance Conditions**
  - **sample results for 96.9 kPa plenum pressurization shown**



Narrow end pressure trace



Resonator mass flow

RESONATOR ASSEMBLY TRANSIENT RESULTS

- The Variable Velocity Field Results in a Different Mass Flow Going Through the Resonator Assembly
- Experiments Show a Net Reduction in the Resonator Mass Flows When Oscillating at the Resonance Conditions
- Numerical Results Also Show a Net Reduction in the Mass Flow Rates When Oscillations are Turned on.
  - predicted values of flow reduction are smaller than those seen in experiments
- Numerical Predictions of the Resonance Frequency is also Lower than the Experimental Value
- Currently Several Aspects are Being Explored to Reconcile Numerical and Experimental Results
  - assessment of the 2-d slit representation of the oscillator
  - effects of air heating seen during experiments

SUMMARY

- Successfully Demonstrated Use of a CFD Code for Calculations of Non Linear Acoustics in a Cone Resonator
  - resonance frequencies, resonator pressurization compared with experiments
  - 'bomb' test could be used for resonance predictions
- Resonator Assembly Simulations with Flow in Progress
  - initial steady-state and transient results
  - validation against experiments underway
- Work in Progress Towards Establishing a CFD Code for Design Prototyping and Optimization of Resonators