Modeling and Control of Lean Premixed Combustion Dynamics for Gas Turbines

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Gas Turbine Technology Needs

DLN/LP Gas Turbines

- Improved Combustion Stability
- Improved Design Methodology

With a focus on:

- – Thermoacoustics
- – Lean Blow Out in Presence of Dynamics

Project Objectives

- Improve understanding of heat release dynamics
- Investigate mixing dynamics
- Develop reduced-order models of combustor dynamics
- Develop finite element acoustic modeling methods for industrial gas turbines
- Understand the impact of fuel blends on combustor dynamics

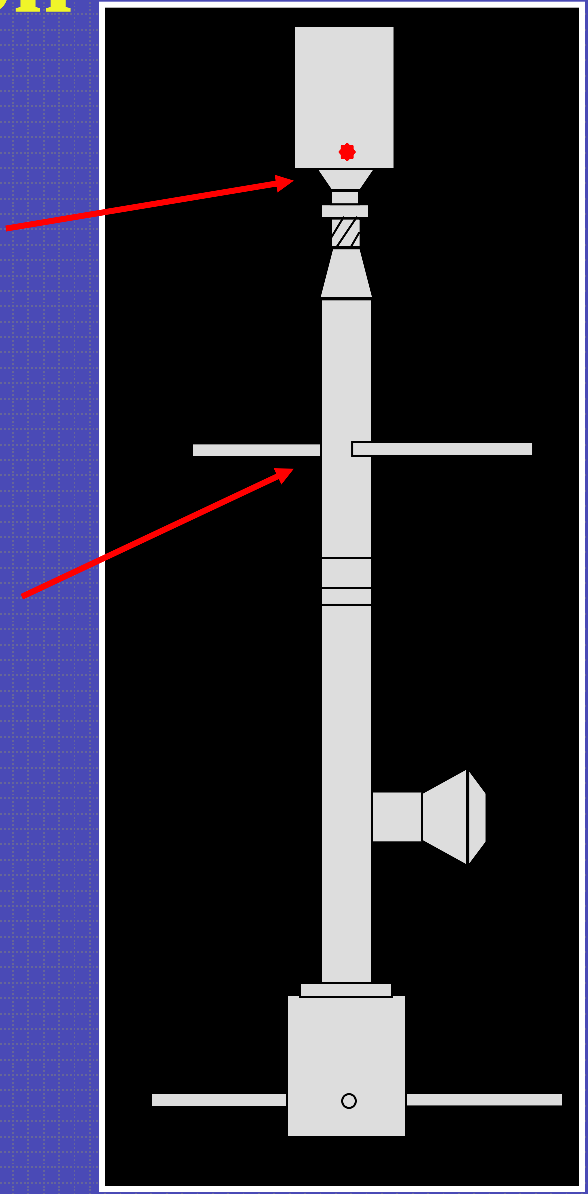
Approach

- Task 1: Heat Release Dynamics – moving to fuel blends
- Task 2: Time Lag and Dispersion – complete
- Task 3: High Temp Acoustics – underway
- Task 4: Flame Stabilization – begin soon
- Task 5: Prediction of Combustor Instabilities – overall model under development

Accomplishments

- Developed and applied two methods for characterization of flame HRR dynamics – u' and Φ'. Used to develop flame models.
- Developed library of combustor elements for FEM of acoustics
- Developed reduced-order model structures for dynamic heat release and mixing.
- Hardware ready for stabilization and fuel variability studies

Mechanisms for Combustion Instability

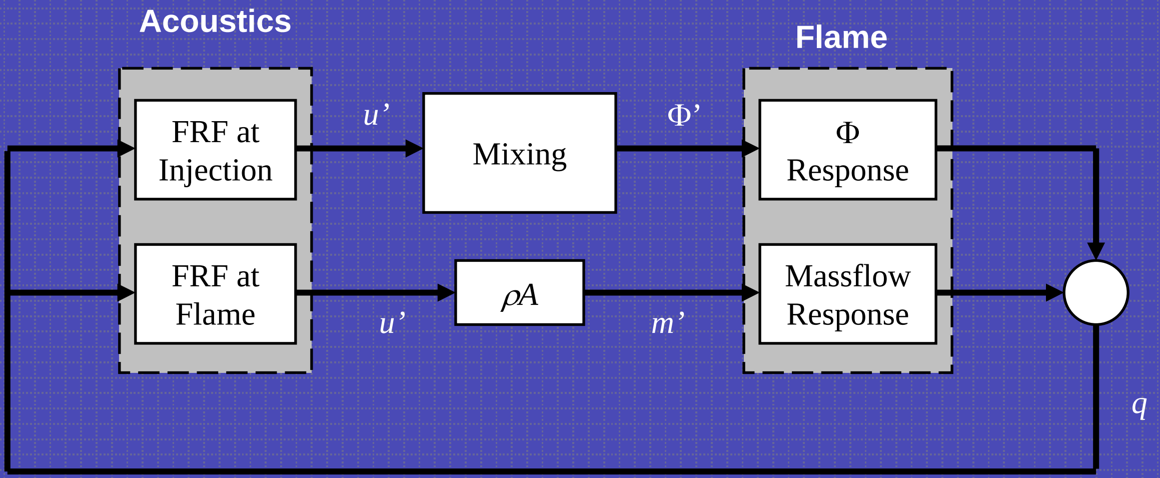


Acoustic velocity perturbations generate mass-flow perturbations to the flame.

Upstream velocity perturbations fluctuate fuel-air mixing when fuel flow is choked.

These perturbations evoke a response in the flame which in turn drives an acoustic response.

Assessment of Stability Through Linear Analysis



1) Use experimentation to guide reduced-order modeling to find linear transfer functions that estimate each element.

2) Use the closed loop above to identify stability trends with respect to the relevant design parameters

Reduced Order Modeling

Acoustic Response

Empirical data

1-D modeling

Full 3-D FE modeling

FRF at Injection

FRF at Flame

Turbulent Mixing

Mixing

Flame Response

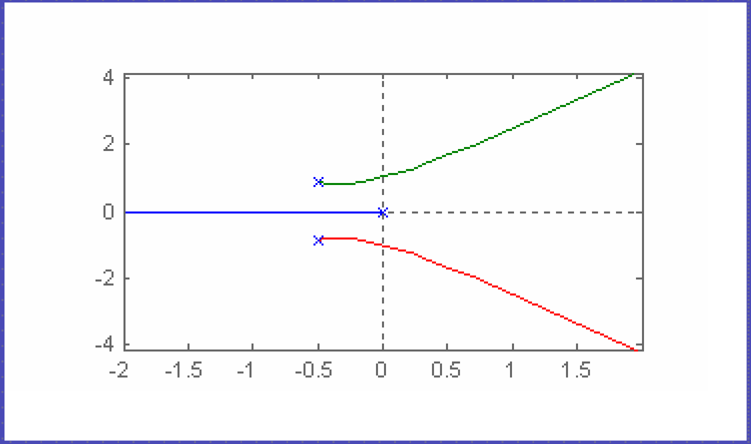
Emperical data

Linearized Dynamic WSR model

Φ Response

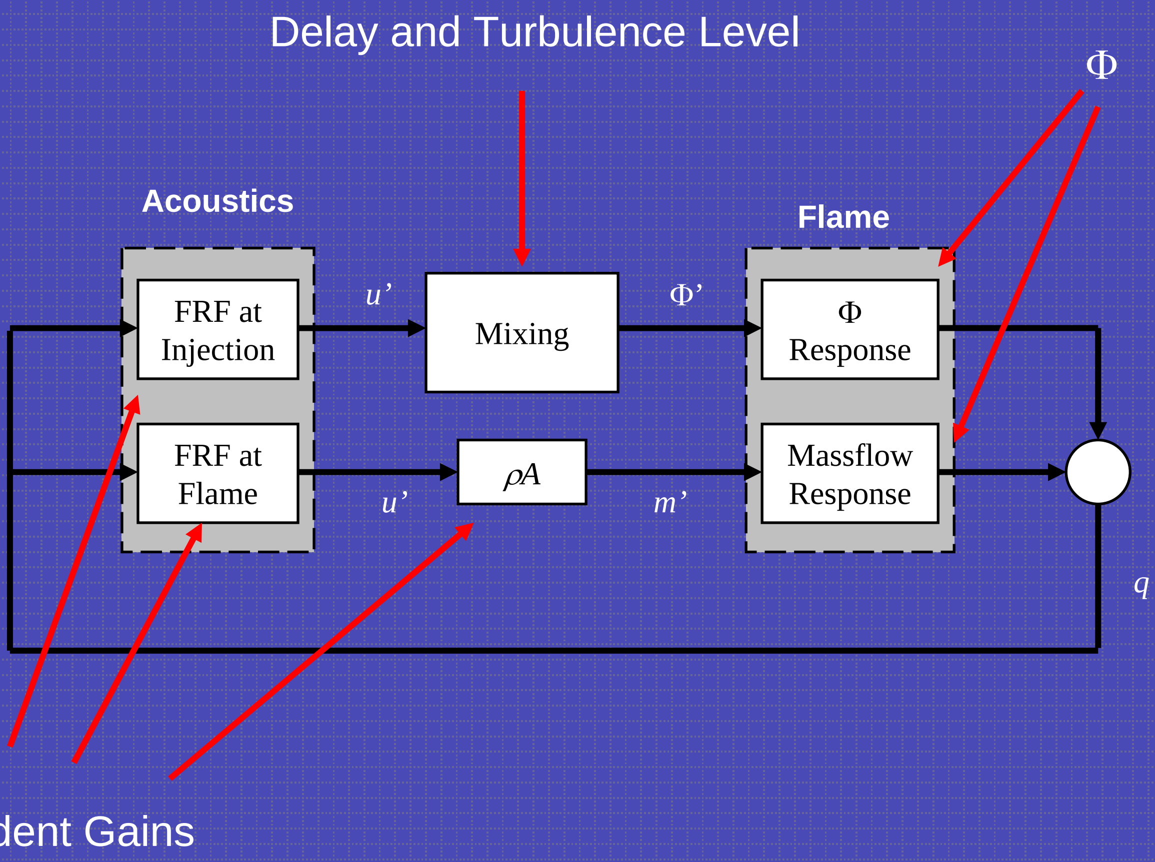
Massflow Response

Reduced order models offer insights into global, non-combustor-specific trends for stability with respect to design parameters.



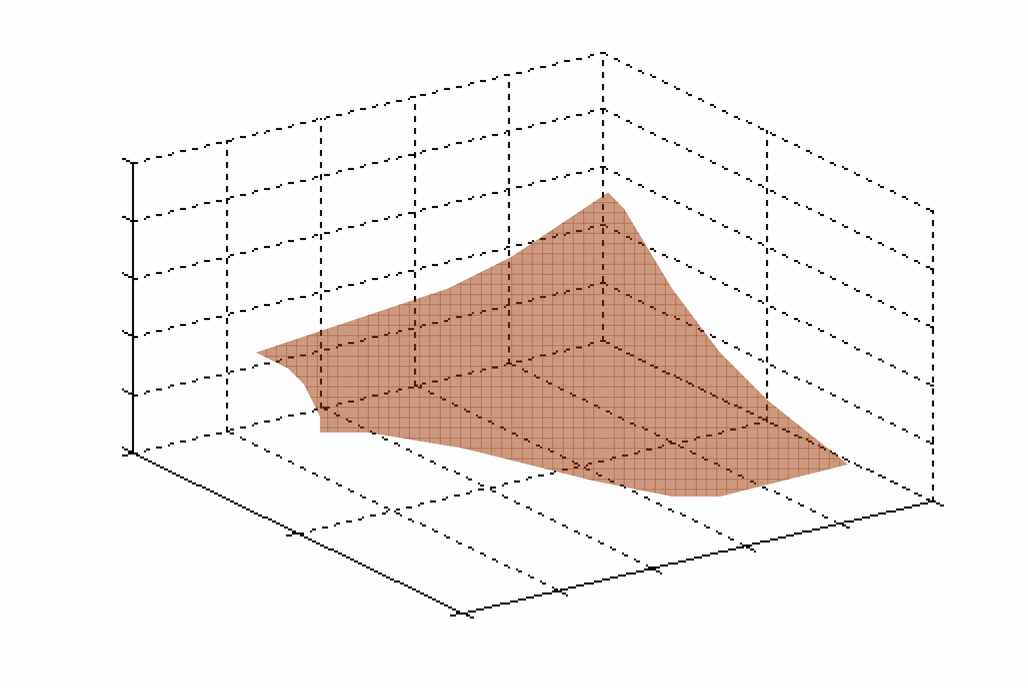
Closing the Loop

There are any number of variable design parameters that affect the closed loop.



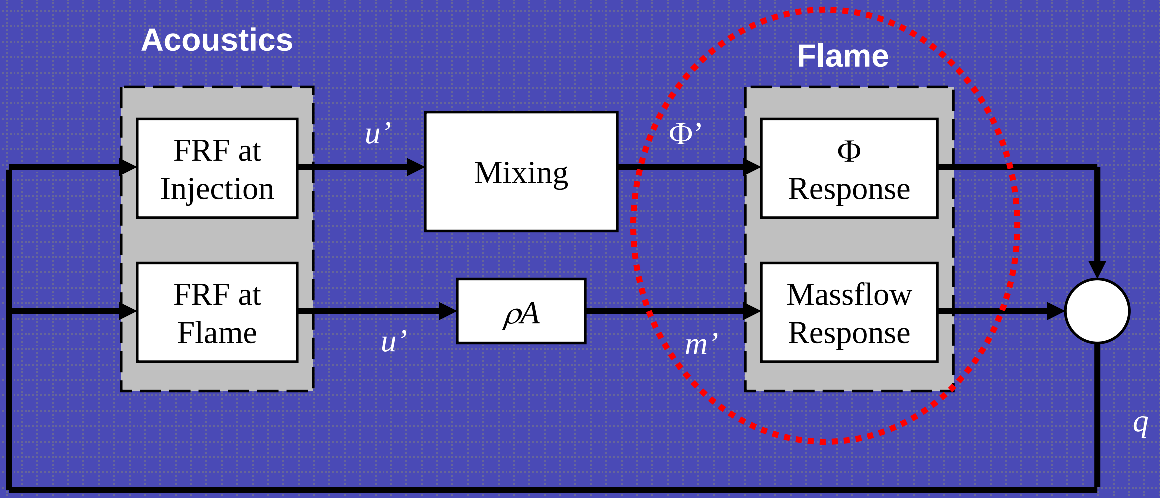
Goal: Predict the Stable Design Space from the Model

Generate surfaces in the design space that corresponds to the conditions for marginal stability.



Can be performed with respect to geometric parameters, fuel parameters, fluid flow parameters, etc…

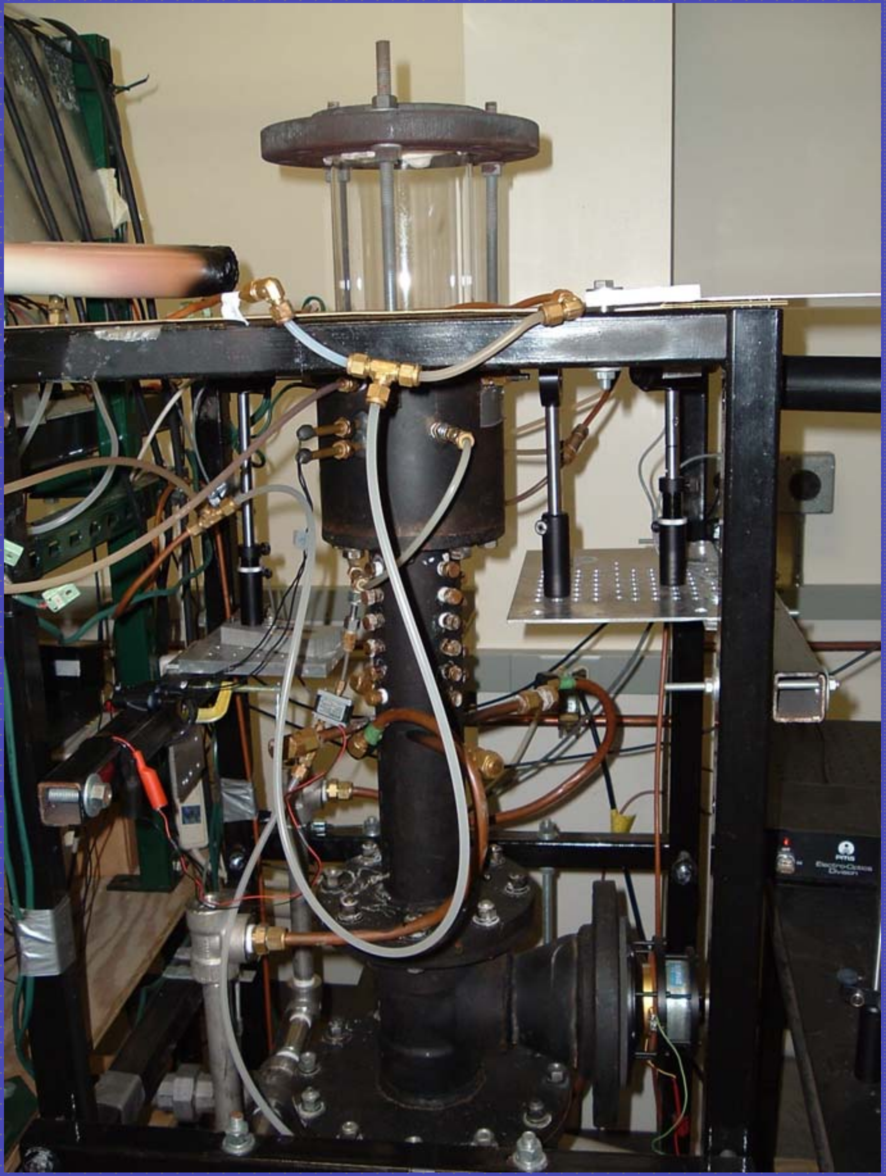
Measurement of Flame Response



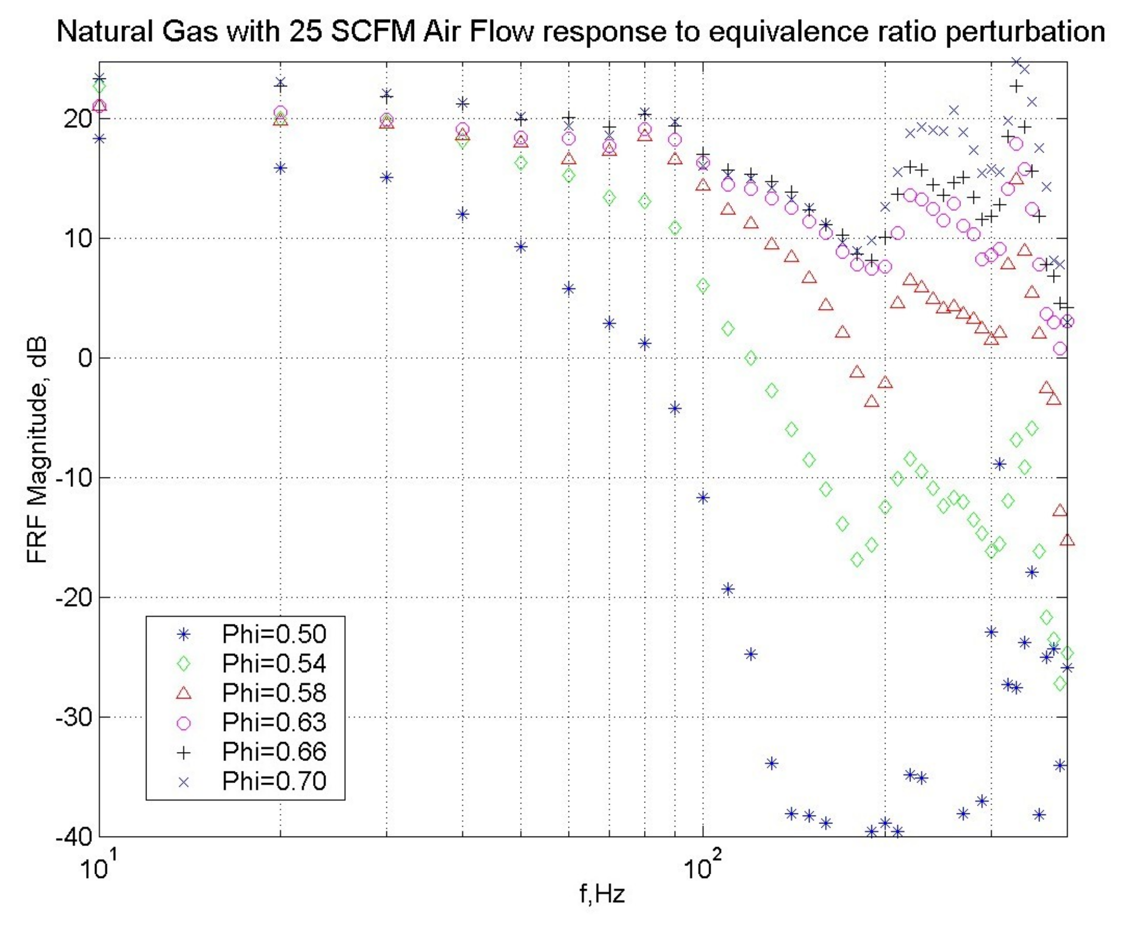
- Flame FRF’s are needed to characterize this block
- Attempt to isolate the flame from the acoustics to make a measurement of just the flame’s response.

Experimental Apparatus

- Swirl stabilized dump combustor
- Air Flows of 25 SCFM
- Phi Perturbation Input
  - Excited via fuel-fed solenoid valve
  - Measured via 3.39μm HeNe Laser Absorption
- Velocity Perturbation Input
  - Excited via acoustic driver
  - Measured via two microphone technique
- Heat Release Rate Output
  - Measured via OH* Chemiluminescence at 307.81 nm

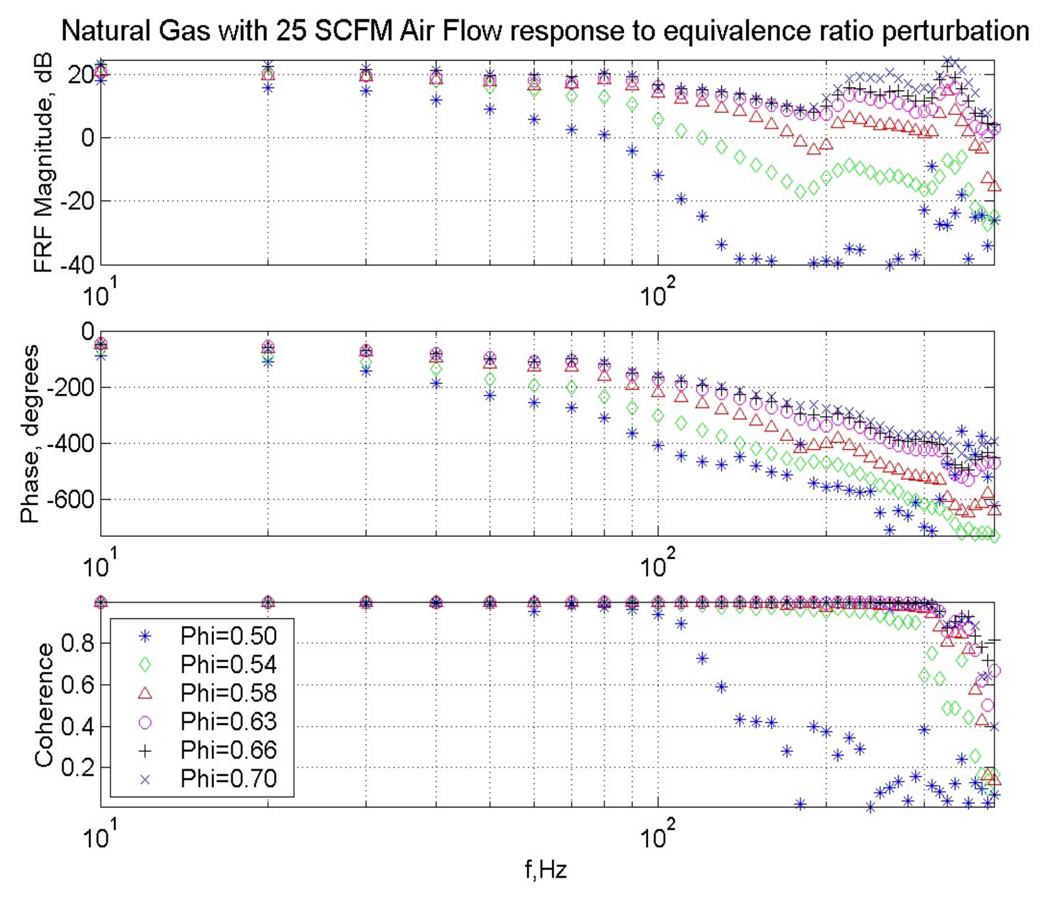


Natural Gas Phi Perturbation Results

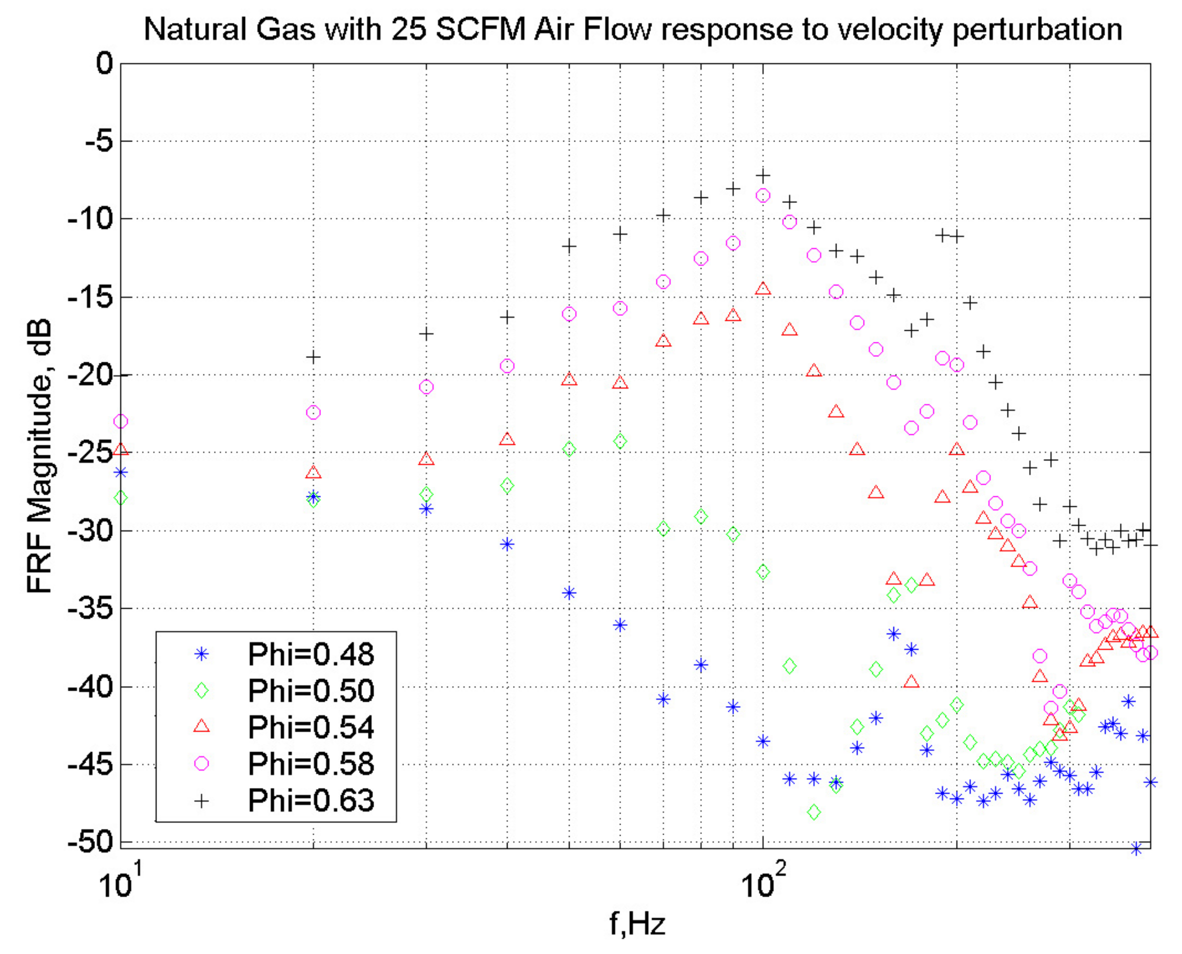


Natural Gas Equivalence Ratio Perturbation Results

- Low pass with plateau
- Bandwidth decreases with phi
- Relatively constant LF gain
- Time delay is evident

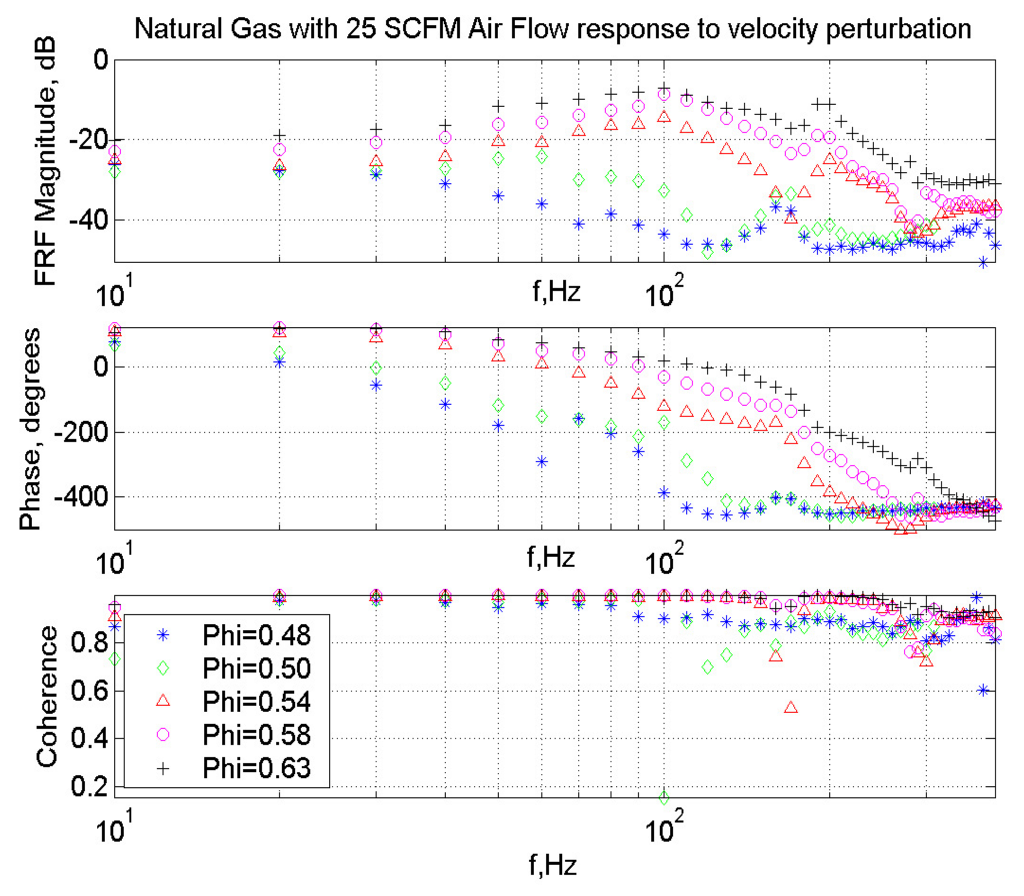


Natural Gas Velocity Perturbation Results



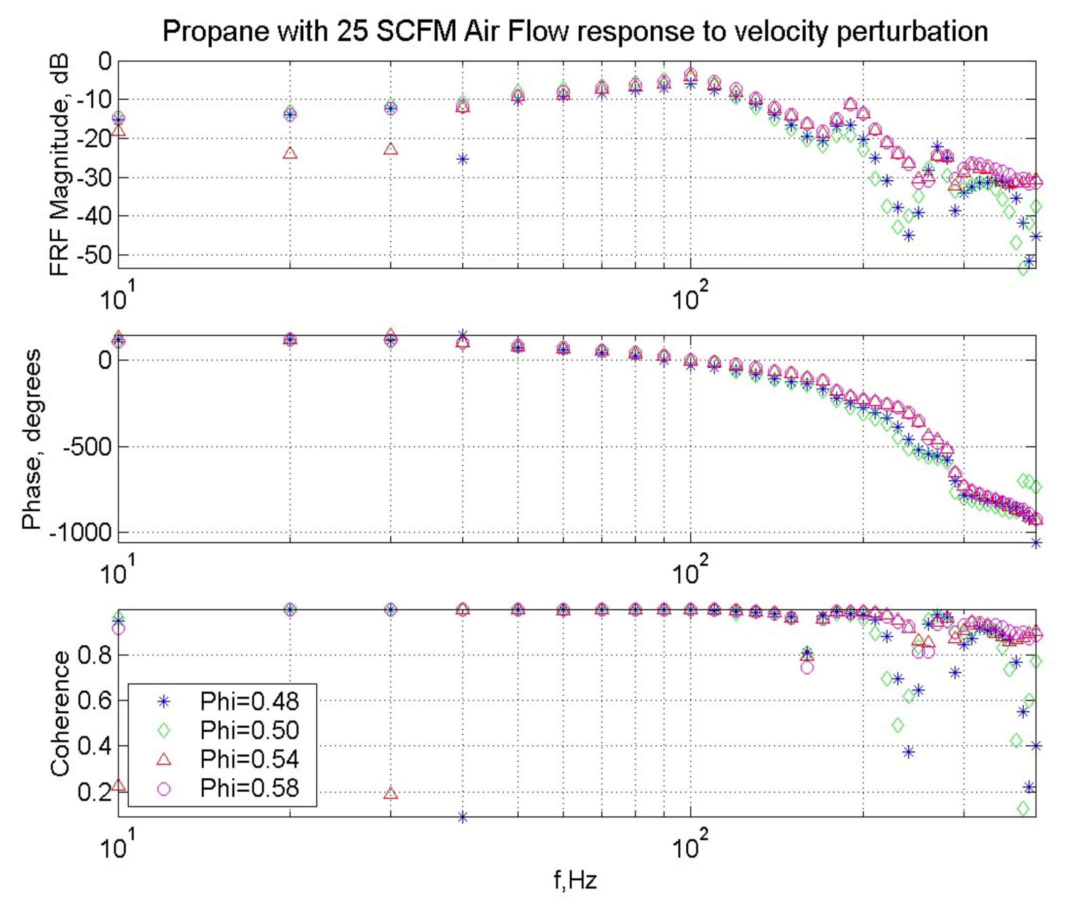
Natural Gas Velocity Perturbation Results

- Peaking evident around 100 Hz
- LF gain decreases with reduction in phi
- Plateaus evident
- No evidence of time delay



Preliminary Propane Velocity Perturbation Results

- Much less variation with mean Equivalence Ratio than natural gas
- Blow off is significantly below Phi=0.48

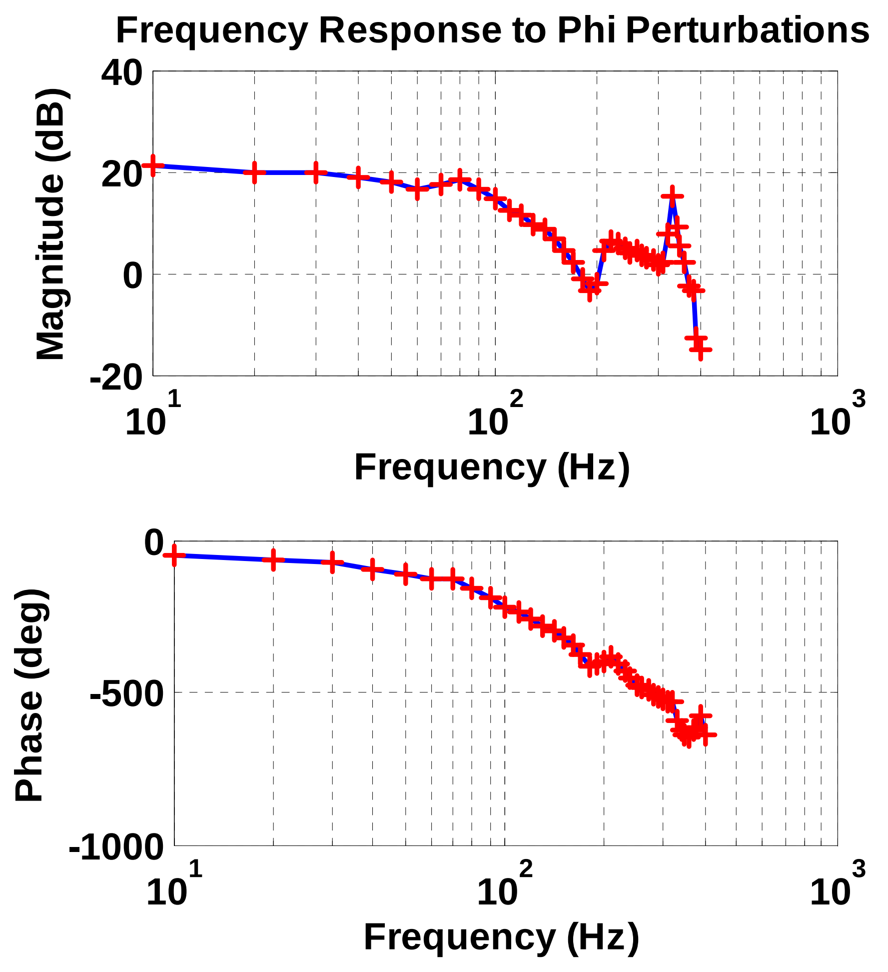


Directions for Continued Experimental Study

- Further work will determine the effects of fuel variability on the observed flame dynamics.
  - Including various hydrocarbons, hydrocarbon mixtures and hydrogen
- Provide an understanding of the physical mechanisms driving flame dynamics

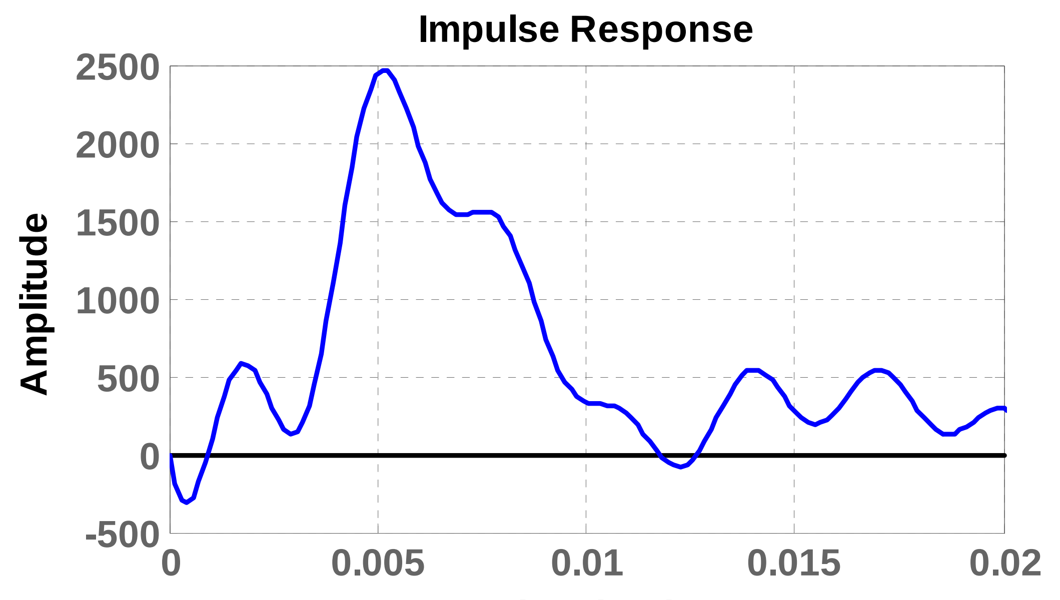
Using Data to Guide Modeling

- Not first order
- Plateaus
- Time Delay is significant
- Bandwidth (Phi)
- Gain (Phi)



Time Delay for Phi Perturbations

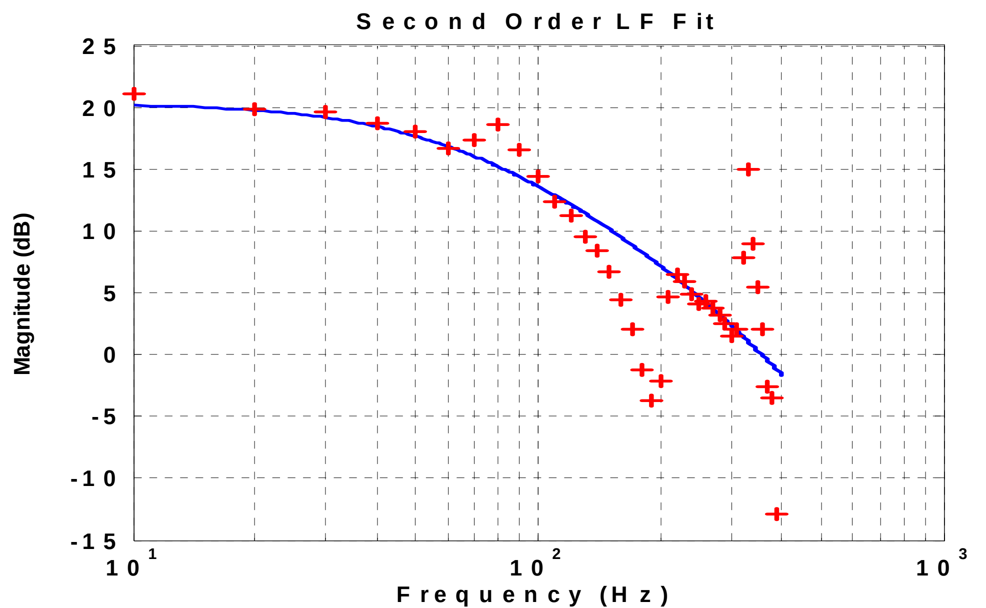
Phi	Delay
0.50	5.0
0.54	4.0
0.58	3.2
0.63	2.8
0.66	2.4
0.70	2.0



- Fit frequency response to generate impulse response
- Additional mixing time

Break Frequencies v. Phi

Phi	F1	F2
0.50	7	67
0.54	20	86
0.58	70	157
0.63	79	257
0.66	67	236
0.70	52	215



- Fit with low-order model
- Account for delay

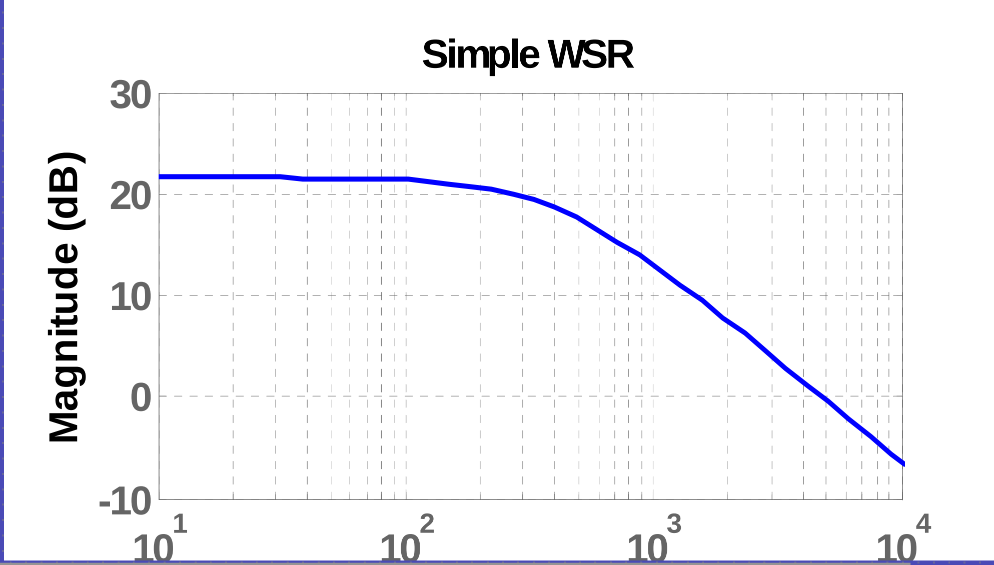
A Simple, Global Reaction WSR

$$\dot{Y}_f(t) = \frac{1}{\rho}\left(\frac{\dot{m}_{in}(t)}{V}\left(Y_{f,in} - Y_f(t)\right) - \dot{\omega}_f(t)\right)$$

$$\dot{Y}_{ox}(t) = \frac{1}{\rho}\left(\frac{\dot{m}_{in}(t)}{V}\left(Y_{ox,in} - Y_{ox}(t)\right) - \dot{\omega}_f(t)\frac{aMW_{ox}}{MW_f}\right)$$

$$\dot{T} = \frac{1}{\rho}\left(\frac{\dot{m}_{in}(t)}{V}\left(T_{in} - T(t)\right) + \dot{\omega}_f(t)\frac{\Delta h_r}{c_p}\right)$$

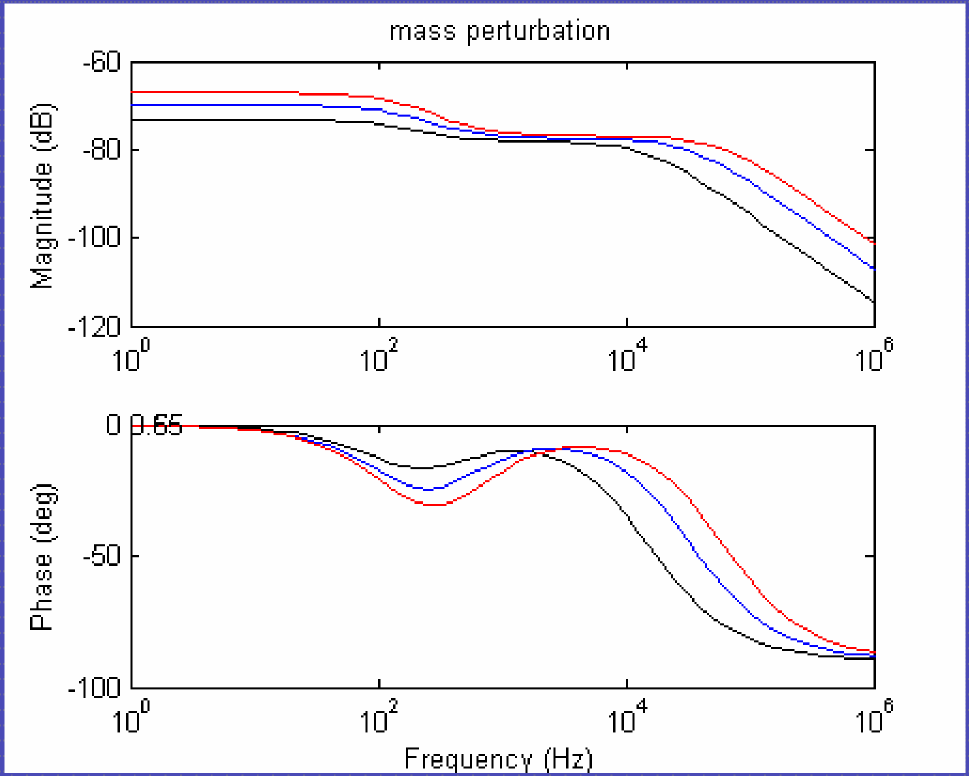
- First order
- Pole is due to chemical time
- Simplicity due to
  - – Symmetry
  - – Constant volume
  - – Global reaction



Breaking the Symmetry

- Unequal c_p's
- Heat loss
- Multistep reactions

- Chemical pole decreases with phi
- LF pole determined by residence time

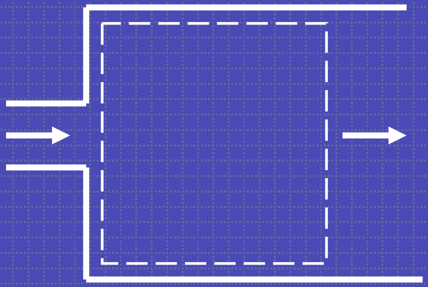


Convective Residence Time

Physical data demonstrates that the low frequency pole bears a strong dependence on phi.

The WSR model fails to reflect this because residence time is arbitrarily fixed.

If the mass occupied by the flame is allowed to vary with Φ, residence time becomes a function of both mass flow and Φ.



$$\tau_{res}\left(\overline{\dot{m}_0}, \overline{\Phi}\right) = \frac{M_f\left(\overline{\Phi}\right)}{\overline{\dot{m}_0}}$$

Fixing Reaction Progress: Determining a Predictor for the Low-Frequency Dynamics

Define reaction progress for lean flames as:

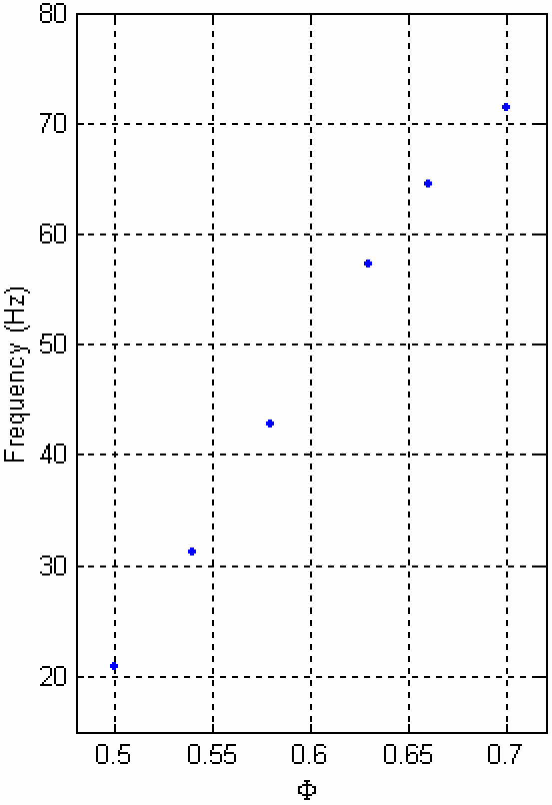
$$\psi = 1 - \frac{Y_F}{Y_{F,0}}$$

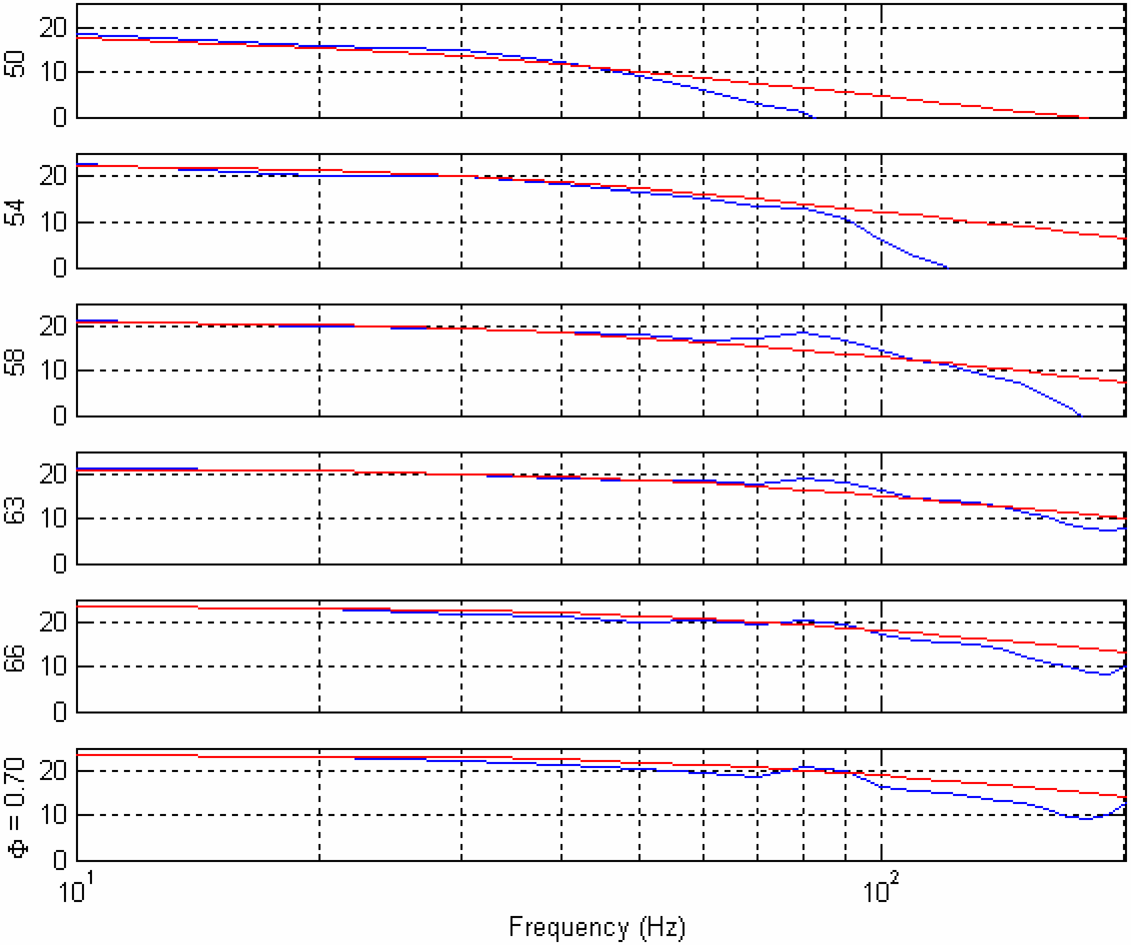
Specify a value for ψ and iterate on τ_{res} for various values of Φ.

The result predicts a transfer function (ignoring other, higher frequency dynamics)

$$\frac{\beta}{\tau_{res} s + 1}$$

Comparing the Predicted Residence Times with Data

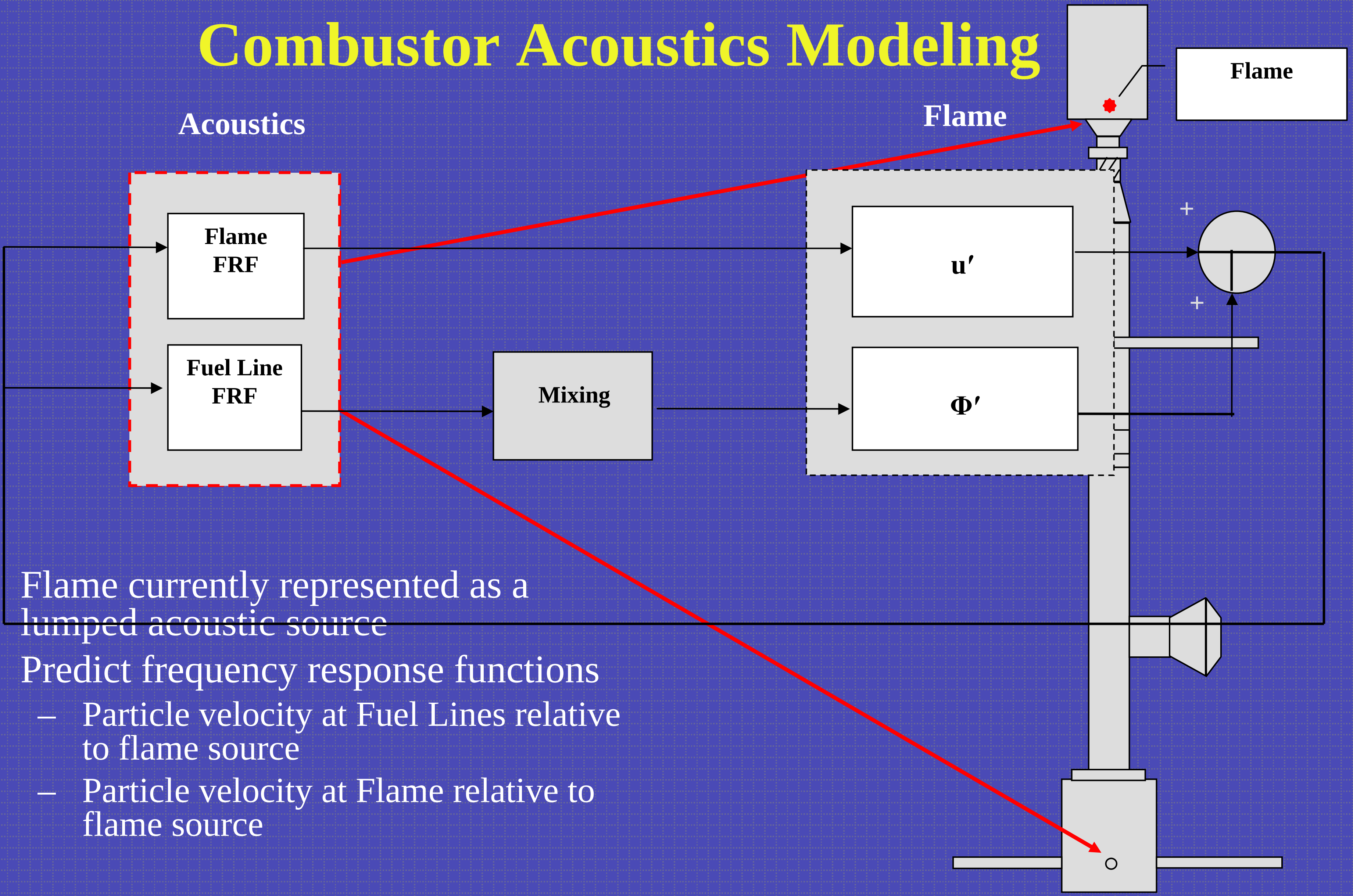




Directions for Future Modeling Work

- Use the concept of a fixed reaction progress reactor, along with symmetry breaking due to heat loss and non-constant c_ps to fit available data.
- Look at cascaded WSRs with recirculation to match peaking in velocity perturbation data.

Combustor Acoustics Modeling



Acoustics

Flame FRF

Fuel Line FRF

Mixing

Flame

u′

Φ′

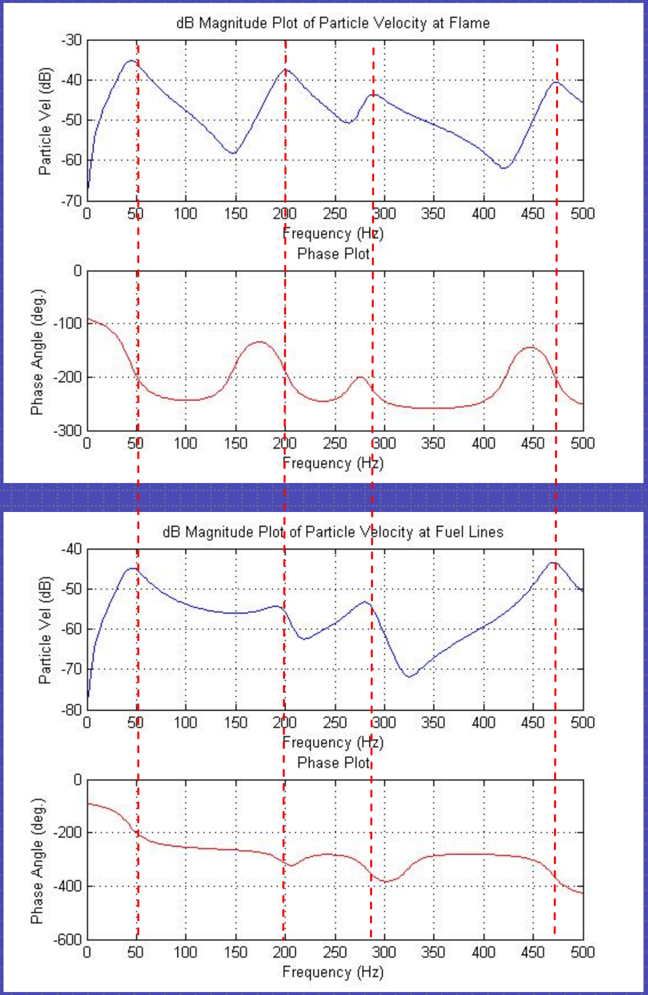
Flame

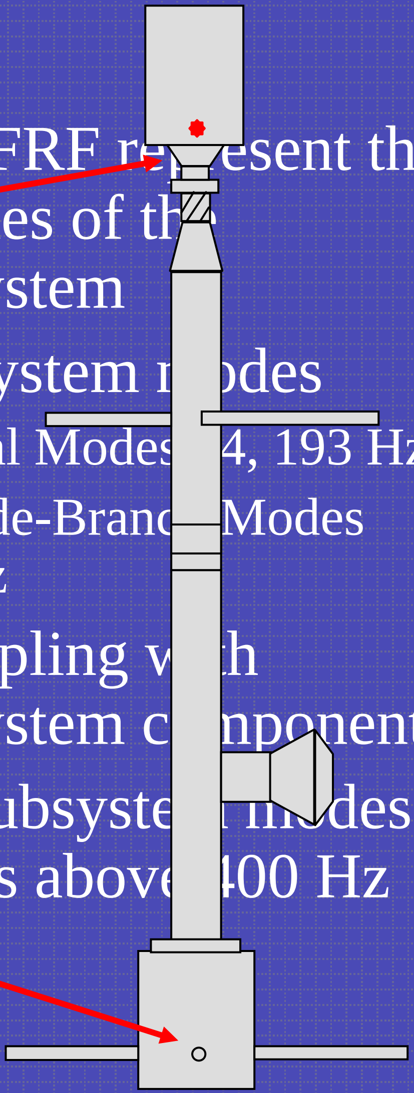
+

+

- Flame currently represented as a lumped acoustic source
- Predict frequency response functions
  - Particle velocity at Fuel Lines relative to flame source
  - Particle velocity at Flame relative to flame source

Acoustic Frequency Response Functions

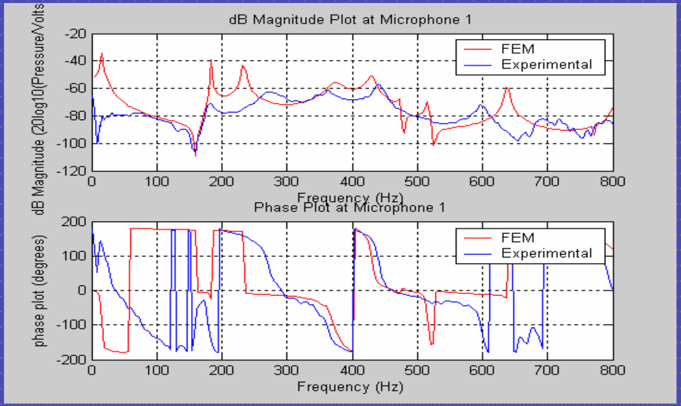




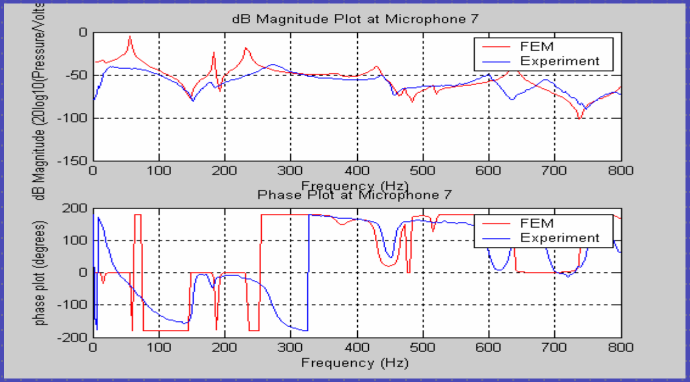
- Peaks in the FRF represent the acoustic modes of the combustor system
- Combustor system modes
  - Longitudinal Modes 4, 193 Hz
  - Coupled Side-Branch Modes 279, 488 Hz
- Acoustic coupling with combustor system components
- Combustor subsystem modes at frequencies above 400 Hz

Exp. Validation - Cold Combustor Acoustics

Combustor exhaust



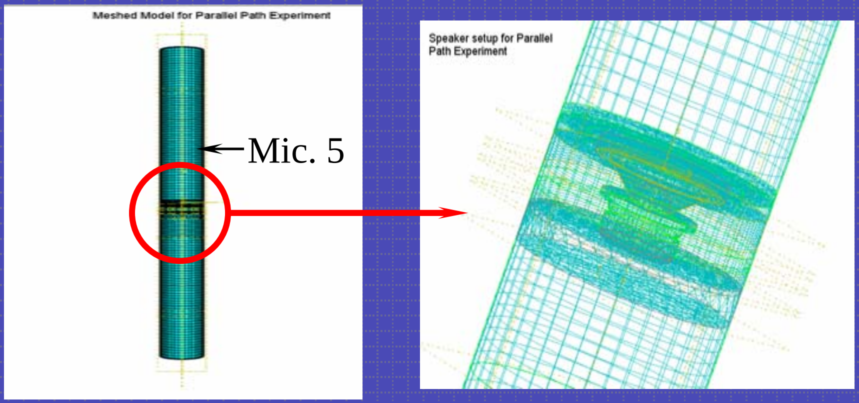
Speaker Main Branch

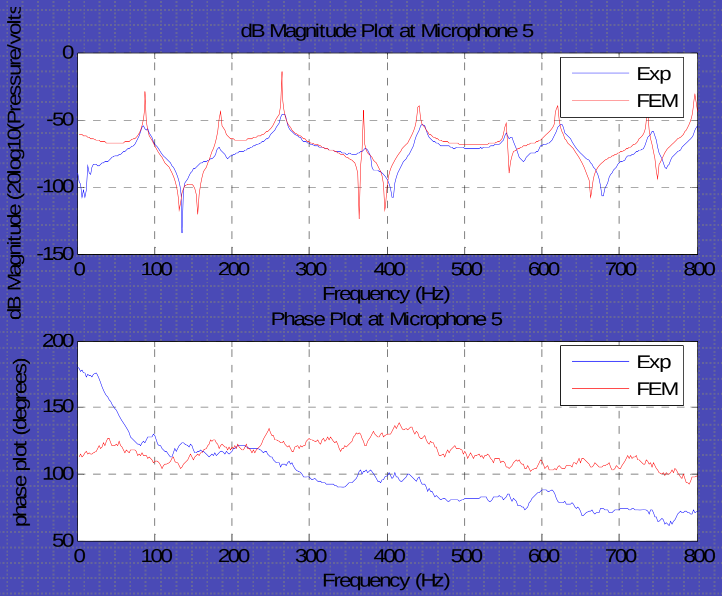


- Excitation at Side Branch
- Response Locations:
  - Combustor exhaust
  - Speaker Main Branch
- Results
  - Frequency content over range of interest (0-400 Hz) represented.
  - Magnitude & Phase captured
  - FE Model results comparable across the entire combustor
- Model Refinement
  - Effects of scattering on phase
  - Subsystem/Section refinement

Exp. Validation - Combustor Acoustics Testbed

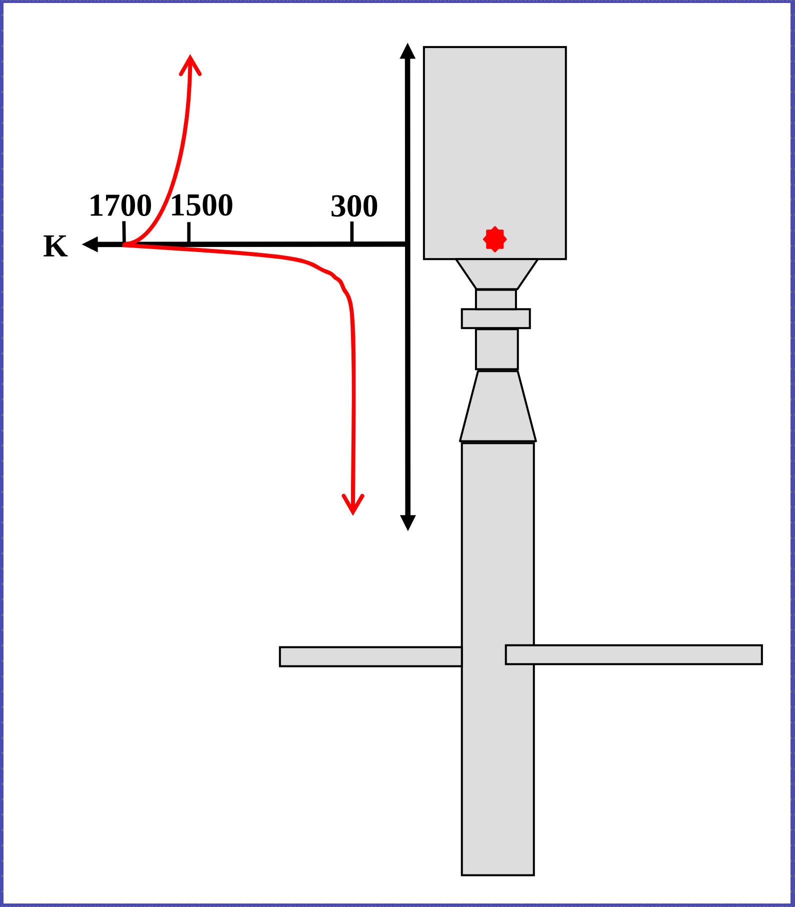
- Purpose:
  - Assess impact of model simplification on acoustics
- Benefit:
  - Isolate effect of subsystem models independently
- Result:
  - Validation strategy for combustor acoustic models
  - Tractable modeling approach to industrial systems
  - Combustor acoustic modeling guidelines for industry





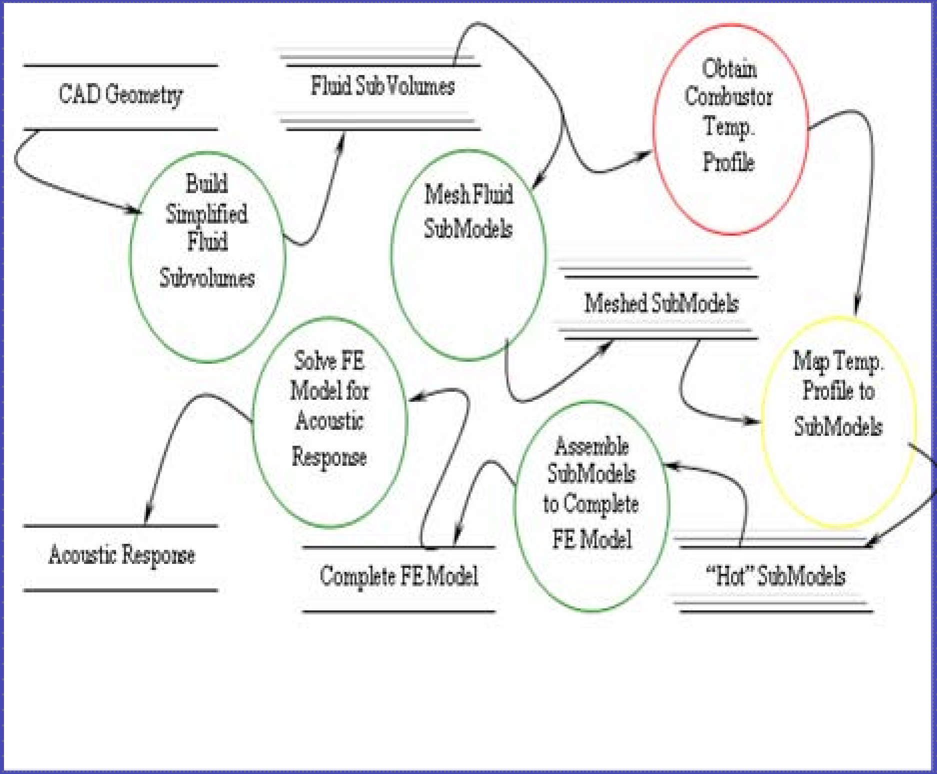
Hot Combustor Acoustics

- Heating Effect
  - Large temperature gradients produce reflection/refraction of acoustic waves
- Solution
  - Map Exp. or CFD temperature profile to the FE model
- Goal
  - Produce hot combustor FRFs at the flame and mixing points
  - Input the hot combustor FRFs into the Reduced-Order Model
- Early Validation Results
  - Good correlation between exp. and model predictions



Conclusions and Future Acoustics Work

- Cold acoustics
  - Validation process in place
  - Good correlation between models and exp. data
- Hot acoustics
  - Refine temperature profile mapping.
  - Validate hot acoustics models
- Refine FRFs for reduced-order model
  - Flame, Mixing
- Develop guidelines for combustor acoustic models



🟩 Done 🟨 Refinement 🟥 Underway

Questions ?