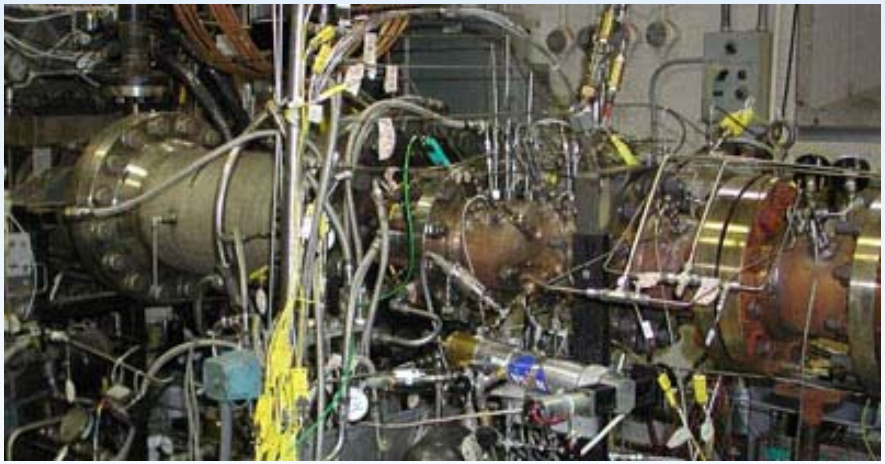
Active Combustion Control for Ultra Low Emissions in Aircraft Gas-Turbine Engines



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Team Members

- Controls and Dynamics Branch
  - Dan Paxson: Dynamic Models
  - George Kopasakis: Control Methods
  - Joe Saus: Actuators
- Combustion Branch
  - Clarence Chang: Combustion Science
- Engineering Directorate
  - Dan Vrnak: Control Software
- Supersonics Project
  - Dan Bulzan – Supersonics (and Subsonics) Combustion API
- Other NASA Participants
  - Sensors, Materials, Combustion and Flow Diagnostics

- Non-NASA Participants
  - General Electric, Pratt & Whitney, UTRC, Honeywell, Penn State, Virginia Tech, Georgia Tech

OUTLINE

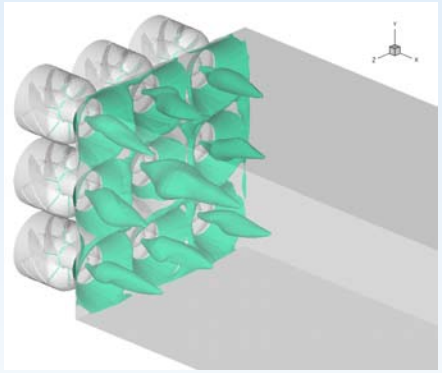
- Motivation: Low Emissions Combustors
- NASA's Overall Combustors Effort
- Thermo-Acoustic Instability => Active Control
- Technical Challenges and Approach
- Early Results, Enabling Technologies
- Recent Results
- *Modeling – Dan Paxson*
- Current Efforts, Future Plans
- Opportunities for Collaboration

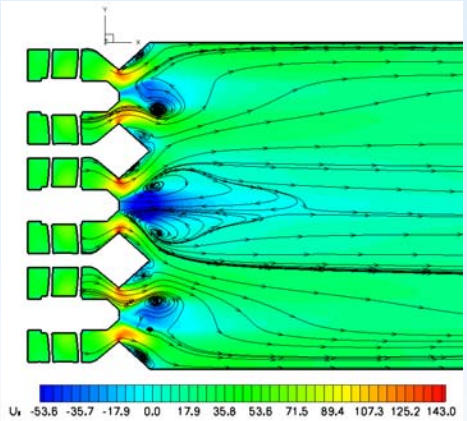
Fundamental Aeronautics, Supersonics
High Altitude Emissions

Objectives

- Develop the necessary technologies to enable low emissions (gaseous and particulate) combustion systems to be developed for supersonic cruise applications.
- Develop and validate physics-based models to enable quantitative emissions and performance predictions at supersonic cruise conditions using Combustion CFD simulations.
- Develop and validate high temperature sensors for use in intelligent engines.

Axial Velocity Predictions of Lean Direct Injection Low NOx Emissions Concept



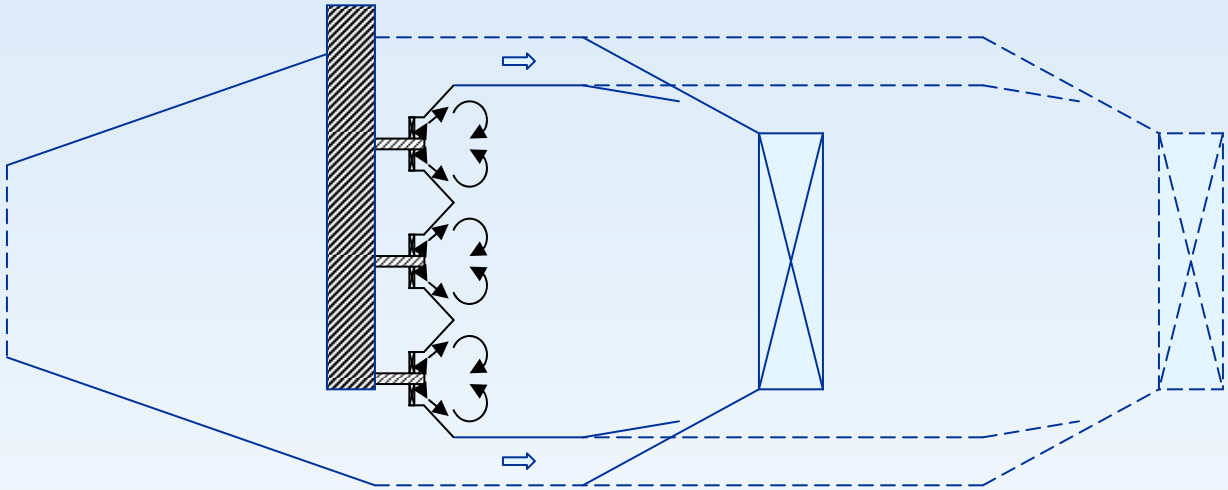


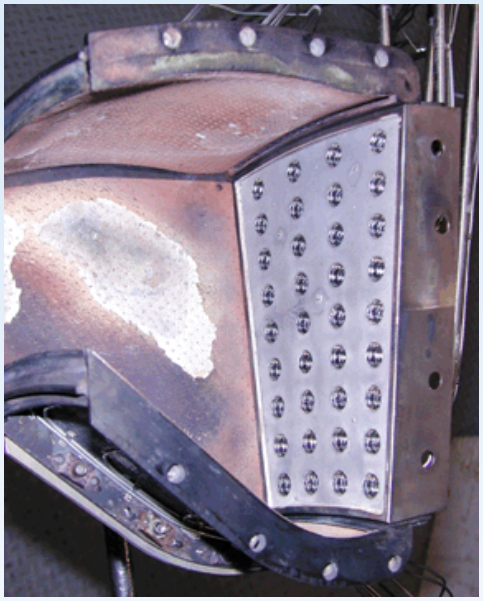
Zero Axial Velocity Contours *Side View through center*

Also - Fundamental Aeronautics, Subsonics, Combustion

•Combustion Chemistry and Turbulence Modeling
•Particulates Sampling and Modeling
•Alternate Fuels

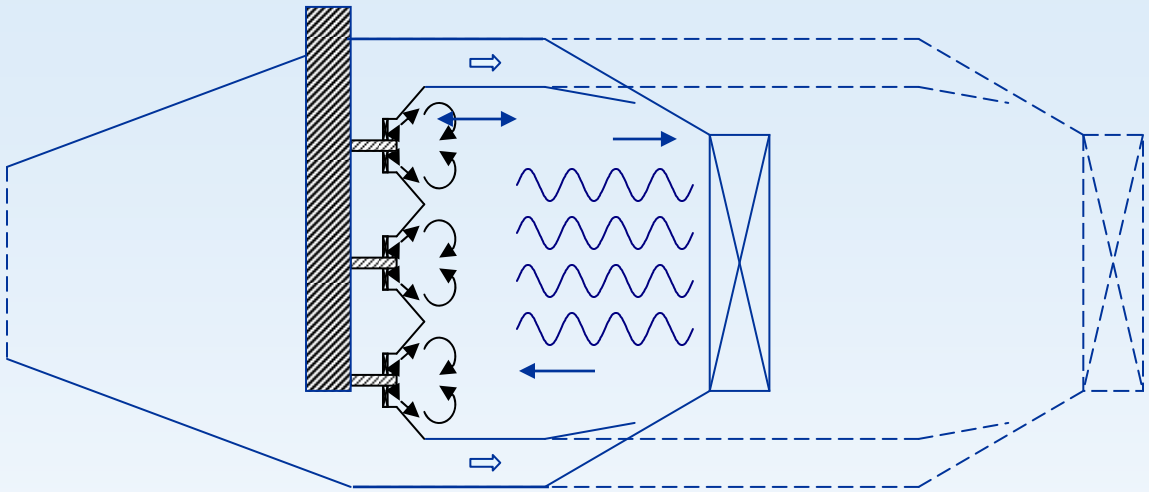
90% NOx Reduction Combustion: Multi-Point Lean Direct Injection





1. Energetic quick-mixing before auto ignition at high power condition
2. Lean and uniform front end makes less CO and NOx initially
3. Less CO initially, shorter combustor needed
4. Shorter combustor, shorter residence time, less additional NOx
5. Multiple injection points allow temporal and spatial fuel/air control
   - allows active fuel-shifting control to improve operability

Ultra-Lean-Burning Combustors Are More Susceptible to Thermo-Acoustic Instabilities



1. Higher-performance fuel injectors: more turbulence

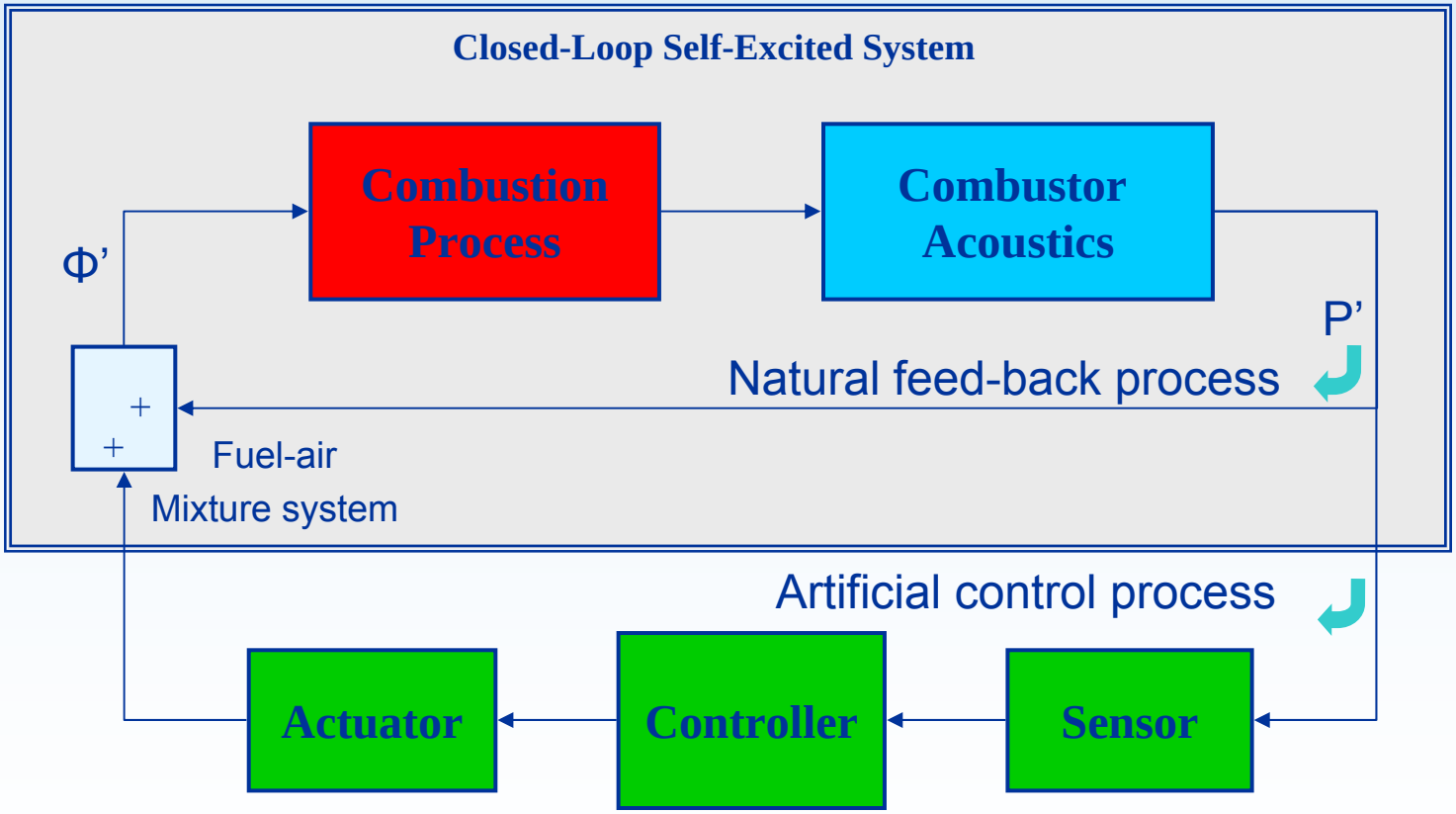
2. Reduced film cooling: reduced damping

3. More uniform temperature and composition

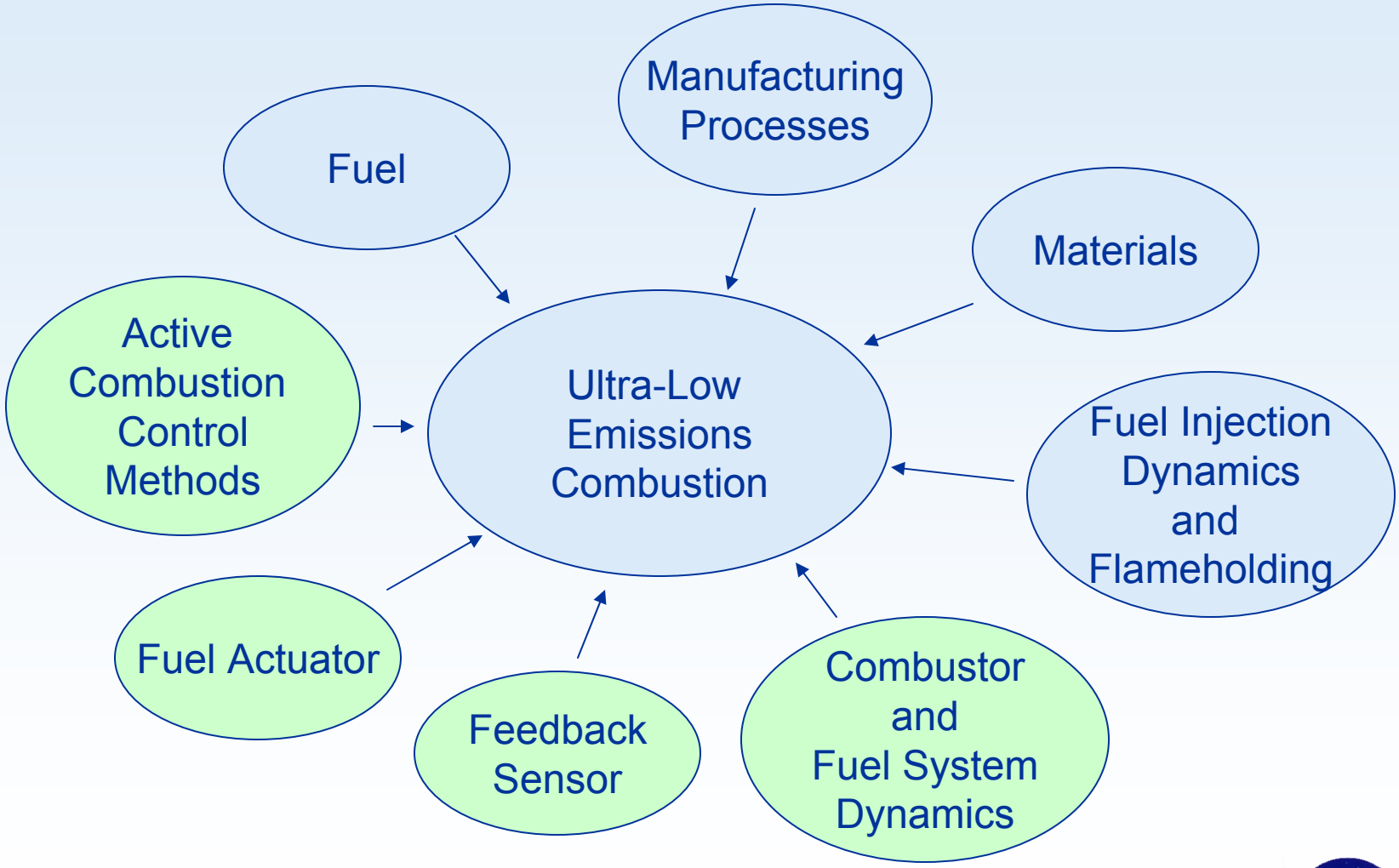
4. No dilution holes: reduced flame-holding

Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur



Synergistic Technologies to Enable Ultra-Low Emissions Combustion

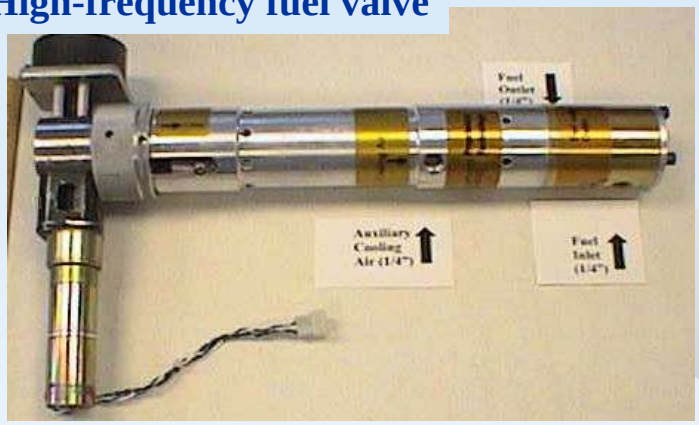


Active Combustion Control - Technical Challenges

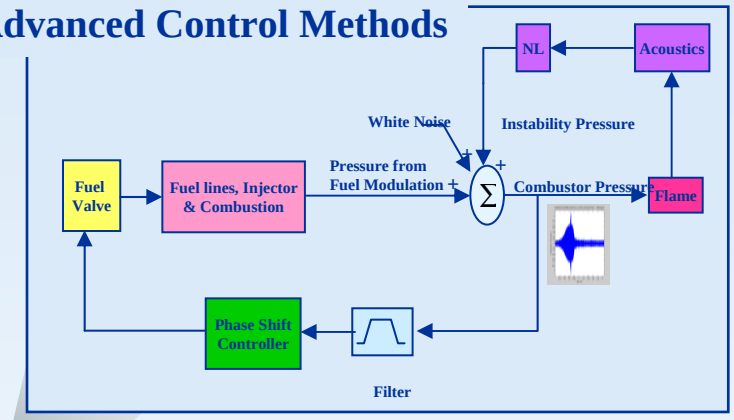
- Combustor dynamics largely unmodeled
- Noisy environment
- Liquid fuel – introduces additional unmodeled dynamics including time delay (atomization, vaporization, …)
- Actuation system – enough bandwidth and authority, not just valve (also feedline, injection, …)
- Simplified models needed for control design evaluation
- Control methods that can:
  - identify instability
  - suppress instability in presence of large time delay, substantial noise, unmodeled dynamics
- Realistic experimental testbeds (combustor, actuation system)

Active Combustion Instability Control Via Fuel Modulation

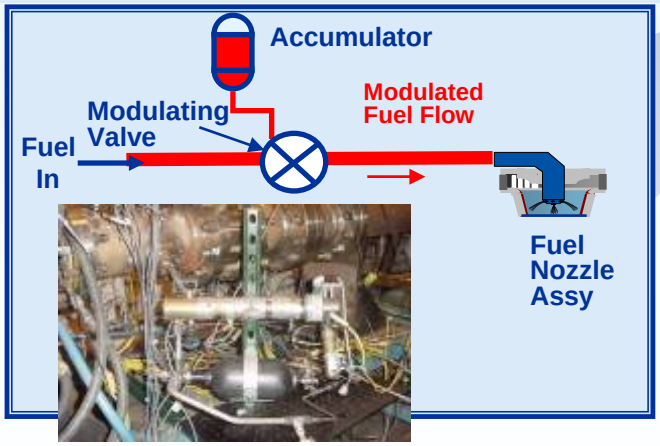
High-frequency fuel valve

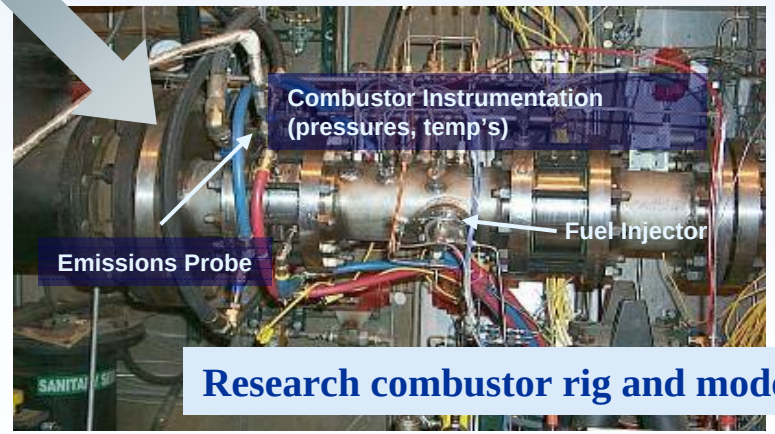


Advanced Control Methods



Fuel delivery system model and hardware





Research combustor rig and models

Combustion Dynamics Modeling

Reduced-order oscillator models

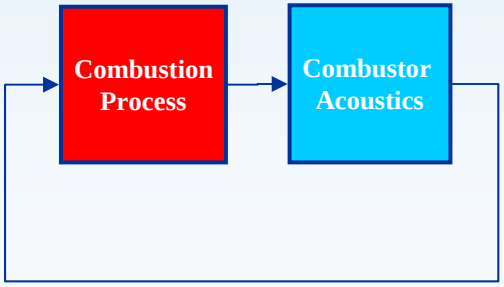
Run fast to allow parametric studies in support of control system development

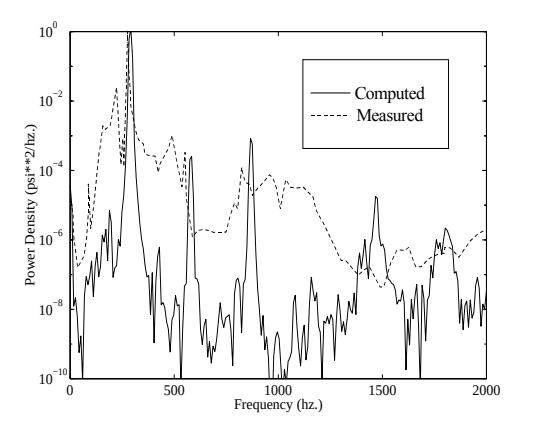
Simplified Quasi-1D dynamic models

Allow physics-based control method validation

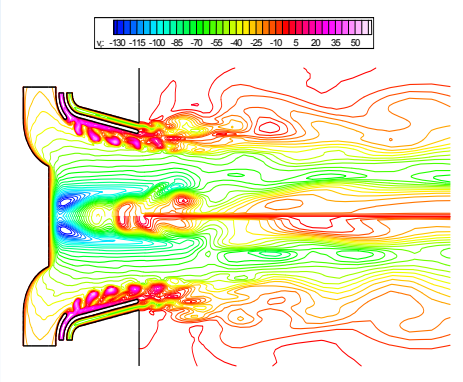
Detailed, physics-based dynamic models

Fundamental understanding of combustor dynamics to aid passive, active instability suppression



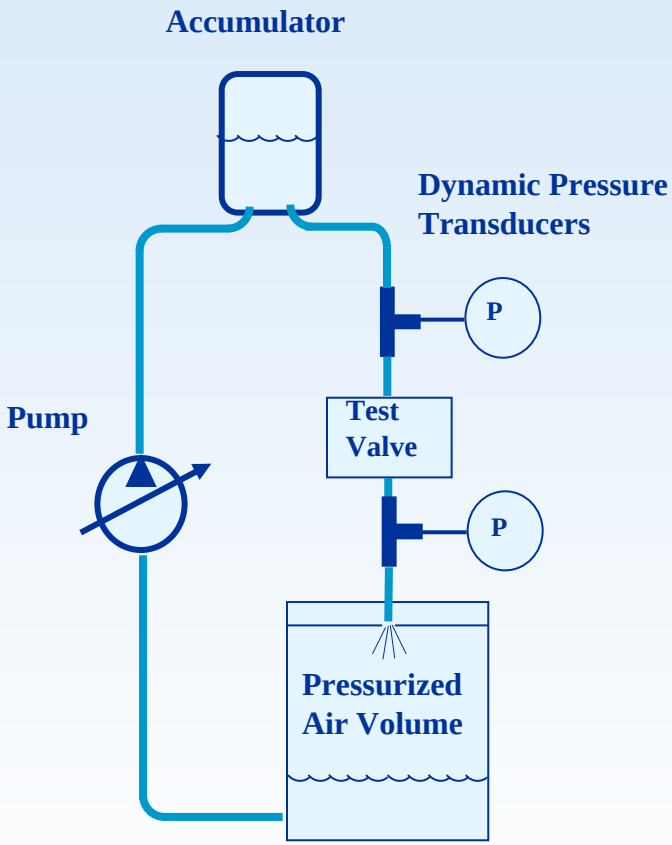


Results from NASA Sectored-1D Model of LPP Combustor Rig – D. Paxson



Penn State Injector Response Model Plot

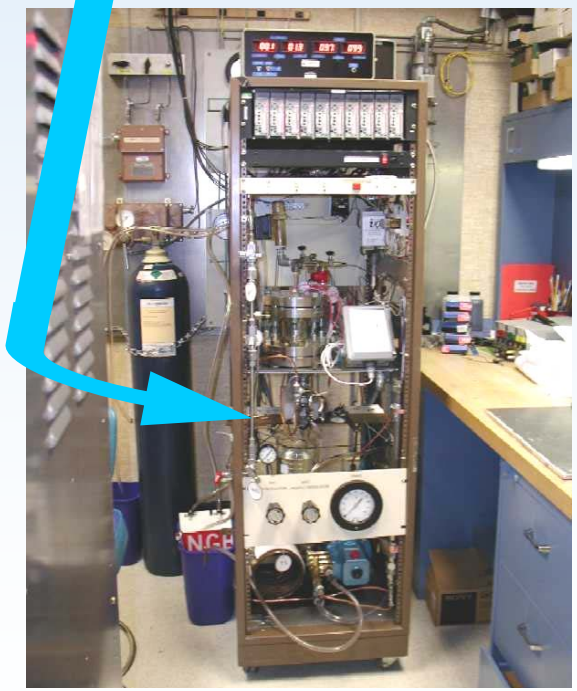
High-Bandwidth Fuel Actuator Characterization Testing – J. Saus



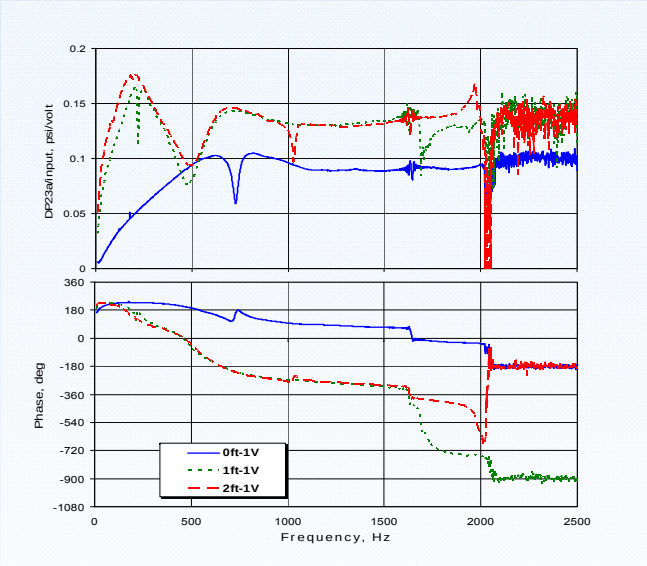
Valve, Feed-system Characterization Rig at NASA GRC

High-Bandwidth Fuel Actuator

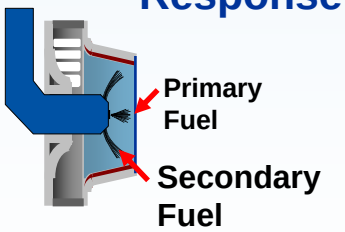
GaTech high-response fuel valve in characterization rig in CE7A

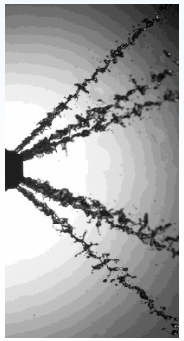


Frequency Response Dynamic Characterization Data



Fuel Delivery System Dynamic Response

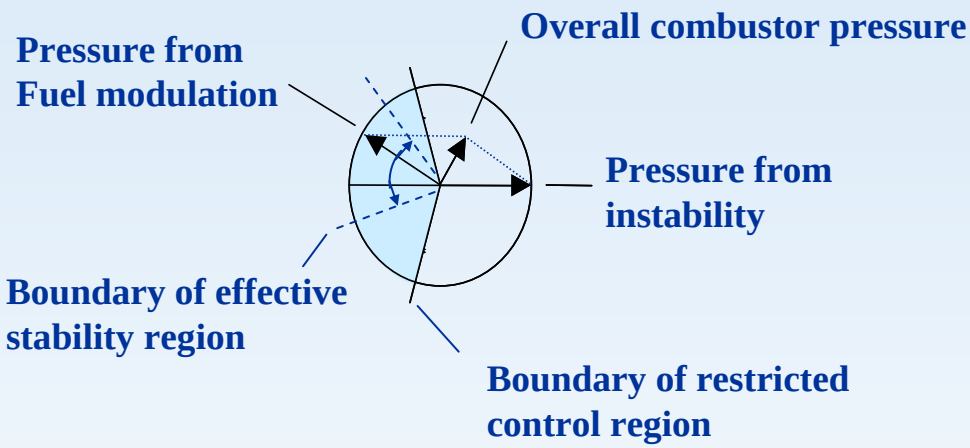


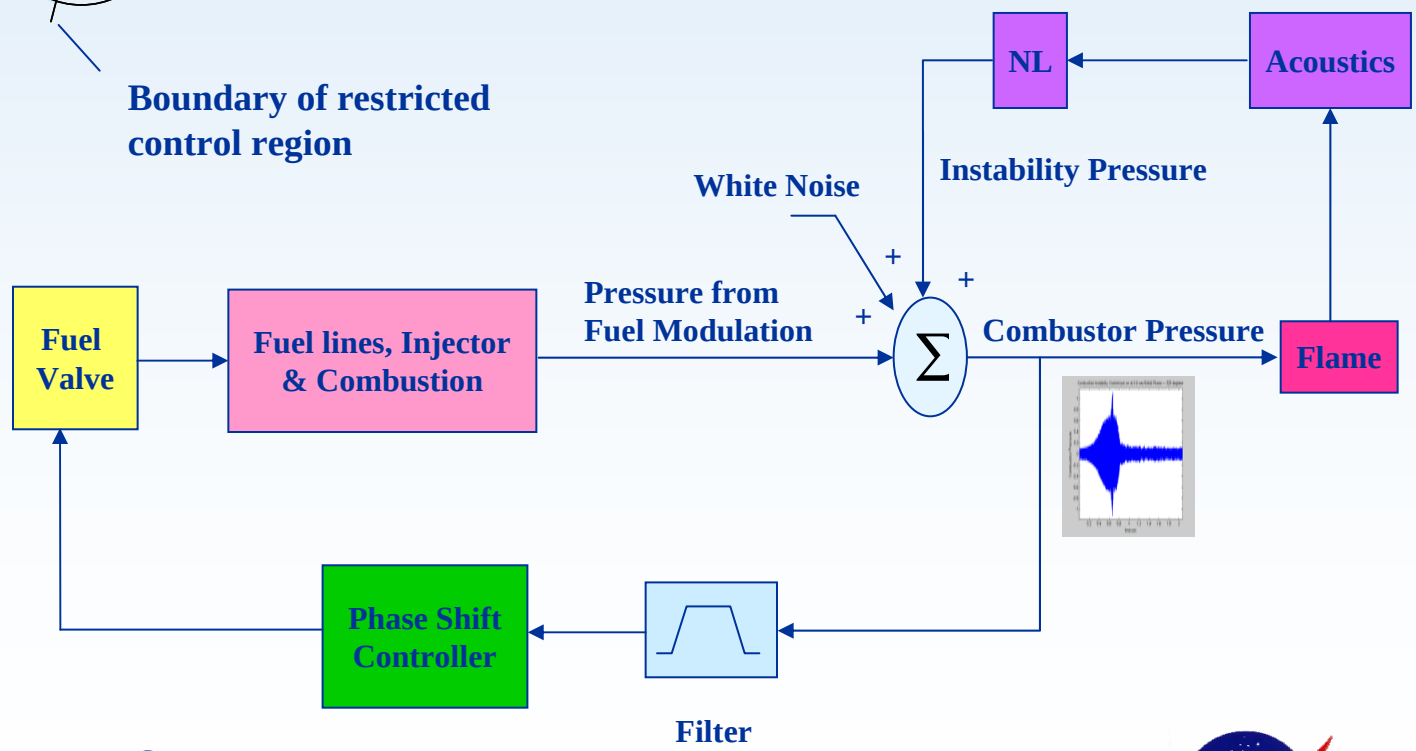


Stroboscopic Image of Dynamic Fuel Injection

Adaptive phase shifting control:

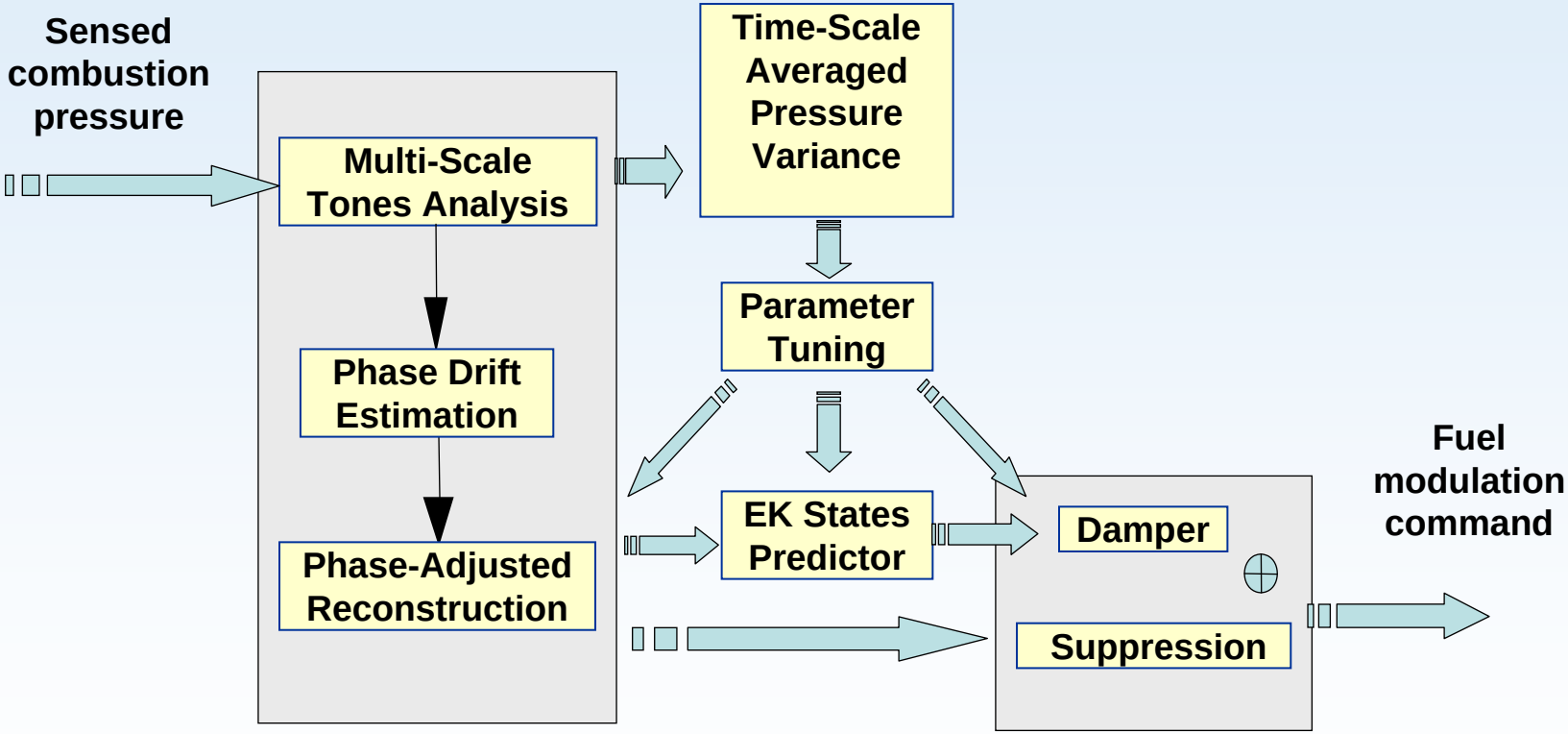
"Adaptive Sliding Phasor Averaged Control" – G. Kopasakis





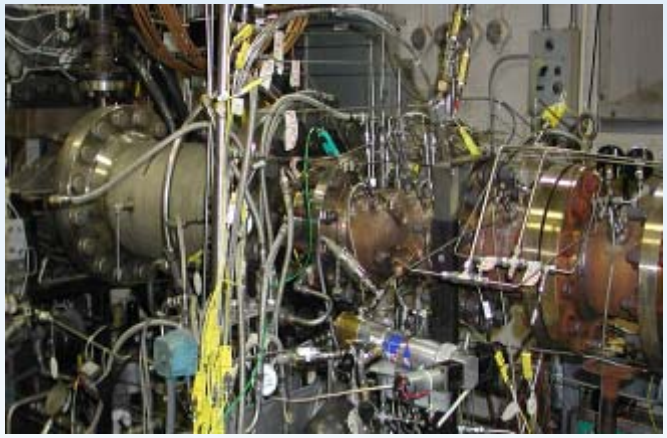
Model-Based Control:

"Multi-Scale Extended Kalman Control" – D.K. Le

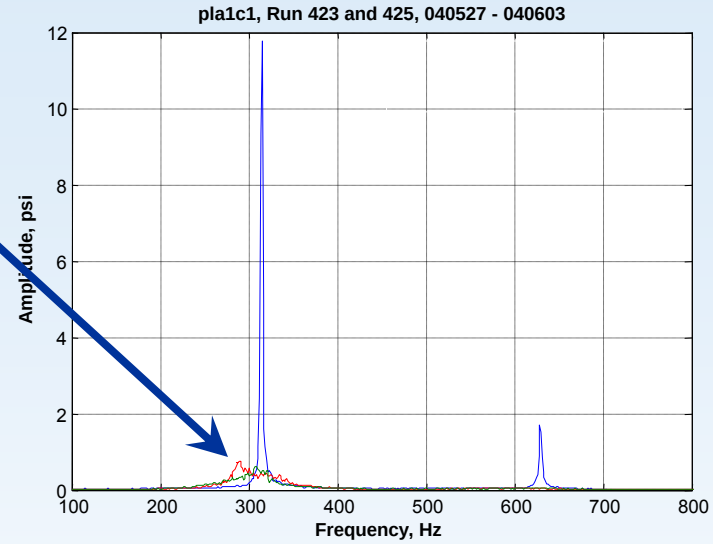


Active Combustion Instability Control Demonstrated Experimentally

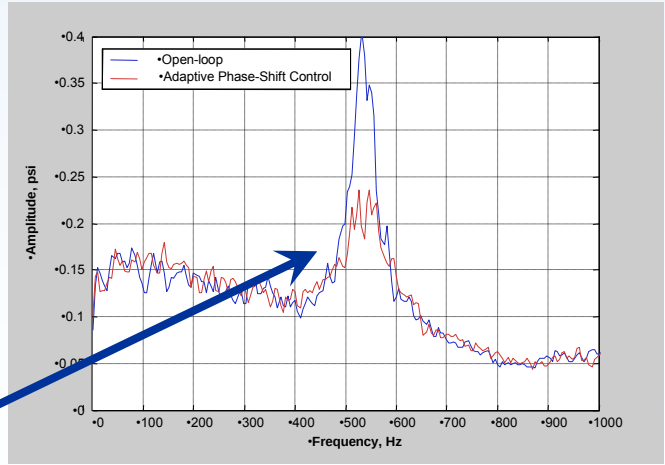
Large amplitude, low-frequency instability suppressed by 90%



Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

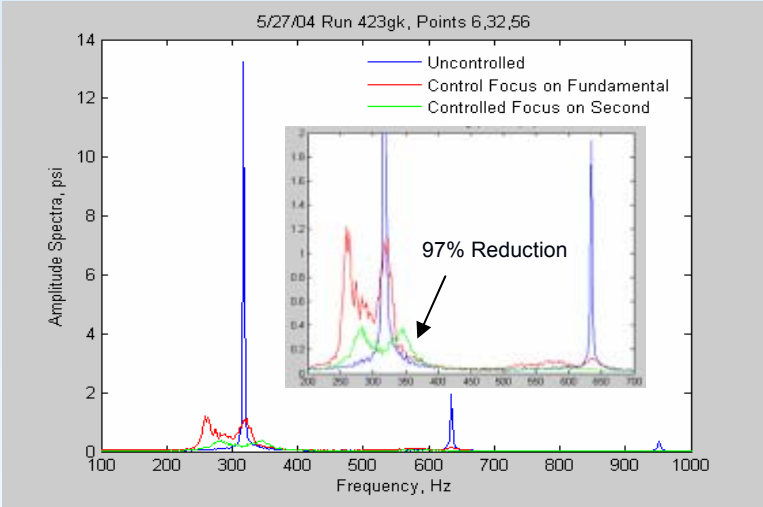


High-frequency, low-amplitude instability is identified, while still small, and suppressed almost to the noise floor.

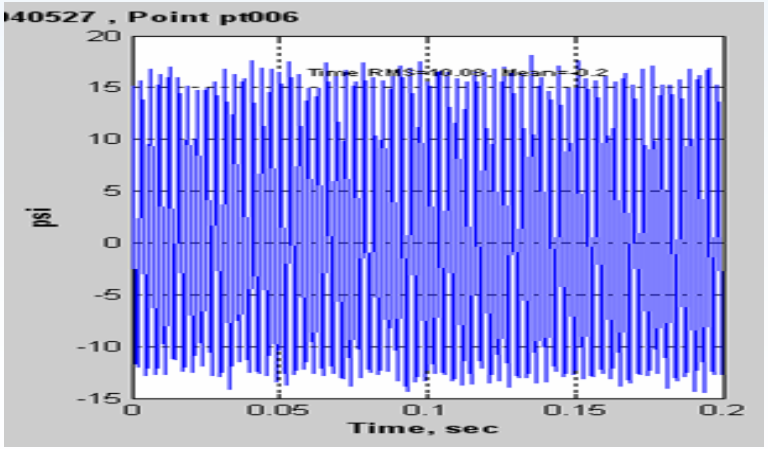


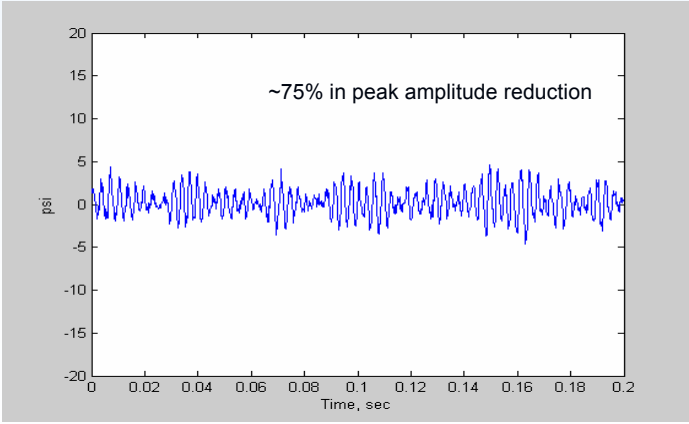
Additional Test Results:

Harmonic-focused control provides over 90% reduction in pressure spectral peak for large, low-frequency instability

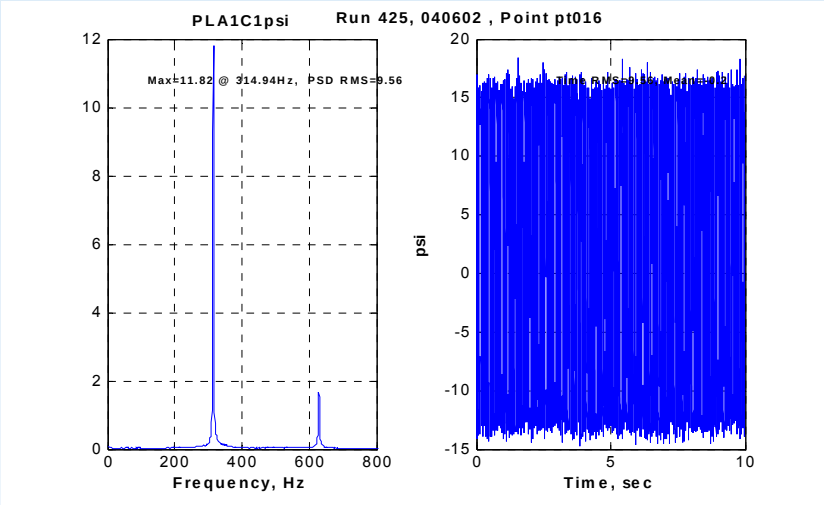


Uncontrolled –vs- Controlled Instability Pressure

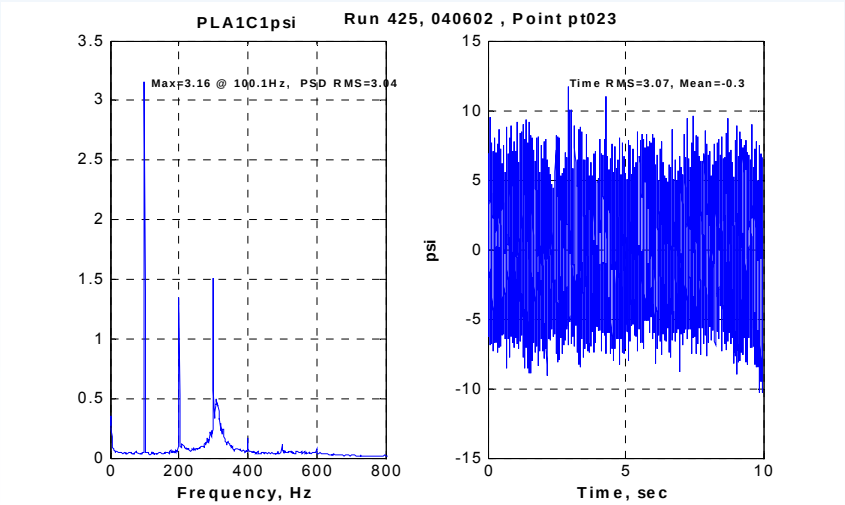




Additional Test observations: Open-loop 100 Hz fuel valve perturbations shows substantial interference with 315Hz instability



Uncontrolled



Open-loop perturbations at 100Hz

Recent Results
– Lean, Low-Emissions Combustor Instability Characterization

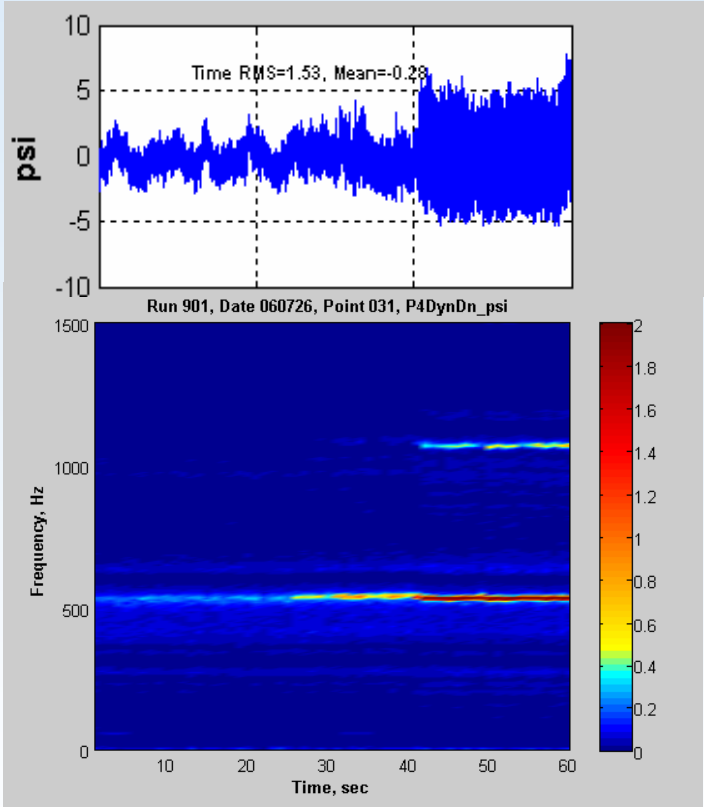
- **Increasing fuel flow increases 530Hz combustion instability, <u>preventing full-power operation</u>**

- **Continuing research to demonstrate instability control/suppression:**
  - **Apply advanced NASA modeling, control, actuation methods**

Combustor Pressure Oscillations

Amplitude

Frequency Spectra



Active Control may extend lean, low-emissions combustor operation

Simulation of Combustion Instabilities: A Sectored-One-Dimensional Approach

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Propulsion Controls and Diagnostics Workshop

Cleveland, Ohio, November 2007

Discussion Outline

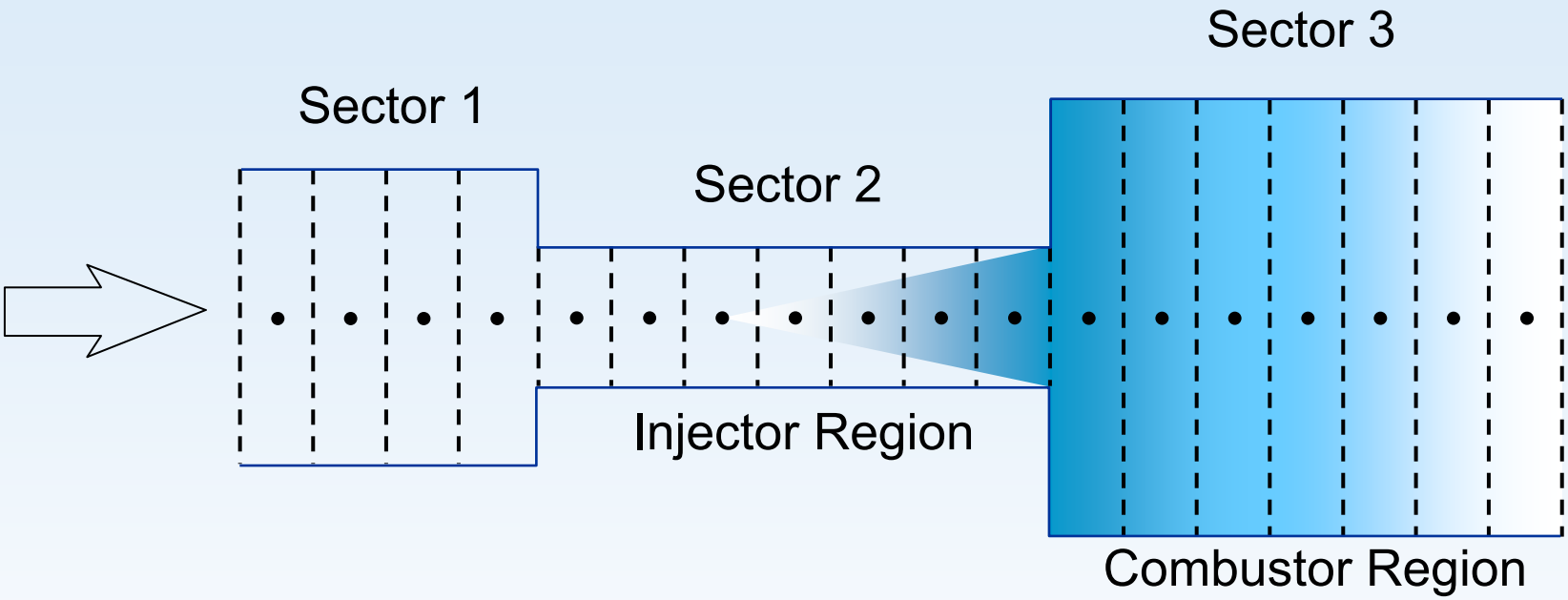
- Motivation
- Simulation Methodology Description
- Results
- Comments

Motivation

- **Low emission combustors may be susceptible to thermo-acoustic combustion instabilities.**
- **One possible solution to the this problem is active control.**
- **Successful active control design requires accurate modeling and simulation.**
  - The essential physical phenomena should be correctly captured (e.g. self-excitation).
  - Characterization and a control design necessitate rapid simulation (i.e. relative simplicity).
  - Simulation must lend itself to implementing a variety of sensing and actuation strategies.

For combustor configurations in which the potential instabilities propagate axially, but which contain abrupt changes in cross sectional area, the method to be described can achieve the simulation goals.

Description-Simplifications



Within Each Sector:

- One-Dimensional
- Perfect Gas

Description-Governing Equations

$$\frac{\partial \overline{w}}{\partial t} + \frac{\partial \overline{F}(\overline{w})}{\partial x} = \overline{S}(\overline{w}, x)$$

$$\overline{w} = \begin{bmatrix} \rho \\ \rho u \\ \dfrac{p}{\gamma(\gamma - 1)} + \dfrac{\rho u^2}{2} \\ \rho z \end{bmatrix} \quad \overline{F} = \begin{bmatrix} \rho u \\ \dfrac{p}{\gamma} + \rho u^2 \\ u\left(\dfrac{p}{\gamma - 1} + \dfrac{\rho u^2}{2}\right) \\ \rho u z \end{bmatrix}$$

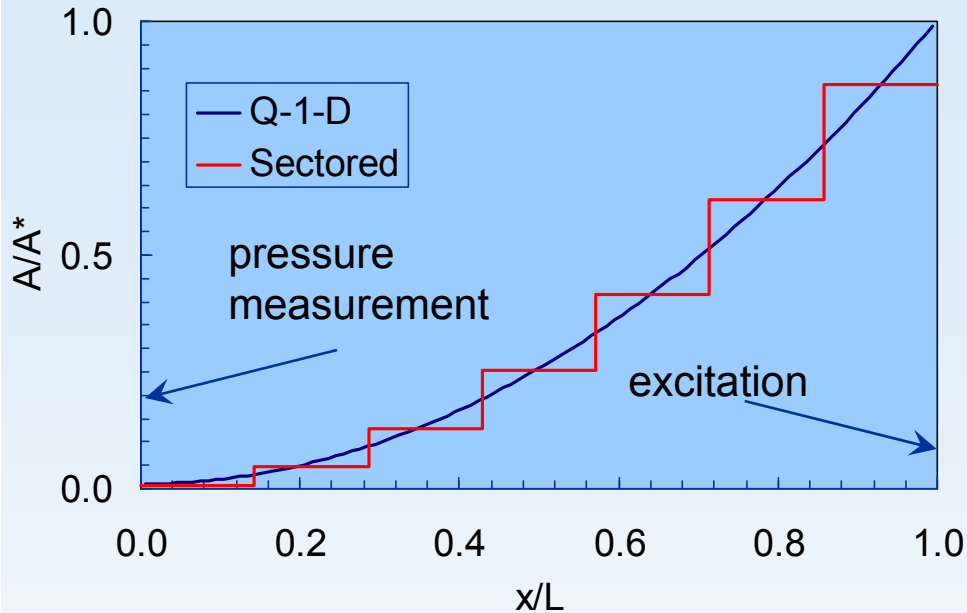
$$\overline{S}(\overline{w}, x) = \begin{bmatrix} \dot{m}_s \\ \dfrac{\partial}{\partial x}\left(\dfrac{\varepsilon_t}{Re^*}\left(\dfrac{\partial u}{\partial x}\right)\right) + \sigma_2 u |\rho u|^{0.75} \\ \dfrac{\partial}{\partial x}\left(\dfrac{\varepsilon_t}{Re^*}\dfrac{\partial}{\partial x}\left(\dfrac{u^2}{2} + \dfrac{T}{(\gamma - 1)Pr_t}\right)\right) + \dfrac{T^0 \dot{m}_s}{\gamma - 1} + q_0 R + Q_{ht} \\ \dot{m}_r + \dfrac{\partial}{\partial x}\left(\dfrac{\varepsilon_t}{Re^* Sc_t}\left(\dfrac{\partial z}{\partial x}\right)\right) - R + \dot{m}_s z_s \end{bmatrix}$$

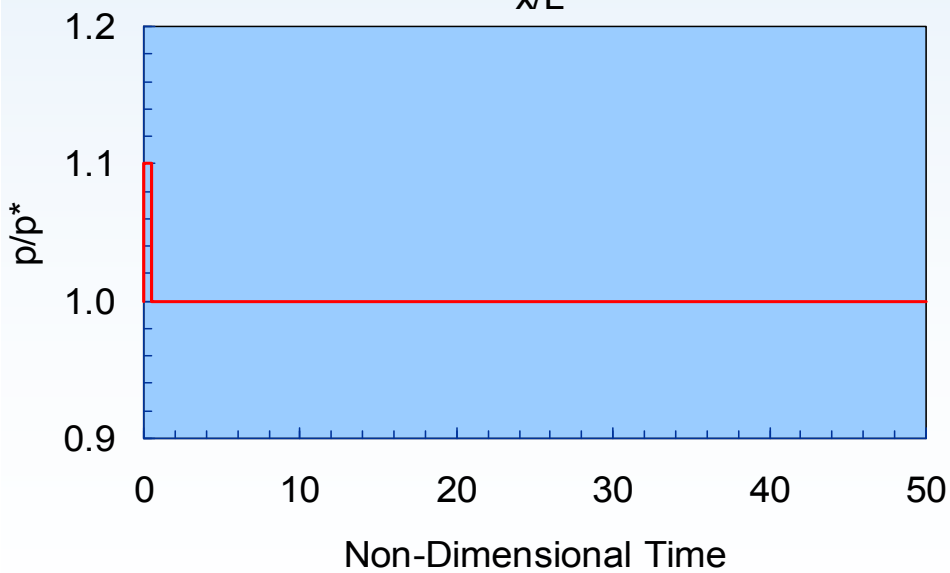
$$R = K_0 \rho z(\zeta_1 - \zeta_2 z)\begin{Bmatrix} 1 - (T_{ign}/T_i) & ; T_i > T_{ign} \\ 0 & ; T_i < T_{ign} \end{Bmatrix}$$

$$Q_{ht} = \alpha(T_{inf} - T_i)$$

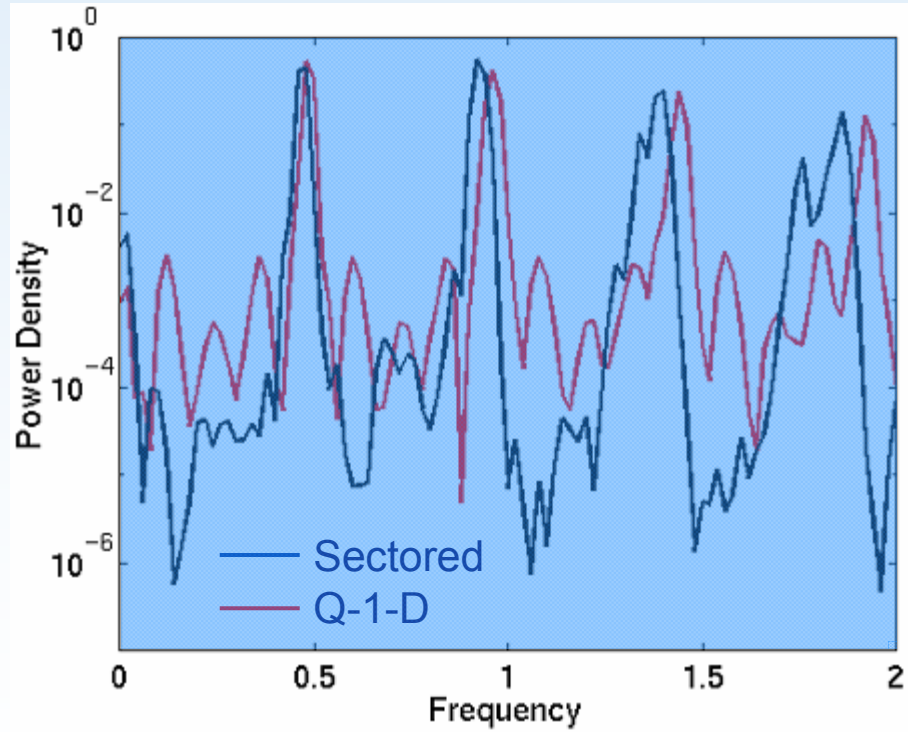
- Reactive Euler Equations with Source Terms
- MacCormack's Method
  - Fast
  - Second Order Accurate
- Artificial Viscosity
  - Baldwin-MacCormack
  - Density Instead of Pressure
- Uniform Grid Spacing
  - Relatively Course
  - Requires Some "Tuning" (e.g. eddy viscosity, reaction rates)
- Sectors Joined With Compatible Boundary Conditions
  - Multi-block Approach
  - Nothing "Stored" @ Interface

Initial Tests-Conical Pipe Acoustics

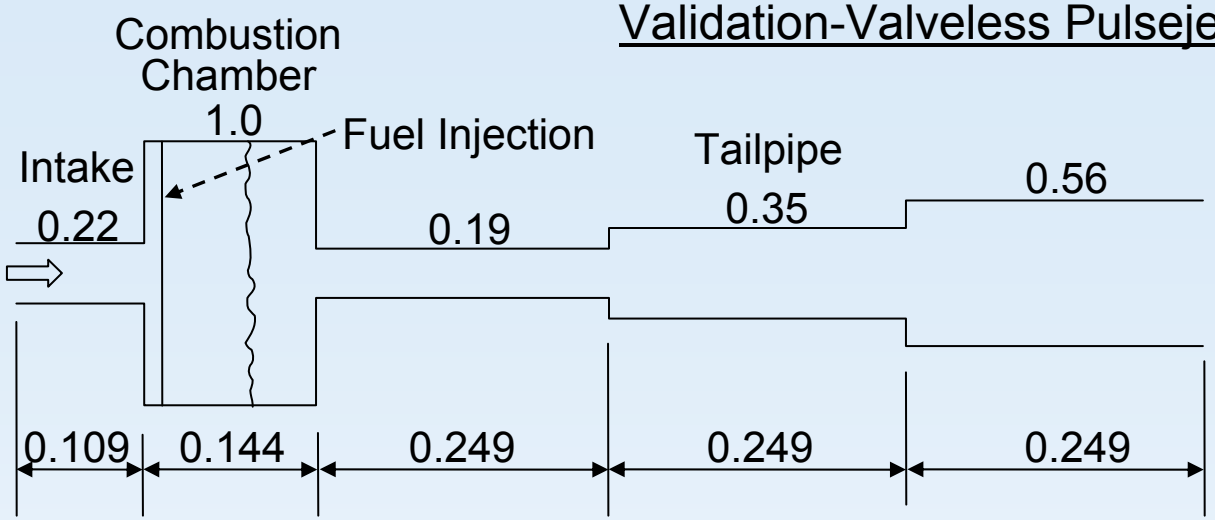




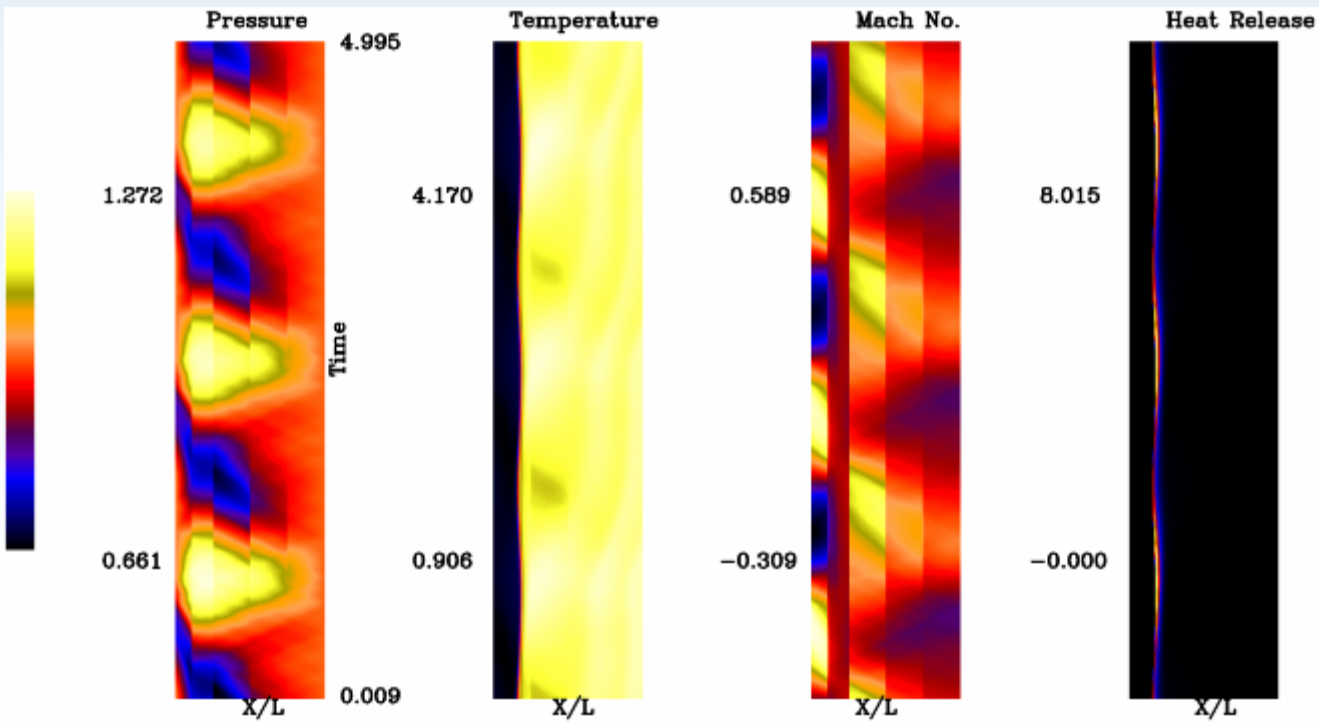
- Theoretical resonant frequencies are integer multiples of the fundamental.
- Q-1-D and Sectored models agree
- 100 numerical cells.

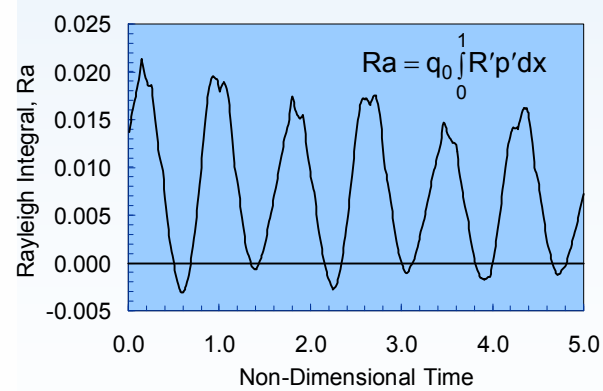


Validation-Valveless Pulsejet



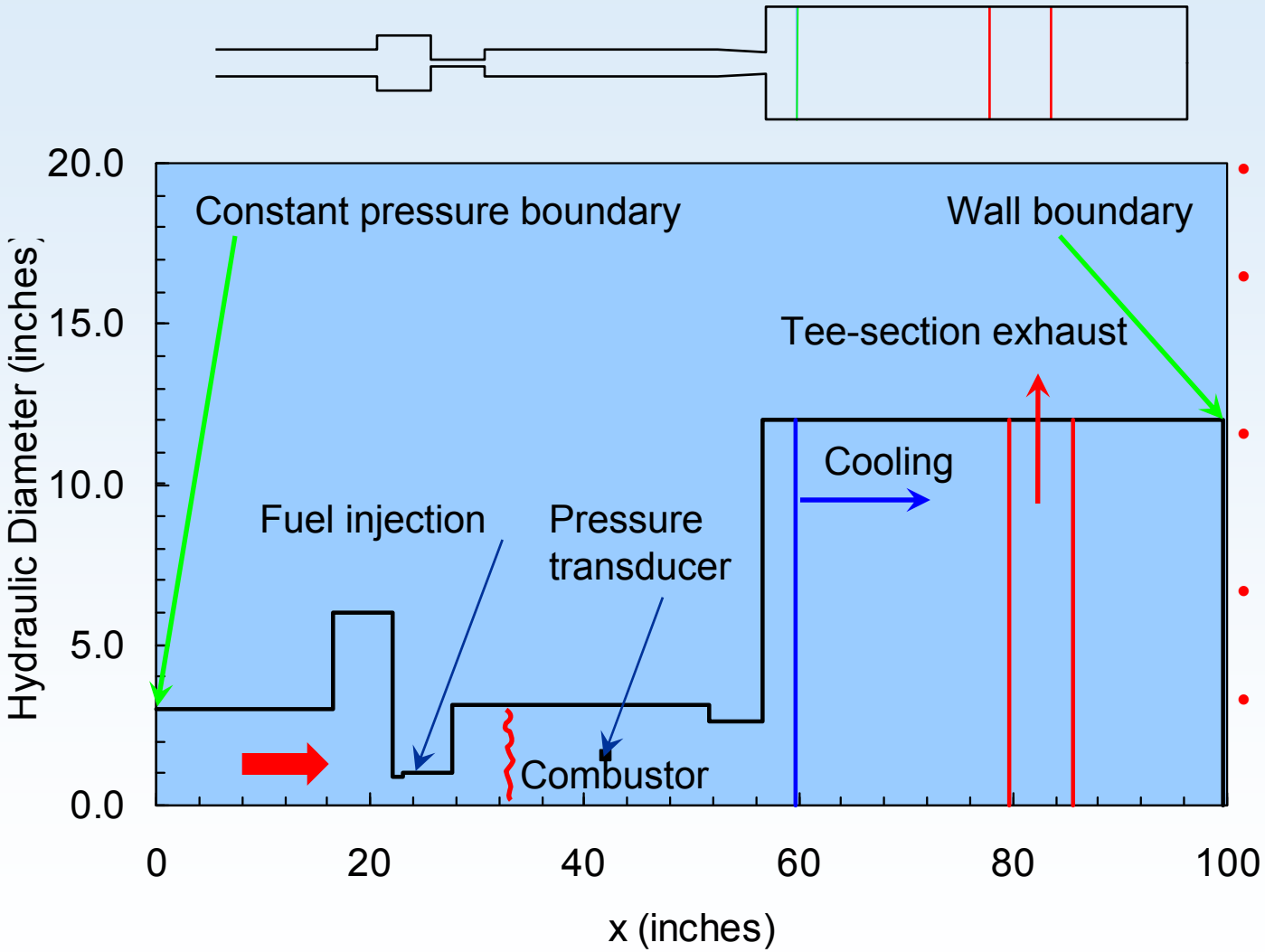
- Coupling between heat release and acoustic modes is self-excited.
- No external, forced excitation.
- Geometry approximates a functional pulsejet.
- Frequency is correct.
- 200 cells.





Comparison With Experiment

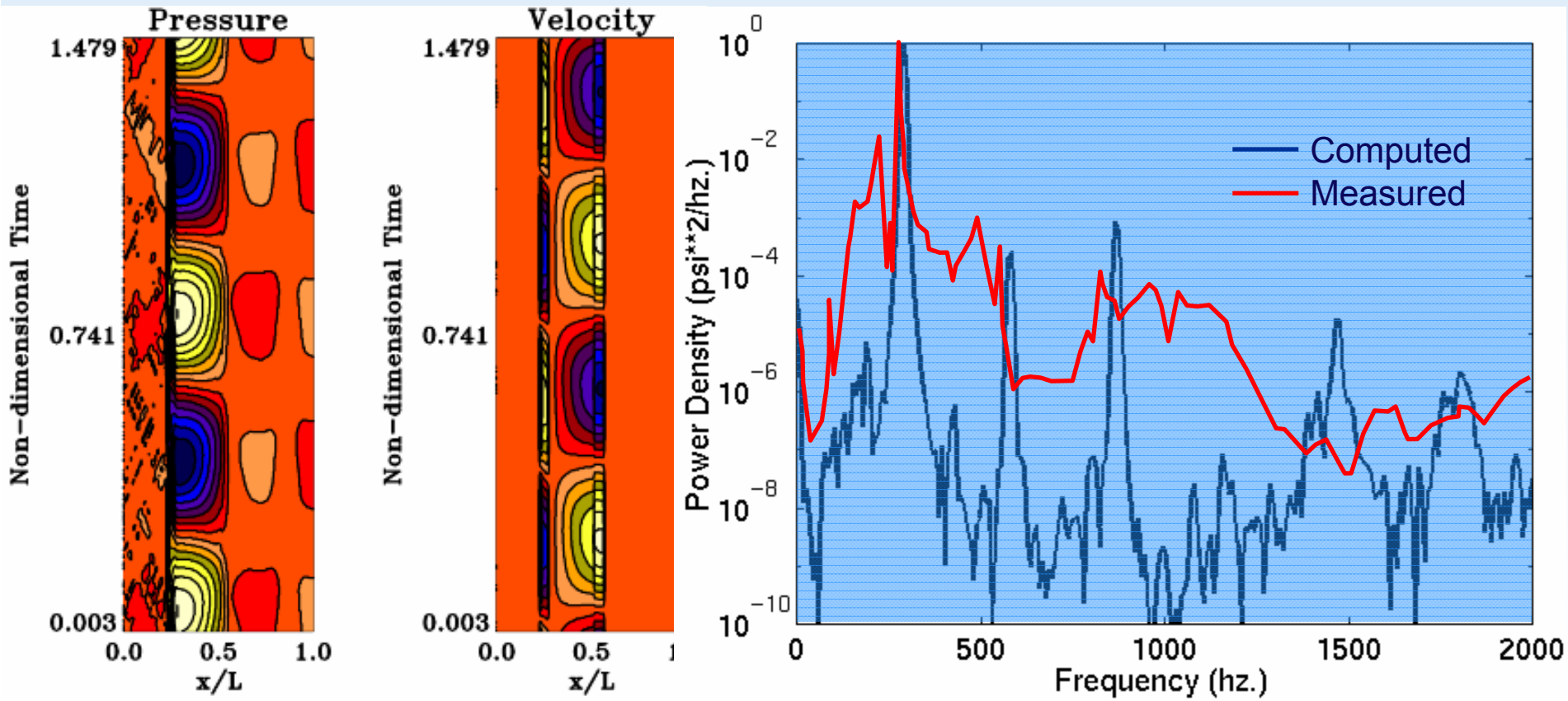
GRC CE-5 LPP



- Exhaust modeled as mass extraction.
- Cooling spray modeled as a high heat transfer region.
- Flame position adjusted with turbulent diffusivity distribution.
- Noise added at inlet boundary.
- 350 cells, CPU time=1600 integration time .

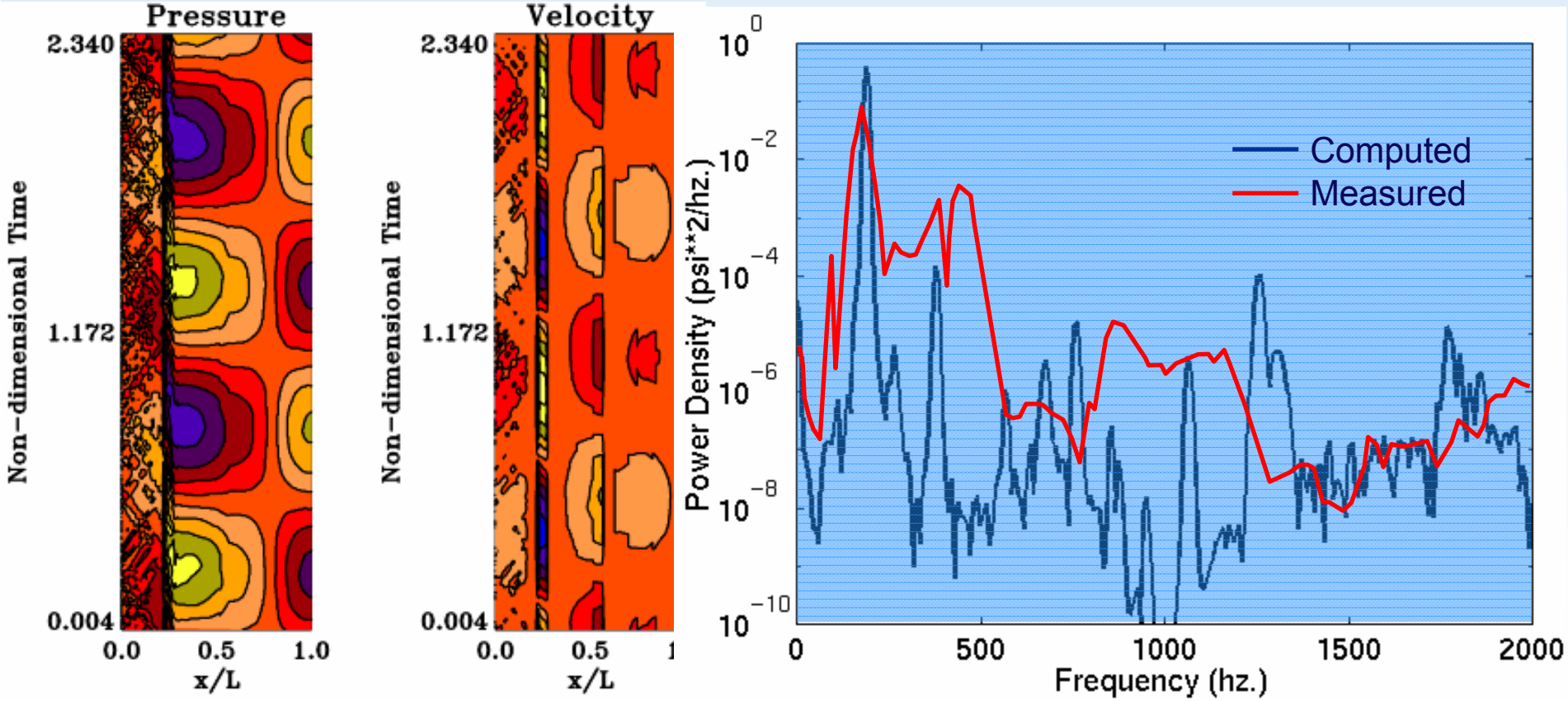
Comparison With Experiment

Low Pressure, Low Mass Flow, Low Inlet Temperature



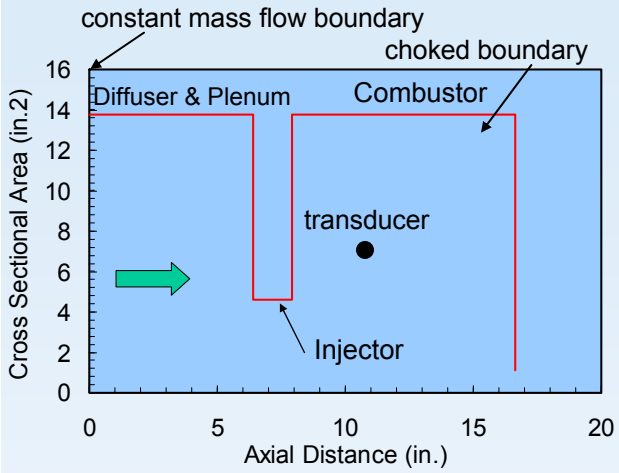
Comparison With Experiment

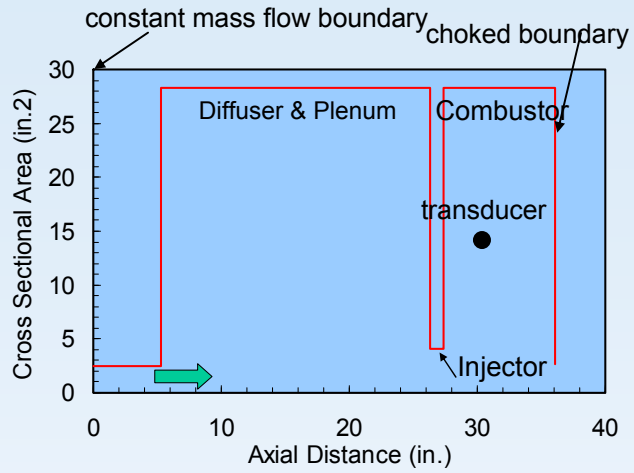
High Pressure, High Mass Flow, High Inlet Temperature

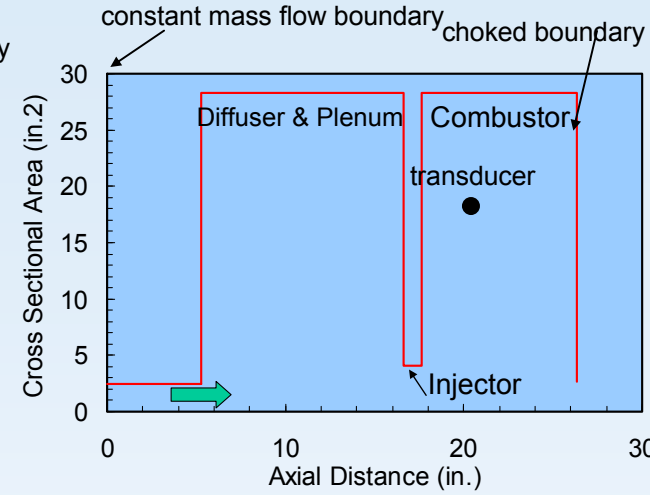


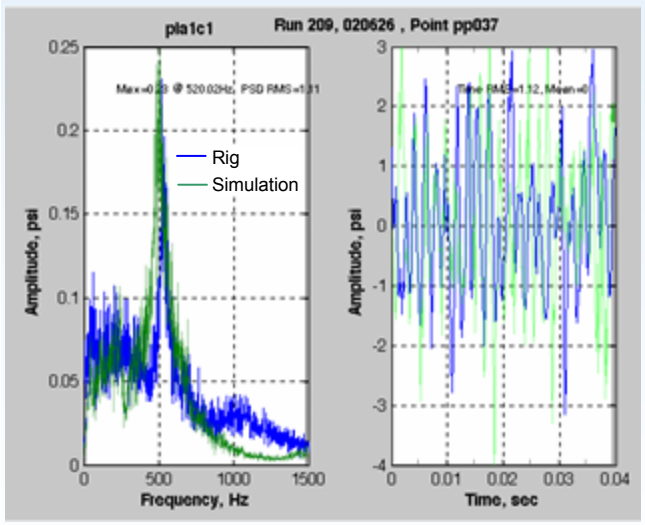
Comparison With Experiment

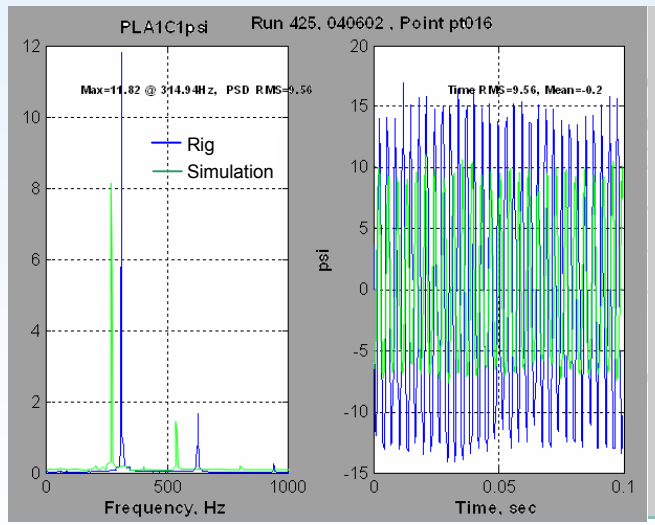
GRC CE-9 SNR

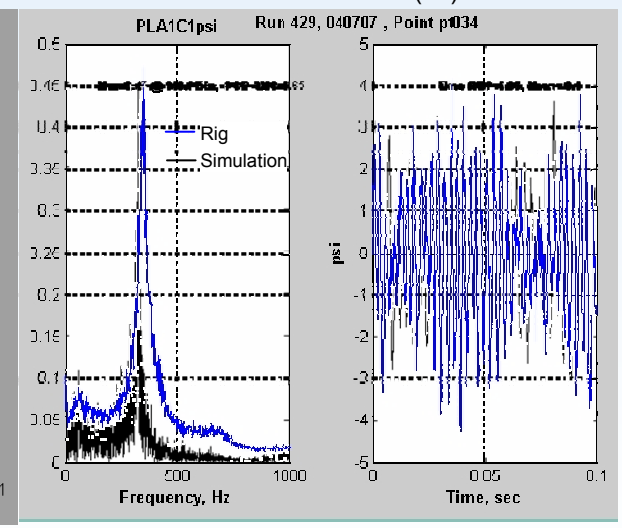












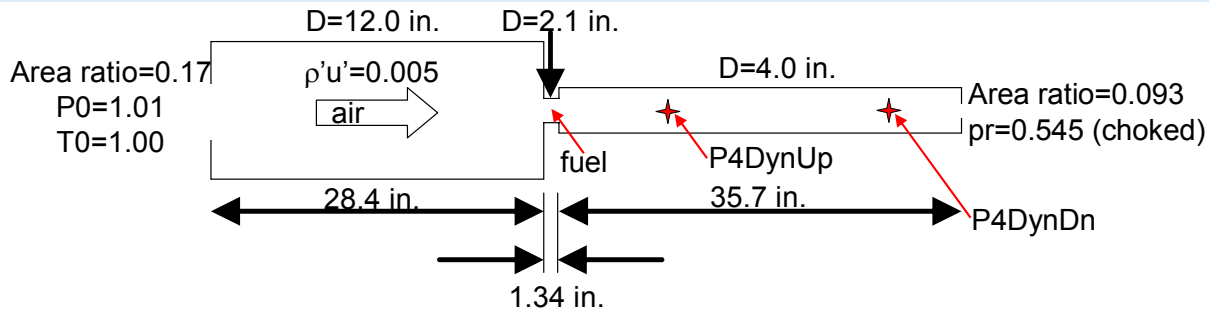
- Weak oscillations @ approx. 500 hz.
- "Pink" noise at injector (momentum source)
- Helmoltz-like.

- Strong oscillations @ approx. 300 hz.

- Strong oscillations @ approx. 350 hz.
- **Simulation preceded testing (i.e. predicitve)**

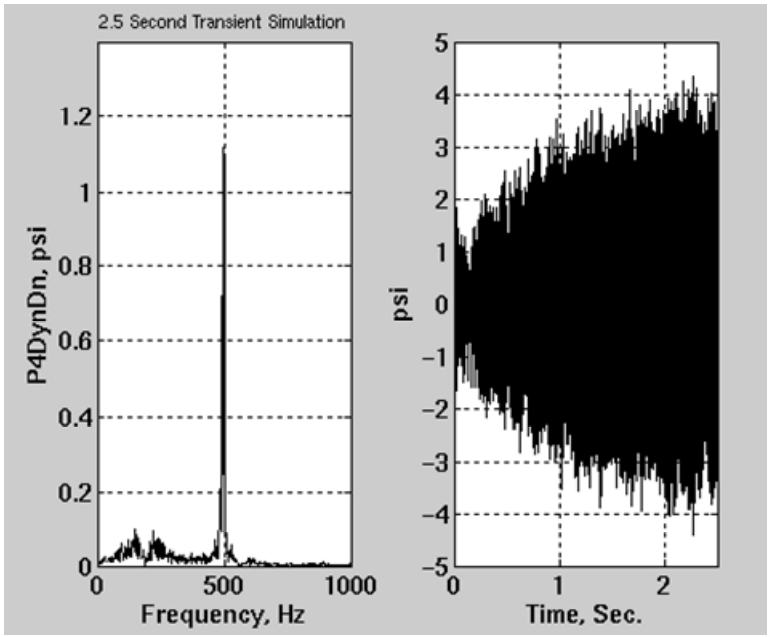
Comparison With Experiment

GRC CE-5B-Stand1 LEC

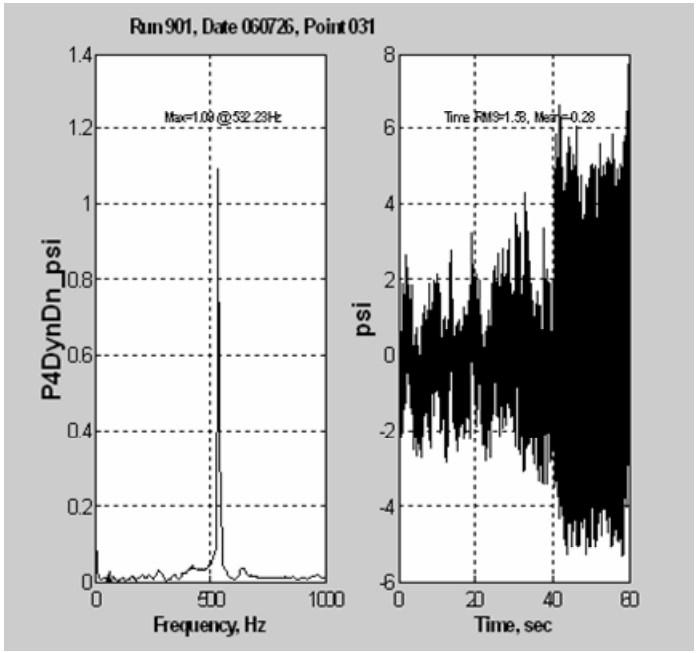


- Dump tank cooling spray simulated with a choked (reflective) boundary condition.
- Amplitude variation with f/a matched.

2.5 second simulation with linear fuel flow increase corresponding to f/a ratio change from 0.025-0.03.



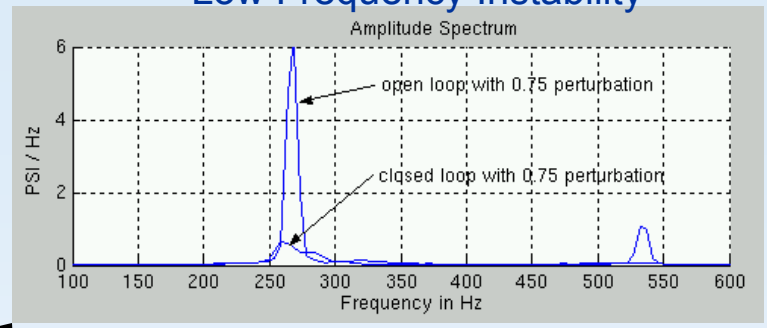
60 seconds of rig data during which f/a ratio increases from 0.028 to 0.03.



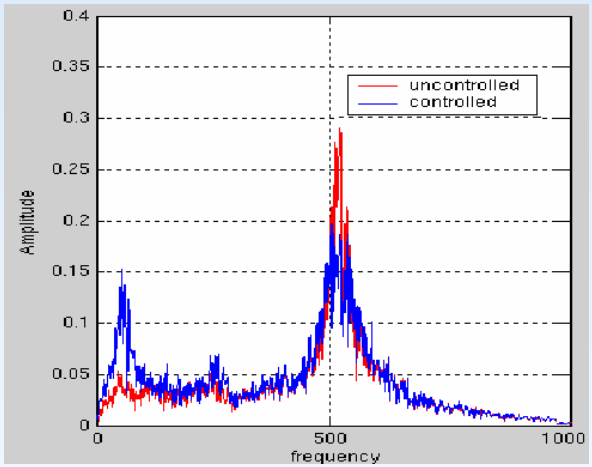
Comparison With Experiment

GRC CE-9 SNR with Active Control Applied

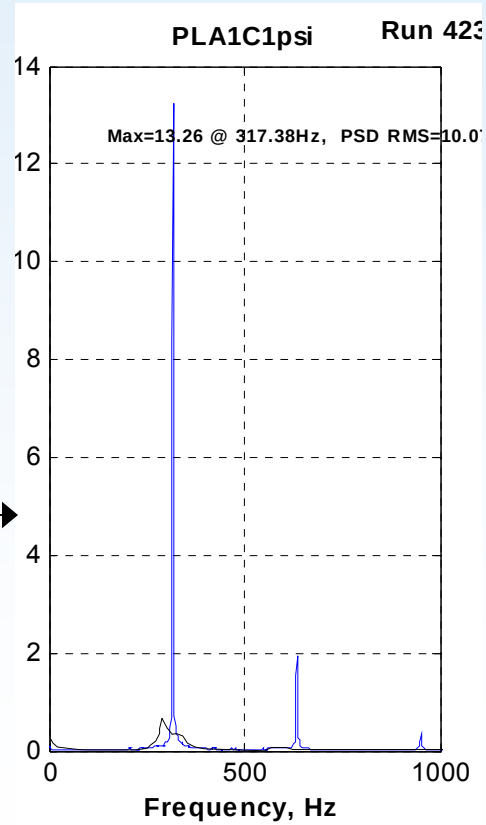
Low Frequency Instability



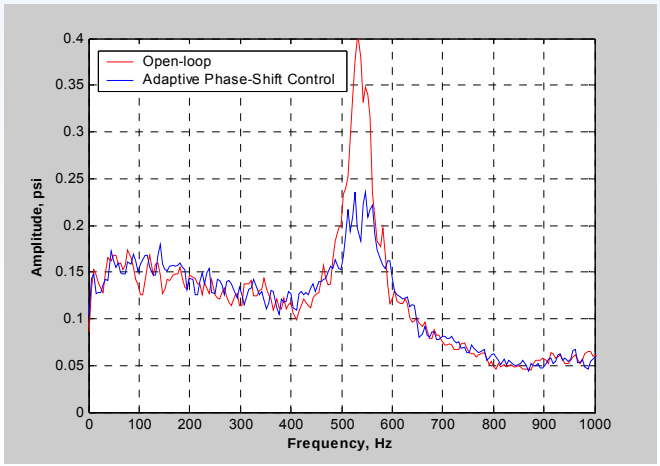
High Frequency Instability



Simulated Control



Measured Control



Sectored 1-D Model Concluding Remarks

- The sectored-one-dimensional technique has successfully simulated instabilities in a variety of combustors with complex geometries.
- Simulations run far from real-time, but fast enough for control design.
- Simulated plant responses to control match measured responses.
- Some success shown in prediction of instabilities, but “tuning” of some parameters is still required.
- More work is therefore needed to model complex phenomena in a 1-D compatible fashion.

Active Combustion Control for Ultra Low Emissions in Aircraft Gas-Turbine Engines

Current Directions and Future Plans

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Controls and Dynamics Branch
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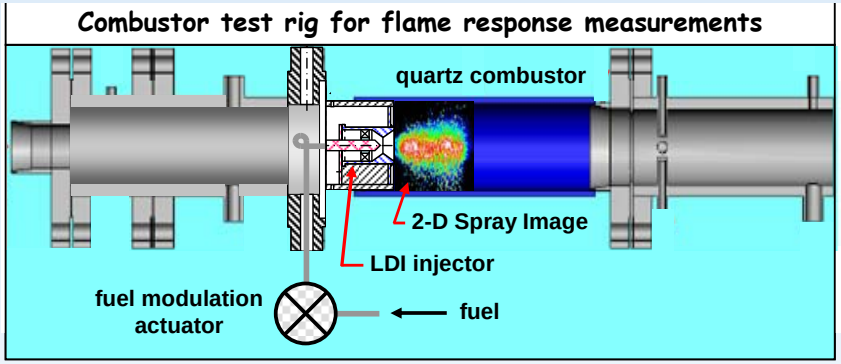
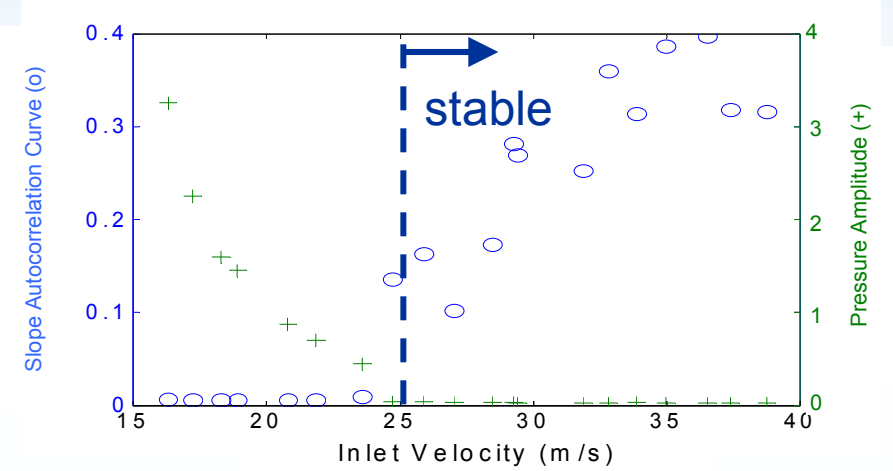
Current Directions and Future Plans

NRA Cooperative Agreements

- Penn State and Virginia Tech
  - Active fuel nozzle, flame transfer function



- Georgia Tech
  - Integrated control of:
    - Dynamic stability margin
    - Static stability margin
    - Dynamic stability mitigation



Current Directions and Future Plans

- Current platform - lean combustor concept (not LDI)
  - Actuator research for small “pilot” flows
  - Dynamic model validation
  - Instability control demonstration
- Future platform - LDI Multi-point injection
  - Fundamentals rig in CE7C
  - High pressure testing in CE5, ASCR
  - Control methods that exploit multipoint injection
  - Multidimensional models
- Incorporate technologies from NRA’s
- Harmonic, sub-harmonic models and control

Opportunities for Collaboration

- Requirements definition and feedback (engine, HW mfrs)
- Realistic testbeds for technology transfer
- Control methods integration and field testing
- Modeling methods field testing
- Multidimensional models development
- Actuator systems, associated models development, field testing

- **NRA's, SBIR – Watch solicitations. Future topics TBD**
- **SAA's – Have one in place, others welcome**

Concluding Remarks - Long Term Goal for Active Combustion Control

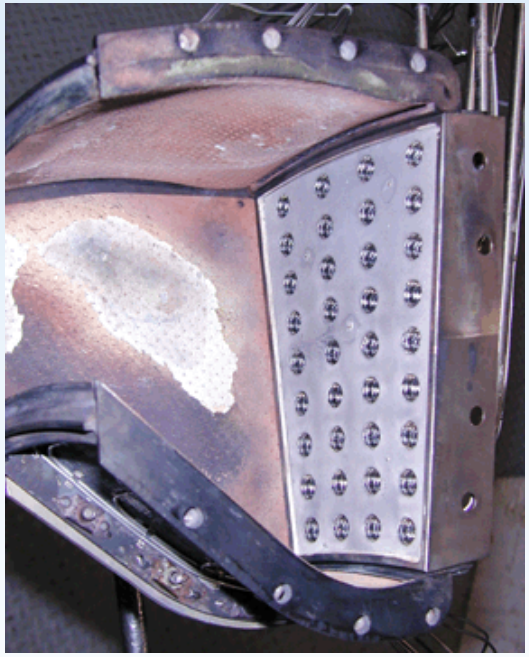
- **Improve fundamental understanding of the combustor processes**

in order to…

- **More effectively integrate multi-point combustor design, controls, sensor, and actuator technologies**

to provide…

  - **An intelligent fuel/air management system with temporal and spatial fuel modulation for**
    - **Instability avoidance/suppression**
      - **Thermoacoustics, blowout**
    - ***Pattern factor control***
    - ***Emissions minimization***



to enable…

➢ **Combustors with extremely low emissions throughout the engine operating envelope**

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