Characterization and Simulation of Thermoacoustic Instability in a Low Emissions Combustor Prototype

John C. DeLaat and Daniel E. Paxson

Extensive research is being done toward the development of ultra-low-emissions combustors for aircraft gas turbine engines. However, these combustors have an increased susceptibility to thermoacoustic instabilities. This type of instability was recently observed in an advanced, low emissions combustor prototype installed in a NASA Glenn Research Center test stand. The instability produces pressure oscillations that grow with increasing fuel/air ratio, preventing full power operation. The instability behavior makes the combustor a potentially useful test bed for research into active control methods for combustion instability suppression. The instability behavior was characterized by operating the combustor at various pressures, temperatures, and fuel and air flows representative of operation within an aircraft gas turbine engine. Trends in instability behavior vs. operating condition have been identified and documented. A simulation developed at NASA Glenn captures the observed instability behavior. The physics-based simulation includes the relevant physical features of the combustor and test rig, employs a Sectored 1-D approach, includes simplified reaction equations, and provides time-accurate results. A computationally efficient method is used for area transitions, which decreases run times and allows the simulation to be used for parametric studies, including control method investigations. Simulation results show that the simulation exhibits a self-starting, self-sustained combustion instability and also replicates the experimentally observed instability trends vs. operating condition. Future plans are to use the simulation to investigate active control strategies to suppress combustion instabilities and then to experimentally demonstrate active instability suppression with the low emissions combustor prototype, enabling full power, stable operation.

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Fundamental Aeronautics Program Annual Meeting
7-9 Oct 2008
Atlanta, GA

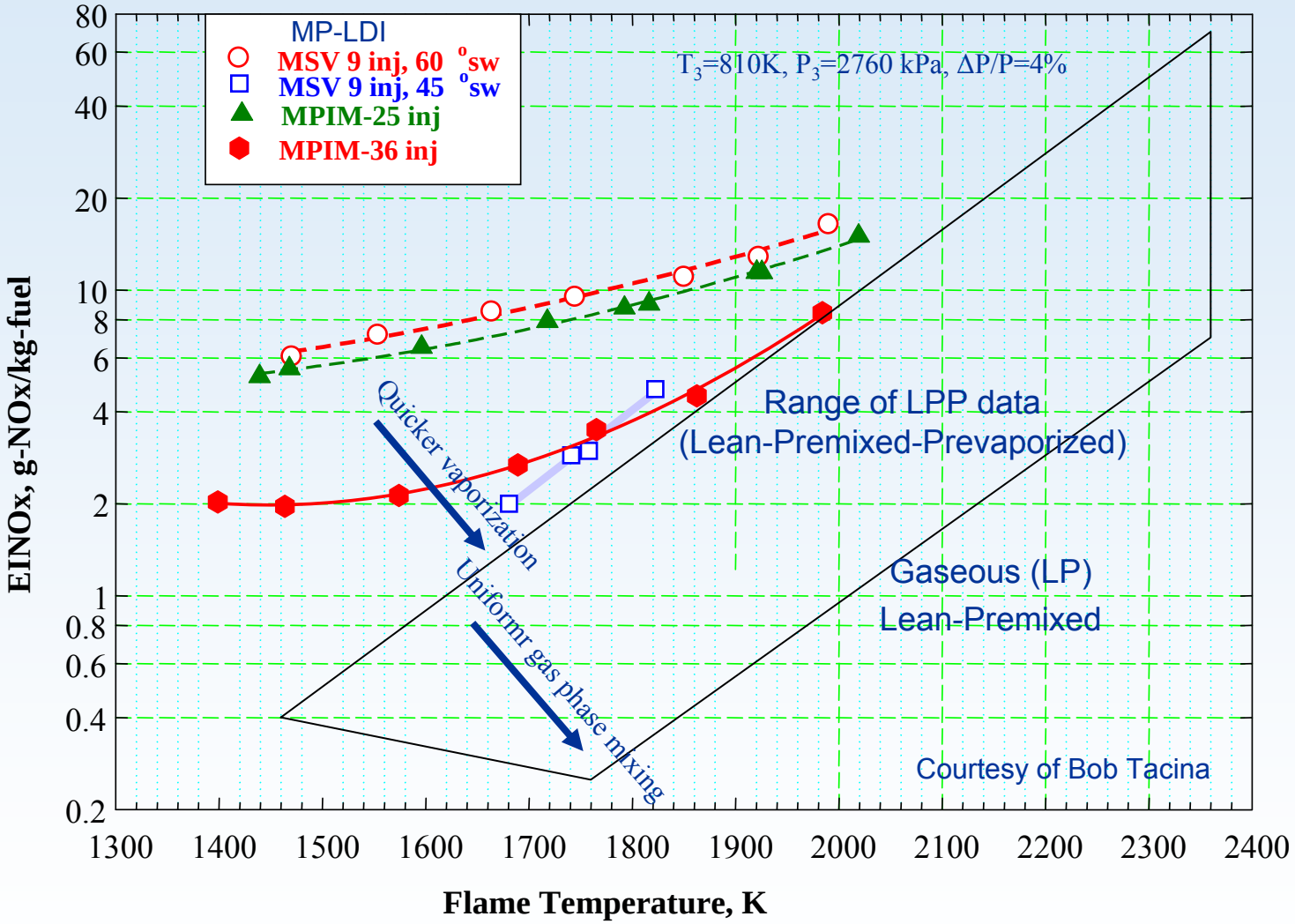
Acknowledgements

- Dr. Changley Wey – NASA Test Engineer
- Operations and Testing staff – NASA Test Cell CE5
- Propulsion 21 Program – John Rohde, Emissions Project Manager
- Fundamental Aeronautics Program – Dan Bulzan, SUP - High Altitude Emissions API

Outline

- Background
  - Motivation: Low emissions combustors for aircraft gas turbine engines
  - NASA's combustor research
  - Thermoacoustic instability => Active control
- Current Effort
  - Identify a low emissions combustor concept with thermoacoustic instability
  - Experimentally characterize the instability behavior
  - Develop a simulation that captures the combustion instability
  - Validate the simulation against experimental data
- Future Plans

Effect of Fuel Injection Schemes on NOx Emission

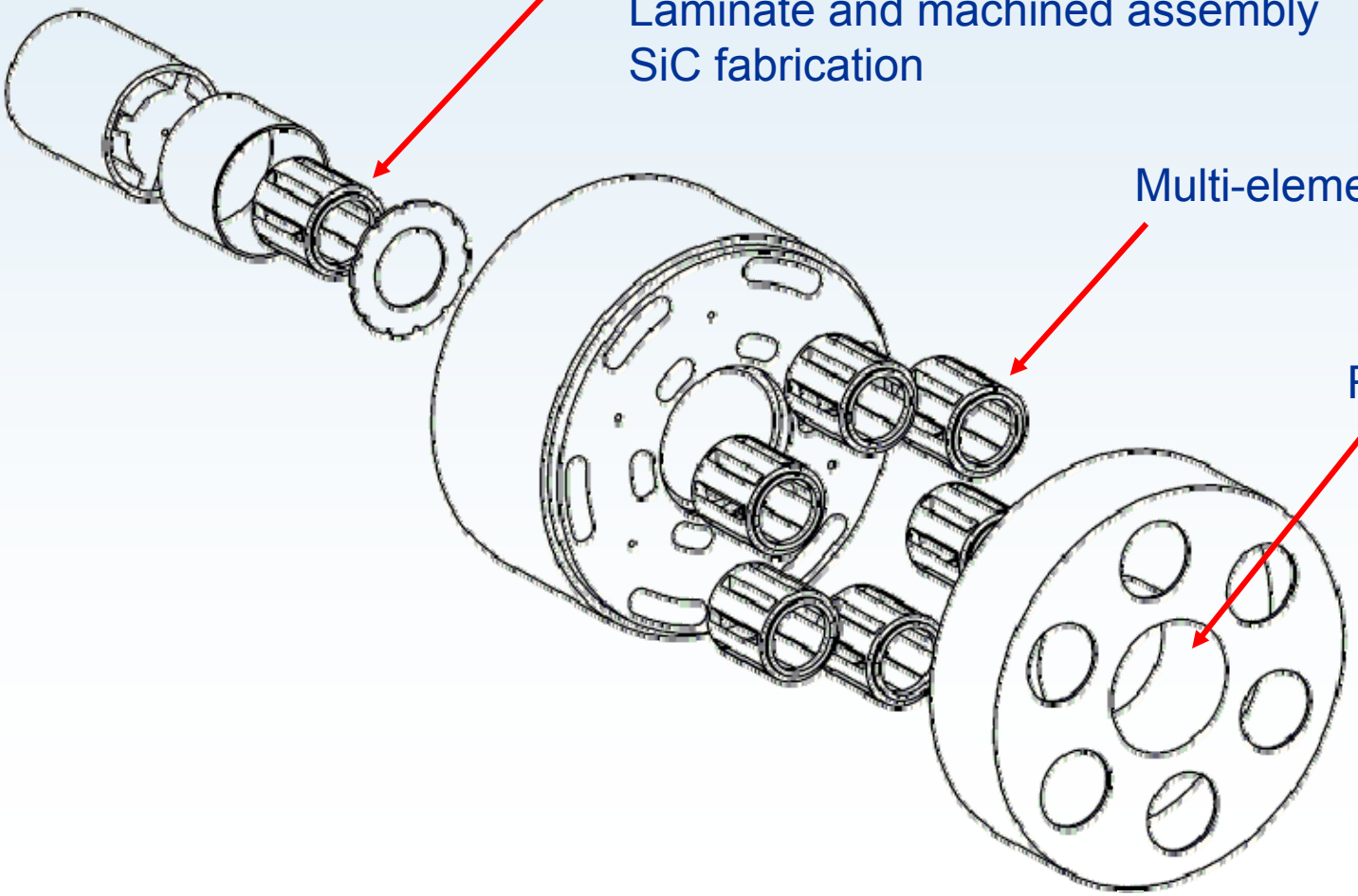


Example 7-point LDI Layout, Research Interests

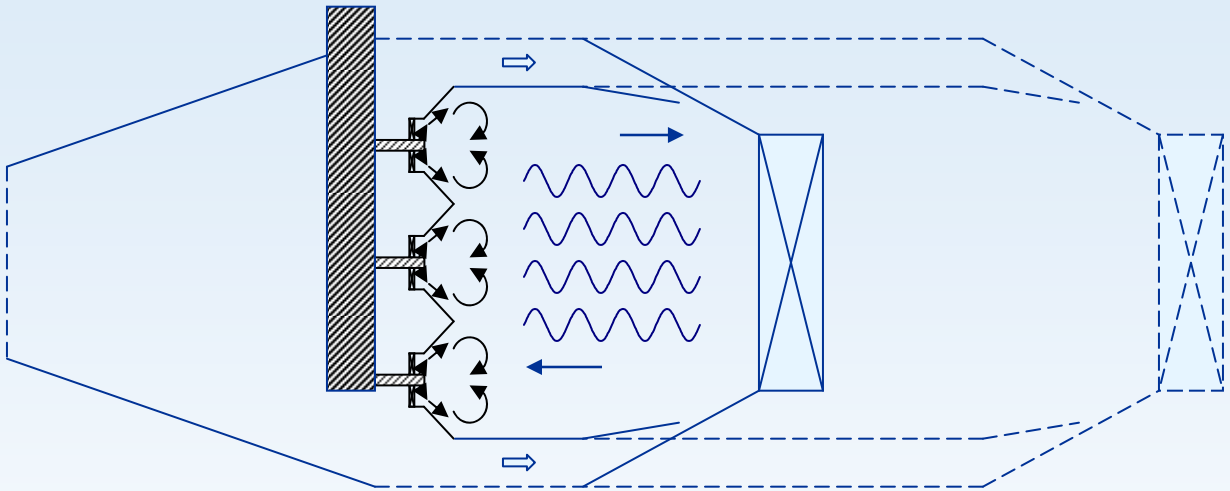
Single element configurations
- Swirl numbers, radial vs. axial
- Venturi contraction
- Downstream recirculation zones
- Laminate and machined assembly
- SiC fabrication

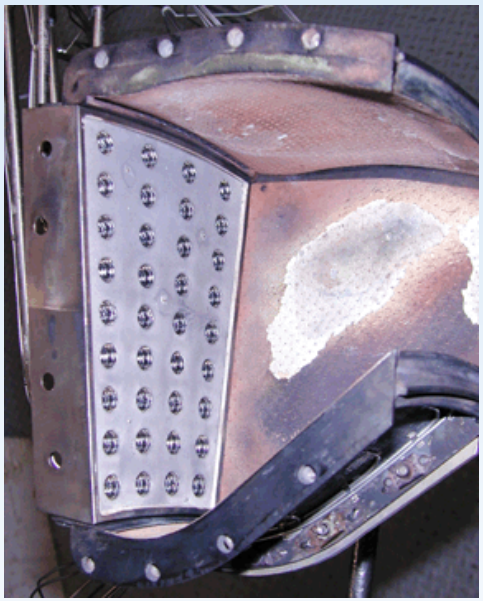
Multi-element interactions

Recessed Pilot



Lean-Burning, Ultra-Low-Emissions Combustors Are More Susceptible to Thermoacoustic Instabilities



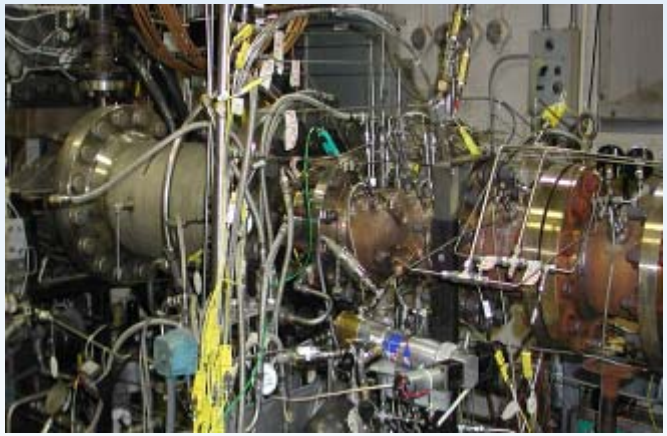


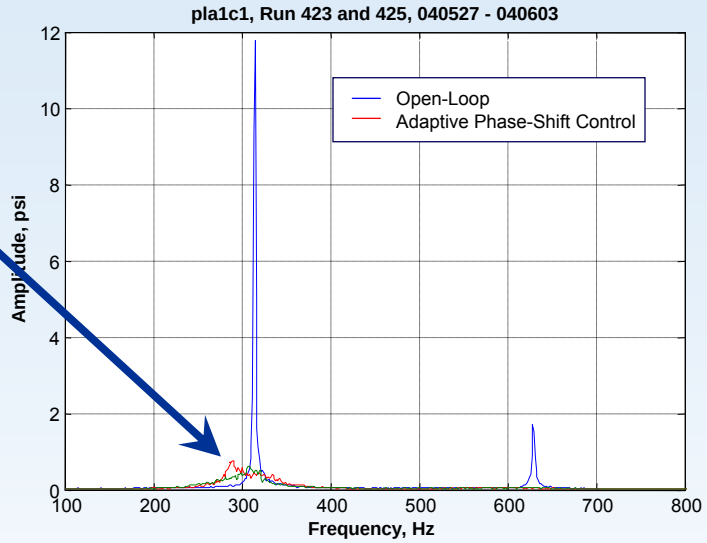
1. Higher performance fuel injectors => more turbulence
2. No dilution air => reduced flame holding
3. Reduced film cooling => reduced damping
4. More uniform temperature distribution => acoustically homogeneous
5. Shorter combustor => higher frequency instabilities

Multiple injection points allow temporal and spatial fuel/air control

Active Combustion Instability Control Demonstrated for Conventional Combustor

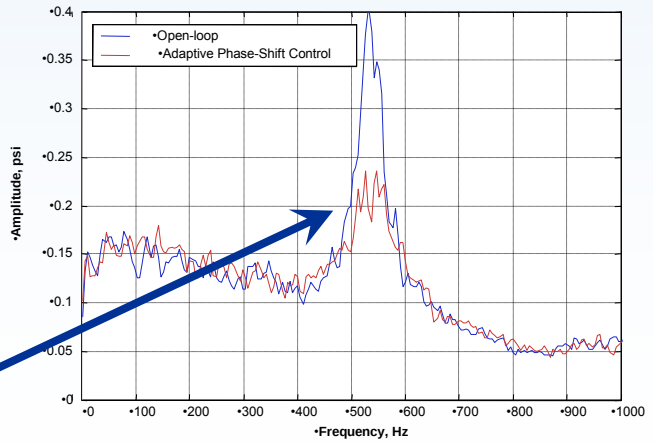
Large amplitude, low-frequency instability suppressed by 90%





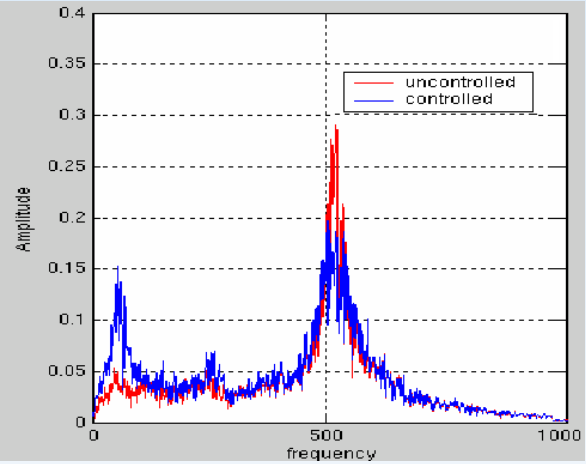
Liquid-fueled combustor rig emulates engine observed instability behavior at engine pressures, temperatures, flows

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



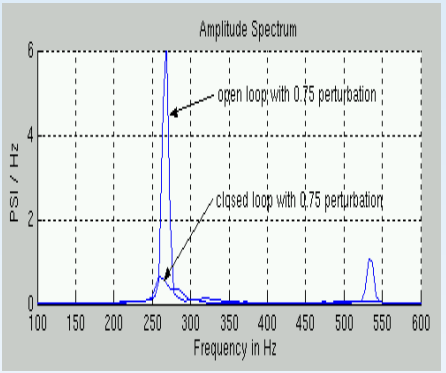
Instability Control Simulation for Conventional Combustor

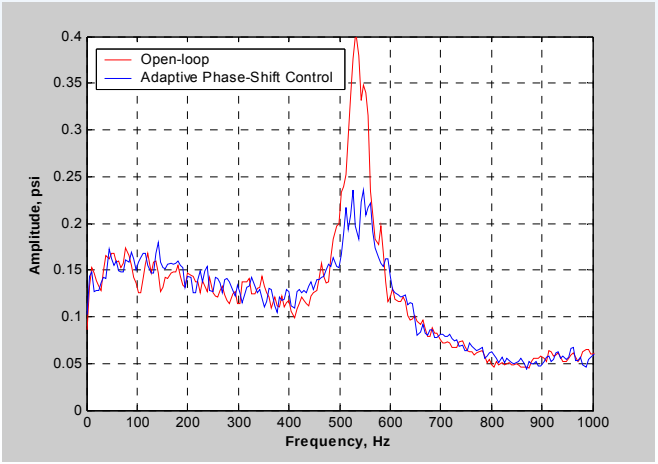
High Frequency Instability



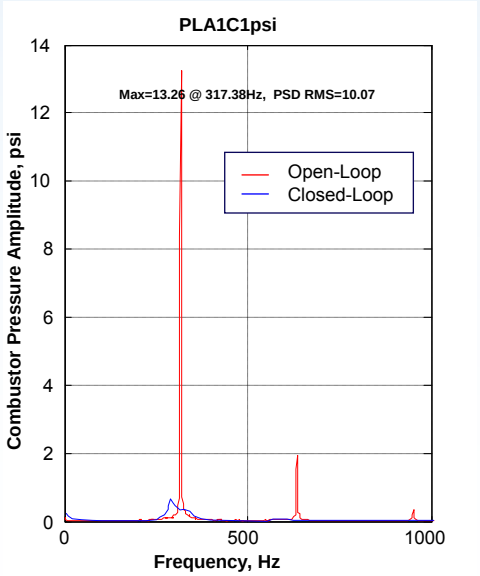
Simulated Control

Low Frequency Instability





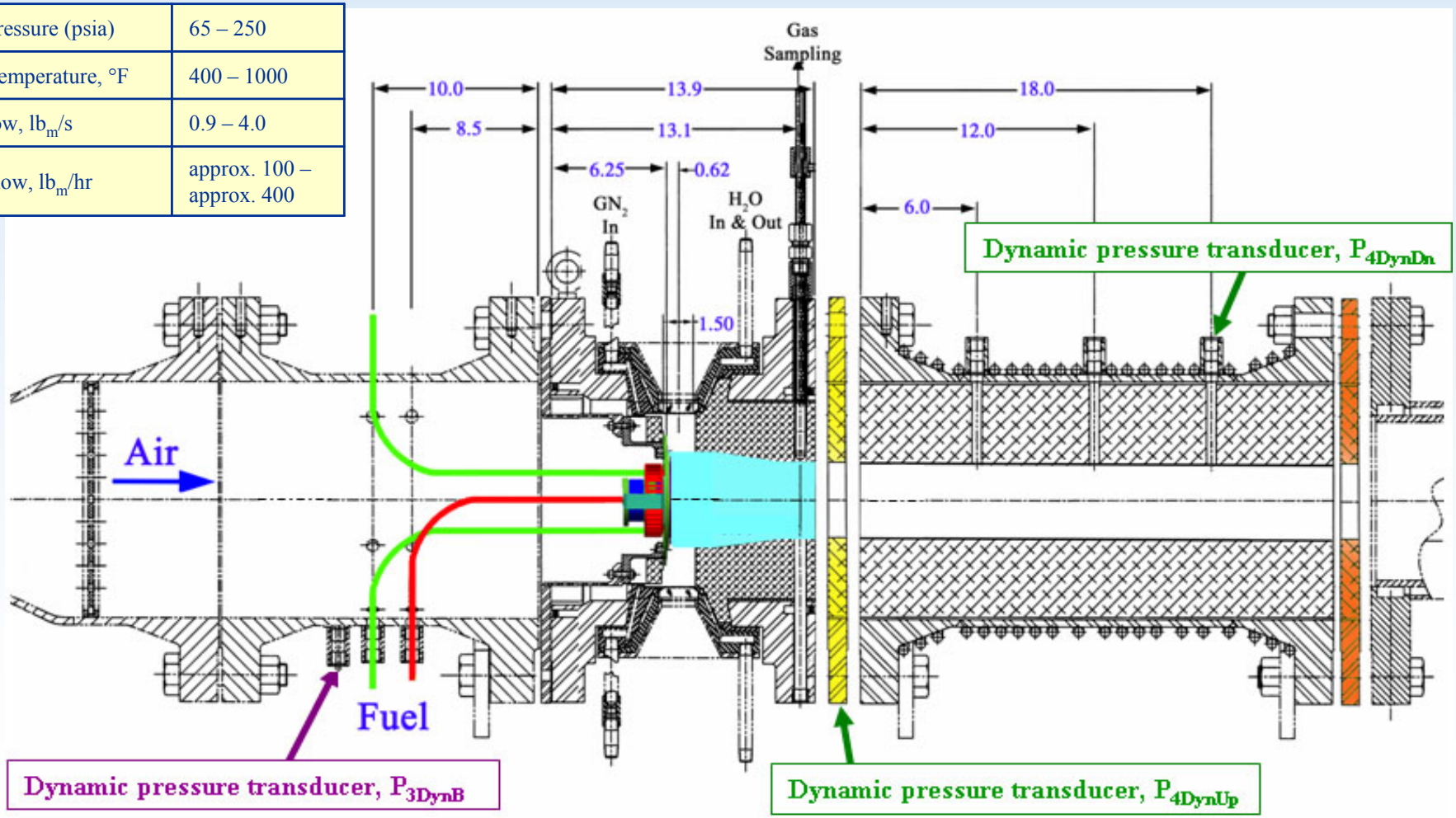
Measured Control



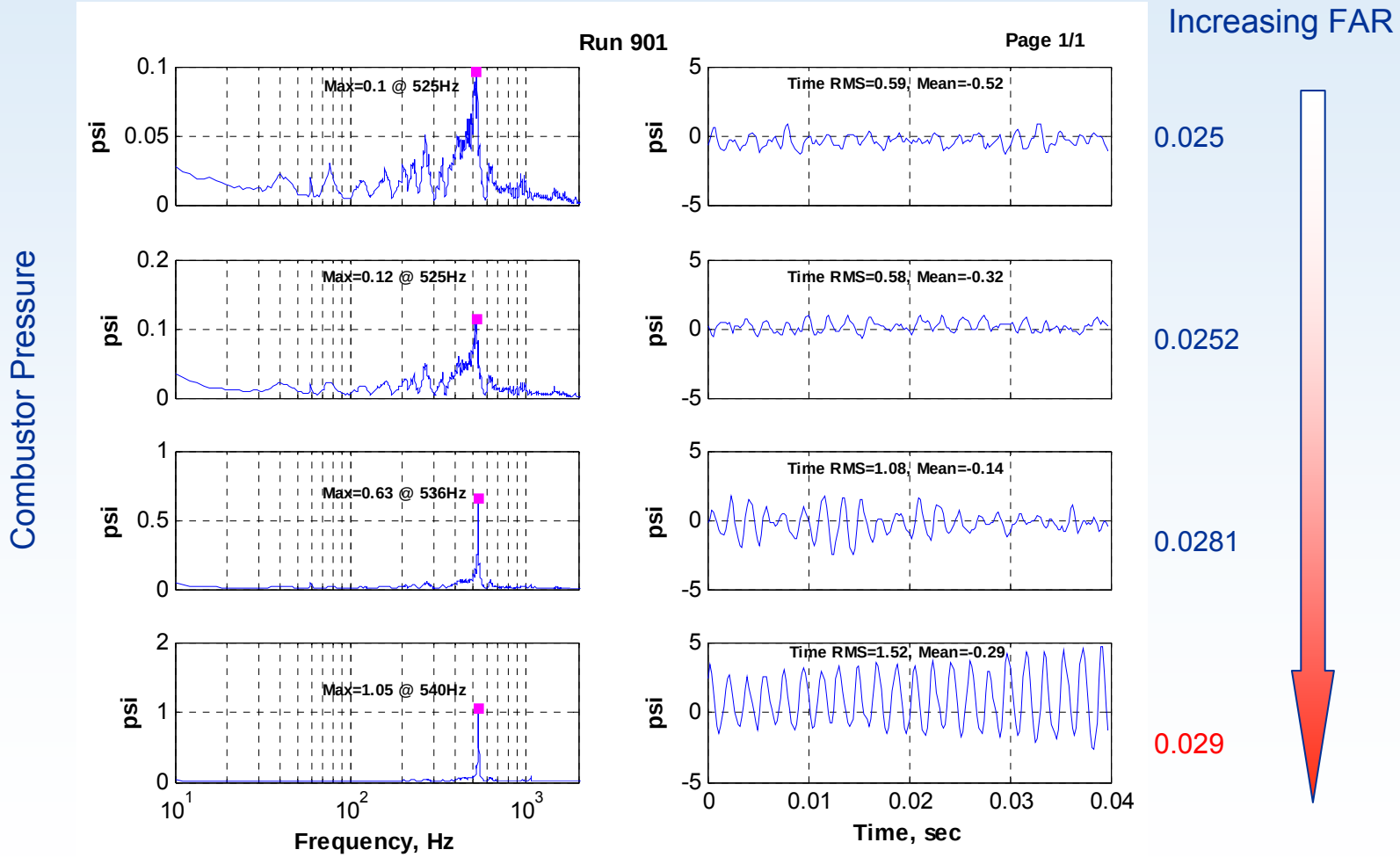
Low Emissions Combustor Prototype with Observed Instability

Range of Combustor Operating Conditions

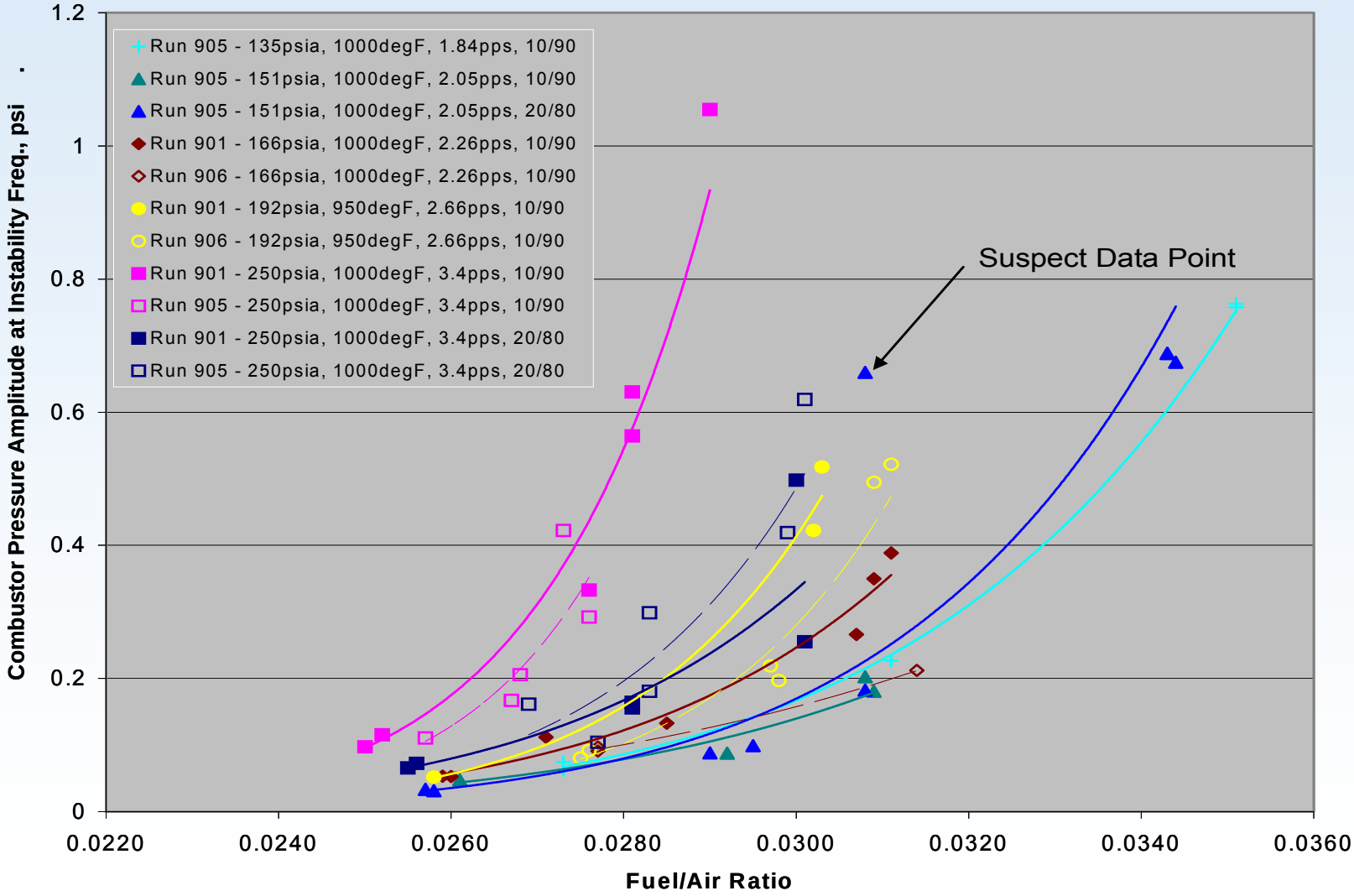
Inlet Pressure (psia)	65 – 250
Inlet Temperature, °F	400 – 1000
Air Flow, lb_m/s	0.9 – 4.0
Fuel Flow, lb_m/hr	approx. 100 – approx. 400



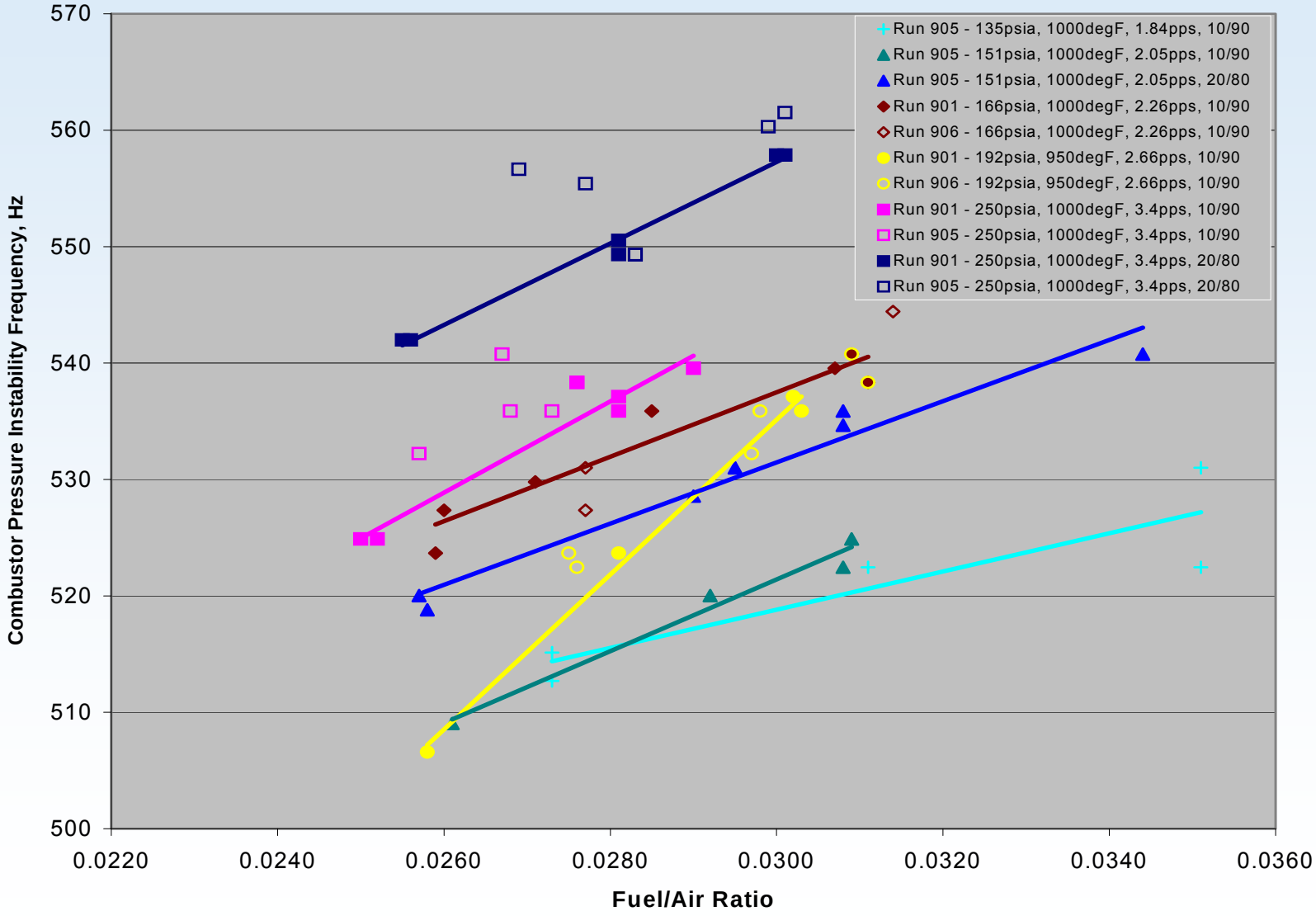
Low-Emissions Combustor Prototype Instability Amplitude Observed to Increase with Increasing Fuel/Air Ratio



Trend in Instability Amplitude vs. FAR Multiple Test Runs



Trend in Instability *Frequency* vs. FAR Multiple Test Runs



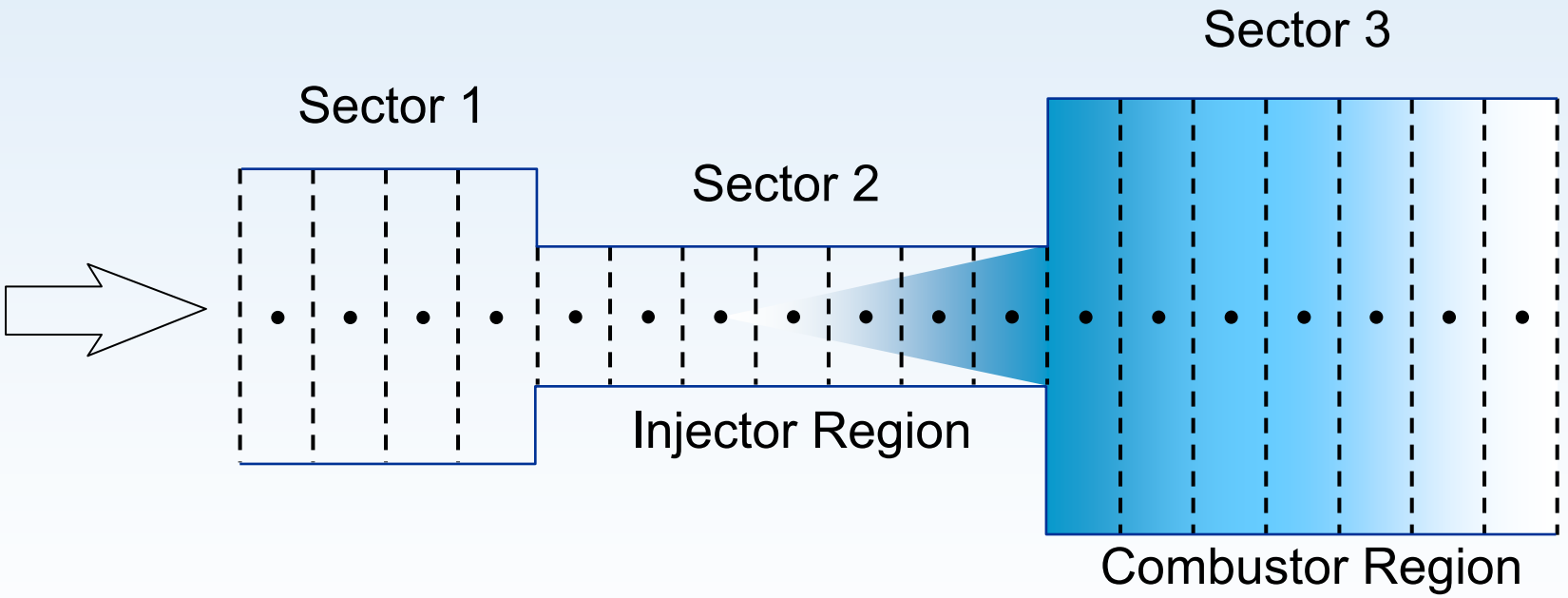
Motivation for Combustion Instability Simulation

- **Successful active control design requires accurate modeling and simulation.**
  - The essential physical phenomena should be correctly captured
    - (e.g. self-excitation).
  - Characterization and control design necessitate rapid simulation
    - (i.e. relative simplicity).
  - Simulation must lend itself to implementing a variety of sensing and actuation strategies.

- **The developed simulation method must achieve these goals for combustor configurations:**
  - in which the potential instabilities propagate axially
  - that contain abrupt changes in cross sectional area

Simulation Features

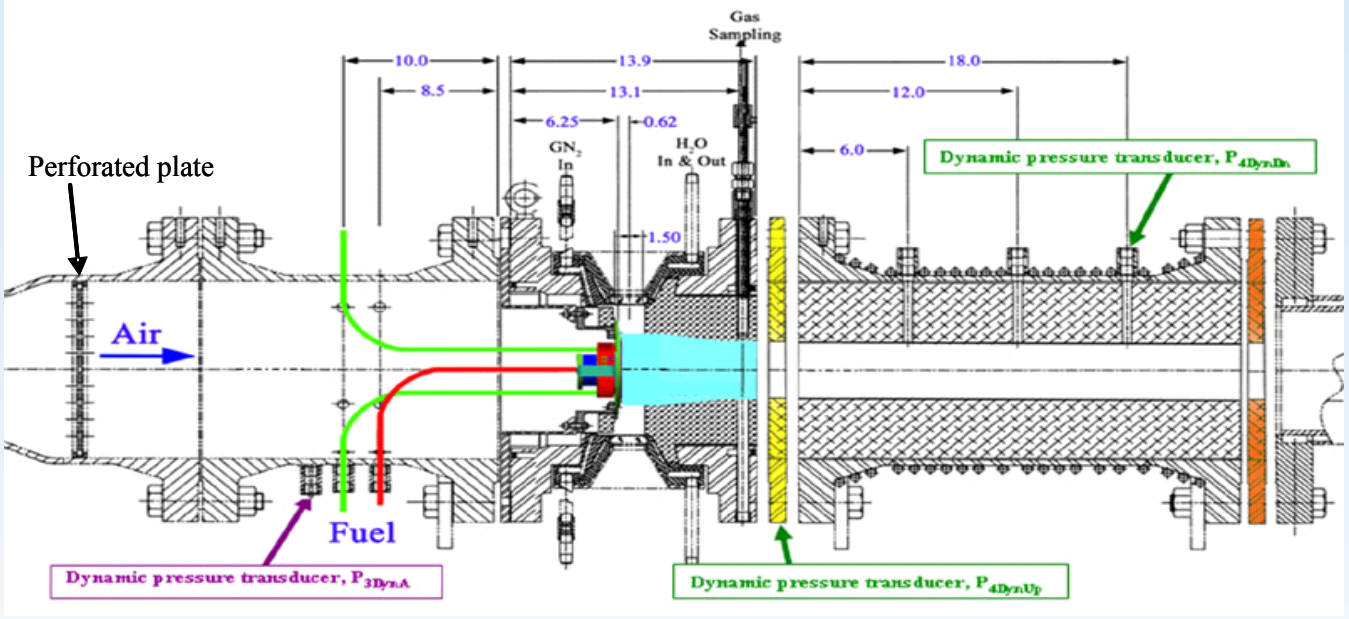
- Time-accurate
- Physics-based, Reacting, Sectored 1-D
  - Computationally efficient area transitions
- Upstream and Downstream boundary conditions modeled to match rig



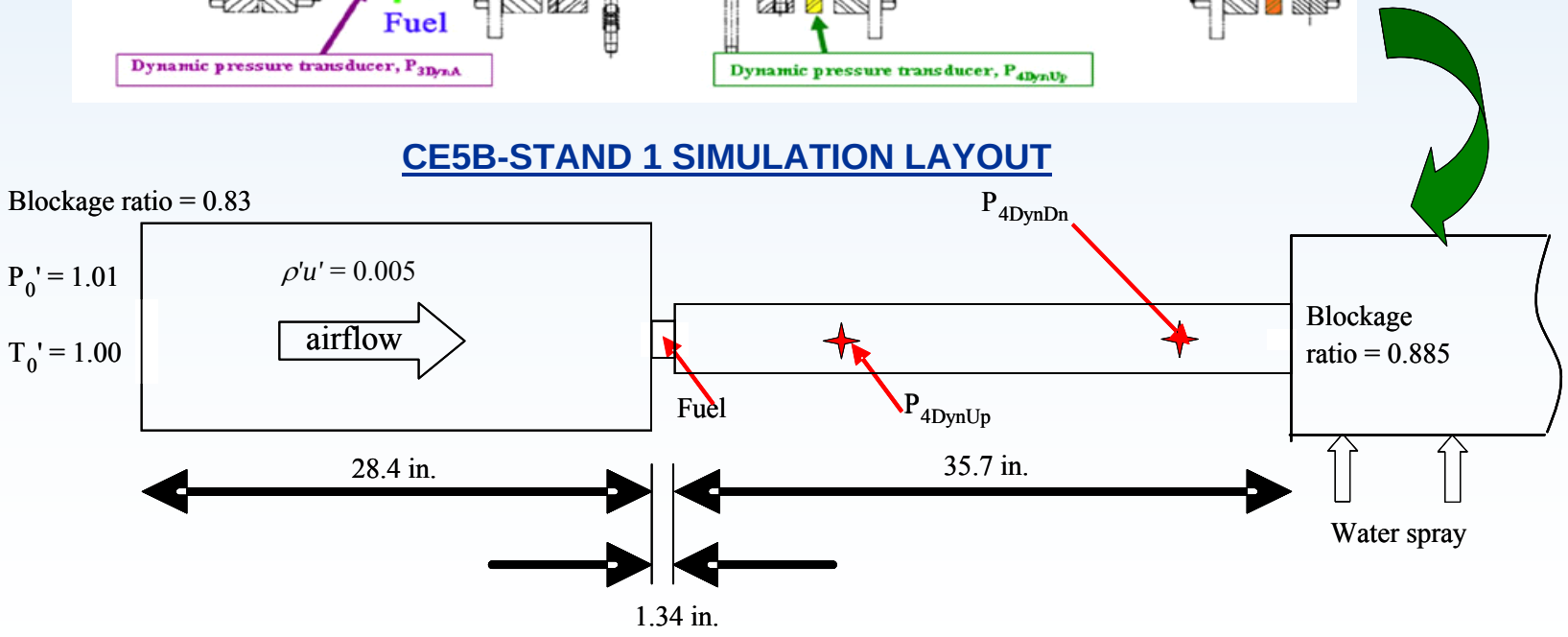
Within Each Sector:

- One-Dimensional
- Perfect Gas

Low Emissions Combustor Instability Model Development

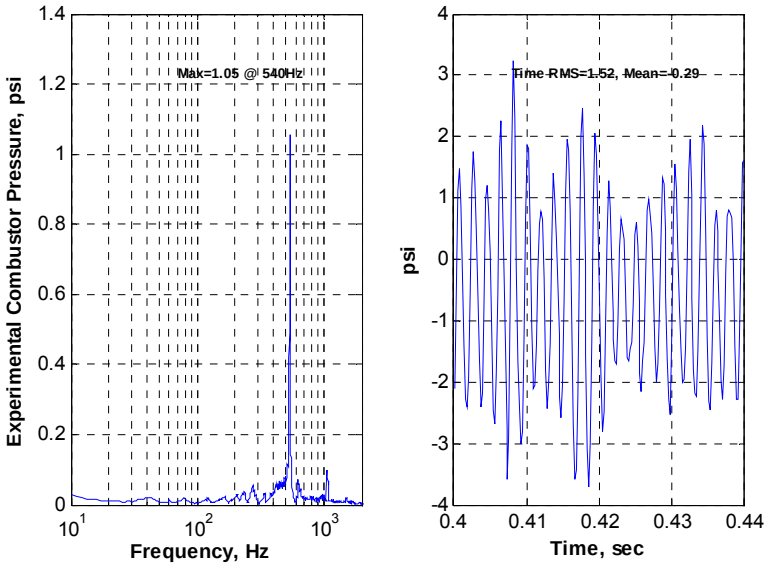


CE5B-STAND 1 SIMULATION LAYOUT



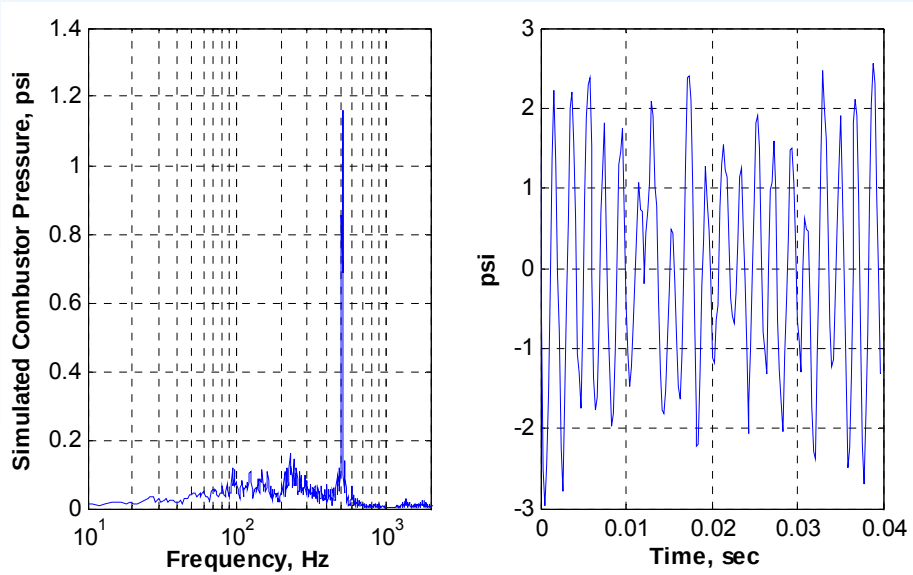
Combustion Instability Simulation Results

- **Self-sustained instability simulated**
- **Instability frequency and amplitude closely match experimental values**

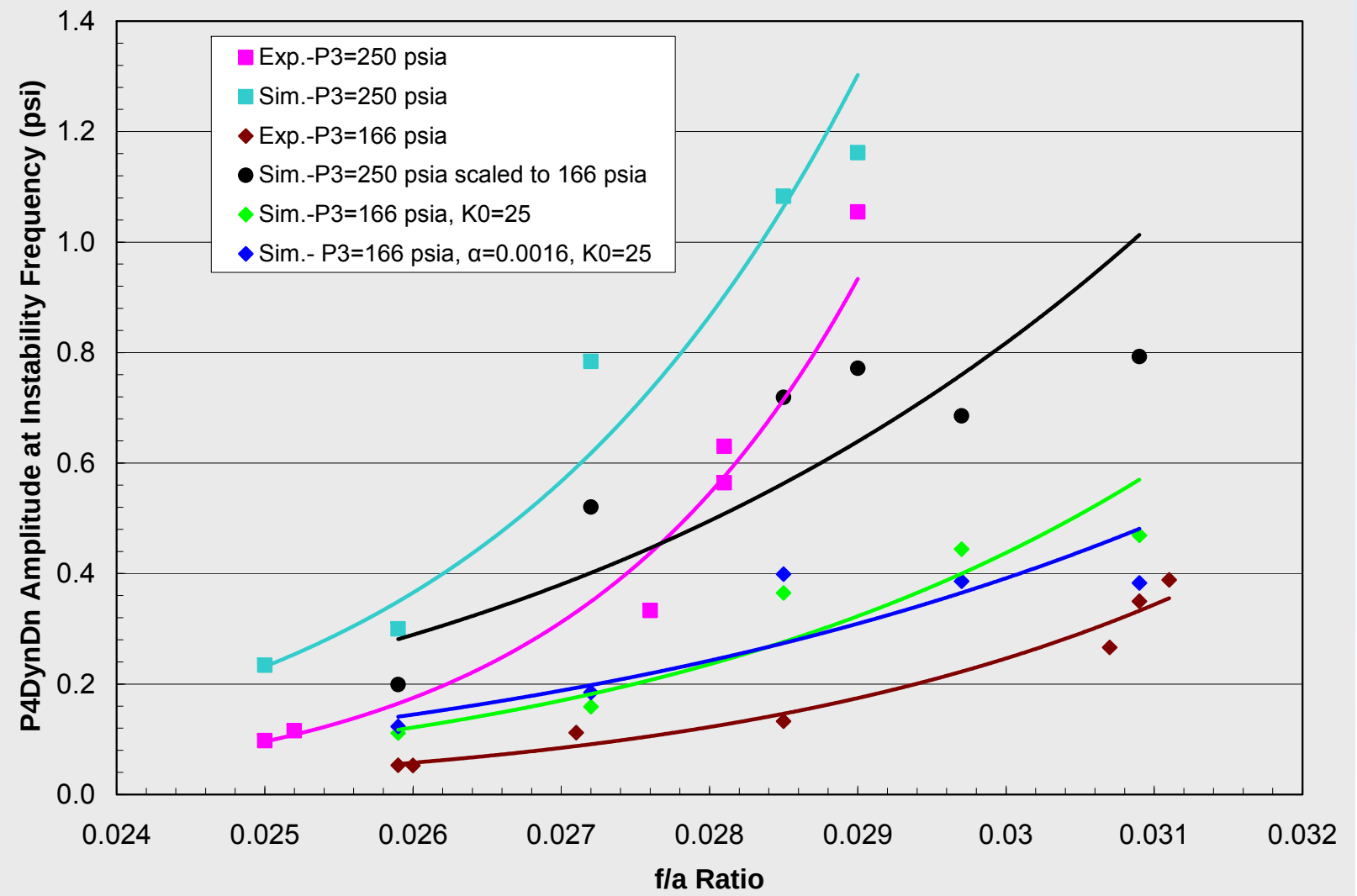


0.04 seconds of rig data with f/a=0.029

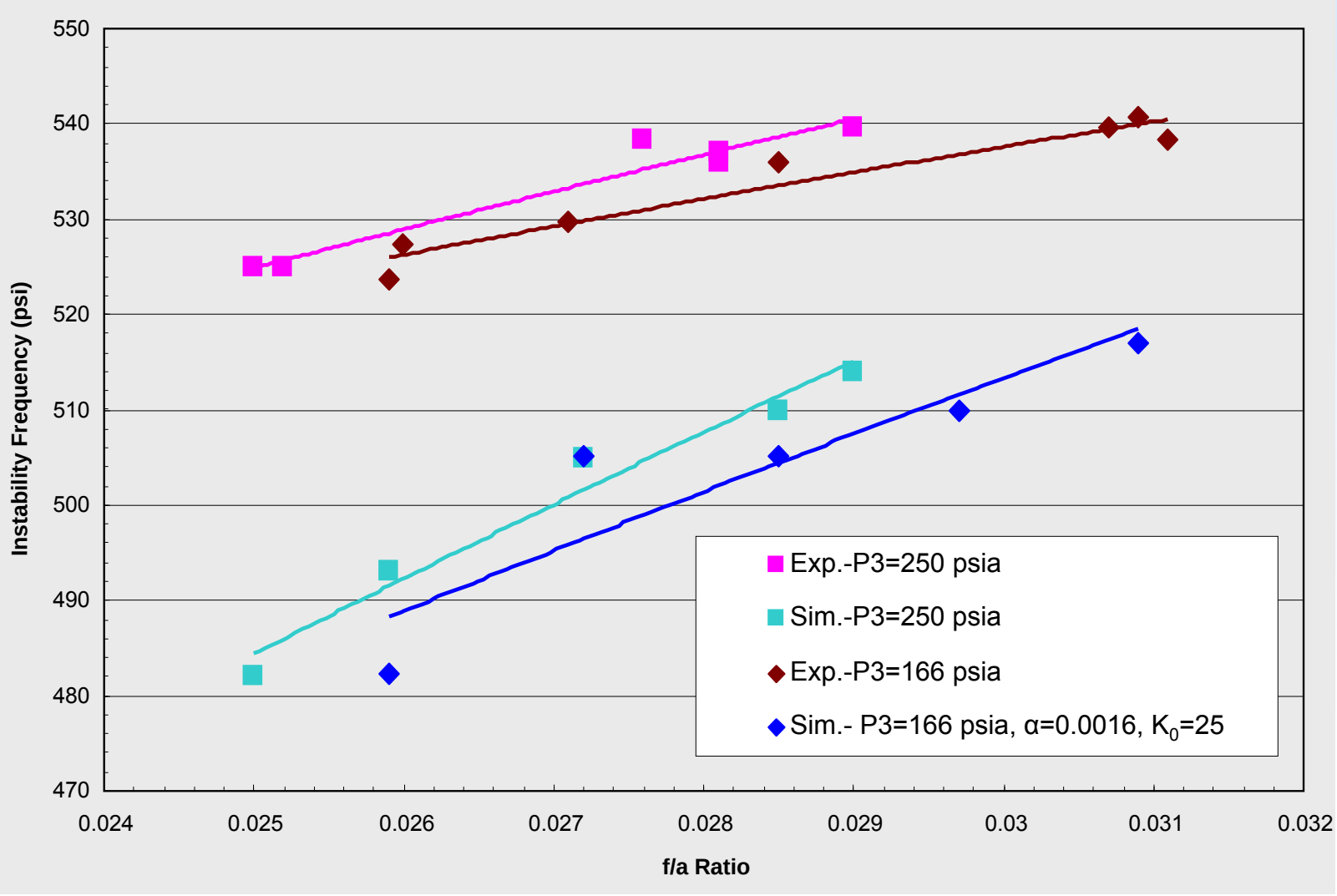
0.04 seconds of simulation data with f/a=0.029



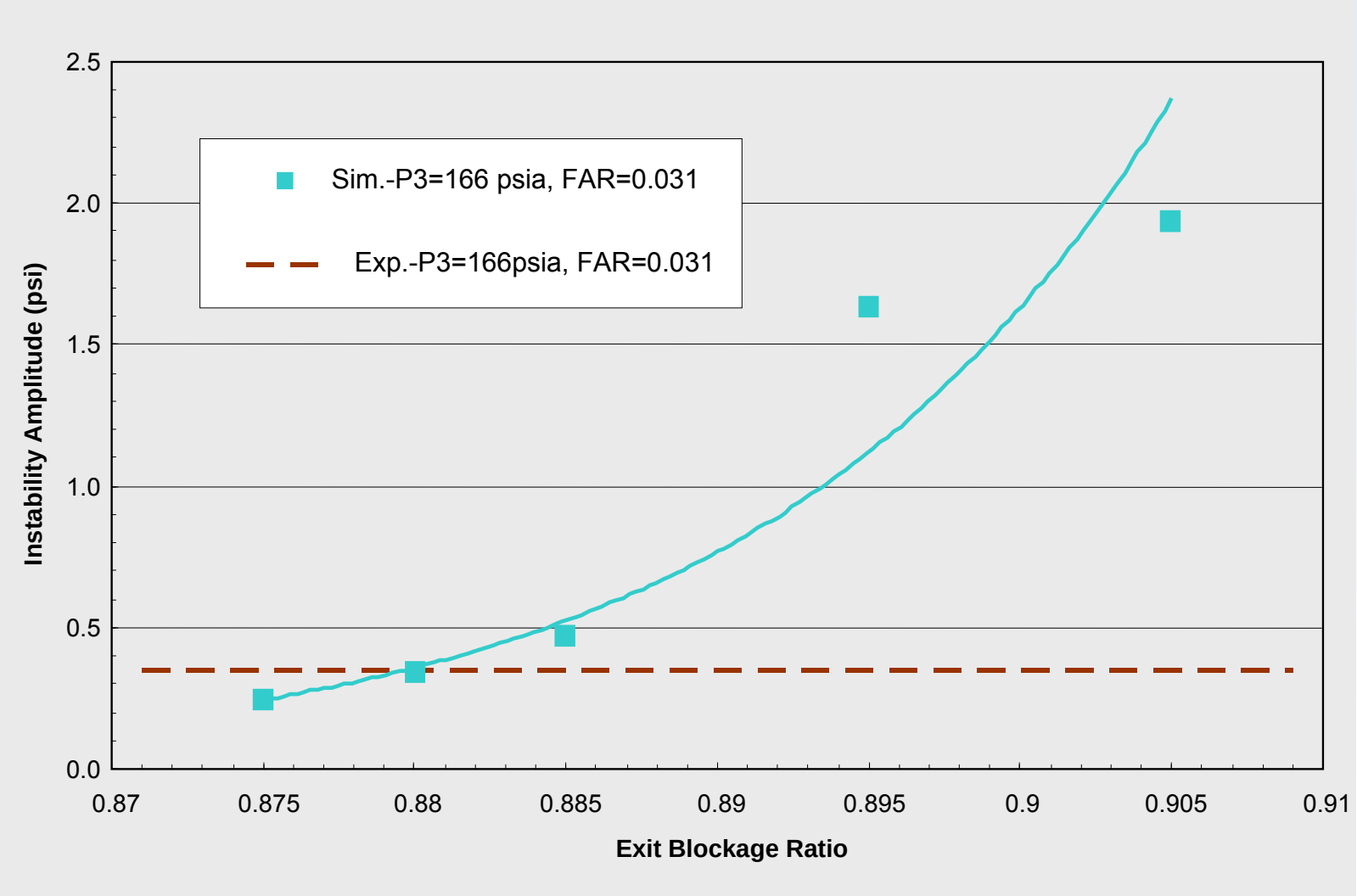
Combustion Instability Simulation Results for Multiple Operating Conditions – Amplitude Trend Replicated



Combustion Instability Simulation Results for Multiple Operating Conditions – Frequency Trend Replicated



Simulated Instability Amplitude is Highly Dependent on Exit Blockage Ratio (Water Spray)



Concluding Remarks

- **Status**
  - A near-term low-emissions combustor prototype has been identified for active combustion control research
  - The combustor's instability behavior has been characterized
    - Trends in instability amplitude and frequency have been quantified
  - A simulation of the combustion instability behavior has been developed
    - Reasonably matches the combustor experimental behavior
  - Characterization and simulation provide physical insights that aid control development

Concluding Remarks

- **Future plans**
  - Utilize the simulation to develop active combustion instability control methods
  - Integrate control methods with appropriate sensors and actuators to demonstrate combustion instability suppression in the combustor prototype
  - Incorporate NRA technologies into combustion control approaches
  - Utilize these tools/techniques as part of the long term plan to develop multi-point LDI combustors with extremely low emissions throughout the engine operating envelope

References

- Paxson, D.: “A Sectored-One-Dimensional Model for Simulating Combustion Instabilities in Premix Combustors,” presented at the 38th Aerospace Sciences Meeting & Exhibit. AIAA-2000-0313, NASA TM-1999-209771, January 2000.
- Cohen, J.M. et al: "Experimental Replication of an Aeroengine Combustion Instability," International Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, ASME Paper 2000-GT-0093, May 2000.
- DeLaat, J.C.; Breisacher, K.J.; Saus, J.R.; Paxson, D.E.: “Active Combustion Control for Aircraft Gas Turbine Engines.” Presented at the 36th Joint Propulsion Conference and Exposition, Huntsville, AL. NASA TM 2000-210346, AIAA –2000-3500, July 2000.
- Kopasakis, G.; DeLaat, J.; Chang, C.: “Validation of an Adaptive Combustion Instability Control Method for Gas-Turbine Engines,” 40th Joint Propulsion Conference and Exhibit, Ft. Lauderdale, FL, AIAA-2004-4028, NASA TM-2004-213198, October 2004.
- Le, D.K.; DeLaat, J.C.; Chang, C.T.; Vrnak, D.R.: “Model-Based Self-Tuning Multiscale Method for Combustion Control.” Presented at the 41st Joint Propulsion Conference and Exhibit, Tucson, AZ. AIAA-2005-3593, July 2005.
- DeLaat, J.C.; Chang, C.T.: "Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines," 16th International Symposium on Airbreathing Engines, Cleveland, OH, ISABE-2003-1054, NASA TM-2003-212611, September 2003.
- Cohen, J.M.; Proscia, W; and DeLaat, J.C.: “Characterization and Control of Aeroengine Combustion Instability: Pratt & Whitney and NASA Experience.” In “Combustion Instabilities in Gas Turbine Engines, Operational Experience, Fundamental Mechanisms, and Modeling”, AIAA Progress in Astronautics and Aeronautics series, Tim Lieuwen, Vigor Yang editors, Chapter 6, p. 113-145, October 2005.
- DeLaat, J.C.; Paxson, D.E.: “Characterization and Simulation of the Thermoacoustic Instability Behavior of an Advanced, Low Emissions Combustor Prototype.” Presented at the 44th Joint Propulsion Conference and Exhibit, Hartford, CT. AIAA-2008-4878, NASA/TM—2008-215291, July 2008.