Recent Combustion Control Test Results

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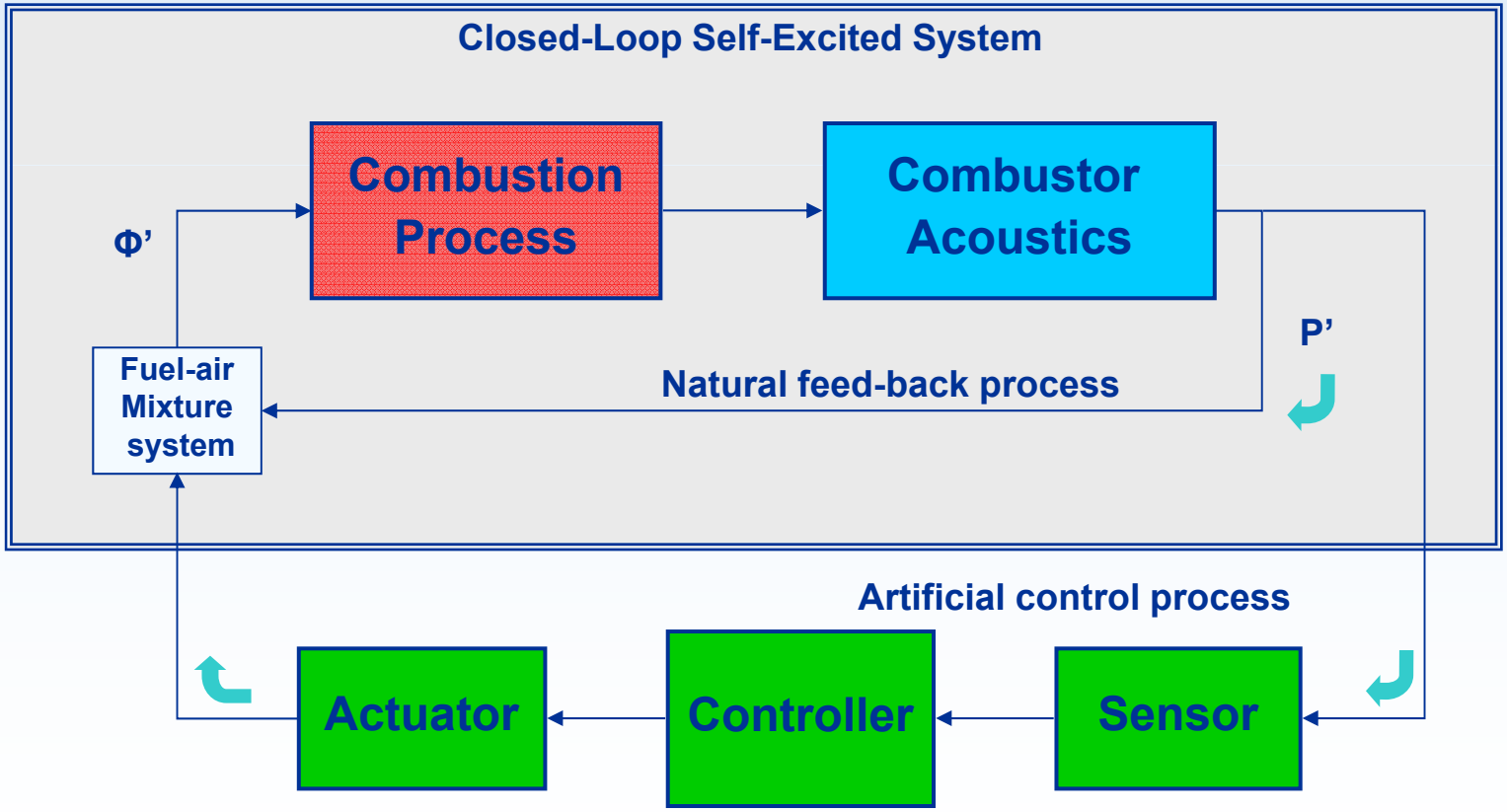
Outline

- Active Combustion Control as an enabling technology to mitigate combustion instability
- Experimental Setup and Approach
  - Advanced, low-emissions combustor prototype
- Experimental Results
- Concluding Remarks and Future Directions

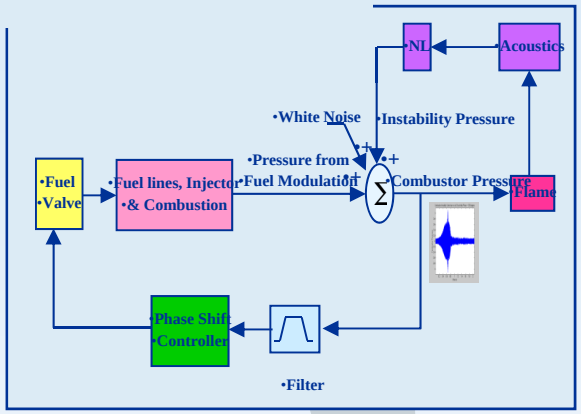
Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur



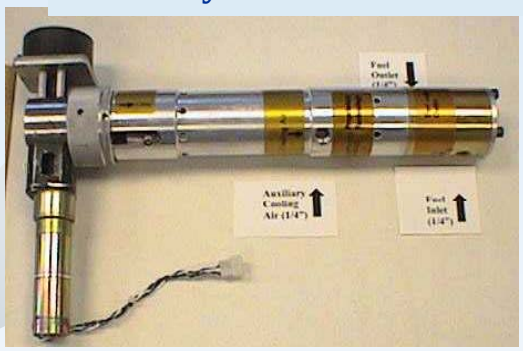
Active Combustion Instability Control Via Fuel Modulation

Advanced control methods

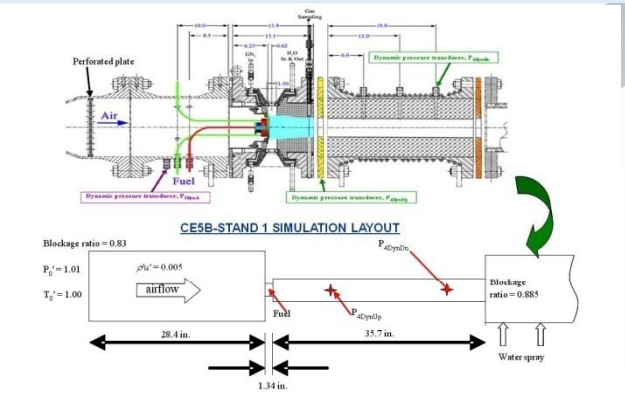


High-temperature sensors and electronics

High-frequency fuel delivery system and models



Physics-based instability models

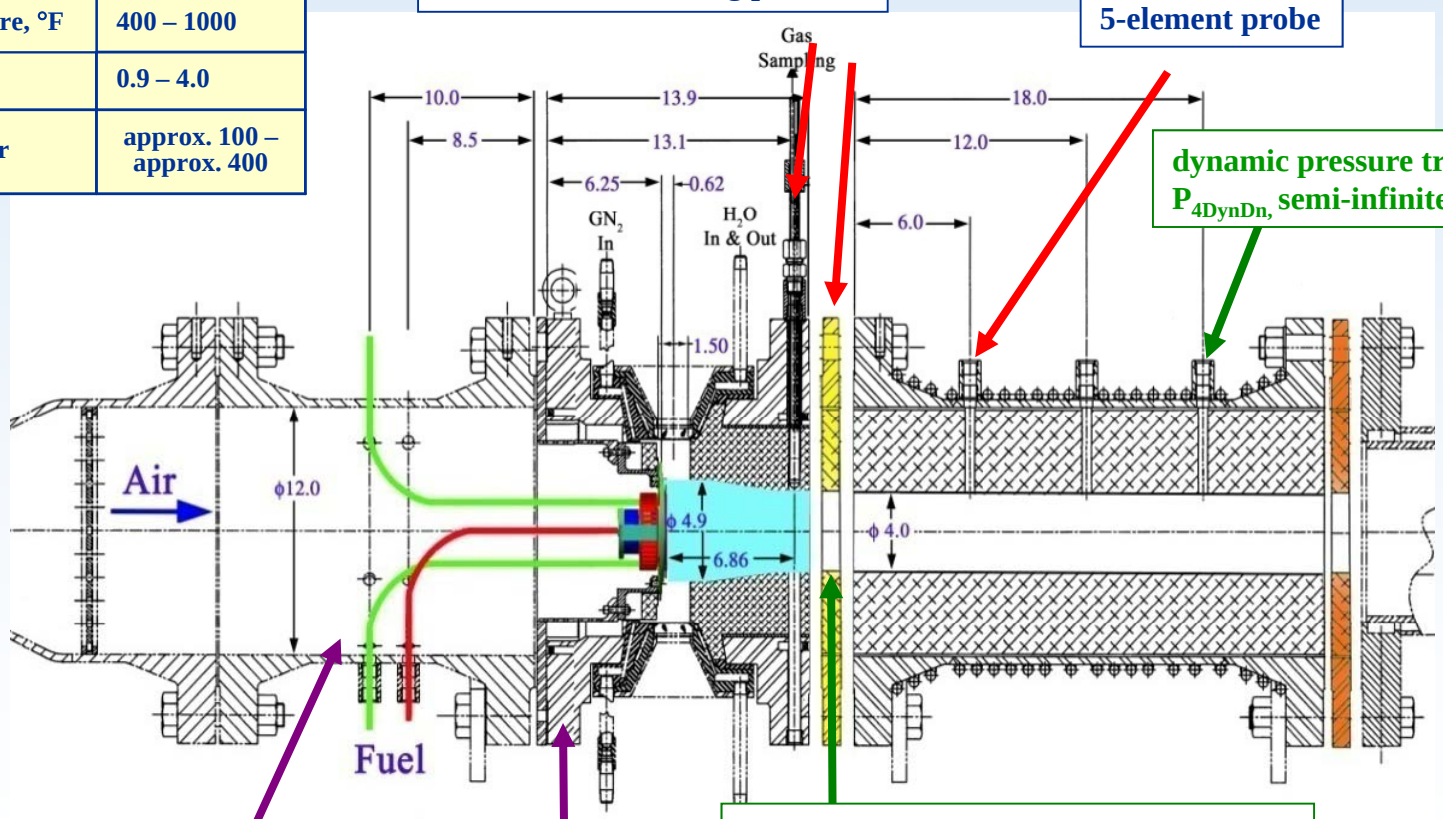


Realistic combustors, rigs for research

Low Emissions Combustor Prototype with Observed Instability, as installed in NASA CE5B-Stand 1

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



2 1-element traversing probes

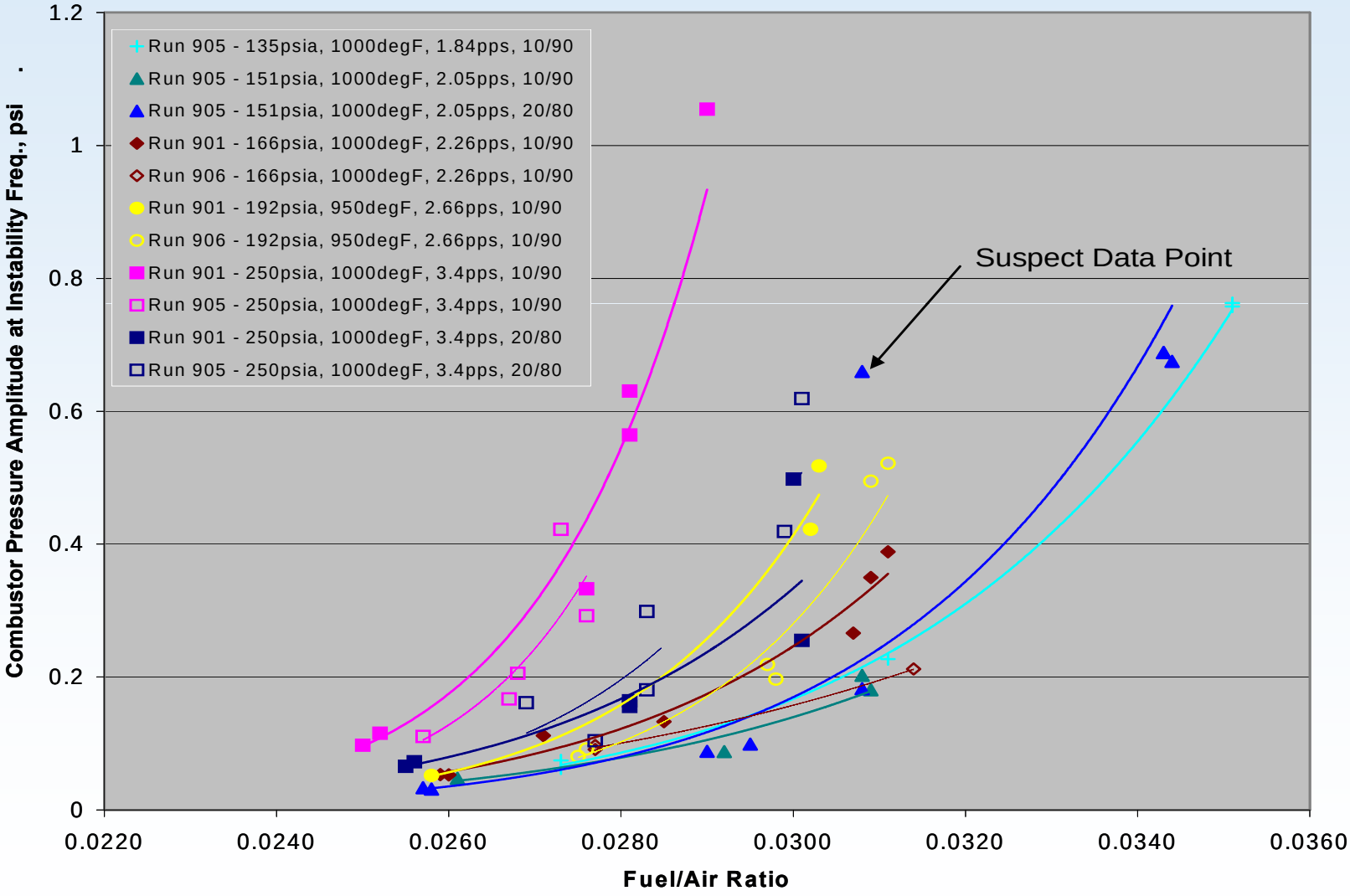
5-element probe

dynamic pressure transducer, P_{4DynDn}, semi-infinite coil

2 dynamic pressure transducers, P_{31},& P_{32}

dynamic pressure transducer, P_{4DynUp}, semi-infinite coil

Trend in Instability Amplitude vs. FAR Multiple Test Conditions and Runs



Experimental Program Research Objectives

A. Replicate previously observed combustion instability behavior of the low-emissions combustor prototype;

B. Demonstrate combustion instability control and extend the combustor operating range into previously unstable regions;

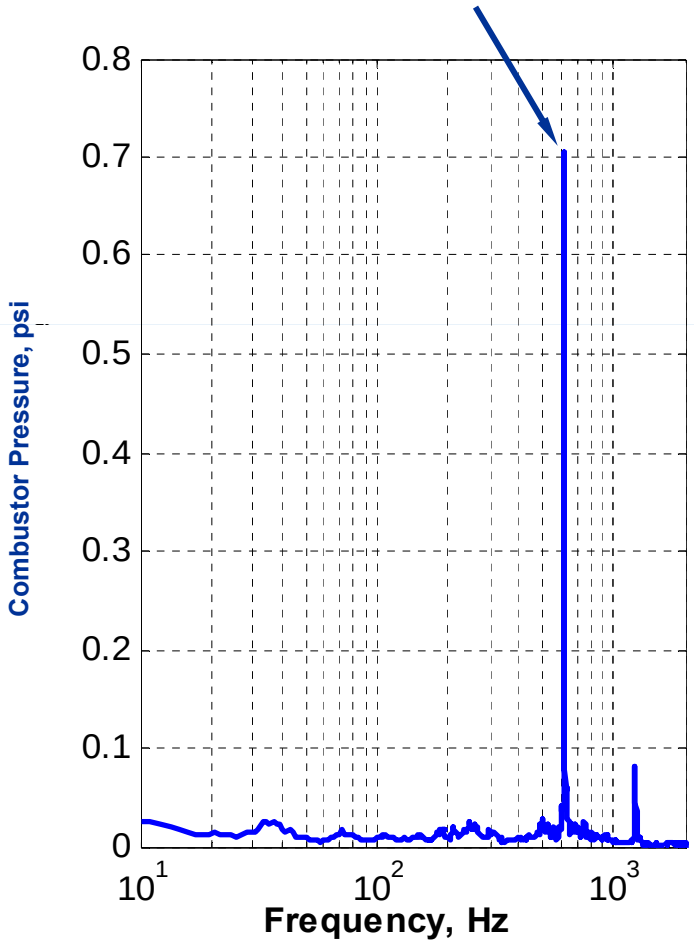
C. Determine if combustion instability control can be accomplished using the dynamic pressure at P3 for feedback;

D. Determine if combustion instability control can be accomplished through modulation of the pilot fuel flow; and

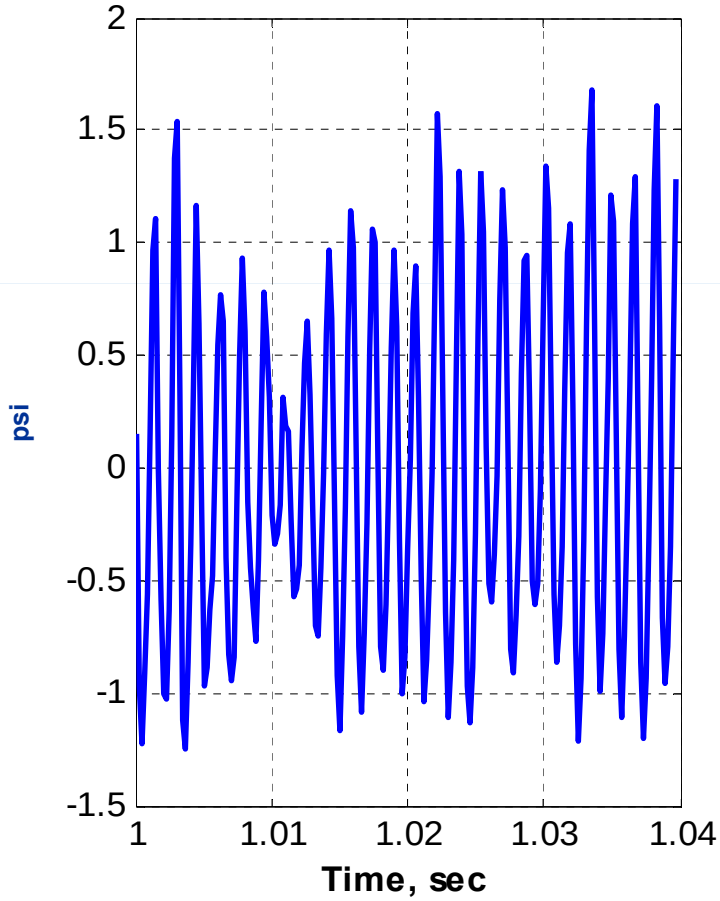
E. Obtain dynamic characterization data for construction of a closed-loop version of the NASA Sectored 1-D combustor simulation as a benchmark problem.

A. Comparison of Combustion Instability Behavior vs. Prior Testing

Instability peak at 620 Hz



Combustor Pressure Amplitude Spectra

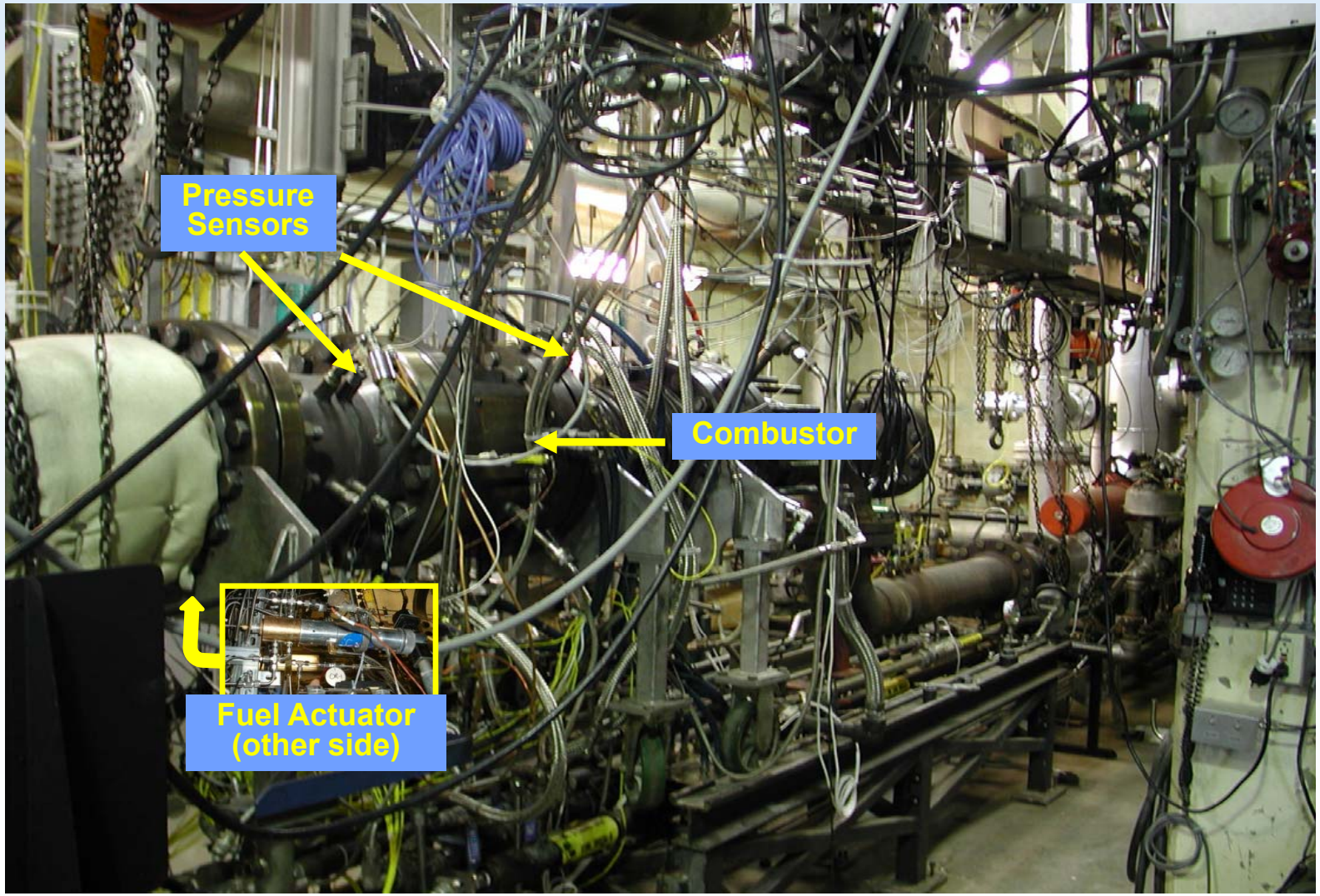


Combustor Pressure Time History

P3=166psia, T3=1000degF, FAR=0.037, combustor ΔP/P=3%

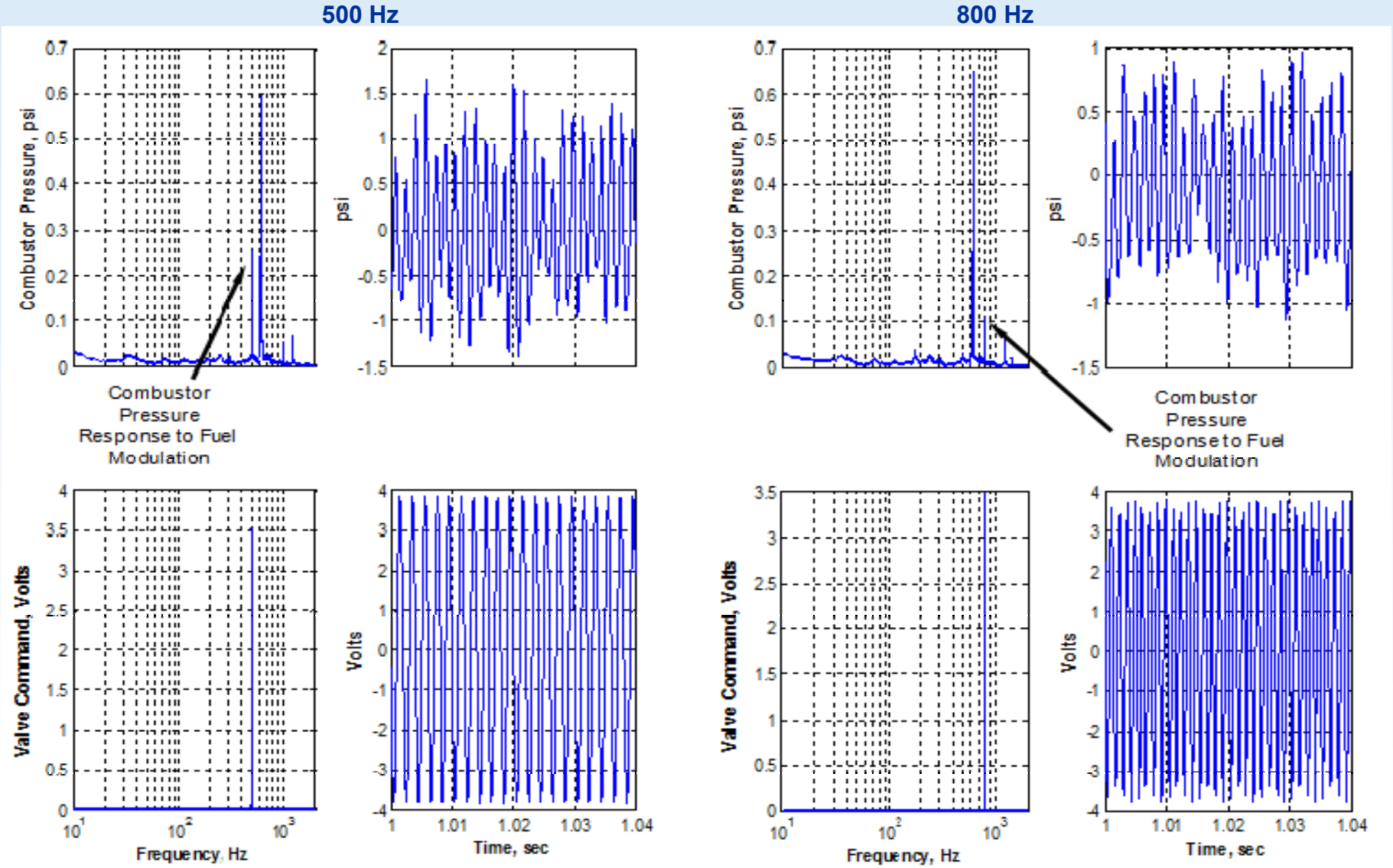
B. Demonstration of Combustion Instability Control

Low Emissions Combustor Prototype with Observed Instability as installed in NASA CE5B-Stand 1

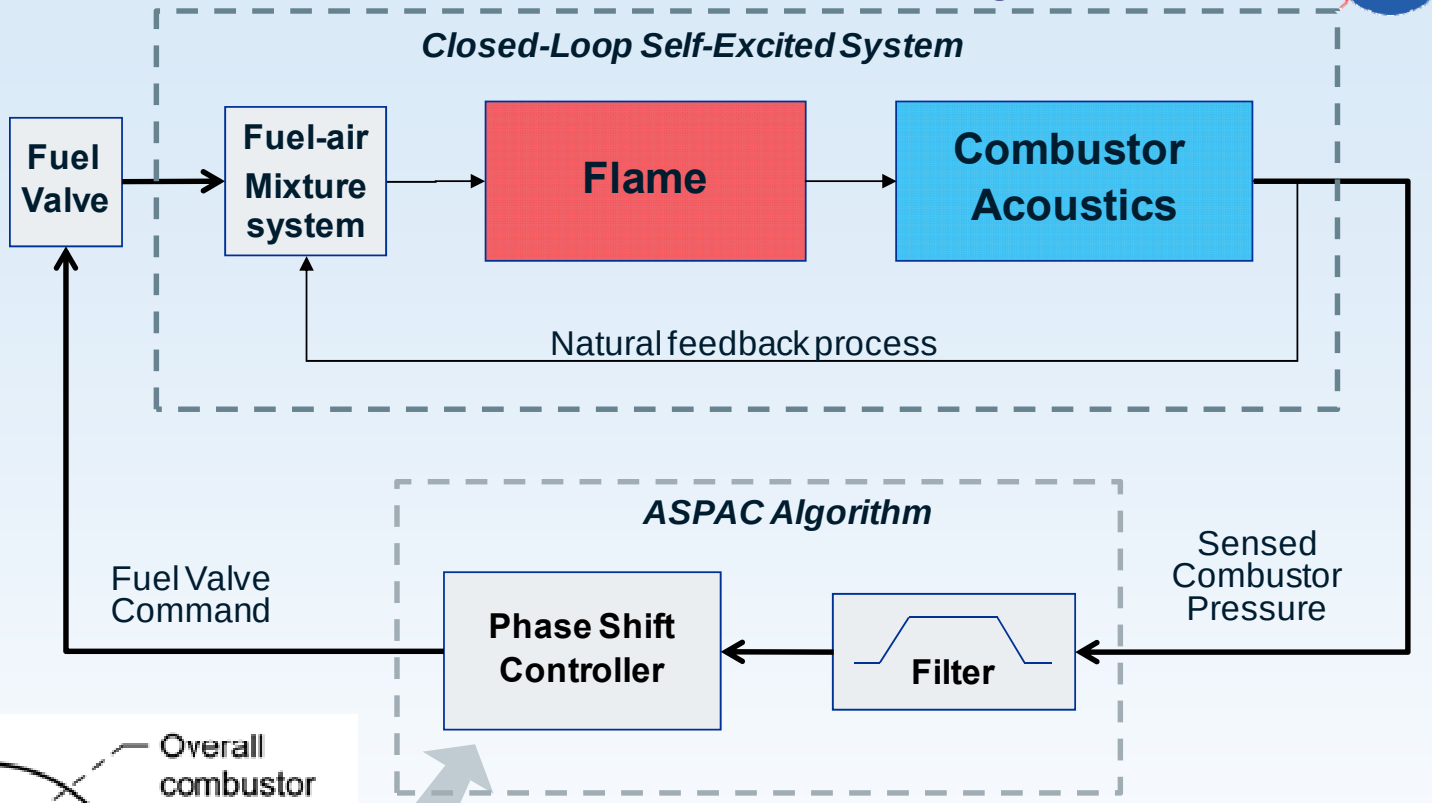


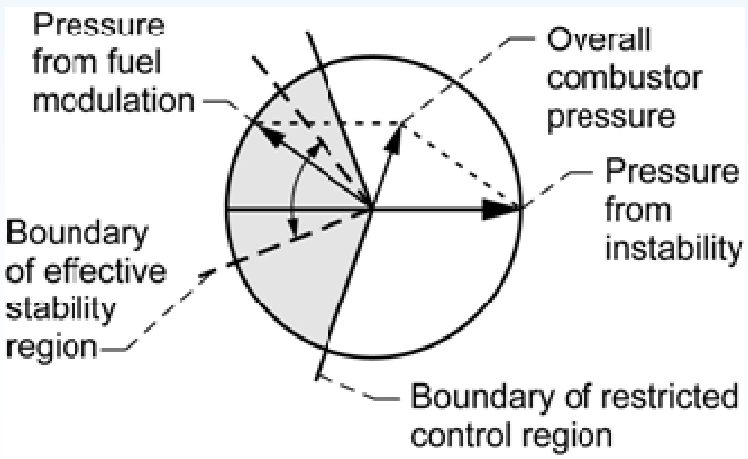
B. Demonstration of Combustion Instability Control

Combustor Dynamic Pressure Response to Open-Loop Fuel Modulation of the Main injector



B. Demonstration of Combustion Instability Control

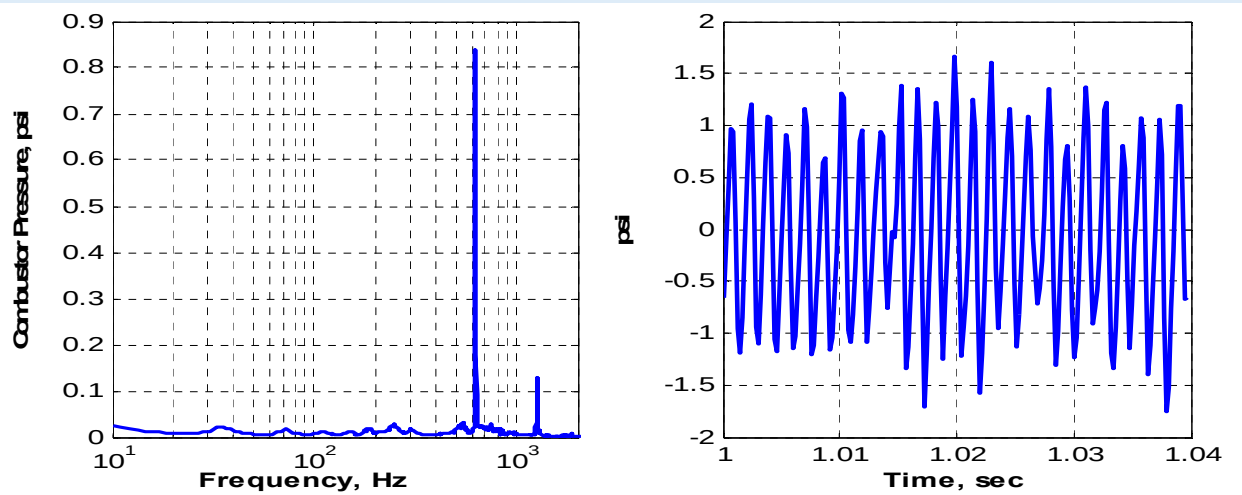




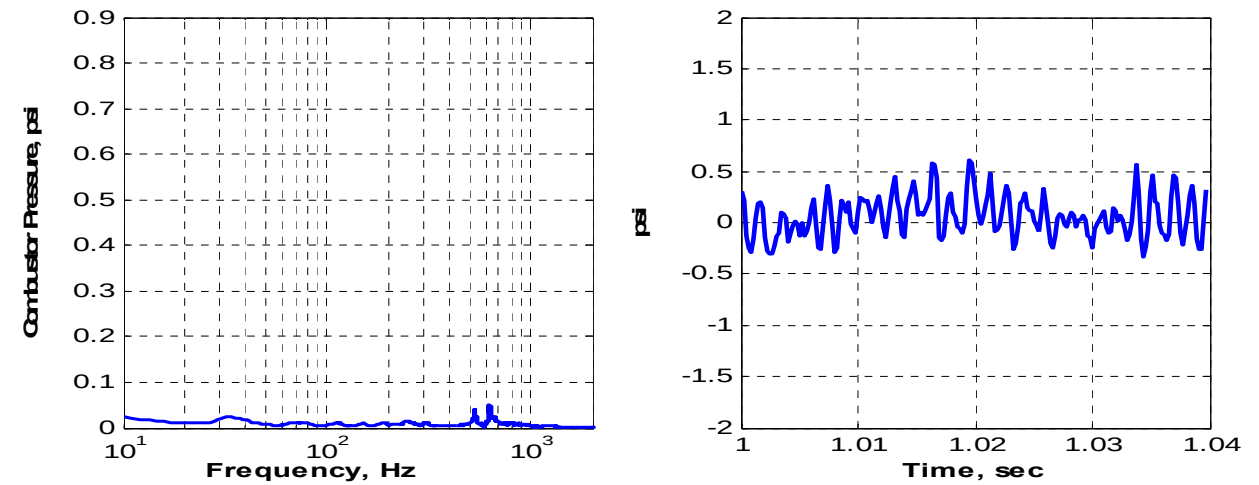
Adaptive Sliding Phasor Averaged Control (ASPAC)

B. Demonstration of Combustion Instability Control

Adaptive Sliding Phasor Averaged Control (ASPAC) able to suppress combustion instability



Uncontrolled



Controlled

94% reduction in peak at instability frequency

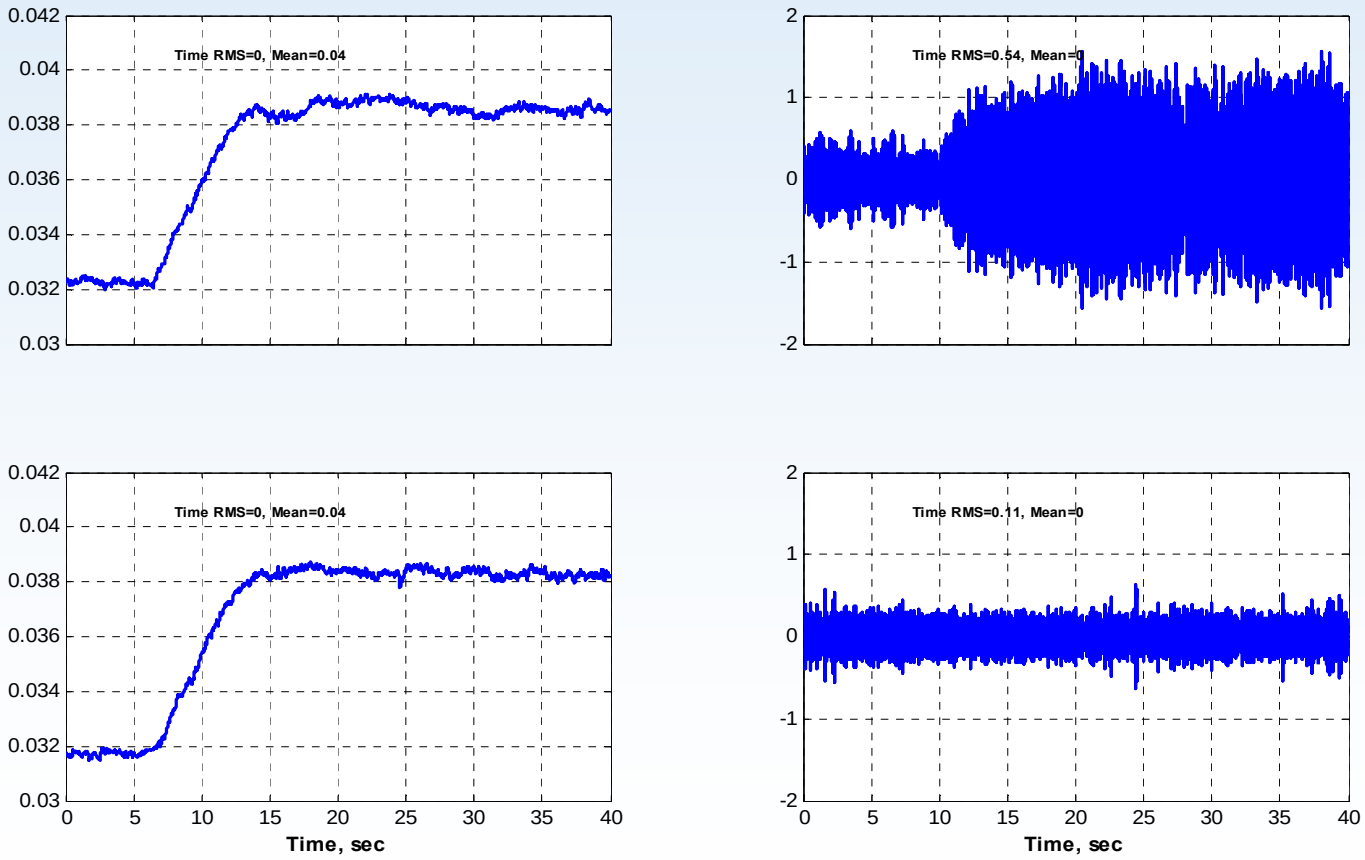
60% reduction in RMS

Estimated ±8% of mean fuel flow

B. Demonstration of Combustion Instability Control

Adaptive Sliding Phasor Averaged Control (ASPAC) able to prevent instability growth

Fuel/air ratio | **Filtered Combustor Pressure**

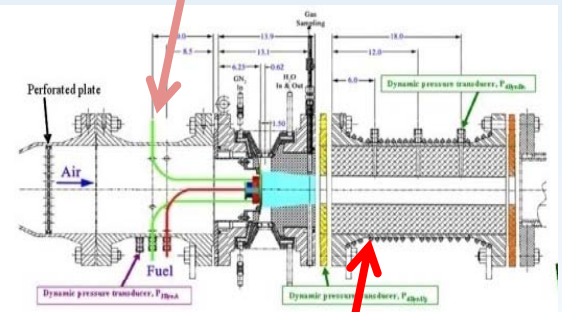


Controller off

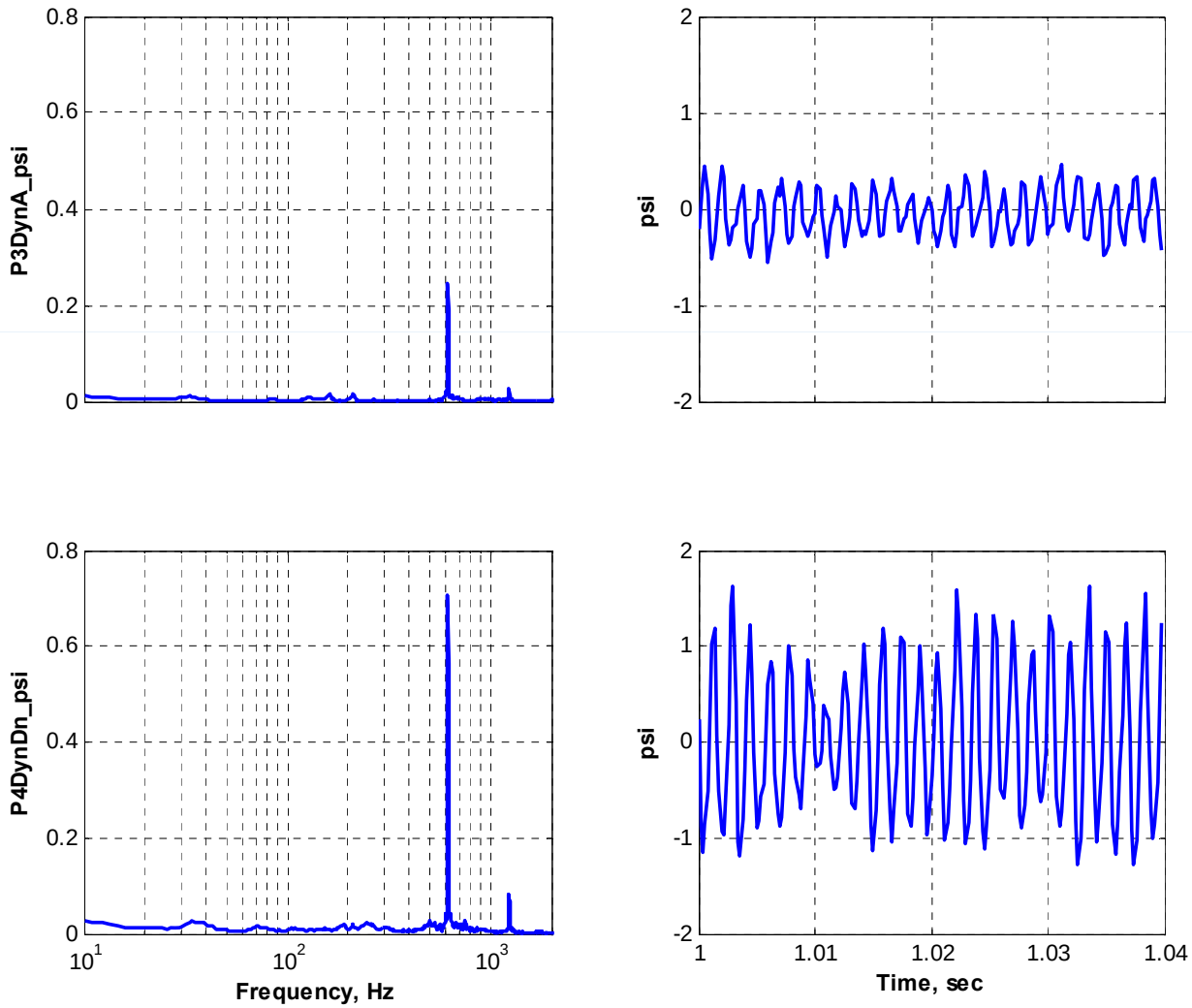
Controller on

C. Combustion Instability Control with P3 Dynamic Pressure as Feedback

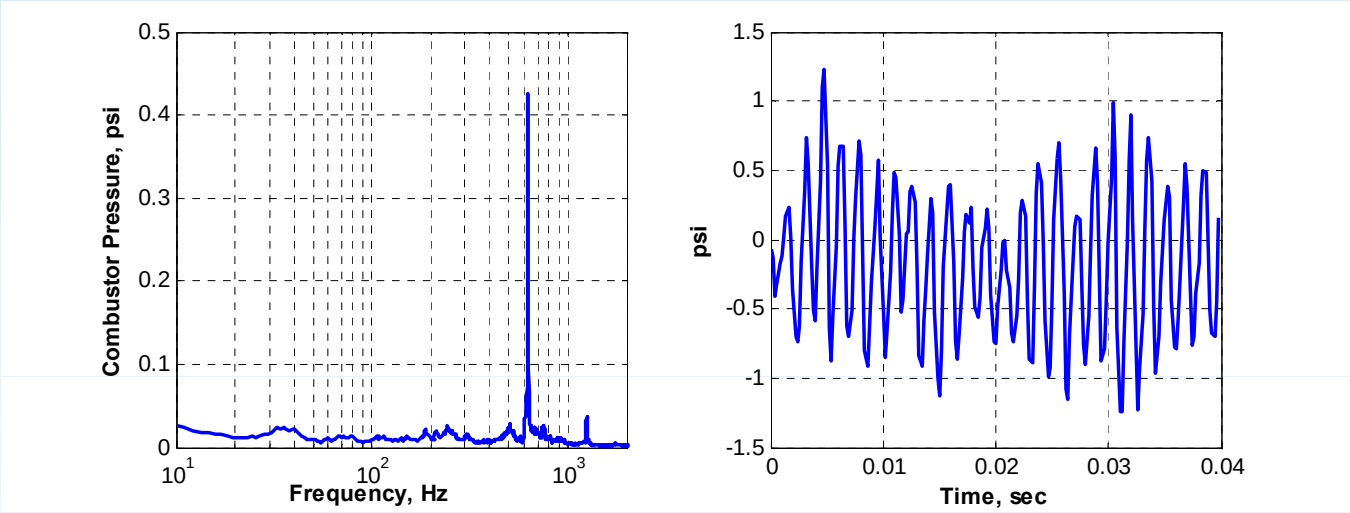
P3' ≤ 1300ºF
(upstream of fuel injector)



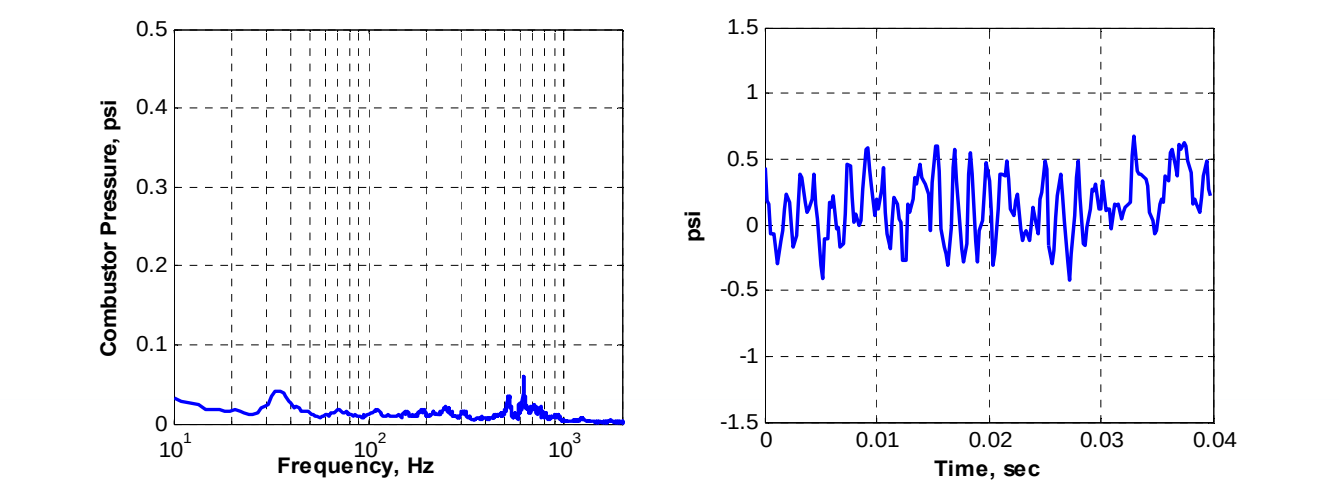
P4' ≥ 3000ºF
(downstream of fuel injector)



C. Combustion Instability Control with P3 Dynamic Pressure as Feedback



Uncontrolled



Controlled

85% reduction in peak at instability frequency

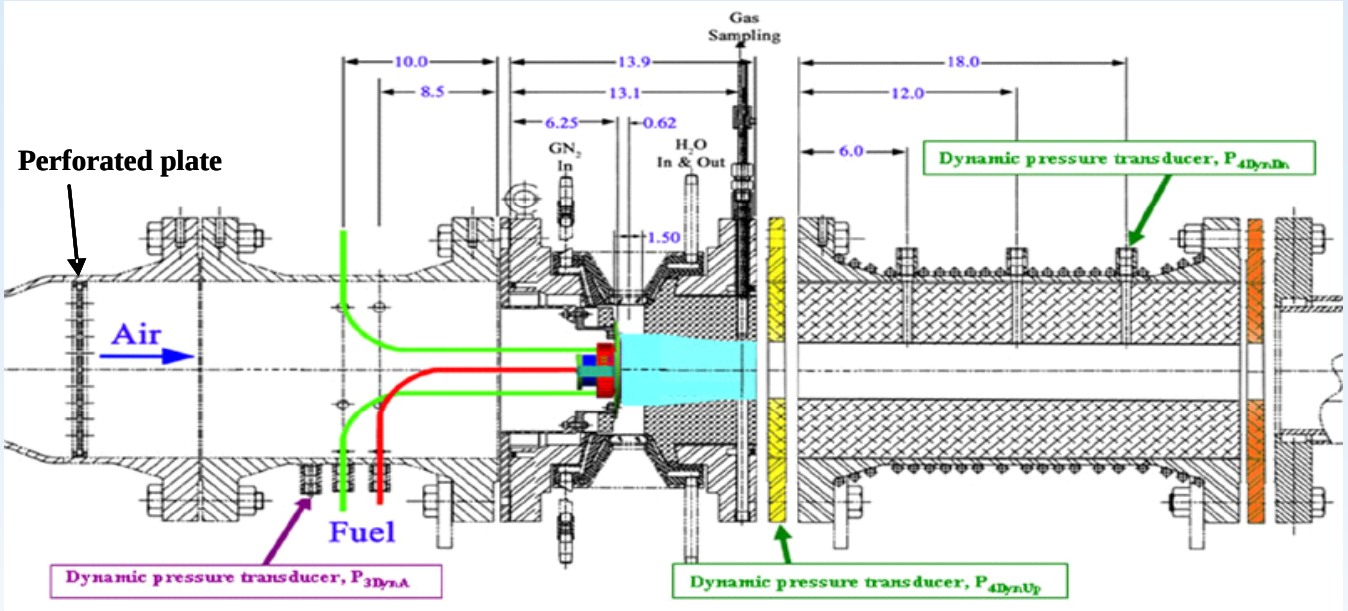
50% reduction in RMS

D. Combustion Instability Control Using Pilot Fuel Injector Modulation

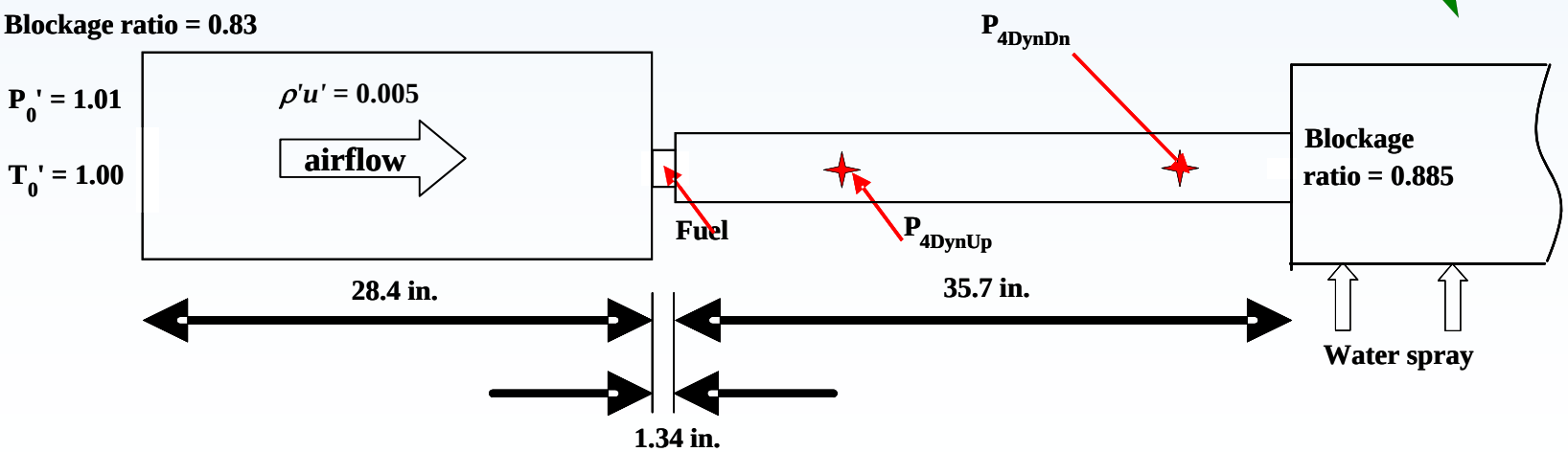
- **Advantage: Pilot carries only 20% of total fuel flow**
  - **Smaller fuel actuator, not lean-burn part of flame**
  - **Possible downside: Smaller actuator authority, different part of flame**

- **Experimental Results:**
  - **Negligible response to pilot fuel modulations in combustor**
    - Optimizations attempted with the high-frequency valve
      - Shorten fuel feed line
      - Optimize valve average Flow Number
      - Vary fuel feed line diameter (volume)
      - Stiffen valve mounting
      - Optimize valve internal return spring force
      - ...
  - **Conclusion: High-frequency valve is oversized for pilot**
    - Was developed for higher-flow operation

E. Closed-Loop Combustor Data for Development of Combustion Control Simulations

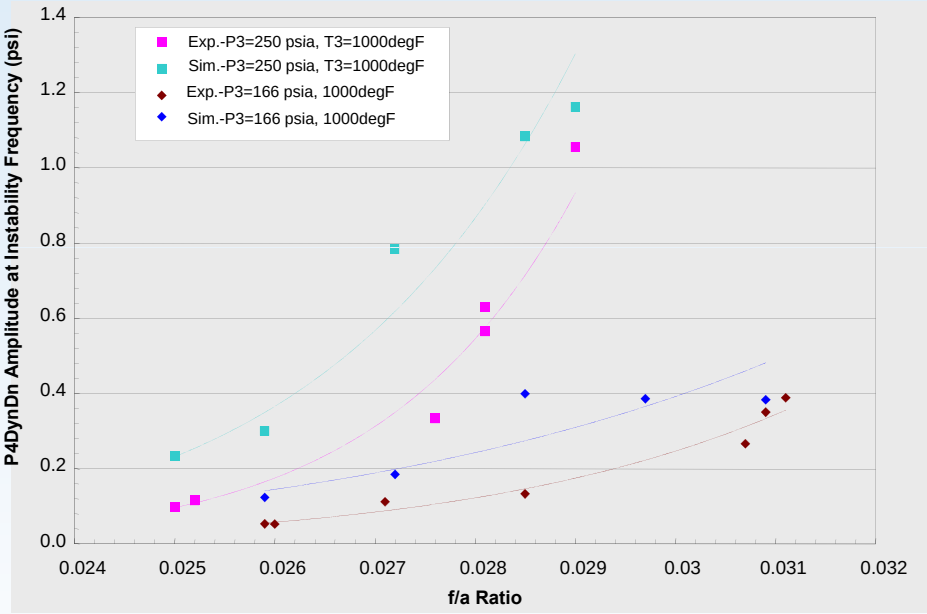


CE5B-STAND 1 SIMULATION LAYOUT



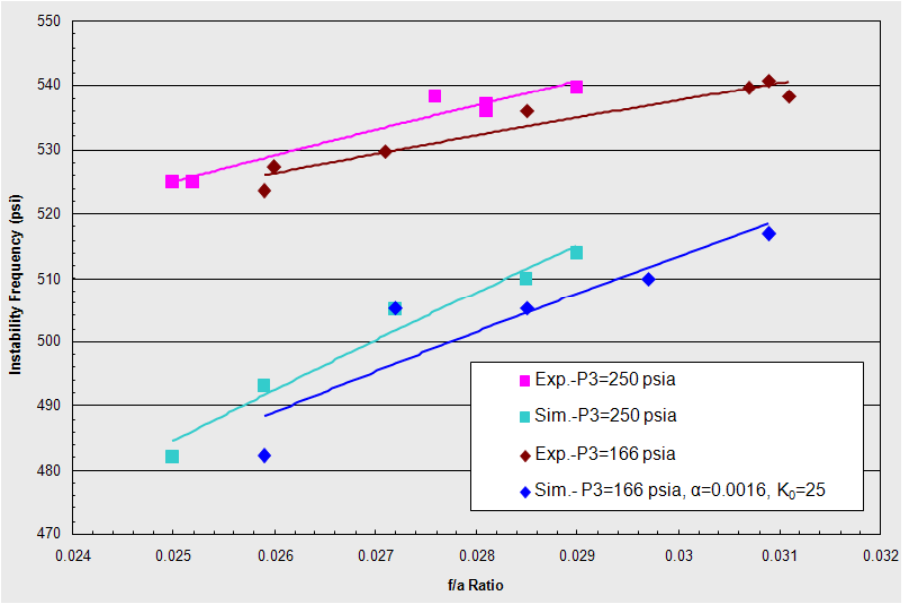
E. Closed-Loop Combustor Data for Development of Combustion Control Simulations

Combustion Instability Simulation Results Match Previous Experimental Results for Multiple Operating Conditions



Amplitude trend replicated

Frequency trend replicated



Concluding Remarks

Active control of combustion instability has been demonstrated for an advanced low-emissions aircraft engine combustor prototype:

- The ASPAC algorithm can suppress an already existing instability
- The controller can also prevent instability growth, enabling high-power operation
- A pressure sensor at P3 was used as a control feedback sensor
- Instability control was demonstrated with main stage fuel modulation.
  - Pilot fuel modulation was investigated, but was unsuccessful due to inadequate fuel modulation strength.

Future plans:

- Development of fuel actuators sized for pilot injectors
- Development of feedback sensors able to operate at engine temperatures
- Extend existing simulation of uncontrolled combustion instability to include the controlled case.
- Apply combustion instability control technologies via pilot fuel modulation to increasingly advanced lean-burn combustors.