National Aeronautics and Space Administration

Fundamental Aeronautics Program

Supersonics Project

Active Combustion Control Applied to a Low Emission Combustor Prototype

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Acknowledgements

- NASA Technical Personnel
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- NASA Aeronautics Program Support
  - Fundamental Aeronautics / SUP Project / High Altitude Emissions
  - Environmentally Responsible Aviation Project

Outline

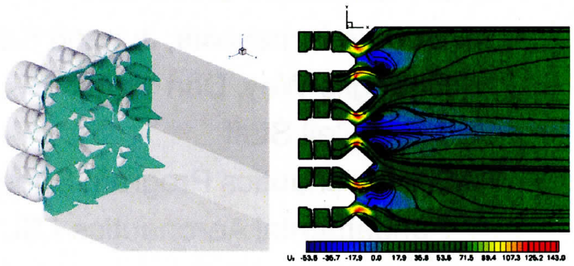
- Motivation: Ultra-low emissions, lean-burning, Multi-point Lean Direct Injection (MP-LDI) combustors
  - More susceptible to instability
- Active Combustion Control as an enabling technology
- Experimental Setup and Approach
  - Advanced, low-emissions combustor prototype
- Experimental Results
- Concluding Remarks and Future Directions

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

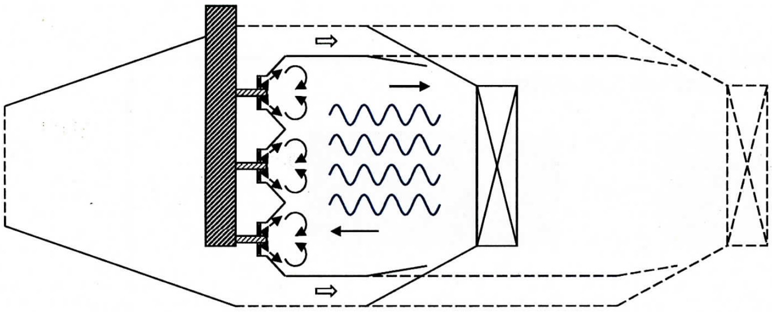


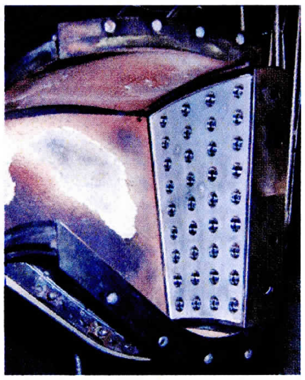
Zero Axial Velocity Contours *Side View through center*

Also - Fundamental Aeronautics, Subsonic Fixed Wing, Clean Energy and Emissions
•Combustion Chemistry and Turbulence Modeling
•Particulates Sampling and Modeling
•Alternate Fuels

Integrated Systems Research
•Environmentally Responsible Aviation
•Airframe Technology
•Propulsion Technology
•Vehicle Systems Integration

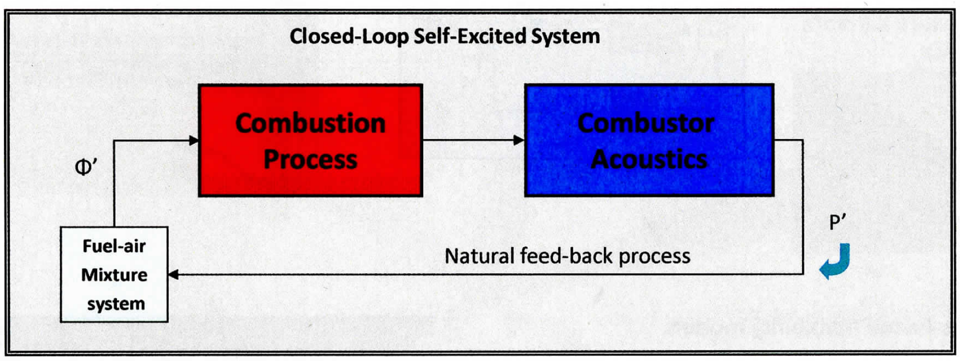
Lean-Burning, Ultra-Low-Emissions Combustors: Are More Susceptible to Thermoacoustic Instabilities





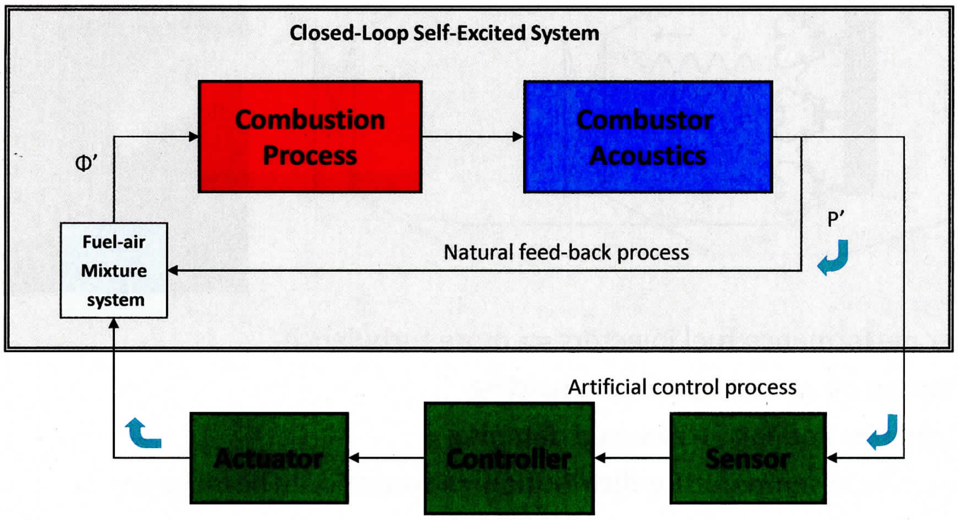
1. Higher performance fuel injectors => more turbulence
2. No dilution air => reduced flame holding
3. Reduced film cooling => reduced damping
4. More uniform temperature distribution => acoustically homogeneous
5. Shorter combustor => higher frequency instabilities

Combustion Instability



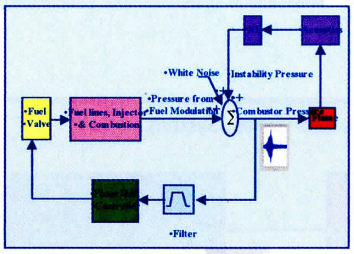
Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur

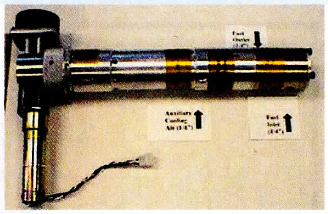


Active Combustion Instability Control Via Fuel Modulation

Advanced control methods

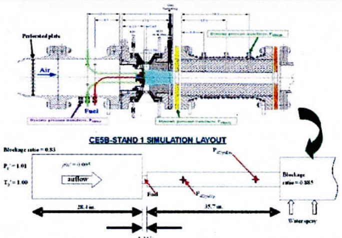


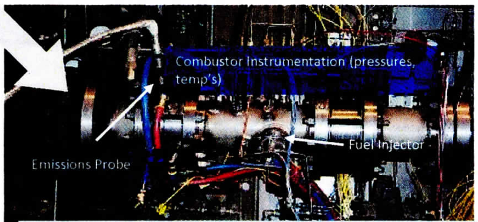
High-frequency fuel delivery system and models



High-temperature sensors and electronics

Physics-based instability models

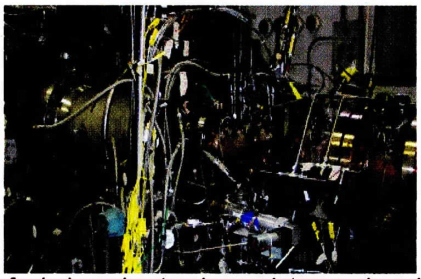




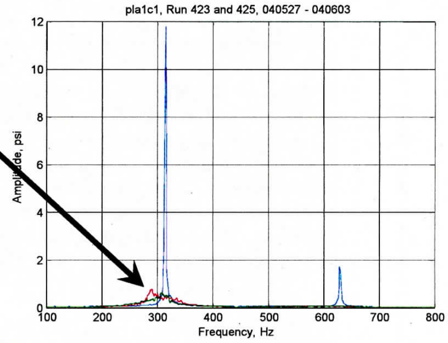
Realistic combustors, rigs for research

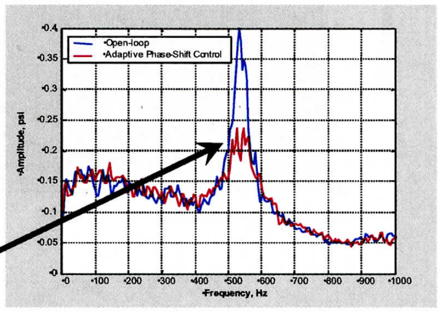
Active Combustion Instability Control Demonstrated Experimentally for Conventional Combustor

Large amplitude, low-frequency instability suppressed by 90%



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



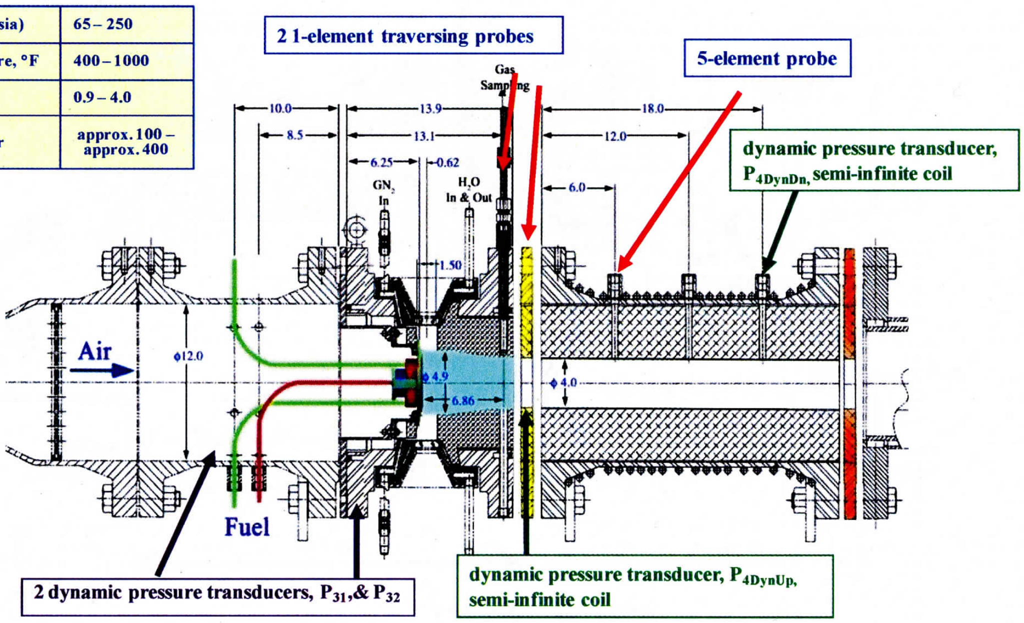


High-frequency, low-amplitude instability is identified, while still small, and suppressed almost to the noise floor.

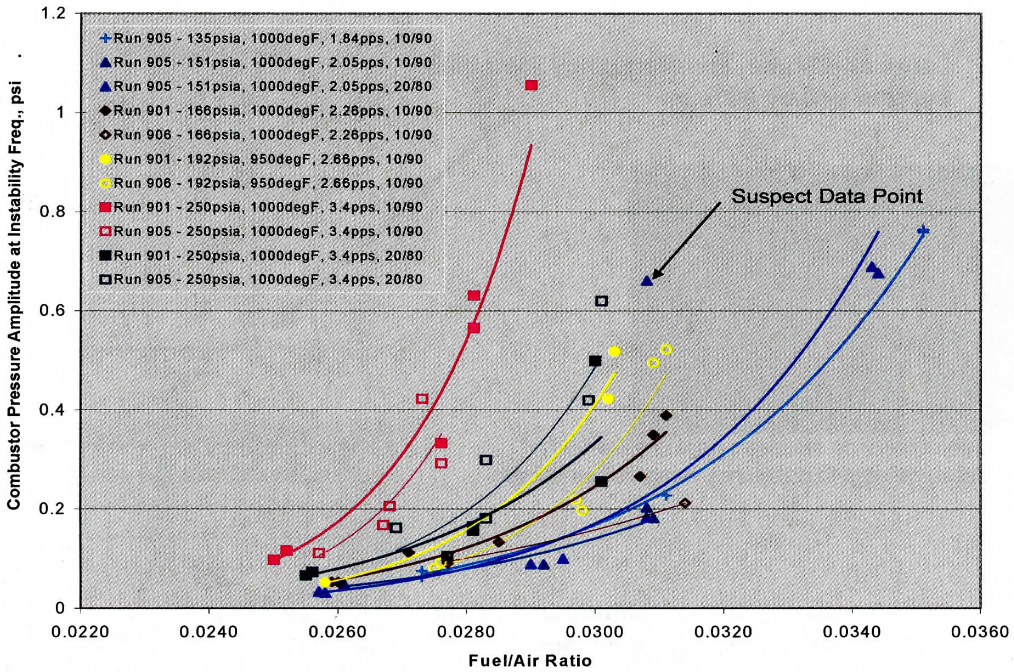
Low Emissions Combustor Prototype with Observed Instability as installed in NASA GRC CE5B-Stand 1

Range of Combustor Operating Conditions

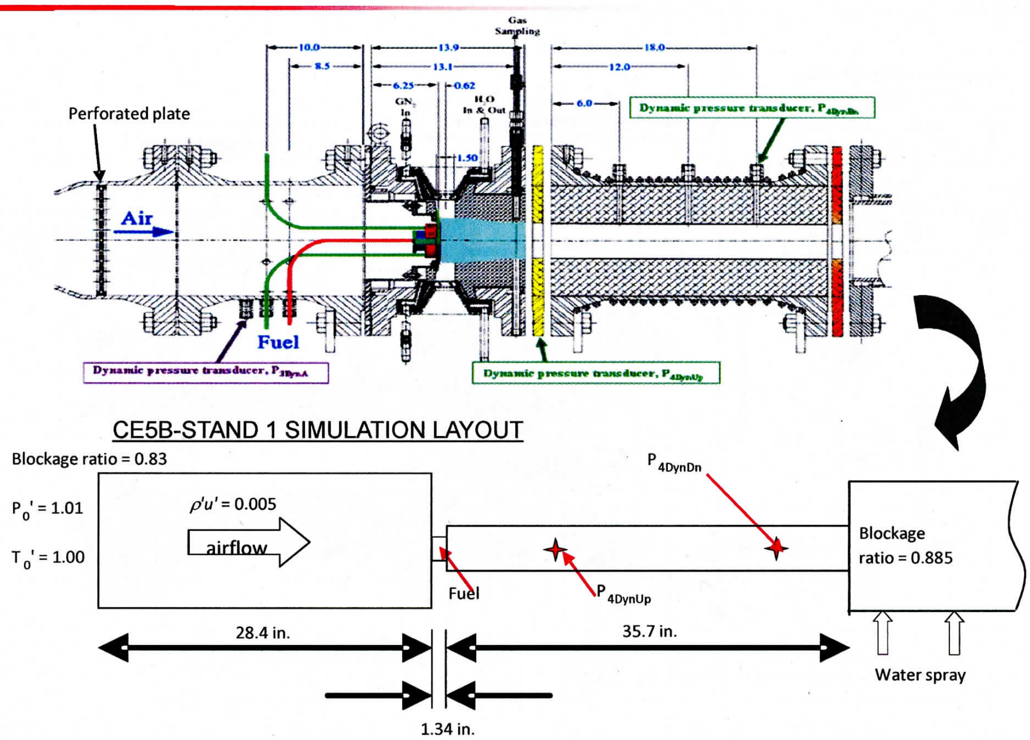
Inlet Pressure (psia)	65 – 250
Inlet Temperature, °F	400 – 1000
Air Flow, lb_m/s	0.9 – 4.0
Fuel Flow, lb_m/hr	approx. 100 – approx. 400



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

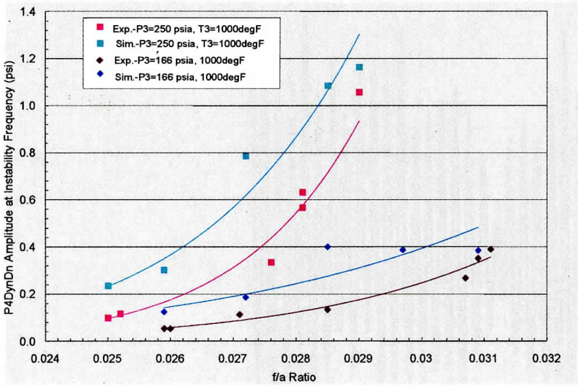


Low Emissions Combustor Prototype
Sectored 1-D Instability Model



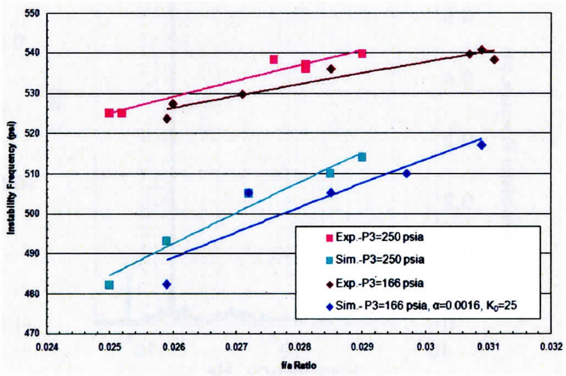
Low Emissions Combustor Prototype
Sectored 1-D Instability Model

Combustion Instability Simulation Results Match Experimental Results for Multiple Operating Conditions



Amplitude trend replicated

Frequency trend replicated



DeLaat, J.C.; Paxson, D.E.: "Characterization and Simulation of the Thermoacoustic Instability Behavior of an Advanced, Low Emissions Combustor Prototype." 44th Joint Propulsion Conference and Exhibit, Hartford, Connecticut, July 21–23, 2008. AIAA-2008-4878, NASA/TM—2008-215291.

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;

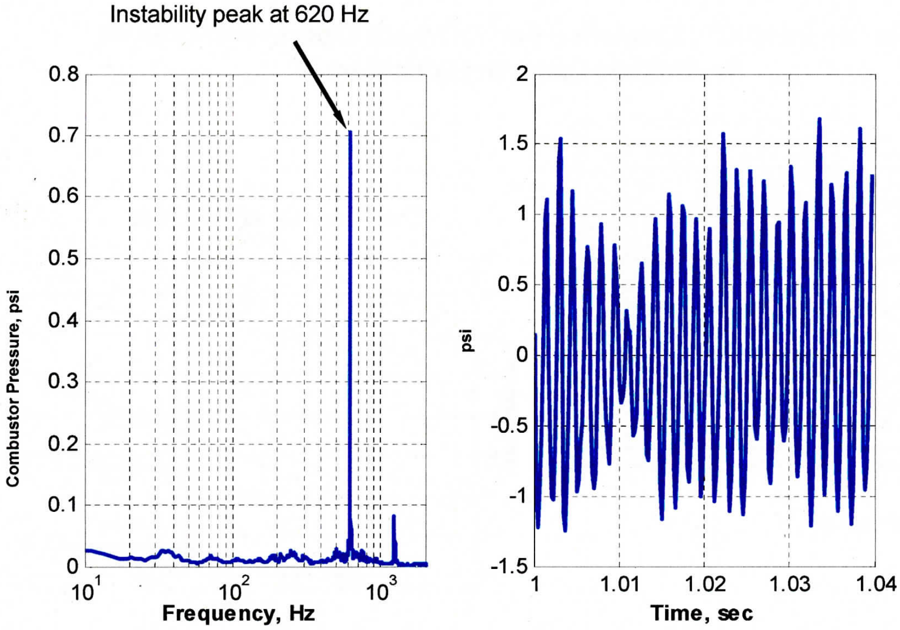
C. Determine if combustion instability control can be accomplished using the dynamic pressure at P3 for feedback;

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.

DeLaat, J.C.; Kopasakis, G.; Saus, J.R.; Chang, C.T.; Wey, C.: "Active Combustion Control for Aircraft Gas-Turbine Engines – Experimental Results for an Advanced, Low-Emissions Combustor Prototype" 50th AIAA Aerospace Sciences Meeting, Nashville, TN, January 2012. AIAA-2012-0783.

A. Comparison of Combustion Instability Behavior vs. Prior Testing

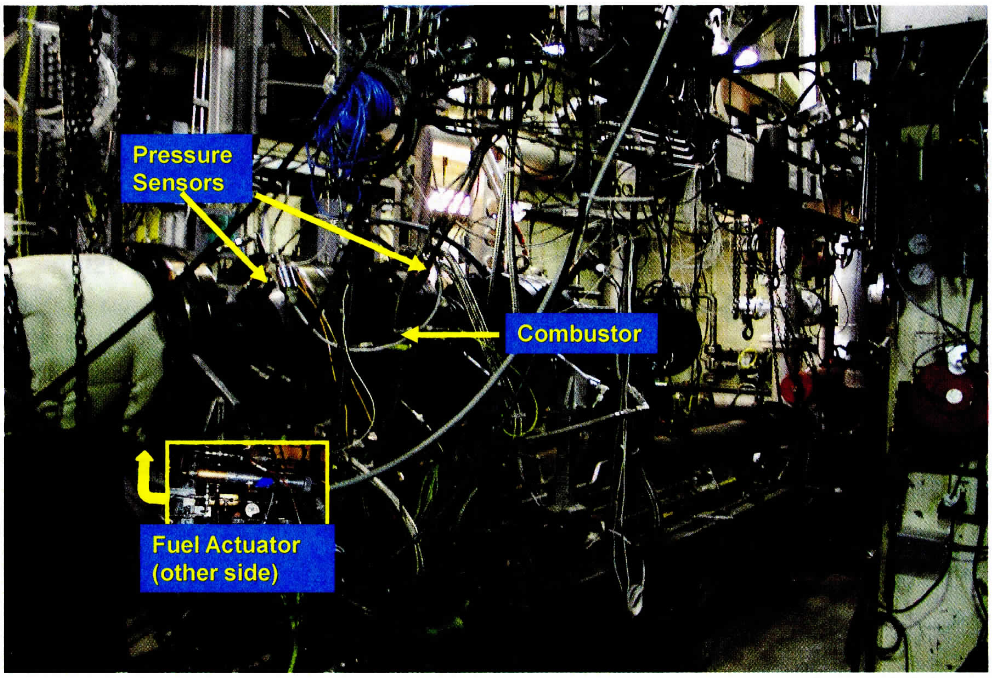


Combustor Pressure Amplitude Spectra   Combustor Pressure Time History

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

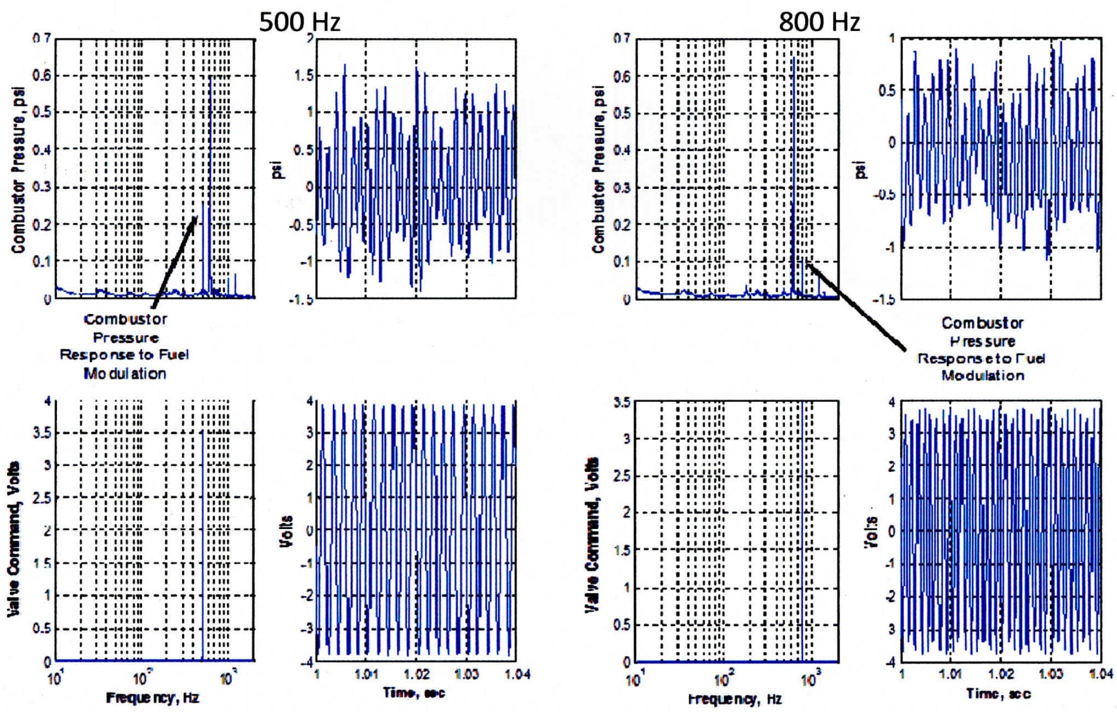
B. Demonstration of Combustion Instability Control

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

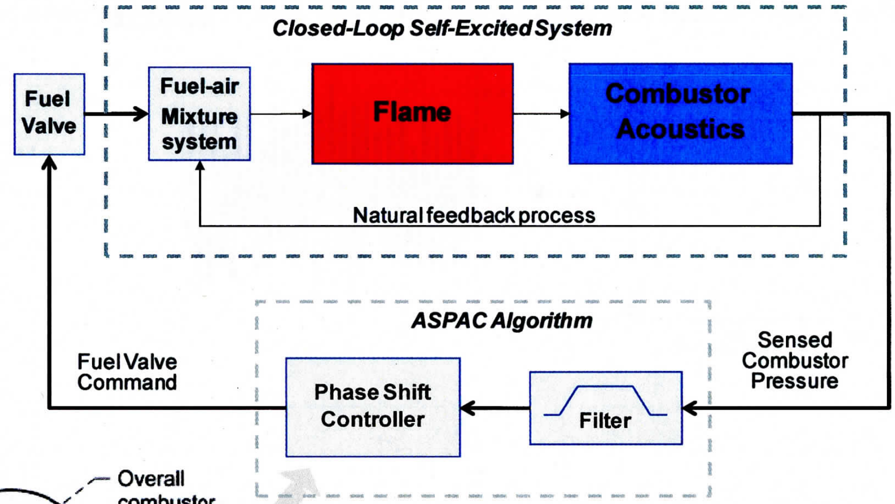


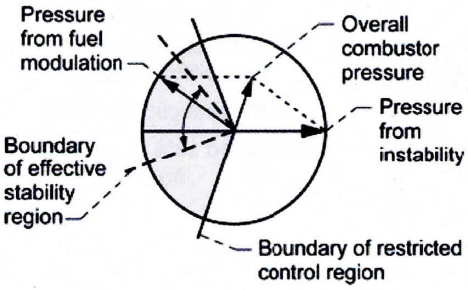
B. Demonstration of Combustion Instability Control

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



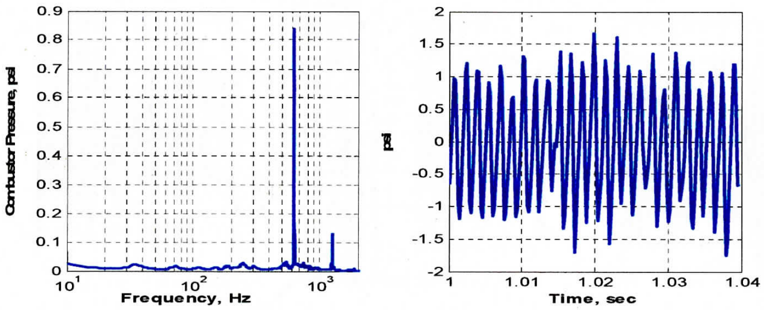
B. Demonstration of Combustion Instability Control





Adaptive Sliding Phasor Averaged Control (ASPAC)

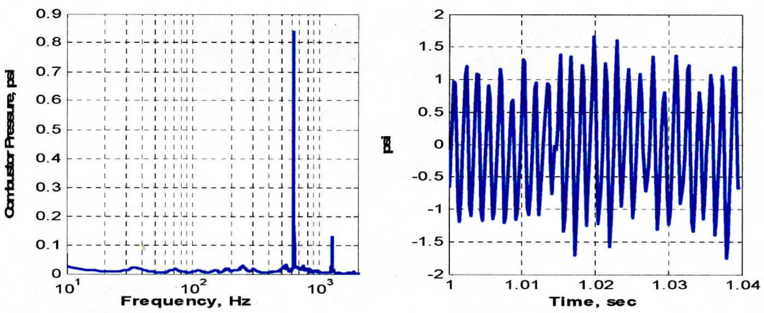
B. Demonstration of Combustion Instability Control



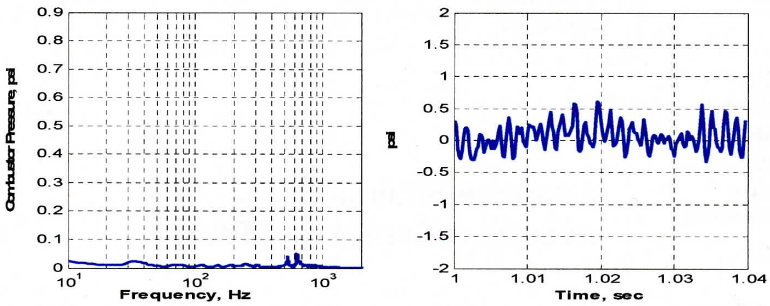
Uncontrolled

B. Demonstration of Combustion Instability Control

Adaptive Sliding Phasor Averaged Control (ASPAC) able to <u>suppress</u> combustion instability



Uncontrolled



Controlled

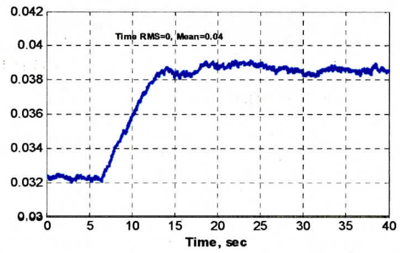
94% reduction in peak at instability frequency

60% reduction in RMS

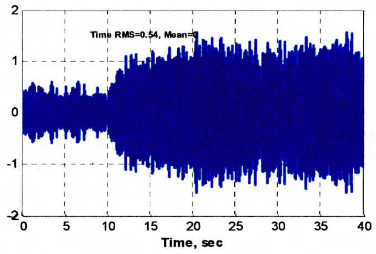
Estimated ±8% of mean fuel flow

B. Demonstration of Combustion Instability Control

Fuel/air ratio



Filtered Combustor Pressure

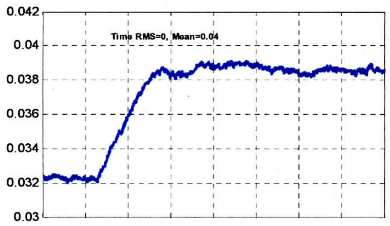


Controller off

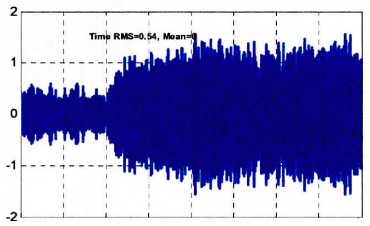
B. Demonstration of Combustion Instability Control

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

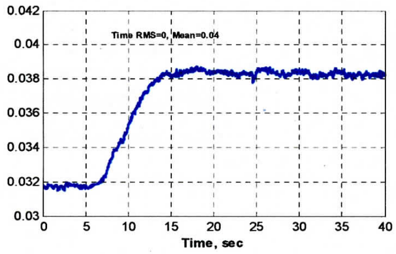
Fuel/air ratio

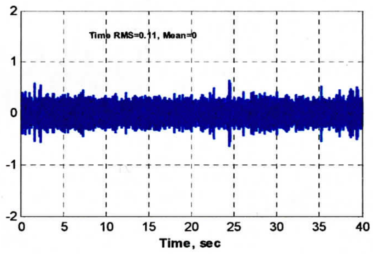


Filtered Combustor Pressure



Controller off

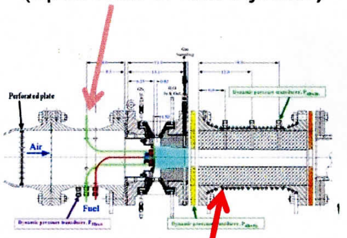




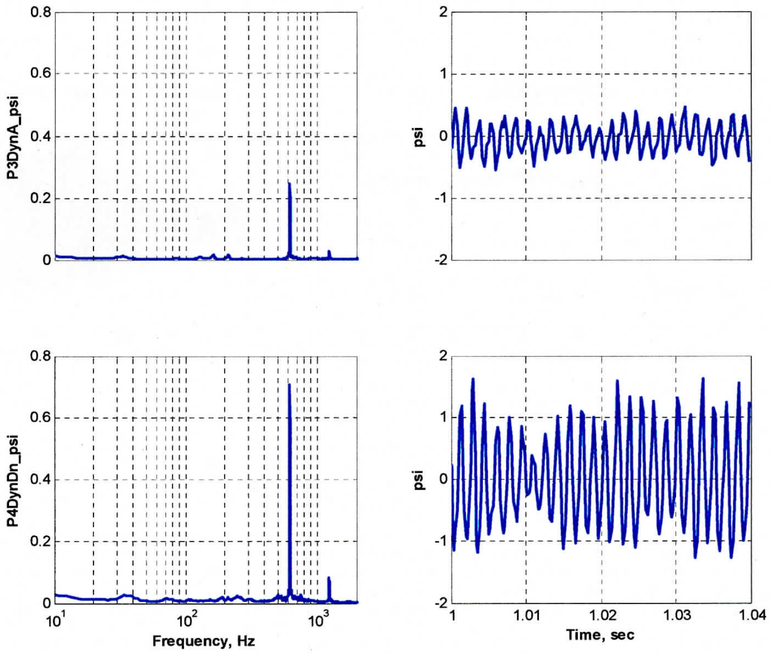
Controller on

C. Combustion Instability Control with P3 Dynamic Pressure as Feedback

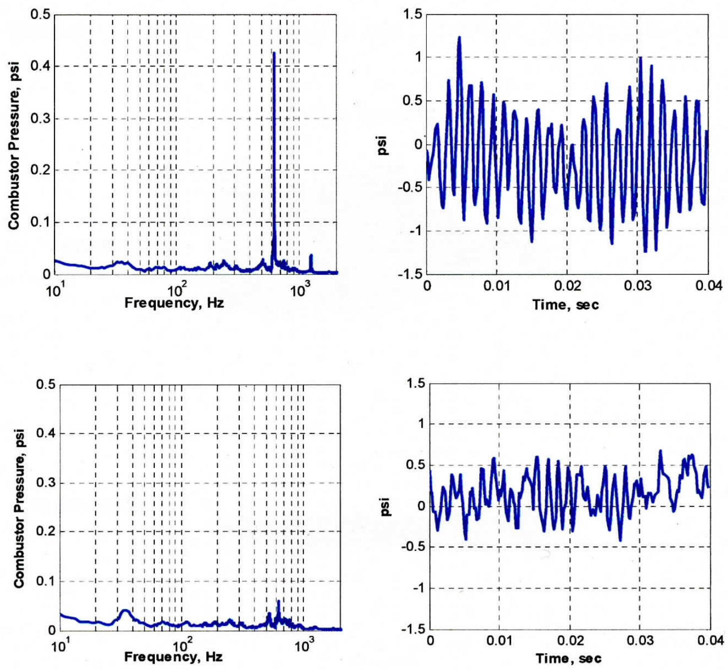
P3' ≤ 1300°F
(upstream of fuel injector)



P4' ≥ 3000°F
(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

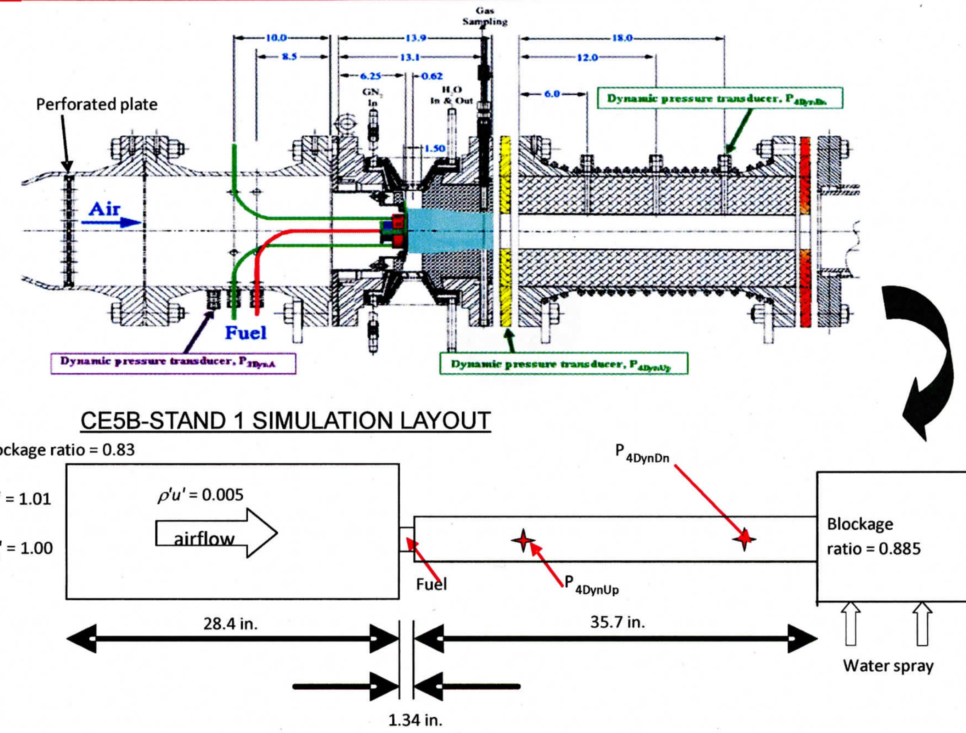
D. Combustion Instability Control Using Pilot Fuel Injector Modulation

- **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

Saus, J.R.; Chang, C.T.; DeLaat, J.C.; and Vrnak, D.R.: "Performance Evaluation of a High Bandwidth Liquid Fuel Modulation Valve For Active Combustion Control," 50th AIAA Aerospace Sciences Meeting, Nashville, TN, January 2012. AIAA-2012-1274.

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



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
- Apply combustion instability control technologies via pilot fuel modulation to increasingly advanced lean-burn combustors.
- Extend existing simulation of uncontrolled combustion instability to include the controlled case.