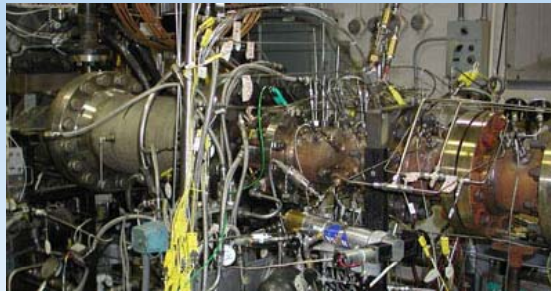


Combustion Dynamics and Control for Ultra Low Emissions in Aircraft Gas-Turbine Engines

Future aircraft engines must provide ultra-low emissions and high efficiency at low cost while maintaining the reliability and operability of present day engines. The demands for increased performance and decreased emissions have resulted in advanced combustor designs that are critically dependent on efficient fuel/air mixing and lean operation. However, all combustors, but most notably lean-burning low-emissions combustors, are susceptible to combustion instabilities. These instabilities are typically caused by the interaction of the fluctuating heat release of the combustion process with naturally occurring acoustic resonances. These interactions can produce large pressure oscillations within the combustor and can reduce component life and potentially lead to premature mechanical failures.

Active Combustion Control which consists of feedback-based control of the fuel-air mixing process can provide an approach to achieving acceptable combustor dynamic behavior while minimizing emissions, and thus can provide flexibility during the combustor design process. The NASA Glenn Active Combustion Control Technology activity aims to demonstrate active control in a realistic environment relevant to aircraft engines by providing experiments tied to aircraft gas turbine combustors. The intent is to allow the technology maturity of active combustion control to advance to eventual demonstration in an engine environment. Work at NASA Glenn has shown that active combustion control, utilizing advanced algorithms working through high frequency fuel actuation, can effectively suppress instabilities in a combustor which emulates the instabilities found in an aircraft gas turbine engine. Current efforts are aimed at extending these active control technologies to advanced ultra-low-emissions combustors such as those employing multi-point lean direct injection.

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



John DeLaat

Controls and Dynamics Branch

NASA Glenn Research Center at Lewis Field, Cleveland, OH

Ph: (216) 433-3744, email: jdelaat@nasa.gov

*Graduate Seminar Series, The Ohio State University
May 9, 2011*

Glenn Research Center

at Lewis Field



Outline

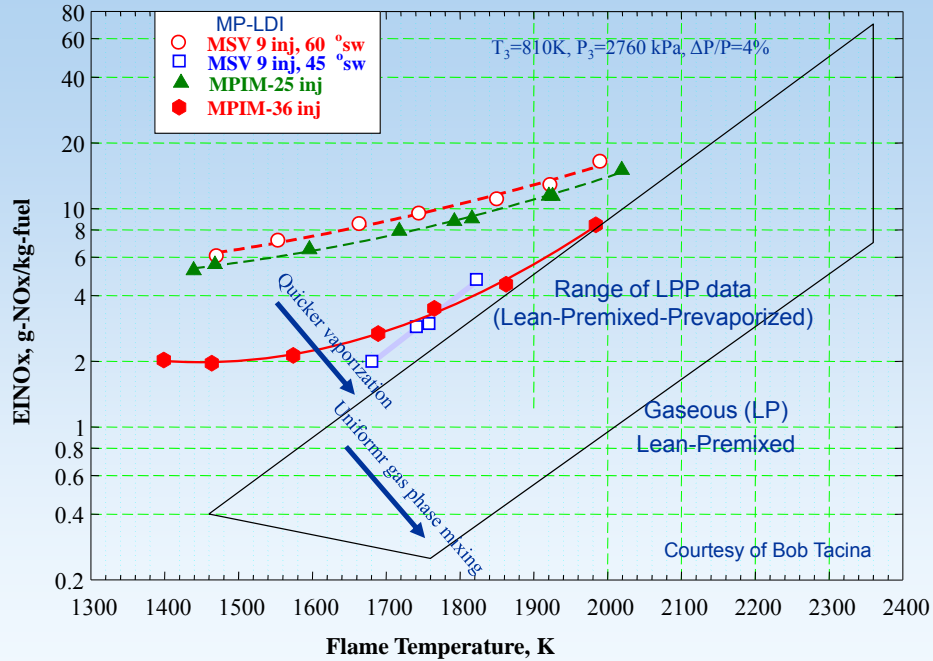
- NASA's Active Combustion Control interests
- Motivation: Ultra-low emissions, lean-burning, Multi-point Lean Direct Injection combustors
 - More susceptible to instability
- Possible approaches for dealing with combustor thermo-acoustic instabilities
- Active Combustion Control as an enabling technology
- Approach and outcomes of instability control experiments
- Future plans

Glenn Research Center

at Lewis Field



Effect of Fuel Injection Schemes on NOx Emission

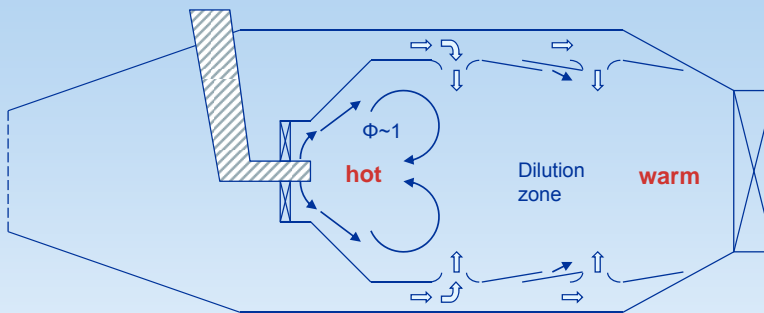


Glenn Research Center

at Lewis Field



Conventional Combustion: Single-Point Rich Front End Injection

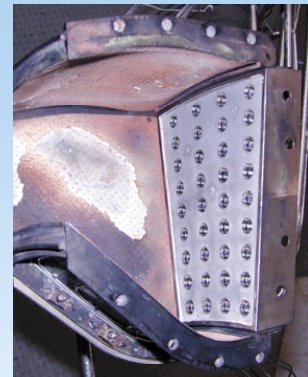
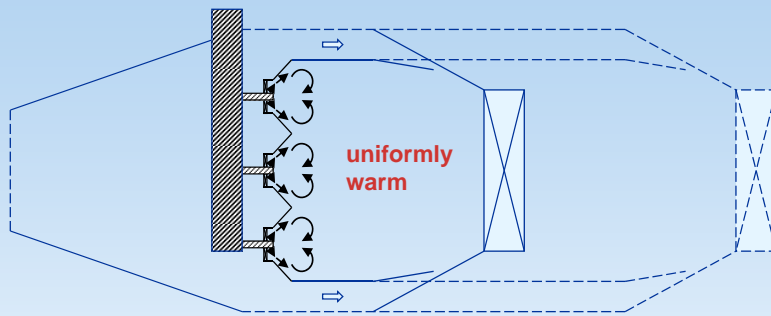


Glenn Research Center

at Lewis Field



Lean-Burning, Ultra-Low-Emissions Combustion: Multi-Point Lean Direct Injection



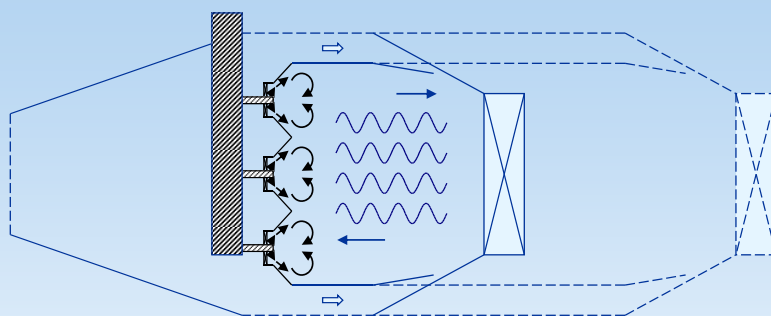
1. Energetic quick-mixing before auto ignition at high power condition
2. Lean and uniform front end makes less CO and NOx initially
3. Less CO initially, shorter combustor needed
4. Shorter combustor, shorter residence time, less additional NOx

Glenn Research Center

at Lewis Field



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

Glenn Research Center

at Lewis Field



How do we deal with combustor instabilities?

1. Smart design
2. Modulate air to get out-of-phase cancellation
3. Fuel-modulation to get out-of-phase cancellation

Method 1 is preferred, but we're not sure it's enough

Method 2 requires lots of actuation power input and bulk

Method 2 also may induce diffuser flow separation due to flow perturbation.

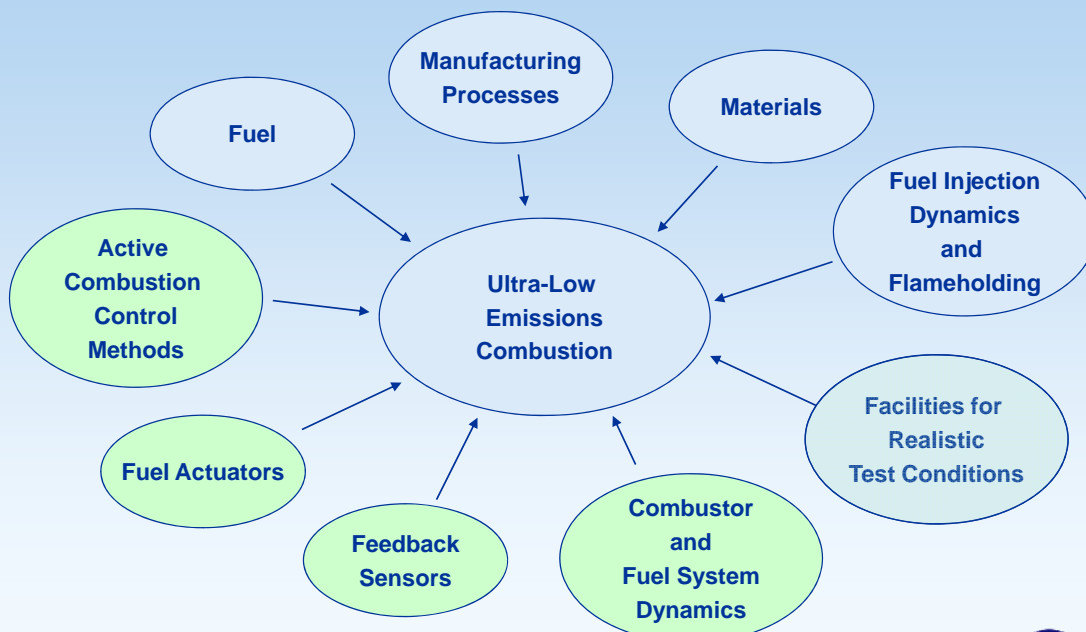
Method 3 requires the least actuation power and bulk and produces the most energy change

Glenn Research Center

at Lewis Field



Synergistic Technologies to Enable Ultra-Low Emissions Combustion

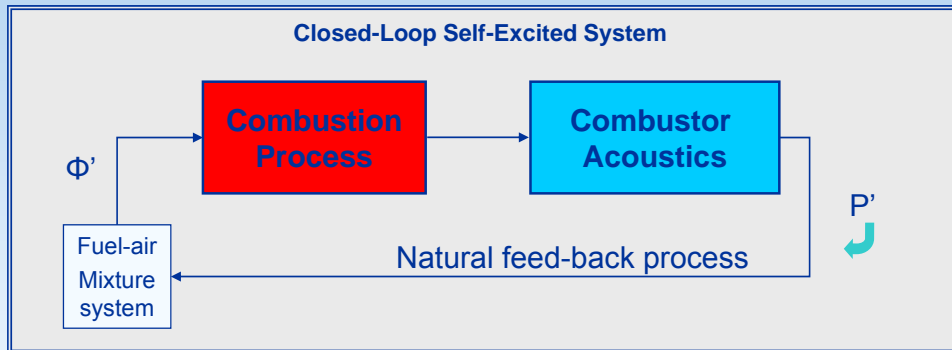


Glenn Research Center

at Lewis Field



Combustion Instability



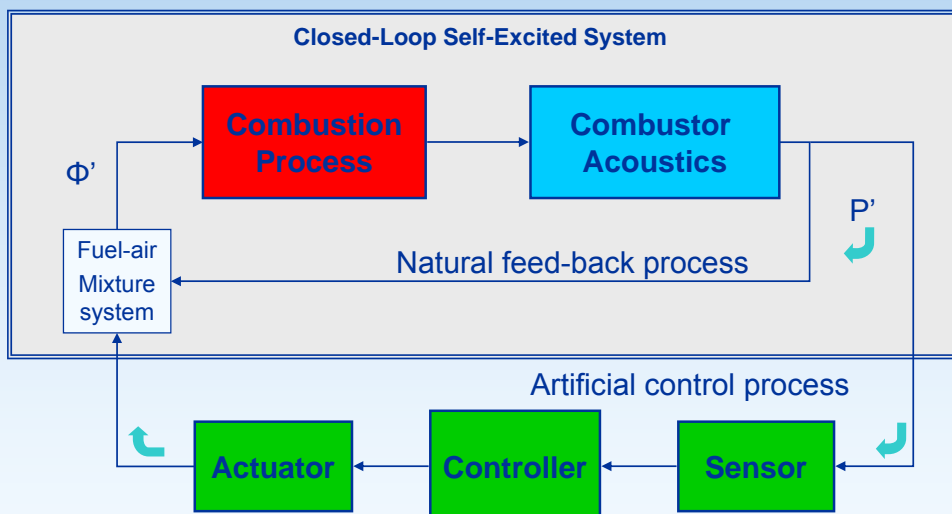
Glenn Research Center

at Lewis Field



Combustion Instability Control Strategy

Objective: Suppress combustion thermo-acoustic instabilities when they occur



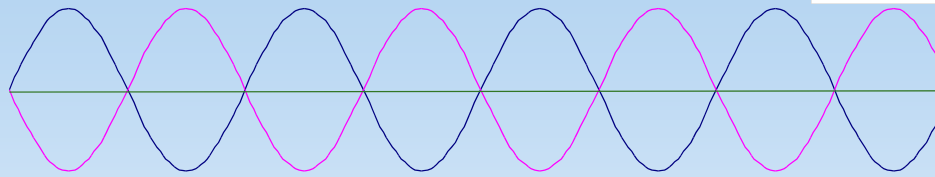
Glenn Research Center

at Lewis Field

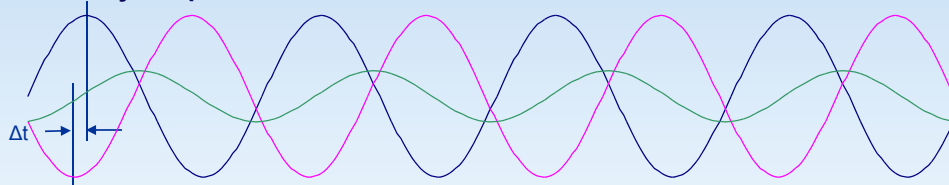


Why is instability control so difficult?

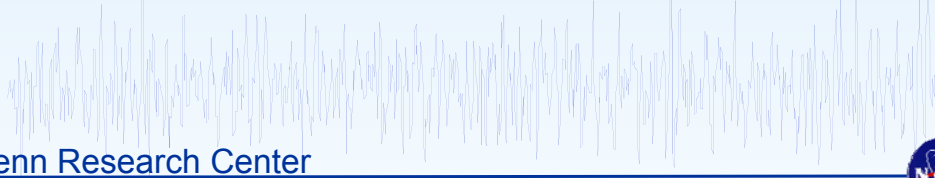
Phase inversion



Time delay & phase shift



Low signal-to-noise ratio – What frequency? What phase?



Glenn Research Center

at Lewis Field



Our Technical Challenges

- Control methods required to:
 - identify instability
 - suppress instability in presence of large time delay, substantial noise
- Combustor dynamics largely unmodeled
- Liquid fuel – introduces additional unmodeled dynamics including time delay (atomization, vaporization, ...)
- Actuation system – enough bandwidth and authority, not just valve (also feedline, injection, ...)
- Experimental testbed for actuation, feedline dynamics required
- Simplified models needed for control design evaluation

Glenn Research Center

at Lewis Field



Active Combustion Instability Control Via Fuel Modulation

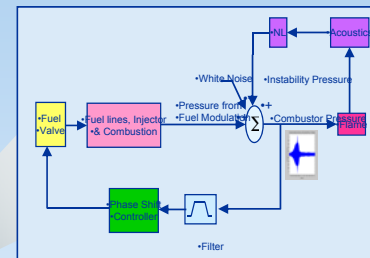
High-temperature sensors and electronics



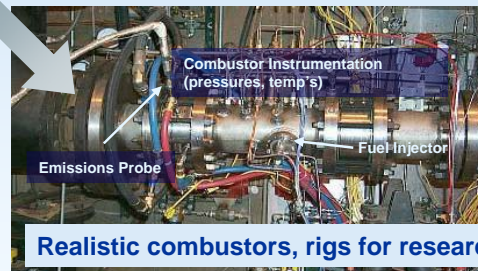
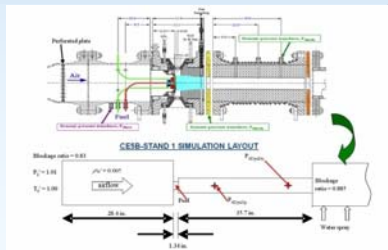
High-frequency fuel delivery system and models



Advanced control methods



Physics-based instability models



Realistic combustors, rigs for research

Glenn Research Center

at Lewis Field



Team Members - from Multiple Disciplines

- Controls and Dynamics Branch
 - Dan Paxson: Dynamic Models
 - George Kopasakis: Control Methods
 - Joe Saus: Actuators
- Combustion Branch
 - Clarence Chang: Combustion Science
- Sensors and Electronics Branch
 - Robert Okojie: Harsh Environments Pressure Sensors
- Engineering Directorate
 - Dan Vrnak: Control Software
- Supersonics Project
 - Dan Bulzan – Supersonics (and Subsonics) Combustion API
- Other NASA Participants
 - Materials, Combustion and Flow Diagnostics, Experimental Staff,...
- NRA Participants
 - Georgia Tech, Penn State, Virginia Tech
 - Other NRA's associated with Combustion Science

Glenn Research Center

at Lewis Field



Control Strategies to Deal with Combustion Instability

- Objective
 - Perturb the fuel with the right amplitude and at the right phase to cancel the instability
- Challenges
 - Control action delay, noise, unknown disturbances
- Approach
 - Use reduced-order models for development
 - Use simplified physics-based model for validation before test
- Control methods
 - Empirical: Adaptive phase shifting based on achieved cancellation
 - Model-based: Set the proper phase for cancellation based on a model of the predicted instability and disturbances

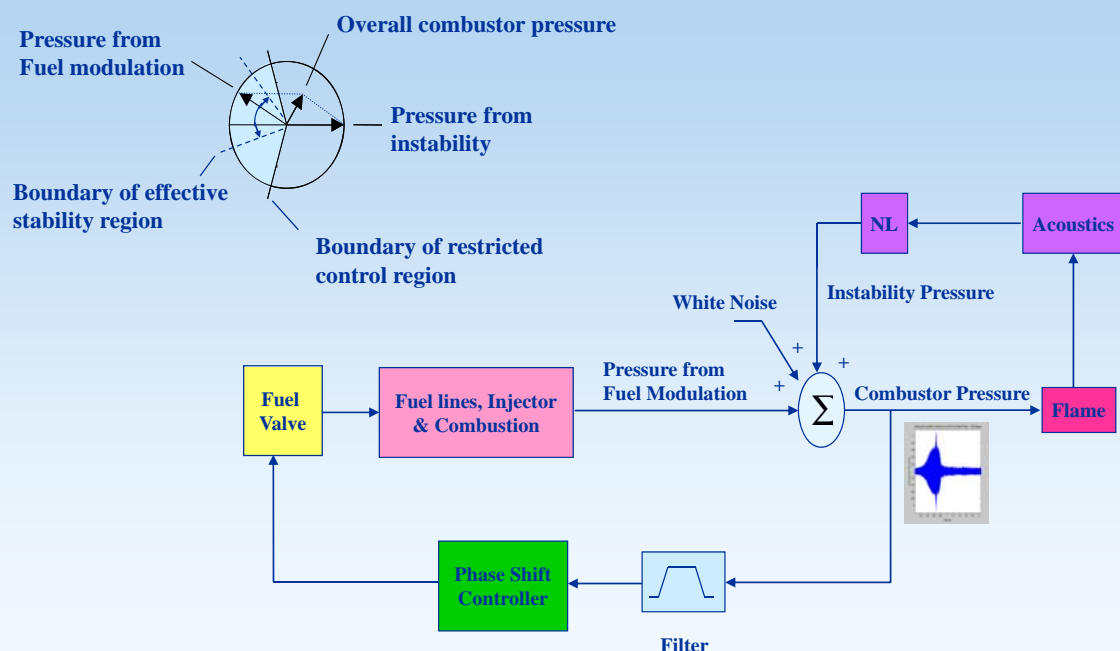
Glenn Research Center

at Lewis Field



Adaptive phase shifting control:

“Adaptive Sliding Phasor Averaged Control” – G. Kopasakis



Glenn Research Center

at Lewis Field



Motivation for Combustion Instability Simulation

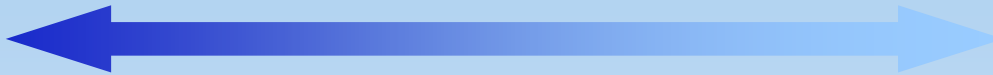
- **Successful active control design requires accurate modeling and simulation.**
 - The essential physical phenomena should be correctly captured
 - (e.g. self-excitation).
 - Characterization and control design necessitate rapid simulation
 - (i.e. relative simplicity).
 - Simulation must lend itself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

Glenn Research Center

at Lewis Field

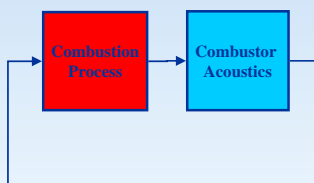


Combustion Dynamics Modeling



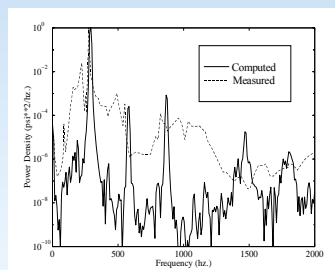
Reduced-order oscillator models

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



Simplified Quasi-1D dynamic models

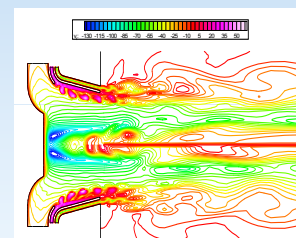
Allow physics-based control method validation



Results from NASA Sected-1D Model of LPP Combustor Rig

Detailed, physics-based dynamic models

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



Penn State Injector Response Model Plot

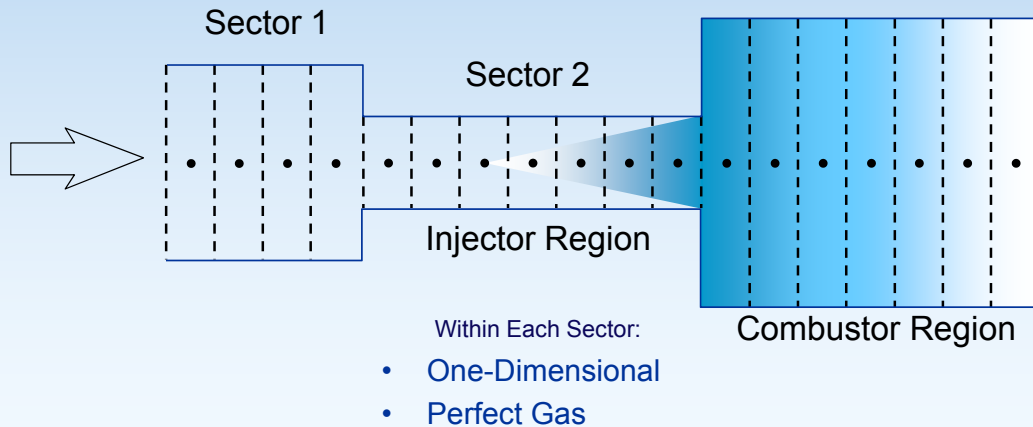
Glenn Research Center

at Lewis Field



Combustion Instability Simulation Features

- Time-accurate
- Physics-based, Sectored 1-D, Reacting
- Computationally efficient area transitions
- Upstream and Downstream boundary conditions modeled to match rig Sector 3

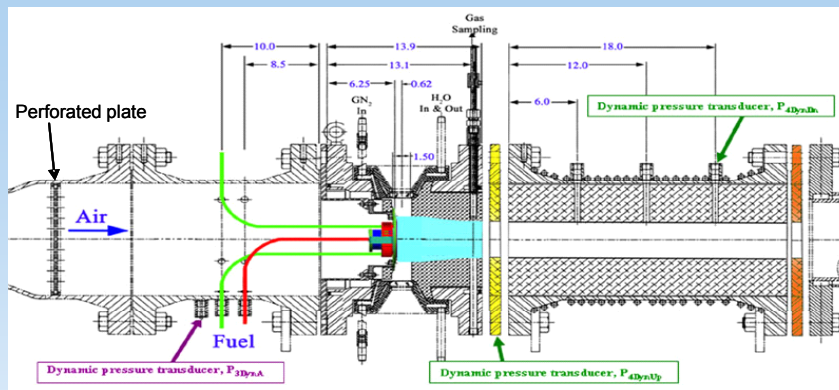


Glenn Research Center

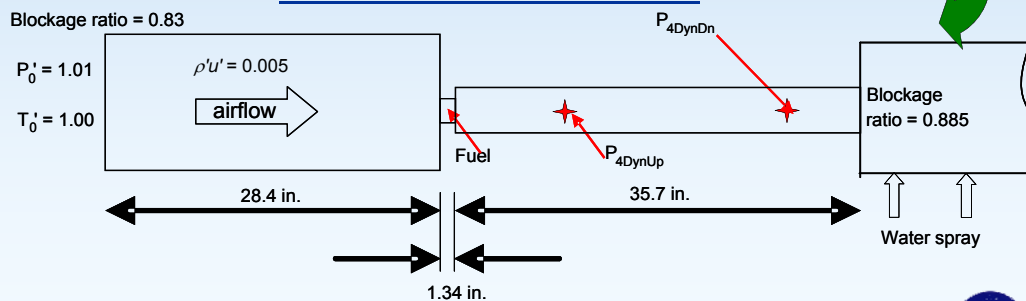
at Lewis Field



Low Emissions Combustor Instability Model Development



CE5B-STAND 1 SIMULATION LAYOUT

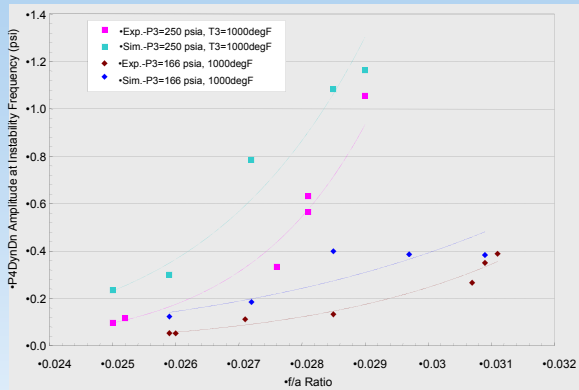


Glenn Research Center

at Lewis Field

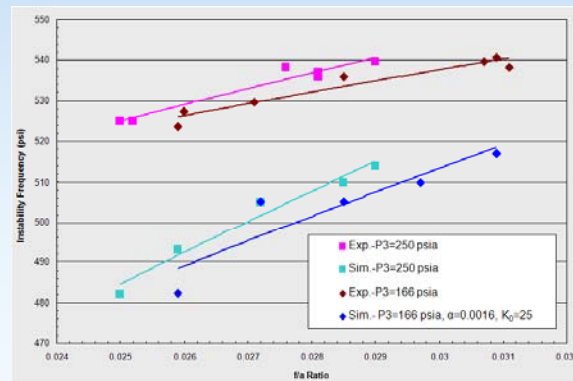


Combustion Instability Simulation Results Match Experimental Results for Multiple Operating Conditions



Amplitude trend replicated

Frequency trend replicated

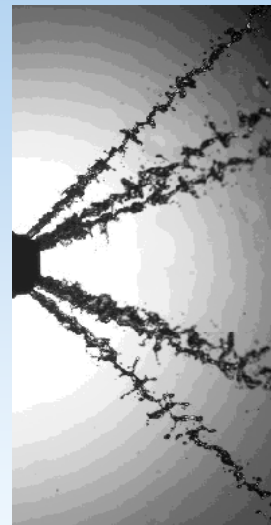
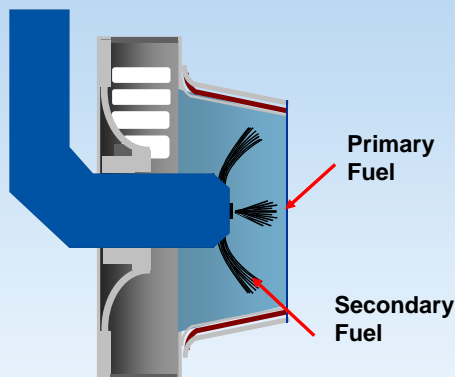


Glenn Research Center

at Lewis Field



Fuel Delivery System Dynamic Response



Stroboscopic Image of Dynamic Fuel Injection (courtesy UTRC)

Glenn Research Center

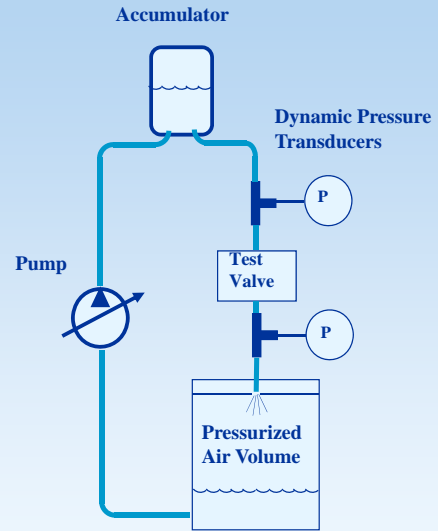
at Lewis Field



High-Bandwidth Fuel Actuator Characterization Testing



Valve, Feed-system Characterization Rig at NASA GRC



Glenn Research Center

at Lewis Field



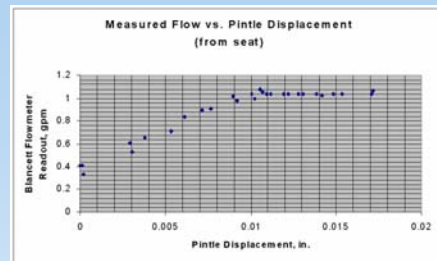
High-Bandwidth Fuel Actuator



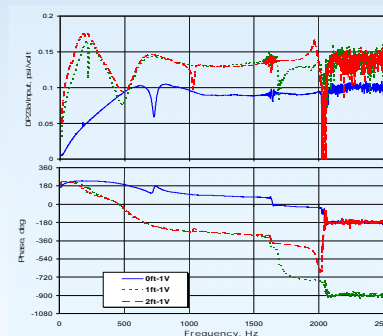
GaTech high-response fuel valve in characterization rig in CE7A



Steady-State Operational Data



Frequency Response Dynamic Characterization Data



Glenn Research Center

at Lewis Field

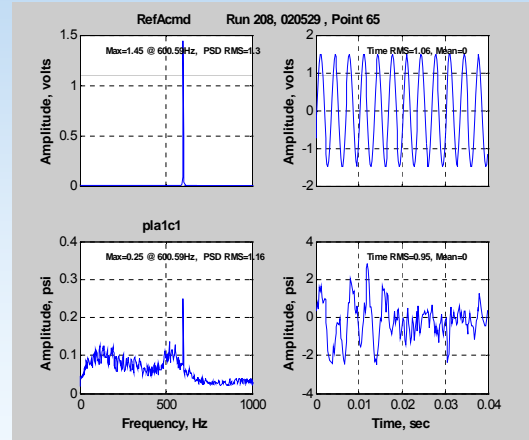
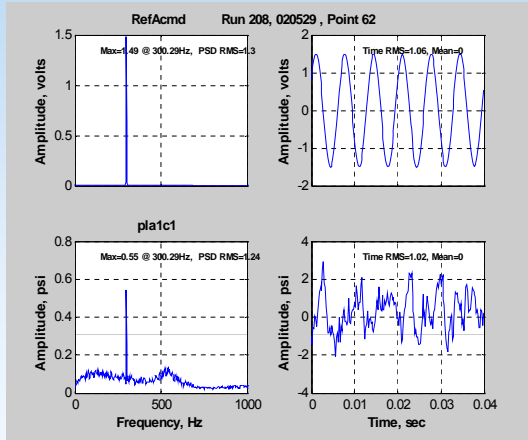


High-Bandwidth Fuel Actuator

Combustor Pressure Response to Fuel Modulation

300Hz

600Hz



Glenn Research Center

at Lewis Field



High Temperature Dynamic Pressure Sensors and Electronics



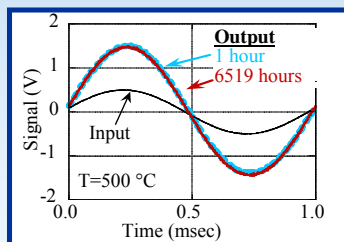
Newly developed 800°C sealing glass demonstrated on a dummy sensor and AIN package header.



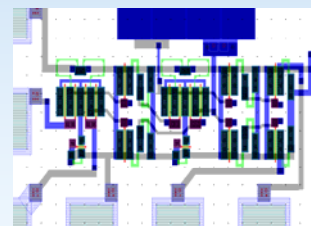
Modified MEMS-DCA package to support 800°C pressure sensor operation.



Differential amplifier circuit using two SiC transistors.



Diff amp test waveforms showing <5% change despite 6500 hrs at 500 °C.



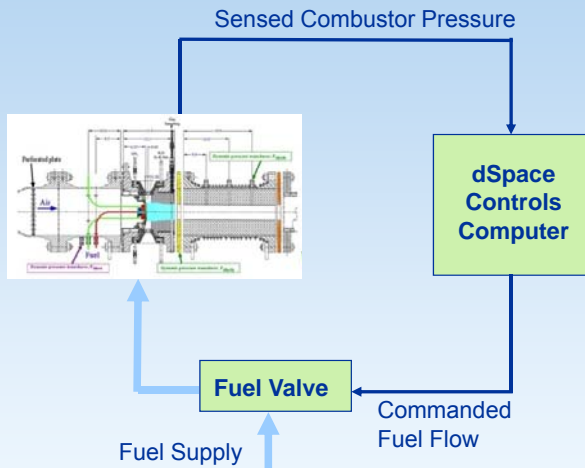
Design of SiC amplifier for dynamic pressure sensor.

Glenn Research Center

at Lewis Field



Combustion Instability Control Test Implementation



- Control methods implemented in real-time computer
- Rig operated at nominal engine temperature and pressure

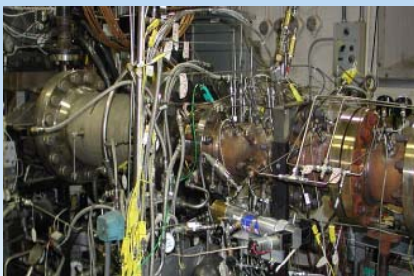
Glenn Research Center

at Lewis Field



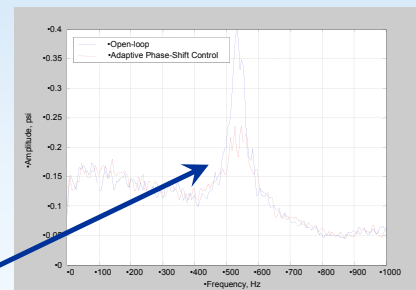
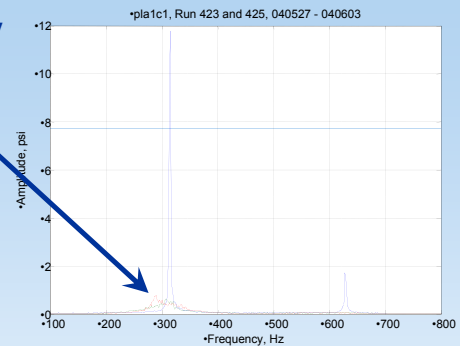
Active Combustion Instability Control Demonstrated Experimentally for Conventional Combustor

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.



Glenn Research Center

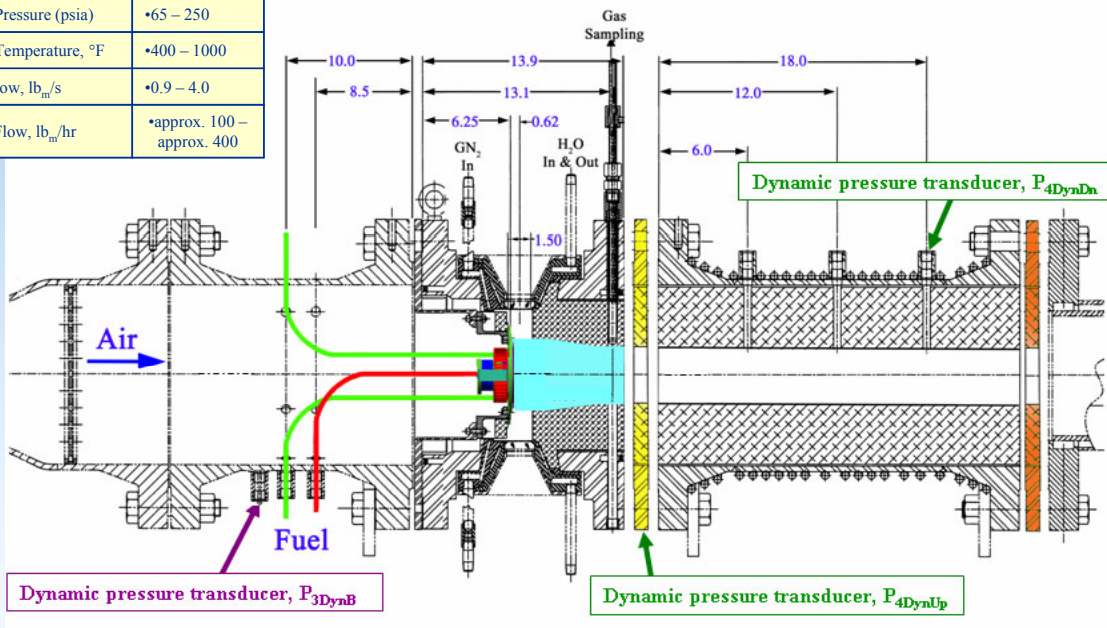
at Lewis Field



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

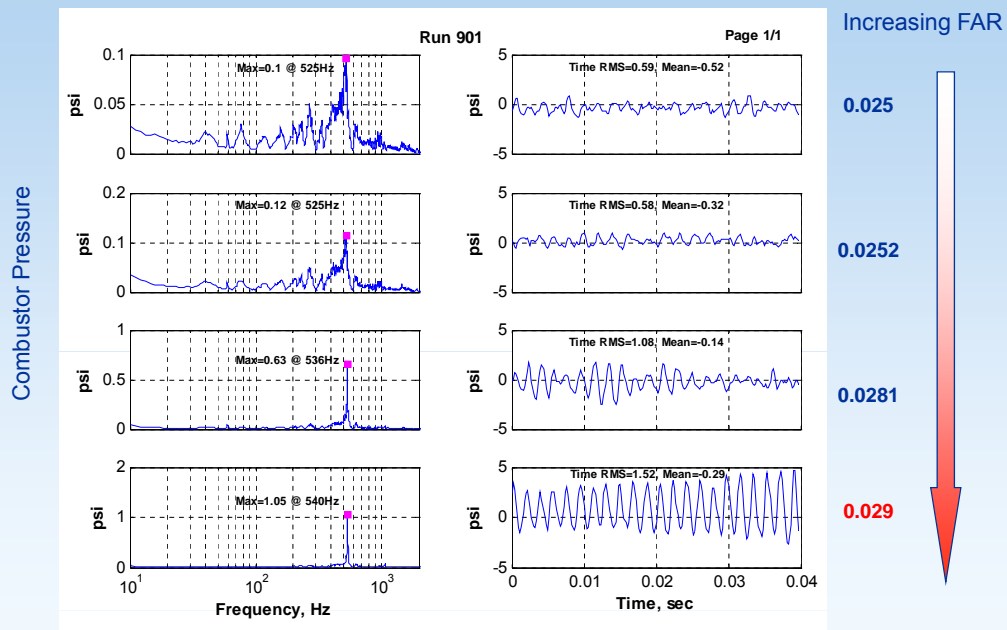


Glenn Research Center

at Lewis Field



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

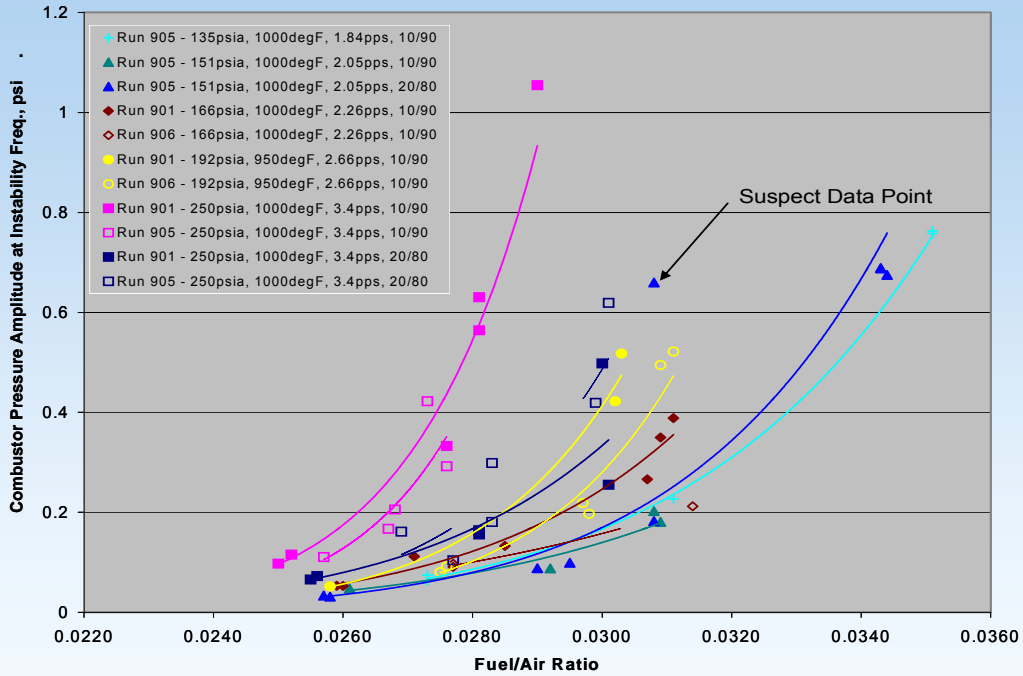


Glenn Research Center

at Lewis Field



Trend in Instability Amplitude vs. FAR for Multiple Test Runs

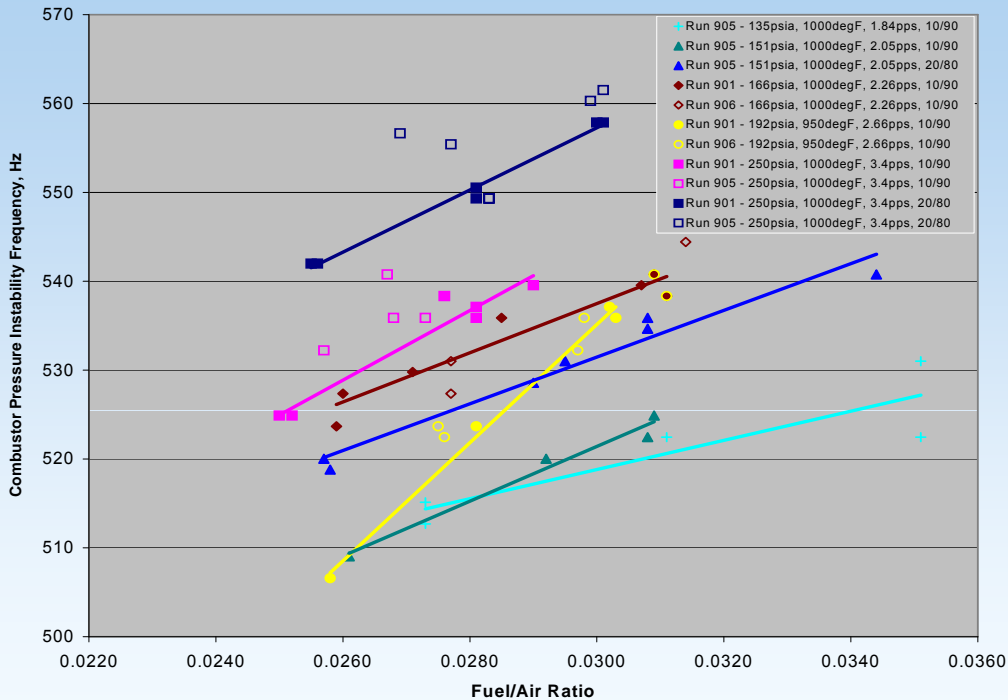


Glenn Research Center

at Lewis Field



Trend in Instability Frequency vs. FAR for Multiple Test Runs

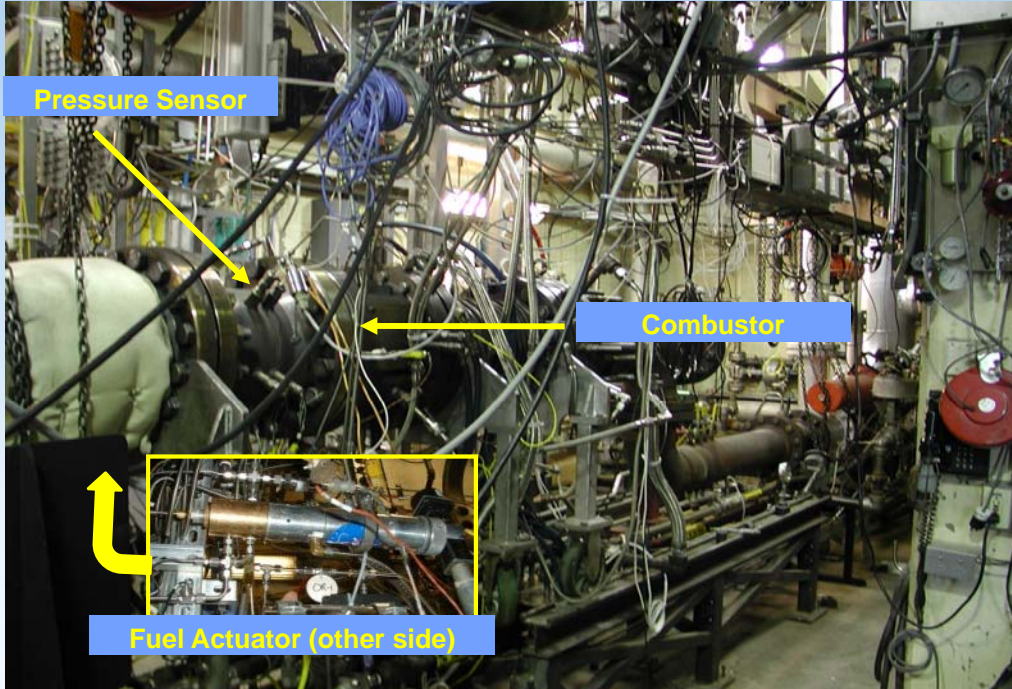


Glenn Research Center

at Lewis Field



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



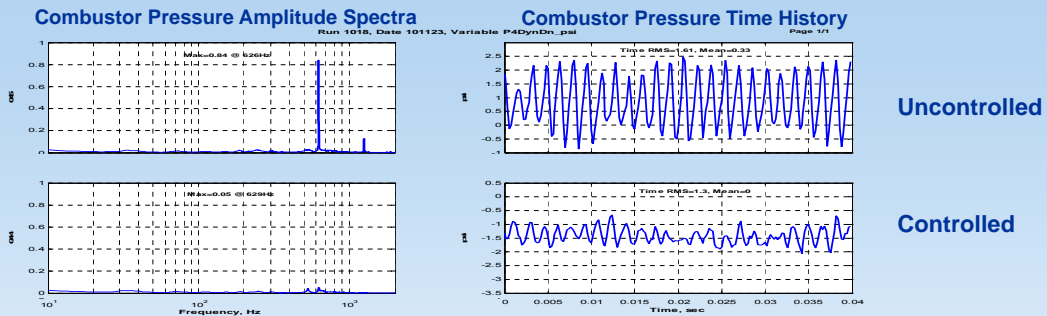
Glenn Research Center

at Lewis Field

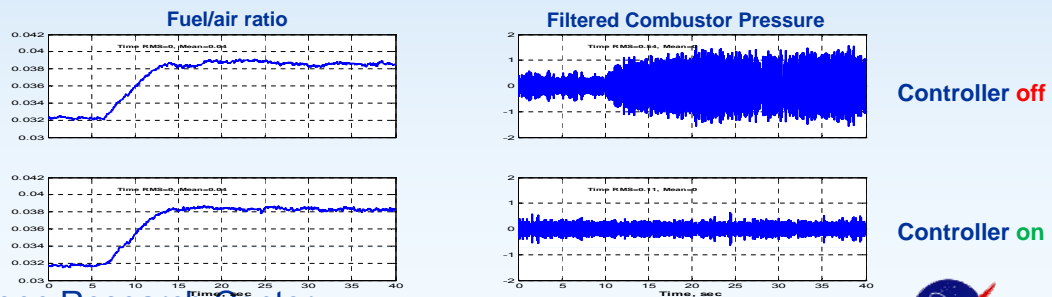


Low-Emissions Combustor - Instability Control Results

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



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

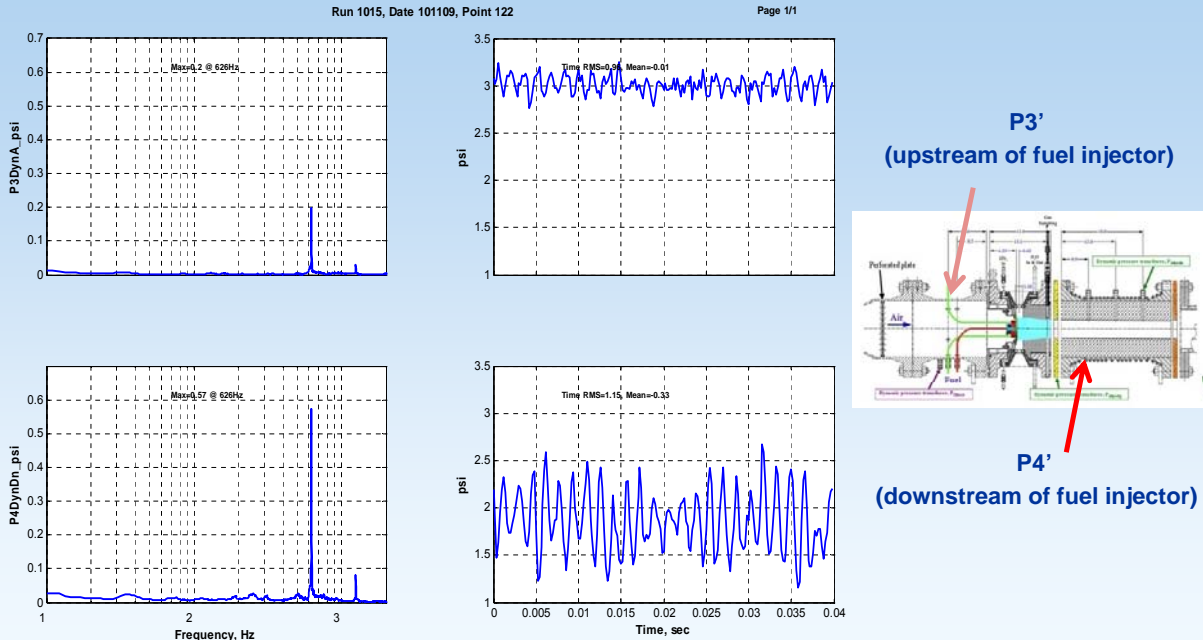


Glenn Research Center

at Lewis Field



Use P3' (1000°F) rather than P4' (3000°F+) as feedback?



Glenn Research Center

at Lewis Field



Future Plans

Mature and demonstrate active combustion control technologies

- High temperature sensors, high-frequency fuel actuators and feed system models, combustion dynamics models, control methods
- Utilize Fundamentals rig in CE13C (5 atm) and medium/high pressure testing in CE5 (30 atm) and ASCR (60 atm)
- **Future platform(s) - LDI Multi-point injection and/or Industry advanced concepts**
 - Instability control demonstration(s) – 2012+
- **Other potential advanced technologies**
 - Control methods that exploit multipoint injection
 - Multidimensional models
 - Incorporate technologies from Fundamental Aeronautics NRA's
 - Harmonic, sub-harmonic models and control
 - Flame Transfer Function models
 - Dynamic stability margin management
 - Static instability (LBO) detection and control

Glenn Research Center

at Lewis Field



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

Glenn Research Center

at Lewis Field



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, Alabama, July 17-19, 2000. NASA TM 2000-210346, AIAA –2000-3500.
- 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 cosponsored by the AIAA, ASME, SAE, and ASEE, Tucson, Arizona, July 10-13, 2005. AIAA-2005-3593.
- 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.
- 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.
- Okojie, R.S.; DeLaat, J.C.; Saus, J.R.: "SiC Pressure Sensor for Detection of Combustor Thermo-Acoustic Instabilities." Presented at the 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005. Volume 1, p. 470-473.
- Kopasakis, G.; DeLaat, J.C.; Chang, C.T.: "Adaptive Instability Suppression Controls Method For Aircraft Gas Turbine Engine Combustors." AIAA Journal of Propulsion and Power, Vol. 25, No. 3, May-June 2009, pp. 618-627.
- 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 cosponsored by the AIAA, ASME, SAE, and ASEE, Hartford, Connecticut, July 21-23, 2008. AIAA-2008-4878, NASA/TM—2008-215291.
- Saus, J.R.; Chang, C.T.; DeLaat, J.C.; Vrnak, D.R.: "Design and Implementation of a Characterization Test Rig for Evaluating High Bandwidth Liquid Fuel Flow Modulators. Presented at the 45th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Denver, Colorado, Aug. 2-5, 2009. AIAA-2009-4886.

Glenn Research Center

at Lewis Field



Questions?

Glenn Research Center

at Lewis Field

