NASA/TM—2003-212611 ISABE–2003–1054

Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines

John C. DeLaat and Clarence T. Chang
Glenn Research Center, Cleveland, Ohio

September 2003

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Prepared for the
16th International Symposium on Airbreathing Engines
sponsored by the International Society for Airbreathing Engines
Cleveland, Ohio, August 31–September 5, 2003

National Aeronautics and
Space Administration

Glenn Research Center

September 2003

Acknowledgments

This work was sponsored by the NASA Smart Efficient Components Project. The authors would like to thank Mr. Bob Corrigan, Project Manager, for his support. The authors would also like to acknowledge the contributions of Dr. Jeffrey Cohen, Karen Teerlink, Prabir Barooah, and Dr. Torger Andersen at UTRC, and Dr. Jeffery Lovett of Pratt & Whitney. Significant technical contributions were made by the following NASA personnel: Joseph Saus, Dr. Daniel Paxson, George Kopasakis, Dr. Dzu Le, and Daniel Vrnak.

The Propulsion and Power Program at
NASA Glenn Research Center sponsored this work.

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ACTIVE CONTROL OF HIGH FREQUENCY COMBUSTION INSTABILITY IN AIRCRAFT GAS-TURBINE ENGINES

John C. DeLaat and Clarence T. Chang
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Active control of high-frequency (>500Hz) combustion instability has been demonstrated in the NASA single-nozzle combustor rig at United Technologies Research Center. The combustor rig emulates an actual engine instability and has many of the complexities of a real engine combustor (i.e. actual fuel nozzle and swirler, dilution cooling, etc.) In order to demonstrate control, a high-frequency fuel valve capable of modulating the fuel flow at up to 1kHz was developed. Characterization of the fuel delivery system was accomplished in a custom dynamic flow rig developed for that purpose. Two instability control methods, one model-based and one based on adaptive phase-shifting, were developed and evaluated against reduced order models and a Sectored-1-dimensional model of the combustor rig. Open-loop fuel modulation testing in the rig demonstrated sufficient fuel modulation authority to proceed with closed-loop testing. During closed-loop testing, both control methods were able to identify the instability from the background noise and were shown to reduce the pressure oscillations at the instability frequency by 30%. This is the first known successful demonstration of high-frequency combustion instability suppression in a realistic aero-engine environment. Future plans are to carry these technologies forward to demonstration on an advanced low-emissions combustor.

Nomenclature

ACC	Active Combustion Control
P3	Compressor Exit Pressure
pla1c1	Combustor rig pressure at axial station #1 and circumferential station #1
RefAcmd	Fuel valve command voltage
T3	Compressor Exit Temperature
UTRC	United Technologies Research Center
VFI	Combined Fuel Valve/Feed-line/Injector

Introduction

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.[1] These interactions can produce large pressure oscillations within the combustor and can reduce component life and potentially lead to premature mechanical failures.

Combustor instability has been problematic in ground-based gas turbines using premixed combustors and will also be a challenge as aero-engine combustor development continues to move toward leaner direct injection schemes. Effective suppression of the high-frequency combustion instabilities which result from the relatively short aero-engine combustor geometries is a critical enabling technology for lean-burning low-emission combustors and requires several key issues to be addressed. First, sensors and algorithms able to detect and interpret the instability need to be developed. Second, a device that can introduce controlled-perturbations into the combustor to affect change on the instability is needed. And lastly, suitable control algorithms are needed to drive the actuators to obtain suppression of the instability.

Additionally, due to non-uniformities in the fuel-air mixing and in the combustion process, there typically exist hot streaks in the combustor exit plane entering the turbine. These hot streaks limit the operating temperature at the turbine inlet and thus constrain performance and efficiency. In addition, these hot streaks can be zones of increased formation of oxides of nitrogen (NOx). Elimination of the hot streaks can provide greater turbine life, can effectively increase the maximum combustor operating temperature and thus increase engine efficiency and performance, and can also contribute to emissions reduction.

Finally, the combustor flame temperature is largely a function of the combustion zone fuel-air mixture ratio. In order to minimize the formation of carbon monoxide (CO) and unburned hydrocarbons (UHC's), it is desirable to maintain a mixture ratio near stoichiometric. Unfortunately, mixture ratios near stoichiometric give high flame temperatures that lead to increased NOx formation. In order to simultaneously minimize CO, UHC, and NOx production, tight control over the fuel-air ratio is required throughout the operating range of the combustor.

Active Combustion Control (ACC), which consists of feedback-based control of the fuel injection, the fuel-air mixing process, and the staging of fuel sources, can provide an approach to achieving acceptable combustor dynamic behavior while minimizing emissions, and thus can provide flexibility during the combustor design process.

In recent years, there has been considerable activity addressing ACC. Government, academia, and industry research efforts, through analysis and the use of laboratory combustors, have shown the considerable potential for active control.[2,3,4,5,6,7,8] However, there is a need to focus on the unique challenges associated with aero-engines.[9] The NASA Glenn ACC Technology effort 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 maturity of active combustion control technology to advance to eventual demonstration in an engine environment.

NASA Glenn's effort in ACC includes three related efforts: Combustion Instability Control, Burner Pattern Factor Control, and Emission Minimizing Control. The long-term intent of this program is to combine the objectives of each control into a single intelligent fuel/air management system to provide low emissions throughout the engine operating envelope.

Prior publications have reported on NASA's earlier efforts in ACC.[10,11,12] This paper describes the most recent activity in Combustion Instability Control. Active suppression of high-frequency (>500Hz) combustion instability has been demonstrated on a NASA single-nozzle combustor rig. This is the first known successful demonstration of high-frequency combustion instability suppression in a realistic aero-engine environment.

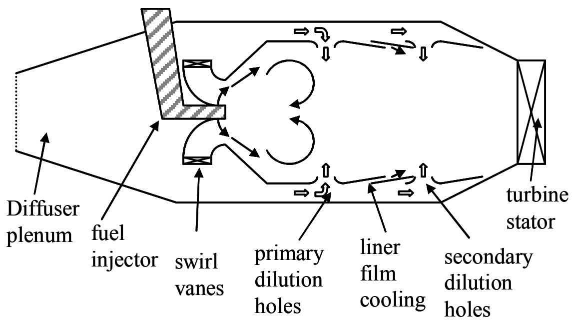
This paper provides a description of why combustion instability will be a significant problem in future aero-engines. Following this problem statement are details on the Combustion Instability Control approach. First, the single nozzle combustor rig on which instability control was demonstrated is described. Next, descriptions of the high-frequency fuel valve and the dynamic characterization of the fuel delivery system are given. The combustor dynamic model and combustion control algorithms are discussed. Next, results of experimental testing on the single nozzle combustor rig are shown. These results include open-loop actuator authority tests and closed-loop instability suppression tests. Finally, the remaining challenges to ACC are discussed along with recommendations for future work.

Combustion Instability in Low-Emissions Aero-Engine Combustors

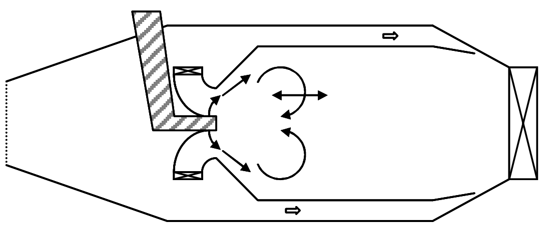
In its simplest form, a combustor is a forced acoustic resonator. The combustor cavity is bounded by the fuel injector at the front and the turbine stator at the back. The stator flow is normally choked, thereby presenting a hard boundary condition that reflects any pressure wave by reversing its phase. Thus, the length of the combustor corresponds roughly to a ¼ acoustic wave in its simplest mode.

The fuel injector serves as the main forcing function that drives the combustion chamber resonator. On conventional combustors, some 2 to 3% of the air pressure is used to accelerate the air through the injector to create strong turbulence in the form of shear layers and mixing jets. These rip apart the fuel spray and aid atomization and mixing of the fuel with the air. The energetic mixing processes produce strong pressure perturbations that have characteristic shedding frequencies. The pressure perturbations normally bleed off through viscous dissipation. But in the near field, these frequencies, their (sub) harmonics, and other secondary flows (such as vortex precession) can be distinctive and can modulate the air flow through the nozzle as well as feeding back into the fuel system, thus temporally modulating the overall fuel-air equivalence ratio going into the combustor.[13] This fluctuation affects the heat release which then in turn increases pressure modulation. If this created pressure wave then couples with the reflected wave from the back of the combustor in a timely fashion, the pressure oscillation can grow to unacceptable levels, creating aerodynamics problems for the compressor or turbine, or even causing mechanical damage to the engine.

Fortunately, two features of current combustors have stabilizing effects (**Figure 1a**). First, combustor liners are cooled with an air film. Pressure waves propagating through a region of severe temperature change, such as that encountered near the liner wall, will be partially reflected and partially refracted in a series of waves. This can break up a strong coherent wave front into a series of incoherent and weaker waves, thus making wave-building more difficult.



a) Conventional aero-engine combustor



b) Low-emissions aero-engine combustor

Figure 1. Features in lean-burning, low-emissions combustors that exacerbate combustion instability.

Second, the mixing zone, encompassing primary and secondary dilution air jets, also provides a similar function. Current combustors burn rich in the front and require dilution air to lower the temperature before the air enters the turbine. The mixing zone contains a constantly fluctuating field of temperatures and mixture composition. Coherent longitudinal waves propagating through this zone will be dispersed and broken into a series of weaker non-coherent waves that are dissipated through viscous action.

Finally, ignition stability relies upon the stable primary recirculation vortex to provide flame stabilization. The fuel spray is normally delivered in a swirling spray cone that forms a flow reversal in the center and brings the hot gas back in contact with the fresh charge. This vortex can move spatially, but the primary dilution jets anchor the vortex longitudinally.

In the development of lower-emission combustors, maintaining stability can become more problematic. The current trend is to move toward leaner combustion in the front end. By injecting all of the air at the front of the combustor, mixing it with the fuel uniformly, and then burning it all at once, a uniformly lower temperature process results that generates less pollutants. However, this takes away much if not all of the liner film cooling as well as the very non-uniform mixing zones (**Figure 1b**). Thus damping is reduced and more of the wave propagation remains coherent. In addition, the forcing function from the fuel injector may be increased as better and quicker fuel mixing requires stronger turbulence. Lastly, the lack of the anchoring effect of the primary dilution jets allows the primary recirculation vortices to move in space, thus potentially affecting the flame stabilization as well as setting up its own perturbation.

These stability issues have already become problematic in current ground-based power generation gas turbine burners due to their use of lean-burning. Careful design of the combustor and fuel injector geometry can steer the combustor operating point away from its unstable regions. Resonators can be designed into the combustor to change the undesirable resonance characteristics. And fuel and air feed systems can be designed not to interact with the combustors acoustics.

However, dealing with these stability issues in aero-engines is more challenging. Since aero-engines operate over a wide range of conditions compared to ground-based engines, geometrical provisions cannot feasibly be designed in to steer the operation point away from all of the potentially unstable regions. Compounding the problem, the smaller size of the aero-engine combustors also raises the characteristic frequencies proportionally, making active instability countermeasures more difficult to process. Aero-engines also use liquid fuels that require atomization and vaporization. Each of these additional sub-processes can have their own timescale that may couple into the other fluid flow phenomena and can also add convective time delays to the combustion process, further complicating control measures. Thus it is important to conduct instability control research in an environment that realistically represents these aero-engine stability challenges.

Combustion Instability Control Rig

In order to demonstrate Combustion Instability Control in a realistic aero-engine environment, an engine-scale, liquid-fueled single-nozzle research combustor rig has been designed, fabricated, and tested. The rig replicates an engine instability experience and operates at engine pressure and temperature conditions. The single-nozzle combustor rig has many of the complexities of a real engine combustor including an actual engine fuel nozzle and swirler, dilution cooling, and an effusion-cooled liner[10,11] (**Figure 2**). The research combustor rig was developed in partnership with Pratt & Whitney and United Technologies Research Center (UTRC). Experimental testing with the combustor rig is taking place at UTRC (**Figure 3**).

The single-nozzle combustor rig was operated at pressures, temperatures, and fuel-air ratios corresponding to three different engine operating conditions. For the conditions corresponding to the mid-power condition chosen for evaluation

(T3 = 770ºF, P3 = 200psia, fuel-air ratio = 0.03), test results established the existence of a combustion instability at approximately 566 Hz.

A comparison between the pressure amplitude spectrum in the engine and in the single-nozzle combustor rig at comparable operating conditions is shown in **Figure 4**. The combustor rig approximates the frequency and amplitude of the engine instability. However, the engine provides a narrower, more coherent frequency peak, and the rig exhibited a higher overall level of background noise. Still, the single-nozzle rig provides a suitable, realistic test environment for combustion instability control research.

In addition to the baseline rig configuration, the combustor rig was also changed to an extended configuration that placed a plenum made up of the ¼-wave spool pieces between the pre-diffuser and the fuel injector (see **Figure 3**). The intent was to try to make the instability stronger. However, this extended configuration, when operated at the same mid-power evaluation condition as the baseline configuration, showed a dramatically different instability frequency (273Hz) and magnitude[11] (**Figure 5**). Higher order harmonics are evident, and the peaks here are narrow and coherent as compared with the results for the baseline configuration.

Essentially, then, the combustor rig behaves like two different combustors. This has been a useful feature for research purposes. For example, before a high-frequency fuel actuator was available, this low-frequency configuration was used for some initial control investigations.[14] Also, in addition to the experimental work conducted by NASA, both configurations of the rig have been used as validation test cases for numerical simulation studies.[15] The remainder of this paper, however, will focus on controls studies conducted on the baseline, high-frequency configuration.

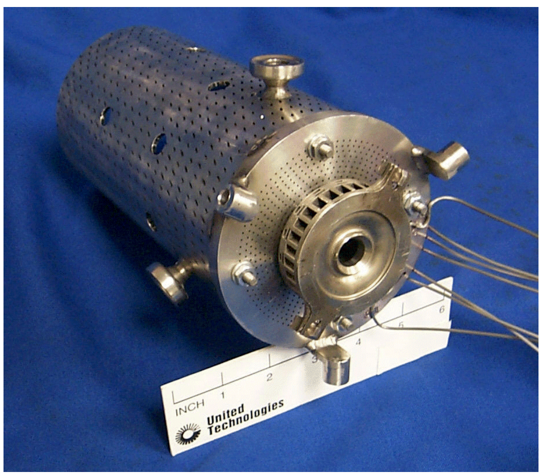


Figure 2. Combustor rig for combustion instability control research.
(*Photo courtesy United Technologies Research Center*)

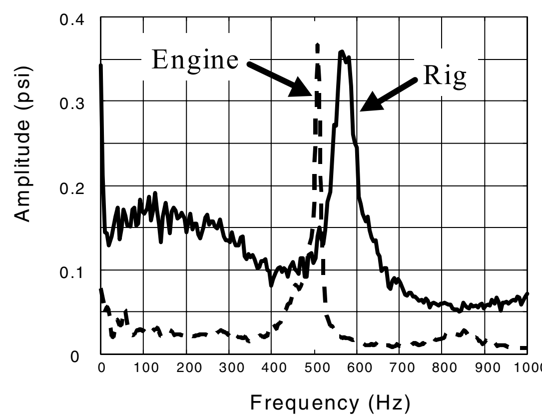


Figure 4. Comparison of engine and baseline combustor rig pressure amplitude spectra.[11]

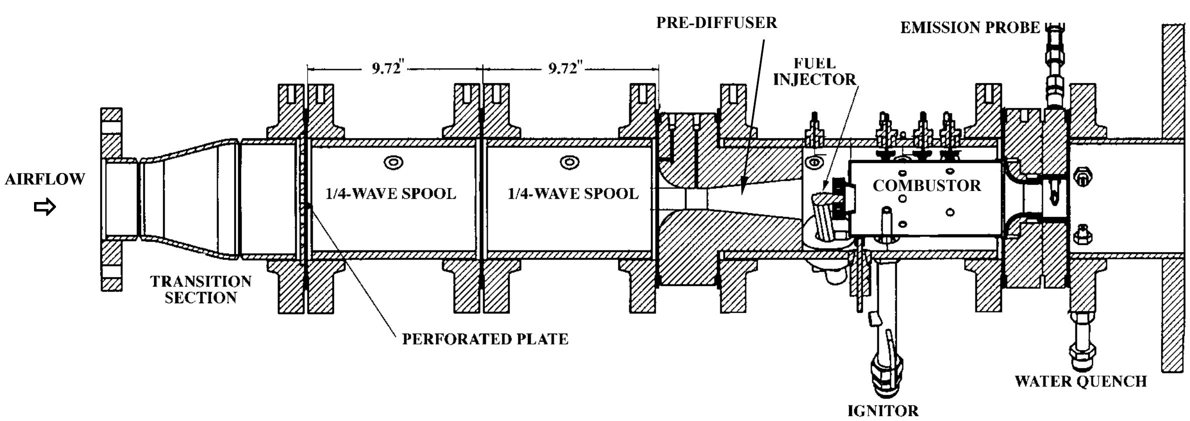


Figure 3. NASA single nozzle combustor rig as installed in the Jet Burner Test Stand at UTRC, baseline configuration.

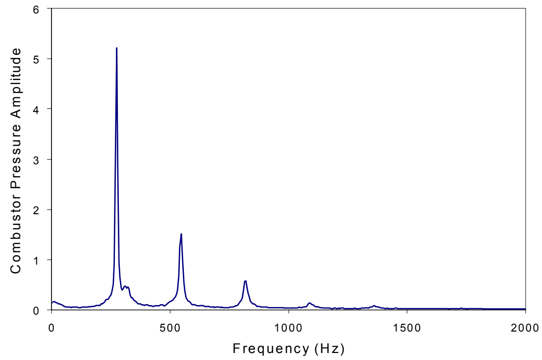


Figure 5. Measured pressure amplitude spectrum of unsteady combustion pressure for the single-nozzle rig in the extended configuration.[11]

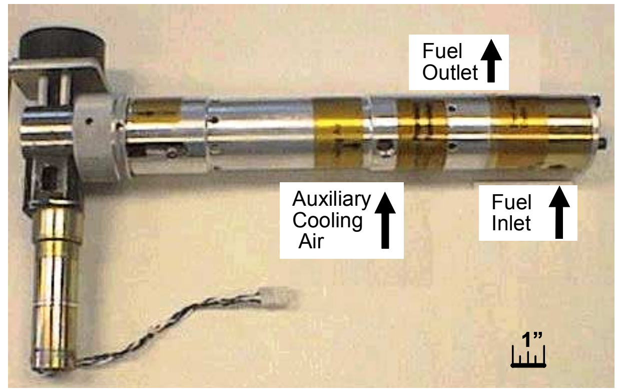


Figure 6. High-frequency fuel valve developed by Georgia Institute of Technology.

Actuation

In order to demonstrate instability control for the high-frequency configuration of the rig, a suitable fuel actuator was necessary. The specifications for the fuel valve are shown in **Table I**.

A number of fuel actuator concepts were investigated by NASA, and two were chosen for further development. Actuators were designed and fabricated by Georgia Institute of Technology (Atlanta, GA) and Fluid Jet Associates (Dayton, OH), and delivered to NASA. The high-frequency fuel valve from Georgia Tech was selected for near term experimental testing because of the maturity of the concept (**Figure 6**). The valve includes both a high-frequency flow modulation component and a mean-flow control component in a single device.

In order to provide a way to conduct steady-state and dynamic characterization of the capabilities of the fuel valve, a characterization rig was developed and fabricated at NASA (**Figure 7**). The rig is able to deliver up to 2gpm continuous fluid flow at up to 600psia. Initial testing with the rig has used water as the working fluid for simplicity. The rig is designed to provide an isolated test section for the valve in order to simulate the valve/feed-line/injector (VFI) environment encountered in combustor rig testing. Fluid pressure is supplied by a pump and regulated to the desired valve inlet pressure. An accumulator at the valve inlet provides isolation from the supply dynamics. Downstream from the valve, an orifice simulates a fuel injector and an air-filled volume emulates the combustor volume. The characterization rig test section can also simulate the VFI of an engine, although this has not been the immediate use. Further details on the actuator characterization rig will be contained in an upcoming NASA report.

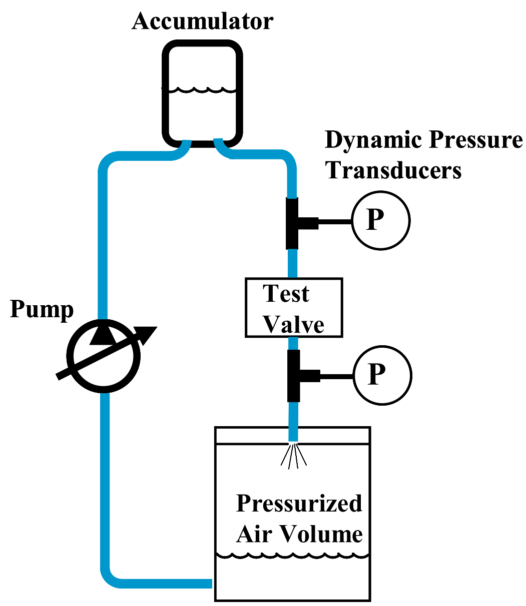


Figure 7. High-frequency fuel actuator characterization rig.

Table I. High frequency fuel valve specifications

Max Mean Fuel Flow Rate	500 lbm/hr
Max Inlet Pressure	600psi
Min Pressure Into Injector	300psi
Max Modulation Flow	± 40% of mean flow
Actuator Bandwidth	Minimum 600Hz
Flow Media	JP-8 jet fuel

Steady valve flow characterization was conducted first. This consisted primarily of mapping fuel flow vs. valve displacement in order to quantify the valve mean-flow control authority. This was also used later to optimize the valve position in order to maximize high-frequency fuel modulation amplitude. The relationship between valve displacement and flow for a fixed supply pressure are shown in **Figure 8.** The valve exhibits a well-behaved, monotonic increase in flow as valve opening increases. Also, once the valve reaches a displacement of approximately 0.015 inches, it is fully open and is no longer able to modulate the flow. In order to control the mean flow and also to modulate the dynamic flow, the valve position must be maintained in the approximately 0.01 inch range between 0.005 and 0.015.

For the dynamic characterization of the valve, dynamic pressure transducers were placed upstream and downstream of the valve, and downstream of the fuel injector. Initially, a minimum feed-line length (just long enough to incorporate the transducer) was used between the valve and the injector. This was done to allow direct measurement of the valve delta-P frequency response while minimizing the interaction with the feed line.

A sinusoidal input signal of ±1 volt was sent to the valve and the pressure drop across the valve was analyzed with respect to the input signal. Line lengths of 1 foot and then 2 feet were then inserted between the valve and the simulated injector orifice to simulate the effect of realistic line lengths as would be encountered when installed on a combustor rig or on an engine.

Figure 9 shows the transfer function between valve command and valve pressure drop. As can be seen from the transfer function, adding line length between the valve and the fuel injector decreases the resonance frequency of the fuel system. As line length increased from 0 to 2 feet, the resonance frequency decreased toward the 500-600 Hz combustor resonance frequency. Having this response singularity at or near the controller frequency of interest should be avoided. This can frustrate attempts to dynamically control the fuel mass flow variations as required for active instability control. Thus, there is a maximum installation fuel line length between the fuel valve and the injector above which the interaction between the fuel system and the combustor instability will become extremely complicated.

In an attempt to help explain the dynamic characterization results, and to attempt to predict the installed behavior of the VFI in the combustor rig, a dynamic model of the VFI was constructed. It was hoped that this simulation would provide a prediction of the fuel mass-flow variations that the valve could impose upon the combustor. Preliminary results concerning the simulation method used were promising. However, there were some difficulties in precisely predicting the installed behavior due to uncertainties in the fluid air content and also uncertainties about the internal valve geometry. NASA will be continuing research in this area in order to refine the predictive capabilities of the simulation.

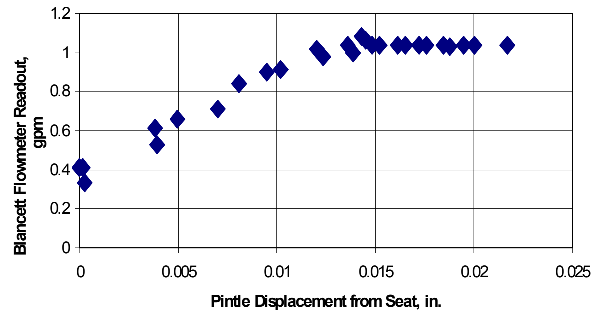


Figure 8. Steady-state valve operation showing flow versus valve displacement.

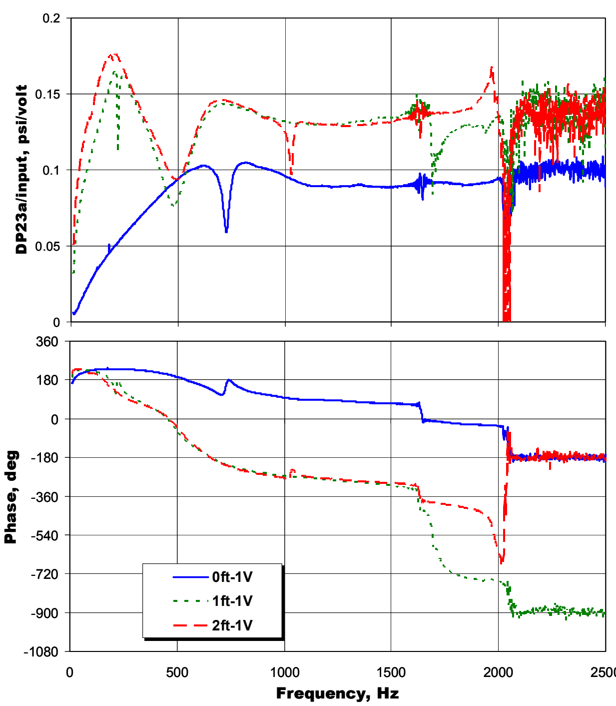


Figure 9. Dynamic valve response showing the transfer function between valve commanded voltage and valve delta-P for three different feed-line lengths.

In the end, the valve authority --that is, the amount that the valve is able to perturb the fuel flow and thus the combustor pressure—was determined experimentally in the combustor rig. The valve was set to a nominal steady-opening based on the characterization rig results. Open-loop, sinusoidal valve command voltage variations were provided to the valve. The combustor rig was operated at conditions that gave a ~530Hz combustion instability. The frequency and amplitude of the valve command voltage were varied, and combustor pressure monitored. Representative results are shown in (**Figure 10**). For a 300Hz, ±2.5V (maximum allowed) valve command, the combustor rig dynamic pressure is shown to have a sharp response to the valve perturbations. The pressure response is imposed on top of the combustion instability pressure variations. Similar results are shown for a 600Hz valve command.

There was some initial concern that, even if the valve was able to impose large fuel mass-flow variations, the high-shear flows and pre-filming features of the high performance engine fuel injector would reduce actuator authority. However, these tests confirmed that sufficient authority (on the order of the instability amplitude) was available.

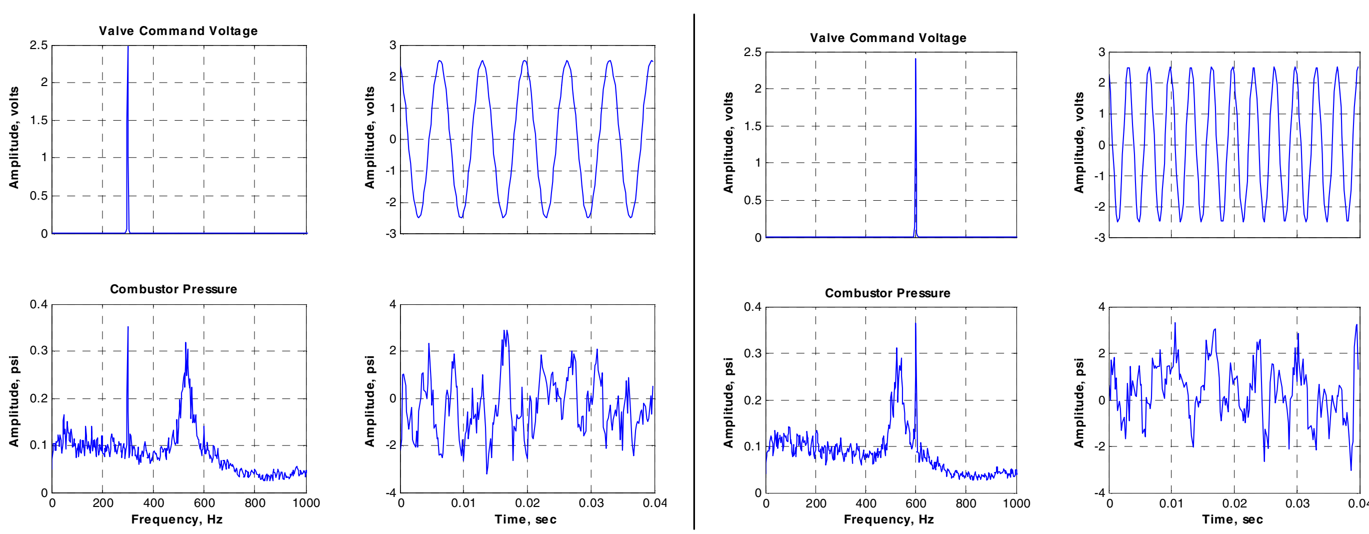
Control Algorithms

In order to achieve closed-loop suppression of the combustion instability, two alternative control methods were developed. These control methods were formulated to deal with the large wideband combustor noise, severe time-delay, and randomness in phase associated with the combustor thermo-acoustic pressure oscillations.

The first control method is based on an adaptive, phase-shifting approach. This controller senses the combustion pressure, calculates the average power in the pressure oscillations, and adapts the phase of the valve-commanded fuel flow variations in order to reduce the power in the pressure oscillations. A fast-acting phase-adaptation algorithm converges to the phase region that causes cancellation. By constantly dithering the phase within that phase region, the algorithm rapidly adapts to randomness in the instability pressure, especially that due to background combustor noise. The algorithm also provides a slower, more gradual adaptation of the controller gain. Further details on the Adaptive Sliding Phasor Averaged Control method can be found in the references.[12,16]

The second control method is a model-based approach. This controller, like the first method, also senses combustion pressure. The method combines a "multi-scale" (wavelet-like) analysis and an Extended Kalman Filter observer to predict (model) the time-delayed states of the thermo-acoustic combustion pressure oscillations. The commanded fuel modulation is calculated from a predictive (damper) action based on the predicted states, and an adaptive, tone-suppression action based on the multi-scale estimation of the pressure oscillations and other transient disturbances. The controller attempts to automatically adjust the gain and phase of these actions to minimize time-scale averaged variances of the combustor pressure. Further information on this control approach is also in the references.[17]

Both control methods were initially evaluated against reduced-order oscillator models of the combustor pressure in order to verify basic functionality. To provide a better-fidelity validation of



a) 300 Hz **b) 600 Hz**

Figure 10. Combustor pressure response to commanded valve perturbations shows open-loop actuator authority.

controller performance prior to rig testing, both controllers were then tested against a Sectored 1-D model of the combustor rig.[18] This model utilizes the one-dimensional (or quasi-one-dimensional) Navier-Stokes equations as their basis. In addition to mass, momentum, and energy equations, there are also one or more species transport equations with associated relatively simple reaction and heat release equations. The model efficiently handles the abrupt changes in cross-section typical of combustors. The modeling approach was able to successfully reproduce the self-excited instabilities in the NASA single nozzle combustor rig, and provided a more-realistic evaluation testbed. Documentation on the use of this model for control evaluation will be published at a future date.

Experimental Demonstration

The high-frequency fuel valve and developed control methods were used to demonstrate closed-loop instability suppression in the NASA combustor rig at UTRC. The rig was operated at the conditions shown in **Table II**, and exhibited roughly the instability behavior shown in **Figure 4**. The experimental setup for the demonstrations is shown in **Figure 11**. Combustor pressure was sensed about 2 inches downstream of the fuel injector. The control algorithms were implemented on a dSpace real-time processor. The fuel flow was dynamically controlled via the high-response fuel valve.

For evaluation of each controller, the baseline operating condition was established first, and open-loop perturbations injected in order to verify actuator health and authority. The closed-loop controller was then engaged. Two sets of tests were run with both controllers being evaluated during each test. During the first test, a reduction in instability amplitude was observed for both control methods (**Figure 12**). However, for both control methods, low frequency (<30Hz) oscillations were seen in the combustor pressure frequency spectra. It was suspected that these low frequency oscillations were due to interactions between the instability controller and the valve mean-flow control or some other low-frequency phenomena.

Table II. Combustor rig operating conditions

Inlet Pressure, P3	175 psia
Inlet Temperature, T3	775 ºF
Air flow	4 lbm/s
Fuel flow	450 lbm/hr

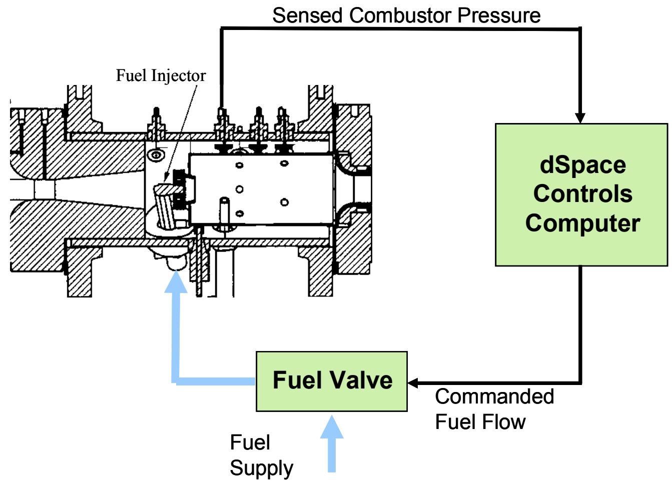
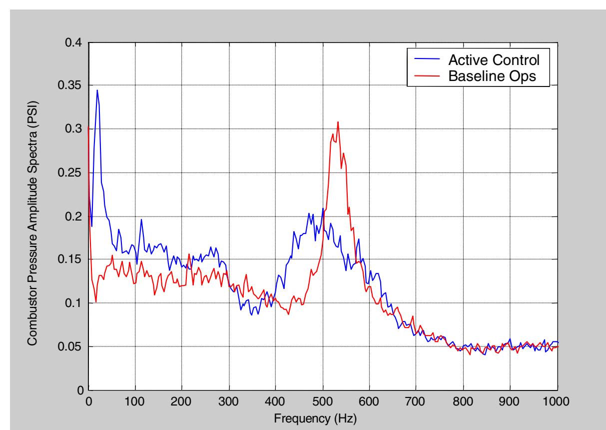
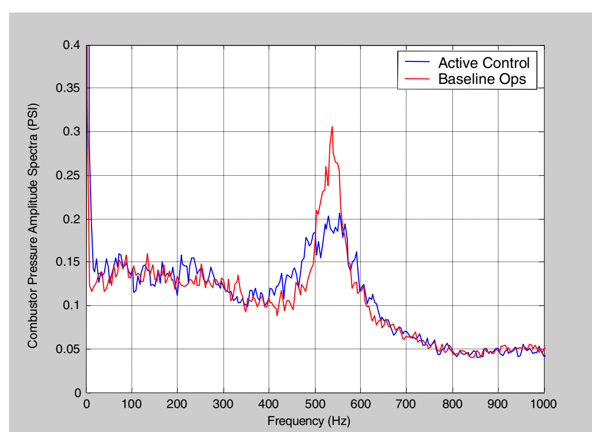


Figure 11. Experimental setup for closed-loop combustion control demonstration.



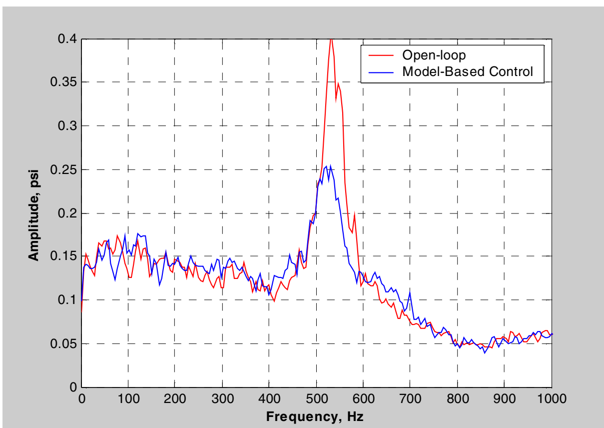
a) Model-based control method



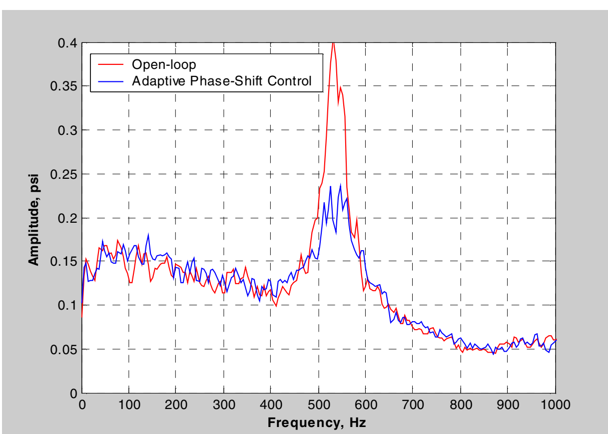
b) Adaptive phase-shifting control method

Figure 12. Combustor pressure amplitude spectra for initial active combustion instability control test showing closed-loop instability suppression for both control methods.

For the second set of tests, additional filtering was added to the controllers to reduce this interaction. The results, shown in **Figure 13,** demonstrated that this approach was effective in greatly reducing the low-frequency oscillations. As can be seen, both control methods were able to identify the instability frequency and reduce the amplitude by about 30%. This was done without inducing secondary peaks at adjacent frequencies as has been seen in other combustion instability control studies (e.g. [5,6,8,14]). Analysis of the data is continuing to explore why this was the case. Additional testing of the control methods, especially with a different combustion instability might also help sort out if this result was configuration dependent.



a) Model-based control method



b) Adaptive phase-shifting control method

Figure 13. Combustor pressure amplitude spectra for second test showing 30% reduction in instability pressure amplitude and improved low-frequency behavior.

Concluding Remarks and Future Plans

Combustion instability suppression has been shown for a high-frequency (>500Hz) combustion instability. This is the first known demonstration of combustion instability control in a realistic aero-engine environment. In order to demonstrate combustion instability suppression, a realistic combustor rig which emulates an engine instability experience was developed. Two high-frequency fuel actuator concepts were developed and the more mature concept was used for the current experiments. Steady-state and dynamic characterization of the valve's ability to modulate fuel flow was done in a rig developed for that purpose. Open-loop fuel modulation tests in the combustor rig showed adequate actuator authority. Two control methods, one based on adaptive phase shifting and one model-based, were developed and evaluated using reduced order combustion instability models. And finally, closed-loop control testing in the combustor rig showed the ability of both control methods to reduce the combustor pressure at the instability frequency by about 30%.

Future plans are to integrate the combustion instability control methods with pattern factor control and fuel injection zone control methods using harsh environment sensors[19] in an advanced, extremely low-emissions combustor concept (e.g. [20]). The goal is to demonstrate that active combustion control can enable an intelligent combustor capable of ultra-low emissions throughout the aero-engine flight envelope.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2003	Technical Memorandum

4. TITLE AND SUBTITLE

Active Control of High Frequency Combustion Instability in Aircraft Gas-Turbine Engines

5. FUNDING NUMBERS

WBS–22–708–28–13

6. AUTHOR(S)

John C. DeLaat and Clarence T. Chang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–14169

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2003-212611
ISABE–2003–1054

11. SUPPLEMENTARY NOTES

Prepared for the 16th International Symposium on Airbreathing Engines sponsored by the International Society for Airbreathing Engines, Cleveland, Ohio, August 31–September 5, 2003. Responsible person, John C. DeLaat, organization code 5530, 216–433–3744.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Active control of high-frequency (>500 Hz) combustion instability has been demonstrated in the NASA single-nozzle combustor rig at United Technologies Research Center. The combustor rig emulates an actual engine instability and has many of the complexities of a real engine combustor (i.e. actual fuel nozzle and swirler, dilution cooling, etc.). In order to demonstrate control, a high-frequency fuel valve capable of modulating the fuel flow at up to 1kHz was developed. Characterization of the fuel delivery system was accomplished in a custom dynamic flow rig developed for that purpose. Two instability control methods, one model-based and one based on adaptive phase-shifting, were developed and evaluated against reduced order models and a Sectored-1-dimensional model of the combustor rig. Open-loop fuel modulation testing in the rig demonstrated sufficient fuel modulation authority to proceed with closed-loop testing. During closed-loop testing, both control methods were able to identify the instability from the background noise and were shown to reduce the pressure oscillations at the instability frequency by 30 percent. This is the first known successful demonstration of high-frequency combustion instability suppression in a realistic aero-engine environment. Future plans are to carry these technologies forward to demonstration on an advanced low-emissions combustor.

14. SUBJECT TERMS

Aircraft engines; Engine control; Combustion control; Combustion stability; Control

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	