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Combustion Dynamics and Control in Liquid-Fueled Direct Injection Systems

John Magill and Matthew Bachmann
Physical Sciences Inc.
20 New England Business Center
Andover, MA 01810

Keith McManus
General Electric Corporate Research and Development Center
Niskayuna, NY 12309

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COMBUSTION DYNAMICS AND CONTROL IN LIQUID-FUELED DIRECT INJECTION SYSTEMS

John Magill* and Matthew Bachmann†
Physical Sciences Inc.
Andover, MA 01810

Keith McManus‡
General Electric Corporate Research and Development Center
Niskayuna, NY 12309

Abstract

Experiments evaluating the performance of a closed-loop combustion stabilization algorithm show that the method can reduce the magnitude of pressure oscillations in a liquid-fueled combustor by more than 50%. This paper describes the gas-turbine type combustor facility used for the experiments, associated instrumentation, unsteady combustion experiments, and the control scheme employed to suppress the natural thermo-acoustic instability. The combustor exhibits a natural instability at 140 Hz, the result of dynamic coupling between the combustor pressure field and the combustion heat release. Experiments to characterize the influence of operating parameters on the behavior of the instability are described. The control algorithm, amplitude-based pulse-width modulation, is used to modulate flow through one stream of a dual-passage fuel injector at such a phase that the instability amplitude is reduced. The paper concludes with a discussion of the control experiments, showing that the algorithm was successful in reducing the pressure oscillation.

Introduction

This paper describes a set of experiments in which an algorithm tested previously on an atmospheric-pressure tube combustor is applied to a gas turbine-type combustor. The algorithm uses pressure feedback to modulate fuel flow, and hence heat release, to suppress instabilities. Because the fuel must be modulated at high frequencies, an important aspect of this work was an investigation of the unsteady flow characteristics of the nozzles.

Recent design trends in gas turbines have led to more compact combustion systems with increasingly high operating pressures and energy release rates. In addition, land-based turbines for power generation have come under strict emissions regulations stimulating the design of lean-premixed burners. Enhanced fuel-air mixing methods, allowing shorter residence times, and improved materials, requiring less cooling air, have enabled much of the progress in this area. However, as a consequence of some of these design changes, combustion dynamics has become more problematic and has severely limited the operability of some new turbine systems. Combustion dynamics can manifest itself through the production of large pressure and energy release fluctuations.[1,2] In extreme cases pressure fluctuation levels greater than 30 psi (peak-to-peak) have been measured. Allowable limits for fielded systems are in the range from 3 to 5 psi. As an alternative to conventional passive, or trial-and-error design changes for combustion dynamics suppression, active control techniques are being examined.[3-6]

This paper describes work concerning the development and demonstration of a control system for combustion dynamics suppression on a laboratory-scale rig. The control method incorporates main fuel flow modulation as an actuation technique. The fuel flow modulation command is based on a feedback signal from a sensor placed directly on the combustor wall. This technique was successfully used to mitigate an instability to a tube combustor, as was described in an earlier paper.[5,6]

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*Principal Engineer, Member AIAA
†Summer Intern
‡ Mechanical Engineer, Member AIAA

Because fuel flow must be modulated at high frequencies, an important aspect of this work was an investigation of the unsteady flow characteristics of the fuel nozzles. The paper describes the fuel system and the non-reacting spray measurements, along with the remainder of the combustor and its subsystems. The natural (uncontrolled) behavior of the combustor and its response to open loop forcing are explored in a discussion of the initial characterization experiments. The final sections describe the closed-loop control algorithm and its success at reducing the combustor instability.

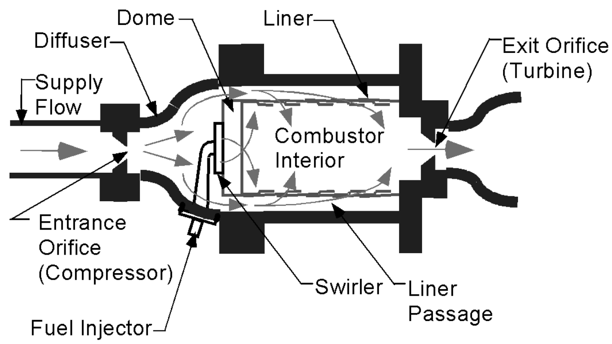


Figure 1. Combustor cross-section - top view.

Experimental Combustor Facility

The combustion control strategies previously tested on a tube combustor were evaluated on a larger facility designed and built specifically for examining combustion dynamics in gas turbine configurations. The system consists of four main components: 1) a 2400 psi pressure vessel which is charged with ambient air using a compressor capable of delivering breathing quality air; 2) a 250 kW immersion-type electric heater capable of heating the air flow to maximum of 530 K; 3) test section; and 4) exhaust system. The system has been designed to provide a maximum mass flowrate of 1 kg/s at 50 atm and 530 K. The facility is designed to accept a variety of test sections including those appropriate for combustion dynamics experiments and for applying optical diagnostics. The test section of the facility is versatile and can accept a variety of fuel injector and combustor dome configurations.

The combustor test section is shown schematically in Figure 1. The chamber is designed to replicate the acoustic and aerothermal conditions in a typical gas turbine combustor. The design point operating conditions are given in Table 1. As shown in Figure 1, flow enters the diffuser through an inlet orifice intended to provide an acoustic boundary similar to that provided by the compressor exit in a full engine configuration. From the diffuser, flow is split between the dome swirler and the liner passages. Two sides of the combustor are lined, simulating the inner and outer liner walls of an annular combustor. The liner walls are louvered to provide a cooling film, and larger holes in the liners feed dilution air to the combustion zone. Approximately 25% of the total airflow enters through the dome and swirler with the remaining 75% used for dilution and cooling flows.

Table 1. Design Parameters

Chamber pressure	202 Kpa (15 psig)
Supply pressure	1.35 Mpa (180 psig)
Air mass flow	0.25 Kg/s (0.55 lbm/s)
Fuel mass flow	12.5 Kg/hr (28 lbm/hr)
Equivalence ratio	0.2
T_{inlet}	500 K (450 F)
T_{exit}	1000 K (1350 F)
Volume ratio	0.95
Inlet orifice area	1.13 cm^2 9.18 $in.^2$
Exit orifice area	9.62 cm^2 1.48 $in.^2$

The chamber is fitted with a 1.75 in. window and several instrumentation ports. Many of the ports are aligned with dilution holes to provide optical access to the interior of the combustor. A spark ignitor is used for an ignition source and protrudes through the lower combustor wall.

Fuel Injectors

Tests were performed using two different fuel injectors: one with a single-stream nozzle and the other incorporating a dual-stream nozzle. Both of the injectors shared the same swirler and dome hardware. The single-stream unit was used in preliminary experiments where the combustion process was controlled by modulating the entire fuel stream entering the combustor. The dual-stream unit was used in later experiments to evaluate combustion control strategies wherein only a part of the total fuel flow was modulated.

The single-stream nozzle was a simplex atomizer. The dual-stream nozzle has separate primary and secondary fuel streams. The primary stream flows through a simplex atomizer located at the center of the nozzle head. The secondary stream flows through a series of orifices placed around the periphery of the nozzle head. The fuel passing through the secondary orifices exits them as coherent jet streams which then impinge on an air swirler cup. The swirler cup acts as an airblast atomizer.

A solenoid valve was closely coupled to the single-stream injector, and later to the primary section of the dual-stream injector, to provide fuel flow modulation. The valve, a General Valve Series 9, was driven by a GV Iota One valve driver. This driver is able to pulse the valve at up to 500 Hz.

The fuel flow modulation characteristics were monitored using a fast-response pressure transducer (PCB Model 112B). The transducer was mounted on the nozzle stem just downstream from the solenoid valve. In the case of the single-stream nozzle, a purge line was used to bleed air from the fuel nozzle stem to maintain incompressible flow characteristics in the fuel system.

Non-reacting experiments were conducted to characterize the nozzle flow characteristics. The test arrangement is shown in Figure 2. The frequency response was measured by applying a train of pulses at varying frequency to the pulsed valve, and observing the flow rate of fluid in the jet cone. For safety reasons, these tests were conducted using a water spray. Cone flow rate fluctuations were detected optically by passing a HeNe laser beam through the spray and onto a silicon photodiode. Variation in the spray density along the beam propagation path causes variation of the extinction of the laser beam and this appears in the photodetector output as a signal modulation.

Both the single- and dual-stream nozzles were tested. Since the dual-stream nozzle was used for the closed loop control experiments described in this paper, only those results are presented here.

Initial tests were conducted at fixed frequency to evaluate individual pulse shape characteristics at different frequencies. Figure 3 shows example pulse shapes from two cases where the nozzle flow was modulated at 100 and 300 Hz. In the figures, the command pulse from the function generator is indicated.

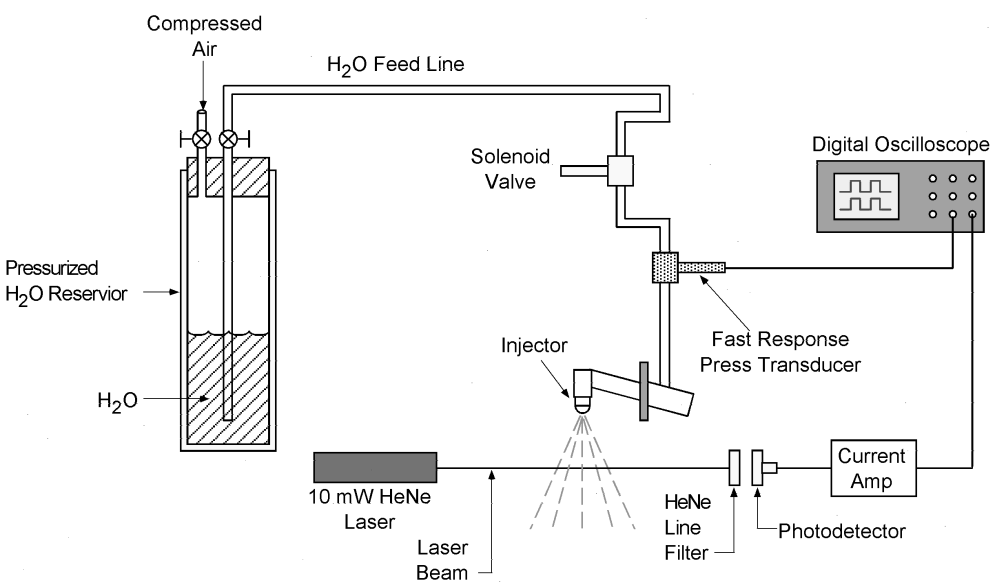
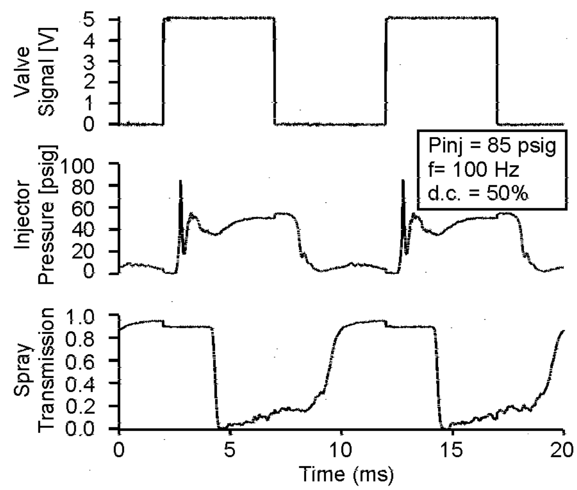
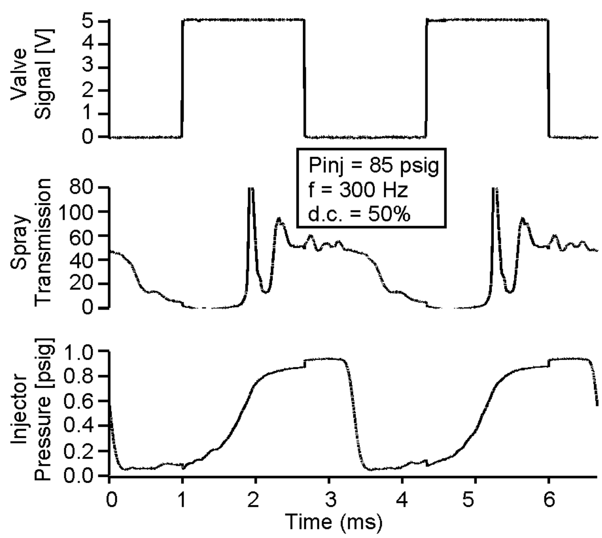


Figure 2. Optical measurement of fuel injector time response characteristics.



(a)



(b)

Figure 3. Time traces of photodetector signals during nozzle characterization. (a) 100 Hz; (b) 300 Hz.

The duty cycle in these examples was 50%. The signatures from the pressure transducer and the optical extinction sensor indicate that the flow modulation produces a coherent fluctuation in the atomizer feed pressure and the spray cone opacity. Additionally, the strength of the modulated signals suggest that the fuel flow is halted completely during much the cycle portion where the valve is closed.

The frequency response was measured by applying a train of pulses at varying frequency to the pulsed valve, and observing the flow rate of fluid in the jet cone. The frequency of the flow pulses was swept from 10 to 500 Hz during a sweep time of 8.1 seconds. The valve command and photodetector outputs were sampled at 1 kHz. The photodetector was amplified and low-pass filtered at 500 Hz to prevent aliasing. The frequency response curve was constructed by computing the cross-spectra of the valve command and detector output. Four sweeps were averaged to compute the curves. The frequency response of the injector for two fuel pressures can be found in Figures 4 and 5. The logarithmic magnitude scale is referenced to the gain at 10 Hz. In both cases, the coherence between valve and sensor is strong over nearly the entire range from 10 to 500 Hz.

Both magnitude plots contain interesting structure which appears at first to be a series of harmonics. A more careful investigation revealed that this structure in the frequency response plot is due to an oscillation (about 2 Hz) in the fuel supply. Since this oscillation is present during the frequency sweep, it appears as a frequency-dependent phenomenon. However, repeated runs conducted under the same conditions exhibit the peaks and valleys at different frequencies, indicating that the oscillation is not correlated with the frequency sweep. This problem appears to be an artifact of the experimental setup, which contains two spring-loaded valves. Since the nozzle will be operated in the rig using an entirely different fuel supply system, more experiments will be needed later to accurately assess its frequency response. These experiments were, however, sufficient to show that the injector has adequate bandwidth for controlling combustion instabilities in the range of frequencies where they are expected (approximately 100 to 500 Hz).

The phase plots for the 80 and 120 psig supply pressures have different slopes. Some of the phase can be attributed to transport delay since the phase varies with pressure and hence with flow rate. The slopes do not vary with the square root of the pressure, as might be expected if the phase delay were due entirely to transport lag. Other delays, such as in the valve response, must play a part in producing the overall phase lag.

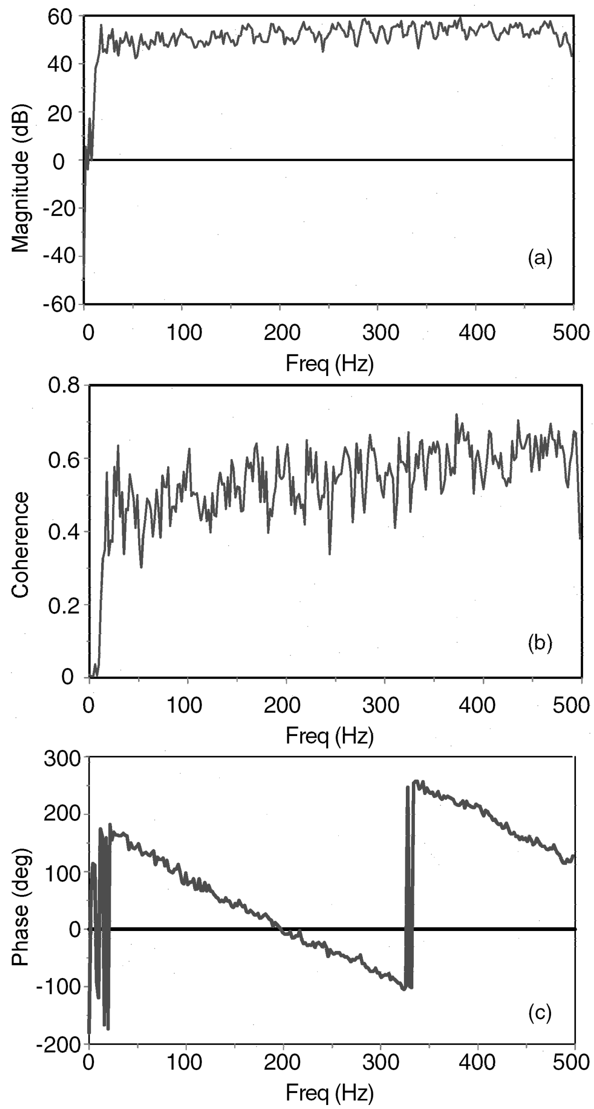


Figure 4. Frequency response of injector with 80 psig water supply.

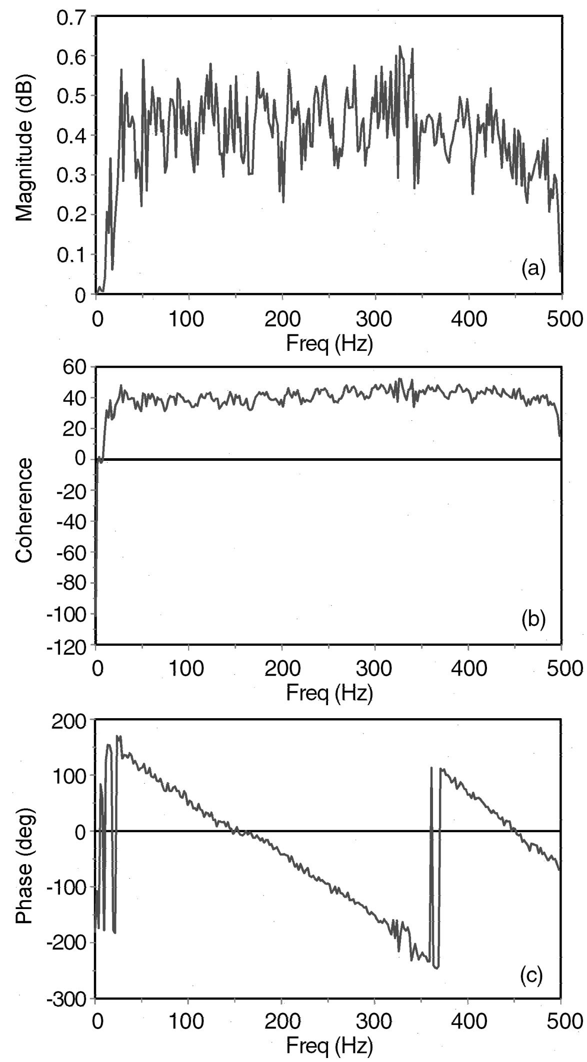


Figure 5. Frequency response of injector with 120 psig water supply.

Combustor Instrumentation

The combustor has been equipped with extensive high-bandwidth instrumentation to facilitate combustion dynamics measurements (see Figure 6). A six-channel flame emission sensor was incorporated into the combustor test section to monitor emission fluctuations at three different locations along the longitudinal axis of the combustor. Several pressure sensors have been installed to measure the unsteady static pressure in the test section and pressure oscillations in the fuel supply upstream of the fuel injector nozzle.

Six-Channel Fiberoptic Emission Sensor

Collection optics are mounted on three ports on the side of the combustion chamber on the horizontal center line at approximately 86, 111, and 160 mm from the fuel injector tip. Each port consists of a 12.7 mm diameter compression type fitting containing a quartz window seated with graphite gaskets. The line of sight for each port is perpendicular to the centerline of the combustion chamber and the viewing cone angle is approximately 12 deg. Attached to each fitting with an aluminum coupler is a collimating beam probe, (Oriel, Part # 77645) that collects light and passes it to a bifurcated optical fiber bundle (Oriel, Part # 77533).

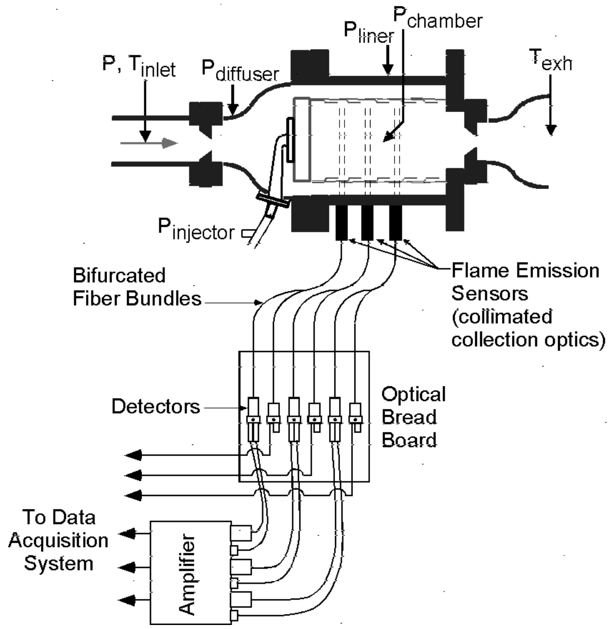


Figure 6. Instrumentation for combustion dynamics experiments.

The fibers in the bundle are made of glass which transmits light from 400 to 1400 nm, and the branches of the bundle are comb randomized to produce evenly divided outputs.

All six exit legs of the fiber bundles are mounted with collimating beam probes. One leg of each set is then fitted to a high-speed photo detector (Thorlabs, Part # DET200), which has a spectral range of 200 to 1100 nm for broadband emission measurement. The other leg of each set is attached to a photo multiplier tube (Hamamatsu, H5783-01) with a radiant sensitivity at 420 nm of 15 µA/nW with a control voltage of +0.8 V. Between the collimating probe and the detector is a 25.4 mm diameter, 430 nm bandpass filter (Corion, Part # P-10-430-F) with a bandwidth at full-width half-max (FWHM) of 10 ± 2 nm.

The collimating probe for all of the detectors are held in place using lens tubes and adapters and are focused to fill each detector. A relative calibration of the system was performed by placing the inlet collimating tube for each bundle at a fixed distance from a tungsten lamp and recording the output voltages for the photo diodes and the output and gain voltages for the photo multipliers with various neutral density filters in place. All six detectors are mounted on a 12 x 12 in. breadboard which provides rigid mounting for the detectors while allowing freedom of movement for the entire unit due to the use of fiber optic cables.

Fast-Response Pressure Sensors

Pressure sensors have been installed to aid in determining the acoustic mode structure in the combustor test section during combustion instability. In the current test section configuration, pressure fluctuations are measured in the diffuser, on the combustor wall, and on the pressure casing behind the liner. Also, a fast response pressure transducer has been inserted in the fuel supply system to monitor pressure fluctuations, both naturally occurring and forced, just upstream of the fuel injector inlet.

The signals from the instrumentation were acquired using a high-speed data acquisition system. Typical sample rates were 2 kHz per channel. The data were subsequently analyzed using signal analysis codes to compute statistical quantities and frequency spectra.

Evaluation of Natural Combustor Instability

The combustor dynamic behavior was first characterized over a range of operating conditions to identify the effects of parameters such as equivalence ratio, chamber pressure, and heat loading on stability. Spectral analysis and total RMS pressure fluctuations were used to characterize the instabilities at each condition. The extensive analysis described below was performed using the single pressure-atomized nozzle.

Figure 7 shows typical pressure spectra. The three curves in the plot represent operation at various equivalence ratios at a fixed fuel flow rate. The equivalence ratio was varied by changing the supply pressure and hence the air mass flow. An instability at 140 Hz is observed at all three operating conditions. They show one of the consistent trends observed: that the instability peak increases in magnitude with equivalence ratio.

Figure 8 shows the effects of mass flow on the RMS fluctuation level in the chamber pressure when the equivalence ratio is held constant. The magnitude of the instability is shown to increase with air mass flow up to about 210 g/s, and remains somewhat flat

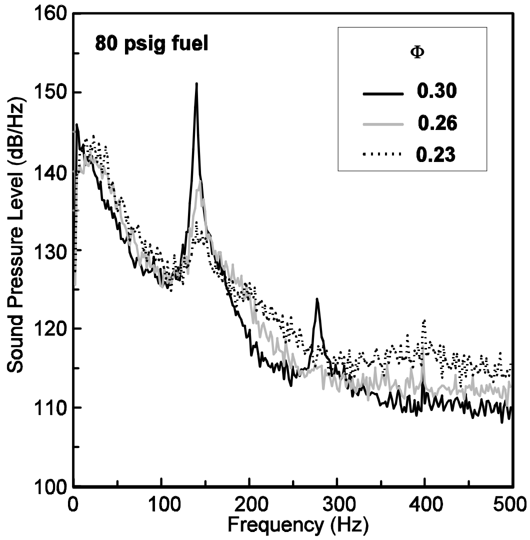
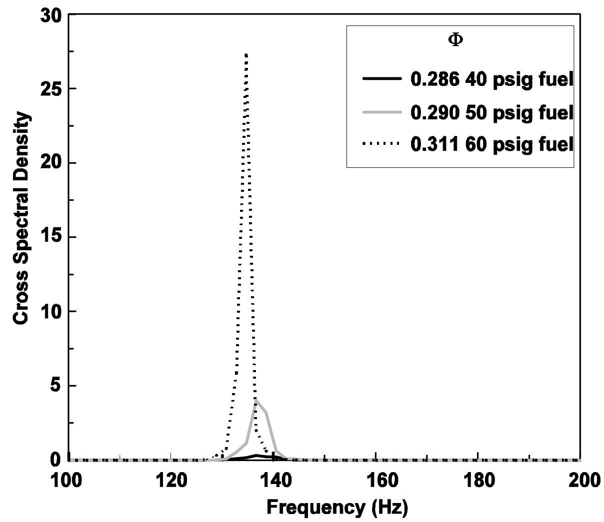


Figure 7. Effect of equivalence ratio on combustor pressure spectra.



(a)

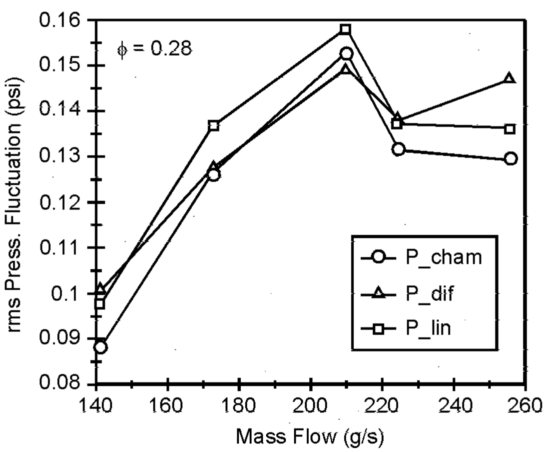
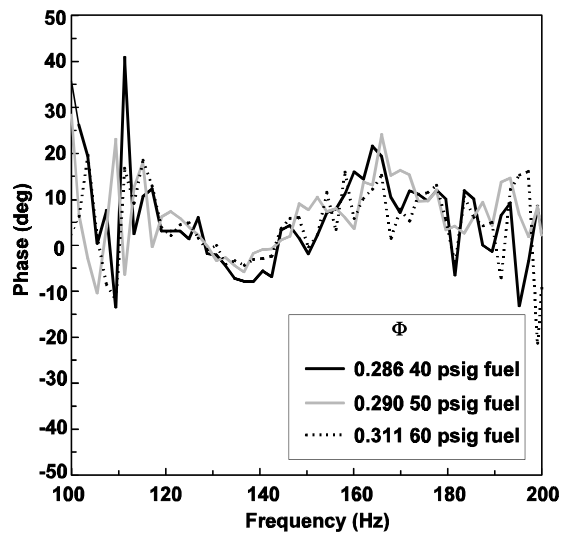


Figure 8. Effect of air mass flow on rms chamber pressure.



(b)

Figure 9. Cross-spectral density (a) and relative phase (b) of pressure and emission signals indicate increased coupling at high fuel pressures.

thereafter. It must be recognized that this is not a pure mass flow effect, since the chamber pressure increases as the mass flow increases.

Figure 9 shows that the dominant instability mode is indeed the result of coupling between heat release and the pressure field. Figure 9a shows that the cross-spectra between the chamber pressure and the CH* emission signal contains a single strong peak. This cross-coupling peak increases with fuel flow when the equivalence ratio is held approximately constant. This is consistent with a trend observed in the pressure fluctuations showing the the magnitude of the instability goes up with heat loading. Figure 9b further validates the cross-coupling behavior as it shows that the pressure and heat release are in phase at the dominant instability frequency (140 Hz).

Figure 10 contains a map of the stability properties over the range of tested conditions. The map shows

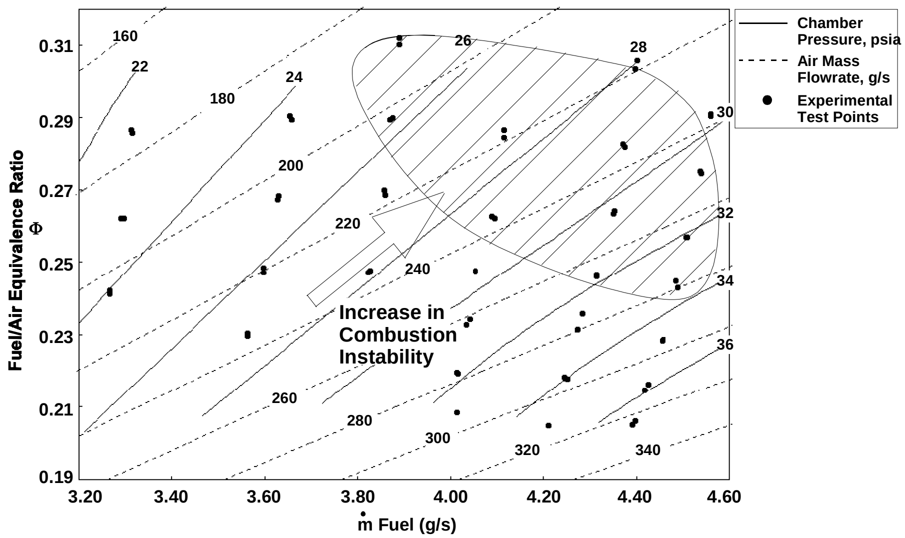


Figure 10. Combustor stability map.

that the instability is strongest at more aggressive operating conditions; that is, high chamber pressure, fuel flow, and equivalence ratio. The upper right quadrant of the map was the region later used for closed-loop control experiments.

Later experiments used the dual-flow fuel injector in place of the single pressure-atomized nozzle. The dual-stream injector produced a much stronger instability. Resources did not permit a complete combustor characterization with the dual-flow injector. However similar trends were observed in the relationship between operating parameters and instability characteristics. Subsequent open- and closed-loop control experiments utilized the dual-flow injector because it permitted modulation of the heat release without completely shutting off the fuel stream.

Open-Loop Forcing

The means of suppressing pressure oscillations was to modulate heat release via fuel flow. The next set of experiments thus examined the influence of unsteady fuel flow on unsteady pressure. The solenoid valve upstream of the primary nozzle was pulsed at various frequencies. The operating condition was chosen so that the natural instability is relatively weak, allowing the forcing to dominate the spectra.

Figure 11 shows the pressure spectra when the fuel is pulsed at 110 Hz. The strength of the driven pressure oscillation increases with the pulse duty cycle. Other spectra show spectral peaks appear at modulation frequencies up to 300 Hz, although both harmonics and sub-harmonics may appear.

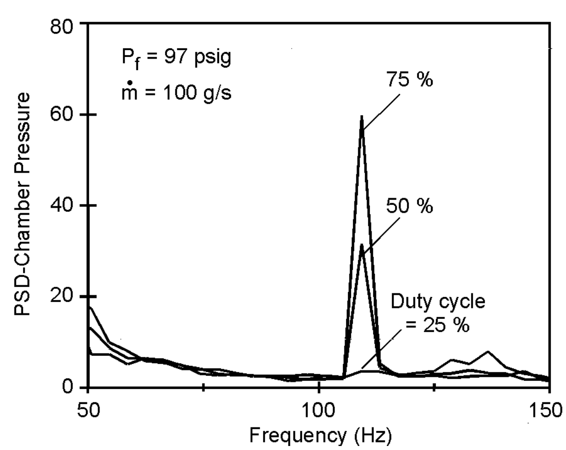


Figure 11. Chamber pressure spectra in open-loop forcing for three duty cycles.

As Figure 12 indicates, both pressure and emission sensors indicate a linear phase response as frequency increases. This indicates a constant time delay between the pulse command and the combustion state variables. The emission sensor lags the pulse by 3.7 ms, while the pressure lags by 7 ms, nearly a complete cycle.

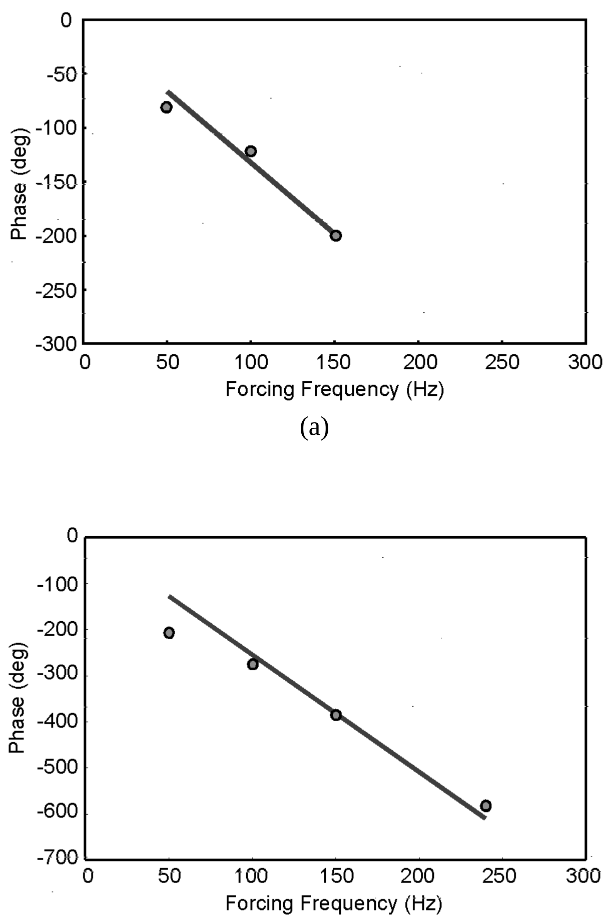


Figure 12. Emission (a) and chamber pressure (b) phase lag relative to forcing signal.

Closed-Loop Control

Algorithm

The closed loop control algorithm applied to this combustor is similar to the amplitude-based pulse width modulation scheme previously used by the present authors to control an instability in an atmospheric-pressure tube combustor. Ideally, a continuous modulation of fuel amplitude would be the best choice for control, so that a heat input equal in amplitude and out of phase with the natural instability would be used to quiet the combustion.

However, no injector permitting such modulation of a liquid spray is presently available. In stead, a solenoid valve is employed to completely turn the fuel stream on and off. Fuel pulses are generated which are proportional in time, and hence magnitude, to the natural instability. The phase of the pulses is such that it opposes the natural oscillation. This approximates the ideal continuous variation of fuel flow. The sign of heat pulses may be either positive or negative, so that a pulse of fuel may be added through the primary injector to create a positive heat release pulse, or the nominal primary flow may be shut off for a brief pulse period to produce a negative heat input pulse. For the experiments described here, the positive pulse method was used.

Figure 13 shows the control scheme. A band-pass filter is first applied to the pressure to produce a signal representing the dominant 140 Hz mode. The band pass filter was composed of cascaded high- and low-pass fourth-order Butterworth filters with respective cut-off frequencies of 50 Hz and 10 kHz. The controller then generates two additional signals from the unsteady pressure.

The first of these signals is a trigger. The trigger is generated when the unsteady pressure crosses zero while increasing, as shown in the representative signal in Figure 14. The trigger is used to determine the phase of the injected pulses of fuel, ensuring that they are out of phase with the natural instability.

The second signal is created by an envelope generator and represents the amplitude of the instability. The envelope generator first rectifies the signal by removing all sign information, and then applies a low pass filter. The low pass filter is a second-order digital filter with a cut-off frequency of 30 Hz. This frequency is well below that of the dominant mode, so that the envelope does not contain large components at the mode frequency.

These signals are then used by the pulse generator to determine when and how long the pulse should be. The width of the pulse is determined at each trigger

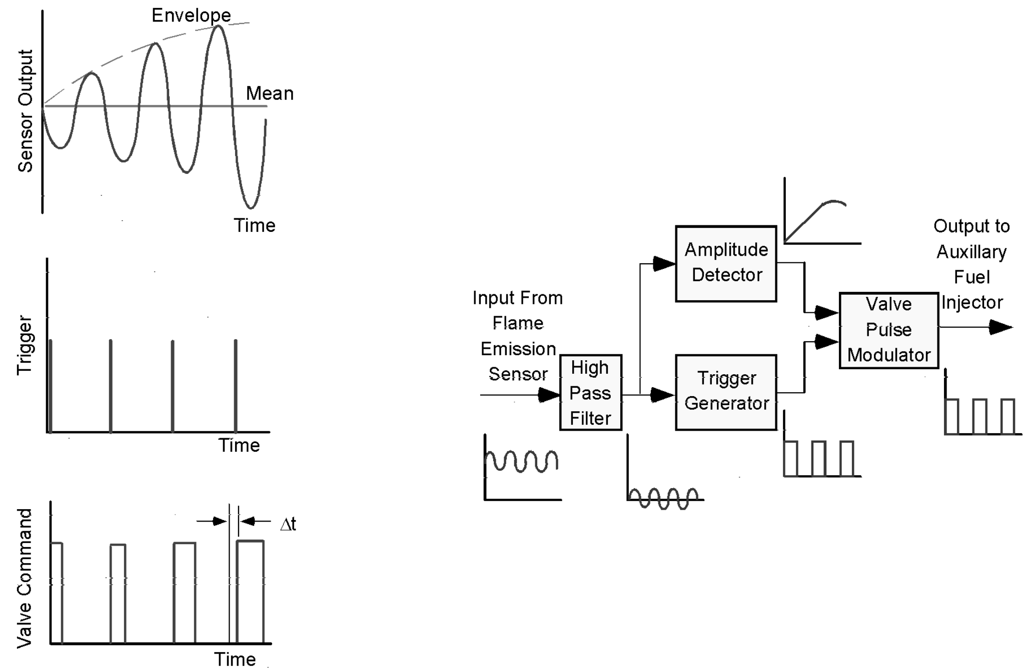


Figure 13. Amplitude-based pulse-width modulation.

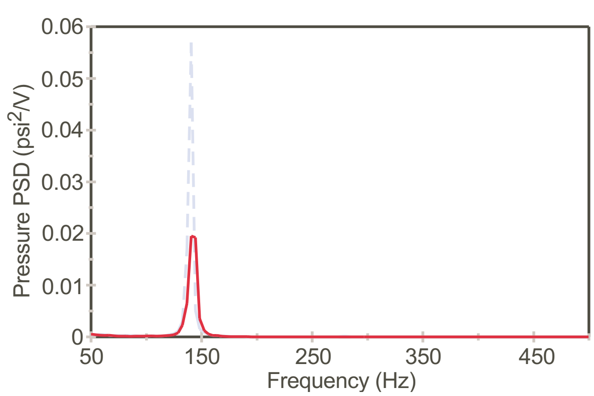


Figure 14. Closed-loop control reduces instability by more than 50%.

proportional to the envelope signal and hence to the instantaneous amplitude. A delay is applied to the trigger pulse to determine when the pulse must occur. The delay ensures that the pulse is commanded at such a time that, once delays of the valve, convection, evaporation, and combustion occur, the resulting heat release perturbation is out of phase with the instability.

Experimental Results

In implementing the control algorithm, the amplitude-based PWM was used to modulate flow through the primary stream of the dual-stream injector. The primary fuel flow constituted 28% of the total fuel flow. The modulated pulse train switched the primary off, so that in the nominal (control off) condition, the primary is flowing.

For the control experiments described below, the nominal overall equivalence ratio was 0.38. The mean chamber pressure was 29 psia. The air flow rate was 350 g/s and the total fuel flow was 30 kg/hr.

Since the controller switches the primary stream for short periods, the mean primary flow rate would be lower when the controller is operating. This would result in a reduction in equivalence ratio and, consequently, a change in the natural instability characteristics. However, to maintain a constant overall equivalence ratio, the primary flow pressure was adjusted during the experiments. Mean fuel flow was not directly measured, so the primary supply pressure was adjusted to maintain a constant chamber pressure. Since the upstream orifice is choked, the air mass flow is fixed and the chamber pressure is thus uniquely correlated with the fuel flow.

A sweep of delay and gain parameters identified the optimal operating parameters for the controllers. For this apparatus, experiments showed that a gain of 2.5 ms/psi with no delay other than that naturally produced the greatest reduction of unsteady pressure amplitude.

Figure 14 compares the pressure spectra for operation of the combustor with and without control. When the control is employed, the strength of the dominant mode is reduced to less than half of it uncontrolled height.

The amplitude reduction is significant, though not as large as the reductions published by others. In drawing the comparison, the reader should bear in mind that the present approach is limited to the use of conventional injectors without the capability for continuous high-frequency flow rate modulation. A control scheme wherein the fuel is either on or off may not be able to achieve the performance of a method employing a high-bandwidth continuously-variable injector. The method described here is, however, compatible with the current, highly refined state of injector technology used in existing engines.

Conclusions

A gas-turbine type combustor test rig exhibits a thermo-acoustic instability like those that often plague combustors in existing engines and many configurations envisioned to power future aircraft. The work described herein has shown that the amplitude of this instability may be significantly reduced by appropriately modulating the fuel flow, and hence, the heat release. The control algorithm, amplitude-based pulse width modulation, shuts off fuel flow through the primary stream of a dual-stream nozzle at intervals synchronized with the instability, in this case 140 Hz. The shut-off pulses are phased to oppose the natural oscillations in heat release and derive their duration from the instantaneous amplitude of the unsteady pressure oscillations.

Operating the combustor at a chamber pressure of 29 psia and an overall equivalence ratio of 0.38 produces an instability with an amplitude of approximately 1 psi peak-to-peak. When the control algorithm is activated, the energy of the dominant mode is reduced by more than 50%.

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