ACTIVE CONTROL OF COMBUSTION INSTABILITY IN A LIQUID-FUELED SECTOR COMBUSTOR

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ABSTRACT
A system for the active control of combustion instabilities in liquid-fueled, lean, premixed combustors was demonstrated in a three-nozzle sector combustor, using full-scale engine hardware. Modulation of a portion of the premixed fuel flow led to a reduction of 6.5 dB (2.1X) in the amplitude of the dominant instability mode. Combustor emissions were not adversely affected by the control.

INTRODUCTION
Emphasis on reducing the levels of pollutants created by gas turbine combustors has led to the development of lean, premixed combustor designs, especially for industrial applications. Premixing large amounts of air with the fuel prior to its injection into the combustor greatly reduces peak temperatures within the combustor and leads to lower NOx emissions. Premixed combustors are often susceptible to thermoacoustic combustion instabilities, which can lead to large pressure oscillations in the combustor. These pressure oscillations result in increased noise and decreased durability due to vibration and flame motion.

In a DARPA (Defense Advanced Research Projects Agency) - funded program, UTRC investigated the feasibility of attenuating combustion instability using active control techniques. Because of DARPA’s interest in marine applications (which typically use liquid fuel), the focus of this research was on a liquid-fueled low-NOx combustor. This combustor exhibited a large-amplitude instability at a frequency near 200 Hz. The goal of the research was to develop a practical active control system, which would reduce the magnitude of the pressure fluctuations caused by the instability without adversely affecting NOx levels. The effort stressed the practicality of the system and its ability to work with full-scale engine hardware at realistic operating conditions.

The initial phase of this program consisted of the development and demonstration of the technology in a 4 MW single-nozzle combustor, using a full-scale engine fuel nozzle at realistic operating conditions (Cohen, et al. 1998). Results from these experiments showed that the control system was capable of achieving reductions of up to 15 dB (5.6X) in the magnitude of the dominant instability mode, without negatively affecting emissions levels. This system used a high-speed solenoid valve to modulate a fraction of the fuel entering the premixing fuel nozzle. The fuel flow pulsations were phased relative to the combustor pressure fluctuations to give optimum performance.

This paper describes the application and scale-up of the techniques developed in the single-nozzle combustor to a three-nozzle sector combustor. The sector combustor allowed a more engine-like environment in which the effects of nozzle-to-nozzle interaction and combustor liner damping could be investigated.

SECTOR COMBUSTOR
A cost-effective alternative to both engine and full annular combustor testing is to test a sector cut from the full combustor annulus containing several fuel nozzles. Sector combustor testing offers savings over full annular combustor testing because of the reduced hardware, and reduced compressor and air heating capacity required. For the three-nozzle sector combustor used in this program the outer fuel nozzles provided the center fuel nozzle with fluid dynamic boundary conditions typical of those in an engine.

The combustor used for this portion of the program was a 67.5° sector cut from an aeroderivative gas turbine engine whose cross section is shown in Fig. 1. Three fuel...
The sector combustor was fueled with No. 2 diesel, delivered to the sector combustor at a nominal flow rate of 460 kg/hr. The nozzle-to-nozzle fuel flow distribution was neither controlled nor measured during combustion tests, but preliminary cold fuel flow measurements indicated that the fuel flow was evenly distributed among the three fuel nozzles.

At each fuel nozzle the fuel flow was divided among six fuel injection spokes, where five spokes were operated steadily and the sixth spoke flow was actuated by a high speed solenoid valve with separate feed plumbing as shown in Fig. 2. The solenoid valves had a maximum operating frequency of approximately 250 Hz. The average fuel flow rate to each of the three control spokes was monitored individually with turbine flow meters. The mean fuel flow through each of the actuated fuel systems was maintained at 1/6 of the fuel flow through that nozzle. Accumulators installed in the fuel supply system upstream of the actuating valve worked to maintain steady fuel supply pressure by adding capacitance to the system. Fuel supply elevations were chosen to minimize trapped air in the system that could introduce undesirable fuel system dynamics. The distance from the fuel modulating valves to the point of fuel injection through the spoke was nominally 1 meter.

INSTRUMENTATION

Both time-averaged and fast-response measurements were collected during sector combustor tests. Time-averaged measurements of mean air and fuel pressures, temperatures, flow rates and emissions concentrations were collected. Species concentrations of NOx, CO, unburned hydrocarbons (UHC), CO2 and O2 concentrations were measured for each data point. Exhaust gas was sampled from an array of locations spanning the exit of the combustor and ganged together to yield a spatially averaged sample. The sampled gas flowed to the emissions analyzers through heated and insulated tubing. All emissions concentrations reported in this paper have been corrected to 15% O2 concentrations.

Fast-time response measurements were collected using a dSpace data acquisition system configured to sample multiple channels simultaneously at a frequency of 2 kHz with a low pass filter at 1 kHz. The sector rig instrumentation layout is shown in Fig. 1. Limited access allowed for only two combustor fluctuating pressure measurements at the same axial location just downstream of the fuel nozzle exit plane and one upstream diffuser pressure measurement. PCB pressure transducers were mounted flush to the flow path walls in special insulated and water-cooled vessels, which protected them from the surrounding containment temperature and pressure.

Photomultiplier tubes (PMT’s) were used to measure the intensity of CH and CO radical emissions in the combustor. The intensity of these emissions has been shown to linearly track the rate of heat release in premixed systems (John and Summerfield, 1957, and Samaniego et al., 1995). Light was collected using fiber-optic probes "looking"
upstream through the dilution air holes in the combustor liner. This orientation allowed the three PMT’s to “see” the primary combustion zone downstream of each of the fuel nozzles. 200 μm diameter quartz fibers with a numerical aperture of 0.37 passed through a flange in the pressure vessel and were directly coupled to each PMT. Bandpass optical filters were installed to selectively admit only those wavelengths associated with CH and CO emissions (430 nm).

High-response pressure measurements in the actuated fuel lines were used to coordinate actuation among the three systems. These transducers were located between the valve and the fuel injector, each the same distance from the fuel injector tips, yielding a measure of the relative fuel injector phasings.

UNCONTROLLED COMBUSTOR CHARACTERIZATION

By operating the sector combustor at leaner premixed stoichiometries, and therefore lower flame temperatures, NOx emissions could be reduced from 40 ppm to less than 20 ppm as shown in Fig. 3. The leaner stoichiometries that led to reduced NOx caused a penalty to CO emissions, increasing concentrations from less than 20 ppm to 130 ppm. A fair compromise could be achieved near a primary zone equivalence ratio of 0.435 with NOx and CO concentrations of 30 ppm and 40 ppm respectively. Figure 4 shows how combustor pressure oscillations increased with decreasing equivalence ratio. Controlling these pressure fluctuations would allow an engine to be operated at an equivalence ratio that optimizes the balance between NOx and CO emissions.

Power spectral density (PSD) plots of combustor pressure for equivalence ratios of 0.41 and 0.45 are shown in Fig. 5. Decreasing the equivalence ratio amplifies the peak and shifts it to lower frequency. PSD’s of the PMT signal corresponding to fuel Nozzle 1 (Fig. 6) show heat release fluctuation spectra similar to the pressure spectra. These modes have been characterized as “bulk” modes, in which there is little spatial variation of the fluctuating pressure within the combustor (Gysling, et al., 1998).

ACTUATION SYSTEM CHARACTERIZATION

Combustor pressure response to open-loop forcing of the control fuel flows at discrete frequencies was used as a measure of actuator authority. Figure 7 shows a combustor pressure PSD plot for a case in which the control fuel flow to Nozzle 2 was forced at 100 Hz. Subtracting the pressure spectra amplitude of the unforced case from the forced case at the open-loop forcing frequency quantified the actuator’s authority at that frequency. Open-loop forcing of a single fuel nozzle could typically raise the pressure spectra at the forcing frequency from 100% to 400% of the unforced amplitude depending on the forcing frequency. Open loop forcing experiments were not performed near the dominant instability frequency for risk of doing damage to the combustor. In addition, the uncertainties associated with likely coupling of the forcing with the instability mechanism would make interpretation of open loop forcing data near the instability frequency difficult. The authors assumed that actuator authority in “quiet” regions of the spectrum was indicative of authority near the instability frequency.

For simultaneous open-loop forcing of multiple fuel nozzles, actuator authority was dependent on the relative nozzle-to-nozzle phasing. The “diamond” curve in Fig. 8 shows combustor pressure spectral amplitudes at a 100 Hz open-loop forcing frequency for two simultaneously forced fuel nozzles versus their relative phase. A broad range of phases, $-60^\circ < \phi_3 - \phi_2 < +60^\circ$, existed where the actuator authority was optimized and relatively insensitive to phase. Phase optimized actuator authority increased linearly with the number of fuel nozzles actuated.

CONTROLLED COMBUSTOR CHARACTERIZATION

A closed loop control algorithm was developed to use the actuators’ authority to damp combustor pressure oscillations. The algorithm chosen consisted of a software “observer” which identified the frequency and magnitude of the combustor instability from a high-response pressure signal which was fed back to the on/off control valve with a phase shift. The phase shift was selected by the user and could be specified independently for each of the three fuel nozzles.

Combustor pressure PSD plots for closed-loop control of Nozzle 2 in Figure 9 shows that depending on the controller phase chosen, the pressure oscillations in the combustor could either be damped or amplified. Figure 10 shows combustor RMS pressures for closed-loop control of individual fuel nozzles for an array of controller phases. Phase-optimized reductions in combustor RMS pressure of approximately 40% (3 dB) were typical for closed-loop control of fuel Nozzle 1 or Nozzle 2. It is possible that the discrepancy between the behavior of Nozzle 3 compared to Nozzle 1 and Nozzle 2 was attributable to a maldistribution of air among the nozzles, likely caused by the artificial walls of the sector. Previous experience with this combustor indicates that Nozzle 3 operates at a slightly higher local equivalence ratio than the other two nozzles.

Speculating that the effectiveness of the controller could be increased with additional actuator authority, produced by actuating more nozzles, the control algorithm was tested using multiple simultaneously actuated fuel nozzles. Figure 11 shows PSD plots for phase-optimized (minimum pressure oscillations) single, dual and triple closed-loop controlled fuel nozzles. Combustor pressure oscillations were reduced by going from single to dual nozzle actuation, but no further reduction was obtained by actuating all three fuel nozzles, in spite of the open-loop forcing results. The best control was achieved with dual nozzle actuation, yielding a 6.5 dB (2.1X or 53%) reduction in the bulk mode pressures and a 25% reduction in broadband RMS pressure. These reductions in combustor pressure oscillations via active control were accompanied with no penalties to emissions compared to uncontrolled operation. The magnitude of the reduction was
limited by the "splitting" of the spectral peak into two smaller peaks. This splitting behavior was evident for both two and three-nozzle actuation, but the amplitude of the secondary peaks was larger for the three-nozzle case.

INTERPRETATION OF THE CLOSED-LOOP RESULTS

The splitting of the bulk mode peak observed during controlled operation of the sector combustor can be explained based on a model of the combustor as a lightly damped, linearly stable system driven by noise. Experimentally determined frequency responses of the combustor pressure to the valve actuation voltage (Fig. 12) closely resembled linear systems with delay. A second-order model with delay was used to fit these dynamics with good agreement in the frequency range of 150 - 400 Hz. Although these empirical fits are necessary but not sufficient to conclude that the combustor dynamics were in fact linearly stable (opposed to perhaps limit-cycling behavior), it will be shown that this model reproduced the peak splitting effect of the controller in simulations with encouraging fidelity to data. This model will be used to provide a phenomenological explanation of the peak splitting observed in the closed-loop pressure spectra.

The transfer functions of combustor pressure to valve command voltage were measured via open-loop swept-sine tests actuating one of the three nozzles. The first step in fitting a measured transfer function was to identify the time delay from the slope of the phase in the frequency range of 220-260 Hz. Next the phase lag due to delay was subtracted from the experimental phase lag yielding a nearly classical 2nd order response with the phase dropping 180° through the instability peak. The "2nd order response" was fitted numerically using 2 poles and 1 zero.

A schematic of the closed-loop simulation block diagram is shown in Fig. 13. The plant Go(jω) is the empirical 2nd order system with delay representing the combustor dynamics. With the controller off, the noise power level was adjusted in the simulation to match the instability peak amplitude to data. The effect of multiple nozzles was simulated by linearly scaling the controller output by the number of nozzles, consistent with experimental open-loop forcing results.

A random input describing function was added to the controller, GC(jω), to represent the saturated on/off valve dynamics. It can be shown (Banaszuk, et al., 1999) that linear analysis techniques can be applied to the nonlinear dynamics of the on/off solenoid valve in the presence of large amplitude noise, as is the case with this closed loop model.

Figure 14 shows that the simulation exhibited similar peak splitting phenomenon to those observed in experiments. The amplitude at the dominant instability frequency was attenuated while secondary peaks were amplified by adding more nozzles and therefore more authority.

The closed loop transfer function of the block diagram in Fig. 13 from noise to pressure is Gp(jω)/(1+GC(jω)Go(jω)), indicating that for:

- |1 + GC(jω)Go(jω)| < 1 pressure oscillations are amplified by the controller
- |1 + GC(jω)Go(jω)| > 1 pressure oscillations are attenuated by the controller

Plotting |GC(jω)Go(jω)| in the complex plane, as shown in Fig. 15, reveals that depending on the frequency, ω, the controller can either amplify or attenuate pressure oscillations. The two nearly symmetric branches of the Nyquist plot that cross into the unit-radius circle, centered at (-1, 0), for frequencies greater than 225 Hz and less than 195 Hz were the root cause of the secondary peaks. While adding more nozzles and therefore more actuator authority increases the control gain in the attenuation band it also increases the control gain in the excitation band as well, imposing a fundamental limit on the phase-shifting controller’s effectiveness.

The large delay in the sector combustor made broad band attenuation of pressure oscillations difficult. Because of the large delay between the valve command signal and pressure pulsations, the plant phase changed rapidly over a relatively wide range of frequencies near the resonant frequency where the plant had considerable gain. The quickly rolling phase resulted in positive feedback control on both sides of an attenuation band centered at the resonant frequency, yielding an apparent splitting of the dominant instability mode.

SUMMARY

An active combustion instability control system was demonstrated on a three-nozzle sector combustor, using engine hardware. The control system was scaled up from a previous system designed for use in a single-nozzle combustor. This system used solenoid valve actuators to modulate a portion of the fuel delivered to each of the premixing fuel nozzles. A phase-shifting control algorithm, using observer software to identify and track the instability on the sensed combustor pressure fluctuations.

Testing of the uncontrolled combustor demonstrated that the dominant instability mode occurred at a frequency of approximately 200 Hz, dependent on the operating conditions.

Open-loop forcing tests illustrated that coordination of the three different actuation systems was insensitive to the relative phasing between the systems over a broad range of phase differences. Overall actuation authority increased linearly with the number of fuel nozzles actuated.

Demonstration of the closed-loop control system showed that reductions of 6.5 dB were possible using dual-nozzle actuation. The combustor emissions did not change relative to uncontrolled operation. Although the open-loop forcing tests demonstrated that overall actuator authority increased linearly with the number of fuel nozzles actuated,
closed-loop control tests showed that the incremental reductions in combustor pressure oscillations diminished with the number of fuel nozzles actuated. This was a direct result of the controller "splitting" the dominant spectral peak, a fundamental limitation of phase shifting controllers in systems with large delays. The peak splitting phenomenon could be reproduced in simulation using an empirical 2nd order system with delay representing combustor dynamics driven by noise.

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BIBLIOGRAPHY

Figure 1. Cross-section of sector combustor test facility with instrumentation and actuation system layouts
Figure 2. Schematic of steady-state and controlled fuel systems in the sector combustor test facility.

Figure 3. Dependence of NO\textsubscript{x} and CO concentrations at combustor exit on the primary-zone equivalence ratio.

Figure 4. Dependence of combustor pressure fluctuation levels on the primary-zone equivalence ratio.

Figure 5. Power-spectrum density plots of uncontrolled combustor pressure fluctuations at two equivalence ratios, $\phi$, showing shift in amplitude and frequency of the dominant mode with equivalence ratio.

Figure 6. Power-spectrum density plots of uncontrolled optical emissions (heat release rate) at two equivalence ratios, $\phi$, showing shift in frequency and amplitude of the dominant mode similar to that seen in the pressure data.

Figure 7. Effect of single-nozzle open-loop forcing at 100 Hz on combustor pressure spectrum.
Figure 8. Actuation authority increases linearly with the number of fuel nozzles actuated, provided the actuation is well coordinated.

Figure 9. Combustor pressure power spectra illustrating the ability of the control system to both amplify and attenuate the instability (single-nozzle actuation).

Figure 10. Effect of controller phase on combustor pressure fluctuation levels for single-nozzle actuation.

Figure 11. Multiple-nozzle, closed-loop actuation led to relatively small incremental reductions in pressure fluctuation levels, due to "peak splitting" phenomenon.

Figure 12. Bode plot of combustor pressure over valve command signal, no control, equivalence ratio 0.44.

Figure 13. Schematic of closed-loop combustor simulation block diagram.
Figure 14. Second-order model of combustor with delay reproduces the peak splitting phenomenon (Fig. 11) in closed loop simulation.

Figure 15. Nyquist diagram for single nozzle closed-loop control near the optimum control phase. Shows that the controller excites secondary peaks, "B" and "C", and attenuates the dominant instability peak, "A."