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Feedback Control of a Dump Combustor with Fuel Modulation

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Closed-loop control tests were performed to suppress the combustion instability of a 0.7-MW dump combustor and to extend its flammability limits. The pressure oscillations originating from the unstable combustion were measured at the dump plane and at the exhaust nozzle. The signals were used as a reference to lock on and to produce an acoustic signal that modulated the fuel flow at a predetermined phase shift relative to them. At a certain range of phase shift angles, the amplitude of the combustion oscillations was reduced to 50% of its unforced level. The control system was most effective when the reference signal was picked up at the dump. The amount of reduction was proportional to the acoustic forcing level, but leveled off for high forcing amplitudes. The effectiveness of the control system was reduced as the mass flow rate of the air was increased. The combustion instability became bimodal with multiple unstable frequencies, and a more sophisticated lock-on and phase-shift system is required to suppress effectively oscillations with more than a single dominant frequency. However, even for the high flow rates, the amplitude of the instability was reduced by nearly 40%.

Introduction

COMBUSTION characteristics of ramjet dump combustors, including flammability limits, combustion instabilities, and combustion efficiency, are closely related to the shear-flow dynamics associated with flow separation at the downstream step into the combustor (dump).

Passive control of the combustion characteristics has been achieved by controlling the formation of large-scale mixing. This was obtained in the Naval Air Warfare Center's (NAWC) 3-MW combustor by changing the initial shear-flow conditions at the dump using nonstandard inlet duct cross section.[1–3]

Active control experiments resulted in improved combustion characteristics in a 500-kW combustor by introducing oscillations into the reaction process.[4] Two approaches for the suppression of low-frequency, longitudinal pressure oscillations were followed. The first approach is the phase-shift type control studied by other investigators. Pressure oscillations[5,6] or light-emission fluctuations,[7–9] have been detected by microphones or diodes, suitably filtered, delayed, and amplified, and fed back to different types of actuators. Loudspeakers were used to impose secondary sound waves into the combustor[5–9]; an oscillating inlet nozzle was studied to increase the energy loss of the system by the changing upstream boundary conditions[10]; and fuel modulation was explored to modify the heat release distribution in the combustor.[11–13] In the NAWC experiments, modulation of the total gaseous fuel (ethylene) mass flow by loudspeakers with a phase-shifted oscillation frequency was chosen.

In the second approach, fuel modulation at higher harmonics of the pressure oscillations was used for active control to disrupt the development of large-scale coherent structures. These vortical structures were identified as drivers of combustion instabilities in the NAWC dump combustor.[14] This type of combustion control was explored at NAWC in a laboratory burner.[15,16] In the unforced flame, intense combustion started only at a certain distance from the burner exit (lifted flame) in the presence of large-scale vortical structures, and the flame was highly unstable. With forcing, combustion was initiated close to the burner exit and the flame was stable, because forcing was promoting early transition to fine-scale turbulence as was also demonstrated in nonreacting tests. The burner experiments showed that this type of active control cannot only stabilize the flame, but also extend flammability limits and enhance energy release. The same burner was also used to demonstrate the use of a closed-loop active control system to stabilize a flame and extend its flammability limits.[17]

A special combustor design was utilized in the present tests. In the regular design, air is ducted into the combustor through a pipe. Fuel is injected into the main flow upstream of the dump plane. In the present design the injector is an orifice plate and fuel is injected into the air through this plate. There are several advantages of this design for controllability purposes. The shear layer that separates from the inlet into the combustor is thinner and is therefore more susceptible to excitation and has higher amplification rates, the fuel is injected directly into the shear layer such that fuel modulations are more likely to affect the combustion process and the shear flow evolution, and combustion oscillations are expected to excite coherent structures in the reacting near field region of the jet. Yu et al.[18] investigated extensively the effect of the fuel injection on the separating shear layer in nonreacting tests. They found that by periodic blowing of the separating boundary layer it is possible to obtain efficient suppression of the large-scale structures produced in the jet. The results showed that this localized control of the initial shear layer can prevent the formation of large-scale structures in the flow and, thus, can be applied to suppress combustion instabilities that are driven by these structures.

The objective of this article was to test the effectiveness of a phase-shift acoustical active control system in a (relatively) high-power combustor of 0.7 MW with a turbulent inlet flow at 53 m/s.

Experimental Setup

The active control system was used to control combustion instabilities in an axisymmetric dump combustor. The schematic of the combustor is shown in Fig. 1. Air was supplied into the combustor through a D = 6.35-cm-diam circular pipe with a flow straightener $10D$ upstream of the dump plane. The pipe expanded through an angle of 7 deg to inject the air through an orifice plate of diameter 6.35 cm into the combustion chamber. The upstream face of the orifice plate was 1.27 cm wide. The ethylene fuel was injected through four

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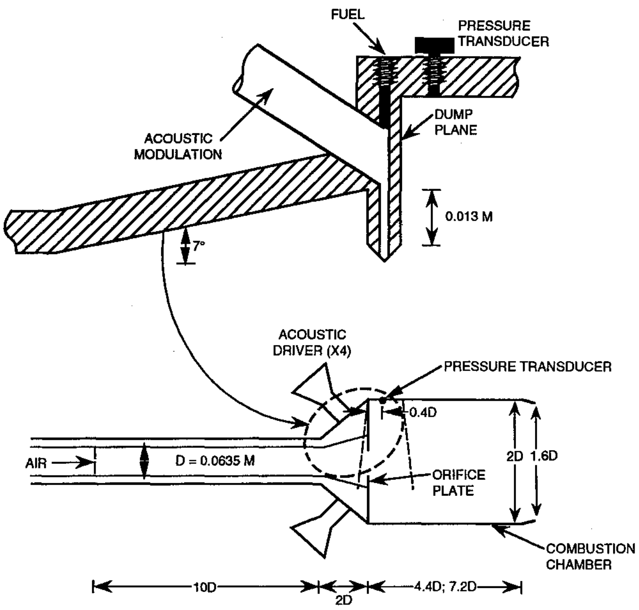

Fig. 1 Experimental arrangement of the combustor.

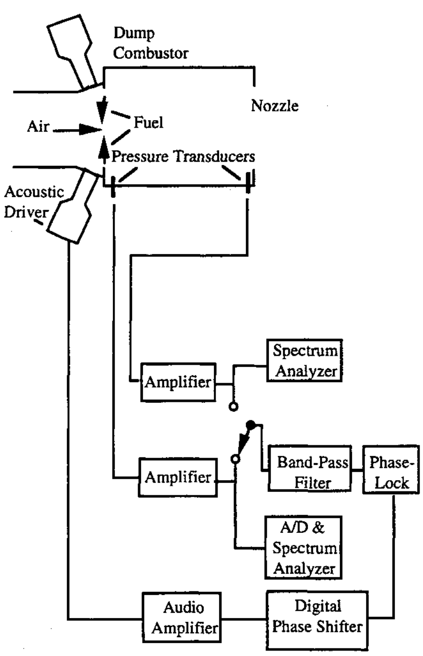

Fig. 2 Block diagram of the closed-loop control system.

slots in the orifice plate into the air. Each slot covered an arc of one-eighth of the orifice circumference. Acoustic modulations were superimposed on the fuel stream through four tubes that were connected to the fuel lines with 75-W acoustic drivers installed at the center end of each tube.

The steel combustion chamber was circular with a diameter of $2D$. Two combustor lengths were tested: 4.4 and $7.2D$. The diameter of the exhaust nozzle was $1.6D$.

Ethylene was injected at a rate of 0.0073 to 0.01 kg/s into a 0.12 to 0.22 kg/s airflow, resulting in an equivalence ratio of ϕ in the range of 0.5 to 1.25. It was injected through a choked orifice to ensure constant flow rate for the various test conditions. The chamber temperature was 1400–1800 K at ambient pressure. A hydrogen/oxygen torch igniter was installed at the dump plane to initiate the combustion.

A Kistler water-cooled pressure transducer was installed $0.4D$ downstream of the dump plane to record the pressure oscillations and to be used as a feedback signal for the control loop. In some of the tests, the pressure transducer was installed at the nozzle. In these tests, the nozzle transducer was used for the control loop and the dump transducer was used to measure the pressure oscillations for performance comparison between the two control systems.

A schematic description of the closed-loop control system is given in Fig. 2. The acoustic drivers excited acoustic resonance in the fuel manifold that modulated the fuel jet and the shear layer at the inlet to the combustion chamber. The signals from the sensors at the dump or the nozzle were passed through a variable gain bandpass filter, phase shifted, and fed-back to lock and drive the acoustic drivers through an audio power amplifier.

Results and Discussion

Nature of the Combustion Instability

The active control system was tested for two combustor lengths (4.4 and $7.2D$), and for two airflow rates (0.12 and 0.22 kg/s). The frequency and amplitude of the pressure oscillations during unstable combustion were dependent on the operating conditions and on the equivalence ratio. Near the stoichiometric ratio, the instability frequency was higher than that which occurred near the lean flammability limit. The combustion oscillations were excited by the interaction between flow instabilities and acoustic modes of the combustor or the air inlet in the combustor. Attempts were made to relate the various combustion instability frequencies to the combustor geometry and flow properties.[18] Acoustic resonance can be induced by the cavity of the combustion chamber and by the air inlet pipe to the combustor. Yu et al.[18] performed a detailed acoustic analysis on the inlet system. They identified the resonance modes of this section of the combustor and showed that interaction of these modes with the flow instabilities can amplify the latter and induce coherent oscillations in the shear layer flow. An effective interaction is contingent upon the achievement of proper matching between the two instabilities. The jet flow instability relates to the concept of the jet preferred mode.[19] The preferred mode of the jet is defined by a normalized frequency, or a Strouhal number, which is defined as $St_D = fD/U_0$, where f is the disturbance frequency, D is the jet diameter, and U_0 is the exit velocity. When the excitation applied to the jet is in the Strouhal number range of 0.24–0.64, the jet will be most responsive to it.[20] When one of the acoustic resonant modes of the inlet duct matches the preferred mode the jet's shear layer will roll into coherent vortices at this frequency.

Unstable combustion at the lean equivalence ratio was always characterized in the tests by an unstable frequency near 200 Hz. Figure 3 shows four pressure spectra for two combustor lengths and two airflow rates. In the short combustor, for both the high and low flow rates (Figs. 3a and 3b), there is a first harmonic of the instability frequency in the spectrum. For the long combustor at low flow rate (Fig. 3d) there is another instability at 260 Hz. The only pure tone instability was observed in the long combustor at a high flow rate (Fig. 3c). The Strouhal number of the dominant pressure peak at the low flow rate was 0.28 and for the high flow rate it was 0.52. Both Strouhal numbers are within the range of preferred mode Strouhal numbers.[20] The higher harmonic of the low flow rate in the short combustor ($St_D = 0.98$) corresponds to one of the resonant modes of the inlet duct.[18] The combustor duct acoustics did not affect the pressure oscillations as evidenced by the fact that the increase in the combustion chamber length did not change the instability frequency. Previous tests in the dump combustor and laboratory-scale flame showed that the peaks in the spectrum are indicative of the presence of large scale vortices in the combustor downstream of the dump plane. The combustion process is dominated by these vortices, resulting in a periodic heat release that further excites the pressure oscillations.

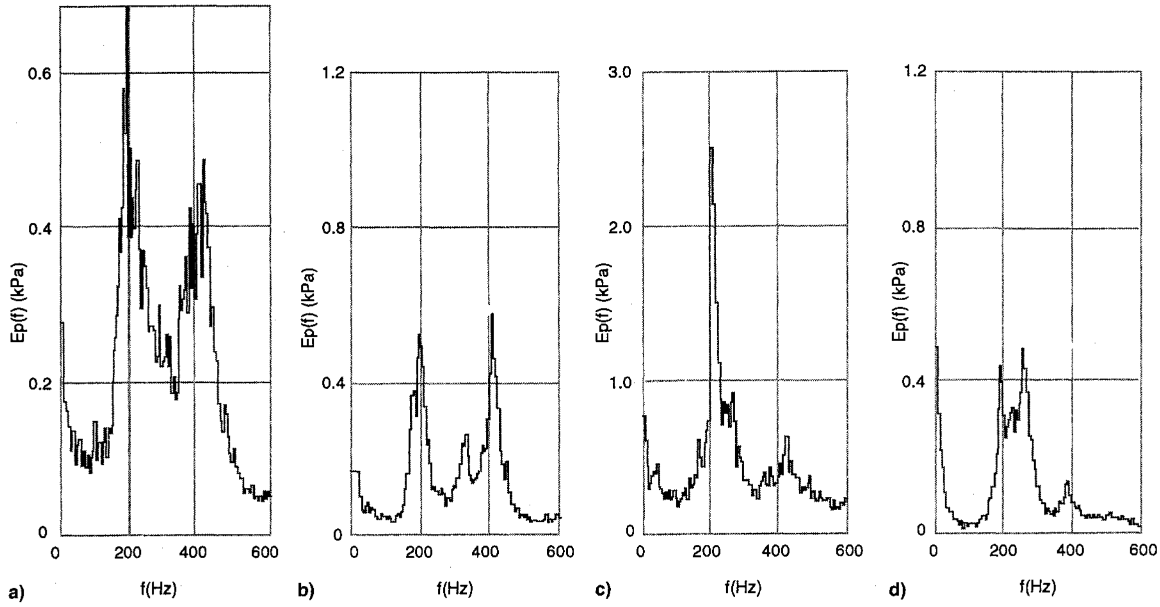

Fig. 3 Spectra of pressure fluctuations during unstable combustion at the lean flammability limit: a) 4.4*D* combustor, $\dot{m}_{air}$ = 0.22 kg/s, b) 4.4*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s, c) 7.2*D* combustor, $\dot{m}_{air}$ = 0.22 kg/s, and d) 7.2*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s.

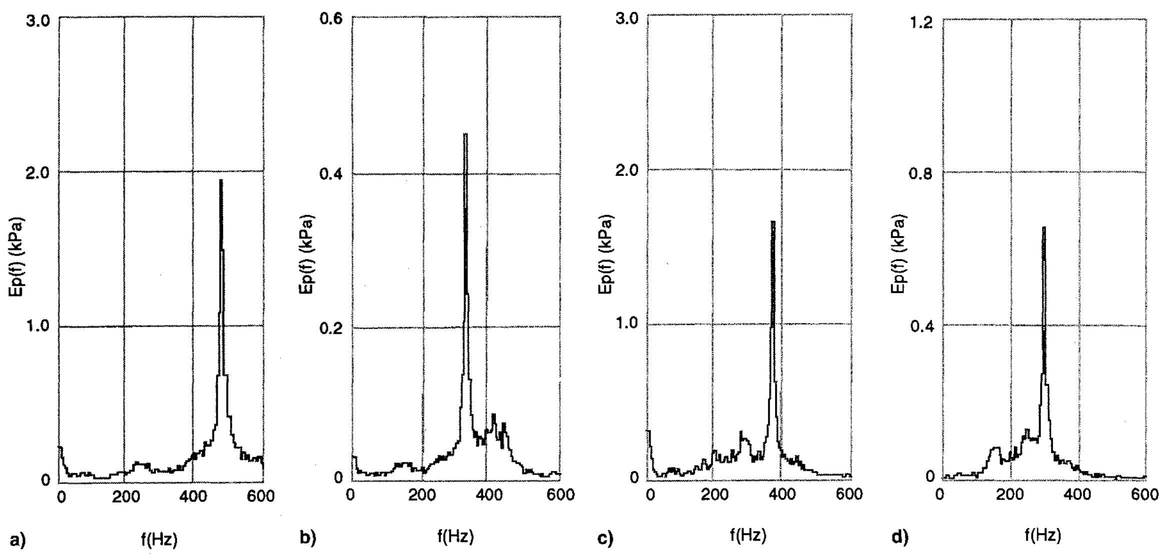

Fig. 4 Spectra of pressure fluctuations during unstable combustion at ϕ = 1.25: a) 4.4*D* combustor, $\dot{m}_{air}$ = 0.22 kg/s, b) 4.4*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s, c) 7.2*D* combustor, $\dot{m}_{air}$ = 0.22 kg/s, and d) 7.2*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s.

The combustion instability near the stoichiometric ratio occurred typically at a higher frequency. Figure 4 shows the four pressure spectra measured for the two combustor lengths for high and low air mass flow rate. The changes in flow rate resulted in corresponding variations of the instability frequency, whereas the combustor length had only a secondary effect. For the lower mass flow rate, the frequency was 325 Hz for the 4.4*D* combustor and 300 Hz for the 7.2*D* combustor (Figs. 4b and 4d, respectively). A higher frequency of 415 Hz for the 4.4*D* combustor and 370 Hz for the 7.2*D* combustor was measured for the higher air mass flow rate (Figs. 4a and 4c). The Strouhal numbers of the high flow rate instability are 0.57 for the 4.4*D*-long combustor and 0.52 for the 7.2*D* combustor. Both numbers are within the preferred jet mode range and are probably flow related instability. The Strouhal numbers associated with the low flow rate are higher: 0.85 and 0.77 for the short and long combustors, respectively, and are more likely to be associated with the inlet duct acoustic modes. The coupling with the combustor acoustic modes is not strong in this case either.

All of the tests described in the following sections were performed near stoichiometric ratio.

Control of 7.2*D* Combustor at Low Air Flow Rate ($\dot{m}_{air}$ = 0.12 kg/s)

Closed-loop control of the pressure oscillations in the 7.2*D* combustor was employed by varying the phase of the acoustic driving signal relative to the pressure fluctuations measured 0.4*D* downstream of the dump plane. The instability frequency was 297 Hz (Fig. 4d) with a peak amplitude of 0.7 kPa. The speakers were driven in a range of ψ = 40–400 deg phase shift angles relative to the pressure signal. The variation of the peak amplitude of the instability frequency as a function of the phase shift angle is shown in Fig. 5. A reduction of 47% in the peak amplitude relative to the uncontrolled combustion was obtained at ψ = 40 and 400 deg. The absolute value of the phase shift angle is insignificant, as it depends on the sensor location and phase shifts of the various components of the control loop. The horizontal line represents the peak amplitude of the uncontrolled combustor. In a range of phase shift angles between ψ = 170–350 deg, the amplitude of oscillations was increased relative to the unforced combustion due to a positive destabilizing feedback, with a peak increase of 50% relative to the unforced conditions at ψ = 300 deg. The spectra of the pressure fluctuations corresponding to the unforced condition, the highest suppression, and the maximum amplification of the instability are shown in Fig. 6. In addition to the effect the controller has on the suppression of the amplitude of the pressure oscillations, it also changes somewhat the instability frequency. The frequency was changed in a range between 280–310 Hz, which is within 5% of the original frequency. Figure 6 shows that the peak frequency sharpens and moves to higher frequency, while the suppressed peak widens and moves to lower frequencies. The narrowing of the peak at the destabilizing phase is a result of the positive feedback that provides higher energy to this frequency. The widening of the peak at optimal control results from the reduced coherence of the vortices, which increases the effect of turbulence and the jitter of the unstable frequency. The reason for the slight drift of the frequency is unclear. The frequency shift did not have a considerable effect on the closed-loop performance since the variation range was small relative to the window width of the bandpass filter.

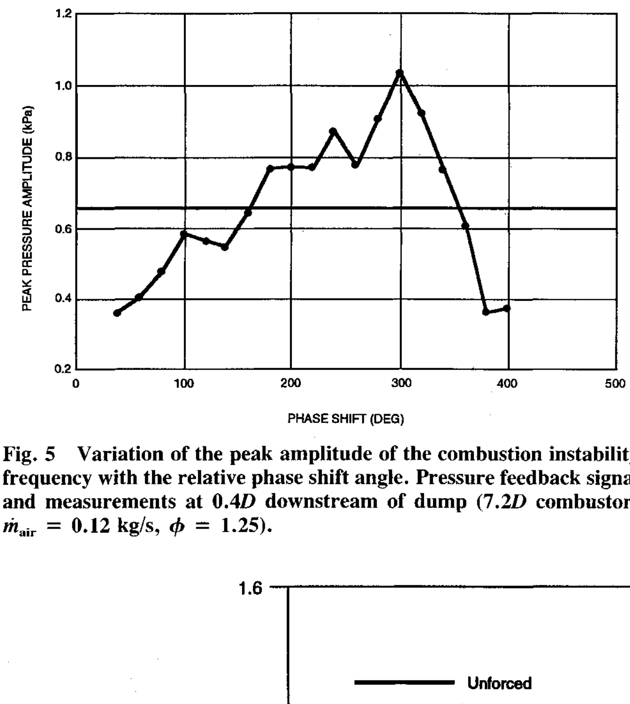

Fig. 5 Variation of the peak amplitude of the combustion instability frequency with the relative phase shift angle. Pressure feedback signal and measurements at 0.4D downstream of dump (7.2D combustor, $\dot{m}_{air}$ = 0.12 kg/s, ϕ = 1.25).

The controller affects the combustion process through two different mechanisms: 1) redistribution of fuel and 2) direct modulation of the shear layer. Yu et al.[18] showed in nonreacting tests that the effect of modulating the shear layer is sufficient to suppress simulated oscillations in a similar configuration. However, the energy release during combustion amplifies the pressure oscillations[6] and the effect of fuel modulation becomes important as well. The fuel modulation effect is based on the fact that the mixing process during the roll-up of vortices changes during the evolution of the vortex. The variation of the phase at which the fuel is being injected relative to the phase of the vortex roll-up affects the local air/fuel ratio and, thus, the energy release rate. By moving the heat release cycle out of phase with the pressure oscillations, the instability can be mitigated.

The control system has some effect beyond the suppression of the peak instability frequency. The level of the total pressure oscillations was reduced (Fig. 7). A reduction of 12% relative to the unforced case (horizontal line) was measured at ψ = 40 and 400 deg, while a similar increase of 8% relative to the unforced combustion was measured at ψ = 260 deg. The fundamental peak frequency is usually exchanging energy with other frequencies through nonlinear interaction. By reducing the fundamental component the others are suppressed as well. This mechanism can explain the observed decrease of the overall level of the pressure oscillations.

A robust control system requires a highly coherent and stable source signal from the sensor. The location for the pressure sensor near the dump plane was chosen since at this place the coherence of the vortices is highest. In order to investigate the effect of the source signal coherence, the pressure transducer used as the feedback loop reference was moved to the vicinity of the nozzle where the flow and combustion process become more turbulent and the signal is expected to lose some of its coherence. The pressure sensor relative to which the driving acoustic signal was locked and phase shifted was moved to 0.4D upstream of the combustor's nozzle. Another pressure transducer was used to measure the controlled combustion pressure oscillations 0.4D downstream of the dump plane. This location was chosen to maintain a consistent data base for comparison with the previous results.

The variation of the instability peak amplitude with the phase angle is shown in Fig. 8. The phase angle of maximum suppression remained unchanged at ψ = 40–100 and 400 deg, but the suppression level was reduced to 35% relative to the

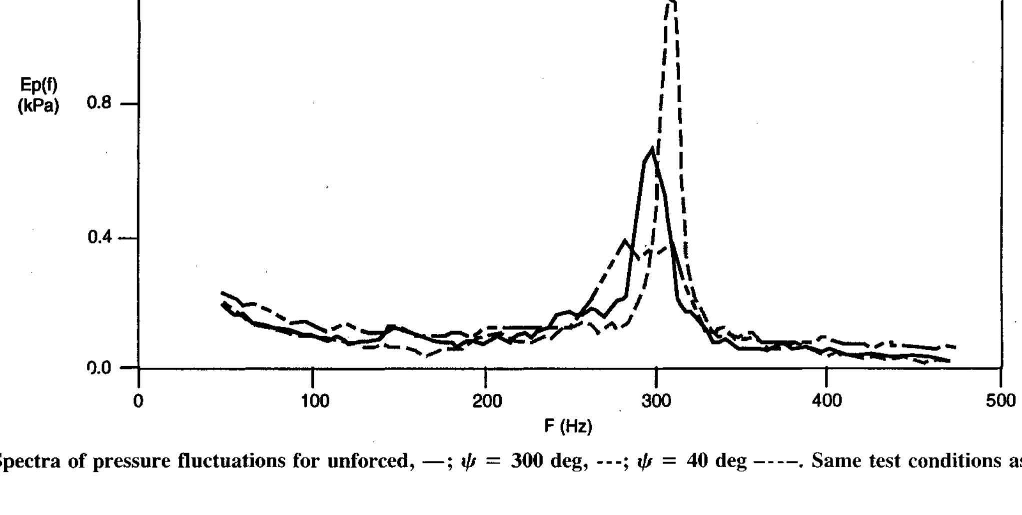

Fig. 6 Spectra of pressure fluctuations for unforced, —; ψ = 300 deg, ---; ψ = 40 deg ----. Same test conditions as in Fig. 5.

unforced level. The highest increase of the oscillations was measured at the range of ψ = 220–320 deg, with a 25% maximum increase relative to the unforced combustion. The total pressure rms suppression was similar to the previous test (Fig. 7) at 12%, whereas the highest increase was 8%, at the same phase angles as the minimum and maximum values of the peak amplitude. The reduction in the effect of the control system with the reference source at the nozzle confirmed that the vicinity of the dump plane is an optimal location for the sensor where it can pick up the pressure signal from the coherent vortices.

The relative phase of the two pressure sensors at the dump plane and at the nozzle was 11 deg at the instability frequency of 295 Hz (Fig. 9). The relative phase angle between the two pressure signals provides additional evidence that the combustion instability is not related to the combustion chamber acoustic characteristics, but rather to the flow instabilities and the inlet duct acoustics.

Effect of Control on the Flammability Limit

The effect of control on the lean flammability limit was studied at two phase shift angles: one corresponding to effective suppression conditions and one at which the instability is augmented. Root-mean-square levels of the pressure oscillations in the combustion chamber were measured as the equivalence rate was varied between 0.5–1.1 (Fig. 10). The instability of the uncontrolled combustion became highly amplified at ϕ = 0.93. The amplitude of the fluctuations increased and the frequency dropped to near 200 Hz. The high level oscillations continued until the lean flammability limit was reached at ϕ = 0.72. When the flame was controlled at a phase shift angle of ψ = 80 deg corresponding to a maximum suppression of the pressure oscillations (Fig. 7), the onset of the high-amplitude instability was delayed to ϕ = 0.81 and was blown out only at ϕ = 0.54. The onset of large-amplitude pressure oscillations was delayed (to ϕ = 0.87) also with a phase shift angle of 320 deg corresponding to augmentation of the instability, but the flammability limit shifted to a higher ϕ of 0.78. The flammability tests were performed with variable equivalence ratio while the control system parameters were optimized for an equivalence ratio of 1.25. Previous work at our laboratory showed that the control parameters need to be adjusted when the equivalence ratio is changing. Such flexibility requires the application of an adaptive controller. In the present case, it is shown that even a nonadaptive system can have a significant effect beyond its optimization point. It is assumed that an adaptive controller would have a more significant effect on reducing the oscillations near the lean flammability limit. Extension of the lean flammability limit by excitation was also demonstrated in a small-scale burner.[15] This effect is achieved by induction of the roll-up of small scale vortices near the flameholder that act as a flameholder. A similar mechanism can explain the extension of the flammability limit in the present case.

Effect of Forcing Level

The effect of the acoustic forcing amplitude on the suppression of instability was measured at the most effective phase shift angle of 80 deg, by changing the gain of the audio amplifier. Figure 11 depicts the change in the peak amplitude of the instability as a function of the audio amplifier's gain. The horizontal line depicts the unforced level, for reference. The

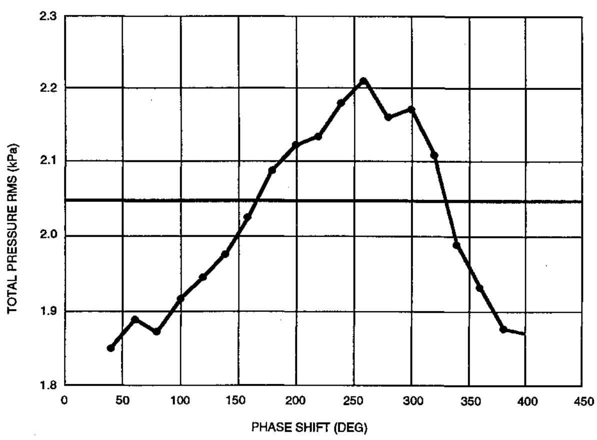

Fig. 7 Variation of the total pressure rms with phase shift angle. Pressure feedback signal and measurements at 0.4D downstream of dump (7.2D combustor, $\dot{m}_{air}$ = 0.12 kg/s, ϕ = 1.25).

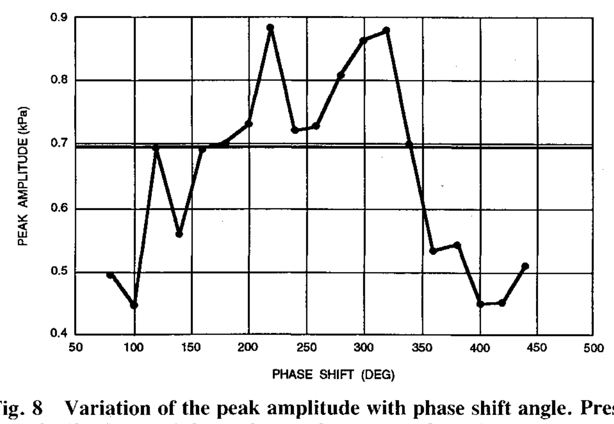

Fig. 8 Variation of the peak amplitude with phase shift angle. Pressure feedback signal from the combustor nozzle and pressure measurement at the dump (7.2D combustor, $\dot{m}_{air}$ = 0.12 kg/s, ϕ = 1.25).

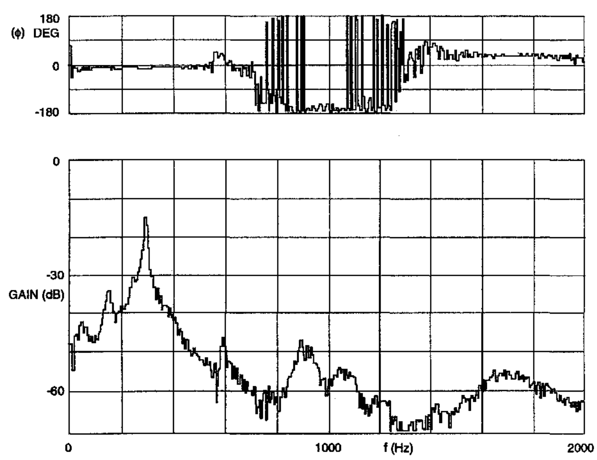

Fig. 9 Cross-spectrum and relative phase of the pressure transducers at 0.4D downstream of the dump plane and 0.4D upstream of the combustor nozzle.

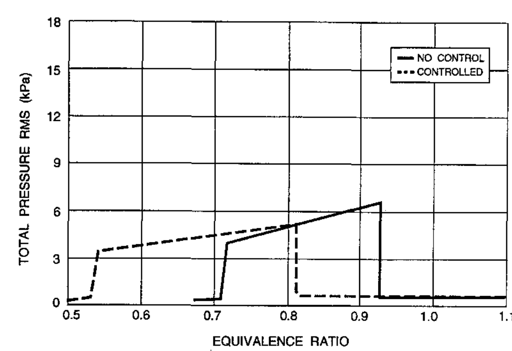

Fig. 10 Variation of rms of pressure oscillation with equivalence ratio for unforced and controlled combustion (7.2D combustor, $\dot{m}$ = 0.12 kg/s).

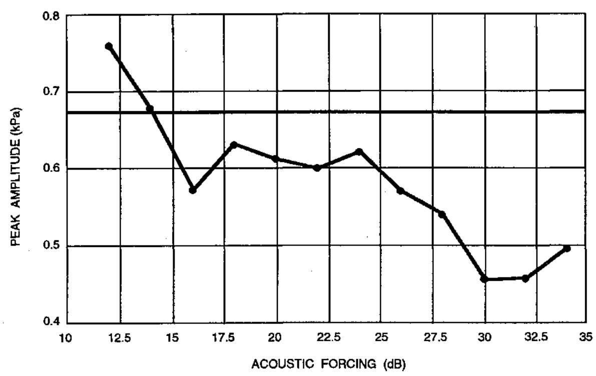

Fig. 11 Variation of the peak amplitude of the pressure oscillations with increasing gain at an effective suppression phase angle (7.2*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s, ϕ = 1.25, phase shift = 80 deg).

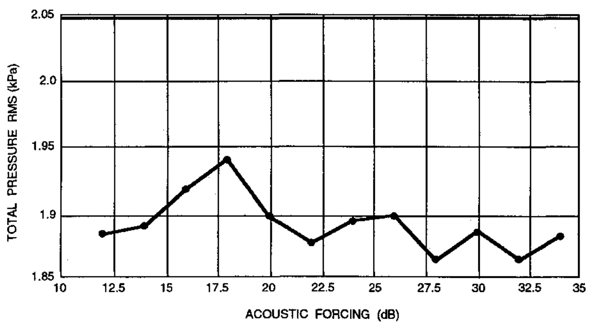

Fig. 12 Variation of the total rms of pressure oscillations with increasing gain at an effective suppression phase angle (7.2*D* combustor, $\dot{m}_{air}$ = 0.12 kg/s, ϕ = 1.25, phase shift = 80 deg).

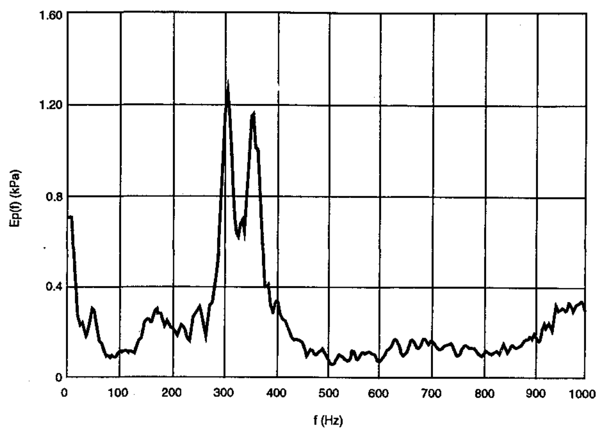

Fig. 13 Bimodal spectrum of pressure fluctuations measured 0.4*D* downstream of the dump (7.2*D* combustor, $\dot{m}$ = 0.22 kg/s, ϕ = 1).

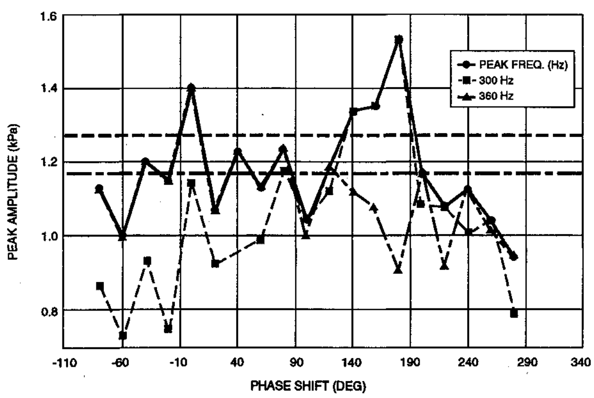

Fig. 14 Variation of the amplitude of peak instability frequency with the relative phase shift. Same test conditions as in Fig. 13.

suppression of the instability increases monotonically with the amplifier gain until saturation is reached at a gain of 30 dB. Higher gain does not produce any additional suppression. The instability frequency varies slightly as the gain is increased. For gains lower than 25 dB, the frequency is similar to the unforced instability frequency of 300 Hz. As the gain is increased beyond 25 dB, the frequency drops continuously to 277 Hz at the highest forcing level.

The variation of the total rms level of the pressure oscillations is quite different than the change in the peak amplitude of the instability. The amplitude drops at the lowest gain of 12 dB to the level that is nearly equal to that of the highest gain and stays nearly constant in the entire range of forcing level (Fig. 12).

Control of 7.2*D* Combustor at High Airflow Rate ($\dot{m}_{air}$ = 0.22 kg/s)

As the airflow rate increases, the pattern of instability becomes bimodal and, therefore, more difficult to control. Figure 13 shows the spectrum of the pressure oscillations for the 7.2*D* combustor with $\dot{m}_{air}$ = 0.22 kg/s, operating at a stoichiometric ratio (ϕ = 1). The unstable frequencies are 310 and 360 Hz (St_D = 0.4 and 0.47). During a cycle of changed phase in the control measurements the amplitudes of the two peaks change and they become alternately dominant. The bimodal instability is an indication of multiple structures in the flowfield. Due to interaction between vortices such as vortex pairing and merging it is possible to find more than one wavelength excited in the flowfield. Multiple modes can also be excited acoustically in the combustor or in the inlet duct. When the convective modes match the acoustic ones, mutual amplification results and the combustion can exhibit multiple-mode instabilities. The suppression of such instabilities is more difficult than the single-mode instability since the various modes can be independent and each one of them needs to be dealt with separately. Due to this bimodal spectrum, the window of the bandpass filter was widened to encompass the two frequencies. Nevertheless, the switching of the dominant frequencies complicates the locking of the driving signal and causes shifts in the relative phase due to the phase variation caused by the bandpass filter when operating off the center frequency. The peak amplitude variation with the phase angle is shown in Fig. 14. Three curves are displayed: the variation of the dominant oscillations (independent of frequency), and the amplitude of the individual frequencies of the bimodal instability. The amplitude of the 300-Hz oscillations (dashed line) shows cyclic response to the forcing, with minimum values at −60 deg and a maximum at 180 deg. The reduction at −60 deg is more than 35% relative to the unforced amplitude. The higher frequency of 360 Hz showed lower variations relative to the unforced level with a minimum at 180 deg and a maximum at 0 deg. The maximum reduction of amplitude was only 20%. The curve that depicts the variation of the overall dominant oscillations overlaps alternately the curve of the dominant frequency as a function of the phase shift angle. The horizontal lines show the reference level of the two frequencies for uncontrolled combustion. The efficiency of the control system in reducing a bimodal instability is lower than for the single mode due to the lack of a stable reference signal to lock on. The higher flow rate produces a more turbulent flow and less coherent structures at multiple unstable frequencies. The attempt of the present work was to control the different modes with a single control loop. The compromise that has to be made with regards to the feedback loop bandwidth reduces its efficiency. A dedicated control loop for each one of the instabilities or an adaptive controller is needed for improved performance.

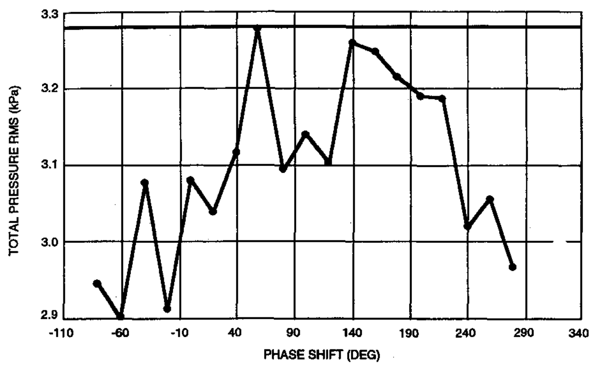

Fig. 15 Variation of the total pressure fluctuations rms with the relative phase shift. Same test conditions as in Fig. 13.

The variation of the rms level of the total pressure fluctuations is shown in Fig. 15. The highest suppression of 12% was obtained for $\psi = -100$ deg. The highest rms level at 140 deg did not exceed the unforced level, which is indicated by the horizontal line. The effect on the total pressure oscillations is similar to that of the low flow rate.

The effect of control on the lean flammability limit for the high flow rate was insignificant.

Summary and Conclusions

Active combustion control was tested in a dump combustor for two air mass flow rates corresponding to 29 and 53 m/s at the inlet. Acoustic drivers modulated the fuel flow rate at the frequency of the combustion instability with varying phase shift relative to the instability. In both low and high airflow rates the fuel modulation suppressed the instability at a certain range of phase shift angles and increased the instability level at other angles. For the low flow rate, a 47% suppression was obtained at a phase angle of 40 deg, whereas an augmentation of 50% was measured at 300 deg. The total rms was reduced by 12% and increased by 8% at the same frequencies, respectively. The reduced oscillations produced also a delayed onset of high-level instability oscillations at the lean flammability limit and an extension of this limit from an equivalence ratio of 0.72–0.54.

Increasing the amplitude of the acoustic forcing resulted in a higher suppression of the peak amplitude at the effective phase shift angles, which was nearly proportional to the forcing level up to a certain limit of forcing level where leveling-off occurred. The total rms reduction was less affected by the forcing level. Similar reduction was measured for the lowest forcing level as for the highest level.

Increasing the forcing at the phase-shift angle, which causes increased instability, yields proportional increase in the instability level both of the peak amplitude and the total pressure rms level.

High-flow-rate combustion instability was characterized by a bimodal spectrum that reduces the effectiveness of the phase-lock control due to the varying dominant frequency. It is required for such operational conditions to widen the window of the bandpass filter that subsequently introduces phase errors due to the dependence of the phase on the frequency when the dominant frequency is off the center frequency of the filter. The effectiveness of the control system is thus reduced, such that the highest suppression was 35%, at a phase shift angle of -60 deg, while the highest increase was 20% at 180 deg. At this flow rate the control did not have any effect on the combustion instability and blowout at the lean flammability limit.

Changing the location of the reference pressure transducer from the dump to the nozzle reduced the effectiveness of suppression by 12%. A possible reason could be the reduced coherence of the vortices and energy release at the nozzle relative to the dump region. A larger jitter in the instability frequency and phase can be detrimental to the operation of the closed-loop controller.

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