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Feedback Control of an Unstable Ducted Flame

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Active control of a naturally unstable ducted flame was realized using acoustic forcing of either the shear layer of the flame jet or the duct itself. The feedback signal was derived from either the duct pressure signal or the CH intensity (related to the flame heat release rate), and delayed in time to produce cancellation of the natural resonant oscillations of the system. Direct driving of the shear layer using the duct pressure signal feedback produced the best control with the lowest power requirements. The controller was able to reduce the acoustic power in the duct at the resonant frequency from 19 Pa to about 0.7 Pa, or nearly 30 dB. When operating in the controlled mode, the driving speaker is producing a sound pressure level more than three orders of magnitude below the natural duct uncontrolled level (both measured in the duct), so the effect is clearly not just acoustic cancellation.

Introduction

OUR previous laboratory scale work on active control of combustion[1] dealt with the stabilization of the height of a turbulent-lifted free jet flame at its lean blowout limit. Practical propulsion systems involve an enclosed combustor, however, and the combustion characteristics, including flammability limits, instability, and efficiency, are closely related to the interaction between shear flow dynamics of the fuel/air jet at the inlet and the acoustic modes of the combustor.[2–5] Strong interaction, leading to highly unstable combustion, occur when the acoustic modes of the combustor match the instability modes of the jet, such as its preferred mode. For such conditions, the shedding of the jet vortices excites air acoustic resonance in the combustion chamber, which subsequently causes the shedding of more coherent energetic vortices at the resonant frequency.

Active control methods have been applied for noise control[6] and for stabilization of compressors.[7] Closed-loop feedback control systems were also implemented in combustion systems. The simplest were demonstrated in laboratory scale experiments.

Collyer and Ayres,[8] Heckl,[9] and Sreenivasan et al.[10] controlled the instability of a Rijke tube by introducing a second controlling heat source into the upper half of the tube. This heat source was operated out of phase with the pressure oscillations and damped them.

Dines[11] actively modified the boundary conditions at the tube's end by using a loudspeaker. The feedback signal used was the light emission from CH radicals in the flame. This emission was shown to be a measure of the heat release rate.[12] Heckl[13] repeated this test using the pressure oscillations as the feedback signal to the speaker. Langhorne[14] used a pressure transducer as the sensor and fuel modulation as the actuator in a closed loop control system to suppress oscillations of a bluff body stabilized ducted flame. They obtained a reduction of 12 dB in the pressure oscillation signal. Gulati[15] used microphone sensors and speaker actuators to control a grid-stabilized ducted flame. A reduction of 15 dB was obtained. Lang et al.[16] and Poinsot et al.[17,18] also controlled a grid-stabilized ducted flame. Lang et al.[16] indicated that the method they were using was antisound. They monitored OH chemiluminescence as a measure of heat release, but did not use it as a sensor signal in the controller. Raghu[19] used periodic heat addition or moving screens to control oscillations in a Rijke tube burner and dump/swirl stabilized combustion tunnel; his maximum reduction was 10 dB. Wilson et al.[20] used acoustic drivers and pressure sensors to control combustion instability in a 500-kW dump combustor achieving a reduction of 6 dB.

In the present experiments the interaction between combustion associated with large-scale vortical structures and chamber acoustics was studied by placing a premixed orifice stabilized flame in an open vertical duct. In contrast to the previous studies mentioned above, which used acoustic or heat release excitation of the duct, we also studied direct excitation of the shear layer of the flame jet by way of a speaker inside the orifice nozzle. The hypothesis was that the amplification of fluid dynamic instabilities near the flame holder would lead to lower control authority power requirements. Large-scale vortical structures have been shown[2–5] to be important in driving combustion instability in large ducted combustion systems. By exciting the shear layer it was hoped that the roll up of these structures could be canceled with a relatively low-level control authority. Amplification is essential for the control of much larger heat release systems such as ramjets.

A second objective was to compare the use of pressure and CH chemiluminescence emission as sensors in the feedback control loop. Combustion oscillations through the Rayleigh criterion are associated with pressure and heat release fluctuations. A microphone measures pressure and it has been previously shown that CH (and C_2) chemiluminescent emission is directly related to heat release.[21–23] These radicals have been found to be good indicators of the location and intensity of the flame front. The OH radical has been found to be somewhat less useful in this regard.[24]

The ducted configuration which enhances the interaction between the combustion and the duct acoustics, allows the detailed study of an idealized system in which the acoustic resonance is pure and the energy release and flow rates are relatively low. The control strategies developed for this system and the understanding obtained of the detailed mechanism can subsequently be applied to more complex combustion systems.

Experimental

The naturally unstable system we chose to control consisted of a ducted orifice nozzle premixed flame, and is shown in Fig. 1. Because we were interested in both using CH emission

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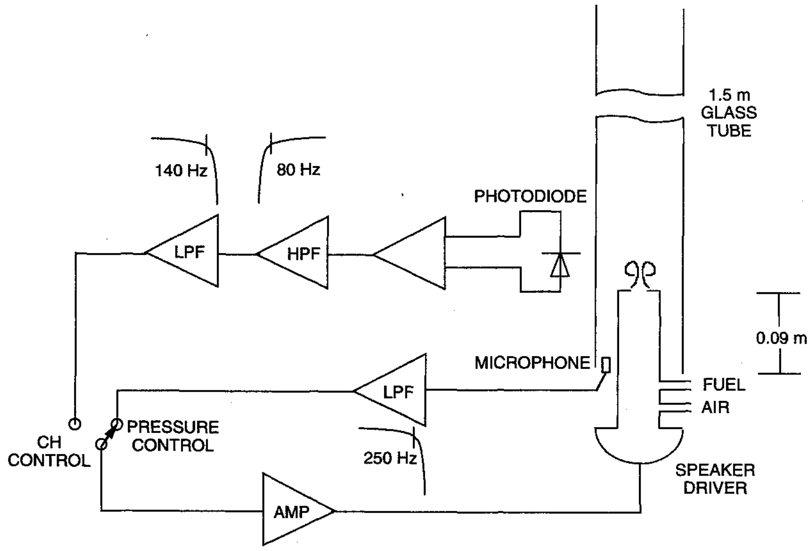

Fig. 1 Apparatus diagram.

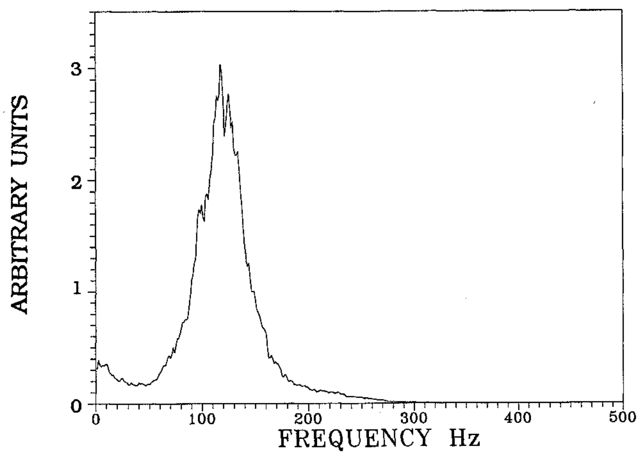

Fig. 2 Turbulence spectrum showing the preferred mode of the nonreacting jet.

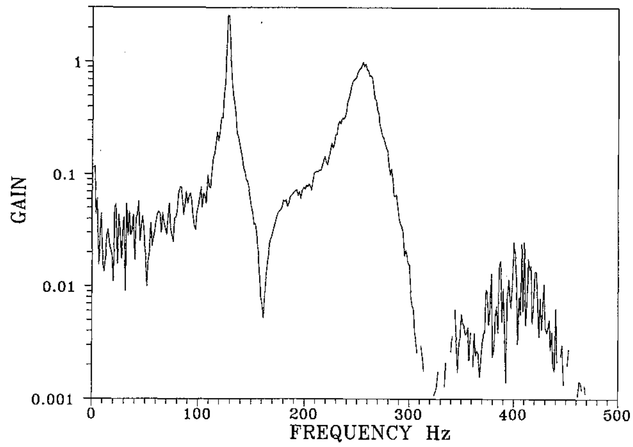

Fig. 3 Open loop gain transfer function of the pressure-based control system.

as a controlling signal and in imaging the fluid dynamic effects involved, a glass duct, 1.5-m long by 95-mm i.d., was used. The length sets the resonant frequency, and this length was required to match the preferred mode of our orifice jet. The diameter controls entrainment: wider tubes failed to become unstable. The nozzle was 53-mm o.d. with a 19-mm orifice plate. It penetrated 90 mm into the duct, leaving 70% of the area of the duct open at the bottom and 100% open at the top. This placed the heat release at a position in the duct not optimal for Rijke burner-like oscillations, which would have been at $\frac{1}{4}$ the length of the duct, but experiments with the flame further into the duct caused such extreme instabilities that the flame would blow out.

A $\frac{1}{8}$-in. condenser microphone with a 150-kHz bandwidth was placed at the bottom end of the duct, facing up into it, and a silicon photodiode for monitoring flame emission was placed outside the glass duct and integrated over most of the unstable flame emission. Because these premixed flames were essentially stoichiometric and nonsooting, no filter was used on the photodiode to attempt to separate molecular emission from blackbody emission due to soot; the majority of flame emission monitored under our operating conditions was chemiluminescence from CH and C_2. Since these radicals are present only at the flame front, this signal was therefore a good indication of combustion intensity. The detector did not respond to OH emission (the other most prevalent wavelength in these flames), because it is too far into the ultraviolet.

The propane entered at 1.88 l/min and was premixed with the air entering at 43.7-l/min leading, with the added air from entrainment, to a stoichiometric or slightly lean flame. These values give a flow rate that leads to blowoff for this orifice jet in the unducted configuration, but the duct stabilizes the flame, even in the oscillating mode. Hot-wire measurements on the centerline of the jet, three exit diameters downstream, indicated a preferred mode near 123 Hz, as shown in Fig. 2. This is the most unstable frequency of the (free) jet; the jet is most likely to generate large-scale vortices at this frequency. The 1524-mm length of the duct gives a 131-Hz resonance and leading to a good coupling with the 123-Hz preferred mode of the jet and a very loud oscillation with the flame present. (During combustion, the gases in the tube are hot and this increases the speed of sound, pushing the resonant frequency above that of a cold 1524-mm organ pipe.)

As shown in Fig. 1, control was affected by a 35-W speaker driver unit that forced the orifice jet from inside, thereby modulating the vortex evolution at the shear layer. Pressure modulation inside the burner at the preferred mode of the jet modulates the velocity through the nozzle, thereby tripping coherent vortices in the shear layer by means of hydrodynamic amplification. The speaker was driven by the filtered microphone signal or filtered photodiode signal. We made use of the time delay properties of brickwall low-pass filters used on the low side of their cutoff frequencies. The use of filters in control loops, rather than straight time delay units or all-pass filters, is common and advantageous. It is usually necessary to both provide the proper phase delay for cancellation and some roll off of response at higher frequencies to prevent instability of the control loop at higher harmonic frequencies. The time delay properties of the filters used were calibrated as a function of filter cutoff frequency.

When using the microphone (pressure) signal for feedback, the best control was obtained with the filter set at 250 Hz. This gave a time delay of 7.25 ms and phase lag of 340 deg. The roll off at 262 Hz was 4.1 dB (460-deg lag), and at 393 Hz was 53 dB. The roll off at higher frequencies turned out to be advantageous: later experiments with an all-pass digital delay unit lead to serious acoustic instabilities at frequencies considerably above the resonant frequency. The open loop gain of the transfer function for the system using pressure control is shown in Fig. 3. This transfer function was measured with the flame present by exciting the speaker with broadband white noise and measuring the filtered pressure signal. The gain is given by Eq. (1), the phase angle by Eq. (2), and the coherence γ_2 is calculated as in Eq. (3)

$$|TF| = \sqrt{(G_{ba\,\mathrm{real}}/G_{aa})^2 + (G_{ba\,\mathrm{imag.}}/G_{aa})^2} \qquad (1)$$

$$\phi = \tan^{-1}(G_{ba\,\mathrm{imag.}}/G_{ba\,\mathrm{real}}) \qquad (2)$$

$$\gamma^2 = (|G_{ba}|^2/G_{aa}G_{bb}) \qquad (3)$$

where G_{aa} is the power spectrum of the input (white noise), G_{bb} is the power spectrum of the output (pressure signal), and G_{ba} is the cross spectrum. Both gain and phase give information about poles and zeros of the system and resonant modes. A monotonic decrease in phase angle (except two pi wraparounds) indicate an effect of time delay. Zeros (null points in the gain curve) show up as positive pi jumps in phase angle. A controller is unstable if the phase angle passes pi while the gain is above 1.0. This corresponds to positive feedback. The coherence is a measure of correlation between the output and input, and indicates how deterministic the system is.

The highest gain in the system occurs at the resonant frequency (about 130 Hz). The gain at frequencies below the resonance, and the coherence in that region, is very low because of the roll off of the speaker driver response towards low frequencies. In fact, the driver unit starts to roll off at frequencies above 130 Hz, causing a loss of gain at the resonant frequency where control is needed and an enhancement in gain at higher harmonic frequencies where it is undesirable. Despite these limitations, the system could be made to control stably over a relatively large range of system gain. Speakers that would have had better low-frequency response would have been much larger and more compliant, and these types are not applicable to practical combustor systems. The decrease in gain and coherence above 250 Hz is due to the sharp roll off of the 250-Hz low pass filter (LPF).

The system for CH emission control is also shown in Fig. 1. The photodiode signal is considerably more chaotic than the pressure signal, and it has a very large low-frequency component. For this reason it was necessary to first pass the signal through a high pass filter (HPF), set for 80 Hz, to block out the dominant low-frequency component so that this signal did not limit the system further downstream. Because of the phase lead inserted by the HPF, the LPF had to be set to a lower frequency to add even more phase lag (i.e., delay) to make the system stable. This lead to the system transfer function shown in Fig. 4 (measured the same way as for the pressure-controlled system as described above for Fig. 3). The action of the two filters lead to a very narrow bandwidth and an extremely complex phase relationship.

Both the solid and dashed curves of Fig. 4 were taken with the flame present. By changing the mixture ratio, the coupling between the flame and the vortices could be changed enough to prevent natural oscillations.[25] The onset of self-excited combustion instability depends on the fuel-to-air ratio. The strongest oscillations were obtained near stoichiometric ratio. During combustion instability the combustion occurs in organized periodic vortices. In fact, the periodic heat release is supplying the energy to sustain the pressure oscillations (when the Rayleigh criterion is satisfied). When the mixture is below or above stoichiometric, the flame speed drops and the flame is stabilized further downstream from the exit where the flow is sufficiently decelerated. The flame is stabilized downstream of the vortices, and even though the flow contains some vortical structures, the combustion does not interact with them, thereby eliminating the driving due to the periodic heat release.

The dashed curve was taken with the airflow reduced so that the system did not go unstable. The solid curve was taken with the airflow adjusted upwards slightly, so the system was oscillating at the resonant frequency. Note that the gain is higher throughout the bandwidth of the system (the gap in the solid curve of Fig. 4 is where the gain goes off scale at the resonant frequency). This result is the first that indicates that the system is fluid dynamically, rather than just acoustically, controlled. In a purely acoustically controlled system such a minor change in the fluid dynamics would not lead to a large change in the system transfer function.

Results and Discussion

The normal uncontrolled oscillating mode of the system gave a sound pressure of about 19 Pa at the fundamental

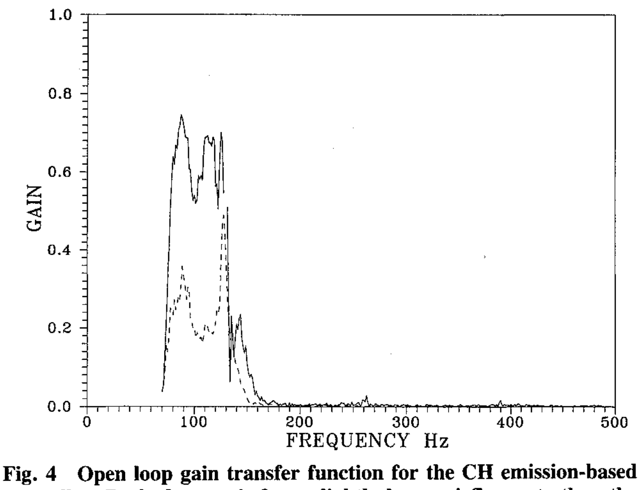

Fig. 4 Open loop gain transfer function for the CH emission-based controller. Dashed curve is for a slightly lower airflow rate than the solid curve.

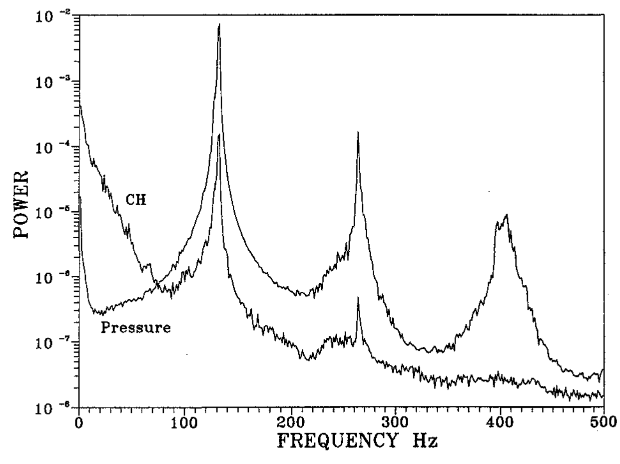

Fig. 5 System power spectra for CH and pressure during uncontrolled operation.

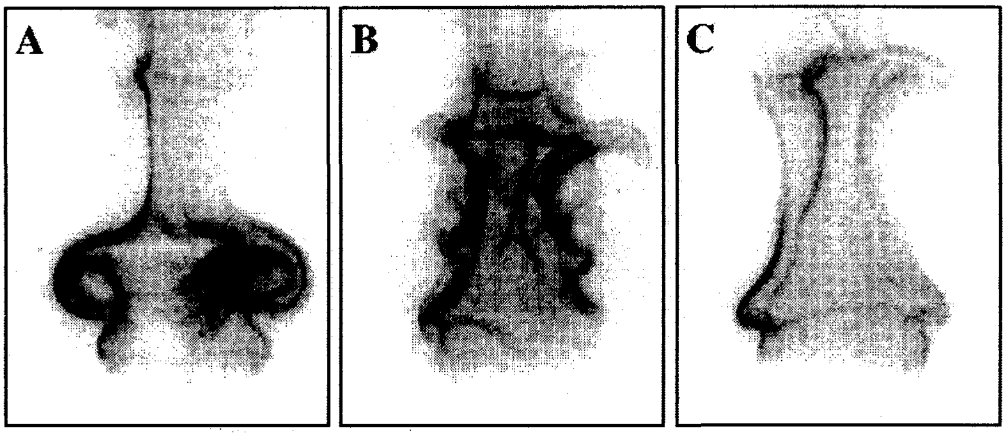

Fig. 6 CH Chemiluminescence image of flame a) during unstable oscillation at resonant frequency, b) during pressure-controlled operation, and c) during CH-controlled operation.

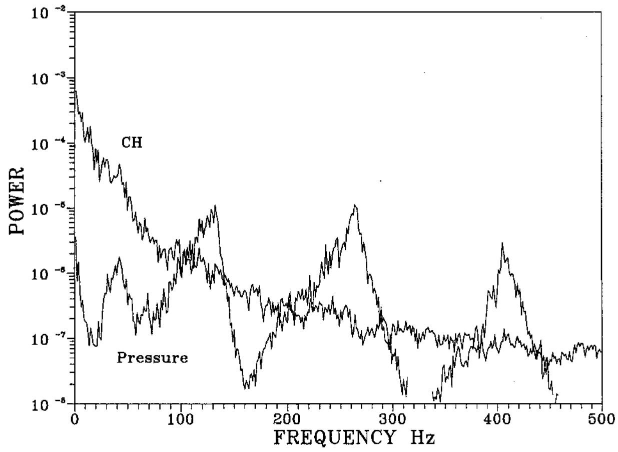

Fig. 7 System power spectra during pressure-based control.

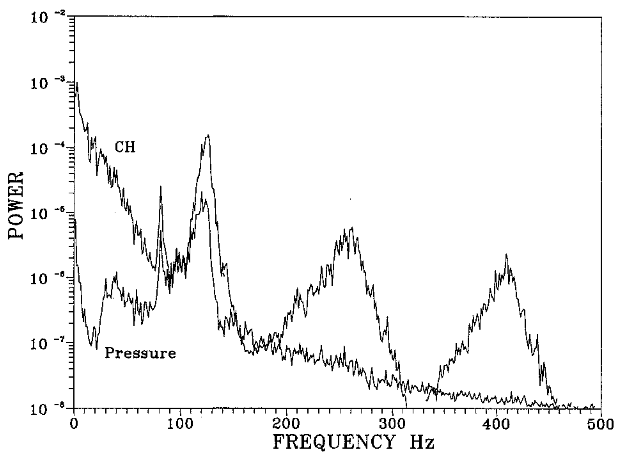

Fig. 8 System power spectra during CH emission-based control.

resonant instability frequency of 130 Hz. The power spectrum is shown in Fig. 5. Figure 6a depicts CH chemiluminescence emission images[25] showing large-scale vortical structures during unstable combustion with the controller off. The combustion occurs in vortical structures and this leads to the same resonant peak (and its harmonics) showing up in both the pressure and CH signals.

When the pressure signal-based controller was turned on, the sound pressure at the resonance fell to about 0.7 Pa for a nearly 30-dB drop, as shown in Fig. 7. The CH intensity at the resonant frequency fell by only 20 dB, but, as shown in Fig. 7, there is essentially no peak left in the CH power spectrum at 130 Hz. The loss of a resonant CH peak corre-

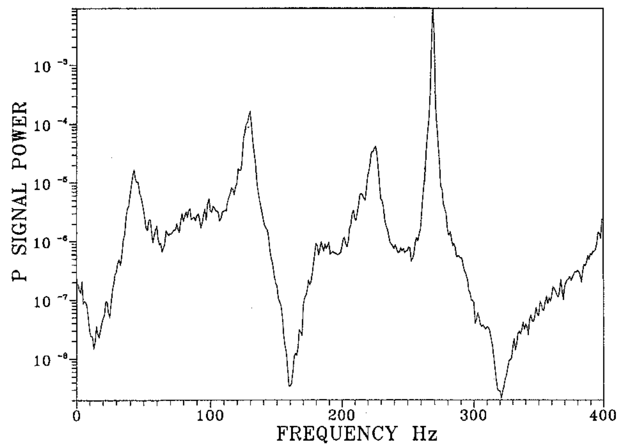

Fig. 9 Pressure signal power spectrum during high-gain pressure control.

sponds to destruction of the coherent vortical structures as shown in Fig. 6b. This clearly indicates that fluid dynamic effects are the source of the instability and the means for its reduction.

When in a pressure-controlled condition, the speaker is controlling the system with a sound pressure level over three orders of magnitude below that present in the uncontrolled mode, both measured at the same point in the duct, so the effect is clearly not just antinoise or acoustic cancellation. If it were, then the speaker would have to be supplying a power level equal in magnitude (and opposite in phase) to the natural acoustic level present during instability. Instead, fluid dynamic amplification greatly reduces the required control power.

The time constant for going from uncontrolled to controlled is about 120 ms (corresponding to about 16 cycles of the instability) and for controlled to uncontrolled about 100–300 ms.[25]

The CH emission signal-based controller is not nearly as efficient at reducing the pressure oscillations as the pressure-based controller. The power spectra for the pressure and CH signal under CH control is shown in Fig. 8. The CH power spectrum still has a significant peak at 130 Hz, and the pressure signal is only reduced by about 15 dB. Notice also the secondary spike at 80 Hz when under CH control; this comes from a latent system instability at its lower bandwidth limit (set by the 80-Hz HPF) that can become unstable at higher system gains.

The CH signal is more chaotic than the pressure signal, and this leads to a lower coherence for the CH controller transfer function with smaller reduction levels and inferior control. With pressure control, however, the duct acts like a prefilter tuned to the resonant peak of the system, and it partially rejects the noncoherent energy in the flame. This leads to a wider latitude for reduction, as there is still a measurable resonant pressure peak above the noise for the controller to lock on to even with a nearly 30-dB reduction in duct acoustic power.

For pressure control (Fig. 7), notice that the harmonic of the fundamental instability frequency is hardly reduced at all when the controller is turned on. At higher system gain levels this frequency can also become troublesome when using the pressure controller.

Figure 9 shows that the controlled system goes unstable at the first harmonic of the fundamental instability frequency when the gain of the system is increased over that used for Fig. 7. The harmonic signal is increased by the controller, and even becomes larger than the fundamental frequency uncontrolled signal. Figure 3 shows that the loop gain is approaching 1 at the harmonic frequency, and if the delay is proper for cancellation of the fundamental (i.e., out of phase), it is necessarily exactly incorrect (i.e., in phase) for the harmonic. Therefore, it is not surprising that when the loop gain is increased, the system goes unstable at the harmonic frequency.

Figure 10 summarizes the effect of system gain on the duct pressure spectral intensities at the fundamental (circles) and harmonic (squares) frequencies. The abscissa of Fig. 10 is speaker amplifier gain only, not system loop gain. Figure 7 was taken at an amplifier gain of 2.2; the fact that the peak system gain shown in Fig. 7 reaches about 2.2 at the resonant frequency is completely fortuitous. Furthermore, because the flame leads to nonlinearities (as evidenced in the difference between the dashed and solid curves of Fig. 4), there is no obvious multiplicative factor between amplifier gain and system loop gain.

Figure 10 shows that for low gains there is virtually no effect on the fundamental instability, and the controller has no effect. As the gain is increased, there is a threshold at which the controller suddenly greatly reduces the oscillations at the fundamental frequency. There is a relatively wide envelope of gains (from 1.2 to 5.0) where the level of the fundamental is held at about 30 dB below the uncontrolled level. At gains above 5, however, the system becomes unstable at the harmonic frequency (260 Hz) and even the fundamental begins

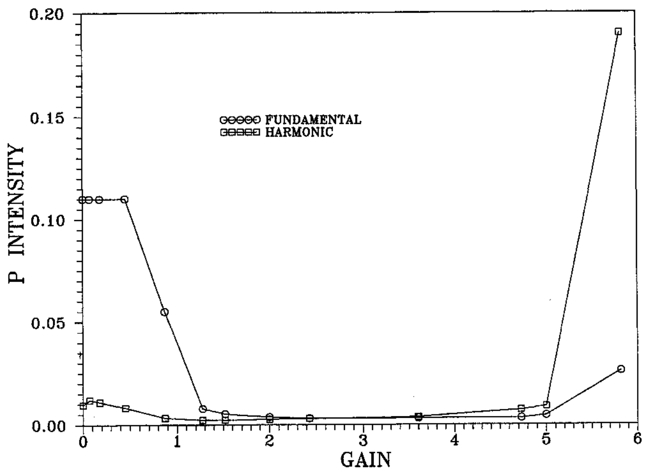

Fig. 10 Peak pressure signal level vs gain for pressure-controlled system.

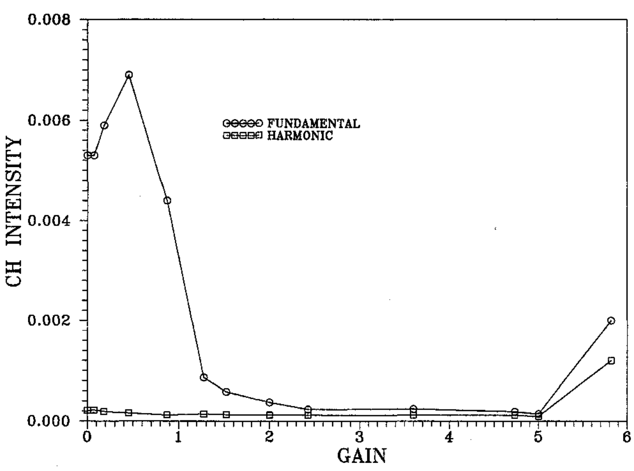

Fig. 11 Peak CH signal level vs gain for pressure-controlled system.

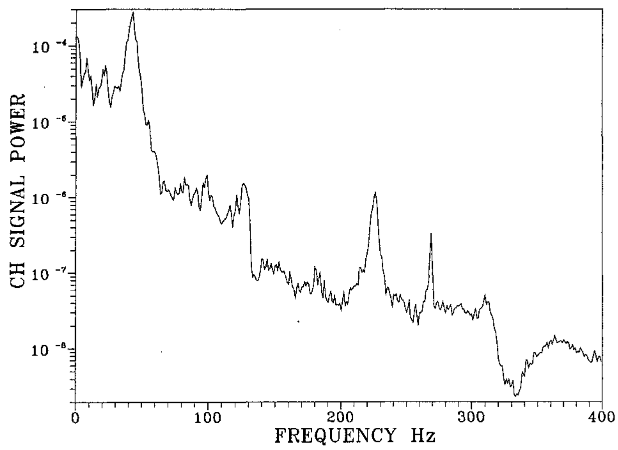

Fig. 12 CH Emission signal power during high-gain operation of shear layer driven pressure-controlled system.

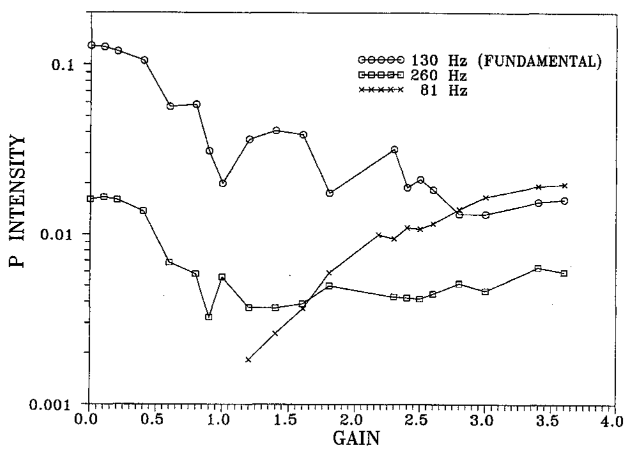

Fig. 13 Pressure signal intensity vs gain for shear layer driven CH emission-controlled system.

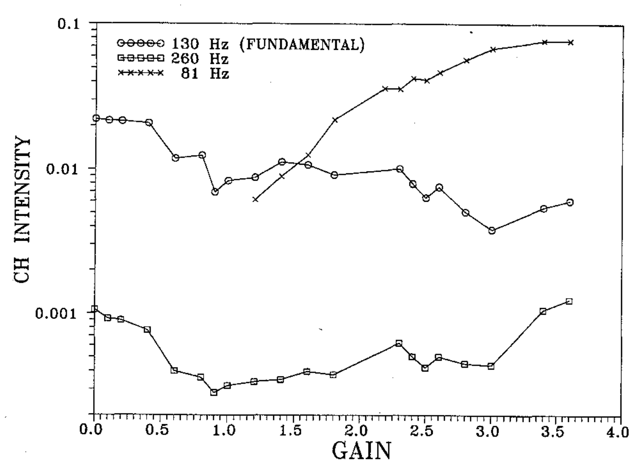

Fig. 14 CH Emission signal intensity vs gain for shear layer driven CH emission-controlled system.

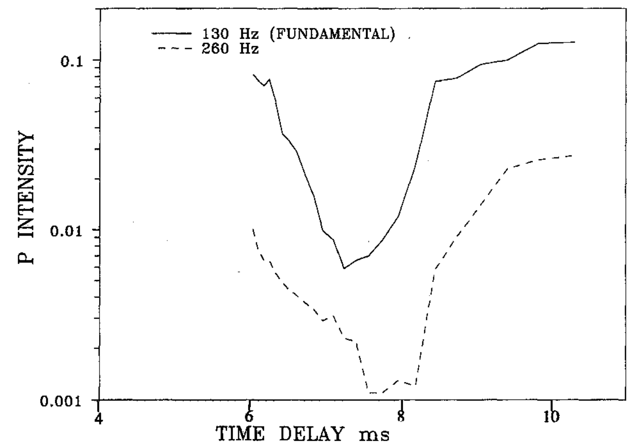

Fig. 15 Pressure intensity vs time delay for shear layer driven pressure-controlled system.

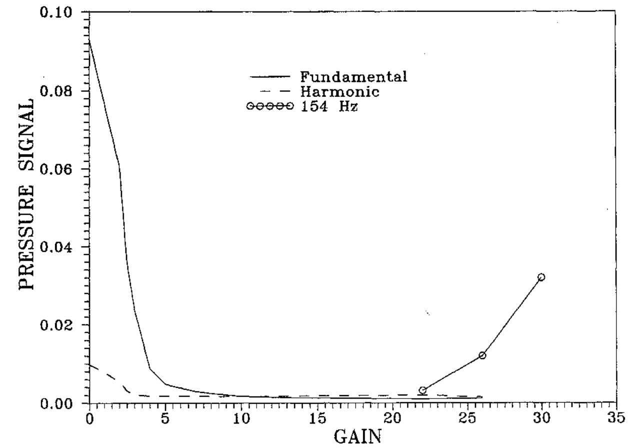

Fig. 16 Pressure signal vs gain for duct driven pressure-controlled system.

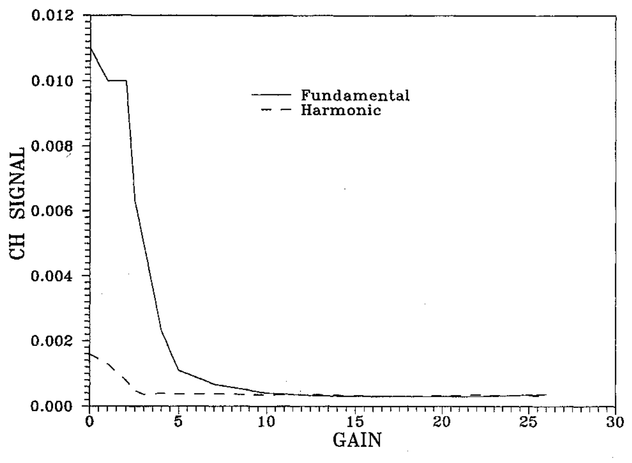

Fig. 17 CH Emission signal vs gain for duct driven pressure-controlled system.

to rise. Figure 11 shows the CH signal for the same range of gains. For some reason, at low gains the CH signal at the fundamental frequency first rises before control takes effect and the oscillation drops. At gains above 5, the fundamental and harmonic begin to rise again, but not nearly as much as in the pressure signal. At the highest gain, 5.8, a subharmonic or nonharmonic becomes very large in the CH power spectrum, as shown in Fig. 12 at about 43 Hz. This signal is so high that it is off scale on Fig. 11. The appearance of 43 Hz in the CH signal (and to a lesser extent the pressure signal, Fig. 9) is all the more surprising, considering that the speaker driver has virtually no output at this low a frequency. This indicates considerable nonlinearities in the system. The 43-Hz signal was shown to be associated with the appearance of very large-scale vortices in the flame.[25]

Figure 13 summarizes the effect of gain on peak pressure signal levels and Fig. 14 on peak CH signals for the system under CH emission control. The drop in fundamental intensity with increasing gain is not as large or as sharp as with pressure control. Furthermore, the system does not go unstable at the harmonic frequency for high gains; instead, the system starts to go unstable at the lower limit of the bandwidth of the controller (81 Hz). This is especially evident in the CH signal (Fig. 14). These curves quantify the previous explanation concerning the inferior performance of the CH-based controller, relative to the pressure-based controller.

Figure 15 shows the variation of fundamental and harmonic pressure levels for the pressure-based controller operating with a speaker gain of 2.2 as a function of time delay. The time delay was varied by changing the cutoff frequency of the LPF, so the frequency response of the system changed markedly with varying delay, and the upper limit of delay is where the cutoff frequency fell below the system resonance frequency. The plot shows a minimum at about 7.25 ms (340-deg phase lag). The presence of a valley indicates the optimum phase angle for cancellation of the resonant instability. The optimum time delay for the controller is related both to acoustic and convective time delays in the system. Cancellations of the fundamental resonance also leads to reduction of the harmonic; the valley in the harmonic curve (dashed line) is slightly skewed towards higher delays because the higher delays are associated with lower filter cutoff frequencies and larger rejection ratios at the harmonic frequency.

We also investigated duct acoustics control to compare it with the shear layer control method. The driver speaker was used to force the duct at the $\frac{1}{4}$-L point (the glass duct was replaced with a same size metal one in these experiments and L was the duct length). The forcing point was $\frac{1}{4}$ the length down from the exit of the duct (i.e., opposite the end with the burner). The driver was mounted perpendicular to the duct. Poinsot et al.[16] point out that a side-mounted speaker excites mostly plane-mode duct waves, and that any transverse modes die out quickly. As expected from Rijke tube theory, the $\frac{1}{4}$-L point was determined to be the highest gain driving location.

The duct acoustics controller works properly in this configuration but, as Figs. 16 and 17 show, much higher speaker power levels were required. The rejection of the fundamental was slightly higher (40 dB) than for shear layer forcing (30 dB). At the high end of the gain curve the system went unstable at 154 Hz, which is not harmonically related to the preferred mode of the jet, or the acoustic modes of the chamber. We did not pursue duct forcing further, as the increase in driving requirements over shear layer forcing would be a serious drawback when scaled up to dump combustors and ramjets with much larger heat release and mass flow values.

Conclusions

We have shown that stable control of a naturally unstable ducted premixed flame is possible with forcing of the flow shear layer or acoustic cancellation in the duct itself. Either the duct pressure or flame CH emission could be used as a feedback signal. Pressure signal feedback and shear layer excitation was found to be the best combination, and it was able to reduce the oscillations in the duct by nearly 30 dB while requiring only minimal power delivered to the driver. When controlling the system the acoustic output of the driving speaker, measured in the duct in the absence of the flame, is over three orders of magnitude below the uncontrolled oscillation level. The control is clearly fluid dynamic in nature and not just acoustic noise cancellation. Fluid dynamic amplification allows much lower control powers to exercise authority over the system.

Images of CH chemiluminescence show that the natural instability is associated with combustion in large-scale vortices. The periodic heat release leads to coupling with the resonant acoustic mode of the duct giving a positive feedback mechanism that excites oscillations in the duct. The controller successfully prevents the roll up of these vortices and stabilizes the system.

The application of duct excitation was found to require much higher forcing power, and therefore, would be of limited usefulness in systems with high-heat release because the acoustic power required would be too high.

Using the CH emission signal for feedback was also found to have limited usefulness due to the more chaotic nature of this signal. This is because the CH emission signal is more directly coupled to the vortical structure. The chaotic nature causes lower coherence of the controller transfer function leading to inferior control. The noise floor of the pressure signal is much lower than that for the CH signal, so the pressure-based controller can create larger reductions and still have a measurable resonant signal above the noise to lock onto.

The operating range of the controlled system, for variable loop gain, is limited by the appearance of instabilities at harmonic, subharmonic, or anharmonic frequencies, depending on the forcing location (shear layer or duct) and the feedback signal (pressure or CH).

Finally, the ability to have nearly instant electronic control over a naturally unstable combustion system affords a good tool for the study of transient behavior in combustion instabilities.

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