Combustion Control and Its Effect on Jet Plume

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ABSTRACT

Three case studies of combustion control are presented that involve organized large coherent structures in the reacting flowfield. In the first case, open-loop acoustic excitation technique was used to organize reacting shear layers into large coherent structures and thereby increasing the volumetric heat release by nearly 40%. Such result could be used to optimize the combustor size. In the second case, a closed-loop feedback control technique was used to dynamically pulse a secondary fuel injection at proper timing with respect to pressure oscillations. This resulted in suppression of combustion instability, reducing peak spectral amplitude of pressure by nearly 20 dB while breaking up large coherent structures associated with combustion instability. Active suppression of combustion instability was for extending combustor operating ranges, but it could be applied to reduce combustor generated noise as well. In the last case, flow-induced cavity resonance was used to set up large coherent structures into supersonic plume mixing layer. The large coherent structures increased the growth rate of compressible mixing layer, depending on frequency. The highest growth rate was observed at the Strouhal number corresponding to the jet-preferred mode. For model afterburning plumes, the intensity of afterburning was modified substantially. Over the range of conditions studied, afterburning intensity was reduced with low-frequency excitation while it was increased at high frequencies. The transition from suppression to amplification occurred at the jet-preferred mode frequency. Since plume afterburning also generates intense acoustic noise, it may be possible to reduce plume noise by controlling the plume afterburning with large coherent structure excitation. The results of these studies open up the possibility of controlling both the combustion core noise and the jet exhaust noise using combustion control. Coherent structures appeared to play a key role in the three cases presented.

1.0 INTRODUCTION

Research and development efforts on combustion control have been motivated by the desire to enhance combustor performance such as suppressing combustion instability, reducing pollutant emission, increasing volumetric heat release, and extending flammability limits. Previously, quantitative improvements in specific performance areas have been demonstrated using various model combustors. Thorough understanding of the basic combustion and mixing processes has proven critical in properly applying combustion control techniques for each specific objective.

In this paper, combustion dynamics that may affect noise generation both in combustion core and jet exhaust will be discussed. In particular, effects of large coherent structures on potential noise generation mechanisms are analyzed using three examples of combustion and mixing control studies previously conducted by the author. The examples are two combustion control studies involving both open-loop and closed-loop control as well as one supersonic mixing control involving passive excitation.

The goal is to show a possible connection between combustion control and its potential for suppressing propulsion noise. Also, the role of large coherent structure in control mechanism is to be highlighted as it appears that the coherent structures played a key role in all these example studies.

2.0 ACTIVE COMBUSTION CONTROL

In active combustion control, combustion performance is regulated using dynamic actuators that can rapidly modify combustion input at repetition rates comparable to the system acoustic time scales. Active combustion control is particularly attractive in that it can modify the dynamics of the combustor with controlling a small amount of combustion input such as oscillating flow rates or acoustic pressures without affecting the overall operating conditions or fuel consumption rates.

Active combustion control can be classified into open-loop and closed-loop controls depending on the presence of feedback control circuit. In the following, several example studies of combustion control are presented.

2.1 Open-Loop Control of Volumetric Heat Release (Premixed Flames)

In propulsion systems where space is premium, increasing the volumetric heat release of a combustor can be an important consideration. Acoustic forcing or periodic fuel injection approaches are utilized to organize coherent structures or large vortices, which are then manipulated to obtain desired mixing characteristics. Typically, dynamic response of reacting shear layers is sensitive to flow excitation frequency. Even a small amount of excitation, typically less than a few percent of the mean flow velocity, can dramatically alter the flow field increasing the entrained volume significantly at certain frequencies [1]. The change is produced by organized vortical structures that become highly dispersive under certain wavelength conditions. The most interesting conditions occur when forcing is applied at a Strouhal frequency, which is based on the jet diameter, ranging between 0.24 and 0.64 [2].

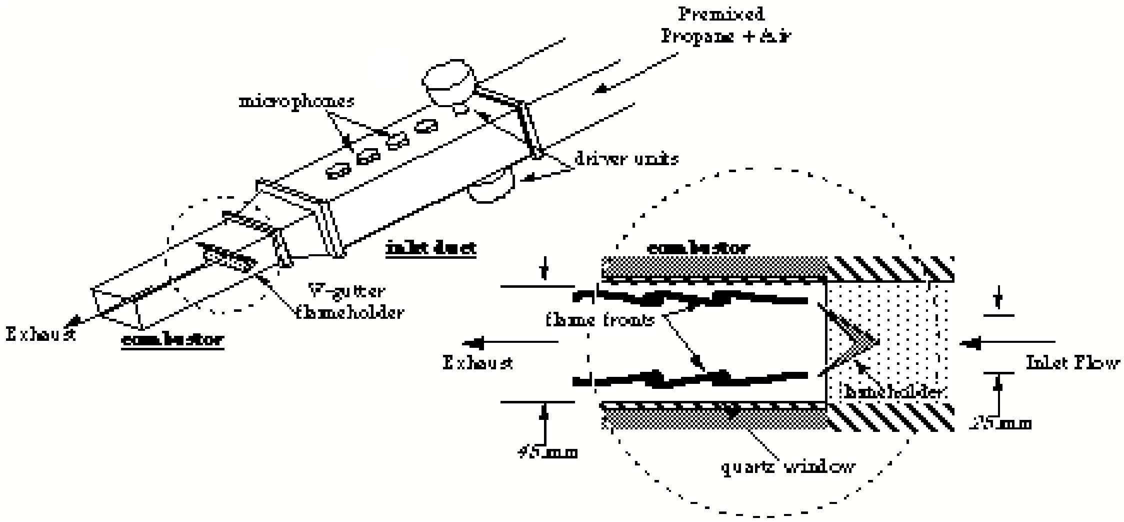

Figure 1: Open-loop active control experiment of Yu et al. [Ref. 3]

Yu et al. [3] studied the effect of acoustic forcing on volumetric heat release using a bluffbody flameholder combustor. An acoustic driver was used to impose periodic acoustic forcing to the premixed propane-air flow over a wide range of frequencies. The combustor set-up featuring a V-shaped flameholder is shown in Fig. 1. The results showed that acoustic forcing in the proper frequency range, accelerated the small-vortex growth in the initial shear layers, creating large-scale coherent vortical structures as shown in Fig. 2. The early entrainment by faster growing vortices broadens the reaction zone, and the continued entrainment by propagating large-scale vortical structures improves the mixing between fresh reactant and hot product gases in the reaction zone.

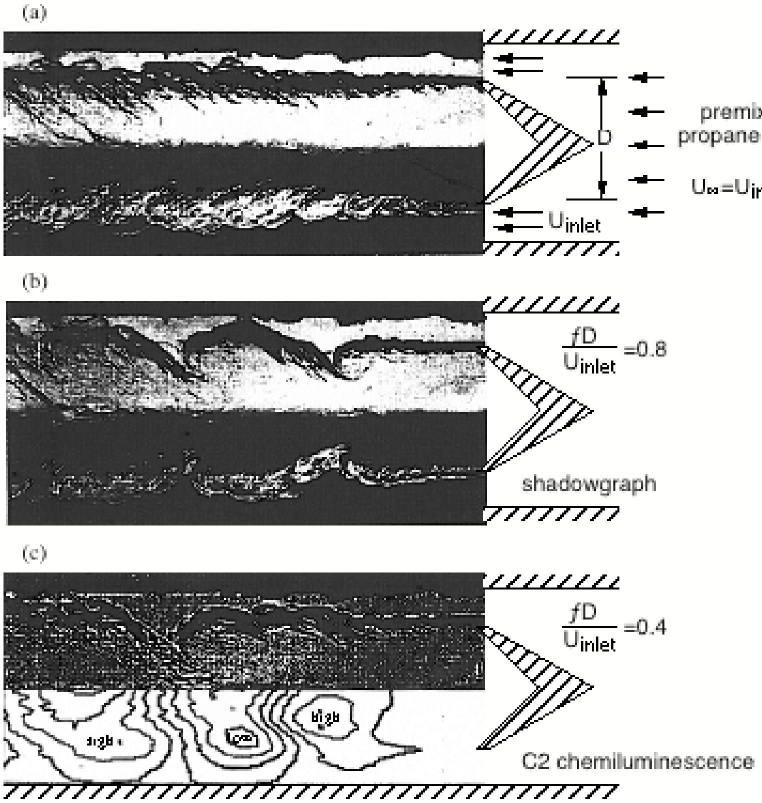

Figure 2: Flame structures associated with open-loop combustion control. [Ref. 3] Reynolds No. = 60,000, u'/U~0.1 (a) Baseline case with Strouhal No., ƒD/U =0, (b) Strouhal No. = 0.8, and (c) Strouhal No. = 0.4.

The results showed that the optimum frequency for enhancing the volumetric heat release was related to the hydrodynamic features in the reaction zone. A comparison with the baseline case revealed a substantial increase in volumetric heat release along with a reduction in the reaction zone length. The amount of increase in volumetric heat release, deduced from time-averaged C2 emission measurements, was around 40 % as shown in Fig. 3.

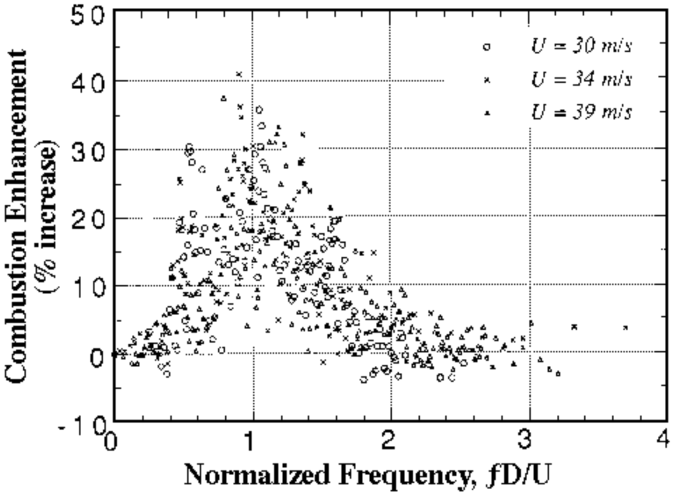

Figure 3: Increase in volumetric heat release due to actively controlled large coherent vortices. [Ref. 3]

2.2 Synchronized Injection of Fuel and Air (Diffusion Flames)

As shown in the previous example, an open-loop control for premixed flames targets the mixing between the reactants and the products. In a diffusion flame set-up, the mixing between fuel and oxidizer can be controlled in a similar manner. Figure 4 shows an actively controlled 50-kW diffusion flame burner investigated by Yu et al. [4] By acoustically forcing both the fuel flow and the air flow separately and controlling the timing between the two, dynamic interaction between the two reactant streams was controlled. This control process allowed a timed injection of fuel jet into air vortex.

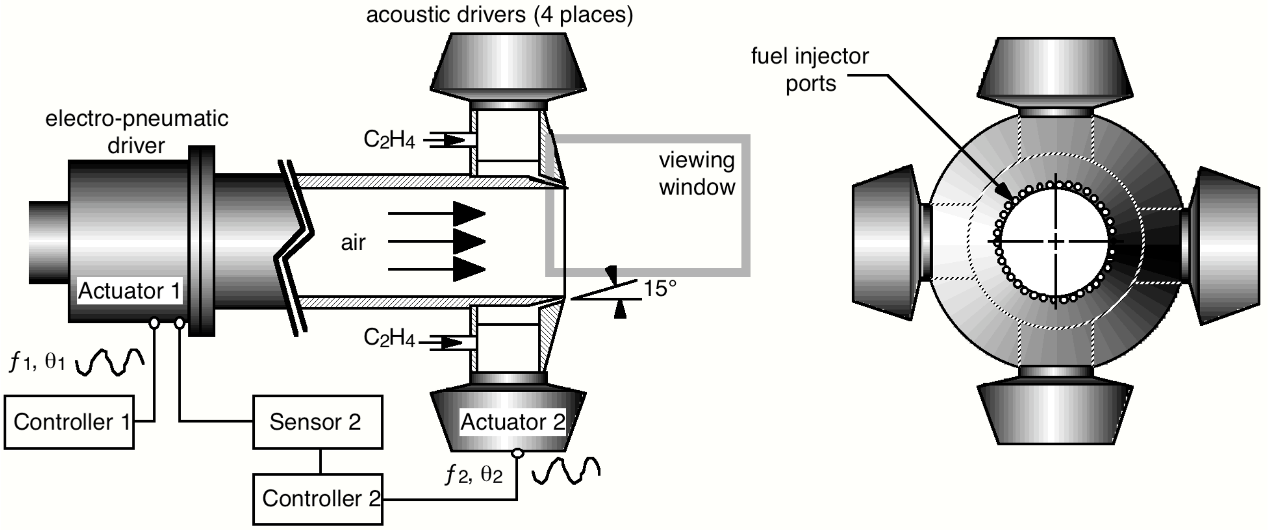

Figure 4: Actively controlled burner experiment from Yu et al. [Ref. 4]

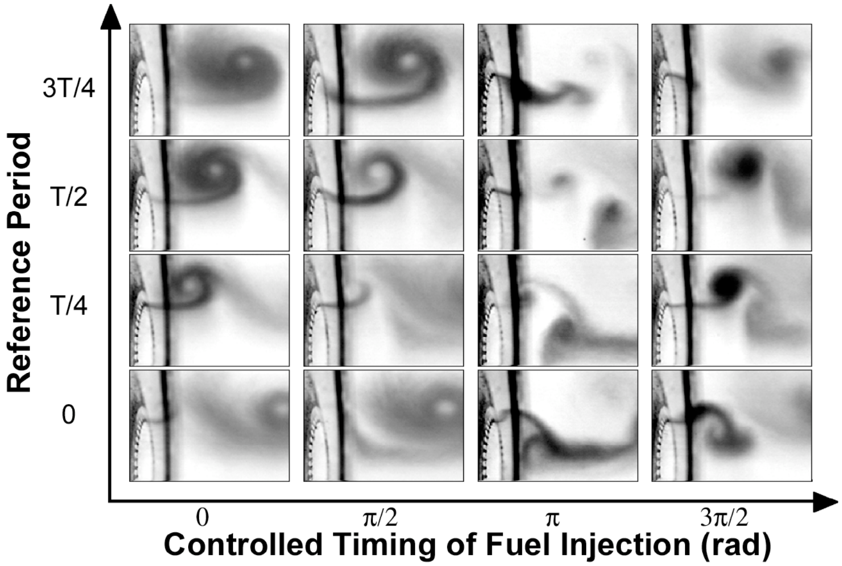

Figure 5: Phase-lock-averaged fuel dispersion pattern as a function of fuel injection timing and vortex shedding phase. [Ref. 4]

A sequence of phase-lock-averaged Mie-scattering images showing the concentration of fuel is shown in Fig. 5. The timing of fuel injection was closed-loop controlled with respect to the air vortex shedding. For example, when the timing was π/2, fuel injection cycle followed that of the air vortex formation. The fuel flow was stretched by the higher-than-average local airflow speed stimulating the turbulent mixing between fuel and air. It resulted in volumetrically efficient flames with little soot production. On the other hand, when the fuel injection timing led the air vortex formation by π/2 (timing=3π/2), a pair of counter-rotating fuel vortices were observed between the air vortices. The result was inefficient sooty flames as shown in Fig. 6.

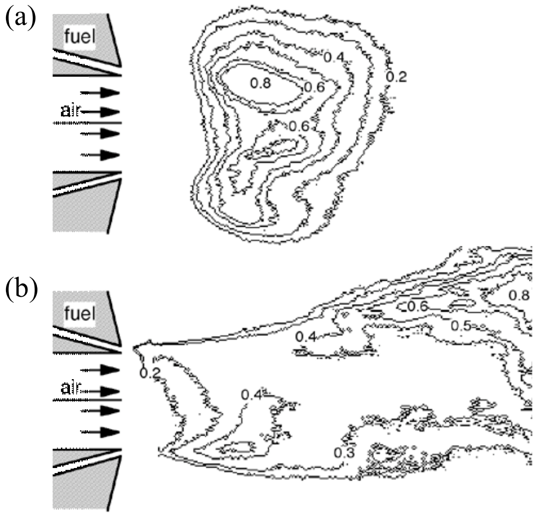

Figure 6: Actively controlled diffusion flames. [Ref. 4]
(a) CH-chemiluminescence intensity contour
(b) Soot incandescence intensity contour

2.3 Closed-Loop Control of Combustion Instability (Two-Phase Flames)

Low frequency combustion instabilities in dump combustors have been studied previously and large coherent structures were shown to be important in driving these instabilities. [5,6] To suppress such instabilities using realistic fuel, Yu et al. [7] studied vortex-droplet interaction mechanism as a means to control fuel droplet dispersion inside an axisymmetric dump combustor, which is shown in Fig. 7. The spatial and temporal distribution of fuel droplets in the combustor as a function of pulsed injection timing is shown in Fig. 8. The vortex shedding process was used as a reference for fuel injection timing. Subsequent experiments revealed that instability was suppressed when the controller fuel was injected in advance of the vortex shedding or synchronized with the vortex shedding event. Adjusting the fuel injection timing to follow the vortex shedding, on the other hand, resulted in higher amplitude oscillations.

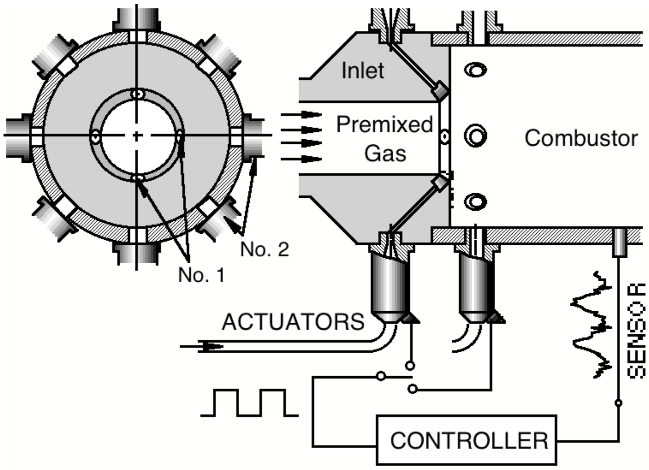

Figure 7: Liquid-fueled closed-loop combustion control experiment from Yu et al.. [Ref. 7]

While the precise timing for proper fuel injection must be rig-dependent, the above experiments shed new light on the physical mechanism. Heat release oscillation in a premixed combustor goes through the low cycle in the leading part of the vortex and the high cycle in the trailing part of the vortex. This is caused by the entrainment of the fresh reactants by vortex action, which initially lowers the temperature in the leading part of the vortex. As the entrained reactants mix with the high temperature products in the trailing part of the vortex, the local heat release cycle goes up. Then, the strategy for active fuel injection is to deliver additional fuel in the leading part of the vortex, where the heat release oscillation tends to be in the low cycle without

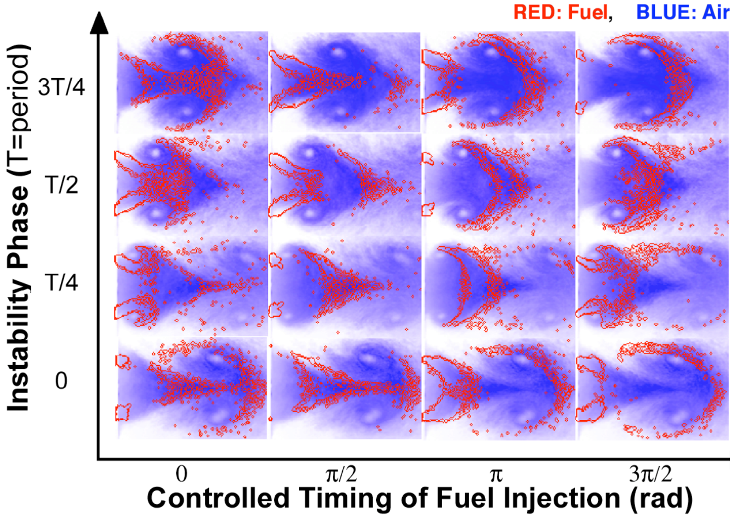

Figure 8: Controlled fuel droplet dispersion (shown in red) with respect to large coherent structures (blue) as a function of various fuel injection timing. [Ref. 8]

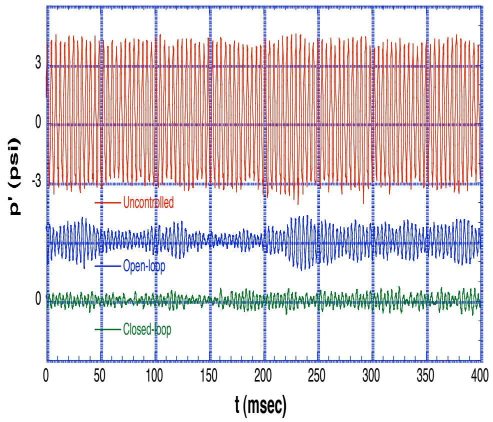

Figure 9: Comparison of uncontrolled and controlled pressure oscillation amplitudes. [Ref. 9]

the additional supply. This would reduce the amplitude of heat release fluctuation, thus leading to potential instability suppression. The relative amplitudes of combustor pressure oscillations are compared in Fig. 9. The reduction in spectral amplitude at the instability frequency was around 20 dB.

3.0 PLUME AFTERBURNING CONTROL

In an application where active combustion control is not very practical, a passive control approach can be considered to organize large coherent structures. For this example, a supersonic plume is to be examined. Far-field noise intensity is often linked to development of large-scale coherent structures in the jet. Thus, in a narrow point of view limited to potential sources of noise generation, the presence of large coherent structures may be less than desirable. However, when afterburning flames are involved, the consideration of combustion noise may outweigh the jet noise consideration.

An example study in this section examines passively excited supersonic afterburning jets studied by Yu et al.

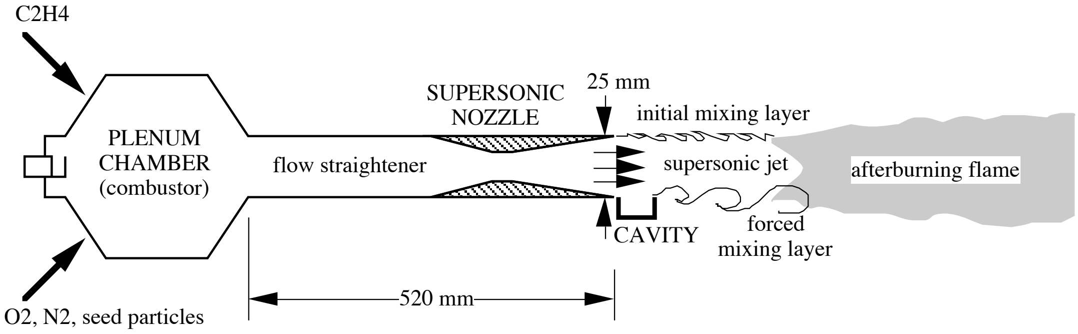

Figure 10: Passive excitation of supersonic plume experiments by Yu et al. [Ref. 10]

[10-12] Schematic of the supersonic plume setup is shown in Fig. 10. An annular or semi-annular cavity placed at the plume exit was designed to produce flow-induced cavity resonance, which in turn was used to passively excite the plume mixing layer. Because the main focus of the study was regarding potential effects of excitation on afterburning reaction, noise measurements made at the time of the investigation are somewhat limited. In Fig. 11, near-field noise spectra for nonreacting and reacting cases are compared. Passive excitation was conducted at frequencies close to the jet preferred mode. For non-afterburning plumes (Fig. 11a), passive excitation resulted in much higher level of noise intensity at all spectrum. For reacting plumes (Fig. 11b), except at the forcing frequency, the noise spectrum appeared to be affected more by the afterburning intensity. In general, any case involving afterburning reaction generated much more intense noise than the corresponding non-reacting plumes.

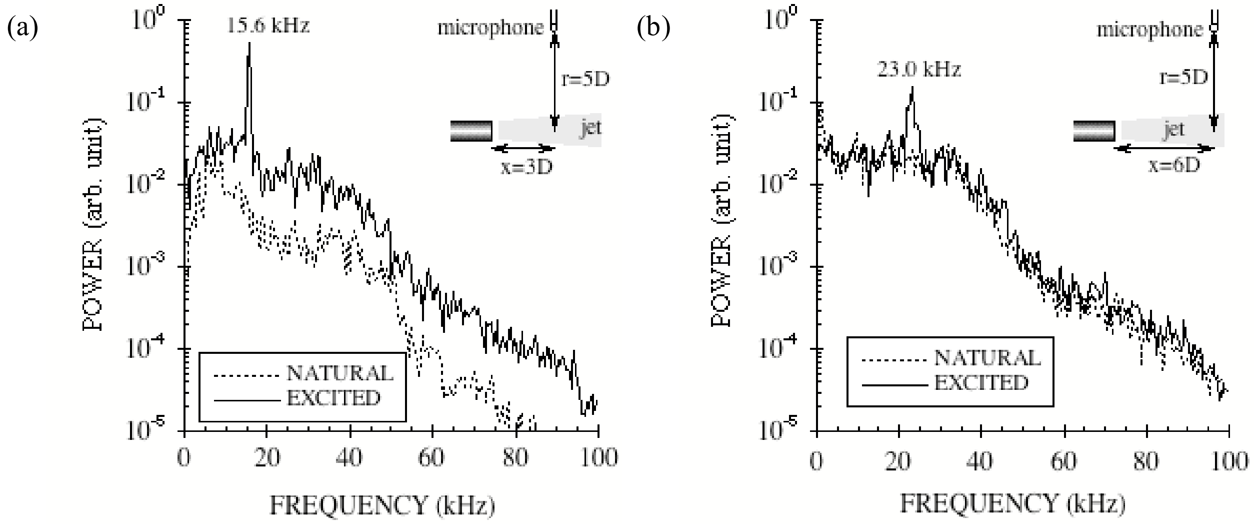

Figure 11: Near-field noise spectra comparing the natural and the excited cases. [Ref. 11]
(a) Non-reacting plume, (b) Reacting plume

Both the afterburning intensity and the flame lift-off height at the exhaust nozzle base were affected by excitation. Their frequency dependency is shown in Figs. 12 and 13.

4.0 CONCLUDING REMARK

From the examples considered in this paper, it is clear that large coherent structures substantially affect turbulent mixing and combustion processes. Numerous combustion control techniques in the past relied on manipulating coherent structure as a means to affect combustion processes. Also, the link between large coherent structure and non-reacting jet noise is fairly well established. Lastly, combustion processes in general tend to amplify the acoustic noise, as even a small amount of chemical energy fluctuations can be orders of magnitude larger than total acoustic energy available in the noise spectrum.

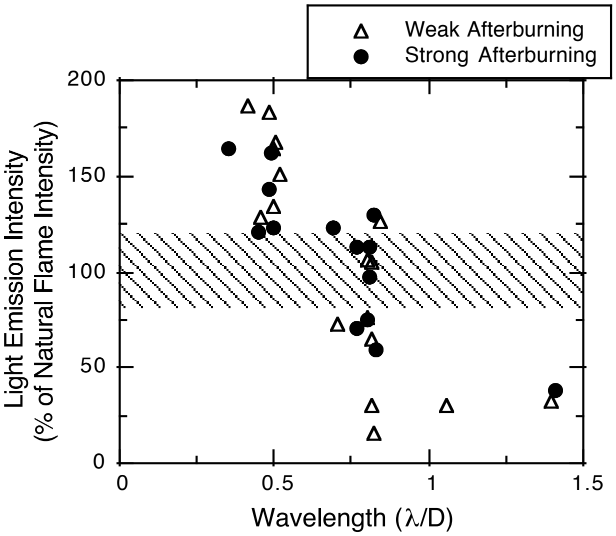

Figure 12: Change in afterburning intensity from excited plumes as a function of large coherent structure wavelength [Ref. 12]

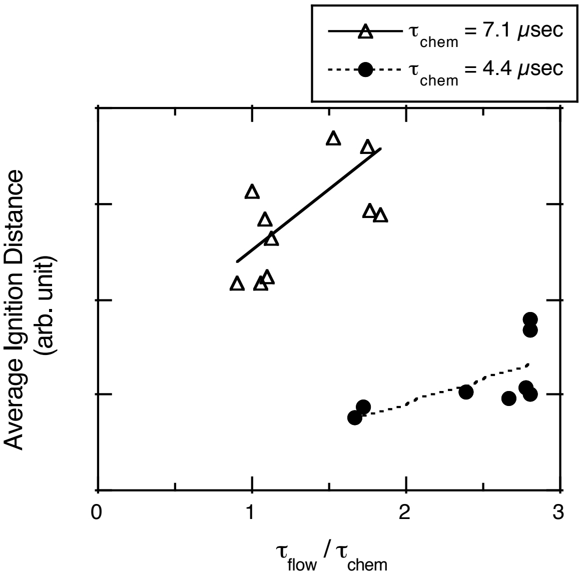

Figure 13: Change in flame liftoff height as a function of forcing period [Ref. 12]

Considering these close relationships between coherent structure and combustion control, between noise and coherent structure, and between noise and combustion processes, it seems logical to consider combustion control as a means to optimize noise suppression. Combustion control techniques in the past have been considered mainly for the purpose of improving combustor performance such as improving volumetric heat release, suppressing combustion instability, extending flammability limits, and reducing signature and pollutant emission. Combustion control for noise suppression is one area which has enough potential but has not been explored sufficiently. At minimum, combustion control can be used to affect combustion related noise sources such as combustor core noise and afterburning plume noise.

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