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ACTIVE CONTROL OF COMBUSTION INSTABILITY IN A LIQUID - FUELED LOW - NO_X COMBUSTOR

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ABSTRACT

A practical active control system for the mitigation of combustion instability has been designed and demonstrated in a lean, premixed, single -nozzle combustor at realistic engine operating conditions. A full -scale engine fuel nozzle was modified to incorporate a simple fuel flow actuator. Results indicate that the system was capable of reducing pressure fluctuations by 82% (15 dB or 5.6X) while maintaining or reducing NO_X and CO emissions levels.

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 NO_X 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, United Technologies Research Center (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 initial focus of this research was on a liquid - fueled low - NO_X combustor. This combustor exhibited a large- amplitude (p'/p ~10%) instability at a frequency of approximately 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 NO_X levels. The effort stressed the practicality of the system and its ability to work with full-scale engine hardware at realistic operating conditions.

EXPERIMENT AND INSTRUMENTATION

Experiments were conducted in a single - nozzle, flametube combustor (see Fig. 1). The nominal energy conversion rate of the single-nozzle combustor was 4 MW. The combustor used fuel nozzles designed for engine use and ran at engine operating conditions (pressure, temperature and flow rate per injector). The fuel nozzles were designed to provide a high degree of fuel - air mixing and have been discussed thoroughly in previous papers (Snyder, et. al, 1994). Figure 2 shows a schematic of the fuel nozzle. Liquid fuel (No. 2 Diesel fuel) was injected through six axially - oriented "spokes" protruding from the nozzle centerbody. High-pressure-drop spray tips were installed at the end of each spoke. The 15.2 cm. - diameter combustor test section was water-cooled with a thermal barrier coating on the inner wall. A pilot fuel injector was located 2.5 cm. downstream of the combustor dump plane. A water - cooled orifice plate provided a choke point to simulate the acoustic boundary of the engine's turbine inlet guide vanes. Upstream of the combustor, the air flow rate was metered using a choked venturi.

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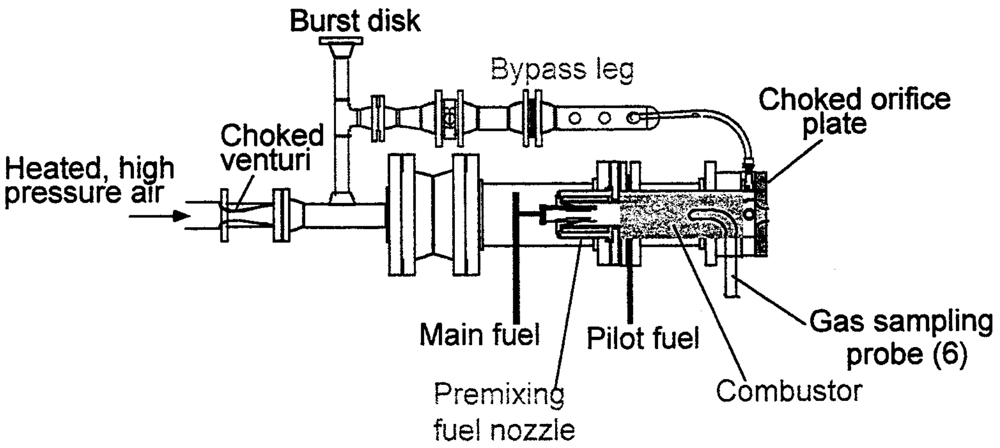

Figure 1. Schematic of single - nozzle combustor rig. Test section diameter = 15.2 cm. For clarity, only one of the 6 sampling probes is shown.

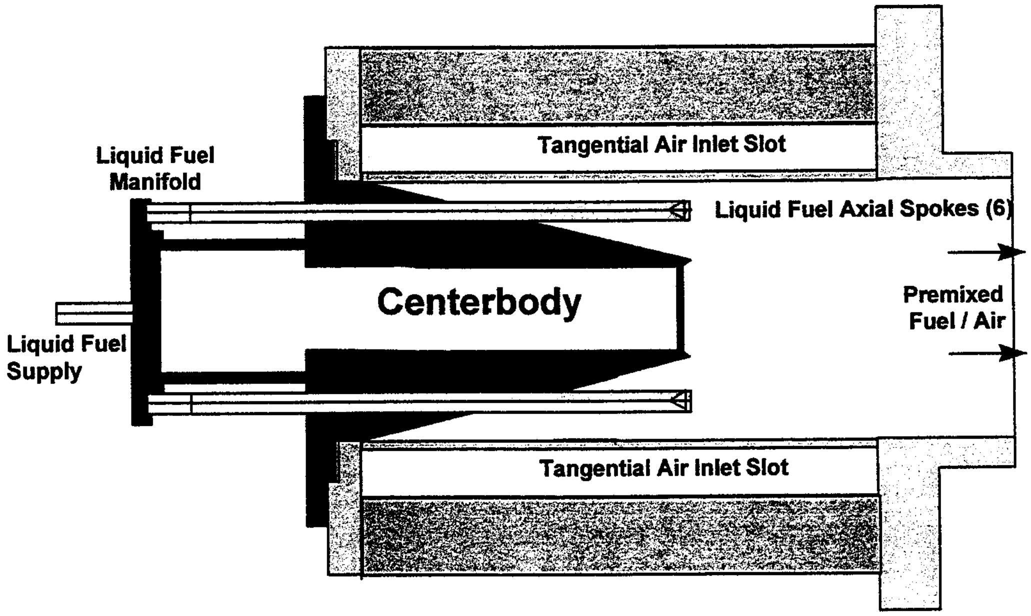

Figure 2. Schematic of tangential - entry fuel nozzle, showing liquid fuel injection spokes.

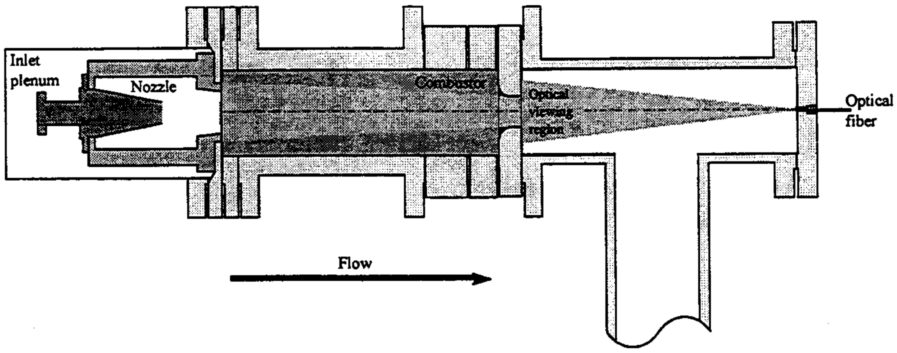

Figure 3. Layout of fiber - optic viewing region for measurement of combustor heat release rate.

After passing through the venturi, the air flow was split between the fuel nozzle and a bypass leg. The air that flowed through the bypass leg was injected at the downstream end of the combustor (upstream of the orifice plate), representing combustor dilution air.

The volumes and lengths of the combustor, diffuser region upstream of the fuel nozzle and bypass leg were set in order to reproduce the instability observed in a full - annular engine combustor.

An array of six gas - sampling probes, located upstream of the bypass air injection was used to measure NO_X and CO concentrations as well as combustor fuel/air ratio and combustion efficiency. Species concentrations are reported here in ppm on a 15% Oxygen basis for a ganged probe arrangement. High-response data were collected at a rate of 5 kHz on a simultaneous sample-hold data acquisition system. The analog signals were low-pass filtered at 2 kHz to prevent aliasing. Fluctuating pressures were measured at two locations in the combustor using high - response pressure transducers. A photomultiplier tube (PMT) was used to measure the intensity of CH and CO radical emissions in the combustor. Light was collected using a fiber optic probe "looking" upstream through the orifice plate at the fuel nozzle (see Fig. 3). This orientation allowed the PMT to "see" the majority of the combustor. A 200 µm diameter quartz fiber with a numerical aperture of 0.37 viewed through a flange in the exit plenum and was directly coupled to the PMT. With a small amount of air purge, this probe required minimal access to the combustor and provided sufficient signal to monitor the emissions from the flame. A bandpass optical filter was installed to selectively admit only those wavelengths associated with CH and CO emissions (430 nm). 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). As such, this measurement yields a time-responsive, volume-averaged measurement of the combustor heat release rate. Control signals, indicating the commands sent to the actuation system, were also recorded.

CHARACTERIZATION OF THE INSTABILITY

The frequency of the primary mode of instability varied from 180 Hz to 220 Hz, depending on the test conditions. Secondary modes are present at higher frequencies, but are smaller in magnitude and of less interest here. Figure 4 shows power-spectral density (PSD) plots of the combustor pressure and the heat release rate during instability. These data are presented on a decibel scale, where the fluctuations are normalized by a reference value and represented on a logarithmic scale:

$$dB = 20 \log_{10}\left(\frac{P'}{P_{ref}}\right)$$

A similar expression was employed for the heat release values.

For fixed inlet pressure and temperature, the magnitude of the instability grew with decreasing fuel/air ratio, as shown in Fig. 5. This feature of the instability limited the lean-ness of the usable mixture, and therefore the level to which the NO_X emissions could be reduced. Application of a steady, sidewall diffusion flame pilot reduced the magnitude of the instability, but resulted in increased NO_X emissions.

The instability mode of interest (~200 Hz) was a bulk mode, characterized as a Helmholtz resonator / spring -mass system in which the combustor volume represented the spring and the masses of gas in the fuel nozzle and the exit orifice represented the masses. Pressure fluctuations were coupled with the heat release process through their effect on the flow rate of air delivered through the fuel nozzle. Time-varying air flow rate led to time-varying equivalence ratio and, therefore, time-varying heat release rate. This conceptual model of the instability is discussed in more detail in Peracchio and Proscia (1998). Additional control - oriented modeling is currently being performed at UTRC using describing function analyses.

DESCRIPTION OF THE CONTROL SYSTEM

The control system consisted of three parts: a sensor to measure the state of the system, a control algorithm to determine the required action, and an actuator to achieve that action. The high-response measurements of combustor pressure and heat release rate had illustrated their capability for tracking the instability with high signal / noise ratio and were both available as control sensors. A variety of control algorithms, ranging from simple phase-shifting algorithms to more complex adaptive algorithms were available for implementation, depending on the need. It was apparent that the critical component was the actuator.

The initial requirements for the actuator were two-fold: it had to be able to affect the dynamics of the combustor system at the 200 Hz frequency and it had to be able to endure the operating environment in which it was placed. In addition, it was preferable that the device be simple and easy to control. Previous applications of active control to combustors have been in lab-scale devices operating at capacities, pressures and temperatures significantly lower than those considered in this study (see Yu; 1997, Billoud;1992 ,McManus;1997, Richards;1995, Zinn; 1997, Hantschk; 1996).

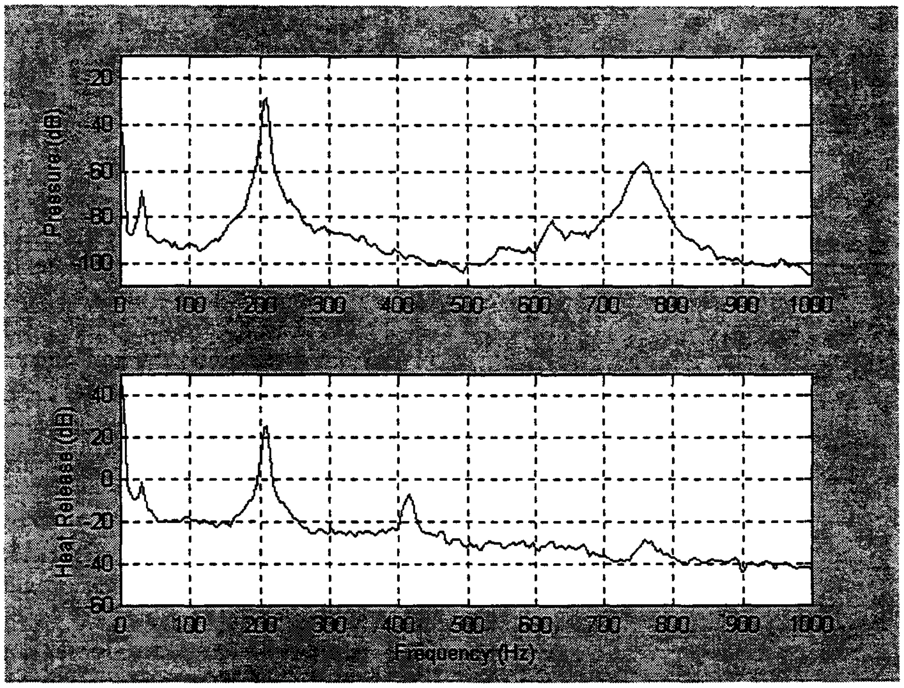

Figure 4. Combustor pressure and heat release spectra for uncontrolled combustion at an equivalence ratio of 0.51.

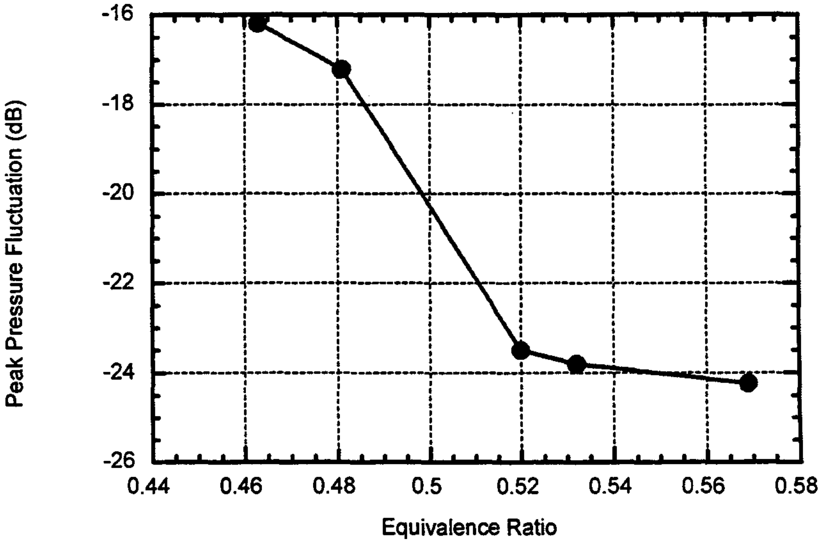

Figure 5. Effect of equivalence ratio on level of combustor pressure fluctuation in the 200 Hz mode.

The high power output (4 MW per nozzle), inlet operating pressure (1.7 MPa) and temperature (730K) of this application eliminated many of the actuation concepts used in these studies from consideration. Actuation of the combustor air flow rate was considered, but it was determined that the durability of this scheme would be inadequate, again due to the high operating temperature. Other, more sophisticated actuators were discarded due to the level of complexity they introduced into the problem. Actuation of the fuel flow remained as a viable candidate. Several configurations of fuel actuation were designed and tested. Only one will be discussed in this paper.

One of the six spokes delivering fuel into the premixing fuel nozzle was disconnected from the main fuel system and was connected to a separately - metered fuel system (see Fig. 6). A high -speed solenoid valve was installed in this system external to the combustor rig, so as to isolate it from the high operating temperature. The volume of tubing between the valve and the fuel injection location was minimized in order to reduce attenuation and time lag due to capacitive effects. An accumulator was installed immediately upstream of the solenoid valve to minimize supply pressure variations. No direct measurement of the time-varying fuel flow rate was made. Open - loop testing of the flow system indicated that the valve responded at frequencies up to approximately 250 Hz, which determined the maximum operating frequency.

Open - loop actuator authority tests were conducted under reacting conditions. In these tests 1/6 of the total fuel flow rate (time-averaged) was delivered through the control fuel system. The remainder of the fuel was delivered through the other five spokes. The solenoid valve was driven at different frequencies, independently of the combustor behavior, using a signal generator. The on/off duty cycle was maintained at 50%. The response of the combustor pressure and heat release rate were then measured. Figure 7 shows the results of open -loop forcing at 100 Hz. Note that the 200 Hz instability was still present. It was not possible to obtain a non-resonant situation under reacting conditions, although these tests were conducted at the highest practical fuel/air ratio in order to reduce the magnitude of the 200 Hz instability.

For diagnostic purposes, a simple threshold control algorithm was designed. The principle of its operation is shown in Fig. 8. Whenever the control sensor signal crossed an established threshold level, a command was sent to the solenoid valve. On positive-direction crossings, the valve was opened and on negative-direction crossings, it was closed. A time delay between the moment of crossing and the valve command was also imposed. The same delay was used for both opening and closing commands. The threshold level and time delay were manipulated via a user interface to the control algorithm. Because the opening and closing of the valve was tied to the pressure signal, the algorithm was self-tuning over the frequency range of interest (100 - 300 Hz).

RESULTS OF CONTROLLED COMBUSTION

Tests with the threshold controller and spoke actuation were conducted using the bandpass -filtered (100-300 Hz) combustor pressure as the control signal. In all the cases discussed here, the threshold level was set at zero, nominally yielding a 50% duty cycle. These tests were conducted at a combustor pressure of 1.56 MPa and a combustor inlet temperature of 730K. The nominal power output of the test combustor was 4 MW. The fuel/air equivalence ratio was varied over a wide range of values, down to near-blowout conditions.

Figure 9 shows the behavior of the controlled combustor as the delay time was varied. Proper choice of the time delay yielded significant reductions in the level of pressure oscillations. (Note that the control system was capable of increasing the magnitude of the instability as well as attenuating it.) This exercise was conducted at five equivalence ratios between 0.47 and 0.56 (based on nozzle air flow). The optimum time delay was constant at 0 ms across this range, and also across a range of air flow rates. This value has no physical significance, in that it represents only a control system time delay and not the acoustic, convective or kinetic time delays involved in the mixing and combustion of the actuated fuel flow. These parameters were not directly measured.

Figure 10 shows PSD's of the uncontrolled and controlled combustor pressure and heat release rate at an equivalence ratio of 0.51. The magnitude of the 200 Hz mode was attenuated by 15 dB (5.6X or 82%) using the optimum time delay. The overall RMS pressure level was reduced from 29.2 kPa to 11.5 kPa.

The control system's effectiveness will ultimately be judged by its ability to suppress the level of pressure oscillations and enable low-NO_X operation simultaneously. It is desirable, then, to minimize both parameters. Figure 11 is a cross plot of the pressure fluctuation level of the 200 Hz mode versus the NO_X emissions for both uncontrolled and controlled operation over a range of equivalence ratios. The shaded regions represent the limits of acceptable operation with respect to pressure fluctuation and NO_X emissions. The reduction obtained by the control system is relatively constant at approximately 15 dB across the range of equivalence ratios. For the majority of the points (all acquired in back-to-back tests) the controlled combustor actually created less NO_X than the uncontrolled combustor. It is believed that this is because temporal "hot spots" created by the fuel/air fluctuations have been removed by the control system

Also shown in Fig. 11 is a comparison of the controlled system to piloted operation. Piloted data were collected at an overall equivalence ratio of 0.49. While diffusion flame piloting reduced the level of pressure fluctuations, it increased the NO_X emissions. Only the actively controlled system was capable of delivering simultaneous low NO_X and low pressure fluctuations. Low CO emissions were also maintained and, especially at low equivalence ratios, lowered using control.

SUMMARY

A practical active combustion control system for application to liquid-fueled, lean, premixed combustion systems has been designed and demonstrated in a single-nozzle combustor at realistic engine operating conditions. A full-scale engine fuel nozzle was minimally modified to incorporate a simple actuation system using an off-the-shelf high-speed solenoid valve. Investigation of the controlled system behavior indicated that a fixed time delay between the input signal and the control signal to the valve yielded optimum effectiveness over a wide range of combustor equivalence ratios. Suppression of the instability by as much as 15 dB was typical. The control system was self-tuning over the 100-300 Hz frequency range, enabling it to track changes in frequency with changing operating conditions. The system demonstrated simultaneous achievement of both NO_X and pressure fluctuation goals and demonstrated its superiority to diffusion-flame piloting.

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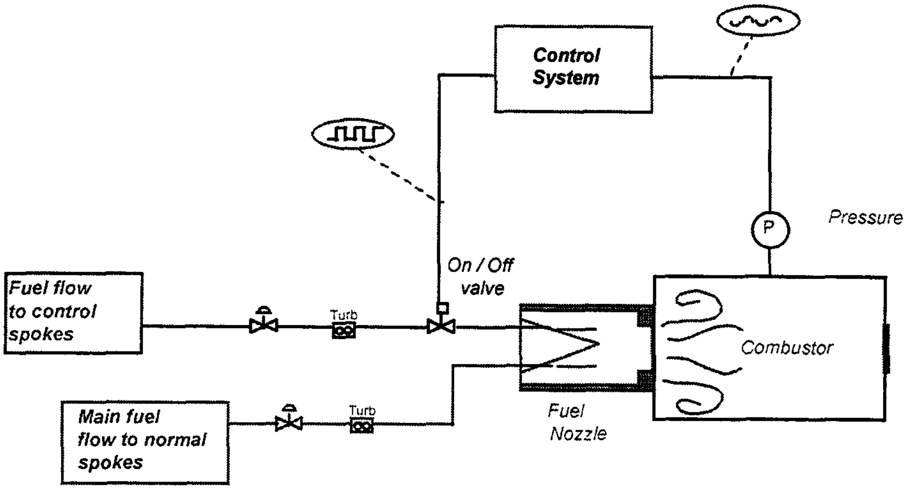

Figure 6. Schematic of fuel control system with block diagram of controller.

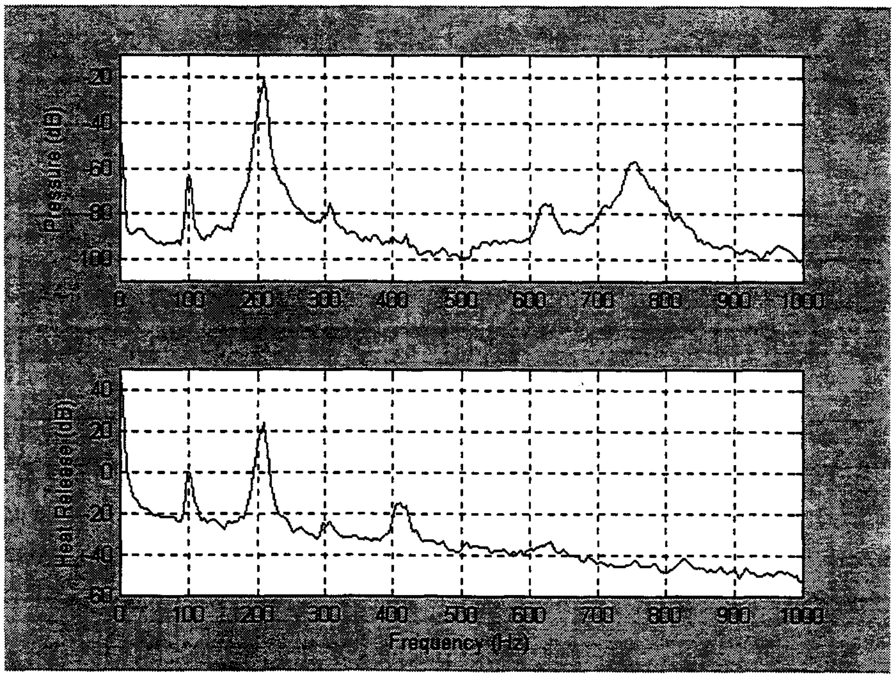

Figure 7. Pressure and heat release spectra at an equivalence ratio of 0.56 with open - loop forcing at 100 Hz.

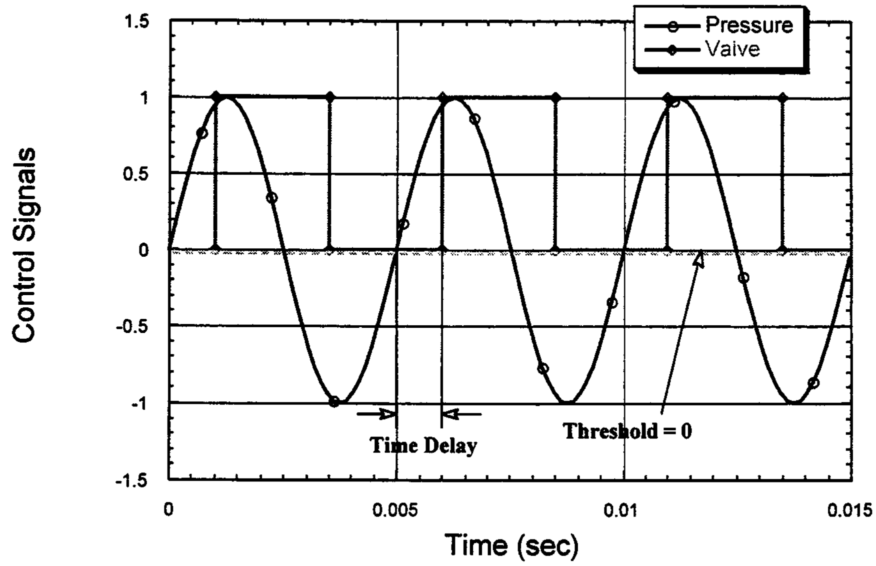

Figure 8. Threshold control algorithm schematic with illusration of delay and threshold settings.

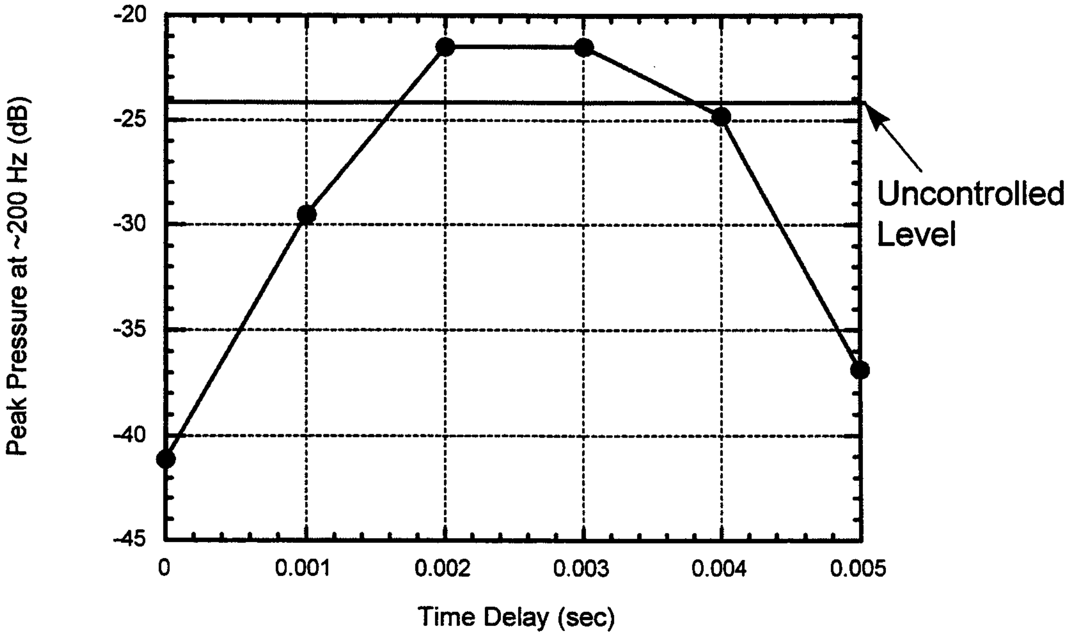

Figure 9. Effect of control delay time on attenuation of pressure fluctuations of 200 Hz mode at an equivalence ratio of 0.56.

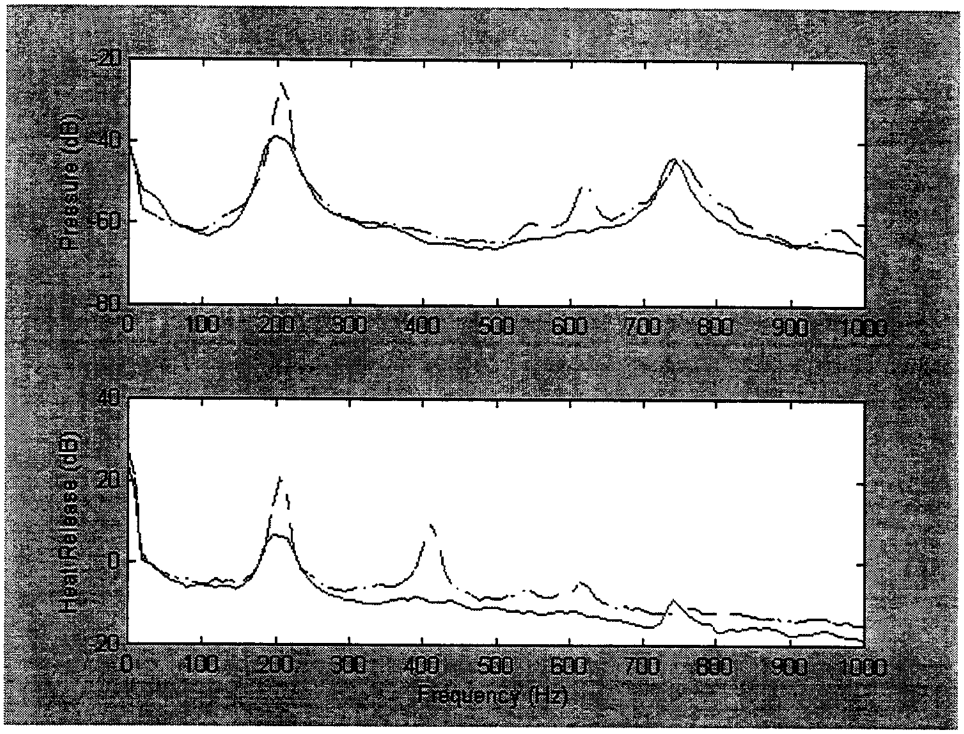

Figure 10. Spectra of pressure and heat release during controlled (solid lines) and uncontrolled (dashed lines) at an equivalence ratio of 0.51 with optimum delay.

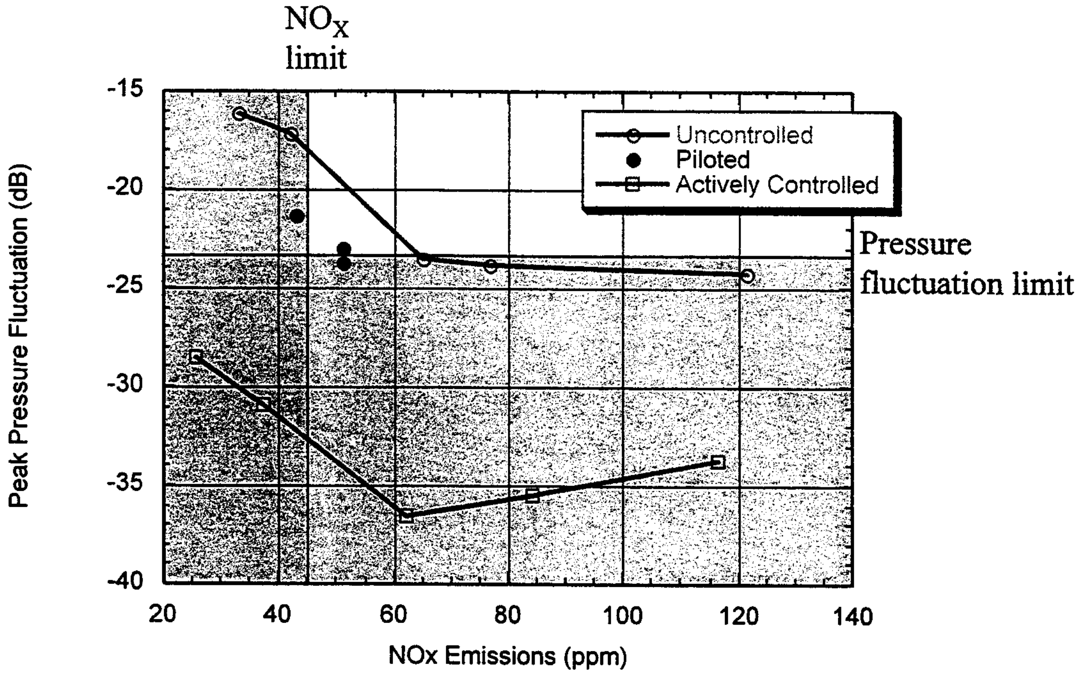

Figure 11. Cross - plot of pressure fluctuation level vs. NO_X emissions. Points represent equivalence ratios of 0.47, 0.49, 0.51, 0.53 and 0.56 from left to right on each curve. Piloted points are for operation at 0.49 with 2.5, 5.0 and 6.5% sidewall pilot, top to bottom (percentage of total fuel flow rate).