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To improve the performance of practical active control system (ACS) for unstable combustors, the effects of system noise and ACS time delay upon combustion instabilities and the ACS performance were studies. Experimental and theoretical studies of an uncontrolled liquid fueled combustor showed that the presence of noise apparently causes the "beating" phenomenon and "phase jumps" exhibited by the unstable pressure oscillations. Next, experiments in which the ACS was operated in open loop showed that the delay between the command signal to the ACS actuator and the response of the combustor pressure is of the order of two cycles of the oscillations. Subsequent simulations showed that this large time delay adversely affects the ACS performance. Futhermore, simulations and experimental studies of the ACS performance when operated in closed loop showed that the "beating" phenomenon depends upon the complex relationship between the noise and the process that drives the instability, they poorly attenuate the random component of these oscillations, which is related to the magnitude of the RMS of the pressure oscillations. The combined effects of the long time delay in the control loop cause this.

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Effects of Noise and Time Delay Upon Active Control of Combustion Instabilities

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Abstract

To improve the performance of practical active control systems (ACS) for unstable combustors, the effects of system noise and ACS time delay upon combustion instabilities and the ACS performance were studied. Experimental and theoretical studies of an uncontrolled liquid fueled combustor showed that the presence of noise apparently causes the "beating" phenomenon and "phase jumps" exhibited by the unstable pressure oscillations. Next, experiments in which the ACS was operated in open loop showed that the delay between the command signal to the ACS actuator and the response of the combustor pressure is of the order of two cycles of the oscillations. Subsequent simulations showed that this large time delay adversely affects the ACS performance. Furthermore, simulations and experimental studies of the ACS performance when operated in closed loop showed that the "beating" phenomenon depends upon the complex relationship between the noise and the process that drives the instability. These studies also indicated that while current ACS effectively damp the "coherent" component of the instability, they poorly attenuate the random component of these oscillations, which is related to the magnitude of the RMS of the pressure oscillations. The combined effects of noise and the long time delay in the control loop apparently cause this.

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Introduction

Efforts during the reported period have investigated the interaction of an active control system (ACS) that damps detrimental combustion instabilities with unsteady flow and combustion processes within the combustor. The ACS that was developed under this program, see Fig. 1, is based upon Rayleigh's criterion; i.e., it damps combustion instabilities by generating combustion process heat release oscillations at the frequency of instability and 180 degrees out of phase with respect to the unstable pressure oscillations. This ACS measures the combustor pressure and sends it to an observer that determines the amplitudes, frequencies and phases of the most unstable modes in real time. The controller then uses these data to determine the control signal for the actuator that modulates the injection rate of all or a fraction of the fuel with the appropriate frequency, phase, and amplitude to generate the combustion process oscillations that damp the instability.

While this ACS has generally performed very well, there is only limited understanding of the fundamental processes that control its performance. Development of such understanding will enable us to further improve the performance of this and other ACS and answer such critical questions as: Why are some control systems more effective than others? or Why does a specific ACS satisfactorily damp combustion instabilities in one combustor and fails to attain the same level of performance in another combustor?
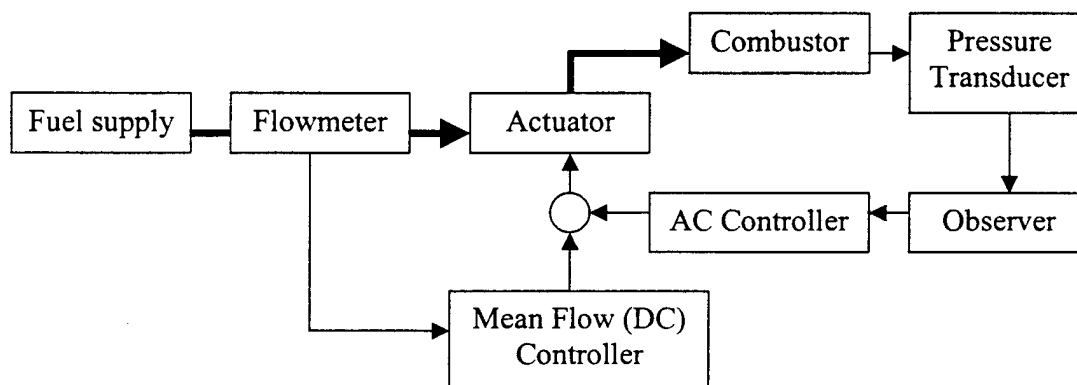

Figure 1. A schematic of the developed ACS.

In an effort to answer these questions, we investigated the effects of the control loop's time delay, describing the time elapsed between the instance at which the command is sent to the actuator and the response of the combustion process, and combustor noise upon the controllability limits of the developed ACS in an unstable liquid fueled combustor. We had decided to investigate the effects of these two processes because random noise, generated by turbulence and combustion processes, and time delays, introduced by the ACS system and combustion process, are always present in practical combustors. The effects of the noise and time delay upon the performance of the ACS were investigated theoretically and experimentally under this program by predicting their effects upon the pressure oscillations in controlled and uncontrolled combustors and comparing these predictions with measured data. More details of these studies are provided in Ref. 1.

Experimental Setup and Simulations

The liquid fueled combustor used in this study burned air and n-heptane (C_7H_{16}). The fuel flow rate into the combustor was controlled by a fuel injector actuator consisting of a Terfenol D magnetostrictive actuator that was connected to a pintle-type automotive injector. The former controlled the time dependence of the pintle's position, thus controlling the time dependence of the liquid fuel injection rate into the combustor. By oscillating the fuel flow rate with the proper frequency and phase, it was possible to actively damp large amplitude instabilities within the combustor. Uncontrolled experiments were first performed to investigate the characteristics of the unstable pressure oscillations. The ACS was then operated in open loop to determine the time delay introduced by the ACS. Finally, the ACS was operated in closed loop to determine its damping and the characteristics of the pressure oscillations in the actively controlled combustor.

In parallel, the combustor performance was theoretically investigated using a Matlab model that described the combustor as a second order oscillator. The simulation included two feedback loops, each with its own time delay. The positive feedback loop represented the feedback process that drives the combustor oscillations while the negative feedback loop represented the active controller that attenuates the instability. In addition, white noise input was used to simulate the presence of persistent noise in practical combustors. The results of the simulations, which used measured time delays in the negative feedback loop and white noise, were compared with measured data to determine the effects of the time delay and noise upon the instability and ACS performance.

Results and Discussion

Uncontrolled and Open Loop Combustor Response Studies. To investigate the effect of noise upon the pressure oscillations in unstable combustors, we first studied the pressure oscillations in the investigated combustor during an uncontrolled instability, see Fig. 2-a. It shows that the amplitude of the pressure exhibits irregular "beating". To gain insight into the causes of this "beating" phenomenon, we correlated the time dependence of the phase and frequency of the unstable oscillations with those of a reference, sinusoidal, signal that oscillated with the frequency of the instability, see Fig. 2-b. It shows that while the frequency of the unstable oscillations remains unchanged, the phase between the pressure and reference signal oscillations changed by a finite amount at the "necks" of the oscillations and remained practically constant during time intervals between the "necks". Specifically, Fig. 2-b shows that the phase of the pressure oscillations changed by approximately 45 and 135 degrees at the "necks" at t=0.915 and t=0.955 seconds, respectively.

To determine whether the above-described phase behavior was caused by combustor noise, we simulated the response of our combustor to white noise excitation. To isolate the effect of noise, the driving by the combustion process and the active controller were "turned off" in the simulation. The predicted combustor pressure oscillations were qualitatively similar to those in Fig. 2; i.e., they also exhibited a "beating" phenomenon and their phase "jumped" by finite amounts at the "necks" of the oscillations. This qualitative agreement between the predicted and measured data strongly suggests that white noise affects the pressure oscillations in unstable combustors.

Next, we performed open loop experiments in which we measured the time delay between the response of the combustor pressure oscillations, which is nearly in phase with the heat release oscillations, and the actuator command. This was determined by measuring the time delay in the pressure response to pulses in the fuel injection rate. A typical pressure response to such a pulse is shown in Fig. 3. It shows the measured time dependence of the fuel flow rate and combustor pressure and the correlation of the pressure with a reference signal. These data show that while the fuel flow rate responded instantaneously to the fuel injection rate pulse, more than two cycles have elapsed before the combustor pressure responded to this pulse. The response of the pressure oscillations to a command signal pulse occurs when it exhibits an abrupt change in amplitude and phase with respect to the reference signal.

Closed Loop Response Studies. Since the above-described studies strongly suggested that persistent random noise excitation affected the instability and that a significant pure time delay was present in the control loop, it was decided to investigate the effect of these phenomena upon the performance of the ACS when operated in closed loop. This was first studied using the simulations. Initially, the delay in the

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controller loop was set to zero and the relationship between gain of the controller and pressure attenuation was studied. As expected, this study showed that unlimited attenuation could be obtained as the gain of the controller was increased. Next, a time delay of two cycles was introduced into to the control loop.
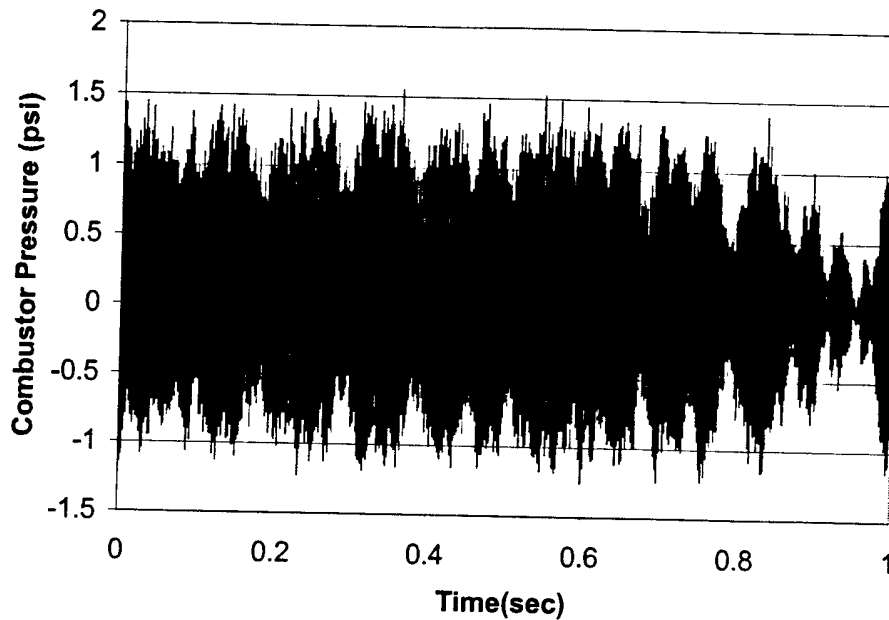

Figure 2-a: Time trace of measured, uncontrolled, combustor pressure.
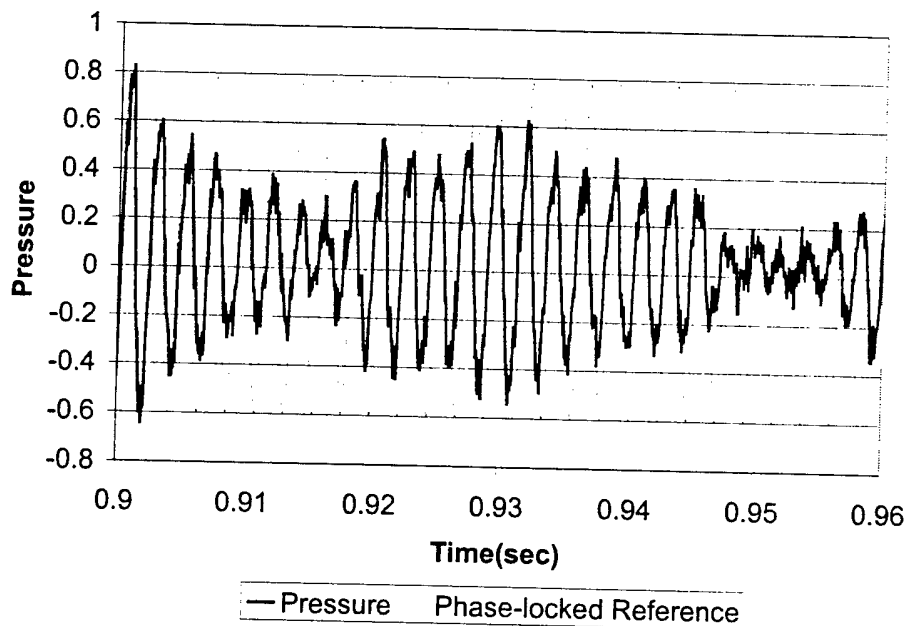

— Pressure   Phase-locked Reference

Figure 2-b: Correlation of measured, uncontrolled, combustor pressure oscillations during the time interval t+0.89 to 0.97 seconds with a reference signal having whose phase and frequency equaled those of the pressure soon after the instant t=0.9 seconds.

With this time delay, the ACS could at best damp the most unstable mode by fifty percent while having very limited effect upon the RMS of the pressure oscillations. When the controller's gain was increased, the controller became less effective as its attenuation was further diminished.
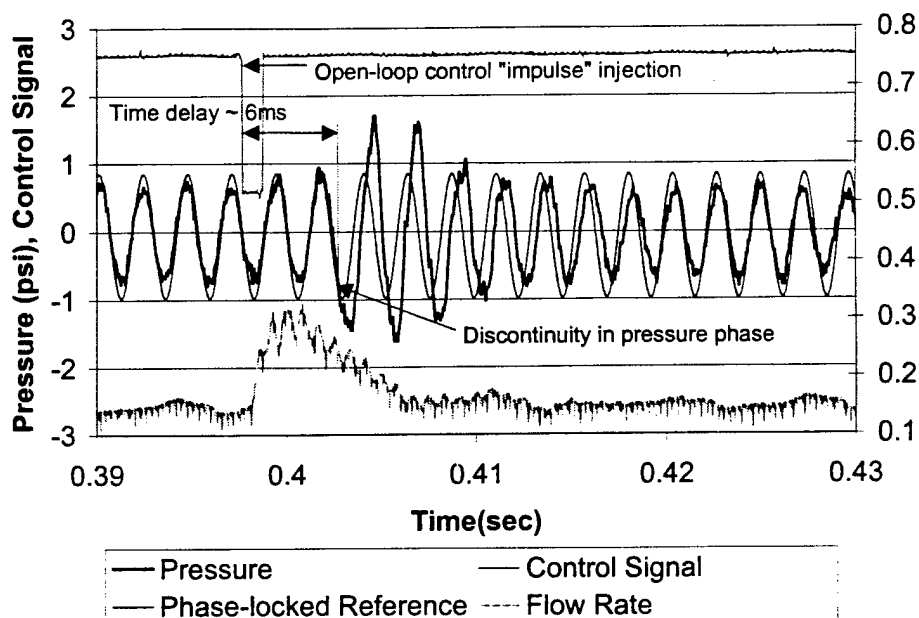

Figure 3: Measured responses of the combustor pressure oscillations and fuel flow rate to a pulse in the fuel injection rate.

Next, the closed loop performance of the ACS was experimentally investigated at equivalence ratios of 0.8 and 1.0. The measured data showed that the performance of the ACS is better than that predicted in the simulations. A close examination of the measured and predicted results has shown, however, that while the ACS has effectively attenuated the "coherent" portion of the instability, it had a limited effect on the random component of the instability that is apparently caused by white noise forcing. This indicates that current ACS might have a limited effect upon the RMS of the pressure oscillations. Thus, we must determine whether we can be satisfied with an ACS that primarily damps the "coherent" component of the instability or whether we must provide existing ACS with capabilities to attenuate both the "coherent" and "random" components of the combustor pressure oscillations.

Summary

Theoretical and experimental studies have shown that the "beating" phenomenon exhibited by the pressure oscillations in controlled and uncontrolled unstable combustors are likely caused by persistent white noise driving. Open loop response tests have shown that the combustor responds with a significant time delay to a command signal. When the measured time delay was incorporated into a simulation of an actively controlled combustor that is forced by white noise, the controller exhibited very limited effectiveness. On the other hand, active control tests have shown that the ACS performs much better than predicted by the simulations. Nevertheless, the "beating" phenomenon persisted in the pressure oscillations of the controlled combustor, suggesting that the presence of white noise and time delay limit the controller's effectiveness. This hypothesis is supported by the prediction of a simulation that modeled the effects of white noise excitation, time delay in the control loop and the process that drives the instability.

Reference

Johnson, C. E., Neumeier, Y., Cohen, J., Lee, J. Y., Lubarsky, E., and Zinn, B. T., "Effects of Time Delay and System Noise Upon Active Control of Unstable Combustors." 39th Aerospace Sciences Meeting, Reno, NV, January 2001.