41st Aerospace Sciences Meeting and Exhibit
6-9 January 2003, Reno, Nevada

AIAA 2003-1009

Studies of Active Instability Control Effectiveness in a High Pressure, Liquid Fueled Combustor

Coker, A., Neumeier, Y., Lieuwen, T., Zinn, B.T., Menon, S.
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

This paper describes active instability control experiments from a high pressure (up to 170 psia), Jet A-fueled combustor. These experiments were performed to improve understanding of the factors limiting control performance. A set of experiments were performed where the desired level of instability amplitude suppression was systematically increased. The controller effectively drove the rms instability amplitude to the desired levels down to approximately 15% of those without control. Attempts to further drive the oscillations to a lower level resulted in deterioration in performance, manifested by a "peak splitting" phenomenon previously described by Hibshman *et al*[1]. Experiments were also performed at different conditions where the linear and nonlinear characteristics of the self-excited oscillations were varied. They show that the combustor's nominal dynamics (i.e., without control) has an important effect upon its response to over-gaining of the fuel injector control signal (resulting in peak splitting).

Introduction

This paper describes an experimental investigation of active control of instabilities in a high pressure, liquid fueled combustor. This work is motivated by the fact that combustion dynamics continues to be an important issue in aircraft and land based gas turbines[2,3,4,5,6]. These instabilities generally occur when the unsteady combustion process couples with one or more of the natural acoustic modes of the combustion chamber, resulting in self-excited oscillations that can achieve significant amplitudes. These oscillations are destructive to engine hardware and adversely affect engine performance and emissions.

Both passive and active means of eliminating these oscillations are under investigation. Passive control refers to, for example, variations in combustor geometry or nozzle fuel splits in order to break the feedback mechanism responsible for the oscillations or to increase combustor damping. It is difficult, however, to design passive approaches that are effective at stabilizing all combustor modes over all operating conditions. Also, combustor driving and damping processes are poorly understood, causing implementation of passive controls to be a trial and error process that is time consuming and expensive. These problems have motivated the development of active control, generally implemented by injecting a secondary, oscillatory fuel source to attenuate the oscillations.

Active control has been demonstrated as a viable method for suppressing combustion dynamics by a number of university, government, and industry research labs (e.g., see Refs. [1, 7, 8, 9]). For example, it has been shown that instabilities can be suppressed by measuring the pressure or heat release in the combustor, suitably phase shifting and amplifying the measured signal, then driving a secondary fuel injector with this signal.

While significant progress has been made, a number of problems are still in need of investigation. Active controllers are often found to work well at certain operating conditions, while their effectiveness is significantly reduced at others. Results in the literature quantifying the degree of suppression of the instability amplitude vary substantially, from factors of under 2 to over 50. At Georgia Tech we have found that the same methodology performs very differently on different combustors and at different operating conditions. Thus, although at this point it is well established that *some degree* of suppression of combustion dynamics is possible, more research is needed to understand the dynamics of actively controlled combustors and the factors that limit control effectiveness.

Consider the various factors that determine the effect of an active control system upon a combustor's dynamics. First, the uncontrolled combustor dynamics play a significant role on the effect active control has upon the oscillations. Control effectiveness will clearly depend upon such issues as instability amplitude, instability frequency and background noise levels. In addition, nonlinear characteristics of the combustor, such as hysteresis and saturation, play less obvious, but equally important roles in control effectiveness. For example, in an unreported study at Georgia Tech, experiments were performed to characterize the effect of a linear, proportional controller's gain upon degree of suppression of instability amplitude. At low gains, control had almost no effect, apparently due to saturation effects. Only above a certain gain value did the control reduce the instability amplitude (at higher fuel injector control gains, the dynamics of the combined combustor-control system became significant as too large a gain resulted in destabilizing the combustor and actually increasing instability amplitudes).

Next, the issues of observability and controllability are significant; i.e., the extent to which the state of the system can be sensed and affected by actuation, respectively. Observability does not appear to be a significant issue limiting control effectiveness, unless, for example, a pressure sensor is located in a node. Rather, at least in experimental combustors, the unsteady pressure and chemiluminescence can be rapidly and accurately measured as at many measurement points as desired.

Controllability issues are more significant due to the challenges of actuating coherent fuel pulses at high frequencies. The coupling of a flow control device with liquid injectors requires special attention. In many cases, liquid fuel is modulated using pulse-width modulated, on-off actuation which cannot simultaneously control the average flow rate and oscillation amplitude. In addition, square wave modulation of fuel flow rate causes spectral broadening of the excited heat release oscillations about the carrier wave frequency. This broadening is partially responsible for the peak splitting phenomenon discussed by Hibshman *et al*[1], reducing the extent to which instabilities can be suppressed. Past efforts at Georgia Tech have led to the development of injectors with more precise control of the time varying degree of restriction that can simultaneously control the amplitude and mean level of the fuel stream. However, coupling these injectors to liquid fuel injection systems affects the atomization process which requires consideration.

In pressure atomization systems, the pressure drop across the orifice determines both the flow rate and the atomization characteristics. As such, modulating the flow rate through such a system results in widely variable atomization characteristics. These issues can be minimized with air blast atomization schemes. Ideally, the area of the atomizing orifice should be varied while maintaining constant feed pressure. Such an approach does not appear to have been realized due to the high degree of mechanical complexity involved. In the work reported here, the fuel injector is placed upstream of part of the fuel supply line, so that the pressure immediately downstream of the injector is nearly equal to that of the combustor. The fuel flows through the fuel supply line and emerges into the combustor just downstream of the swirlers where it is atomized by the shearing action of the high velocity air. Another issue which has been pointed out by Cohen *et al.*[10] is that of fuel placement and/or mixedness.

Turning to the controller itself, the poorly understood nonlinear and stochastic nature of crucial combustor processes renders classical model based approaches useless for implementation on actual hardware. Prior experimental controllers have either filtered the pressure/ chemiluminescence signal about the instability frequency (which must be known *a priori*) or used observers to extract the amplitude and frequency of the instability. This information is used to construct a control phasor with certain phase shift and magnitude. Prior control implementations have used either off-line testing or, more recently, adaptive schemes to find the optimal phase. Various proportional or integral controller schemes have been used to determine the control signal magnitude. In prior work under this program, we have used a fuzzy control algorithm to determine this controller gain. In this study, we use a fixed gain integral controller in order to focus on combustor effects on control effectiveness. The various issues associated with the different gain schemes have not been investigated but merits close consideration. This point is illustrated by the effects of proportional gain on instability amplitude experiment at Georgia Tech discussed above

Probably one of the most significant factors determining the effectiveness of the combined controller-actuation system is the overall time delay. As might be expected, several studies have shown that the combined effects of background noise and time delays substantially impair control effectiveness. For example, it has been observed that the combustor appears to “run away” from the control when sufficient control actuation is applied; e.g., the phase of the oscillations rapidly moves around or even seems to jump[1,8]. In addition, time delays are partially responsible for the peak-splitting phenomenon encountered with high controller gains[1].

The above discussion emphasized a number of issues in need of investigation to better understand the factors determining control effectiveness. In this study, we primarily focus on the effects of uncontrolled combustor dynamics. A systematic study of these effects requires capabilities to alter the nature of the investigated combustor. In order to accomplish this *in a known manner*, self-excited oscillations were created by feeding back the measured pressure through a phase-shifter to an air actuator mounted in the rear of the combustor. This actuator drove oscillations by pulsing a high pressure air flow. The linear and nonlinear characteristics of the self-excited feedback loop were then systematically varied by changing the gain and phase of the pressure signal that was used to drive the air actuator. Control of the induced oscillations was achieved by pulsing the flow rate through the liquid fuel injector.

Facility and Instrumentation

Experiments were performed on a high pressure, 150 kW combustor capable of burning gas or liquid. Tests were performed over the mean pressure and temperature ranges of 40-170 psia and 250-380 F inlet temperatures, respectively. The data reported here were taken at 65 psia and 310 F for active control studies and at 65 psia and 265 F for forced response studies. Equivalence ratios were 0.90 and 0.55-1.28 for active control and forced response studies, respectively. Jet A at room temperature was used as fuel.

The combustor facility consists of inlet, combustor and exhaust sections. High-pressure air is supplied through 720 psi building lines and metered through calibrated critical orifices. A block diagram of the air control distribution system is shown in Figure 1.

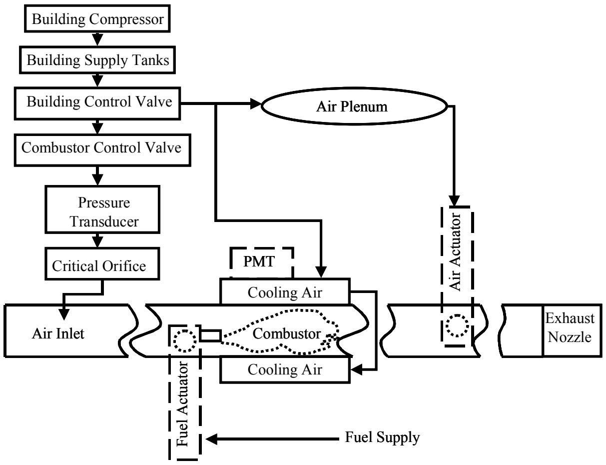

Figure 1: Block diagram of air delivery system.

The air passes through the circular 4.75cm diameter, 60cm long inlet section and a 45 degree swirler prior to entering the combustor. A detail of this section is shown in Figure 2.

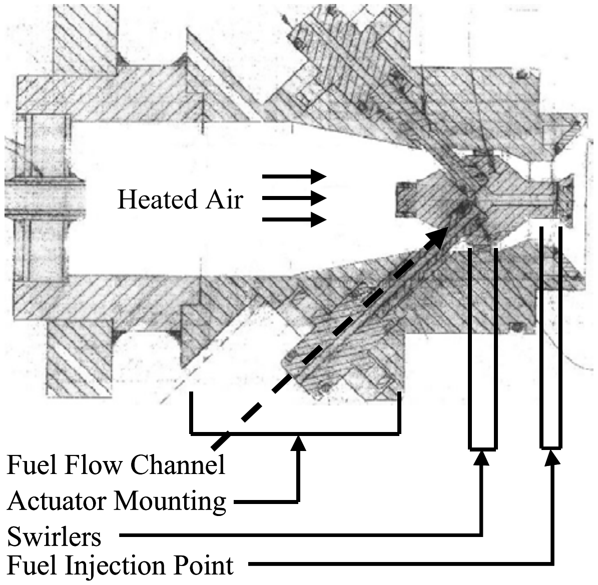

Figure 2: Detail of fuel nozzle assembly.

The Jet A fuel used for these experiments was delivered to the combustor via a portable, high pressure system. Typically, the fuel was delivered at pressures between 250 psig and 400 psig depending upon combustor mean pressure. Mean fuel flow rate measurement was accomplished using a subcritical, calibrated orifice coupled with a differential pressure transducer. The signal from the pressure transducer was sent to the control computer where it was converted to a mass flow rate and used to close the fuel flow rate loop.

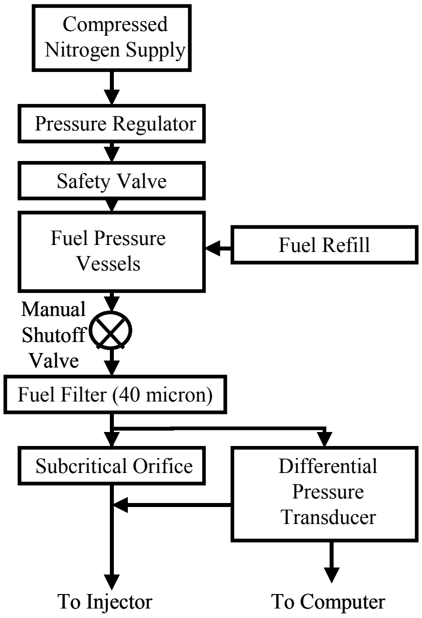

Figure 3. Block diagram of liquid fuel delivery and metering system.

The fuel is injected into the high temperature air stream at the end of a conical bluff body. The fuel is atomized by the shearing action of the high velocity air. Combustion occurs in the 5x5x51cm square combustor downstream of the conical flame holder, and the combustion products then flow through a circular 7.6cm diameter, 195cm long exhaust section before leaving the system. The flow leaves the setup through an exhaust nozzle and an adjustable bypass valve. A separate high-pressure air stream cools the combustor side walls.

Pressure oscillations were measured with a Model 211B5 Kistler pressure transducers mounted in the combustor. This transducers was mounted 5.1 cm downstream of the conical flame holder, flush mounted and water-cooled. CH* chemiluminescence measurements were made with a Schoeffel Instruments photomultiplier tube (PMT) fitted with a 10 nm bandwidth filter centered at 430 nm.

Oscillations were driven in the combustor with an actuator developed at Georgia Tech for active combustion control applications[11]. The actuator is capable of driving oscillations over a frequency range of approximately 0-1500Hz. The actuator modulates a constant secondary supply of air that is introduced near the combustor exit by periodically varying the degree of constriction of a valve. Maximum amplitude of driving occurs when the flow passage is completely blocked for a portion of the cycle and, thus, the air actuator modulates 100% of the flow through the valve. The amplitude of forcing can be controlled via the supply pressure of air to the actuator.

In order to generate self-excited oscillations, whose linear and nonlinear characteristics could be varied in a *known and systematic manner*, the pressure signal was fed back to the air actuator through a gain and phase shifter. Note that simply driving oscillations with a function generator does not emulate the critical features of combustion instabilities because the phase and amplitude of the exciting oscillations remains fixed, regardless of the control action. The combustor was operated under conditions under which it was nominally stable. By setting an appropriate gain and phase shift, the air actuator could excite oscillations. The linear and nonlinear (e.g., saturation amplitude) characteristics of the oscillations could then be systematically varied by changing the gain/saturation amplitude of this feedback loop.

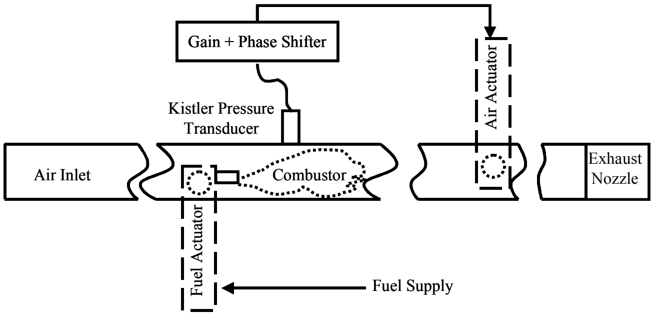

Figure 4. Block diagram of gain/phase shifter between pressure transducer and air actuator used to generate self-excited oscillations.

Control Implementation

Real time control was implemented via a 40 kHZ control loop on a 1.5 GHz Pentium 4 based computer running QNX RTOS 4.0. The data I/O hardware used for these experiments were United Electronics Powerdaq input and output boards. The input board has 12 bit resolution with 1.25 MS/s capability, while the output board has a 16 bit resolution with simultaneous channel update.

The main components in the AC controller are a pressure transducer, a real-time observer, an adaptive controller, and the magnetostrictive actuator. During operation, the sensor continuously measures the combustor pressure. The sensor output is fed to a Model 3343 Krohn-Hite analog bandpass filter. The sampled signal is the input to the scheme shown in Figure 5.

The scheme in Figure 5 features an observer that analyzes the measured pressure and rapidly determines the amplitudes and frequencies of the largest amplitude combustor modes[12]. Although not used in the experiments whose results are presented here, a phase optimizer has also been tested and developed to adaptively determine the optimal phase for maximum attenuation.

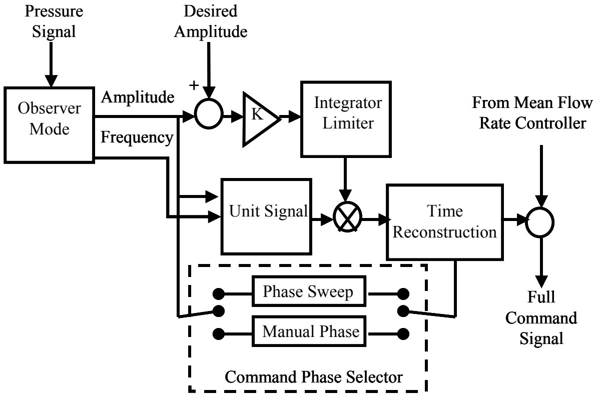

Figure 5. Block diagram of the active control system

The control amplitude is determined by temporally integrating the difference between the desired and observed amplitude. The "desired" amplitude is the amplitude to which the controller attempts to drive the actual amplitude toward. It is not necessarily zero. Note that if the permissible amplitude is set to zero, the integrator will continuously increase and saturate, since it is impossible to drive the actual amplitude to zero. As shown in prior studies[1] and below, the large control signal that is applied to the fuel injector may result in reduced controller performance. However, if the desired amplitude is set to an attainable value, the integrator will stabilize at some non-saturated value and automatically set the control amplitude to the prescribed optimal value. This can be used to determine the optimal control amplitude by adaptively adjusting the desired amplitude to minimize the actual amplitude.

Fuel is modulated using a Terfenol-D magnetostrictive actuator connected to a reed valve, which creates the complete fuel injector. The actuator rod length varies with the magnetic flux which, in turn, is controlled by the current through the magnetostrictive coil. The instantaneous flow rate is varied by changes in the rod length, which also change the gap size between the reed plate and a stationary orifice plate. Previous experience with this kind of fuel injector shows that the required movements of the order of 0.1 mm can be attained over a large frequency range; the principle problem with this fuel injector is hysteresis. Also, significant displacement is induced by temperature variations resulting from heat dissipation in the coil.

A mean flow controller is used to maintain the mean flow rate through the valve around a desired value. In this arrangement, the command to the fuel injector consists of two components: 1) a slowly varying command from the flow controller that controls the mean position of the reed valve and 2) oscillatory command from the AC controller that fluctuates the reed around its mean position, see Figure 6 and Figure 7. A mechanical knob is manually adjusted to minimize the current required by the mean flow control so that the oscillating actuator current can be maximized.

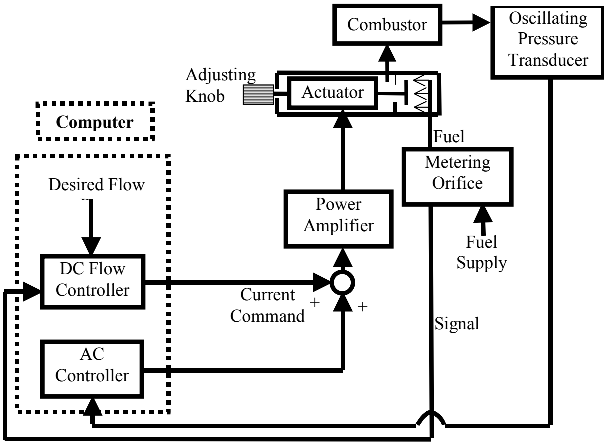

Figure 6 Block diagram of mean and fluctuating fuel injector flow control systems.

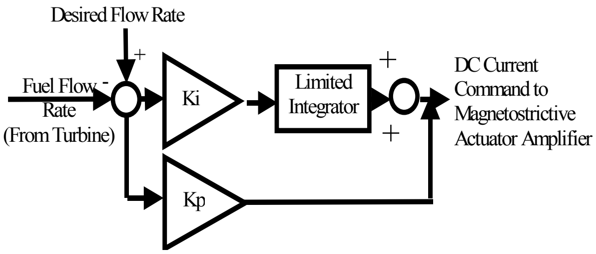

Figure 7 Block diagram of the mean flow rate controller

Results

Forced Response Tests

A set of open loop experiments were performed to investigate the response of the system to fuel supply rate oscillations.

The figures below summarize the amplitude and phase dependence of the CH* response. They indicate that heat release fluctuations on the order of 20% and 10% of the mean were excited at frequencies below and above 300 Hz, respectively. The amplitude value can be thought of as quantifying the "effective" fluctuation in fuel flow rate into the combustor. Between 300-600 Hz, the phase between the CH* signal and fuel injector command decreases linearly, suggestive of a constant time delay behavior. The deviation of the phase from this behavior at frequencies above and below these frequencies indicates a more complex dynamic in general, however. Although caution must be exercised in attempting to infer system time delays from this result, note that the slope of the line drawn through the phase in the linear regime corresponds to a 6 ms delay.

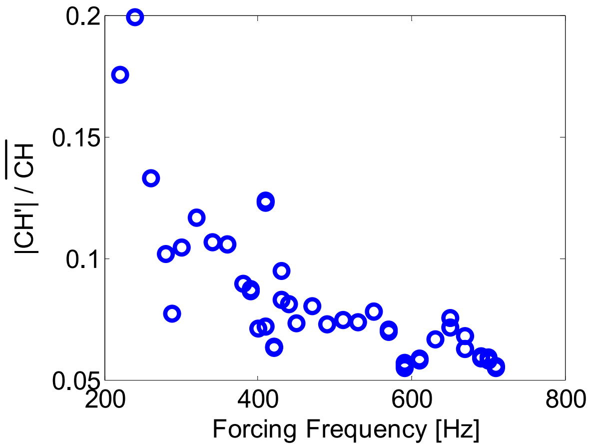

Figure 8. Frequency dependence of the amplitude of the normalized CH* response (at the driving frequency) to pulsations in fuel supply rate.

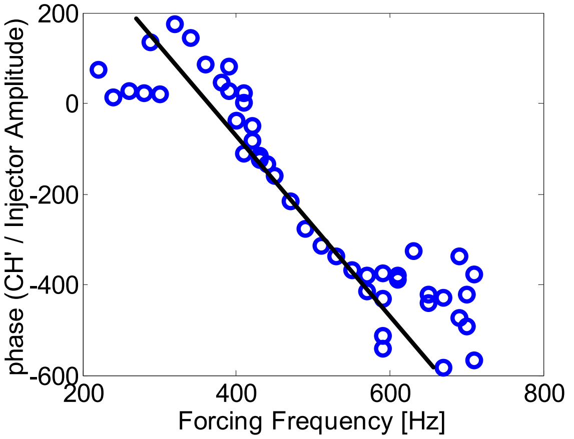

Figure 9 Frequency dependence of the CH* - control signal phase (at the driving frequency) to pulsations in fuel supply rate.

Closed-Loop Control -

As noted earlier, instabilities were generated by feeding back the pressure signal with a phase shift to the air actuator. A typical result showing the combustor pressure during a 92 Hz instability with and without control is shown in the figures below. In these data, control was turned on at the indicated point, with the desired amplitude set to 0.18 psi. The fluctuating pressure amplitude was determined by bandpass filtering the raw combustor pressure between 69-115 Hz. The envelope of the oscillations were then determined by low pass filtering the square of the filtered signal at 10 Hz. The signal was then multiplied by two (to convert rms to amplitude squared), and its square root taken.

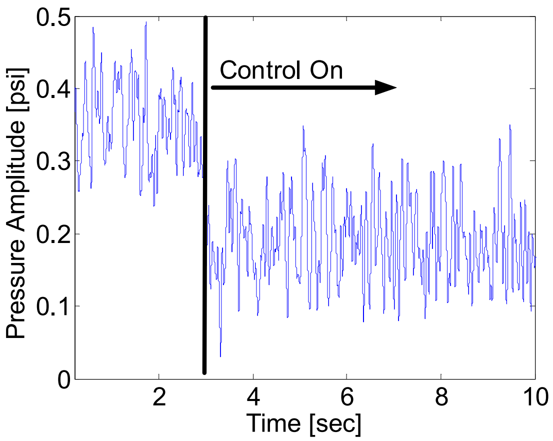

Figure 10 Time dependence of oscillatory combustor pressure with and without control.

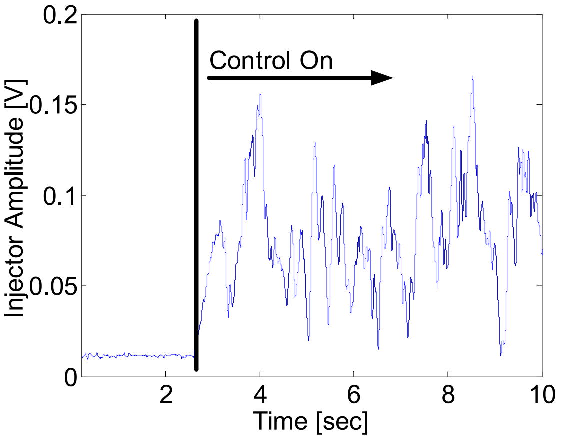

Figure 11 Time dependence of fuel injector command signal with and without control

Once actuated, the control requires a total of about 0.3 seconds to bring the amplitude to the desired level, due to integrator windup. Note that the control successfully brings the instability amplitude to the desired level; however, there is substantial "breathing" in amplitude of the oscillatory pressure both before and after control. In the controlled region, the pressure amplitude ranges from a low of 0.1 psi to a high of about 0.3 psi.

The same data plotted in Figure 10 is replotted below. The envelope of the pressure amplitude has been low pass filtered at 0.5 Hz, in order to better show the effect of control upon the average instability amplitude.

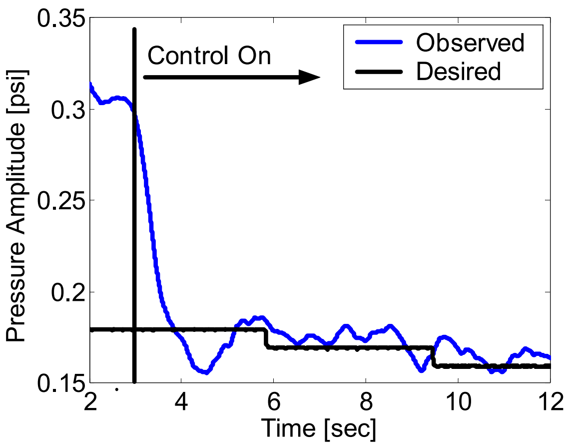

Figure 12 Low pass filtered time dependence of oscillatory combustor pressure with and without control.

Effect of Desired Amplitude

In order to elucidate the factors limiting control effectiveness, a series of experiments were performed where the "desired" instability amplitude was successively reduced. Recall that the "desired" amplitude refers to the amplitude the controller attempts to drive the oscillation level to, even if it is capable of reducing the instability amplitude further. Control performance was investigated as the desired amplitude level was monotonically decreased from 100% of its nominal value without control to 0%. Results quantifying the dependence of the actual oscillation amplitude upon the "desired" level are shown below.

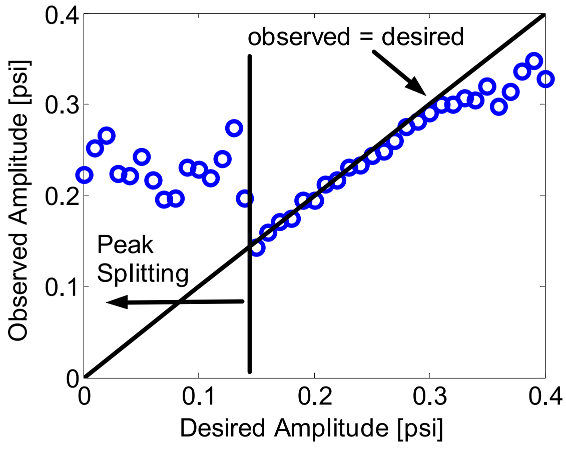

Figure 13. Dependence of actual instability amplitude upon desired level.

The figure indicates that the nominal instability amplitude (without control) is 0.35 psi. Once the desired amplitude level drops below this value, the controller turns on to reduce the instability amplitude. The figure shows that the controller precisely drives the average instability amplitude to the desired levels down to about 0.14 psi, a 60% reduction in amplitude.

At any instant in time, the actual instability amplitude varies about this value by about 0.06 psi., as shown in Figure 14. The error bars in this plot indicate the standard deviation of the instability amplitude. The dependence of the amplitude standard deviation upon desired amplitude is quantified in Figure 15. The figure indicates that amplitude fluctuation magnitudes are relatively insensitive to the mean amplitude value, see Figure 15. As such, the ratio of the amplitude fluctuations to their mean values grows with decreasing instability amplitude. As will be discussed further below, this result indicates a corresponding reduction in coherence of the oscillations.

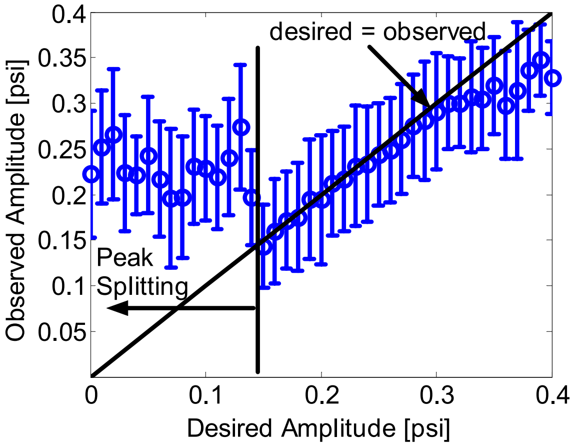

Figure 14. Dependence of mean and fluctuating instability amplitude upon desired level.

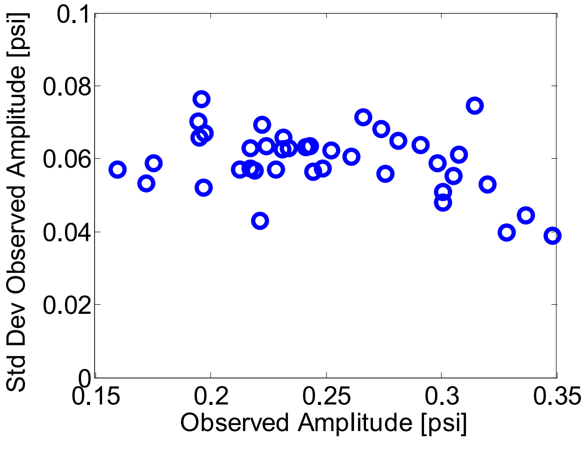

Figure 15 Dependence of standard deviation of amplitude upon mean amplitude /level.

The corresponding amplitude of the fuel injector command signal is shown in Figure 16. As expected, it shows a monotonically larger actuation requirement as the desired amplitude is reduced.

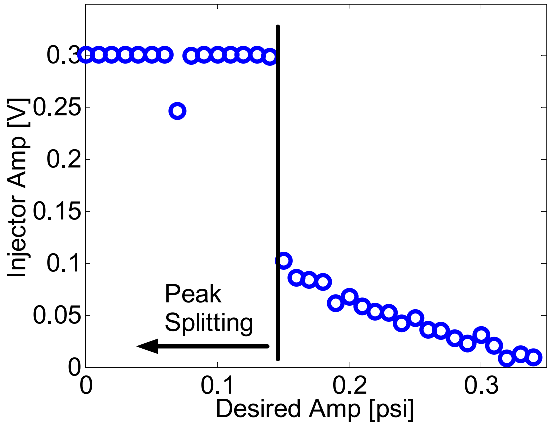

Figure 16. Dependence of amplitude of oscillatory fuel injector command signal upon desired amplitude.

Returning to Figure 13, note the jump in instability amplitude for desired amplitude levels at and below 0.14 psi. This result clearly shows that *optimal control performance is not necessarily achieved by attempting to drive the instability amplitude to zero*. Rather, the best performance occurs at an intermediate value. This reduction in performance is due to imposing too large a gain on the system that introduces undesired dynamics in the combustor response. This can be seen from Figure 17 and Figure 18, which plot the Fourier transform of the combustor pressure at several desired amplitudes. Note the monotonic reduction in instability amplitudes at the instability frequency of 92 Hz in the Figure 13 and Figure 14. Figure 17 and Figure 18 show that the 92 Hz oscillations are nearly absent and are replaced by two larger amplitude sidebands at 77 and 115 Hz. This behavior is quite similar to the "peak-splitting" phenomenon that has been extensively discussed by the UTRC group[1] for stable, noise driven combustor oscillations. Note also the corresponding saturation of the fuel injector command signal in Figure 16 at and below 0.14 psi desired amplitude.

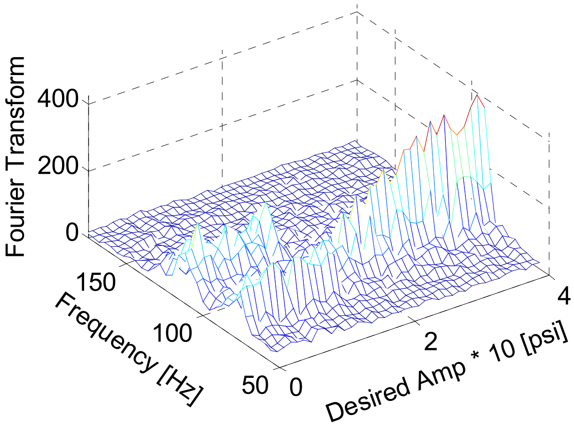

Figure 17. Fourier transform of combustor pressure at desired amplitude levels of 0-0.4 psi.

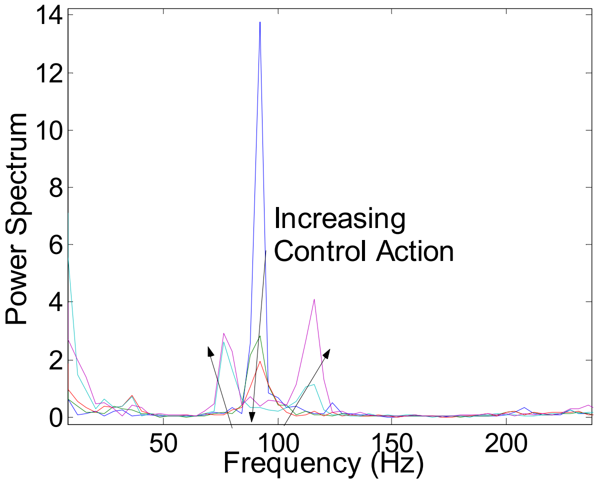

Figure 18. Fourier transform of combustor pressure at desired amplitude levels of 0.4, 0.2, 0.16, 0.14, and 0.13 psi (nominal instability amplitude = 0.35 psi).

Focus attention now on the results obtained where the peak splitting phenomenon is absent. Figure 19 plots the dependence of the percentage of instability reduction upon fuel injector amplitude. This plot quantifies how much is achieved for a given amount of control effort. The figure indicates a nearly linear dependence of control effort upon achieved instability amplitude reduction.

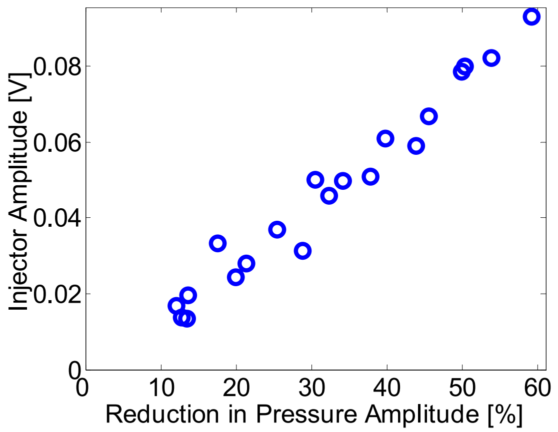

Figure 19. Dependence of percentage reduction in instability amplitude upon fuel injector amplitude.

For completeness, it is instructive to quantify the loss in coherence of the fluctuating pressure as its amplitude is reduced. Although this was not the primary factor limiting control effectiveness in this case, a reduction in the amount of time the pressure is correlated with itself could also limit control effectiveness – particularly if this time is on the order of or shorter than the controller time delays. This correlation time is inversely related to the bandwidth of the oscillations; e.g., the narrower the spectral peak in the frequency domain, the longer the signal is correlated with itself. This correlation time is quantified in Figure 20 below. The bandwidth, B, was determined from the relation:

$$B = \frac{\int_f | f - f_{instability} | F(f)df}{\int_f F(f)df} \qquad (1)$$

where F(f) denotes the pressure power spectrum at the frequency, f.

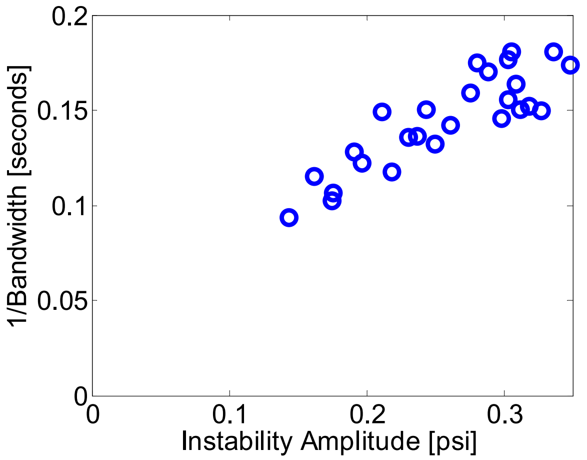

Figure 20. Dependence of the inverse of the signal bandwidth (related to signal correlation time) upon instability amplitude (desired amplitudes = 0.14-0.4 psi).

The figure shows that the correlation time of the signal is on the order of 0.2 seconds without control and 0.1 seconds (i.e., 18 and 9 cycles of oscillation) with maximum control (before peak splitting).

Effect of Air Actuator Gain and Saturation

Control experiments were performed at several values of the gain between the unsteady pressure and the air actuator. The purpose of this experiment was to emulate the affects of different heat release dynamics (linear gain as well as saturation characteristics) and the resultant impact upon control effectiveness. The dependence of the instantaneous air actuator amplitude upon pressure is plotted in the figure below for two feedback gain values. This plot allows for a convenient illustration of the instability driving characteristics. Although difficult to see in this plot, the air actuator and pressure amplitudes are linearly related at low amplitudes. At higher levels the air actuator amplitude driving signal is saturated, regardless of the pressure amplitude.

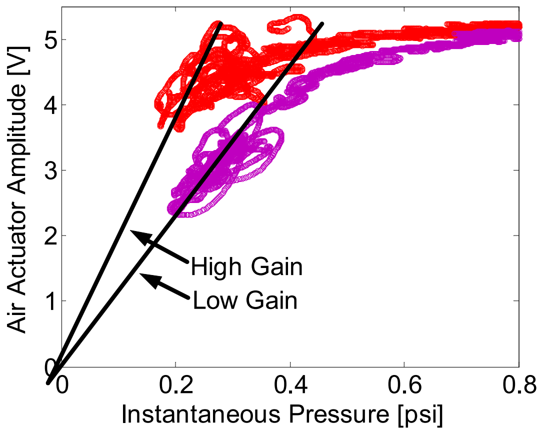

Figure 21. Instability driving characteristic visualized by plotting the dependence of the instantaneous air actuator driving signal upon pressure.

The effect of active control upon instability amplitude for these two air actuator gains is plotted in Figure 22. These data were taken by slowly sweeping (0.1 Hz) the phase of the control signal relative to that of the pressure at a desired amplitude of zero. Note that without control, the nominal instability amplitude is 0.4 psi. As expected, the instability amplitude is reinforced or damped, depending upon phase. Comparing the two gain results, note the similarity and difference, respectively, in the amount the pressure amplitude is reinforced or damped. That is, the pressure amplitude is increased by nearly the same factor (two) in both gain results. The amplitude minima, however, are approximately 0.22 and 0.16 psi, a difference of 40%.

The same maximum amplitude is achieved because the actuator driving command signal is saturated; i.e., Figure 21 shows that there is no difference in driving characteristics above a pressure amplitude of about 0.6 psi. The difference in minima is apparently due to the effect that the combustor's nominal dynamics (i.e., without control) has upon its response to over-gaining of the fuel injector control signal (resulting in peak splitting). This over-gaining of the control signal is due to the fact that the desired amplitude was always set to zero. Analysis of the moving average of the Fourier transform shows the peak splitting phenomenon in the pressure over approximately 1/8 of the phase sweep cycle in the low gain case. In contrast, the peak splitting phenomenon just barely appears in the higher gain case, occurring only at the pressure minimum over about 1/32 of the phase sweep cycle.

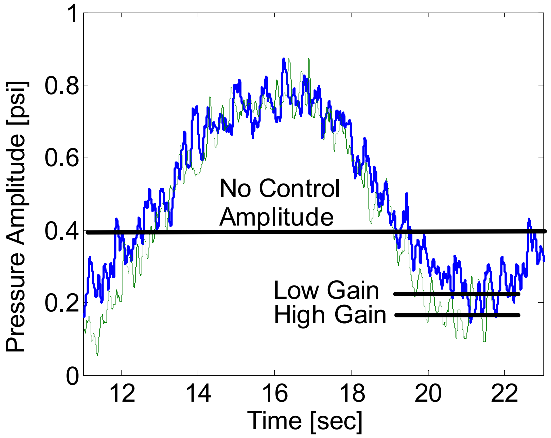

Figure 22. Dependence of instantaneous pressure amplitude upon time as phase of control signal is swept at 0.1 Hz. Data taken at two air actuator gains illustrated in Figure 21.

Concluding Remarks

These results demonstrate that optimum instability control performance can be achieved by not attempting to drive the instability amplitude to zero, but rather some low value that is attainable without requiring too large a fuel injector controller gain. They also show the important role that the linear and nonlinear characteristics of the self-excited oscillations (without control) have upon the effect of active control performance.

While these studies have demonstrated the significance of the fuel injector control gain and nominal combustor dynamics on active control effectiveness, future work is needed to systematically investigate other limiting factors. For example, Hibshman *et al.*[1] have shown that control system time delays are partially responsible for the peak splitting phenomenon. Thus, it would be instructive to repeat the experiment where the desired amplitude is incrementally stepped down (see Figure 13) at several time delays which can be electronically added to the control loop. Also, effects of lowered pressure oscillation correlation time with increased amplitude reduction did not appear to be a limiting factor in these studies. It seems likely that reduced correlation time effects could also be significant. We plan to assess these affects by performing experiments at longer time delays where reduced signal coherence effects may be more significant than peak splitting effects.

Acknowledgments

Research supported by Air Force Research Laboratory STTR under contract # F33615-00-c-2072, (Contract Monitor, Barry Kiel) under a sub-contract with EERGC (Mark Sheldon, technical monitor) and

US Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, under contract 02-01-SR095 (Contract monitor Dr. Richard Wenglarz,) Any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Air Force Research Laboratory or the DOE.

References

---

[1] Hibshman, J., Cohen, J., Banaszuk, A., Anderson, T., Alholmm H., Active Control of Combustion Instability in a Liquid-Fueled Sector Combustor, *ASME Paper 99-GT-215*.

[2] Cohen, Jeffrey, Anderson, Torger, Experimental Investigation of Near-Blowout Instabilities in a Lean, Premixed Combustor, *AIAA paper # 96-0819*, 1996.

[3] Straub, D.L., Richards, G.A., Effect of Fuel Nozzle Configuration on Premix Combustion Dynamics, *ASME paper # 98-GT-492*, 1998.

[4] Paschereit, C.O., Gutmark, E., Weisenstein, W., Control of Thermo-Acoustic Instabilities and Emissions in an Industrial Type Gas Turbine Combustor*, 27th Int'l Symp. on Combustion (The Combustion Institute)*, Pittsburgh, PA, 1998.

[5] Hsiao, George C., Pandalai, Raghavan P., Hura, Harjit S., Mongia, Hukam C., Combustion Dynamic Modeling for Gas Turbine Engines, *AIAA paper # 98-3380*.

[6] Cowell, L.H., Experience at Solar Turbines with Combustion Oscillations in Lean Premixed Combustion, *Proceedings of AGTSR Combustion Workshop*, Penn. State, Sept. 10-11, 1995.

[7] DeLaat, J., Breisacher, K., Saus, J., Paxson, D., Active Combustion Control for Aircraft Gas Turbine Engines, *AIAA Paper #2000-3500*.

[8] Johnson, C., Neumeier, Y., Lubarsky, E., Lee, J., Zinn, B.T., Suppression of Combustion Instabilities in a Liquid Fuel Combustor using a Fast Active Control Alghorithm, *AIAA Paper # 2000-0476*.

[9] Seume, J.R., Vortmeyer, N., Krause, W., Hermann, J., Hantschk, C., Zangl, P., Gleis, S., Vortmeyer, D., Orthmann, A., Application of Active Instability Control to a Heavy Duty Gas Turbine, ASME Paper # 97-ASME-119.

[10] Cohen, J.M., Stufflebeam, J.H., Proscia, W., The Effect of Fuel/Air Mixing on Actuation Authority in an Active Combustion Instability Control System. *Transactions of the ASME; Journal of Engineering for Gas Turbines and Power*, Vol. 123, No. 3, pp. 537-542, July 2001.

[11] Neumeier, Y., Nabi, A., Zinn, B.T., *AIAA paper # 96-2757*, 1996

[12] Neumeier, Y., Markopolous, N., Zinn, B.T., "Procedure for Real-time Mode Decomposition, Observation, and Prediction for Active Control of Combustion Instabilities," *IEEE Conference on Control Applications*, 1997.