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Abstract

An adaptive control algorithm has been developed for the suppression of combustion thermo-acoustic instabilities. This technique involves modulating the fuel flow in the combustor with a control phase that continuously slides within the stable phase region, in a back and forth motion. The control method is referred to as Adaptive Sliding Phasor Averaged Control (ASPAC). The control method is evaluated against a simplified simulation of the combustion instability. Plans are to validate the control approach against a more physics-based model and an actual experimental combustor rig.

Introduction

Lean-burning, low emission combustors are being investigated for aircraft gas turbine engines. Lean combustion is shown to be advantageous for low NOx emissions, better turbine temperature distribution and efficiency, but suffers from an increased susceptibility to thermo-acoustic instabilities. These instabilities typically result from coupling of the fluctuating heat release of the combustion process with the lightly damped acoustics of the combustion chamber.[1] These instabilities cause pressure oscillations within the combustor that can reduce component life and potentially lead to premature mechanical failures.

In recent years, suppression of thermo-acoustic instability has been attempted through active control.[2] The goal of these active control efforts is to reduce the energy concentrated at the instability frequency and to reduce the overall amplitude of the combustor pressure oscillations. Some active control concepts involved speaker actuation or placing another heating source.[3,4,5,6,7,8,9] Speaker actuation simplifies the problem by eliminating the need for fuel modulation control with all its adverse process characteristics. However, acoustic actuation may not be directly applicable to aircraft-type engines due to the harsh environment and weight restrictions. Others have attempted to actuate the fuel modulation with some limited success.[10,11,12,13,14] These later control investigations have demonstrated some ability to reduce the frequency spectra of the instability but have been less successful at reducing the time domain pressure fluctuations.

Many of these active combustion control (ACC) techniques rely on accurate knowledge of the plant dynamics. However, the combustion process is rather complicated and difficult to model. The combustion process characteristics include large dead-time phase shifts, large wideband noise compared to the amplitude of the instability, exponential growth of the instability, frequency and phase shift randomness,[15], and a system that transitions through inherently unstable operation. Because of these adverse process characteristics, the instability may grow very fast to unacceptable levels even when momentary loss of control tracking occurs. This momentary loss of control is inevitable when the instability has been suppressed down to the noise level.

In the effort described in this paper, an adaptive phase shifting controller has been developed for suppression of the instability in a liquid-fueled single nozzle combustor. The pressure fluctuations due to the instability are sensed, filtered, and phase shifted by the controller to actuate the fuel modulation in order to generate combustion pressure or heat release oscillations that are opposing to the chamber acoustics. The control method developed under this effort is based on adaptive phase shifting where the phase of the control vector continuously bounces from one boundary of an effective stability region to the other, in a back and forth sliding

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motion. This Adaptive Sliding Phasor Averaged Control (ASPAC) algorithm requires very little detailed knowledge of the plant dynamics. Rather, the combustor pressure is sensed and the average power of the instability signal is calculated. If the power is decreasing, the direction of change in control phase is maintained. If the power starts to increase, the direction of control phase change is reversed. Therefore, in a heuristic sense the controller converges to an optimal region verses an optimal point. Due to the general behavior of resonances and the need of averaging due to large dead time phase delay in the process dynamics, this control method was envisioned to produce faster and better results than a search algorithm that attempts to compute and control the plant to an optimal phase. A good amount of the control logic in this algorithm is devoted to quickly identifying instability growth and suppressing it again before its amplitude increases to unacceptable levels.

The current effort is aimed at eventually demonstrating the ASPAC controller on a liquid-fueled single nozzle combustor rig. The combustor test rig emulates a real aero-engine instability experience.[16,17] Control studies are to be conducted at actual engine pressures, temperatures and flows. This paper describes the simulation evaluation leading up to combustor test.

The paper is organized as follows. A description of the combustor rig is given, followed by a description of the plant reduced-order model. The control method is then described. The results of simulation studies using the ASPAC method are presented to demonstrate its effectiveness for suppressing thermoacoustic instabilities. Finally, future plans, including testing with a detailed, physics-based model and with the combustor rig are presented.

Combustion Instability Rig

In order to focus control development toward realistic combustion instabilities, a combustor rig which replicates an engine combustion instability has been developed.[16,17] The sample problem selected for this rig is a combustion instability that was observed during the development of a high-performance aircraft gas-turbine engine. The frequency of the observed instability at a mid-power operating condition was 525Hz, and the magnitude of the pressure oscillations was sufficient to cause unacceptable vibratory stresses in the turbine.

The rig successfully replicates the engine instability and operates at engine pressure and temperature conditions. The single-nozzle combustor rig has many of the complexities of a real engine combustor including an actual engine fuel nozzle and swirler, dilution cooling,
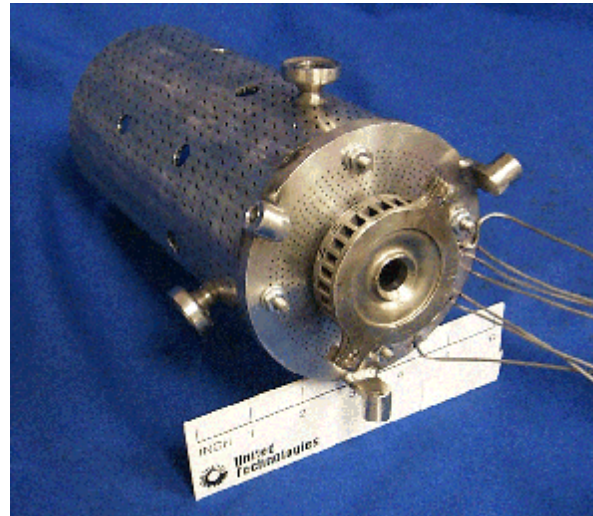

Figure 1 – Combustor Rig for Combustor Instability Control Research
(Photo by United Technologies Research Center)

and an effusion-cooled liner (**Figure 1**). The single-nozzle combustor rig was operated at pressures, temperatures, and fuel-air ratios corresponding to three different engine operating conditions. For the conditions corresponding to the mid-power condition chosen for evaluation (T3=770ºF, P3=200psia, fuel-air ratio=0.03), test results established the existence of a combustion instability at approximately 566 Hz.

A comparison between the pressure spectrum in the engine and in the single-nozzle combustor rig at comparable operating conditions is shown in **Figure 2**. The combustor rig approximates the frequency and
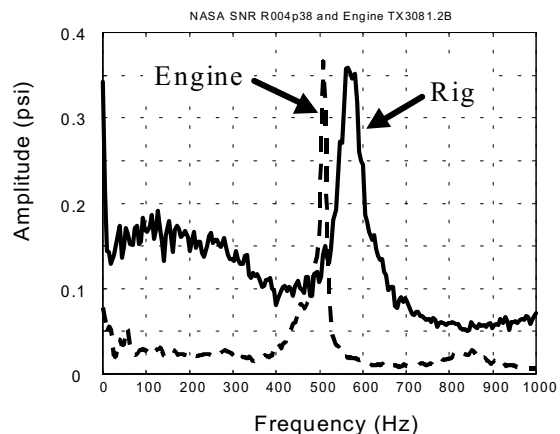

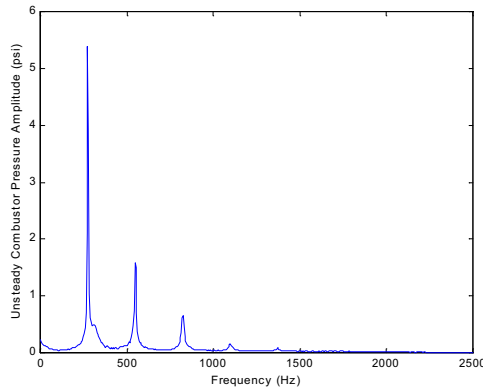**Figure 2 – Comparison of Engine and Baseline Combustor Rig Pressure Spectra[16]**

Figure 3 – Measured Pressure Spectrum Of Unsteady Combustion Pressure For The Single Nozzle Rig In The Extended Configuration[7]

amplitude of the engine instability. However, the engine provides a narrower, more coherent frequency peak, and the rig exhibited a higher overall level of noise. Still, the single-nozzle rig provides a suitable, realistic test environment for combustion instability control research.

In addition to the baseline rig configuration, the combustor rig was also changed to an extended configuration that placed a plenum between the diffuser and the fuel injector[17] in order to make the instability stronger. This extended configuration, when operated at the same mid-power evaluation condition as the baseline configuration, showed a dramatically different instability frequency (273Hz) and magnitude (**Figure 3**). Higher order harmonics are evident, and the peaks here are narrow and coherent as compared with the results for the baseline configuration. This configuration was chosen for the initial control investigations until a high-frequency fuel actuator became available for the baseline configuration. The ready availability of experimental data for the extended configuration made it a good candidate for the initial control studies described in this paper.

The research combustor rig was developed in partnership with Pratt & Whitney and United Technologies Research Center (UTRC). Experimental testing with the combustor rig is taking place at UTRC.

Combustion Instability Simulation

The ASPAC control diagram is shown in **Figure 4**. A reduced-order model was created to represent the combustion instability. This model, based on the extended combustor rig configuration just discussed (273Hz instability), consists of the flame dynamics, acoustics, and a saturation non-linearity. The instability is self-excited, that is, it requires no input via fuel injection modulation. The respective transfer functions for the flame (G_F), acoustics (G_A), and non-linearity (NL) are:

$$G_F = \frac{2262}{s + 1885} \tag{1}$$

$$G_A = \frac{-750,000}{s^2 + 245s + 3e6} \tag{2}$$

$$NL = \tanh(p) \tag{3}$$

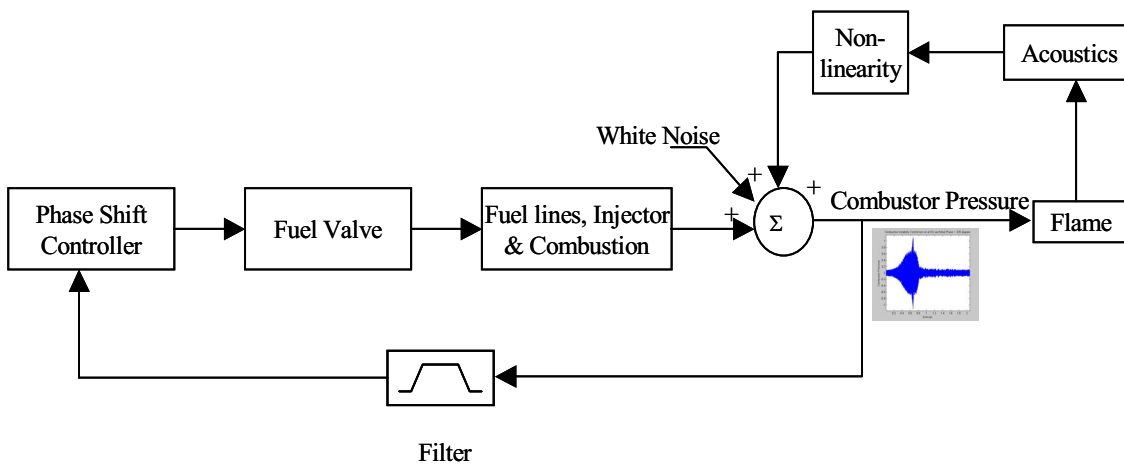where p is the acoustic pressure. The G_A transfer function dynamics correspond to an instability frequency

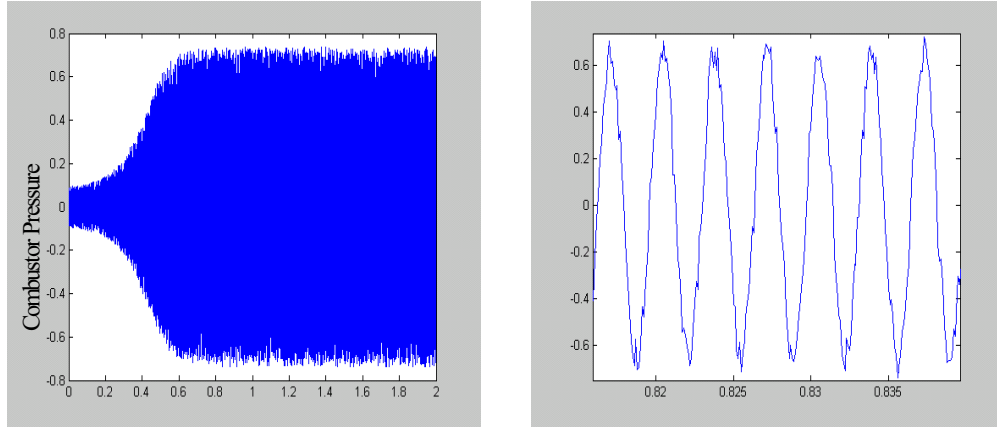

Figure 4 – Combustion Instability Control Block Diagram

Figure 5 – Self-Excited Instability Time Response

of 275Hz with low damping (ς = 0.0707), based on instability time response measurements.[2] The non-linearity (NL) limits the amplitude of the instability. The parameters of the reduced-order model were determined to closely match the response behavior of the extended configuration rig data.

The open-loop plant was discretized and simulated in MATLAB. Results from simulation of the self-excited instability are shown in **Figure 5**. The sampling time T_s is 0.0001 sec. The response time of the instability depends on the damping ς of the transfer function G_A and the sampling time T_s. Given these two parameters this simulation is numerically unstable, that is, the response depends on the sampling time chosen. The instability amplitude is limited by the nonlinearity in the model and is thus repeatable. However, the instability growth can be influenced by random effects such as the noise with initial seeding, along with the severity of the numerical instability. This can sometimes give unrepeatable results even for the same initial conditions. For this simulation, however, the results are repeatable and match expected rig characteristics.

To conduct closed-loop control studies, the dynamics of the controlled system were added to the open-loop instability simulation. The dynamics of the fuel valve, feed lines, injector, and heat release or flame dynamics due to the fuel modulation (G_V), have been simulated with a second order transfer function as:

$$G_V = \frac{25.3e6}{s^2 + 6e3s + 25.3e6} \quad (4)$$

Two identical band pass filters are placed in series in the feedback path. These filters achieve two objectives: 1) filtering out the process and sensor noise; and 2) representing the dead-time phase shift in the combustion process. Normally, the time delay associated with the delivery, injection, atomization, vaporization, and burning of the fuel would be included in the dead-time phase shift of the plant. However, for convenience, this dead-time phase shift has been included in the feedback path.

Based on experimental data from the NASA combustor rig at UTRC, the phase lag amounts to approximately 760° at the instability frequency. The state space model of the band pass filter is:

$$\dot{x} = Ax + Bu$$
$$y = Cx \quad (5)$$

With

$$A = 1000 \begin{bmatrix} -0.4 & 0 & 0 & 1.69 & 0 & 0 \\ 0.4 & -0.4 & -0.4 & 0 & 1.69 & 0 \\ 0 & 0.4 & 0 & 0 & 0 & 1.69 \\ -1.69 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1.69 & & 0 & 0 & 0 \\ 0 & 0 & -1.69 & 0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 400 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \quad C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

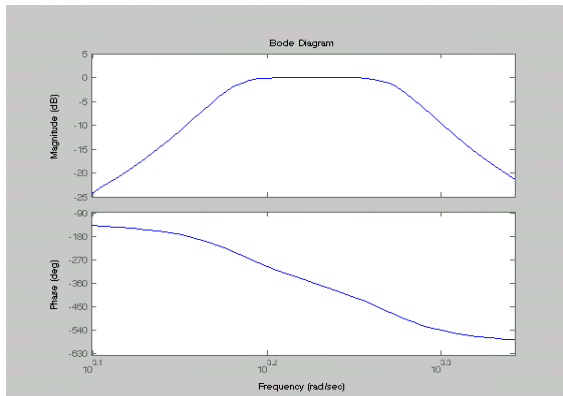The bode plot of the band pass filter is shown in **Figure 6.**

Figure 6 – Bode Plot of Band-Pass Filter

Control Algorithm

The ASPAC algorithm is based on sensing the instability pressure, filtering it, and then phase shifting this signal to control the fuel valve in order to suppress the instability. The pressure sensing and phase shifting is done at the sampling frequency of 10Khz.

Although the combustion process is rather complex, from a controls perspective, the desire is to simply find an opposing modulation phase that will suppress the instability. From this viewpoint, this behavior is equivalent to vector summation and vector rotation. The equivalent controller phasor diagram in a stationary frame of reference is shown in **Figure 7**. The shaded area in this figure is the stable region in which the phase of the fuel modulation relative to the instability pressure is such that the power of the combustor pressure oscillations is reduced. The overall combustor pressure is the vector sum of the combustion pressure from heat

addition due to the fuel modulation and the combustor pressure due to the instability. The phase difference between these two waveforms is continuously changing, even within each oscillation cycle and especially when the instability is sufficiently suppressed. In this case, even complete phase reversal can occur. Therefore, at least momentarily, the stable region can shift anywhere within the circle in **Figure 7**. It is desired that the control logic maintain the appropriate fuel modulation phase even in the presence of large changes in the phase relationship.

In order for the ASPAC algorithm to adapt the phase, the power in the sensed combustor pressure is averaged over the adaptive control cycle, which in this case is 40Hz. The rate for the adaptive controller depends on the noise and the process phase-shift. 40Hz was chosen empirically to obtain good averaging of the instability signal power. Based on the average power, the controller then modifies the relative phase between the sensed combustor pressure signal and the controlled fuel modulation. This phase advancement (sliding phase) occurs in a fixed phase step in the direction that reduces the average combustor pressure power from one control cycle to the next. If the power reduces for a given number of phase steps, the controller establishes a restricted control region. The restricted control region provides an initial estimate of the region of proper relative phase for pressure oscillations reduction. Phase excursions are then limited to this region until a new region is established.

Within the restricted control region, the controller reverses the phase-change direction if the power in the signal increases. When the phase-change direction reverses, this establishes a boundary of an effective stability region. This effective stability region, which varies within the restricted control region, is where the
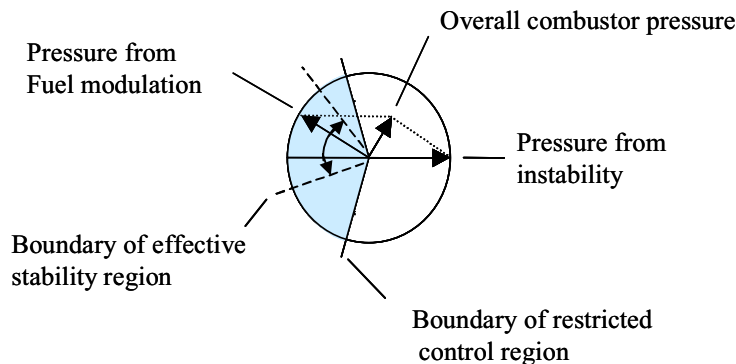

Figure 7 – Phasor Diagram of Combustor Pressure Showing Pressure Due to Instability and Fuel Modulation

phase causes a reduction in average power. The control phase then continuously slides back and forth within the boundaries of the effective stability region. In this sense, the controller converges to a stable region rather than to an optimal phase. Under closed-loop operation, the relative phase between the fuel modulation and the combustor pressure is constantly changing at a rate considerably faster than the adaptive control cycle of 40Hz. The convergence to a stability region accounts for the fact that there is no optimal phase *per se* (in a global sense) at this lower control rate.

As the instability is suppressed, the effective stability region begins to shrink. The ASPAC bounces from one boundary of the effective stability region to the other in a back and forth sliding motion. When the instability has been suppressed to about the noise level, there is no longer an effective phase for instability suppression. The effective stability region vanishes and the system becomes inherently unstable. Following that, the instability begins to grow and the controller reestablishes the effective stability region. Therefore, the system constantly cycles between stable and unstable operation. How quickly the controller cycles through stable/unstable operation, is a basic qualitative measure of how far down the instability can be suppressed.

If, however, there is a persistent increase in signal power over several adaptive control cycles, the control algorithm exits the current restricted control region. A new restricted control region is established when power decrease in the signal again persists for a given number of control cycles.

The control algorithm combines tracking control of the relative phase between instability pressure and fuel modulation with phase adaptation. This combination is designed to allow good control of the instability even in cases when there are changes in the phase required for instability suppression such as those due to net random phase walks. [15]

Simulation Evaluation

As stated in the Introduction, the goal of active combustion instability control is to reduce the energy at the instability frequency and to reduce the overall amplitude of the combustor pressure oscillations. Initial simulation evaluations of performance of the ASPAC have been conducted with the simplified instability model described earlier. The model provides a non-dimensional instability amplitude of about 0.7, which is representative of combustor pressure oscillations. A noise to signal ratio of ~0.14 was used.
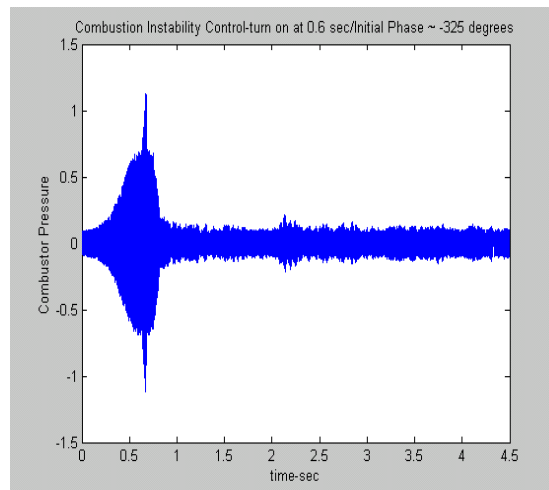

Figure 8 – Combustion Instability Control Using ASPAC, control turned on at 0.6 sec.

The controlled combustion instability is shown in **Figure 8**. Initially, the instability is allowed to grow to steady-state sustained oscillation levels previously shown in **Figure 5**. Then the controller is turned on suppressing the instability. How much the instability pressure can be suppressed seems to depend, first, on the noise level and then on the process dead-time phase shift. The response shows relatively fast control reaction to suppress the instability. However, when the instability has been sufficiently suppressed, loss of control tracking is inevitable because noise becomes the primary driver for phase adaptation. Several instances of the instability pressure starting to increase can be seen in **Figure 8.** However, the controller quickly reestablishes control tracking before the instability grows appreciably.

Figure 9 shows the power spectral density (PSD) of the uncontrolled vs. the controlled instability. A reduction in PSD of nearly 40db on a 20log scale has been achieved in this simulation. Both the PSD and the time domain show important performance criteria. The peak reduction in the PSD is an indication of how much the amplitude (power) at a single frequency has been suppressed. The amplitude of the oscillations in the time domain indicates the vectorial sum of the amplitudes of all the frequencies in the broadband signal. Therefore, if the controller reduces the instability peak in the PSD but merely spreads out the energy, the time domain signal can have the same amplitude as the uncontrolled instability.
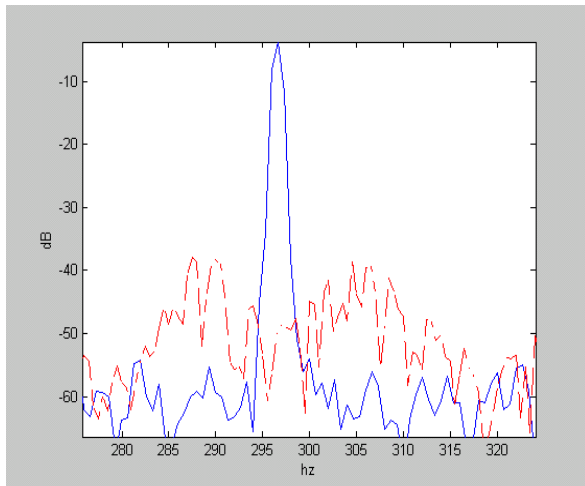
Figure 9 – Power Spectral Density of Uncontrolled (solid) vs. Controlled (dashed) Combustor Pressure

Also shown in **Figure 9** is evidence of peak splitting, a phenomena that has been observed in many other published works in the area of combustion instability control. The peak splitting phenomena would be best explained by the action of phase change in the instability waveform, which, at least momentarily, results in frequency change. However, the action of the ASPAC controller itself, due to its low frequency of 40 Hz, can't impart significant sideband energy that would explain peak splitting. For instance, due to the controller action, only ~ $1/14^{th}$ of the energy (275Hz / 40Hz / 0.5, where

the 0.5 factor is used because only half a cycle will be impacted by the phase change caused by the controller) will be distributed to the sidebands. Assuming that on the average, half the time the phase change due to the controller action is such that the frequency is increasing and half the time the action is such that the frequency is decreasing, then ~$1/28^{th}$ of the energy will be distributed on each sideband. Therefore, the peak splitting sideband energy due to the controller action is rather insignificant.

The most logical explanation is that the peak splitting phenomena is due to continuous phase rotation and phasor summation. This action causes phase changes on each half cycle of the waveform and therefore, it introduces maximum sideband energy around the instability frequency.

After the initial evaluation, modifications were made to the controller to design for discontinuous exponential gain modulation. The attempt was to gain additional attenuation of the instability due to the increased challenge of the high frequency instability problem (~565 Hz), where the wideband noise to signal ratio for the experimental rig was expected to be significantly greater than 1. This design developed for this problem, involves modulating the control gain and applying a time delayed exponential gain when the cycle instability signal power decreases. **Figures 10** and **11** show simulations of the instability time response and PSD respectively, with the addition of discontinuous exponential gain modulation control. The time domain plot shows similar performance to the previous results (**Figure 8**). However, as shown by further reduction in
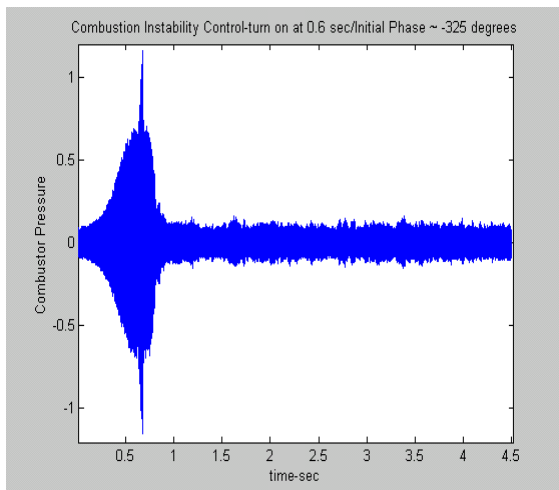

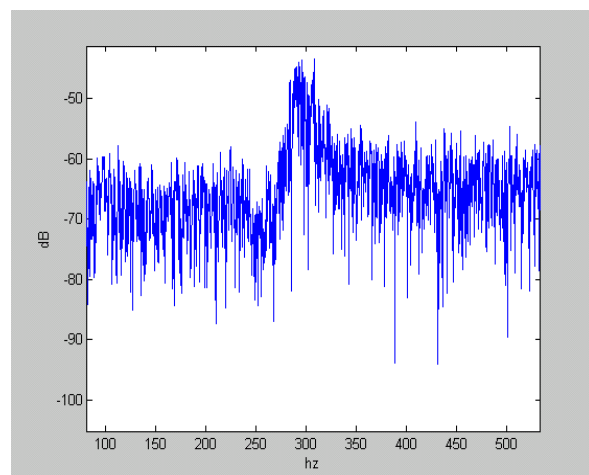**Figure 10 – Combustor Pressure with Discontinuous Exponential Gain Modulation Control**

Figure 11 – Power Spectral Density of Controlled Combustor Pressure with Discontinuous Exponential Gain Modulation Control
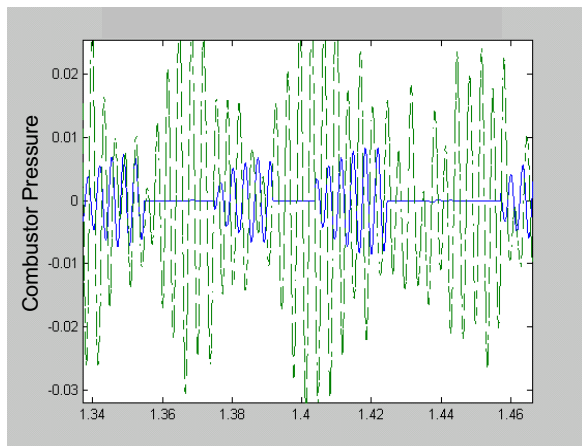
Figure 12 – Instability Pressure (dashed) and Controlled Pressure due to Heat Release Fluctuations (solid) Using Discontinuous Exponential Gain Modulation Control

the PSD, this additional control augmentation achieves better performance. **Figure 12** shows the instability pressure and the pressure due to controlled fuel modulation (heat release). The discontinuous controlled pressure fluctuations due to the control augmentation can clearly be seen.

Future Plans

Future plans for the ASPAC algorithm include evaluation against a more physics-based model and experimental evaluation on a combustor rig. Preparations are underway for both of these activities. Plans include testing of the ASPAC algorithm with and without discontinuous exponential gain modulation.

The physics-based simulation evaluation will use a Sectored 1-D model, of the combustor written in FORTRAN.[18] This simulation has been updated to model the NASA combustor rig at UTRC. Preparations for controller evaluation with this simulation have been completed. The MATLAB code from the previously described controller evaluation was converted to C-code and integrated with the FORTRAN combustor model. As of the writing of this paper, the evaluation of the controller against this simulation is in progress.

In parallel, preparations are being made to run the ASPAC with the NASA combustor rig at UTRC. The simulation and control C-code were integrated with the appropriate analog-to-digital and digital-to-analog interfaces and compiled to run on a dSpace real time

control system. The preliminary evaluation on the dSpace system has demonstrated control of the plant simulation in real time. The next step will be to run the controller on the NASA combustion rig at UTRC in order to evaluate the controller performance on the combustion rig itself.

Conclusion

A combustion instability suppression control algorithm has been developed and demonstrated on a simplified simulation of a self-excited combustion instability pressure oscillation. The Adaptive Sliding Phasor Averaged Control (ASPAC) algorithm performs well with relatively high combustion noise and dead-time phase shift. In addition, the algorithm responds relatively fast to suppress the instability and also recover from loss of control tracking. This loss of tracking is unavoidable when the instability is sufficiently suppressed during control action. Future work includes demonstration of this control approach on a physics-based model of the combustion process and controls testing on NASA's single nozzle combustor rig at UTRC.

References

1 . Lefebvre, A.H.: *Gas Turbine Combustion, 2nd edition, Taylor and Francis, 1999.*

2. McManus, K. R.; Poinsot, T.; and Candel, S. M.: "A Review of Active Control of Combustion Instabilities", in *Progress in Energy and Combustion Science*, Volume 19, Issue 1, P. 1-29, February 1993.

3. Dines, P. J.: "Active Control of Flame Noise", Ph.D. Thesis, Cambridge University, 1984.

4. Heckl, M. A.: "Active Control of Noise from a Rijke Tube", IUTAM Symposium on Aero and Hydro-Acoustics, Springer Verlag, pp. 211-216, 1985.

5. Sreenivasan, K. R.; Raghu, S.; and Chu, B. T.: "The Control of Pressure Oscillations in Combustion and Fluid Dynamical Systems", AIAA Shear Flow Conference, 1985.

6. Gleis, S.; Vortmeyer, D.; and Rau, W.: "Experimental Investigation of the Transition From Stable to Unstable Combustion by Means of Active Instability Control", Propulsion and Energetics Panel, 75th Symposium, AGARD, pp. 22:1-6, 1990.

7. Dowling, A. P.; Hooper, N.; Langhorne, P. J.; and Bloxsidge, G. J.: "Active Control of Reheat Buzz", AIAA 25th Aerospace Sciences Meeting, 1987.

8. Brouwer, J.; Ault, B. A.; Bobrow, J. E.; and Sumuelsen, G. S.: "Active Control for Gas Turbine Combustors", 23rd Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1990.

9. Allgood, D.; Campos-Delgado, D. U.; Acharya, S.; and Zhoo, K.: "Acoustic Control of Thermoacoustic Instabilities Using Experimental Model-Based Controllers," Proceedings of ASME Turbo Expo, New Orleans, LA, 2001.

10. Cohen, J.M.; Rey, N.M.; Jacobson, C.A.; and Anderson, T.J.: "Active Control of Combustion Instability in a Liquid-Fueled Low-Nox Combustor," International Gas Turbine & Aeroengine Congress and Exhibition, Stockholm, Sweden, 1998.

11. Hibshman, J. R.; Cohen, J. M.; Banaszuk, A.; Anderson, T. J.; and Alholm, H. A.: "Active Control of Pressure Oscillations in a Liquid-Fueled Sector Combustor," International Gas Turbine & Aeroengine Congress & Exhibition, Indianapolis, Indiana, 1999.

12. Johnson, C. E.; Neumeier, Y.; Nuemaier, M.; Zinn, B. T.: "Demonstration of Active Control of Combustion Instabilities on a Full-Scale Gas Turbine Combustor," Proceedings of ASME Turbo Expo, New Orleans, LA, 2001.

13. Murugappan, S.; Park, S.; Acharya, S.; Annaswamy, A. M.; Gutmark, E. J.; Ghoniem, A. F.: "Optimal Control of Swirl-Stabilized Combustor Using System Identification Based Model," Turbine Conference, Cesme, Turkey, 2000.

14. Murugappan, S.; Acharya, S.; Gutmark, E. J.; and Messina, T.: "Characteristics and Control of Combustion Instabilities in a Swirl-Stabilized Spray Combustor," 35th Joint Propulsion Conference and Exhibit, Los Angeles, CA, 1999.

15. Lieuwen, C.; Zinn, B. T.: "Investigation of Cycle-to-Cycle Variability in an Unstable Gas Turbine Combustor," International Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, 2000.

16. Cohen, J.M. et al: "Experimental Replication of an Aeroengine Combustion Instability," International Gas Turbine & Aeroengine Congress & Exhibition, Munich, Germany, 2000.

17. DeLaat, J.C.; Breisacher, K.J.; Saus, J.R.; Paxson, D.E.: "Active Combustion Control for Aircraft Gas Turbine Engines," 36th Joint Propulsion Conference and Exhibition, Huntsville, AL, 2000.

18. Paxson, D.E.: "A Sectored One-Demensional Model For Simulating Combustion Instabilities in Premix Combustors, AIAA 38th Aerospace Sciences Meeting and Exhibition, Rene, NV, January 2000. NASA TM 1999-209771, AIAA-2000-0313.

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13. ABSTRACT (Maximum 200 words)

An adaptive control algorithm has been developed for the suppression of combustion thermo-acoustic instabilities. This technique involves modulating the fuel flow in the combustor with a control phase that continuously slides within the stable phase region, in a back and forth motion. The control method is referred to as Adaptive Sliding Phasor Averaged Control (ASPAC). The control method is evaluated against a simplified simulation of the combustion instability. Plans are to validate the control approach against a more physics-based model and an actual experimental combustor rig.

14. SUBJECT TERMS

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