NASA/TM—2004-213198 AIAA–2004–4028

Validation of an Adaptive Combustion Instability Control Method for Gas-Turbine Engines

George Kopasakis, John C. DeLaat, and Clarence T. Chang
Glenn Research Center, Cleveland, Ohio

October 2004

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2004-213198 AIAA–2004–4028

Validation of an Adaptive Combustion Instability Control Method for Gas-Turbine Engines

George Kopasakis, John C. DeLaat, and Clarence T. Chang
Glenn Research Center, Cleveland, Ohio

Prepared for the
40th Joint Propulsion Conference and Exhibit
cosponsored by the AIAA, ASME, SAE, and ASEE
Fort Lauderdale, Florida, July 11–14, 2004

National Aeronautics and
Space Administration

Glenn Research Center

October 2004

Acknowledgments

The authors would like to thank Kevin J. Melcher and Joseph R. Saus
for their insightful discussion and review of this paper.

This work was sponsored by the Low Emissions Alternative Power Project of the Vehicle Systems Program at the NASA Glenn Research Center.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Validation of an Adaptive Combustion Instability Control Method for Gas-Turbine Engines

George Kopasakis, John C. DeLaat, and Clarence T. Chang
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

This paper describes ongoing testing of an adaptive control method to suppress high frequency thermo-acoustic instabilities like those found in lean-burning, low emission combustors that are being developed for future aircraft gas turbine engines. The method called Adaptive Sliding Phasor Averaged Control, was previously tested in an experimental rig designed to simulate a combustor with an instability of about 530 Hz. Results published earlier, and briefly presented here, demonstrated that this method was effective in suppressing the instability. Because this test rig did not exhibit a well pronounced instability, a question remained regarding the effectiveness of the control methodology when applied to a more coherent instability. To answer this question, a modified combustor rig was assembled at the NASA Glenn Research Center in Cleveland, Ohio. The modified rig exhibited a more coherent, higher amplitude instability, but at a lower frequency of about 315 Hz. Test results show that this control method successfully reduced the instability pressure of the lower frequency test rig. In addition, due to a certain phenomena discovered and reported earlier, the so called *Intra-Harmonic Coupling*, **a dramatic suppression of the instability was achieved by focusing control on the second harmonic of the instability. These results and their implications are discussed, as well as a hypothesis describing the mechanism of intra-harmonic coupling.**

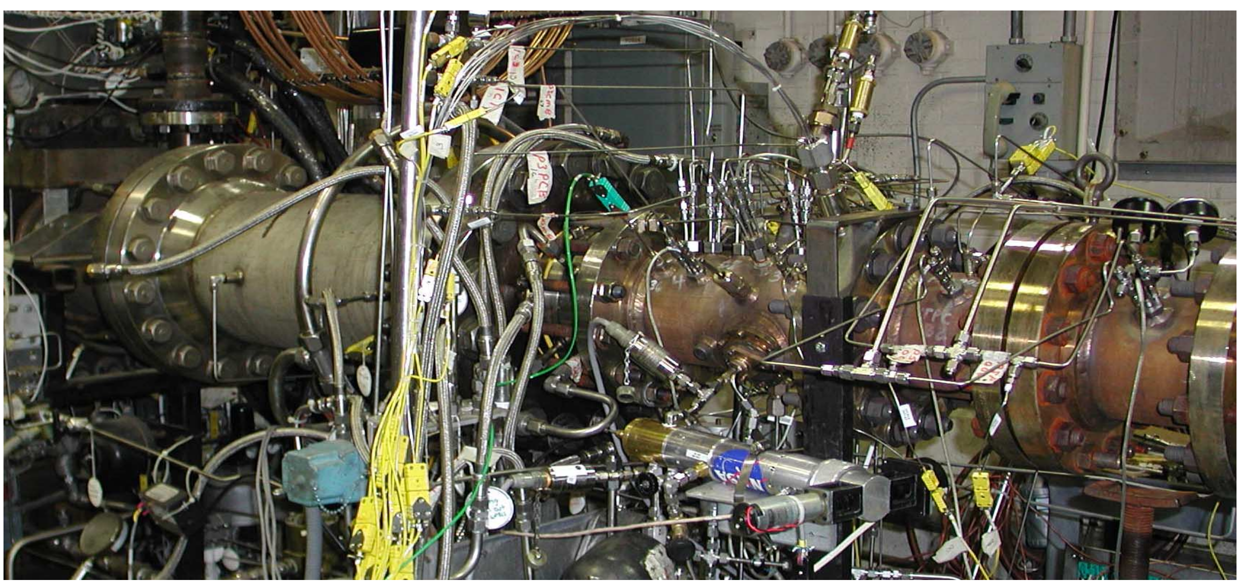


Figure 1.—Test Rig for Aircraft Gas-Turbine Engine Combustion Instability Research at NASA GRC.

I. Introduction

LEAN-burning, low emission combustors are being investigated for aircraft gas turbine engines. Lean combustion is shown to be advantageous for reducing NOx emissions and enhancing turbine temperature distribution and efficiency; but is also more prone to thermo-acoustic instabilities. These instabilities are typically the result of the coupling of the fluctuating heat release[1] (of the combustion process) with the lightly damped acoustics of the combustion chamber. The exact mechanism involved in this coupling is not well understood and different hypotheses as to its precise nature exist.[2]

Suppression of the thermo-acoustic instability has been attempted through active control.[3] 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[4,5,6,7,8,9,10] and others involve fuel modulation.[11,12,13,14,15] Fuel modulation is more applicable to aero-type engines. But even the latter techniques have shown limited success in suppressing the frequency spectra of low frequency instabilities, and even less success in suppressing the time domain pressure fluctuations.

Combustor instability suppression presents a challenging problem for controls design due primarily to large dead-time phase delay (of many hundreds of degrees or more) and noise in the combustion process. Besides large phase delay and noise, there are other characteristics of combustor instabilities which could play an important role in control design.[2,16] The Adaptive Sliding Phasor Averaged Control (ASPAC) methodology was first applied to control a High Frequency Rig Configuration (HFRC) during tests conducted in 2002 at United Technologies Research Center (UTRC). The results presented in Ref. 17 demonstrated the effectiveness of the methodology in reducing the frequency spectra of the combustor pressure. This represented the first known control demonstration of actively controlled, high frequency, thermo-acoustic instabilities in a realistic aero-engine (gas-turbine) combustor rig.[17,18]

This year, control was attempted on the Low Frequency Rig Configuration (LFRC) that was assembled at NASA Glenn Research Center (GRC) to further test and verify the control methodology. As will be shown later, the LFRC exhibited a strong coherent instability compared to the HFRC. The actual aero-engine exhibited instability with coherence somewhere between the LFRC and the HFRC. The controller was successful in suppressing the low frequency, coherent instability. However, the level of suppression at the fundamental frequency was less than expected based on the experience gained from application of the control to the HFRC. This will also be discussed as there seems to be other factors that influence the control of coherent instabilities.

In analyzing the control test results with the HFRC, it was hypothesized that there seems to exist some sort of inertia that promotes amplification of the instability during instability flare-ups, even though the controller modulation opposes this action.[17] Later, an analysis of the coherence showed that a dynamic coupling seemed to exist between the instability and its harmonics.[2] Based on this result, the controller design for the LFRC was altered to also control the second and the third harmonics of the instability. In so doing it was possible to determine whether additional suppression of the instability was possible, as the analysis seemed to indicate. The test results demonstrated not only that additional suppression was possible by controlling the second harmonic, but the results were unexpectedly dramatic. In fact, focusing the control on the second harmonic produced large suppressions, which may be possible even with simplified or unsophisticated control designs. A preliminary hypothesis will be offered as to why controlling the harmonic has such a pronounced effect on suppressing the instability. This hypothesis, that will be discussed in detail later, deals *with wave coupling asymmetry*.

This paper is organized as follows: A description of the combustor rig is given, followed by a brief description of the control methodology. Then test results for the HFRC and the LFRC are presented. These are followed by a discussion about harmonic control and its implications. Finally, further insights are presented on possible causes for these coupling dynamics.

II. Combustion Instability Rig

In order to focus control development toward realistic combustor instabilities in aeronautics, a combustor rig that replicates an aero engine combustor instability has been designed and fabricated.[19,20] A picture of the rig is shown in Figure 1 and a corresponding schematic in Fig. 2. 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 in the developmental engine was about 525 Hz and the magnitude of the pressure oscillations was sufficient to cause unacceptable vibratory stresses in the turbine.

The combustor rig successfully replicates the observed real-world engine instability and operates at engine pressure and temperature conditions. This is a single-nozzle combustor rig, which has many of the complexities of the actual engine combustor including a state-of-the-art engine fuel nozzle and swirler, dilution cooling, and an effusion-cooled liner.

Conditions corresponding to a mid-power engine condition were chosen for evaluation (T3=770 °F, P3=200 psia, fuel-air ratio = 0.03). Test results established the existence of a combustion instability at approximately 533 Hz. Figure 2 shows the test rig apparatus for the 533 Hz, high frequency configuration. The LFRC is obtained by removing the diffuser section in Fig. 2 and placing it before the two ¼ wave spool section. This has the effect of elongating the wavelength by ~ 19 in and produces an instability at 315 Hz.

A comparison between the pressure spectrum in the actual engine and in the single-nozzle combustor rig at comparable operating conditions for the HFRC and LFRC is shown in Figs. 3 and 4 respectively. This comparison shows that in terms of instability frequency, the HFRC closely simulates the actual engine instability. In terms of instability coherence for the fundamental, however, the engine more closely resembles the behavior of the LFRC. These two rig configurations provide essentially two control problems. The HFRC provides a high frequency, low signal-to-noise instability problem, and the LFRC provides a lower-frequency, high-amplitude, high signal-to-noise problem.

This single nozzle research combustor rig was developed in partnership with Pratt & Whitney and UTRC. The first experimental testing with the HFRC took place at UTRC, and the more recent control testing with the LFRC took place at NASA GRC.

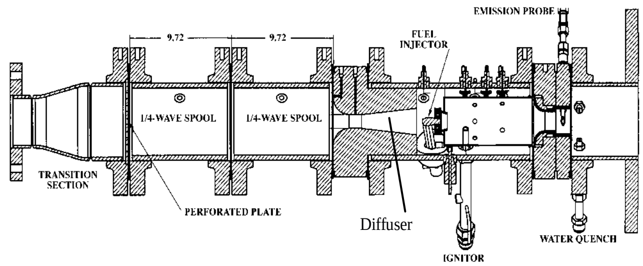


Figure 2.—Combustion Instability Test Rig Configuration.

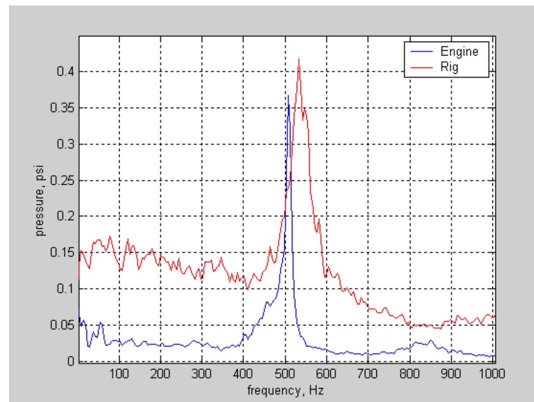


Figure 3.—Pressure Spectra Comparison of Engine (Mid-Power) and Baseline High Frequency Rig Configuration (HFRC).

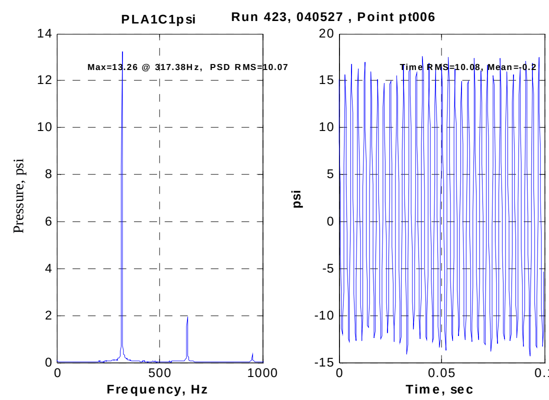


Figure 4.—Pressure Spectra and Time Domain for Low Frequency Rig Configuration (LFRC).

III. Description of ASPAC Algorithm and Modifications

The ASPAC algorithm is described in detail in Refs. 17 and 21. In essence the algorithm calculates a restricted control phase region in a stationary reference frame; an approach that is favorable for instability suppression. The combustor instability pressure is sensed using a band-pass filter in order to isolate the instability frequency. The sensed pressure is phase shifted, with a phase that slides back and forth inside a restricted control region. This phase shifted pressure is used to generate a command to the fuel valve, which produces pressure oscillations in the combustor that oppose the instability pressure.

The controller command is generated at a 10 KHz rate and the controller calculates and applies a new phase shift at a rate of 40 Hz. Also, this controller optionally employs discontinuous exponential gain modulation control. In this control mode the gain toggles on and off with an exponential decay in order to counteract the effective proportional gain variability produced by the large dead time phase delay of the plant. In addition, controller parameter adaptation is employed to tune some of the key parameters of the controller.

The combustor instability feedback control diagram is shown in Fig. 5. The flame, acoustics, and the nonlinearity loop generates the self excited instability. The pressure oscillations generated by combustion of the controller modulated fuel are opposing in phase the pressure oscillations generated by the instability, reducing the net amplitude of the instability.

The analysis of the test results for the HFRC[17] revealed that during instability control some sort of *instability inertia*, or a self-reinforcing mechanism, seemed to exist that went beyond the effects of the large dead time phase delay.[17] In Ref. 2 this affect was further analyzed and through a coherence plot it was observed that strong coherence existed between the fundamental and its harmonics. This type of effect, even though its exact nature remained unknown, was called *Intra-Harmonic Coupling*. This result suggested that additional suppression of the instability was possible by also controlling higher order harmonics of the instability. Based on this analysis, the control design for the LFRC was modified from the controller version used for the HFRC in order to verify whether additional suppression was possible through harmonic control. Modifications provided for simultaneous control of the first three harmonics of the instability or any combination thereof. Figure 5 shows the control diagram for the modified controller, which includes the adaptive phase control and algorithm for parameter adaptation. A concern with this approach is whether the fuel valve would have the high frequency authority required to control the third harmonic of the instability.

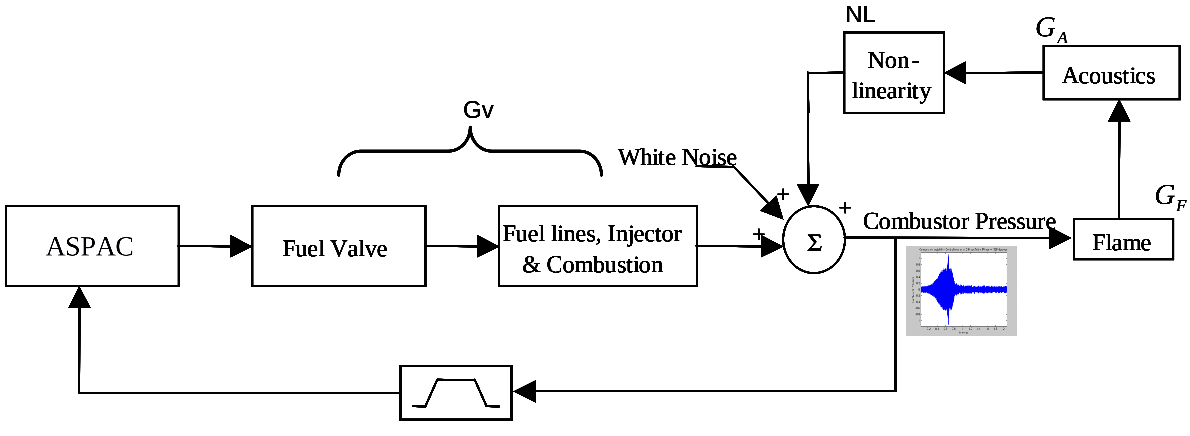


Figure 5.—Combustion Instability Control Block Diagram.

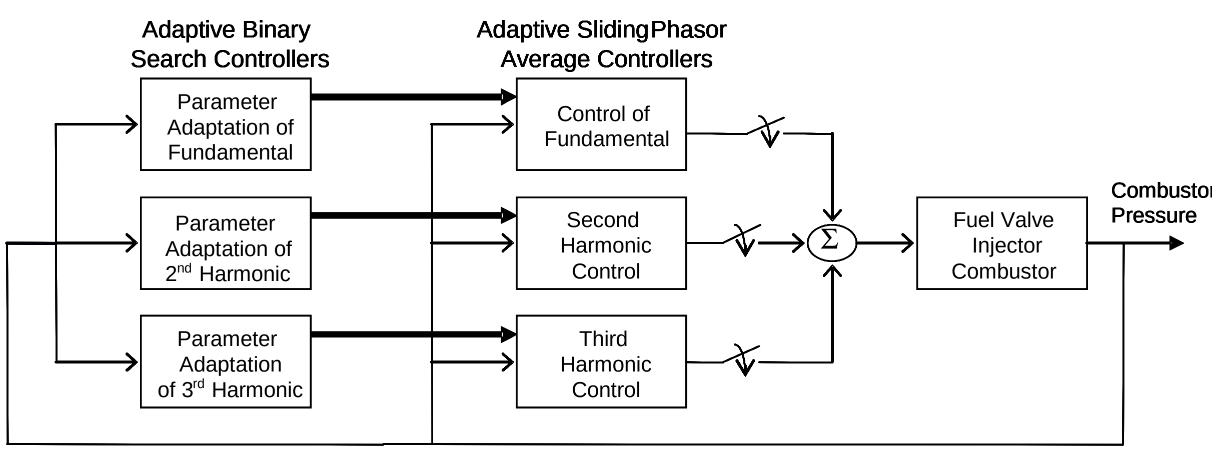


Figure 6.—Overall Combustion Instability Control Block Diagram with Modifications for Harmonic Control.

IV. Test of ASPAC Algorithm and Modifications

This section discusses the test results of the ASPAC control methodology. Two separate sets of tests were conducted over the last couple years to validate the methodology. The first set of tests was carried out on the HFRC at UTRC during June and September of 2002. The most recent tests were performed on the LFRC at NASA GRC during the beginning of June 2004. The HFRC instability suppression test results will be described here only in brief, since these results have already been reported in Ref. 17.

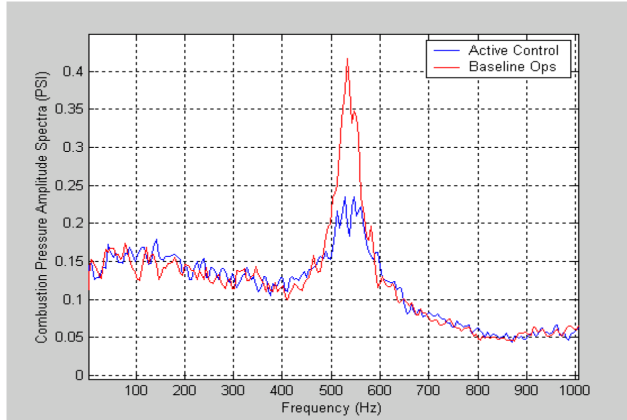


Figure 7.—HFRC, Amplitude Spectral Density of Uncontrolled vs Controlled Instability using Original ASPAC Method.

A. HFRC Test Results

A typical test result[17] using the control algorithm for the HFRC is shown in Fig. 7. In these tests the controller successfully suppressed the instability to near the noise floor. In terms of time domain reductions, the instability amplitude in the HFRC is small compared to the overall wideband noise (~1/7th the noise amplitude) and no apparent reductions were visible in the time domain. For the instability of the HFRC, which was not very coherent compared to the actual engine instability (Fig. 3) the noise floor seemed to impose a lower limit on how far down the instability could be suppressed.

B. LFRC Test Results Focused on the Fundamental

Initially control tests focused only on controlling the fundamental frequency of the instability (~315 Hz), before initiating control at the harmonics. Besides verifying whether controlling the harmonics would improve instability suppression, the original objective remained (i.e., to demonstrate control on a more coherent instability like the one experienced with the actual aero engine). Figure 8 shows a typical frequency response of the controlled instability. A comparison with results from the uncontrolled instability in Fig. 4 shows that the instability amplitude spectra were suppressed by almost a factor of 10. The time domain combustor pressures, along with the control fuel modulation command (REFAcmd) in volts are also shown Fig. 8. Prior open-loop testing showed the fuel modulation command causes a modulation pressure in the combustor of approximately 1 psi/volt up to about 350 Hz, and drops off significantly above this frequency. The control fuel modulation required, as shown in Fig. 8, is only about a third of the maximum available (+-3V).

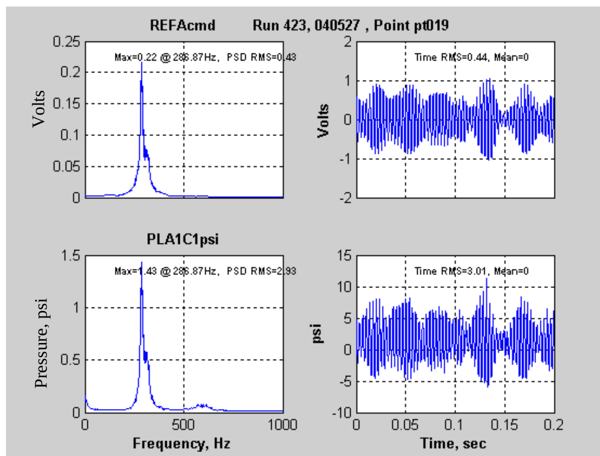


Figure 8.—Pressure Spectra and Time Domain of Controlled Instability (PLA1C1psi) and Control Command (REFAcmd) for Control Focus on the Fundamental.

Given the large dead time phase delay experienced in combustor instability control it was conjectured that combustor noise was the primary limitation of how far down the instability could be suppressed. While noise appears to be the dominant limiting factor for suppression of less coherent instabilities like the HFRC, in general noise doesn't seem to be the only dominant factor. In Section V, a hypothesis will be offered to try to explain this additional mechanism involving instability dynamic behavior and control.

C. LFRC Test Results Focused on the Second Harmonic

During the same test run, controller action was focused on the second harmonic. During the test, it became apparent that the instability fundamental not only responded to the second harmonic control, but the suppression of the fundamental was more drastic than with just the fundamental control (Fig. 9). The scale in Fig. 9 is the same as Fig. 4 for direct comparison. The peak instability pressure in this amplitude spectra plot is 0.7 psi. Comparing this result to the uncontrolled instability of Fig. 4 there is ~ 20 times or 26 dB of instability suppression with this control. In the time domain, the peak-to-peak pressure fluctuation is reduced from approximately 30 psi to less than 10 psi. The corresponding control command for this controlled combustor pressure is shown in Fig. 10. Open-loop fuel modulation testing had shown that during a frequency sweep, the combustor pressure response to the fuel modulations was barely noticeable above the noise floor at 600 Hz. Therefore, relatively little control authority at the second harmonic was needed to suppress the instability.

Another control test focusing on the second harmonic is shown in Fig. 11. This result, in terms of the peak amplitude spectra, is better than the result shown in Fig. 9 (0.39 vs 0.7 psi). This represents about 35 times or 31 dB attenuation of the instability. The reason for the improved controller performance in this second test is still being explored. In both tests the second harmonic of the instability has been essentially eliminated. Some peak splitting is evident in this latter test. Coupling oscillations with the facility feed pressure are shown as very low frequency content in the amplitude spectra of the combustor pressure in Fig. 11. A direct comparison of the uncontrolled vs the controlled instability for this test is shown in Fig. 12.

Testing that focused on the third harmonic of the instability was also carried out during the course of this test run. However, based on this testing and from frequency sweep tests, very little fuel modulation authority of the fuel valve exists at the third harmonic which occurs at about 945 Hz. Control of the third harmonic was only able to reduce the instability by a few psi. This may be due to limited actuator authority at the frequency of the third harmonic.

The results presented here are preliminary. Due to time considerations related to the publishing of this paper, detailed analysis of the test results, including more precise descriptions of the conditions of the controller for these tests, are planned to be published at a future date.

V. Cause of Intra-Harmonic Coupling - Hypothesis

In this section a hypothesis will be offered in an attempt to explain the mechanism that causes the phenomena of *Intra-Harmonic Coupling*. This explanation is based on phenomena observed during testing, and on results from tests involving successful suppression of the instability by focusing control on the second harmonic.

During testing, the combustor pressure was perturbed both at various discrete frequencies and by semi-continuous frequency sweeps. This was done mainly in order to assess the modulation authority of the fuel valve. In the process of conducting these tests some unexpected phenomena were observed. First, the

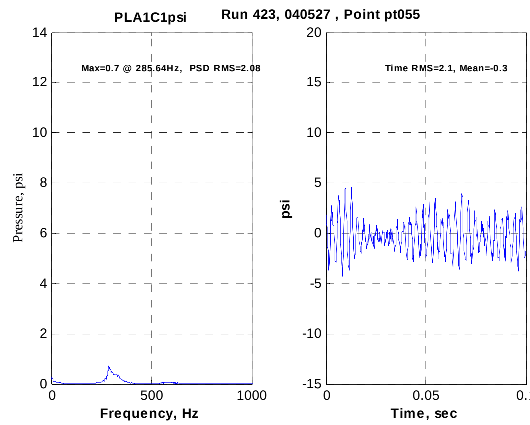


Figure 9.—Pressure Spectra and Time Domain of Controlled Instability of LFRC for Control Focus on the Second Harmonic.

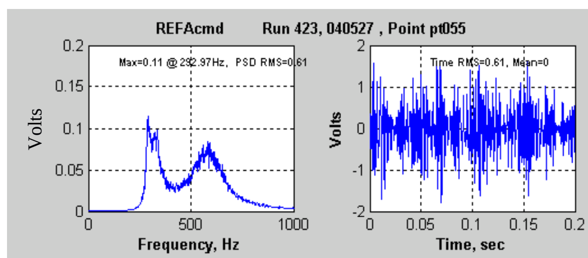


Figure 10.—Amplitude Spectra and Time domain (volts) of Controlled Fuel Command for Figure 9 Combustion Pressure.

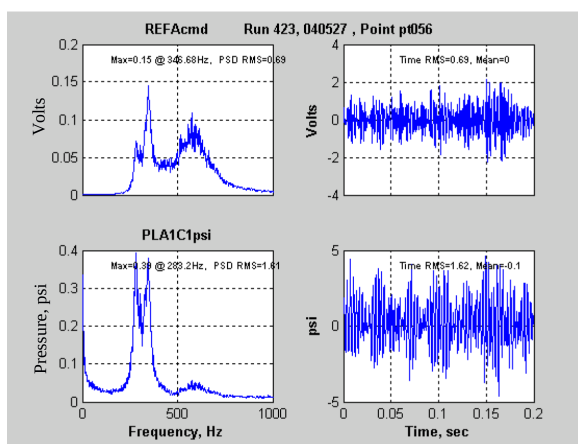


Figure 11.—Pressure Spectra and Time Domain of Controlled Instability and Control Command for Control Focus on the Second Harmonic.

application of a discrete fuel excitation amounting to about 3 volts peak at a frequency of about 200 Hz, initially caused a barely visible pressure in the amplitude spectra. However, as shown in Fig. 14, after about 10 minutes of running time, this modulation produced combustor pressure oscillations which rapidly grew to about 2 psi in the combustor pressure. The growth of this discrete modulation seemed to interact with the instability, reducing its peak somewhat. Discrete excitations at frequency bands near the instability frequency of ~ 315 Hz, on either side, had a more pronounced effect, causing the perturbation to grow significantly, while considerably reducing the instability amplitude spectra as shown in Fig. 13. This is not instability suppression *per* se. Rather, the combustor process is susceptible to instability at frequencies near the instability, and as a result the perturbations introduced through fuel modulation entrain the instability energy. Also, as can be seen in Fig. 14(b) and Fig. 13, discrete frequency excitations seemed to create their own sub-harmonics, as well as harmonic frequencies. Overall, this combustor process seems to be very conducive to dynamic coupling between harmonics and also between discrete frequencies.

It would seem that these types of coupling phenomena between harmonics and discrete frequencies are primarily caused by some coupling asymmetry between these pressure waves in the combustor, called here *Wave Coupling Asymmetry* (WCA). Here, the meaning of WCA is that when two or more waves interfere, the interference is non-symmetrical causing a net suppression or amplification of the individual waves. *Wave asymmetry* is a phenomena discussed in more depth in the field of *Oceanography*,[22] which primarily deals with asymmetry in ocean waves. *Coupling asymmetry* and *harmonic coupling* are often covered in Physics[23,24] and even in Electrical Engineering, (e.g. the coupling asymmetry in the positive sequence produced by three phase unbalanced power[25]). Harmonics or waves of different frequencies can still interfere with one another. But such interference will typically manifest itself as cycle-by-cycle suppression or amplification of each wave, depending on whether their phases promote amplification or suppression at a given instant in time. However, over the course of a *combined periodic cycle* (defined by the largest common multiple of the two frequencies), the net change in suppression and amplification of each wave will be zero. As a result, in an amplitude spectra density plot the two waves will seem unaffected, as if

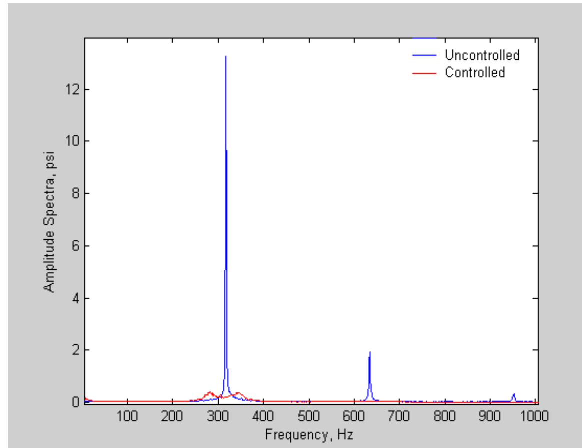


Figure 12.—Amplitude Spectra of Uncontrolled vs Controlled Instability for Control Focus on the Second Harmonic.

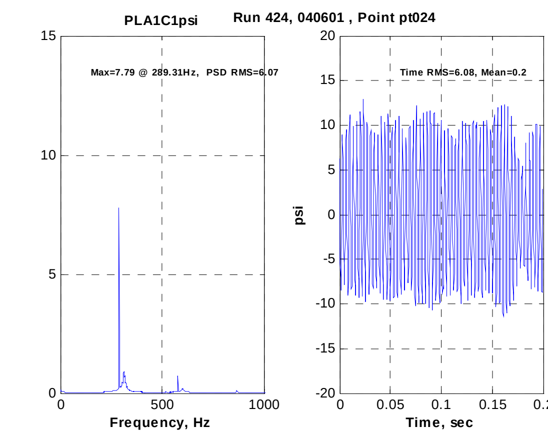
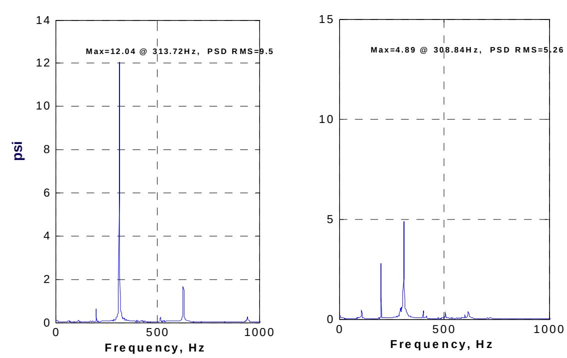


Figure 13.—Open-Loop Fuel Pressure Modulations at 289 Hz Entrain the Energy from the Instability.



(a) (b)

Figure 14.—Comparison of Initial Fuel Modulation Authority (a) and Authority After About 10 Minutes (b).

they do not interfere or couple with one another. This will generally be the case, unless there is asymmetry (uneven coupling) in either the direction of suppression or amplification.

In the case of the combustor pressure waves; when the phases of the two waves are such that amplification is supported, this action is likely opposed by damping in the form of friction (like skin friction with the walls of the chamber). This friction damping could be non-linear, with damping increasing as the amplitude of the wave increases. On the other hand, when the phases of the two waves are such that it promotes suppression in some portion of the overall periodic cycle, the suppression will be uninhibited by damping. Therefore, in such a case there will be WCA or unbalance in suppression and amplification which overall favors suppression. However, as suppression increases, at some point this asymmetry no longer favors suppression. This is because as the wave amplitude diminishes and becomes comparable to the amplitude of the combustor noise, the noise increasingly drives the process preventing further suppression. At this point WCA favors amplification. At some point a balance is reached, where the two sided WCA reaches an equilibrium point. In an amplitude spectra density plot the two waves reach a balance between suppression and amplification, where likely the higher amplitude wave looses some net energy and the lower amplitude wave gains some net energy. It is possible that the relative phase between the two pressure waves, which promotes amplification of one wave and suppression of the other, automatically adjusts in this process driven by a *Minimum Energy Systems* (MES) effect, whereby the system naturally settles at a minimum energy state. This energy or power in a MES will be proportional to a damping quantity analogous to a resistance and a squared quantity such as flow.

Assuming this hypothesis is correct, the question remains as to why controlling the second harmonic has such a significant impact in suppressing the fundamental mode. The explanation may also involve the periodicity of the combined wave cycle. This effect deals with applying a control action favoring suppression based on the WCA at a rate equal to the combined wave cycle frequency of the fundamental and its second harmonic. In this case the control rate will be the same frequency as the fundamental. On the other hand, the effectiveness in instability suppression when the harmonics are also involved in the control action may also be due to the *Intra-Harmonic Coupling* mechanism itself. That is when suppressing the harmonic(s), the cycling energy transfer between the fundamental and its harmonic(s) diminishes, and thus it becomes easier to suppress the fundamental.

With a more pronounced or coherent instability where the damping is less, the equilibrium level in the WCA will likely be higher, that is, less suppression will be possible. In summary, the combustor noise alone (given the large dead time phase delay in the process) doesn’t seem to be the only limiting factor in combustor instability suppression of large coherent instabilities. The other limiting factor is likely the instability damping. The equilibrium reached by the two-sided WCA, also, based on the effectiveness of the control action, likely dictates the final suppression levels of the instability. Further experiments are planned to determine the validity of this hypothesis.

VI. Conclusion

This paper reports on test results from test runs of a high frequency aero-engine-like combustor rig and a low frequency configuration of the rig. The test results validate the effectiveness of an adaptive control method for suppressing combustor instabilities in liquid-fueled gas turbines for both high and low frequency. Further, a certain characteristic called *Intra-Harmonic Coupling*, discovered in previous analysis, was exploited to produce even higher suppression levels during active control of the instability. This was accomplished by focusing control on the second harmonic of the instability. This new control approach that exploits harmonic couplings could lead to a new and more effective class of combustor instability controllers. A hypothesis has been offered to explain the mechanisms involved in intra-harmonic coupling, which is attributed to a two-sided wave coupling asymmetry and possibly a minimum energy systems effect. The phenomena of *wave asymmetry* has been observed before in other disciplines and could open the door for a more in depth understanding of combustor dynamics. Ongoing analysis of the test results will provide a better understanding of these effects in order to choose the most effective control strategies in an attempt to achieve even better results. Ultimately, the goal of these combustor instability control efforts is to extend these control approaches to lean-burning combustors that are enabling technologies for reducing NOx emissions from aircraft gas turbine engines.

References

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

[2]Kopasakis, G.: "Systems Characterization of Combustor Instabilities with Controls Design Emphasis," AIAA 42nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 2004, NASA/TM—2004-212912, AIAA-2004-0638.

[3]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.

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

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

[6]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.

[7]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.

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

[9]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.

[10]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.

[11]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.

[12]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.

[13]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.

[14]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.

[15]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.

[16]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.

[17]Kopasakis, G.: "High Frequency Adaptive Instability Suppression Controls in a Liquid-Fueled Combustor," AIAA 39th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2003, NASA/TM—2003-212535, AIAA-2003-9581.

[18]Le D.K.; DeLaat J.C.; Chang C.T.: "Control of Thermo-Acoustic Instabilities: The Multi-Scale Extended Kalman Approach," AIAA 39th Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2003, AIAA-2003-4934.

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

[20]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.

[21]. Kopasakis, G.; DeLaat, J.C.: "Adaptive Instability Suppression Controls in a Liquid-Fueled Combustor," AIAA 38th Joint Propulsion Conference and Exhibit, Indianapolis, IN, July 2002, NASA/TM—2002-211805, AIAA-2002-4075.

[22]Shuvalov, V.V.: "Mechanisms of Tsunami Generation by Impacts," Institute for Dynamics of Geospheres RAS, Leninsky pr. 38-1, 119334 Moscow, Russia.

[23]Meister, M.; Vazquez, L.: "Diffusion of Intrinsic Localized Modes by Attractor Hopping," Journal of Physics A: Math. Gen. 36 (11779-11790), 2003.

[24]Zheng, Z.; Hu, B.; Hu, G.: "Spatiotemporal Dynamics of Discrete Sine-Gordon Lattice with Sinusoidal Couplings," Physical Review E, Volume 57, Number 1, 1997.

[25]Zhong, S.; Abur, A.: "Effects of Non-transposed Lines and Unbalanced Loads on State Estimation," IEEE, 2001 (PSERC project publication).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
October 2004

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Validation of an Adaptive Combustion Instability Control Method for Gas-Turbine Engines

5. FUNDING NUMBERS
WBS–22–708–01–02

6. AUTHOR(S)
George Kopasakis, John C. DeLaat, and Clarence T. Chang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–14698

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2004-213198
AIAA–2004–4028

11. SUPPLEMENTARY NOTES
Prepared for the 40th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASEE, Fort Lauderdale, Florida, July 11–14, 2004. Responsible person, George Kopasakis, organization code 5530, 216–433–5327.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 01 or Categories: 02 and 07 Distribution: Nonstandard
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
This paper describes ongoing testing of an adaptive control method to suppress high frequency thermo-acoustic instabilities like those found in lean-burning, low emission combustors that are being developed for future aircraft gas turbine engines. The method called Adaptive Sliding Phasor Averaged Control, was previously tested in an experimental rig designed to simulate a combustor with an instability of about 530 Hz. Results published earlier, and briefly presented here, demonstrated that this method was effective in suppressing the instability. Because this test rig did not exhibit a well pronounced instability, a question remained regarding the effectiveness of the control methodology when applied to a more coherent instability. To answer this question, a modified combustor rig was assembled at the NASA Glenn Research Center in Cleveland, Ohio. The modified rig exhibited a more coherent, higher amplitude instability, but at a lower frequency of about 315 Hz. Test results show that this control method successfully reduced the instability pressure of the lower frequency test rig. In addition, due to a certain phenomena discovered and reported earlier, the so called Intra-Harmonic Coupling, a dramatic suppression of the instability was achieved by focusing control on the second harmonic of the instability. These results and their implications are discussed, as well as a hypothesis describing the mechanism of intra-harmonic coupling.

14. SUBJECT TERMS
Active combustion control

15. NUMBER OF PAGES
15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102