50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition
09 - 12 January 2012, Nashville, Tennessee

AIAA 2012-0542

Low Frequency Combustion Instabilities Imaged in a Gas Turbine Combustor Flame Tube

Jacob E. Temme[1], Patton M. Allison[2], James F. Driscoll[3]
University of Michigan,Ann Arbor, MI, 48109

An "equivalence ratio oscillation" was studied that produced a strong low frequency combustion instability (at 80 and 160 Hz) when a commercial lean premixed prevaporized (LPP) fuel injector was operated using Jet-A fuel at realistic conditions. The elevated pressures, temperatures, air flow rates and overall equivalence ratios were close to conditions at engine idle. However the fraction of fuel diverted to the various injector ports was sufficiently off-design to create an instability. High speed movies showed that the flame base violently moves upstream and downstream at 80 Hz, and that flashback plays a role in the rapid upstream movements. Flame shape also changes at 80 Hz from a flat flame to a more elongated flame, which affects the heat release pattern and causes oscillations in the air flow rate. A regime diagram is reported which contains the boundary that marks the onset of the instability. Other higher frequency instabilities were also present and were due to longitudinal and azimuthal organ tones, but their magnitudes were more than ten times smaller than the pressure fluctuations caused by the equivalence ratio oscillation.

I. Introduction

LEAN Premixed Prevaporized (LPP) combustion has been proven to be one important new way to reduce nitric oxide emissions in practical gas turbine engines[1]. However, the premixed nature of LPP combustion can lead to a variety of combustion instabilities[2-9]. The present study differs from the many previous investigations of instabilities in two ways. First, we focus on a large amplitude, low frequency naturally-occurring oscillation that has a frequency in the range 80-160 Hz; this is commonly referred to as growl and it is a serious problem in the gas turbine industry. Second, there is a need to show the connection between the instabilities that occur when a realistic, commercial LPP multi-swirl fuel injector is operated with Jet-A fuel at elevated pressures, temperatures and mass flow rates (such as in the present study) and the instabilities that previously have been studied in simple laboratory burners. Simple laboratory burners normally are run on gaseous fuel at low flow rates, low pressures and with small injector sizes. More work is needed to show which of the many types of instabilities that occur in laboratory burners are most important in real LPP devices.

The instability in the present experiment will be shown to be a type that is called an "equivalence ratio oscillation"[5,7]. That is, the fuel and air are not initially premixed and the air flow rate oscillates whilethe fuel flow rate does not. However, there are a number of possible causes forthe air flow oscillations (and the feedback mechanisms) that can be subdivided into several categories. Air flow can be periodically blocked by the precession of the recirculation zone or by the periodic liftoff and flashback of the flame itself. Thus the burner can act as a driven Helmholtz resonator (driven by the flame or recirculation zone which can act as a piston). The driven oscillator can have properties that differ from that of a conventional Helmholtz resonator. Periodic air flow blockage also can lead to oscillating flow "switching" between the two different air orifices in the injector. Other mechanisms that are not "equivalence ratio instabilities" were ruled out as sources of our low frequency instabilities, based on the data, as described below.

Previous work in our laboratory, using a similar type of LPP fuel injector, focused on a different type of instability that occurred only at very low overall equivalence ratios of approximately 0.15. It is called a "lean-limit" or "incipient blowout" instability[1]. It was found to have a large magnitude of pressure fluctuations, but very low frequencies of less than 20 Hz[10-12]. Movies showed that as the flame periodically lifted off, the liftoff region filled with an unreacted mixture, and then flashback occurred into this mixture which caused a large (1.5 psi) pressure rise.

---

[1] Research Assistant, Department of Aerospace Engineering, AIAA Member
[2] Research Assistant, Department of Aerospace Engineering, AIAA Member
[3] Professor, Department of Aerospace Engineering, AIAA Fellow

It is one form of an “equivalence ratio oscillation”. In the present work a similar LPP injector is operated at higher overall equivalence ratios (near 0.40) and the frequency of the instability is found to be in the range from 80 to 160 Hz. The amplitude of r.m.s. pressure fluctuations was relatively large and was typically 0.75 psi (5 kPa).

II. Experimental Setup

All experiments were carried out in the University of Michigan High-Pressure Gas Turbine Facility [10-12] that is seen in Figure 1a. The facility consists of a 1.5 m long high pressure vessel having an inner diameter of 21 cm. The first section is a plenum/flow straightener, the second section contains a flame tube, and the third section leads to a constriction and exhaust valve. Inside the pressure vessel is mounted a rectangular flame tube that is 10 cm high, 10 cm wide and 18 cm long. Optical access is provided by three quartz windows in the flame tube and three quartz windows in the pressure vessel. Pressure traces were measured using an Omegadyne PX01C1 transducer placed approximately 14 cm downstream of the injector. High speed digital images were recorded with a Phantom V9.0 camera at a frame rate of 1000 Hz that was synchronized with the simultaneous pressure measurements.

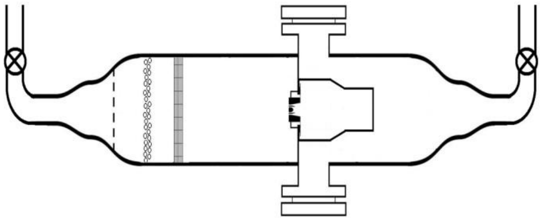

Figure 1A. Experimental Setup.

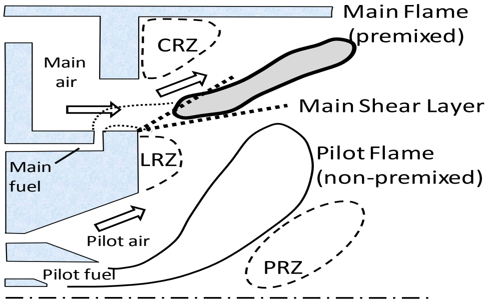

Figure 1B. Schematic of the Flow Pattern in the Lean Premixed Prevaporized Combustor.

A realistic aviation gas turbine fuel injector was used to atomize the liquid Jet-A fuel. This injector is very stable near the design condition, when the proper ratios of fuel flow rates are provided to two different sets of pilot fuel orifices and to the main fuel injector. In this study these ratios were purposely chosen to be far from their design values to create an instability. The baseline conditions are similar to that of near-idle engine operation: combustor pressure was 3.5 atm, preheated air temperature was 464 K, air flow rate was 0. 33 kg/s and total fuel flow rate was 8.69 g/s. The overall equivalence ratio was 0.40. After characterizing the instability at this baseline condition the equivalence ratio was varied from 0.25 to 0.45.

A schematic of the basic flow pattern of an LPP injector is shown in Figure 1b. Fuel for the central pilot flame enters on the centerline and is mixed with swirling coaxial air. The air for the main flame enters through an outer annular port. The main fuel is injected into the main air stream just upstream of the burner face. Our previous PIV and PLIF measurements identified the locations of the primary recirculation zone, the lip recirculation zone and the pilot and main flames [10-12]. The main flame is initially non-premixed but it is lifted; when combustion occurs downstream the fuel and air have mixed but may be stratified. Hot products from the pilot flame enter the shear layer and are required to stabilize the partially-premixed main flame. In this study the self-excited instabilities of interest were observed both with and without a main flame present. Since this indicates that the oscillations are controlled by the pilot flame, subsequent runs were conducted with only pilot fueling.

III. Results

Figure 2 shows a power spectrum of the pressure oscillations caused by the combustion instability. The wall pressure was measured 14 cm downstream of the injector face. Five major peaks are observed, two of which (at 80 and 160 Hz) are much larger in magnitude than the others. These two peaks occur only when combustion is present. The r.m.s fluctuation of the pressure at 80 Hz is a relatively large value of 0.75 psi (5 kPa) which is 1.5% of the mean pressure. The 80 Hz and 160 Hz peaks are seen to be 25 db (more than ten times) larger than the other peaks. The three smaller peaks occur for both reacting and non-reacting conditions. The 860 Hz peak is due to a quarter-wave organ tone associated with the flame tube. This frequency scales with c/(4L) where c is the speed of sound and L is the 18 cm length of the flame tube. The 560 Hz and 1210 Hz peaks are the fundamental and first harmonic of an azimuthal organ tone. The two large peaks at 80 and 160 Hz are not organ tones because these frequencies did not change when the lengths of the plenum or the pressure vessel were changed. The frequencies of the 80 Hz and 160 Hz instabilities also did not change when the air mass flow rate was increased, so these could not be convective-acoustic instabilities that are associated with vortex shedding. In addition, the properties of the liquid fuel were varied by adding various amounts of gasoline to the Jet-A fuel. The frequencies of the 80 and 160 Hz instabilities did not change, indicating that these resonances are not spray-related.

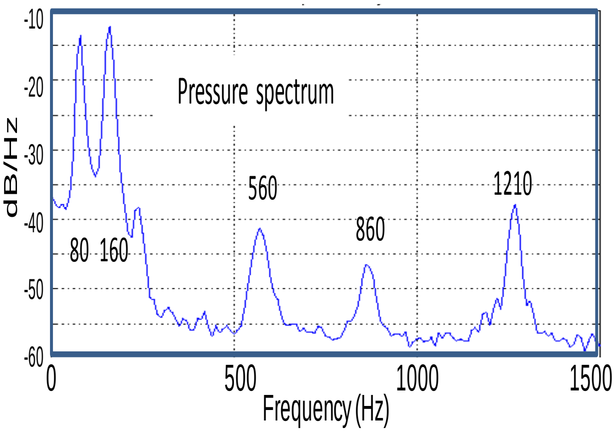

Figure 2. Typical PSD of a pressure trace. *Major peaks of interest are the 80 and 160 hz which are 30 dB larger in magnitude than the other observed frequencies.*

High-speed images of the flame taken at 1 KHz also reveal interesting phenomena occurring at 80 Hz, as seen in Figure 3. A simultaneous pressure trace also is plotted. At times when the pressure is highest (frames 2,7,8,14), the flame lifts off of the injector and compresses into a flat shape. At times when the pressure is lowest (frames 5,10) the flame reattaches and reforms into a conical, elongated structure. This periodic motion can be quantified by measuring the flame front location in each frame. First the chemiluminescence in each image was integrated in the transverse (vertical) direction to obtain a plot of intensity versus the streamwise (horizontal) direction, shown in Figure 4A. The flame front is defined as the x-location where this curve has increased to 75% of its maximum value. Similarly, the width of the flame at the flame tube exit was calculated by integrating the exit region in the streamwise direction, shown in Figure 4B. The width is measured at 50% of the maximum resulting value.

Figure 5 is a plot of the resulting time history of the flame front location and the simultaneous pressure trace. The flame front location and the pressure are seen to be approximately 180° out of phase. The mean liftoff height is 40.5 mm with an average fluctuation of ±7.75 mm. The total distance of the flame motion is about 15% of the flame tube. Additionally, the speed at which the flame moves away from the injector face is about 2.6 m/s, which is considerably less than the speed at which it returns (approximately 8.6 m/s). This is an indicator that flashback of the lifted flame base plays a role in accelerating the flame motion, which can alter the frequency of the oscillation.

The measurements in Figures 3 and 5 are strong evidence that the air flow rates are oscillating, and that an “equivalence ratio oscillation” is occurring. Figure 3 shows that there are large downstream and upstream motions of the flame base. The only logical way that the flame base would rapidly move downstream is if the air flow rate rapidly increased, which would cause an increase in the liftoff height. The rapid upstream movement of the flame is also logically explained by a decrease in the air flow rate, which allows the flame to flash back. Similarly, the data in Figure 5 also indicate that the air flow is periodic. It shows that at certain times the pressure is large and then it drops, which is explained by a “puffing” of the plenum chamber and this would cause a temporary increase in the air flow rate. During this time of decreasing pressure the flame liftoff height is seen to increase. That is, Figure 5 shows that pressure and flame height are out of phase. In addition to this information, phase-averaged PIV data are described elsewhere[13] that verify that air flow rate oscillations occur. In the present work the fuel flow rate is known to be constant; the pressure drop across the liquid fuel nozzles was so large that any pressure fluctuations (of typically 1 psi) in the combustor could not cause any oscillation in the liquid fuel mass flow rate.

The actual feedback mechanism is currently unclear. Some feedback must occur since the pressure and liftoff height traces are very periodic. Most likely the flame is acting as an obstacle and its shape and position can block all of the air flow; or perhaps the flame blocks a fraction of the inner (pilot) air stream or a fraction of the outer (main) air stream causing “fluid switching”. The recirculation zone also can block the air flow, but it is present during non-reacting conditions when the 80 and 160 Hz pressure oscillations are not. Wiegand et al.[7] previously have concluded that the complex flow pattern in their laboratory-scale gaseous-fueled swirl burner can cause a periodic blockage to the air flow.

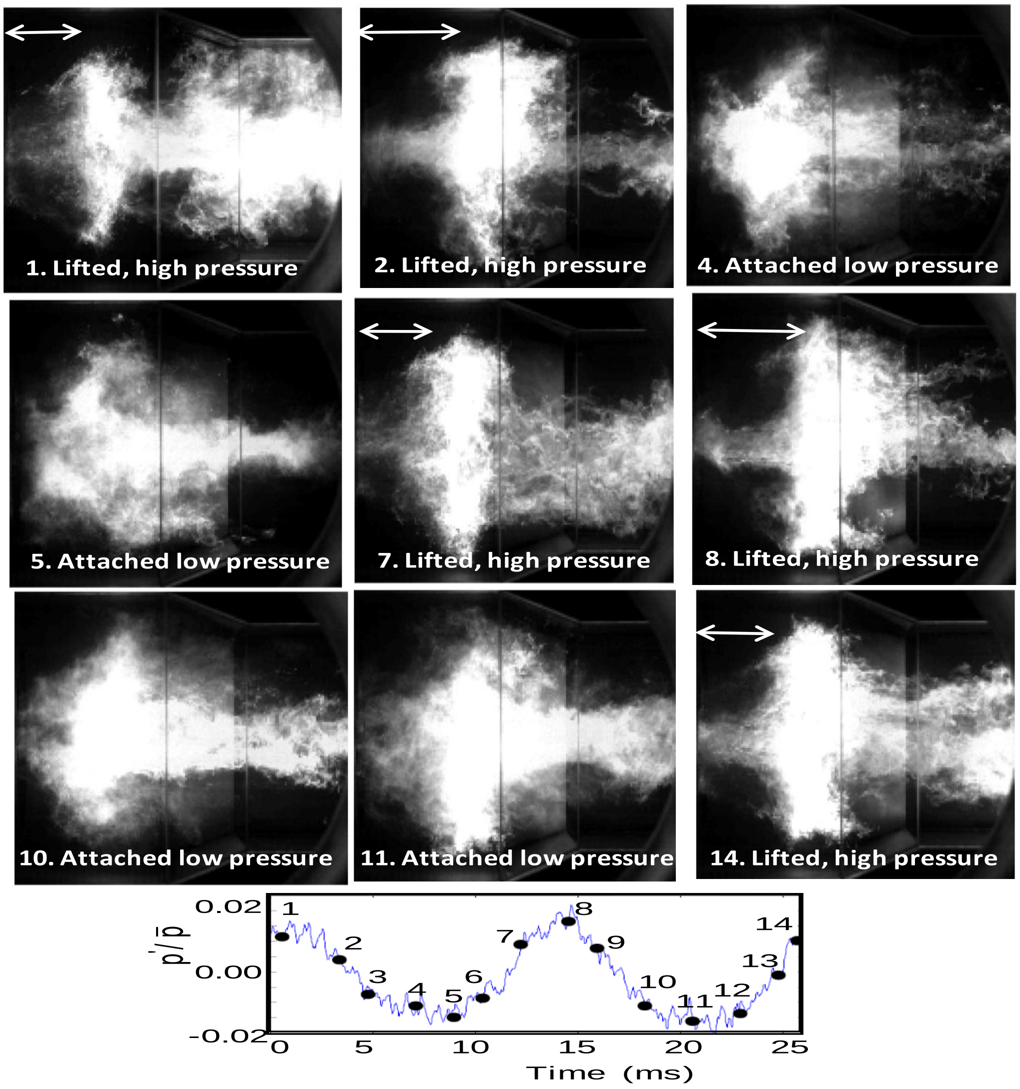

Figure 3. Flame sequence with simultaneous pressure trace. *The flame oscillates between a lifted, compact mode and an attached, v-shape mode.*

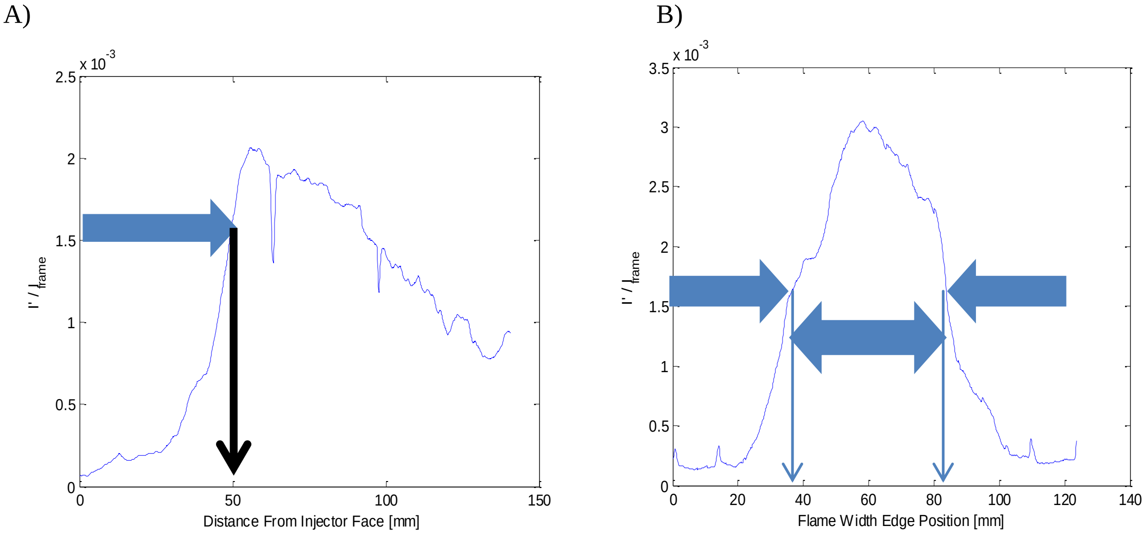

Figure 4. Flame Front Location Calculation from High Speed Video Frame. A) *Flame fronts were determined to occur at 75% of the rise in luminosity in the axial direction.* **B)** *Flame width follows a similar calculation but is taken to be at the full width half maximum (FWHM).*

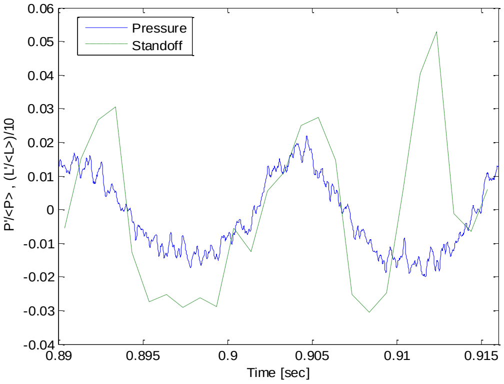

Figure 5. Time history of flame front location and pressure trace. *Positive values for flame location indicate motion downstream away from the injector. The flame front location shows that the downstream motion occurs slower than the upstream returning motion.*

Figure 6 includes power spectra of several measured quantities: flame width, flame front location (which is the liftoff distance), total intensity of the chemiluminescence (which is proportional to the heat release rate), and the pressure. All four spectra display similar peaks at both 80 and 160 Hz. It is noted that while these discrete peaks appear in the spectra, the oscillations tend to be intermittent; the signal will be highly periodic for some time then for certain times the instability will disappear and reappear at a later time. For this reason the movies and the correlations were measured only during the times when the instability was present. Including the quiet periods would lead to values that do not realistically represent the instability.

Figure 7 is a measured regime diagram that quantifies the boundary that marks the onset of the instability defined by the 80 and 160 hz peaks growing to 10 dB larger than the background frequencies. The equivalence ratio was varied from 0.25 to 0.55. The frequencies of the 80 and 160 Hz oscillations did not change. Figure 7 shows that the boundary of the instability is a line with a negative slope. Thus the magnitude of the instability increases when either the equivalence ratio increases or the total fuel flow rate increases. Predicting this type of measured boundary remains a challenge for current computational models. Previously it was shown that a “lean-limit” incipient blowout instability occurs for overall equivalence ratios below 0.15 for this type of LPP injector.[10-12] This is further proof that care must be taken to select the correct overall equivalence ratio and the proper fuel injection location to avoid combustion instabilities. Proper location of the fuel injection to avoid combustion instabilities was not the focus of the present study.

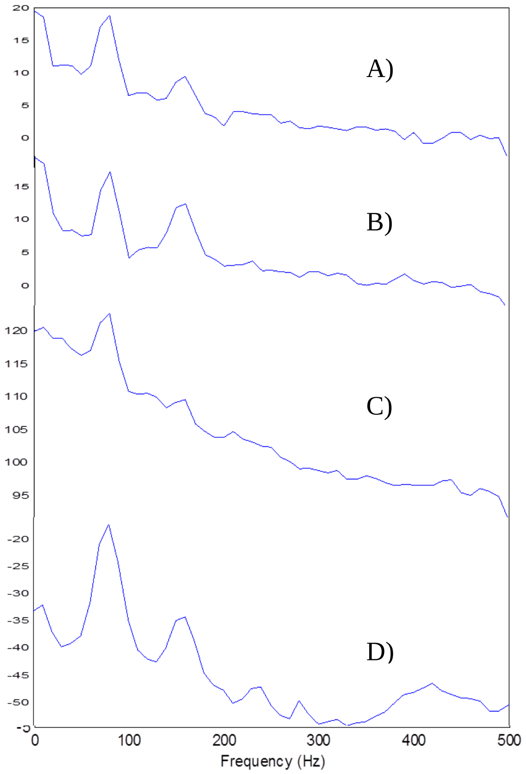

Figure 6. Computed Quantities from High Speed Video showing similar 80hz trend. *Spectra correspond to* **A)** *Flame width,* **B)** *Flame Liftoff height,* **C)** *Flame Chemiluminescence,* **D)** *Pressure*

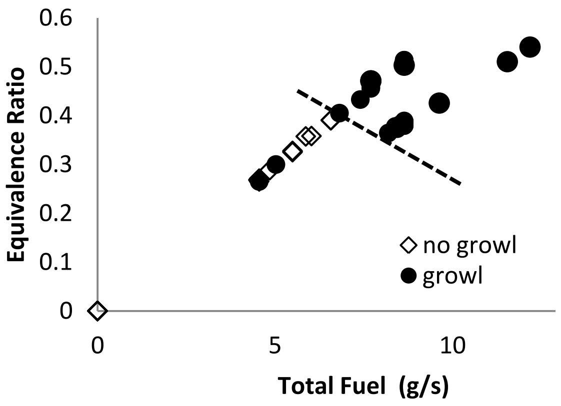

Figure 7. Regime diagram with the boundary that marks the onset of the combustion instabilities at 80 and 160 Hz in the present experiment.

IV. Conclusion

1) A strong, low-frequency combustion instability (at 80 and 160 Hz) was generated by operating a commercial LPP gas turbine fuel injector at sufficiently off-design conditions. The overall fuel and air flow rates were matched to realistic (near-idle) values, as were the combustor pressure and air preheat temperature, but the ratio of fuel distributed to the different ports was off-design. Strong pressure oscillations at 80 Hz (of 0.75 psi, 5 kPa) are more than ten times stronger than the observed quarter-wave longitudinal organ tone at 560 Hz or the azimuthal organ tones. These 80 and 160 Hz oscillations disappear without combustion.
2) Violent downstream and upstream motions of the flame base at 80 Hz were observed in high speed movies. Since the flame base rapidly moved upstream (at 8.2 m/s) and slowly moved downstream (at 2.6 m/s) it is concluded that flashback and blowout play a role. It also is concluded that the observed periodic flame base movement indicates that the air flow rate must be oscillating at 80 Hz, which is the only way to explain the increase in the liftoff height and the subsequent flashback. The pressures and liftoff heights are 180^o out of phase, which also is consistent with the idea that the plenum is "puffing" air. This explains why the pressure decreases when the flame liftoff height increases.
3) The spectra of several other quantities also displayed sharp peaks at both 80 and 160 Hz. These quantities are the flame liftoff height, the luminosity (which is proportional to heat release rate) and the flame width.
4) A regime map of the instability was measured. The boundary that marks the onset of this type of instability indicates that oscillations occur only for sufficiently large values of equivalence ratios and for sufficiently large total fuel flow rates.
5) Results reported herein and in a separate PIV study[13] indicate that the strong combustion instability is due to an "equivalence ratio oscillation" and is not an organ tone or a standard Helmholtz resonance involving the plenum or outer pressure vessel. It also is not spray related since gasoline was added to the Jet-A fuel and no change in the frequency of the pressure oscillations were observed.

Acknowledgments

Funding for this project was provided by General Electric Aviation, Cincinnati Ohio through the GE-USA program.

References

[1] Mongia, H.C., Held, T. J., Hsiao, G. C., Pandalai, R. P.,"Challenges and Progress in Controlling Dynamics in Gas Turbine Combustors", *J. Propulsion and Power*, Vol. 19, No. 5, 2003, pp. 822-829.

[2] Lieuwen, T., McManus, K., "Introduction: Combustion Dynamics in Lean-Premixed Prevaporized (LPP) Gas Turbines", *J. Propulsion and Power*, Vol. 19, No. 5, 2003, pp. 721–721.

[3] Cohen, J.M., Banaszuk, A., "Factors Affecting the Control of Unstable Combustors, *J. Prop. Power*, Vol. 19, No. 5, 2003, pp. 811-821.

[4] Huang,Y., Yang, V., "Bifurcation of flame structure in a lean-pemixed swirl-stabilized combustor: transition from stable to unstable flame", *Combustion and Flame*, Vol. 136, 2004, pp. 383–389.

[5] Lieuwen, T., Torres, H., Johnson, C., Zinn, B., "A Mechanism of Combustion Instability in Lean Premixed Gas Turbine Combustors." *ASME Transactions*, Vol. 123, 2001,pp. 182–189.

[6] Garcia, M.d.C. , Mastorakos, E., Dowling, A.P., "Investigations on the Self-excited Oscillation in a Kerosene Spray Flame." *Combustion and Flame*, Vol 156, 2009, pp. 374-384.

[7] Weigand, P., Meier, W., Duan, X., Aigner, M., "Laser-based Investigations of Thermoacoustic Instabilities in a Lean Premixed Gas Turbine Model Combustor." *ASME Transactions*, Vol 129, 2007, pp. 664-671.

[8] Rodriguez-Martinez, V. M., Dawson, J. R., O'Doherty, T., Syred, N., "Low-Frequency Combustion Oscillations in a Swirl Bruner/Furnace." *J. Prop. Power*, Vol. 22, No. 1, 2006, pp. 217-221.

[9] A.P. Dowling, S.R. Stow, "Acoustic Analysis of Gas-Turbine Combustors", *Combustion Instabilities in Gas Turbine Engines: Operational Experience, Fundamental Mechanics, and Modeling*, edited by T. C. Lieuwen, and V. Yang, Progress in Astronautics and Aeronautics AIAA, Virginia, 2005, pp. 369-414.

[10] Dhanuka, S.K., Temme, J.E., Driscoll, J.F., "Vortex-shedding and mixing layer effects on periodic flashback in a lean premixed prevaporized gas turbine combustor" *Proc. Combust. Inst.*, Vol. 32, 2009, pp. 2901-2908.

[11] Dhanuka, S.K., Temme, J.E., Driscoll, J.F., "Lean-limit combustion instabilities of a lean premixed prevaporized gas turbine combustor" *Proc. Combust. Inst*., Vol. 33, 2011, pp. 2961-2966.

[12] Dhanuka, S.K., Temme, J.E., Driscoll, J.F., "Unsteady Aspects of Lean Premixed Prevaporized Gas Turbines Combustors: Flame-Flame Interactions." *J. Prop. Power*, Vol. 27, No. 3, 2011, pp. 631-641.

[13] Temme, J.E., Ph.D. Thesis, Department of Aerospace Engineering, University of Michigan, Ann Arbor MI, 2012, in preparation. PIV data to be presented for publication, 2012.