Combustion Powered Actuator with Integrated High Frequency Oscillator

Thomas M. Crittenden[1] and Surya Raghu[2]
[1]Virtual AeroSurface Technologies, Inc.
Atlanta, Georgia, 30318, USA
tom.crittenden@vastechnologies.com

[2]Advanced Fluidics, Inc.
Ellicott City, Maryland, 21042, USA
sraghu@advancedfluidics.com

ABSTRACT
A new actuation concept for flow control has been tested combining the high jet strength of chemically-based, combustion powered actuation with the high frequency of fluidic oscillators. The device exhausts the jet from a combustion powered actuator through a fluidic oscillator and embeds a high frequency [~ O(1-10) kHz] oscillation into the lower frequency [~ O(10-100) Hz] of the repetitively ignited combustion bursts. The present work includes characterization of the fluidic oscillator in steady operation for the properties which vary over the combustion burst (pressure, temperature, and gas composition) and results from test firing of the fully integrated device successfully indicating high frequency oscillation in the high speed actuation jet while maintaining a no moving parts design.

1. INTRODUCTION

In recent years, active flow control techniques have achieved varying degrees of separation control by manipulation of the unstable separated free shear layer using pulsed blowing on the time scale of the flow about the airfoil (e.g., Chang et al. [1], McManus et al. [2], and Seifert et al. [3]). In these experiments, the excitation was typically applied at a Strouhal number, *St,* ~ O(1) such that the excitation period scaled with the time of flight over the length of the reattached flow. In other flow control experiments actuation is applied at frequencies that are at least an order of magnitude higher than the characteristic frequency of the base flow [e.g., *St* ~ O(10)] creating a quasi-steady interaction domain between the jet and the cross flow, resulting in modification of the apparent aerodynamic shape of aero-surfaces for suppression of separation (e.g., Smith et al. [4] and Amitay et al. [5]). This approach has been demonstrated with synthetic jet actuation at frequencies up to *St* ~ O(100). Most of this flow control work has emphasized the utility of time harmonic momentum-based (jet) actuation having a (dimensionless) momentum coefficient, C_μ, on the order of 10^{-3}. While it is relatively simple to develop such actuators either for wind tunnel testing or for small-scale vehicles operating at relatively low speeds (e.g., UAVs), it is clear that pulsed jet actuation having similar (or even potentially higher) levels of momentum coefficient at higher flight speeds (e.g., transonic or supersonic) will require high speed actuator jets and different actuation hardware, while at the same time maintaining high frequencies.

Combustion-based actuation presents an attractive alternative to mechanical actuation techniques for the generation of high-impulse actuation jets for high-speed flow control. COMPACT (COMbustion Powered ACTuation) exploits the chemical energy of gaseous fuel/oxidizer mixture to create a high pressure burst and subsequent high momentum jet (often with sonic orifice velocities) of exhaust products. At the scales envisioned, the entire combustion process is complete over a period of milliseconds and the pressure within the chamber drops again to a baseline level at which refill of the chamber with fresh reactants begins (Crittenden, et al. [6]). This actuation approach has previously been demonstrated for reattachment of separated flows at high angle of attack (Funk, et al. [7] and Brzozowski and Glezer [8]) and has demonstrated sufficient momentum for jet penetration and flow effects to be exerted on supersonic cross-flows. A limitation of this approach is the frequency of the actuator which is typically dictated by the time required for the combustion and refill processes to complete, with demonstrated frequencies limited to roughly 500 Hz and a significant decrease in jet strength at the higher frequency levels (Crittenden, Warta, and Glezer [9]). The present research describes a novel approach for combining high frequency excitation with the high momentum of COMPACT by exhausting the actuator jet from the combustor through a fluidic oscillator, thus embedding a high frequency oscillation into the comparatively lower frequency firing of the combustor. In this concept, the advantage of a no moving parts actuator is maintained while yielding performance advantages over the two constituent technologies by themselves. Section 2 of this paper gives technical background on both COMPACT and fluidic oscillators and their operation. Section 3 describes the prototype device and the experimental set-up used for characterization. Finally, Section 4 describes the experimental results and details the ways in which the fluidic oscillator performance varies while using COMPACT to drive it.

2. TECHNICAL BACKGROUND

2.1. Compact

COMPACT (Combustion Powered Actuation) is a novel actuation technology which exploits the chemical energy of gaseous fuel/oxidizer mixture to create a high pressure burst and subsequent high momentum jet of exhaust products. The basic element of the system may be regarded as, essentially, a fluidic amplifier where fuel and oxidizer having comparatively low momentum fill a small (O~1 cm^3) combustion chamber bounded by an orifice plate (Fig. 1). A spark (or other ignition source) ignites the mixture, creating a high pressure burst within the combustor and a subsequent jet emanating from one or more exhaust orifices. A conceptual diagram of the pressure-time history of the actuator is presented in Fig. 2. The characteristics of the high pressure burst (i.e., amplitude, duration, etc.) are essentially governed by a balance between the heat release and subsequent pressure rise from the combustion process (which are affected by the fuel type, mixture ratio, and flame propagation properties) and the pressure reduction due to the flow out of the combustion chamber and heat transfer to the combustor walls. At the scales envisioned, the entire combustion process is complete over a period of milliseconds and the pressure within the chamber drops again to a baseline level below the supply pressure. Following a characteristic dynamic time lag related to the inlet configuration properties, the flow of fresh reactants into the chamber resumes, displacing the remaining exhaust gases and filling the chamber for the next cycle. The cycle frequency is set by the spark/ignition source and is continuously variable, with its upper limit set by the characteristic times of the high pressure pulse within the chamber (t_{pulse}) and the refill of reactants to the chamber (t_{refill}) with whatever dynamic lag takes place between the two. For nonpremixed operation, an additional characteristic mixing time of gases within

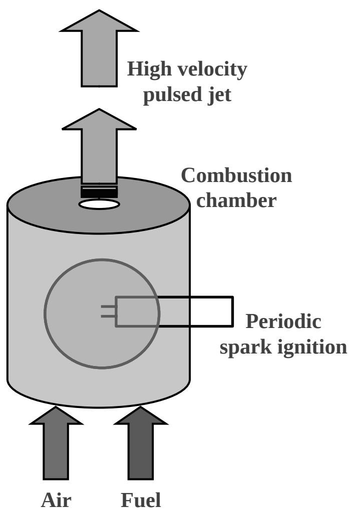

Figure 1. Conceptual schematic of combustion powered actuation – COMPACT.

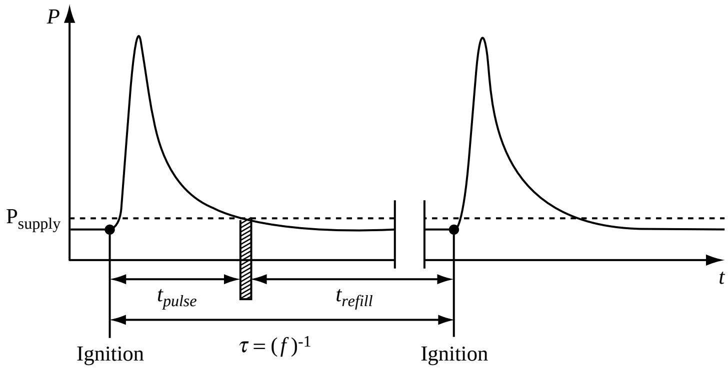

Figure 2. Pressure–time history for COMPACT.

the chamber (t_{mix}) may be considered. However, this mixing time overlaps with the required refill time and does not necessarily decrease frequency range for nonpremixed operation.

A representative actuator burst is shown in Fig. 3 which includes the pressure-time history within a 1 cm^3 combustor and a sequence of corresponding phase-locked Schlieren flow images of the ejected jet at the exhaust orifice. The images are recorded at $t = 0.44$, 0.70, 1.2, 2, 3, and 4.8 ms following the spark trigger (using a 125 μs shutter speed) and the streamwise field of view is approximately 25 orifice diameters ($d = 1.3$ mm). Following the spark ignition ($t = 0$), there is a sharp rise in the chamber pressure with a peak normalized pressure (P_r, defined as the ratio of the chamber pressure to atmospheric pressure) of approximately 2.8 at t = 0.7 ms. A jet emanates from the exhaust orifice as soon as the pressure in the chamber begins to rise, with flow in the far field appearing to be turbulent as is evidenced by the presence of small-scale motions. The strength of the jet increases with the chamber pressure and, near the peak pressure level, shock cells are detected in the flow within 5 orifice diameters (6 mm) of the exhaust ($P_r \geq 1.89$ required to generate sonic orifice velocities). The pressure subsequently decays and, at $t = 2.7$ ms, reduces to atmospheric levels, at which point a jet no longer emanates from the exhaust orifice although its earlier flow is visible in the far field. After a delay of 1.7 milliseconds, a small vortex ring appears at the orifice which is followed by a low-velocity steady jet, indicating the resumption of flow of fuel and oxidizer into the chamber and the displacement of remnant exhaust gases.

The flow of fuel and oxidizer into the chamber is typically regulated by small passive pressure drop elements which exploit the pressure rise within the chamber to shut off the inlet flow, obviating the need

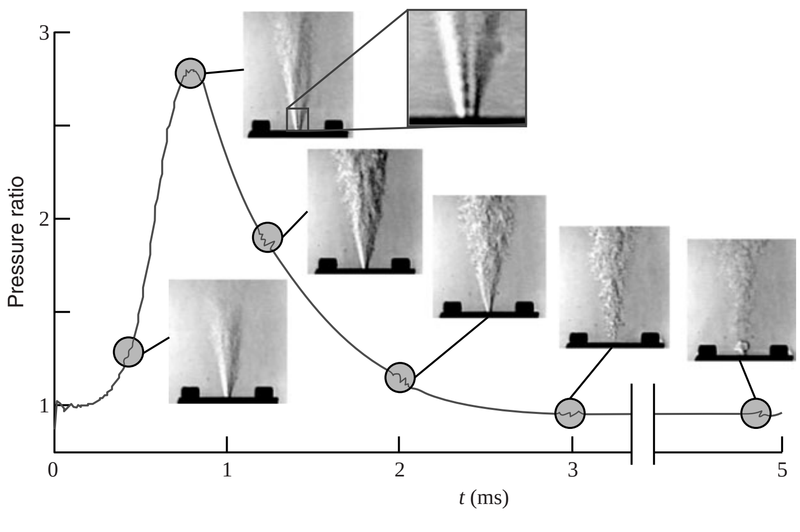

Figure 3. Phase-locked Schlieren images and combustor pressure over single burst for 1 cc volume with 1.3 mm orifice diameter and hydrogen/air mixture.

for mechanical valving. While these elements cannot provide tight closure of the inlets to the chamber during the combustion process, they can be designed to have a lower pressure drop in the downstream direction (i.e., into the combustion chamber) and therefore minimize backflow. Within the context of the combustion actuator, these elements may be considered analogous to "aerovalves" in pulsed combustors which have numerous designs (as described in the review article of Putnam, Belles, and Kentfield [10]). More elaborate designs based on classic fluidic vortex diodes were recently demonstrated by Lin, Hariharan, and Brogan [11] for the control of gas flow into combustion chambers while minimizing the back flow of products. It is noteworthy that fluidic elements are particularly compatible with flow control applications, which typically emphasize simplicity and weight considerations as important design criteria, and as a result, the characterization of COMPACT carried out thus far has focused exclusively on fluidic regulation of the inlet flow. Thus, the COMPACT concept provides a means of creating high velocity, high momentum jets for flow control from a small integrated package with no moving parts in the actuator. In this approach, the only moving mechanical components required by the system are upstream valves which set the mixture ratio and overall flow rate to the actuators.

2.2. Fluidic Oscillators

Fluidic actuators with no moving parts are based on bi-stable states of a jet of fluid in a cavity caused by either inherent fluid dynamic instabilities or by a specially designed feedback path (Raghu [12]) and (Stouffer [13]). Two examples – one based on inherent instabilities and another with a feedback – are shown in Figures 4 and 5.

Referring to Figure 4, the two jets A and B impinge at each other and by proper design of the cavity, the impingement becomes unstable and an oscillatory jet flow is generated at the output. In Figure 5, a traditional method of producing an oscillating flow using a feedback channel is shown. A jet of fluid attaches to one of the two sides of a surface due to the "wall attachment", commonly know as the "Coanda" effect. The pressure distribution in the cavity is accordingly changed and the feedback channel transmits this pressure differential back to the point of the jet separation thus deflecting the jet to the other side. This cycle is repeated on the other side of the cavity through the feedback channel on the left thus producing an oscillating jet at the exit of the cavity. Thus, both these type of devices do not need external signals or actuation to produce oscillating jets. Frequencies from 1-10 kHz have been obtained with meso-scale (nozzle sizes in the range of 200 microns – 1mm) fluidic actuators with very low mass flow rates of the order of (10-3 Kg/sec) (Raghu and Raman [14]).

Exploratory work conducted using miniature (1 mm) fluidic devices to suppress jet-cavity interaction tones (Raman and Raghu [15]) have shown that cavity tones were reduced by as much as 10 dB with mass injection rates of the order of only 0.12% (~ 10-3 Kg/sec) of the main jet flow. Jet mixing and thrust vectoring using fluidic actuators have also been demonstrated by Raman et al [16].

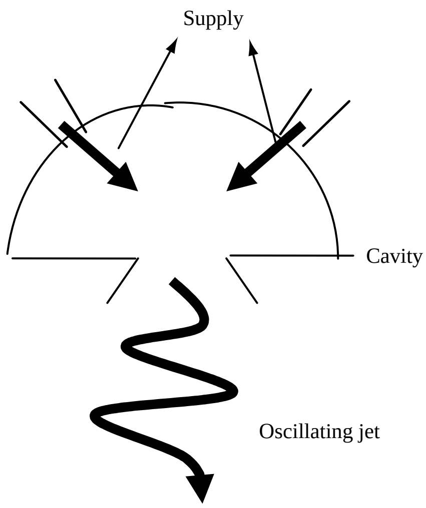

Figure 4. A fluidic oscillator with no feedback paths (Raghu [12]).

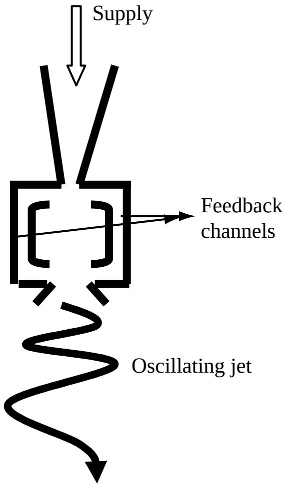

Figure 5. Fluidic oscillator with feedback channels (Stouffer [13]).

3. TEST DEVICE AND EXPERIMENTAL SET-UP

The modular prototype combustion powered actuator and integrated fluidic oscillator is shown in Figure 6. The primary components were fabricated from aluminum with one large block containing part of the combustion chamber volume, the spark igniters, and attachment points for pressure and temperature measurements within the chamber. The second large block includes the remainder of the combustor volume and a converging nozzle path through which gas exhausts into the fluidic oscillator and ultimately out of the device. The overall combustor volume is 1.69 cm^3 (10 mm by 12.7 mm by 13.3 mm) and the oscillating jet exits from a nozzle of 1 mm $\times$ 2 mm. The oscillator was designed and fabricated by Advanced Fluidics Corporation (www.advancedfluidics.com).

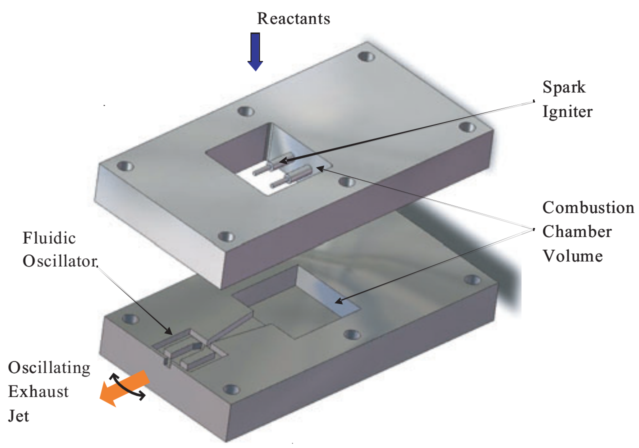

Figure 6.

Reactants are introduced through the pressure drop-element (not shown in Figure 4) and are premixed upstream of the device in all of the present experiments. The air is supplied from a local compressor system and hydrogen from a standard compressed gas bottle. The flowrates are controlled using pressure regulators and needle valves and independent measurements of both the air and hydrogen streams are obtained from thermal mass flowmeters of varying ranges to create the desired overall mixture flowrate (Q) and mixture equivalence ratio (Φ). The mixture is ignited with a spark produced by a modified automotive ignition system, with frequency and spark duration controlled from Labview programs and a National Instruments DAQ board. A spark gap of approximately 1.5 mm is used, located 5 mm from the reactant inlet and oriented normal to the direction of the inlet flow. (The spark energy is not measured in these experiments, however previous results suggest that spark energy plays little role in the device performance provided it is sufficient to ignite the mixture – see Crittenden, et al. [6]).

The oscillation frequency produced by the fluidic oscillator is measured using a small microphone located approximately 2.5 cm from the oscillator exit orifice along the plane of the device such that the exhaust jet does not impinge on the microphone. The time-dependent pressure within the chamber is measured using an Endevco piezoresistive high-temperature pressure transducer that is mounted into the wall of the chamber. The previously mentioned DAQ measures and records both signals and the spark trigger signal and performs a running FFT of the microphone signal to yield frequency data. Pressure values are presented as the ratio of the chamber pressure to the ambient conditions across the exhaust orifice (the ambient is standard atmosphere throughout the present tests, making the pressure ratio equivalent to pressure in atmospheres). Although dynamic temperature measurements were not possible in the present experiments, static temperature measurements for some cases were performed using a small thermocouple inserted into the chamber near the nozzle entrance. The temperature of the inlet gas was controlled using an in-line heater and variable AC controller.

4. RESULTS AND DISCUSSION

The combination of a COMPACT actuator with a fluidic oscillator is expected to yield certain changes in the performance relative to the performance of each element separately. For COMPACT, the overall effect of adding a fluidic oscillator to the exhaust orifice is expected to be not significantly different than changes made to the exhaust orifice size, with smaller orifices yielding greater pressure drop and subsequently higher chamber peak pressures and longer pulse durations as the amount of time for the pressure to exhaust is increased (Crittenden, et al [6]). The only expected difference in this case is that the longer flow path of the fluidic oscillator may yield greater thermal losses to the heated exhaust jet compared to the typically used thin orifices.

In contrast, using a COMPACT actuator as the pressure source for a fluidic oscillator is expected to cause several changes in the operational frequency compared to supplying the oscillator from a steady compressed air source. As noted by many sources on fluidic oscillators, the frequency of a fluidic oscillator may be considered a function of two characteristic times within the device: the transmission time of the pressure pulse through the feedback loop and the switching time of the jet attachment from one wall to the other. The transmission time of the pressure pulse is primarily a function of the length of the feedback channel and the speed of sound in the channel (as well as transmission losses which are effectively negligible at the scale of the present device). The switching time of the oscillator is a complex relation between a number of geometric and flow factors but is often found empirically as a function of the gas flow rate or pressure (e.g., Goel and Kar [17]). Using COMPACT as the oscillator supply result in key changes to critical parameters for these times including varying supply pressure, varying gas temperature, varying gas composition, and the transients in all of these factors during actual firing of the combustor. Each of these four factors is discussed below with characterization of the prototype device for steady variation of each of the first three followed by results for full operation with COMPACT firing indicating unsteady effects.

4.1. Pressure Variation

Over the duration of the COMPACT operation cycle, the chamber pressure varies typically from slightly above atmospheric during the supply and refill followed by a sharp pressure peak and subsequent decay back to the original supply pressure or even slightly below depending upon the dynamic timing of the gas refill resuming. The steady effect of pressure variation on the test oscillator frequency is shown in Figure 7 for air at a constant temperature of 294K for the range of 6.9 to 206.7 kPa. The results are generally typical with a sharp increase in frequency at low pressures followed by a reduced rate of increase as the pressure is increased further. It is noted that the pressure effect is in theory limited exclusively to changes in the switching time (transmission time is invariant with pressure ignoring loss effects). In the present oscillator with a total transmission loop length of approximately 20 mm, the transmission time for the cycle for this data set is only 58.1 μs. Thus for the measured frequencies of Figure 7, the switching time is the dominant time scale (e.g., at 206.7 kPa, the measured frequency is 4415 Hz, yielding a switching time of 168.4 μs with longer switching times associated with the lower frequencies at reduced pressures).

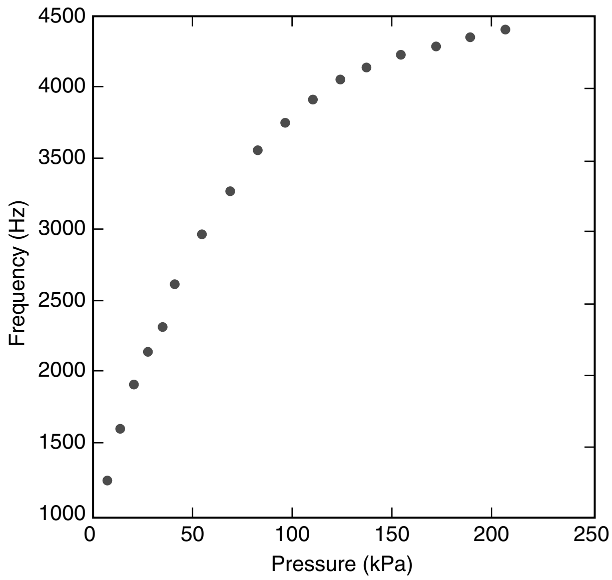

Figure 7. Oscillator frequency as a function of pressure for steady air flow at 294K.

4.2. Temperature Variation

Since the COMPACT actuator utilizes an intermittent combustion process to achieve high chamber pressures and exhaust velocities, significant variation in the exhaust gas temperature takes place. In theory, this ranges from temperatures at the low reactant inlet temperatures to the flame temperature itself if the combustion process is not completed within the chamber. In practice, the flame is typically quenched as it exhausts from the system and the gas flow between actuator pulses consists of a mixture of hot exhaust products from earlier cycles and cool fresh reactants entering the chamber (with the refill process analogous to that for a two-stroke engine with a limited scavenging efficiency). Also residual heating of the combustor walls becomes significant at higher actuation frequencies with longer run times further contributing to a rise in temperature of gas passing through the oscillator. A gas temperature increase inherently yields significant effects on fluid properties such as speed of sound, density, and viscosity.

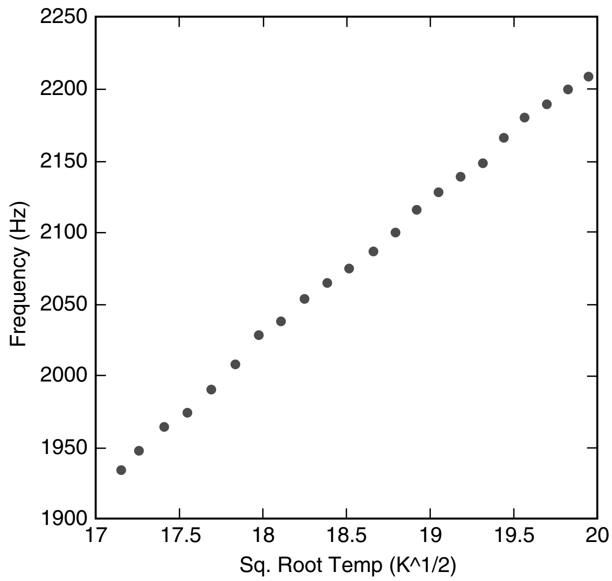

Figure 8. Oscillator frequency as a function of temperature for steady air flow at 20.7 kPa.

Results for frequency change with steady temperature variation for a constant pressure air stream at 20.7 kPa are presented in Figure 8. Due to limits on the available heater system, the measurement range was from 294 to 398 K. The data is presented as frequency versus the square root of temperature thus following the dependence of temperature in the speed of sound equation

$$c = (\gamma RT)^{1/2} \tag{1}$$

It is noted that the specific heat ratio (γ) is also a function of temperature, but varies only slightly over the range tested. A linear relationship is obtained from the data suggesting that the temperature effect (at least over the measured range) is almost exclusively due to changes in the speed of sound rather than any factors which might affect the switching time.

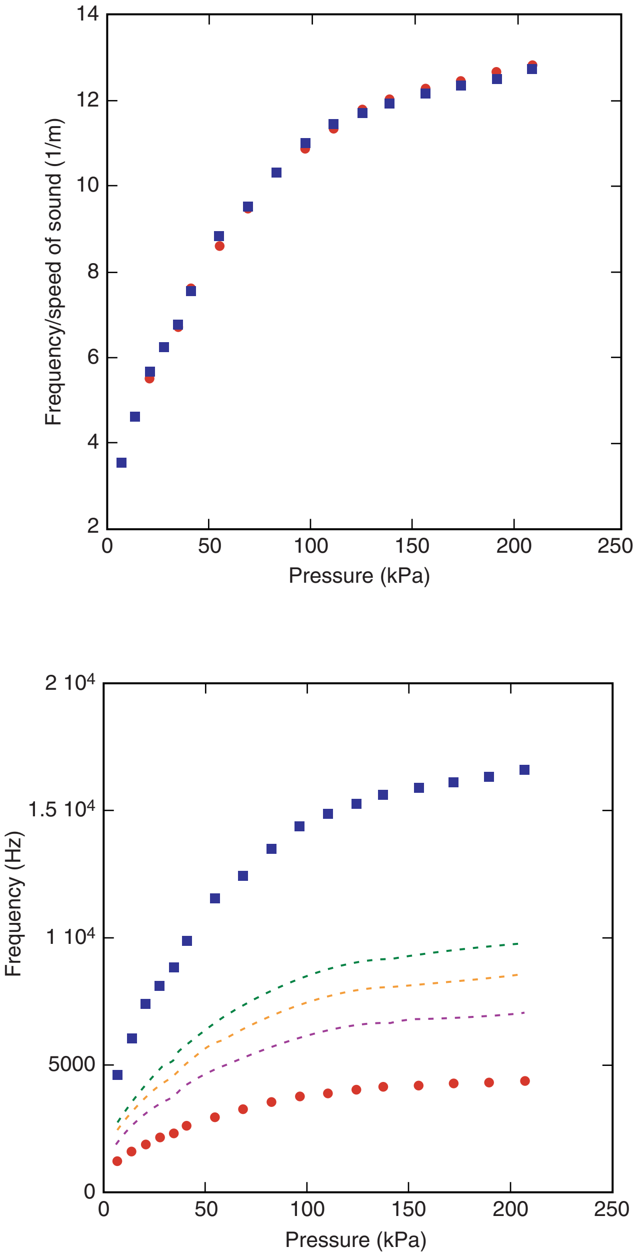

Figure 9. Oscillator frequency as a function of pressure with experimental values for air (•) and hydrogen (■) with calculated expected values for air-hydrogen mixtures of Φ = 1.0, 0.7, and 0.4 included in lower plot . All results at 294K.

4.3. Gas Composition Variation

The gas composition through the oscillator will inherently vary from air as the reactants will include fuel with the air and will also include products during the combustion pulse and refill. The present experiments are limited to COMPACT utilizing hydrogen-air mixtures although the results for variation in molecular weight/gas constant are expected to hold for other gas mixtures. Variation in fluidic oscillator performance with gas molecular weight is well documented and such oscillators have been used specifically to act as molecular weight sensors (e.g., Leroy and Gorland [18]). The present experiments confirm the strong impact of molecular weight comparing oscillator function for pure air versus pure hydrogen in Figure 9. The upper plot presents only experimental data for air and hydrogen with the frequency values for each pressure normalized by the speed of sound for the gas (including change in both the gas constant and specific heat ratio). A strong match between these normalized results is observed. It is again noteworthy that the effect of change in speed of sound appears to account entirely for the variation in frequency over this temperature range. For this result to hold, both the switching times and transmission times must scale directly with the speed of sound. This is particularly true since the switching time is the larger time scale in oscillators of this size. Although the Reynolds number for the air stream is 2.56 times greater than for equivalent operation with hydrogen, it has no apparent effect on the switching times. The lower plot of Figure 9 presents the experimental actual frequency values along with expected curves for several mixture ratios of air and hydrogen (stoichiometric plus two lean mixtures, encompassing the typical range of COMPACT operation). The expected results for mixtures are calculated by taking the mean of the experimental normalized frequency values and then multiplying times the calculated speed of sound for the gas mixture. As would be expected, the stoichiometric mixture yields the highest frequencies, with the leaner mixtures progressively approaching the values for pure air.

4.4. COMPACT Dynamic Effects

The actual operation of COMPACT with the fluidic oscillator results in changes to all three of the parameters above in dynamic fashion introducing a number of transient effects into the system. Typical sample results are shown in Figure 10 for an actuator firing frequency of 10 Hz and a mixture ratio (Φ) of 0.5 and an overall flowrate of 6 sL/min with the spark ignition corresponding to the falling edge of the TTL trigger signal. A lean mixture was used to minimize fuel consumption (and thus required weight associated with the flow control system) while still maintaining relatively high pressures (although even higher pressures can be obtained with richer mixtures). The pressure signal

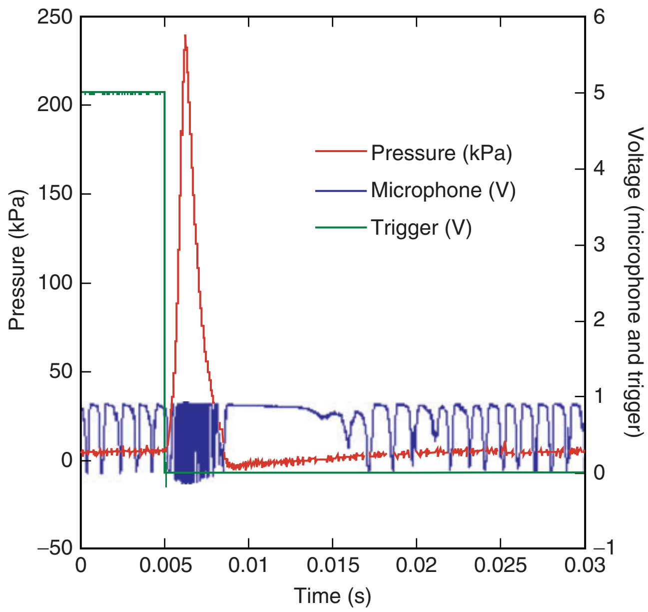

Figure 10. Sample results from COMPACT firing at 10 Hz showing cavity pressure and oscillation frequency at exhaust.

is the dynamic pressure within the combustor itself while the microphone signal only provides a measure of frequency with no calibration attached to its voltage levels. Prior to spark ignition there is a comparatively low frequency oscillation at 1 kHz observed resulting from the low pressure in the chamber during the refill process. Following ignition, there is a sharp pressure rise within the chamber (also yielding increases in the gas temperature and composition changes) with a corresponding large increase in the oscillation frequency. Over the roughly 3 ms duration of this pressure pulse, the high frequency varies with the pressure with values in the ranging up to 10 kHz near the peak pressure. (A direct comparison to the frequencies expected from the single variable effects is not possible since the exhaust temperature and gas composition can not be measured dynamically over the combustion process.) Following the dissipation of the combustor pressure, there is a lag of approximately 8 ms in which no apparent oscillations are observed. This may be attributed to either reduced outflow or even backflow through the oscillator during this period or transients in the oscillator preventing stable operation as the wall attachment and feedback flows re-establish themselves.

Figure 11 shows operation with a similar mixture ratio with the combustor firing frequency increased to 50 Hz. There is a decrease in the peak pressure achieved in the chamber due to scavenging inefficiencies allowing more exhaust to remain in the chamber between cycles and dilute the reactant mixture. However, the overall effect remains the same with a stable lower frequency oscillation between ignition pulses, followed by a high frequency burst corresponding to the high pressure within the chamber, and a subsequent time lag as the stable oscillation reasserts itself. It may be noted that for these results, the time lag between the combustion pulse and oscillations resuming is somewhat smaller (~6 ms) than for the 10 Hz case. This appears to correspond to the reduced actuator peak pressure which may allow stable operation to resume more quickly. It is conceivable that for a high enough actuator firing rate the stable oscillation between pulses would essentially disappear as the high pressure pulses approach one another in time. With the present premixed actuator geometry however, the repetition rate for stable combustor firing operation was insufficient to show this effect.

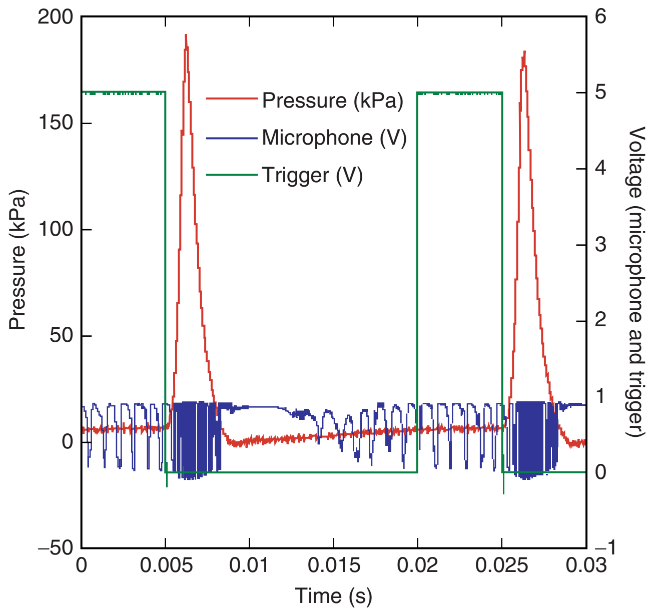

Figure 11. Sample results from COMPACT firing at 50 Hz showing cavity pressure and oscillation frequency at exhaust.

5. CONCLUSIONS

The integration of a combustion powered actuator with a fluidic oscillator has been successfully demonstrated. This approach combines the high jet momentum of the combustion powered actuator with the high frequency excitation of fluidic oscillator while maintaining the advantages of each in their no-moving-parts designs. The result from the combined device is a comparatively low frequency oscillation during most of the low-pressure chamber refill process with a burst of high frequency oscillation corresponding to the high-pressure period following each combustor ignition pulse. Further characterization of the combined device would be useful to assess what causes the period after the combustion pulse in which no oscillations occur. However, since the expected flow control utility of the device will be during the high-pressure, high-frequency burst, this does not need to be fully controlled. Testing of the device for flow control effectiveness (particularly under high speed conditions requiring both high frequency and high jet momentum) is a natural next step to assess possible applications.

6. REFERENCES

1. Chang, R.C., Hsiao, F.-B., and Shyu, R.-N.,"Forcing Level Effects of Internal Acoustic Excitation on the Improvement of Airfoil Performance," *J. of Aircraft*, 29(5), p.823-829, 1992.
2. McManus, K.R., Ducharme, A., Goldey, C., and Magill, J., "Pulsed Jet Actuators for Suppressing Flow Separation," AIAA Paper 96-0442, January 1996.
3. Seifert, A., Darabi, A., and Wygnanski, I., "Delay of Airfoil Stall by Periodic Excitation," *J. of Aircraft*, 33(4), p. 691-698, 1996.
4. Smith, D.R., Amitay, M., Kibens, V., Parekh, D.E., and Glezer, A., "Modification of Lifting Body Aerodynamics Using Synthetic Jet Actuators," AIAA Paper 98-0209, 1998.
5. Amitay, M., Kibens, V., Parekh, D.E., and Glezer, A., "Flow Reattachment Dynamics over a Thick Airfoil Controlled by Synthetic Jet Actuators," AIAA Paper 99-1001, 1999.
6. Crittenden, T., Glezer, A., Funk, R., and Parekh, D., "Combustion-Driven Jet Actuators for Flow Control," AIAA Paper 2001-2768, 2001.
7. Funk, R., Parekh, D., Crittenden, T., and Glezer, A., "Transient Separation Control Using Pulsed Combustion Actuation," AIAA Paper 2002-3166, 2002.
8. Brzozowski, D. and Glezer, A., "Transient Separation Control using Pulse-Combustion Actuation," AIAA Paper 2006-3024, 2006.
9. Crittenden, T., Warta, B., and Glezer, A., "Characterization of Combustion Powered Actuators for Flow Control," AIAA Paper 2006-2864, 2006.
10. Putnam, A.A., Belles, F.E., and Kentfield, J.A.C., "Pulse Combustion," *Progress in Energy and Combustion Science*, Vol. 12, pp. 43-79, 1986.
11. Lin, R.-S., Hariharan, N., and Brogan, T., "Analysis of Fluidic Vortex Valves for Airflow Control in Combustors," AIAA Paper 2002-2946, June 2002.
12. Raghu, S., "Feedback-free Fluidic Oscillator," US Patent 6,253,782, 2001.
13. Stouffer, R.D., "Liquid Oscillator Device," U.S. Patent 4,508,267, 1985.
15. Raghu, S. & Raman, G. (1999) "Miniature fluidic devices for flow control," ASME FEDSM 99-7256, 1999.5} Ganesh Raman and Surya Raghu, "Cavity Resonance Suppression Using Miniature Fluidic Oscillators", AIAA Journal, Vol. 42, No. 12., 2608-2612, 2004.
16. Raman, G., Packiarajan, S., Papadopoulos, G., Weissman, C. and Raghu, S., "Jet thrust vectoring using a miniature fluidic oscillator, The Aeronautical Journal, pp. 129 – 138, March 2005
17. Goel, R., and Kar, S., "Investigation of Frequency of Sonic Fluidic Oscillator," 3rd Triennial International Symposium on Fluid Control, Measurement, and Visualization – FLUCOME '91, pp. 509-512, 1991.
18. Leroy, M.J., and Gorland, S.H., "Evaluation of a Fluidic Oscillator as a Molecular-Weight Sensor of Gases" NASA Technical Memorandum TM X-52780, June 1970.