Temporal Flow Characteristics of High-Frequency Supersonic Actuators Integrated in REM-Nozzle Assembly

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ABSTRACT
Temporal flow characteristics of a high-frequency supersonic actuator integrated to a nozzle-injector assembly designed for high-speed flow mixing is presented in this paper. This resonance enhanced microactuator nozzle system (REM-Nozzle) injects a fluid through four micro-nozzles (each 400 μm diameter) positioned symmetrically around a 1.0 mm nozzle through which a high-frequency supersonic actuation jet pulses out in the frequency range of 13 - 21 kHz. Compressed CO₂ is used as mixing fluid and compressed nitrogen is used for generating the actuation jet. The pulsed flow generates strong compressible vortex in the shear layer of steadily injected fluid that entrain and grows downstream enhancing microscale mixing of the injected fluid and nitrogen at very high-speed, and at a designated frequency. This paper summarizes the design details and characteristics of REM-nozzles, and reports the ongoing studies on temporal characteristics of pulsed actuator flowfield using high-speed microschlieren imaging technique.

Keywords: Supersonic Flow Mixing, Flow Control, Actuators, High-speed microschlieren, REM-nozzle

1. INTRODUCTION
Improved air-fuel mixing is critical for extending economic and efficient operational envelopes of high-speed air vehicles1. Although mixing is a microscopic, molecular level diffusion problem, the macroscopic phenomena such as entrainment and vorticity dynamics resulting from the shear layer instabilities of the mixing fluids play a significant role in the overall efficiency of the process. It is well understood that the essential goal of any mixing scheme that involves fluids in motion is to introduce streamwise vorticity in the flowfield2. A highly motivating problem is that of air-fuel mixing inside a scramjet engine, a very complex phenomenon involving high-speed interactions of shock and turbulent flow structures within the design constraints of limited residence time and combustor space3. Ideally, the injected fuel should mix with the incoming air within a fraction of a second (of the order of 2-10 milliseconds), depending on the flow Mach number and the combustor length, for an efficient combustion process and heat release. Due to the short residence time and the compressible

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conditions existing within the combustor, efficient and controlled of mixing still remains as an elusive technical challenge. Although significant understanding have been gained on this fundamental problem and the researchers have proposed several strategies for efficient fuel injection, robust technologies that can be integrated to the next generation high-speed systems have not been realized yet.

For the efficient mixing of air and fuel, researchers have proposed several techniques, passive and active, over the years. These passive schemes require no moving parts and tend to be less complicated and the less expensive. However, they often do not work well at off-design conditions. Two classes of parallel fuel injectors that have been heavily studied are the strut and the ramp injectors. The active flow control schemes in the form of periodic excitation, on the other hand, require additional system functions as well as some form of energy input. The hypothesis is that introduction of periodic perturbations accelerates and regulates the generation of large coherent structures, which are responsible for the jet entrainment through transporting momentum across the shear layers. A typical example of an active flow control scheme is the Hartmann-Sprenger tube, which was reported to have improved mixing with a reduced total pressure loss. In this excited fuel-injection technique deeper penetration, enriched large-scale structures, and better combustor efficiency were reported. In addition, it is reported that a right excited frequency could shorten the mixing and combustion distance, thereby reducing the vehicle size and weight.

The current research on fuel injection technologies has been directed towards achieving this goal of deep penetration and rapid mixing of high-speed air and fuel, with less complexity and with a possible handle on its control. Some studies show that supersonic pulsed injection is beneficial for scramjets operating over a wide range of conditions. It is reported that the mean penetration was increased using pulsed injection at high-frequencies. Also, studies show that pulsed injectors with shorter duty cycle tend to aid the formation of vortex ring structures in the mean flow. The development of an operational and scalable fuel injector that is optimized based on combustion dynamics as well as on overall system performance is essential for the design of next generation scramjet systems with improved safety and fuel economy.

In this paper, we summarizes the design, development and characterization of a fuel injection assembly that are integrated with high frequency, pulsed supersonic actuators that can be
operated in a frequency range of 12 - 22 kHz, and report the temporal characteristics of REM-actuator flowfield captured using a high-speed microschlieren technique. The essential goal of this active nozzle injection assembly is to inject a fluid enriched with strong compressible vortex at a designated frequency from a robust configuration. The actuator technology used in this study has been developed by Solomon et al.\textsuperscript{14-16} and it can produce pulsed supersonic microjets in a wide range of bandwidth (100 Hz - 60 kHz). These actuators are proven to be useful for various supersonic flow control applications\textsuperscript{17-21}. These resonance enhanced microactuators integrated to the nozzle assemblies (REM-nozzles) are expected to assist turbulent mixing of an injected fluid by the microscale compressible vortex structures infused within the flowfield.

2. EXPERIMENTAL DETAILS

The experiments presented in this paper are conducted in the flow diagnostic laboratory at Tuskegee University. A vibration free optical table equipped with state-of-the art data acquisition and flow imaging systems were used for the experiments.

A Photron mini\textsuperscript{TM} high-speed camera is used for image acquisition. This monochromatic camera can capture up to 4000 frames per second at its full resolution of 1080x1080 pixels and up to 500k fps at lower resolution. A lens based microschlieren system has been set up on
the optical table for visualizing the microscale flowfield as shown in the Fig. 1. A customized LED light source that provides pulsed white light having a pulse width of nearly 80 ns, and operate up to 200 kHz, is used in this microschlieren system to capture the time resolved microscale flowfield. Such a light source with extremely short pulse duration allows to ‘freeze’ and capture the fast moving microscale flow structures of the flow domain. In this system, the light from the LED is focused to a sharp rectangular aperture using a condensing lens. This light is then collimated and focused to a point where a sharp knife edge is placed as indicated in Fig. 1. Actuator flow is kept in the test section for the Schlieren imaging. This microschlieren system uses 60 mm lenses with 60 mm focal length for collimating and condensing purposes.

The unsteady spectra of REM-nozzle flow were measured using GRAS™ 1/4” Free-Field Microphone with a sensitivity of 4 mV/Pa located approximately 4 cm from the location of source jet emission. National Instruments 9234, 24 bit, 51.2 kHz data acquisition module is used for acquiring the microphone data using LabVIEW™. Standard fast Fourier transformation (fft) procedures were used for calculating the acoustic spectra of the REM-nozzle flowfield.

3. RESULTS AND DISCUSSION

3.1 REM nozzle design and characteristics

A schematic of REM-nozzle assembly designed and developed for this study is shown in Fig. 2. The major components of the assembly are: 1) an underexpanded actuator source jet that enters into a nozzle block, 2) nozzle block with internal cavities, 3) a sonic nozzle through which pulsed actuator flow ejected from the nozzle block, and 4) micro-nozzles integrated around the sonic nozzle for injecting the fluid to be mixed. These nozzles each 400 μm diameter are positioned along the circumference of the 1 mm sonic nozzle through which a supersonic pulsed air actuation air jet flows out at a high frequency range of 12-22 kHz. In this study, CO₂ is used as the mixing fluid and compressed nitrogen as the pulsed actuation stream. Under certain geometric and flow parametric conditions such as the source jet nozzle pressure ratio, NPR, and distance between the source jet nozzle and the cavity entrance, h, this actuator configuration produces a pulsed supersonic stream that flows through the sonic nozzle at the bottom of the cavity. Figure 3a shows top and bottom views of the REM-nozzle assembly. The four micronozzles surrounding 1 mm sonic nozzle is clearly visible in these photographs. Figure 3b shows the frequency spectra of the actuator integrated to the REM-
nozzle assembly. The supply nozzle pressure is varied from NPR=6.7 to 8. In this NPR range the frequency of pulsing is varied from 13.1 - 21 kHz. More design details are available in reference\textsuperscript{21-23}.

Fig. 2 Schematic of REM-Nozzle used in this study. Four micronozzles each 0.4 mm diameter are integrated circumferentially around a 1 mm nozzle through which pulsed, supersonic actuation stream ejected at 12-21 kHz.

The REM actuator integrated to this assembly has been developed and studied by Solomon et al.\textsuperscript{14-16}. With extensive parametric studies, Solomon et al. have reported a strong correlation between the actuator’s maximum frequencies to its volume\textsuperscript{15}. Based on a LEM (lumped element modelling) approach, that considers the actuator as an aero-acoustic resonating system, and with an assumption that acoustic impedance due to the inerance and compliance of the resonating acoustic mass influences its maximum resonance frequency, a semi
empirical relation as shown in equation 1 has been suggested as a first hand design tool for REM actuators. The present REM-nozzle block used this correlation for its design.

\[ f_{\text{max}} = \frac{c_0}{2\pi} \left( \frac{nS_m c_m^\prime + S_c c_c^\prime}{\ell_m \ell_c^\prime V} \left(1 - \frac{nS_m}{S_c}\right) \right)^{1/2} \]  

(1)

In this equation 1 the major parameters are the total volume of the actuator \( V \) and the inflow-outflow cross-sectional area ratio \( nS_m/S_c \), where \( S_m \) is the area of each micro nozzles through which pulsed microjets flows out and \( S_c \) is the area of cross-section of the inflow cavity. Other geometric parameters \( \ell_c^\prime \) and \( \ell_m^\prime \) are the effective column length of the fluid resonating inside cavity and outside respectively. If the inflow-outflow area ratio is 1, the system ceases to resonate. This REM-nozzle block has a cavity volume of 13.7 mm\(^3\) and its design follows previous studies on REM actuator\(^{14-16}\). The actuator source jet enters REM-nozzle block through a 1.3 mm cavity as indicated in Fig 3a. The source jet is supplied from a 1.5 mm diameter sonic nozzle. More design details are available in reference [21-23].

### 3.2 Instantaneous global flowfield of REM Nozzle

Figure 4 shows instantaneous Schlieren images of the REM nozzle flowfield corresponds to \( NPR=6.7 \) and \( h/d=1.0 \) where the jet is pulsing at 21 kHz. The images were captured using a synchronized trigger signal supplied to the camera and the LED light source operating at 1 kHz and its full resolution (1280x1280). Highly unsteady oscillating flow is noticed at the impinging side of the source jet.

The image shown in Fig.4a shows the beginning of the pulsing phase of the actuator jet when the micronozzles injects mixing fluid into it. A compressible vortex begins to appear with a bow shock upstream of the flow. Fig 4b-c shows evolution of this compressible vortex further downstream. It is evident that the evolving jet is supersonic with the presence of shock cells and oblique shock patterns in the flow. As it evolves it entrains more fluid and diffuses downstream. The source jet oscillations are marked by unsteadiness in the flow structure formed by the first shock cell, the impinging normal shock and Mach disc. The pulsing of flow at the bottom side creates compressible vortex that evolve and move downstream at this ultrasonic frequency and at a supersonic speed. The sound pressure level (SPL) spectra shown earlier in Fig. 3b of the actuator shows evidence to strong acoustic waves in the nearfield generated by the pulsing supersonic jet. This also shows that the REM actuator technology used and integrated to the nozzle assembly provides high momentum unsteady actuation to the jet to be injected and mixed. The spectra show that the amplitude of maximum frequency response is more than 30dB above the broadband noise level.
3.3 Temporal characteristics of REM actuator source jet oscillations

To understand the ultra-high frequency characteristics of the pulsed flow and highly unsteady oscillatory nature of Mach disc of the actuator source jet, the flowfield is captured at higher frame rates. Fig. 5 shows time resolved six images of source jet with 3.125 milli-second interval (32 kHz). The ultra-sonic spectra of source jet in this operating condition is measured as 22.4 kHz as indicated as red curve in Fig. 7a. Fig 6 shows time resolved six images of source jet with 16 micro second interval (64 kHz frame rate) captured at a lower resolution (1280x72 pixels). The corresponding spectra is measured as 12.7 kHz as shown in Fig. 7a as green curve. This data indicate that the frequency of actuator integrated to REM-Nozzle block has a bandwidth of ~10 kHz. The exposure time of camera is set 1/250000 seconds to freeze the fast moving shock structures at this scale. Since the actuator is pulsing at 12.72 kHz, 5-6 images were captured for the 1 complete cycle of the periodic oscillation of the source jet.

To better understand the oscillatory nature of source jet and its correlation to the nearfield microphone data, these images captured in each cycle are analyzed using ImageJ analysis software and MATLAB. The oscillations frequency, displacement and average velocity fluctuation of the Mach disc were estimated using this technique.

3.4 Oscillation Frequency, displacement and average velocity of Mach disc

The Fig. 8 shows representative images of Mach disc oscillations of two cycles. The displacement of Mach disc is 380 micrometers for a period of 0.039 milliseconds. This will provide an average velocity of 9.74 m/sec for the shock motion. The period of oscillation is
measured as 0.078 milli seconds and the corresponding frequency is calculated as 12.8 kHz for both sets of images.

Fig. 5 Oscillatory source jet of actuator captured at 1250x152 pixel resolution and 32 kHz frame rate at 1/60000 exposure time. The pulsing frequency is 22.7 kHz.

Fig. 6 Oscillatory source jet of actuator captured at 1250x72 pixel resolution and 64 kHz frame rate at 1/256000 sec. exposure. The pulsing frequency is controlled to 12.7 kHz.

The nearfield pressure spectra measured by the microphone captures this frequency as 12.72 kHz (fig. 7a), which very close to this calculation. It is evident that these Mach disc oscillations, which is correlated to the filling and spilling phases of actuator, is responsible for the discrete tones in the nearfield. For more statistically accurate estimate of Mach disc
oscillation frequency a larger sample of two thousand and three (2003) images were analyzed using the ImageJ software as shown in Fig. 9.

Fig. 7a Frequency spectra of actuator measured using the microphone for images shown in Fig. 5 and 6. b) Frequency of Mach disc oscillation estimated using ImageJ software for images captured at 64 kHz shown in Fig. 6.

Fig. 8 Mach disc oscillation of source jet images (two sets) captured at 64 kHz frame rate shows 0.078 milli seconds as its period and 12.8 kHz as frequency.

Fig. 9 Intensity of 1D array of pixels that contains Mach disc location, sequentially arranged for the sample of 2003 temporal images and analyzed using ImageJ software. This representation captured the transient oscillation of Mach disc more systematically. These processed image matrix is then analyzed using MATLAB™ to find the maximum intensity value and its frequency using an fft analysis. This data shown in Fig. 7b indicates the
frequency of oscillation as 12.87 kHz which is matching with the predictions from the sample sets and microphone data.

3.5 Temporal Characteristics of pulses actuation jet

The instantaneous global flowfield of REM-nozzle as shown earlier in figure 4 indicate pulsed actuator flow evolution with entrained injected fluid. In order to quantify mixing of pulsed actuation jet and the mixing fluid, velocity of pulsed vortex is required. A typical wave front motion is shown in figure 10a. To capture the temporal evolution of fast moving microscale jet front, and to find the velocity, image pairs were captured at a lower resolution of 1280x32 pixels at a high frame rate of 100 kHz with camera exposure of 3.9065 microseconds as indicated in Fig 10b.

Fig. 10 Image pairs used to calculate the speed of pulsed vortex generated by the REM-Nozzle. These image pairs are separated at 0.01 milli-seconds time interval.

Fig. 11 Jet front associated with the travelling compressible vortex captured by 100 kHz frame rate indicate that these structures are moving 200 m/sec velocity.
Figure 10b i-iii shows sequential image pairs captured with wave front propagation with time signature. As indicated in Fig. 11, the compressible wave front travels 2 mm in 10 microsecond time interval. The average velocity is calculated as 200 m/sec in all the sample image pairs. The spectra corresponds to these images were measured as 15.1 kHz as indicated in Fig. 12.

**Fig. 12 Frequency spectra of actuator corresponds images shown in Fig. 10**

### 4. SUMMARY

In this paper we report temporal flow characteristics of a high-frequency supersonic actuator integrated to a nozzle-injector assembly designed for high-speed flow mixing applications. This resonance enhanced microactuator nozzle system (REM-Nozzle) injects a fluid through four micro-nozzles of 400 μm diameter each positioned symmetrically around a 1.0 mm nozzle through which a high-frequency supersonic actuation jet pulses out in the frequency range of 12 - 22 kHz. The pulsed air flow generates strong compressible vortex in the shear layer of steadily injected fluid that entrain and grows downstream enhancing microscale mixing very high-speed, and at a designated frequency. The unsteady oscillations of actuator source jet and pulsed flow from the REM-nozzle were studied using high-speed microschlieren image processing techniques and using a nearfield microphone. Average velocity of compressible vortex generated for mixing is calculated as 200 m/sec. This data will be useful for quantifying high-speed mixing characteristics of REM nozzles –a study which is ongoing at Tuskegee University.

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