Investigation of a pulsed-plasma jet for shock / boundary layer control

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Abstract

Pulsed jets with peak exit velocities as high as 250 m/s are generated by rapidly heating the air inside a chamber with an electrical discharge. The heated pressurized gas issues from a small orifice to form the pulsed plasma jet or ‘spark jet’. Pulsing frequencies as high as 5 kHz are obtained. An array of these jets, in a pitched and skewed configuration, is used to force the unsteady motion of the interaction formed by a 24° compression ramp in a Mach 3 flow. The Reynolds number of the incoming boundary layer is Reθ=3300. The effect of the plasma jet array on the separation shock motion is studied by using 10 kHz Schlieren imaging and fast-response wall pressure measurements. Results show that when the pulsed jet array is placed upstream of the interaction, the jets cause the separation shock to move in a quasi-periodic manner, i.e., nearly in sync with the pulsing cycle. As the jet fluid convects across the separation shock, the shock responds by moving upstream, which is primarily due to the presence of hot gas and hence the lower effective Mach number of the incoming flow. Once the hot gases pass through the interaction, the separation shock recovers by moving downstream, and this recovery velocity is approximately 1% to 3% of the free stream velocity. With forcing, the low-frequency energy content of the pressure fluctuations at a given location under the intermittent region decreases significantly. This is believed to be a result of an increase in the mean scale of the interaction under forced conditions. Pulsed-jet injection was also employed within the separation bubble, but negligible changes to the separation shock motion were observed. These results indicate that influencing the dynamics of this compression ramp interaction is much more effective by placing the actuator in the upstream boundary layer.

Introduction

Development of surface plasma actuators for the control of high-speed flows has received considerable attention in recent years. The plasma actuators used for supersonic flow application typically rely on electrothermal heating, MHD forces (from external magnetic field), and electrostatic forces as their flow actuation mechanisms. Several types of discharges like glow discharge (e.g. [1,2,3]), arc discharge [4,5,6], RF discharge [7], MHD discharge [8] etc., have been shown to cause noticeable flow actuation. Recently pulsed arc discharges were employed by Caraballo et al. (2009) [9] for controlling an impinging shock/boundary layer interaction generated from a 10° shock generator placed in a Mach 1.9 flow. They employed 8 actuators that operated either in phase or out of phase with one another for this experiment. They found that the velocity profile measured downstream of the interaction appeared fuller with actuation. They attributed this observation to the formation of streamwise vortices because of the plasma discharge. Wang et al. [10] employed pulsed plasma arcs in the presence of external magnetic
field to control separation shock generated by a 20° compression ramp placed in a Mach 2.1 flow. The tests with plasma discharge in the absence of external magnetic field caused the separation shock to move upstream, simultaneously decreasing the shock angle. They observed a corresponding decrease of 8.6% in surface pressure proving that the actuation indeed has weakened the separation shock. Further weakening of the separation shock was observed by adding external magnetic forcing directed both the upstream and downstream directions.

More conventional techniques have also been used to achieve control of shock wave / boundary layer interactions (SWBLIs). Transverse jet injection has been shown to cause considerable changes in the SWBLI mean structure and dynamics [11,12,13]. Selig et al. [11] reported the locking of the frequency of separation shock motion when they injected a transverse pulsed jet normally at high frequency. Bueno et. al. [12,13] showed a permanent downstream shift in the separation shock caused by SWBLI of a cylinder [12] and compression ramp [13] in a Mach 2 flow by injecting a pulsed and continuous pitched-skewed jet. These studies clearly demonstrate the potential of using jet injection for SWBLI control.

Recently electric discharges were used to obtain pulsed synthetic jets [14,15] (called “spark jets”). Computational simulations [14] have shown that the jet velocity as high as several hundred of meters per second can potentially be achieved. Preliminary experimental results [15] have also shown that the velocity several diameters away from the jet exit is as high as 100 m/s. This concept was extended in our laboratory to create high frequency (several kHz) and high amplitude (~300 m/s) synthetic jets which we termed “pulsed plasma jets”. The operation and characteristics of these pulsed plasma jets are reported in detail in Ref. 16 and 17. These jets were employed to control the unsteadiness of a compression ramp SWBLI. Phase average Schlieren at 60 Hz was used to study the interaction between the pulsed plasma jet and the separation shock. It was demonstrated that these pulsed plasma jets, when pitched and skewed, can create streamwise vorticity and act as vortex generator jets that cause a momentary decrease in the length scale of the separation bubble. However, the more dominant effect of the pulsed plasma jets is to cause significant upstream motion of the separation shock. This latter effect will be discussed further in this paper.

Our previous preliminary results reported in Ref. 16 reflect predominantly mean characteristics of the interaction. However, these previous results shed little light on the dynamics of the shock response to the individual disturbances. Therefore, in this paper we perform 10 kHz schlieren imaging to study the time-resolved motion of the
separation shock as it interacts with the pulsed plasma jet. Furthermore, high-frequency wall pressure measurements under the intermittent region and inside the separation bubble were used to study the response of the interaction to the pulsed plasma jets. The effect of actuator location on influencing the SWBLI unsteadiness was also explored. Actuators were placed in the upstream boundary layer, and at two locations within the downstream separated flow.

2. Experimental Setup

Pulsed plasma jet actuator

The schematic and the circuitry of the pulsed plasma jet actuator are shown in figure 1. A cylindrical hole of 2.3 mm dia. was drilled into a boron nitride plate and electrodes (2.3 mm dia.) were inserted from both ends to form a cavity bounded by the electrodes. The gap between the electrodes can be varied to provide different cavity volumes. The plasma jet exhausts from a small orifice (≈ 1.8 mm dia.) that was drilled into the middle of the cavity. The tip of the cathode was sharpened to decrease the breakdown voltage. A capacitor (0.22 μF) was charged by the DC power supply (Spellman, SL2PN1200) until the discharge is formed between electrodes. Upon breakdown, the capacitor provides a high current to generate a non-equilibrium arc between the electrodes. A timing circuit including BNC delay generators and MOSFET switches was made to repeat the charge-discharge cycle at kilohertz rates. Instantaneous peak discharge currents of about 1.2A to 11 A have been tested. Pulsing frequencies up to 5 kHz at 10% duty cycle has been achieved at 2 A discharge current. The main restriction to the pulsing frequency is the replenishment time required to fill the partial vacuum created in the cavity at the end of each pulse. In the present study the discharge current for the pulsed plasma jet was set at 4 A and the pulse width of the discharge was set at 50 μs. A spanwise array of three pulsed-plasma jets pitched at 45° and skewed at 90° was employed. The spacing between individual jets was 3.75 mm.

Wind tunnel facility

The experimental work was conducted in a Mach 3 wind tunnel located at The University of Texas at Austin. The overall schematic of the apparatus is shown in fig. 2. The wind tunnel test section had a cross sectional area of 5 cm × 5 cm and a length of 0.4 m. An acrylic splitter plate extended from the plenum section into the test section. The plasma actuator was placed at the trailing edge of the splitter plate. Pressurized air from a 14-m³ high-pressure tank was fed to the tunnel and is discharged into a 30 m³ vacuum tank. The test section static pressure was maintained at 45 torr for all the cases studied. The incoming boundary layer was allowed to undergo natural
transition to a turbulent boundary layer and the 99% boundary layer thickness of the incoming boundary layer was about $\delta=4.5$ mm, and the Reynolds number based on momentum thickness was $Re_\theta=3300$. The SWBLI was generated using a 24° compression corner. The pulsed plasma jet was injected upstream of the compression corner, and at two locations within the separated flow.

**High-speed schlieren imaging**

High-repetition rate Schlieren imaging was used to study the interaction between the pulsed plasma jet and the separation shock. The lamp was pulsed using high-brightness LED (ISSI, Inc.) lamp that was operated at 10 kHz. The pulse duration of the lamp was about 6 $\mu$s. This was short enough to provide a nearly instantaneous snapshot of the flow. The flow was imaged through acrylic windows on each side of the test section. The light was collimated and focused by 1 m focal length concave mirrors. The schlieren images were captured using a Photron APX camera with a framing rate of 10 kHz, triggered internally, and an exposure time of 0.1 ms. The images (512×512 pixel resolution) were acquired for 0.3 seconds for each run. The images at each run were acquired at a predetermined delay from the start of the discharge trigger, and thus the images were phase locked, as well as being time-resolved.

**Wall pressure fluctuation measurements**

Wall pressure fluctuation measurements were made in the streamwise direction along the SWBLI region generated using the compression ramp. Separate measurements of the wall pressure fluctuations were made with and without forcing. In both the cases fast-response pressure transducers were used. During pressure measurements with forcing, only a single pulsed plasma jet was employed. The transducer employed for pressure fluctuation measurements with, and without, forcing was made by using a Kulite Semiconductor Products, Inc. transducer (model XCQ-062-05A). The transducer had a nominal diameter of 0.0625 inch and a silicon sensing membrane whose diameter as specified by the manufacturer was 0.71 mm. The natural frequency of the membrane was 150 kHz. Perforated screens above the diaphragm protect the transducer from being damaged by dust particles in the flow. The protective screen limits the frequency response to about 50 kHz. These transducers were housed in a copper tube and the entire unit was mounted flush with the floor of the splitter plate.

Measurement of wall pressure fluctuations without forcing was straightforward and did not require any additional procedures. However modifications to the present experimental setup were required in order to make
pressure fluctuations with forcing owing to the presence of charged species from the pulsed plasma jet in the vicinity of the transducer. The problem arises because the transducer casing has to be grounded in order to minimize noise during measurement. However, this grounded casing drains the ions that convect past it and can cause permanent damage to the transducer including: (1) loss of frequency response, (2) a permanent DC offset, (3) loss of sensitivity, and (4) permanent physical damage to the sensing element because of heat load from the reacting ions.

In order to protect the transducers from the incoming ions and obtain meaningful wall pressure fluctuation measurements, a second pulsed ground electrode was located upstream of the transducer. This electrode drains the incoming charged species before they can reach the transducer. This technique was shown to be highly effective in enabling fluctuating pressure measurements to be made in the presence of the pulsed discharge, although significant noise spikes were still present on the pressure signal as will be shown below.

Sample pressure time series with pulsing

Pressure time series data was taken for 2 s while the pulsed plasma jet was in operation. The pulsing frequency of the pulsed plasma jet was varied between 2 kHz and 4 kHz. The pulse width of the jet was fixed at 20 μs and the peak discharge current was set at 4 A. The measurements were started after 0.5 s from the start of pulsed plasma jet in order to make sure steady state has been established. A sample time series of the pressure fluctuations with a single 2 kHz pulsed plasma jet located 10δ upstream of the compression corner is shown in figure 3. The corresponding discharge current waveform measured simultaneously as the voltage drop across a 1.2Ω resistor placed in the circuit is also shown (marked Discharge current). It can be seen that the pressure fluctuations look predominantly free of spikes due to electromagnetic (EM) noise. However, spikes occur shortly after the start of the discharge and at the end of the discharge. The spikes are due to the maximum time rate of change in current (from OFF to ON and ON to OFF) which causes very high levels of EM noise. The maximum magnitude of these noise spikes is approximately two times larger than the rms pressure fluctuations present in the unforced flow. It is important to note that the width of the noise spikes is less than 30 μs and the interaction of the pulsed plasma jet with the separation shock begins only at about 45 μs from the start of discharge trigger. By this time the pressure signal is free of EM noise, which makes it possible to study the effect of the pulsed plasma jet on SWBLI unambiguously. Note that increasing the number of pulsed plasma jets from one to three increases the noise considerably, and it becomes too hard to process the data to obtain meaningful results.
Data processing

The effect of the pulsed plasma jet on the SWBLI was studied by computing the power spectra of the pressure fluctuations. However, the short duration spikes that occur occasionally with the discharge cause non-negligible energy at all the frequencies. The reason for this can be understood by considering the spike as an approximate delta function whose width in the frequency domain is very broad. Hence it is necessary to pre-process the data to remove the spurious spikes before their power spectrum is computed. The procedure followed in pre-processing the data includes identifying the spikes by computing the slope at each point using a forward difference scheme. The spikes due to EM noise are identified as those whose gradient is above a user-defined threshold. The threshold is chosen to be +/- 2 standard deviations, and it was found that none of the data points that correspond to the actual signal are removed. Typically the number of data points that correspond to EM noise is about 1% to 2% of the data samples. Once the spurious data points are identified, they are replaced by interpolating the data values before and after the spike. The number of interpolated data points per identified spike was about 3 to 5; hence the total number of modified data points was between 5% to 10% of the total number of data points.

Results and Discussion

Actuator Placed in the Upstream Boundary Layer

The characterization of the response of the separation shock to the incoming pulsed plasma jet injected into the upstream boundary layer was accomplished using 10 kHz schlieren imaging. The actuator was located 10δ upstream of the compression corner. The intermittent region is located about 4δ from the compression corner. A representative time sequence that shows the unsteady motion of the separation shock during 400 μs of a 2 kHz discharge cycle is shown in fig. 4. Fig. 4(a) shows the location of the separation shock 75μs after the start of the discharge trigger. It was observed from phase-locked planar laser scattering (PLS) imaging from a condensed CO2 fog (not shown for brevity) that the jet reaches the separation shock after about 45 μs from the start of the discharge trigger and the entire pulsed plasma jet convected through the separation shock after about 100 μs. From Fig. 4(a) it can be seen that the separation shock moves upstream by about 0.7δ (3 mm) as the pulsed plasma jet convects through the shock. This corresponds to a shock velocity of about 0.05U∞. Figure 4(b) corresponds to the time, t = 175μs, when the entire pulsed plasma jet has convected through the separation shock. It can be seen that the separation shock in Fig. 4(b) is at a downstream position compared to Fig. 4(a). However it has not reached its mean
unforced position. In fact, it continues to recover to its mean position in fig. 4(c) and 4(d) corresponding to 275 and 375 μs after the start of the discharge trigger. In Fig. 4(d), i.e. after about 375 μs, it has reached its mean unforced position. Thus the separation shock spends about 70% of the time upstream of the unforced mean shock location.

A shock tracking program was developed in house to capture the motion of the separation shock from the schlieren images. The program identifies the presence of the shock from the relative pixel intensity across the row at different wall-normal locations. The closest location above the wall at which the program can unambiguously identify the shock is 0.5δ. The shock location used for analysis is computed as the average location over a height of 0.2δ (i.e., average shock location between 0.5δ to 0.7δ). Note that this analysis is used only to illustrate the periodic motion of the separation shock and no quantitative inference was made about the separation shock foot location.

To start with, figure 5(a) shows the separation shock motion of the unforced case with respect to its mean. The Δt between successive points is 100 μs (0.1 ms). It can be seen that the time trace of separation shock motion appears broadband without any clear periodic motion. The maximum amplitude upstream and downstream motion of the separation shock is about 0.4δ and the separation shock tends to stay within +/- 0.2δ from the mean location for the majority of the time.

Figure 5(b) shows the separation shock motion with respect to the mean unforced shock location when forced using 2 kHz pulsed plasma jet over 20 injection cycles (100 images). The mean unforced location is denoted by x/δ = 0. The first image was taken 25μs (0.025ms) after the start of the discharge trigger. It can be clearly seen that the separation shock moves over 0.7δ between 25μs (0.025 ms) and 125μs (0.125 ms) and it repeats over all injection cycles. This quick upstream motion is followed by a rather gradual recovery motion. It can be seen that in a majority of the injection cycles shown, the separation shock reaches farther downstream (to about -0.3δ) as compared to the unforced case (where the typical downstream motion extends to about -0.2δ). Finally, it is also clear that the broad aperiodic motion of the shock seen in the unforced case never occurs when forced. This shows that the separation shock motion has been locked to the pulsing of the jet.

Figure 6 (a,b) shows pdfs of the separation shock velocity for different portions of the forcing cycle. Approximately 1500 images (300 cycles) were used to compute the statistics. Positive velocities correspond to downstream shock motion and negative velocities correspond to upstream shock motion. Figure 6(a) is the pdf of maximum upstream (negative) velocity of the separation shock over the first half of the cycle. Note that this velocity can be positive if no negative velocity occurs during this time window. Figure 6(b) shows the maximum
downstream (positive) velocity over the second half of the forcing cycle, i.e. recovery of the separation shock after forcing. The upstream shock motion corresponds to the response of the shock due to the passage of the pulsed plasma jet, and the downstream shock motion corresponds to the recovery of the separation shock to its equilibrium position, which in turn might correspond to the relaxation of the separation bubble perturbed by the pulsed plasma jet. The upstream shock velocities seem to encompass velocities between 0 to 35 m/s, which corresponds to 0 to 6\% $U_\infty$ with most probable value around 0.03 $U_\infty$. However the downstream shock velocities seem to be limited to 0 to 21 m/s which corresponds about 0 to 3.5\% $U_\infty$, with the most probably value of about 12 m/s, or 2\% $U_\infty$. Interestingly, Gonzalez and Dolling [18] measured shock velocities for a wide-range of shock/boundary layer interactions and found that the typical shock foot velocity was about 2\% of $U_\infty$. The present case seems to correspond to one where the separation shock is perturbed upstream of its mean position and then allowed to recover naturally. Whether this recovery speed is coupled to the recovery of the separation bubble is not yet known conclusively. It should also be noted in fig 6(b) there is a small fraction of velocities which correspond to upstream motion ($U_{\text{shock}}/U_\infty < 0$). This is because in those cases the separation shock has fully recovered from the effect of forcing before the next pulse and it executes its natural unforced (upstream) motion before the next pulse arrives.

To quantify the effect of upstream pulsed injection on the separated flow unsteadiness, the power spectra of the wall-pressure signals measured at different locations under the interaction region were computed. For this part of the study, only a single 45° pitched and 90° skewed pulsed plasma jet was used since employing multiple jets resulted in severe EM noise and eventual transducer damage. The spanwise location of the transducer was roughly in line with the path of the pulsed plasma jet which was determined by following the trajectory of the pulsed plasma jet by using phase-locked spanwise PLS imaging. Figure 7 shows sample power spectra where the pulsed plasma jet was issued from the fixed location of 10\d upstream of the compression corner, and pressure measurements were made at different downstream locations under the separated flow. In the present study, the pressure-measurement locations are given relative to the interaction length $L$, which is defined as the distance between the mean separation shock foot location (inferred from schlieren imaging) and the compression ramp corner. For the present case $L \approx 3.5\d$.

Figure 7(a) shows plots of power spectral density (PSD) of wall pressure fluctuations measured under the intermittent region ($x/L = 0.95$), normalized by the square of the mean pressure, with and without upstream forcing. It should be noted that the data are presented without normalizing by the $rms$ fluctuations in order to study the quantitative changes in the power spectra. The spectra of both the forced and unforced cases contain noticeable
spikes at discrete frequencies. The spikes in the unforced case are due to structural vibration of the splitter plate that holds the transducer. The spikes in the forced case occur because of structural vibration as in unforced case, and also because of the EM noise associated with pulsed plasma jet. The spikes due to EM-noise occur at the pulsing frequency and its higher harmonics. The spikes due to structural vibration and EM noise are marked in the figure. It should be noted that the argument for using the power spectra, despite the presence of interference-spikes, is because we are interested in observing changes over broad frequency bands that are induced by the pulsing, and no quantitative conclusions are drawn at the specific frequencies that coincide with the spikes.

In Fig. 7(a), each plot corresponds to an average of two experimental runs which were highly repeatable. Without forcing the power spectrum is dominated by energy at low frequency as is typical of a canonical SWBLI [18,19]. The Strouhal number based on separation length, defined as \( St_L = f L / U_\infty \), at the location where the peak of the power spectrum occurs is about 0.023, which is in the range reported in several previous SWBLI studies (0.02-0.05) [18,19]. The frequency of forcing is chosen such that it lies in the low frequency range of the separation shock motion. The maximum amplitude of the frequency-multiplied power spectrum normalized on the square of mean wall pressure is about \( 0.6 \times 10^{-3} \). It can be clearly seen that with forcing there are noticeable changes in the power spectrum of the pressure fluctuations. The magnitude of the peak pressure fluctuations at separation shock frequencies (\( St_L = 0.02 \) – 0.05) has decreased by about 50% and the maximum amplitude of the pre-multiplied power spectrum normalized on the square of mean pressure is about \( 0.35 \times 10^{-3} \). Above Strouhal number of 0.3, the spectra of forced and unforced cases overlap, indicating that the higher frequencies are not affected by the forcing.

Pressure fluctuations with and without upstream forcing were also measured at locations inside the separation bubble, i.e., at \( x/L = 0.86, 0.66 \) and 0. The pulsed plasma jet is located 10\( \delta \) upstream of the compression corner for these measurements. The pressure fluctuation measurement locations span the range of just downstream of the intermittent region to the compression ramp corner. Figure 7(b) shows the power spectra at \( x/L = 0.66 \), where the unforced case shows the pressure fluctuations are shifted towards higher frequencies than those under the intermittent region (Fig. 7a). The unforced power spectrum shows the presence of two high-amplitude bands separated by a relatively low-amplitude valley. These broad peaks occur at \( St_L = 0.02-0.06 \) and 0.1-1, separated by a valley between 0.06 – 0.1. The maximum amplitude of the power spectrum in the low-frequency regime occurs at \( St_L = 0.04 \) and its value normalized on the wall pressure is about \( 0.35 \times 10^{-3} \). Upon forcing the amplitude of pressure fluctuations in the range of frequencies between 0.03 – 0.8 clearly decreases. The maximum decrease in amplitude
in the low frequency regime occurs at around St_L = 0.06. The average amplitude of pressure fluctuation between St_L = 0.04 – 0.08 has decreased from 0.3×10^{-3} to 0.22×10^{-3}. Figure 7(b) also shows that with forcing, the frequency of peak pressure fluctuation is shifted to a lower value — the peak amplitude occurs at St_L = 0.02 with forcing, whereas the peak amplitude in the low frequency band without forcing occurs at St_L = 0.04.

Figure 7(c) shows the case where pressure measurements were made at the compression corner (x/L = 0). In this case, the unforced-case pressure fluctuations are shifted to still higher frequencies. The unforced spectrum continuously increases till St_L = 0.1 and stays constant till St_L = 1. Beyond St_L = 1 the frequency response of the pressure transducer limits the accurate measurement of energy content. The maximum amplitude of the pressure fluctuations normalized on the square of the mean wall pressure is about 0.45×10^{-3} and it occurs at St_L ≈ 0.1. With forcing the power spectrum looks very similar to the unforced case. There are no noticeable changes in the amplitude of the spectrum at low frequencies. Considering the limitations due the high frequency EM noise, the effect of forcing at high frequencies could not be ascertained within the experimental uncertainty at the high frequency region (St > 1). Nevertheless, these results seem to show that the effect of upstream forcing is not felt close to the compression corner.

An interesting case emerges when the pressure fluctuations are measured at x/L = 0.86, which is in between the intermittent region and x/L = 0.66. This measurement location is notable for the effect of forcing that is not observed. The power spectrum at x/L = 0.86 with and without forcing is shown in fig 7(d). The pressure fluctuations without forcing exhibit a continuously increasing amplitude till St = 0.1. The low frequency peak that was dominant at x/L = 0.86 does not make a dominant contribution to the total fluctuations unlike the intermittent region (x/L = 0.95). Instead, the pressure fluctuations are dominated by high frequency fluctuations. The maximum power spectral density normalized by the square of the wall pressure is 3×10^{-4}. Interestingly, the power spectrum does not change with forcing. The magnitude of the fluctuations, and the trend with increasing frequency, remain the same with forcing. Thus it is seen that forcing does not seem to affect the fluctuations at x/L = 0.86 even though significant modifications were observed at surrounding locations.

The influence of forcing on the separation bubble pressure fluctuations brings up two interesting questions:

a. What is the physical mechanism that leads to the suppression of pressure fluctuations in the intermittent region and the shift of the dominant frequency to lower value at x/L = 0.66?
b. Why is the effect of forcing observed at x/L = 1 and 0.66, but not at x/L = 0.86 and 0?

These two questions will be addressed in the following paragraphs.

It was earlier pointed out that the separation shock spends about 70% of its time upstream of its unforced mean location with pulsed plasma jet injection. It is possible that the modified pressure spectrum with forcing is because of the increased average distance of the separation shock from the transducer due to the average upstream shift of the separation shock. This is illustrated in the schematic shown in figure 8. To investigate this possibility, wall pressure fluctuation measurements were obtained at several downstream locations under the SWBLI of an unforced 24° compression corner placed in the Mach 3 flow. The spatial evolution of the power spectra along the SWBLI region is shown as a contour plot in figure 9(a). The red color in the contour indicates larger amplitude at a given Strouhal number while blue indicates smaller amplitude. The dominant Strouhal number at each location was identified as the peak in the dominant broadband feature, and the spatial variation of this dominant Strouhal number is shown in figure 9(b). The plot shows that the dominant Strouhal number peaks at x/L = 0.8, which is within the intermittent region. Downstream of this location, the dominant Strouhal number decreases significantly. It is therefore quite plausible that forcing causes a shift to a lower dominant frequency at x/L=0.66 because the mean location of the separation shock is farther upstream and so the transducer is in a region of lower dominant frequency.

To understand why forcing does not seem to affect the pressure fluctuations at x/L = 0.86, it is instructive to study the organization of the separation bubble, i.e., how the pressure fluctuations inside the separation bubble are correlated with those in the intermittent region. Figure 10 shows the coherence of the wall pressure fluctuations measured at locations x/L = 0.8 and x/L = 0.6 to those at the intermittent region (x/L = 1). Coherence spectra show the linearity of two fluctuating signals as a function of frequency. A coherence of 1 signifies a linearly coupled system and values less than 1 signifies the degree of non-linearity, with a value of 0 signifying an uncoupled system. For the present case, the frequencies of interest are those of the low frequency unsteadiness of the separation shock motion (St = 0.01 – 0.03). The coherence between pressures under the intermittent region (x/L = 0.95) and x/L = 0.8 (in the relevant Strouhal number range) is about 0.05, which shows significant non-linearity between x/L = 1 and x/L = 0.8. Hence a perturbation in pressure in the intermittent region does not create a corresponding fluctuation in pressure at x/L = 0.8. This could be a reason why the power spectrum is not affected by forcing. The corresponding value of coherence between x/L=-.95 and x/L = 0.6 is about 0.3, which signifies considerably higher linearity
between the signals. Hence with forcing the separation shock motion causes pressure fluctuations, which in turn cause a corresponding fluctuation at x/L = 0.66, as seen in fig 7(b).

**Effect of forcing location**

A detailed study was made to assess the effect of location of forcing on the separation shock. Three different locations: x=10δ, 1.7δ and 0 upstream of the compression corner were tested. While the x=10δ injection case corresponds to the location upstream of the separation shock, x=1.7δ and 0 corresponds to locations inside the SWBLI interaction region. The x=10δ injection case has been presented in detail in the previous sections and will not be repeated here. For the x=1.7δ and 0 injection cases, an array of three pulsed plasma jets pitched at varying angles between -30° and 30° were employed. For these experiments the jets were not skewed.

First, the response of the separation shock to the pulsed plasma jet injected at different locations is compared using 10 kHz schlieren imaging. Figure 11 shows instantaneous images of the interaction between the separation shock with the pulsed plasma jet injected at different locations. The pitch angle of the downstream injection case is -30° (i.e., 30° counter to the upstream flow direction). The images correspond to the maximum upstream shock displacement that was observed. The corresponding mean shock location for the unforced case is also indicated by dotted line. In all the cases the pulsed plasma jet can be clearly seen in the schlieren images and its boundary is marked in the images. For the case of upstream injection, most of the jet seems to extend along the outer boundary of the separation bubble without largely penetrating into the bulk of the bubble. This observation is supported by the plasma luminosity image shown in fig. 12, where the luminous region corresponds to the pulsed plasma jet. For the case of injection from inside the separation bubble, the boundary of the pulsed plasma jet at the instant of maximum upstream separation shock motion is shown in fig. 11 (b) and (c). It can be seen that the pulsed plasma jet penetrates upstream through the bulk of the separation bubble before it is convected by the upstream flow. Thus with injection from inside the separation bubble, the pulsed plasma jet is expected to cause considerable changes inside the separation bubble, e.g., a change in the speed of sound owing to the introduction of hot gases. In order to appreciate the magnitude of the disturbance caused by the pulsed plasma jet, the peak momentum ratio of the pulsed plasma jet to the freestream was estimated to be about 0.6 in a previous study and the exit velocity of the jet is about 0.5U∞.
Figure 11 shows that upstream injection causes significant upstream displacement of the separation shock, whereas injection from inside the separation bubble causes much less separation shock movement. The same result was also observed when the pitch angle was changed from -30° to 0° (normal injection) and 30° (i.e. 30° along the upstream flow direction).

The specific case of injection located 1.7 δ from the compression corner (x/L≈0.5) was also studied by using wall pressure measurements. The pitch angle was varied between -30° to +30°. The wall pressure measurement was made inside the intermittent region at (x/L = 1) for all cases. Figure 13 shows the power spectra, normalized on mean pressure, of the wall pressure fluctuations with and without pulsed plasma jet injection, and for a jet pitch angle of -30°. The spectra of both the forced and unforced cases contain few spikes at discrete frequencies due to structural vibration and EM noise as marked in the figure. As argued for the upstream injection cases no quantitative inferences are drawn at any resonant frequencies and we are concerned with understanding the overall effect of the pulsed plasma jet injection. It can be seen that the spectra with and without injection are identical to one another but for the spikes due to EM noise. This indicates that the pulsed plasma jet injected inside the separation bubble does not cause any noticeable change to the separation shock motion. Similar results were also obtained for the case with injection at the compression ramp corner (x=0). Also similar results were obtained by varying the pitch angle of injection from -30° to 30° at both downstream injection locations (x/L = 0.5 and 0). These results clearly indicate that the injection from inside the separation bubble has negligible impact on the low frequency motion of the separation bubble. Thus we can infer that disturbances of a given amplitude, when injected from upstream of the separation shock, cause significantly larger changes in the separation shock motion than injection from within the separation bubble.

Conclusions

A kHz-frequency, high-amplitude (~ 300 m/s) synthetic jet actuator generated using pulsed plasma discharges was employed to control the separation shock unsteadiness from a 24° compression corner placed in a Mach 3 flow. The effect of actuator location was explored by placing the actuator in the upstream boundary layer and at two locations within the downstream separated flow. The first case studied was with the actuator placed in the upstream boundary layer. Time resolved schlieren imaging showed that separation shock motion could be characterized by an initial quick upstream motion when the pulsed plasma jet enters the separation shock followed by a slower recovery to its unforced mean position. By following the separation shock close to the floor it was found
that the shock motion is locked to pulsing frequency. The fluctuating wall pressure measurements showed about 50% decrease in pressure fluctuation in the intermittent region at the frequencies that corresponds to the low frequency unsteadiness of the shock motion. With upstream forcing, the effect of the forcing depended strongly on where the pressures were being measured within the interaction. Some pressure measurement locations showed considerable changes in the power spectrum with forcing, whereas some locations showed no effect of forcing. This observation is believed to be related to the organization of the separation bubble, i.e., how strongly the dynamics of different regions of the flow are coupled.

A study was also made to study the effect of injection location. It was found that the pulsed plasma jet, when injected from upstream of the separation shock, caused a significant modification to the separated flow dynamics. However, the same jet did not cause a noticeable change to the dynamics when injected from inside the separation bubble or near reattachment. The lack of effect with downstream injection location was observed for jets that were skewed by 30 degrees in the upstream and downstream directions.

References


Figure 1: Schematic diagrams of the pulsed-plasma jet actuator. (a) actuator design (b) high-voltage circuit.
Figure 2: Schematic of the compression ramp with upstream pitched and skewed pulsed plasma jet actuator array.
Figure 3: Sample time series of the pressure transducer signal (red line). The black dotted line corresponds to the discharge current waveform (scaled).
Figure 4: 10 kHz framing rate schlieren movie sequence of the separation shock motion with pulsed plasma jet actuation. Each frame is separated by 100 μs, starting from 75 μs after the start of the discharge trigger (frame (a)). Arrow (1) points to a line that indicates the mean shock position for the unforced case, and arrow (2) shows the location of the perturbed shock location.
Figure 5: Sample time series separation shock motion obtained from schlieren images. The shock location corresponds to the average location between $y = 0.5 - 0.7 \delta$. Fig. (a) represents the shock motion of the unforced case while (b) represents the shock motion with 2 kHz forcing. The mean unforced shock location is denoted by $x/\delta=0$. 
Figure 6: Probability density function of the separation shock velocity while it is being forced using a 2 kHz pulsed plasma jet placed 10δ upstream of the compression corner. The separation shock locations are calculated from the schlieren movies. Figure (a) shows the pdf of the shock velocity immediately after the pulse and (b) shows the pdf of the shock velocity during its relaxation phase.
Spikes due to structural resonance

Spikes due to EM noise

2 kHz forcing
unforced
(b)
unforced
4 kHz forcing

(c)
Figure 7: Comparison of the power spectra of the wall pressure underneath SWBLI region with and without forcing.

(a) corresponds to intermittent region $x/L \approx 0.95$, (b) $x/L = 0.66$, (c) $x/L = 0$ and (d) $x/L = 0.86$. The pulsed plasma jet is located at $10\delta$ upstream of the compression corner in all the cases.
Figure 8: Schematic illustrating average downstream shift of the transducer relative to the separation shock when the shock is forcing used pulsed plasma jets.
Figure 9: (a) Evolution of power spectra of pressure fluctuations under an unforced SWBLI region. Blue indicates small amplitude at a given frequency and red indicates large amplitude. (b) Evolution of $St_L$ with the highest amplitude obtained from fig. 9(a)
Figure 10: Coherence spectra of the wall pressure fluctuations between intermittent region and inside SWBLI region

\( \rho_{12}(St_L) \)  

\( x/L = 0.8 \)  
\( x/L = 0.6 \)

\( (x/L = 0.8 \text{ and } 0.6). \)
Figure 12: The effect of location of pulsed plasma jet injection on the separation shock motion. Arrow “1” marks the approximate boundary of the pulsed plasma jet injected. Arrow “2” shows the approximate mean location of the unforced separation shock and arrow “3” shows the separation shock forced by the pulsed plasma jet. In figure (a) the jet is injected from $10\delta$, (b) the jet is injected from $0\delta$ and (c) the jet is injected from $2\delta$ upstream of the compression corner.
Figure 12: Luminosity image of the pulsed plasma jet interacting with a 24° compression ramp. The luminosity is due to radiative transition of the excited species present in the pulsed plasma jet.
Figure 13: Power spectra at $x/L = 1$ of the wall pressure fluctuations with and without forcing using pulsed plasma jets. The jet array is placed at $2\delta$ from the compression corner (inside the separation bubble) and is pitched at $-30^\circ$ (i.e. counter to the incoming flow)