Experimental Study on the Unsteadiness of an Axisymmetric Shock-Wave/Turbulent-Boundary-Layer Interaction with Separation

G. Chandola, X. Huang, and D. Estruch-Samper

Abstract An axisymmetric shock-wave/turbulent-boundary-layer interaction (STBLI) induced by a step is studied experimentally at $M_\infty = 3.93$. A detailed discussion of the unsteady flow field developed along the upstream and downstream separation regions – ahead and behind the step – is presented in terms of the time-dependent pressure data and its spectral analysis. The separation shock exhibits low-frequency motions at a dominant frequency of 391 Hz, and evidence suggests the dominance of downstream flow effects (in the recirculation region) on the large-scale low-frequency pulsations of the separation bubble. The dominant instabilities at the inception of the shear layer are found to be two orders of magnitude higher than the shock unsteadiness and decrease progressively along the interaction as shear layer eddies grow in size.

1 Introduction

In this paper, experimental results for a shock-wave/turbulent-boundary-layer inter-action (STBLI) with separation conducted at $M_\infty = 3.93$ and $Re_\infty = 70 \times 10^6$ m^{-1} are presented. The experimental geometry has an axisymmetric configuration consisting of a forward and backward facing step and is realized by considering a disk over a cylindrical base body. The motivation behind using this configuration is to generate a large separation region which in turn produces a large shear layer, thus facilitating a detailed characterization of the disturbances inside the shear layer.

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Table 1 Test flow conditions: free stream Mach number M_∞, total pressure P_o, edge velocity U_e, edge Reynolds number Re_e, and boundary layer thickness δ_o

M_∞	P_o (kPa)	U_e (m/s)	Re_e (m^{-1})	δ_o (mm)
3.93	1543	683	61.0×10^6	3.80

2   Methodology

The measurements carried out comprise simultaneous surface pressure obtained using flush-mounted Kulite (XCQ-055 rated at 25 psi) fast-response pressure transducers complemented by high-speed schlieren imaging. To check axisymmetry of the interaction mean wall pressure, measurements using ESP pressure transducers are also obtained at a location diametrically opposed to the Kulite measurement location. The output signal from the fast-response transducers is digitized at a sampling rate of 200 kHz using a 24-bit analogue-to-digital converter unit. The flow conditions considered during the tests are listed in Table 1.

   The interaction essentially consists of two different separation zones – one ahead of the step and one behind the step (respectively, referred to as the upstream and downstream interactions from here on). Step height is $h/\delta_o = 5.9$, which results in an upstream separation region with streamwise extent of $30\delta_o$ and a downstream separation region of $10\delta_o$.

3   Results

For presentation purposes, making a distinction between the upstream and downstream interactions, different scaling is used for non-dimensionalizing the axial distance. For the upstream interaction, a non-dimensional axial distance $X_U^* = (x + L_U)/L_U$ is defined. Similarly, for the downstream interaction, $X_D^* = (x - L_s)/L_D$ is defined, where $x = 0$ is taken at the step leading edge. Here, L_U and L_D represent the mean separation and reattachment lengths, respectively, and L_s is the step thickness.

3.1   Mean Flow Description

Figure 1 shows the schlieren image of the largest interaction case. Noting that the strength of density gradient varies across the various flow features, greatest being across the separation and detached shock and relatively weaker across the expansion fans, all the flow entities are not clearly captured in the schlieren. Hence, this has been complemented with the flow schematics of the interaction to show the salient features clearly. The incoming boundary layer of thickness δ_o is deflected over the
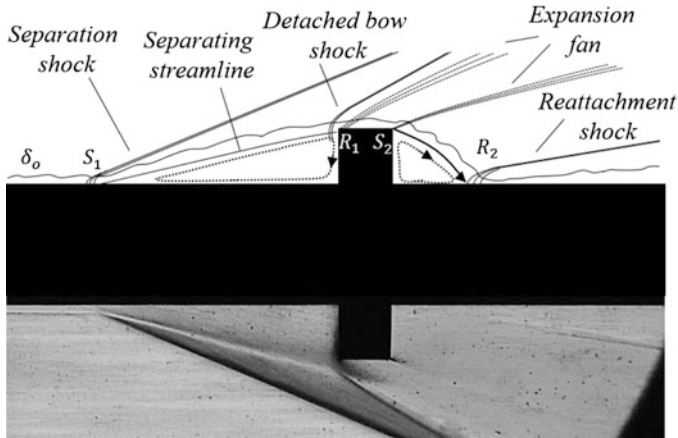
Fig. 1 Schlieren image of the STBLI induced by the $h/\delta_o = 5.9$ step alongside the interaction flow schematics

separation region at the upstream separation point (S1) by a series of compression waves which combine to form the separation shock. The line joining the separation (S1) and the reattachment point (R1), on the step leading face, is the dividing streamline and separates the recirculation region with the outer high velocity flow. Because of the large variation of fluid properties across the dividing streamline, a free shear layer develops in this region. The reattachment point on the step (R1) lies slightly below the leading sharp corner thus forming a strong detached bow shock which deflects the flow upward toward the corner. The flow is then accelerated as it crosses the expansion wave at the corner. At the trailing sharp corner, the flow separates (S2) forming another free shear layer. The flow outboard of the boundary layer is accelerated past the expansion wave at this corner. The boundary layer reattaches (R2) downstream forming a reattachment shock, and a region of reversed flow exists below the separating streamline (line joining S2 and R2). The boundary layer gradually recovers downstream of this region.

3.2 Time-Dependent Pressure

The unsteady nature of the interaction, especially that of the separation and reattachment shock, can be seen from Fig. 2 which shows the contours of instantaneous pressure plotted in the (x,t)-plane. Please note that different contour levels are used in the upstream and downstream interactions to show the respective shock unsteadiness clearly. Here $X_U^* = 0$ and $X_D^* = 1$ correspond to the mean separation (S1) and reattachment (R2) location, respectively, obtained from the local maxima in the standard deviation of pressure signals. The streamwise excursions of the separation shock are evident from the intermittent streaks of low pressure
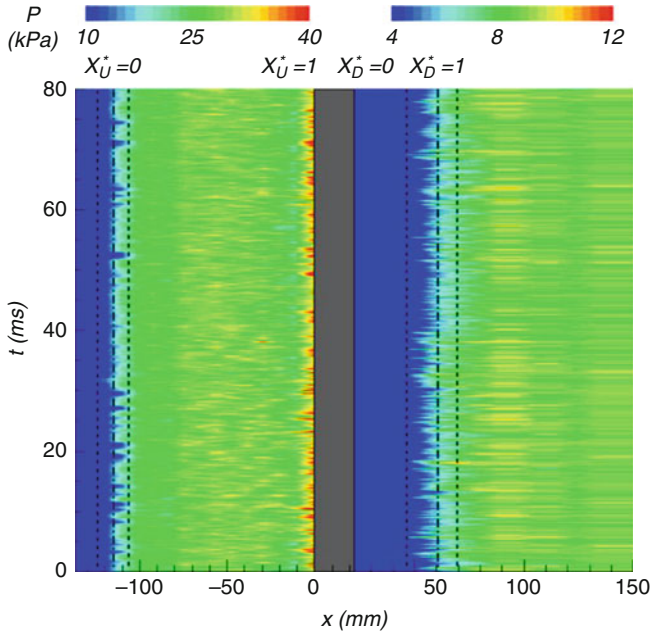
Fig. 2 Contours of instantaneous pressure plotted in the (x,t)-plane

downstream of the mean separation line (represented by the dashed-dot lines) and similarly the intermittent extension of the high-pressure streaks upstream of the mean separation line. Similar behavior is also observed in the vicinity of the reattachment point. This also gives an estimate of the intermittent length (L_i) over which the shocks oscillate, as delimited here using the dashed lines and yielding $L_i \approx 18$ mm for the separation shock (S1) and $L_i \approx 22.5$ mm for the reattachment shock (R2), as based on the wall pressure data.

In the upstream interaction, the presence of a large pressure plateau region is also evident from Fig. 2. This region extends from a location slightly downstream of the separation point all the way up to a location slightly upstream of the step. Near the step, the pressure rises again. A closer look at Fig. 2 reveals that this region also exhibits unsteadiness, with the plateau region extending all the way up to the step intermittently. This probably is related to the expansion and contraction of the separation bubble. It has been shown by previous DNS studies [1] of STBLI for a compression ramp that the structure of streamlines downstream of the separation shock can be quite different during the bubble growth and collapse phase. In our case, during bubble collapse (as the size of the interaction or bubble decreases), it is expected that the streamlines near the step will be forced to turn even more sharply. In other words, the curvature of the streamlines will increase thus resulting in increased pressure. On the other hand, during the bubble's expansion, the curvature decreases thus resulting in a slightly lower pressure rise. The validity

of this assertion is checked by taking a cross-correlation between pressure signals at separation location and next to the step. This finds a correlation coefficient of -0.5 at negative time delay, indicating that the pressure variation at the two locations is out of phase with the signal next to the step following the signal at separation location. Thus, a fall of pressure at separation location, associated with a downstream sweep of the shock, results in an increase in pressure in the vicinity of the step and vice versa. Since a downstream sweep of the shock essentially means collapsing phase of the bubble, this shows that the pressure increase in the vicinity of the step is associated with bubble collapse.

3.3 Spectral Analysis

Spectral analysis presented here mainly relies on the output of fast-response surface pressure transducers. The analysis window is chosen such that the variation of freestream properties is minimal and corresponds here to a total duration of 5.24 s (15–20.24 s from tunnel start). All spectral quantities are obtained using Welch's method considering 64 segments of 2^{14} elements each with 50% overlap combined with the Hanning window function applied to each segment. Figure 3a, b presents the premultiplied pressure power spectral density (PSD) for sensors placed in axial direction for the upstream and downstream interactions, respectively. Please note that all spectra are non-dimensionalized with respect to the spectra maxima which occurs at the location nearest to the step in the upstream interaction.

The pressure spectra at the separation location, $X_U^* = 0$, show a dominant peak at $f = 391$ Hz which is nearly three orders of magnitude lower than the expected energetic scales in the incoming boundary layer – based on a scaling U_e/δ_o (of the order of 10^5 Hz). This low frequency is associated with the unsteadiness of the separation and corresponds to a Strouhal number ($St = fL/U_e$) of 0.066, where U_e and L (interaction length) as the characteristic velocity and length scales, respectively. This is higher than the typical value of 0.03 reported in the literature for impinging shock (IS) [2] and compression corner [3] STBLIs. Downstream of this region and up to $X_U^* = 0.12$, most of the energy lies at low frequencies (<1000 Hz). However, downstream of $X_U^* = 0.16$, energy at higher frequencies (>1000 Hz) begins to increase with a broadband peak centered around 37.5 kHz (first appearing at $X_U^* = 0.20$). Further downstream, this high-frequency peak gradually shifts to lower frequencies and attains a value of 8.8 kHz in the vicinity of the step. This can be clearly seen from Fig. 3a. Pressure spectra also show the presence of another dominant peak centered around 15.4 kHz starting at $X_U^* = 0.86$. A broadband peak at low frequency is also visible which as explained in Sect. 3.2 is associated to the rise and fall of pressure linked to the expansion and contraction of the separation bubble.

A possible interpretation of this frequency evolution can be given in terms of the classical behavior of turbulent plane mixing layer in which the large coherent
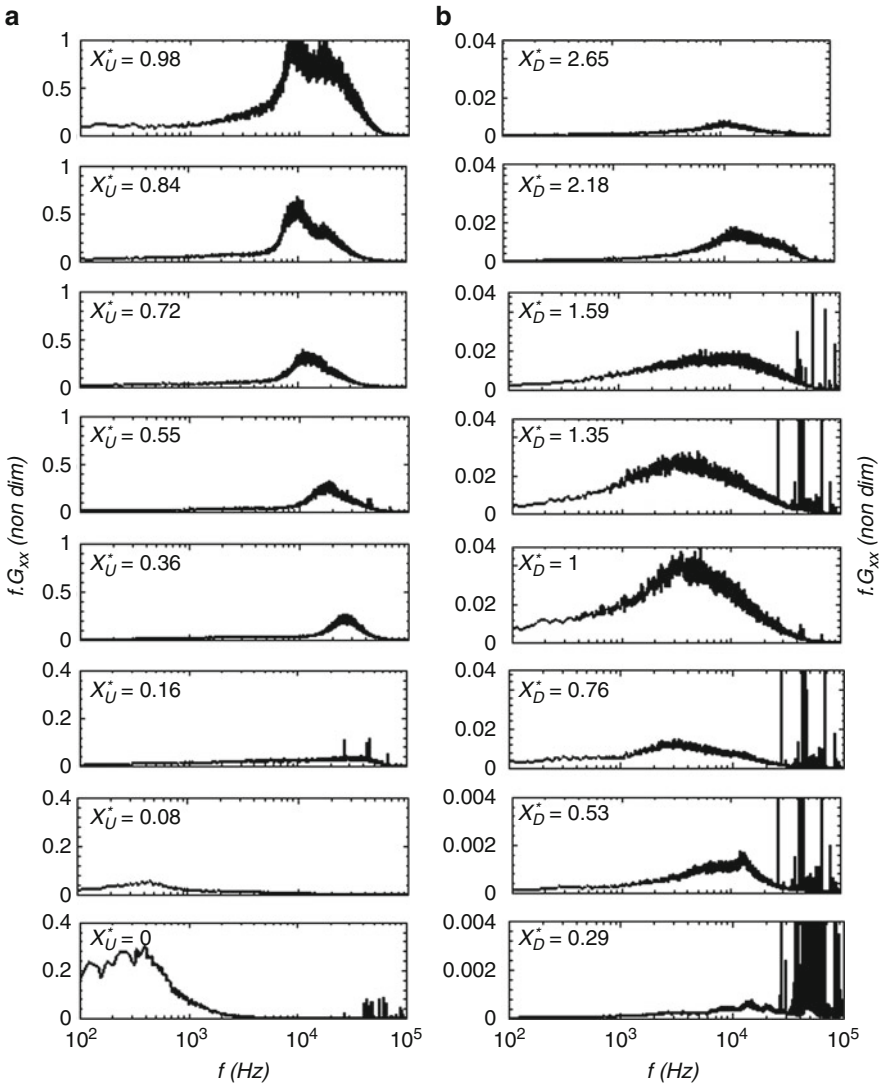
Fig. 3 Premultiplied pressure spectra at different axial locations for (**a**) upstream interaction and (**b**) downstream interaction

structures arising at the shear layer inception location then grow in size as they evolve [4], here leading to a gradual shift to lower frequencies along the interaction.

Compared to the upstream interaction, the frequency evolution in the downstream separated flow is much more complicated with multiple peaks appearing in the spectra. However, in the vicinity of the reattachment location, starting around $X_D^* = 0.65$, a single peak centered around 3.55 kHz begins to dominate, and this

trend continues up to $X_D^* = 1.59$. Downstream of the reattachment, a dominant frequency centered around 12 kHz begins to dominate. This is slightly greater than the dominant frequency of instabilities present in the upstream shear layer just ahead of the step. However it is possible that as these instabilities expand over the step leading and trailing corners, they are accelerated to these higher frequencies.

4 Conclusion

Results obtained on analyzing time-dependent data and spectral content of the wall pressure signal from the experimental study of an axisymmetric step-induced STBLI at $\mathbf{M_\infty = 3.93}$ are presented. Power spectra of the pressure signal in the vicinity of the separation shock are used for characterizing the dominant shock frequency. The phase of separation bubble "breathing" process is shown to affect the flow structure inside the separation bubble which manifests itself as a low-frequency pressure variation superimposed on the much higher frequency turbulent fluctuations in the vicinity of the step. Finally, the evolution of dominant instabilities in the upstream shear layer is obtained, which is to a large extent analogous to the classical behavior of a turbulent plane mixing layer.

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