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Analysis of shock unsteadiness in a supersonic over-expanded planar nozzle

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ABSTRACT

An experimental investigation has been conducted to study the unsteady nature of the shock structure in an over-expanded planar nozzle. The main emphasis was to investigate (i) the effect of resonance associated with laminar shock-wave/boundary-layer interactions on the unsteady characteristics of the wall pressure signals in the region of the interaction and, (ii) the change in these characteristics as the state of boundary layer undergoes transition to turbulence and a resonance free interaction. The tests were conducted in a Mach 2 planar nozzle with wall-half angle of 5.7°. For almost all the NPR for which the nozzle is tested, the boundary layer state is seen to be in the laminar/transitional range and exhibits resonance for nozzle pressure ratios less than 2.3. The resonance tones associated with the laminar interactions result in a considerable increase in the length of the intermittent region. However, as the boundary layer state goes into the transitional regime and the resonance tones disappear, the length of intermittent region is seen to decrease significantly. A decrease in this length also causes the peak standard deviation values to decrease. Further a free interaction region is observed for separated nozzle flows irrespective of the NPR of operation for resonance free interactions.

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1. Introduction

Flow separation in supersonic nozzles has been the subject of several experimental and numerical studies in the past [1–7]. Today, with the renewed interest in supersonic flights and space vehicles, the subject has become increasingly important, especially for aerospace applications. The separation inside the nozzle occurs at pressure ratios much below its design values (see Fig. 1). In such cases a separation shock formation occurs is being continuously pushed downstream with increase in the nozzle pressure ratio (NPR). As a result, the state of the boundary layer which grows downstream of the nozzle throat can change during the flow development from low to high NPR and hence, influence the nature/characteristics of the interaction [8]. Earlier studies on shock wave/boundary-layer interactions suggested that the separation shock oscillates at frequencies much lower than the characteristic frequencies of the turbulence near the shock [9,10]. However, the frequency of the shock motion was found to be sensitive to both upstream and downstream conditions or to the geometric nature of the separation [11,12]. Further the amplitude of the unsteady shock motion was generally found to increase with the increase of the shock strength ($\Delta p/p$) [13,14]. Increase in shock strength in turn causes local thickening of the boundary layer which results in the separation shock to fan out more near its foot due to the series of compression waves that begin ahead of the main fluctuating shock [13,15]. Due to the unsteady nature of the separated shock, the mean wall pressure was seen to rise some characteristic length ahead of the average shock position and hence, the region of influence was found to increase with increase in shock strength [13]. The unsteadiness of the shock motion therefore generates an intermittent pressure signal whose level fluctuates between its value in the undisturbed boundary layer and that of the disturbed flow downstream of the shock [9,16]. The spatial extent of these low-frequency large-amplitude wall pressure fluctuations was found to be strongly dependent on the shock strength [9,12,13,16–18].

Several explanations came up to describe the dynamics of shock separation and explain the physical mechanisms driving its motion. For instance, Smits and Dussauge [19] suggested that the flow over the separated zone is sensitive to the compression effects and imposes unsteady conditions on the shock that makes it oscillating. Maull [20] on the other hand suggested that the flow unsteadiness in separated flows is caused by mass imbalance of the reversal flow at the reattachment point to that scavenged from the separation point and is responsible for the "breathing" motion of the separation bubble. The model of mass-exchange reported by Charwat et al. [21] seems to produce more accurate semi-empirical correlations of measurements in separated flows. Significant flow

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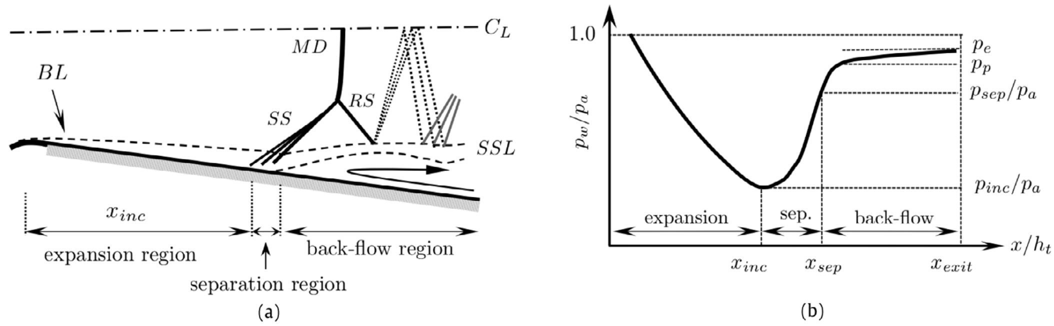

Fig. 1. Schematic representation of nozzle flow separation showing (a) the flow features of an over-expanded planar nozzle and, (b) the associated wall pressure distributions. *MD*: Mach disk, *SS*: separation shock, *RS*: reflected shock, *SSL*: Separated shear layer, *BL*: boundary layer.

unsteadiness has also been reported in separated nozzle flows in the past that is associated with side-load generation [22,23]. A detailed investigation by Verma [23] on large area-ratio thrust optimized (TOP) suggests the generation of flow unsteadiness in free shock separation (FSS) conditions to be the back-flow region that is set into pressure pulsations due to the proximity of the turbulent shear layer, emanating from the separation point, to the nozzle wall. This in turn affects the intermittency in the separation region caused by the reversed flow at the location of physical separation and is a strong function of the radial size of the re-circulation zone ($A_e - A_{sep}$), where A_e and A_{sep} are areas of nozzle exit and separation location, respectively.

In the past, asymmetric separated flow conditions have also been reported especially inside low-wall angled planar nozzles. For instance, Papamoschou et al. [24] and Johnson et al. [25] have shown that for $A_e/A_t > 1.4$, (with A_t the area at the nozzle throat) the separation inside the nozzle occurs asymmetrically with one lambda foot larger than the other. They also observed that the shock asymmetry was sensitive to the start-up conditions and could flip if the run was stopped and restarted. They attributed the flow asymmetry as a manifestation of "Coanda effect". Asymmetric flow conditions were also observed in the experimental studies of Hunter [26], Reijasse et al. [27] and Verma and Manisankar [28]. Hunter [26] however did not attribute the asymmetry to sensitivity in start-up conditions but to the natural tendency of an over-expanded nozzle flow to detach and reach a more efficient thermodynamic balance. Reijasse et al. [27] observed that the introduction of wall roughness on one side (near the nozzle throat) introduced flow symmetry towards that side and modified the shock patterns and the associated separation zones significantly. Also, the presence of a moveable secondary throat in their experiments placed on one side of the nozzle (the top part) to control the back pressure may have a strong influence on the asymmetry of the separation. Although the shocks were observed to exhibit significant unsteadiness, there was no evidence of resonant tones. The apparent lack of acoustic feedback indicates that the shock motion is perhaps caused by the shear-layer instability and not vice-versa. Aeroacoustic resonance in low half-angled nozzles ($<10°$) was also studied by Zaman et al. [29] who associated it to the unsteadiness of the shock system. They showed that these frequency tones scaled well with the distance from the shock foot to the nozzle exit and depend on the state of the boundary layers at separation, and possibly on the nozzle cross-sectional shape. Tripping the boundary layer was observed to suppress these tones. Verma and Manisankar [28] recently reported that both the state of the boundary layer and the nozzle wall angle play a major role in initiating flow asymmetry in such flows. They showed that as the wall angle is increased, keeping area-ratio constant, although the state of the boundary-layer remains similar, flow asymmetry could be avoided. Their lowest nozzle wall angle of 5.7° always showed a restricted shock separation (RSS) on the lower wall (with a free shock separation on the upper wall) irrespective of multiple runs and restarts. The transition from RSS to FSS on the lower wall occurred once the reattachment location is pushed towards the nozzle exit causing the separation bubble to open. This leads the separation location to jump upstream resulting in flow symmetry. On the other hand, for an intermediate wall angle of 7.5°, the asymmetry was seen to switch from lower to upper wall and vice-versa for NPR=1.8 after which the flow preferred either RSS on upper or lower wall. However, for the highest angle of 10.5° tested, flow asymmetry was observed to be almost absent. These results clearly support the idea that the flow separation characteristics are sensitive to both upstream and downstream conditions. The present tests were conducted using a Mach 2 planar nozzle (area-ratio 1.79) of wall angle of 5.7° tested earlier by Verma and Manisankar [28]. The study is aimed at investigating the unsteady characteristics of the shock motion and the length of the intermittent region for a resonance associated laminar shock-wave/boundary-layer interaction (SWBLI). The major part of the study involves statistical analysis of the unsteady nature of the shock motion captured using an array of fast piezo-resistive pressure transducers both on the top and on the bottom walls of the nozzle.

The objective of the present work is (i) to investigate the effect of resonance associated with laminar SWBLI on the unsteady characteristics of the wall-pressure signal in the region of separation and the length of the intermittent region and, (ii) how these characteristics change as the state of boundary layer undergoes transition to turbulence and the resonance disappears. These aspects of the flow have not been reported before in separated nozzle flows and forms the main focus of the present study.

The paper is organized as follows. A brief description of the experimental setup together with Signal conditioning and data acquisition system is presented in Section 2. Statistical analysis of the flow separation and the intermittent region is presented and discussed in Section 3. Unsteadiness of the shock motion are also investigated. Finally, the main conclusions are drawn in Section 4.

2. Experimental setup

2.1. Wind tunnel facility and model details

Experiments were conducted in the 0.55 m base flow facility at the Experimental Aerodynamics Division (EAD) in the National Aerospace Laboratories (NAL) of Bangalore which comprises of a co-flow arrangement wherein the inner pipe supplies pressure for simulation of jet-flow exhausting from a nozzle and the outer-flow helps to simulate the desired freestream conditions [30]. For the present tests, the test nozzle assembly was mounted on the inner jet pipe while the outer section of the wind-tunnel was kept open so that the nozzle exhaust flow was exiting into the sea-level conditions. In order to make a planar flow, a transition in the jet pipe from circular to square configuration was made as shown

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