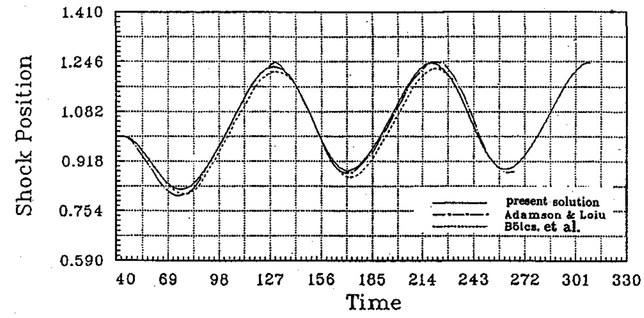

Fig. 5 Comparison of the computed shock oscillation with the results of Adamson and Liou[5] and of Bölcs et al.[6]

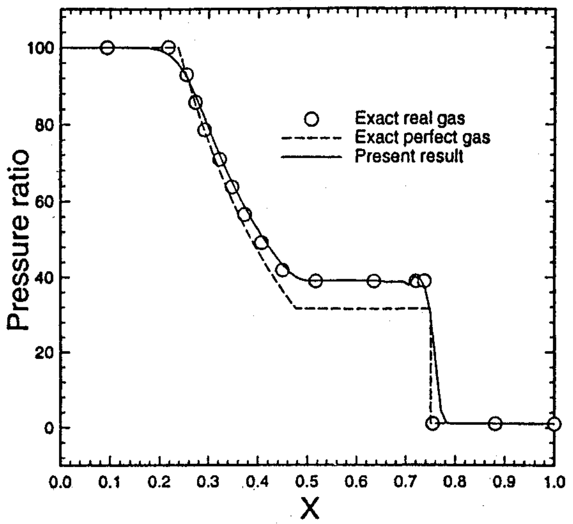

Fig. 6 Comparison of the computed pressure distribution of a shock tube with an initial pressure ratio of 100:1 with other data.

$p_0 = 1$ atm, $\rho_0 = 1.174$ kg/m^3, $e_0 = 51.33$ kcal/kg, and $T_0 = 300$ K, where subscript 1 denotes the high-pressure side and 0 the low-pressure side. The diaphragm is located at $x = 0.5$. A uniform grid with 300×5 cells on the computational domain, $-0.82 < x < 2.45$ and $0 < y < 0.0505$, is chosen. The CFL number is set to be 1.3. It was found that the solution obtained is independent of y. Figure 6 shows the computed pressure ratio distribution when the normal shock moves to the location of $x = 0.75$ and is compared with other solutions. Note that the pressure has been normalized by the initial low-pressure side condition. It is found that the perfect gas solution greatly deviates from the real gas solutions and the present solution agrees well with the analytic real gas solution.[7] The suggested flux limiter was also used to solve the two-dimensional problem of shock focusing over concave, circular, and parabolic reflectors. A satisfactory result was obtained but is omitted here for brevity.[8]

In summary, an improved flux limiter was found that is more efficient than the other two flux limiters for obtaining steady-state solution of the Euler equations and is robust for unsteady flow calculations based on the preceding tested problems.

Acknowledgment

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Reduction of Fluctuating Pressure Loads in Shock/Boundary-Layer Interactions Using Vortex Generators: Part 2

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Introduction

THE renewed interest in hypersonic vehicles using air-breathing propulsion systems has led to a need for methods to reduce the fluctuating pressure loads resulting from the naturally occurring unsteadiness in shock wave/turbulent boundary-layer interactions (SWTBLIs). For Mach 5 flight at 50,000 ft, these loads can be 185 dB or higher[1] with much of the wall pressure fluctuation energy contained in the structural resonant frequency band. As a result of the magnitude and the frequency content of these loads, the structural fatigue life can be significantly reduced. Pozefsky et al.[2] reported that when metal matrix composite structures like those being considered for use on hypersonic vehicles are exposed to these loads, their fatigue life is reduced from 1000 h to less than 1 min.

Barter and Dolling[3] have previously shown that Wheeler[4] doublet vortex generators (VGs) can be used to reduce the fluctuating pressure loads in an unswept compression corner induced SWTBLI. These VGs are effective in reducing the loads because they energize the boundary layer thereby decreasing the scale of the interaction. Furthermore, they increase the magnitude of the turbulent fluctuations in the boundary layer thereby increasing separation shock jitter, which causes the wall pressure fluctuations associated with separation shock motion to shift to a higher frequency band. The purpose of the work described in this Technical Note was to explore the effectiveness of the VGs in other flowfields. The results show that these VGs reduce the loads under moderately swept compression corner induced interactions but have no effect on the loads under unswept blunt fin induced interactions. These results are consistent with the current understanding of the effects of the VGs on the undisturbed turbulent boundary layer and the sensitivity of the interactions to changes in the incoming boundary layer. Interactions which are sensitive to the incoming boundary-layer properties are favorably influenced by the VGs; however, interactions that are insensitive to changes in the incoming boundary layer are essentially unaffected by the VGs.

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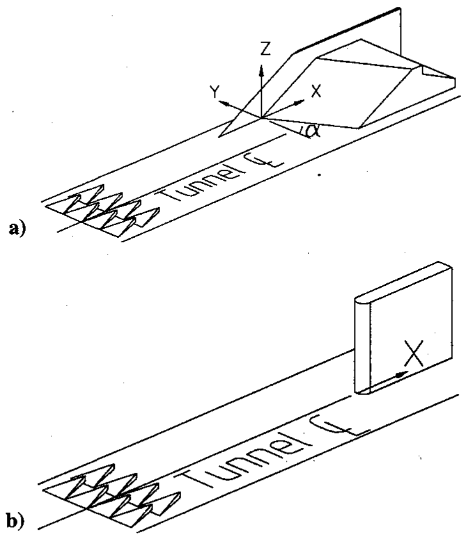

Fig. 1 Models: a) 30-deg swept corner and b) hemicylindrically blunted fin.

Experimental Program

The experiments discussed herein were conducted in the Mach-5 blowdown wind tunnel at the University of Texas at Austin. The experimental facility, measurement techniques, and VGs are identical to those discussed by Barter and Dolling.[3,5] The swept interaction was generated by a 30-deg swept compression corner with a 28-deg streamwise angle as shown in Fig. 1a. This model is 2.63 boundary-layer thicknesses (δ) high and 5.59δ wide and had a 0.12δ thick, beveled fence attached at its apex. The fence extended 0.99δ above and 3.95δ upstream of the model. The blunt fin interaction was generated by a 0.75 in. diameter (d), 5.33d high, unswept, hemicylindrically blunted fin shown in Fig. 1b. For consistency with the earlier unswept compression corner experiments, the VGs were arranged symmetrically about the tunnel centerline and were placed 15.8δ upstream of the models as measured from the center of the swept corner leading edge and from the leading edge of the blunt fin. Barter and Dolling[3] discuss the effect of the VGs on the incoming boundary layer when placed in this arrangement.

Fluctuating pressure measurements were made with Kulite XCQ-062 series absolute pressure transducers. When installed flush with the tunnel floor, these transducers have a frequency response of about 50 kHz, which is more than adequate to capture the wall pressure fluctuations due to separation shock motion. For measurements upstream of the swept corner, the transducers were placed in a row normal to the corner leading edge, and for measurements upstream of the blunt fin, the transducers were in a streamwise row along the tunnel centerline which was coincident with the blunt fin model centerline.

Discussion of Results

Swept compression ramp flows are either cylindrically or conically symmetric. Cylindrically symmetric means that beyond the inception region near the corner apex the upstream influence, separation, and reattachment lines are parallel to each other. Conically symmetric means that beyond the inception region these same lines radiate conically from a virtual conical origin located upstream and outboard of the corner apex. Settles and Teng[6] provide a detailed discussion of these features. Since the undisturbed 30-deg swept compression corner interaction has been shown to be conically symmetric,[7] the interaction properties, shown in Fig. 2, have been plotted in the conical reference frame, α (see Fig. 1a), with respect to the virtual conical origin of the undisturbed interaction. Flow visualization of the disturbed interaction (not shown) shows that unlike the unswept compression corner interaction the separation line is essentially straight with negligible variations due to the three dimensionality of the incoming boundary layer. For the undisturbed 30-deg swept corner interaction, the maximum normalized wall pressure rms $(\sigma_{pw}/P_\infty)_{max}$ is 0.38, and the maximum fraction of wall pressure fluctuation energy contained in the structural resonant frequency band (100–500 Hz), β_{max}, is 0.25. Based on repeated measurements, the uncertainties of σ_{pw}/P_∞ and β are estimated to be 4% and 7%, respectively.

Table 1 Summary of the effect of the VGs on the loads under the intermittent region

Sweepback angle, deg	σ_{pw}/P_∞ reduction, %	β reduction, %
0	23	11
20	43	12
30	45	24

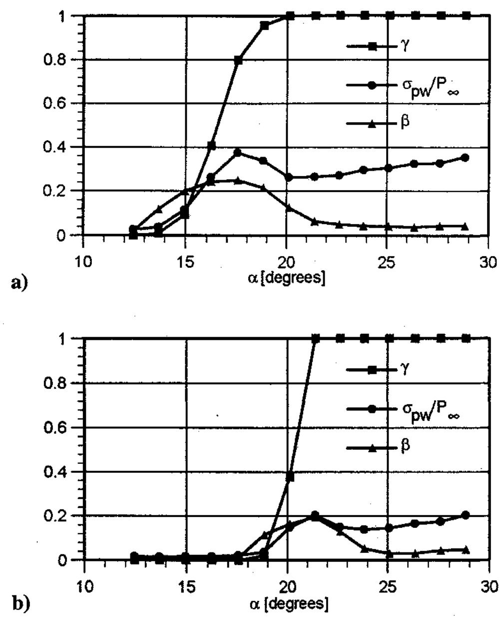

Fig. 2 Intermittency, wall pressure rms, and β distributions upstream of the 30-deg swept corner: a) undisturbed interaction and b) disturbed interaction.

By comparing Figs. 2a and 2b, it can be seen that the intermittent region (i.e., the region of separation shock motion) is shifted downstream, and its length is significantly reduced when the VGs are placed upstream of the interaction. The intermittent region length is defined as the distance from where the intermittency (i.e., the fraction of time the separation shock is upstream of a given point), γ, is 0.01 to where $\gamma = 0.99$. Based on repeated measurements, the experimental uncertainty of γ is 5%. It is impossible to accurately quantify the reduction in the intermittent region length as the intermittent region of the disturbed interaction is too small to accurately resolve; however, the reduction is conservatively estimated to be 50%. Placement of the VGs upstream of the swept corner also reduces the magnitude of the fluctuating pressure loads and shifts their frequency content to a higher band. The maximum wall pressure rms is reduced by 45%, and maximum β is reduced by 24%.

The results for the 30-deg swept corner are similar to those obtained upstream of a 20-deg swept corner; namely, the fluctuating pressure loads and the intermittent region length are reduced. In addition, unlike what was observed for the 30-deg swept interaction, the VGs also reduce the scale of the separated flow. For the undisturbed 20-deg swept interaction, the maximum σ_{pw}/P_∞ is 0.42 and the maximum β is 0.26. With the VGs upstream, the maximum wall pressure rms is reduced by 43% and the maximum β is reduced by 12%. By comparison, Barter and Dolling[3] report that placement of the VGs upstream of a 28-deg unswept compression corner interaction causes a 23% reduction in the maximum wall pressure rms and an 11% reduction in the maximum β. A summary of the effects of the VGs on the maximum loads and the maximum fraction of energy in the structural resonant frequency band for unswept and swept compression corner interactions is given in Table 1. It can be seen that as the sweepback angle increases, the VGs become more effective in reducing the loads under the intermittent region of the interaction.

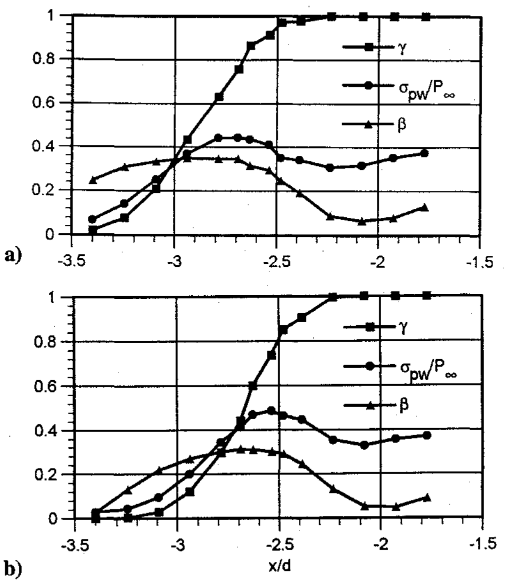

Fig. 3 Intermittency, wall pressure rms, and β distributions upstream of the blunt fin: a) undisturbed interaction and b) disturbed interaction.

The effects of the VGs on the scale of swept interactions are consistent with the current understanding of swept compression corner interactions and the effect of the VGs on the boundary layer. Undisturbed 20-deg swept corner interactions have been shown to be cylindrically symmetric, and the size of the interaction scales with the incoming boundary-layer thickness. Undisturbed 30-deg swept compression corner interactions, however, have been shown to be conically symmetric because the scale of the separated flow is driven by the size of the root vortex, not the incoming boundary layer thickness. The intermittent region length and the scale of the separated flow for the 20-deg swept interaction are reduced by the presence of the VGs upstream (due to the fuller velocity profile), which is consistent with the cylindrically symmetric nature of the interaction. The fuller velocity profile of the VG disturbed boundary-layer, however, causes the size of the intermittent region in the 30-deg swept corner interactions to be reduced but essentially does not change the scale of the separated flow which is consistent with conically symmetric interactions.

Results of the measurements upstream of the blunt fin, shown in Fig. 3, reveal that the VGs have essentially no effect on the loads under the intermittent region of the interaction. The location and scale of the intermittent region is essentially unchanged. Under the intermittent region, the undisturbed interaction has a maximum wall pressure rms (normalized by P_∞) of 0.45 and a maximum β of 0.35. With the VGs upstream, the maximum wall pressure rms increases by 9%, and the maximum β is reduced by 11%.

The effect of the VGs on the scale of unswept blunt fin interactions is consistent with current understanding of these interactions. Unswept blunt fin interactions primarily scale on the fin thickness and are relatively insensitive to changes in the incoming boundary-layer thickness. The present results show that the intermittent region scale and the scale of the separated flow are essentially unaffected by the presence of the VGs upstream.

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Impact of Tab Location Relative to the Nozzle Exit on Jet Distortion

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Introduction

SEVERAL investigations have been conducted recently on the effect of tabs, which are small protrusions into the flow exiting a jet nozzle, on the subsequent evolution and mixing of free jets.[1–4] These studies are motivated by the technological need to increase mixing and reduce noise, especially in high-speed jets. Although most earlier studies dealt primarily with tabs placed right at the nozzle exit, the effect of the streamwise location of the tab relative to the nozzle exit is examined in the present investigation.

Cursory observations during the course of the present study revealed that the flowfield distortion produced by the tab changed drastically if the location of a tab was slightly varied relative to the nozzle exit. The difference in the effect due to the tab location was found to be particularly pronounced for underexpanded supersonic jets. These effects were studied systematically and are summarized in the following.

Experimental Setup

The experiments were performed at the NASA Lewis Research Center using a small jet facility.[2,3] The nozzle consisted of an axisymmetric contoured convergent section and a straight attachment for most of the experiments ($D = 1.27$ cm). For ease of fabrication and assembly, cylindrical tabs were used. Holes were drilled through walls of the straight attachment so that the tabs with a diameter $t = D/8$ could be inserted at desired upstream locations. Figure 1 shows a sketch of the nozzle with such a tab in place. A retainer disk was used to place the tabs downstream of the nozzle exit. The penetration height of each tab was kept at approximately $0.17D$.

Flow visualization using laser sheet lighting was performed for supersonic jets using natural moisture condensation as a source for Mie scattering.[2] Pitot pressure measurements were performed with a 0.76-mm probe and an automated traversing mechanism. Static wall pressure distributions were obtained for limited cases.

Results

The effect of the tab location for an underexpanded supersonic jet is illustrated in Fig. 2. The data are for a fully expanded Mach number (M_j) of 1.63, based on the pressure ratio. The left column shows flow visualization pictures; the undisturbed jet in Fig. 2a may be compared with cases where the tab is located at $x/t = -1.5, 0.5$, and 1.5 in Figs. 2b–2d, respectively. Here x denotes the distance of

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