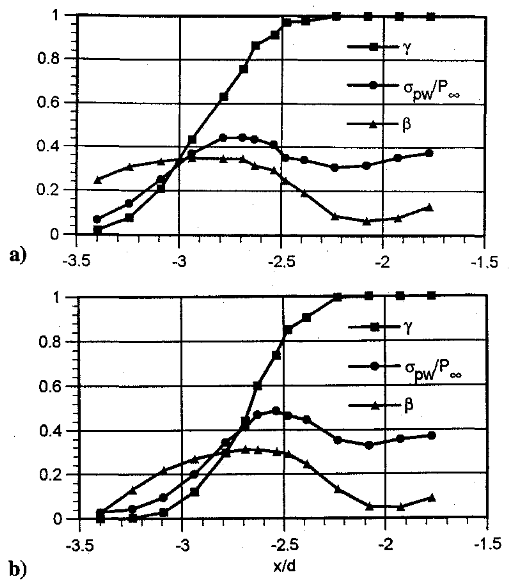

Fig. 3 Intermittency, wall pressure rms, and β distributions upstream of the blunt fin: a) undisturbed interaction and b) disturbed interaction.

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

Presented as Paper 94-3385 at the AIAA/ASME/SAE/ASEE 30th Joint Propulsion Conference, Indianapolis, IN, June 27–29, 1994; received April 6, 1995; revision received Aug. 30, 1995; accepted for publication Sept. 15, 1995.

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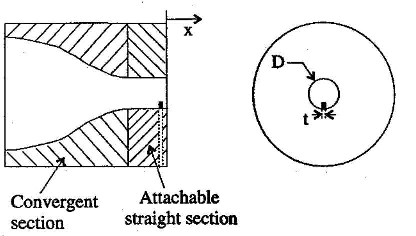

Fig. 1 Side and front views of the nozzle. A cylindrical tab with diameter $t = D/8$ is shown at $x/t = -1.5$.

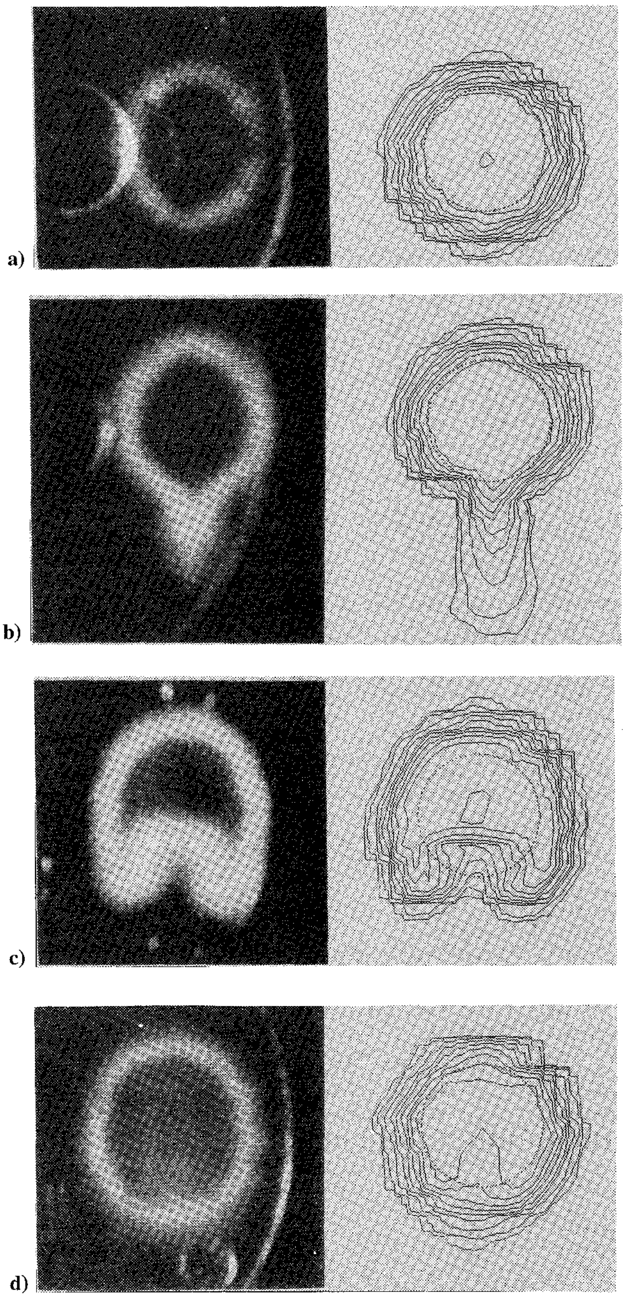

Fig. 2 Effect of tab location for $M_j = 1.63$ is shown by flow visualization (left) and pressure contours (right) for a) no tab; b) a tab at $x/t = -1.5$; c) a tab at $x/t = 0.5$; and d) a tab at $x/t = 1.5$. Data are for $x/D = 2$.

the tab axis from the nozzle exit. In other words, the $x/t = 0.5$ configuration represents the case where a cylindrical tab was pressed against the exit surface of the nozzle. The jet distortion patterns observed in the flow visualization are confirmed by the pitot pressure contours shown in the right column of Fig. 2. The contour levels are plotted for p_t/p_a of 1.01, 1.03, 1.10, 1.21, 1.35, 1.56, 1.83, 2.25, and 2.94; p_t represents the pressure as measured by the pitot tube, accurate to ±0.01 psi, and p_a is the ambient pressure. The three highest levels, which occur in the core of the underexpanded jet, should be considered qualitative because of possible probe interference. However, the mixing layer region should be well represented. The outline of the nozzle is shown by the dashed lines in all of the contour plots. The case where the tab is located upstream of the nozzle exit, in Fig. 2b, is striking in that the jet ejects flow outward directly downstream of the tab. The effect of a tab placed at the nozzle exit was previously observed to produce an inward ingestion of fluid.[1–3] This is confirmed by the results shown in Fig. 2c. Also confirmed, in Fig. 2d, is the prior observation that the tab effect practically vanishes when a gap exists between the nozzle exit and the tab.[3] The dramatic ejection of core fluid in Fig. 2b was seen only for underexpanded jets and was not observed in subsonic flows (see Ref. 6 for corresponding data at $M_j = 0.5$).

The location of the tab with respect to the nozzle exit not only impacted the flowfield distortion but also the effect on jet noise. The noise field of an imperfectly expanded supersonic jet is dominated by a narrow frequency band, often referred to as screech. Far-field noise spectra were gathered for the same tab locations examined in Fig. 2. Consistent with earlier findings,[2,5] tabs placed against the nozzle face ($x/t = 0.5$) completely eliminated the screech. The tabs placed with a gap, for which the flowfield remained practically unaffected, had virtually no impact on the screech. Interestingly, for the $x/t = -1.5$ tab location, the screech tone also remained basically unaffected. Details of the noise data can be found in Refs. 6 and 7. The effect on the noise field could not be satisfactorily explained at this time; however, the observed distortions of the flowfield could be explained as elaborated in the discussion section.

It should be mentioned here that several variations of the experiments with underexpanded ($M_j = 1.63$) jets were conducted to obtain insight into the flow mechanisms. Flow visualizations of cases with tab locations of $x/t = -3$ and -5 showed an ejection, although for $x/t = -14$ the overall effect of the tab had diminished greatly. Also investigated was a case where the tab was placed halfway inside the nozzle; i.e., the axis of the tab was aligned with the exit plane. In that instance, both an ejection and an inward ingestion were identified but neither were prominent. Visualizations of jets issuing from a convergent-divergent (Mach 1.36 design) nozzle showed a similar ejection for the $x/t = -1.5$ case, as long as the flow was underexpanded. In another series of tests for the nozzle shown in Fig. 1, the tab was replaced by an injecting secondary jet. The overall effect of the injecting jet was similar to that which would be caused by a tab displaced slightly downstream.[6,7]

Discussion

Streamwise vortices originating from the pressure gradients created by a tab are thought to be responsible for both the ingestion and the ejection effect. The analysis presented by Zaman et al.[3] regarding the generation mechanism of the streamwise vortices may be extended to explain the flowfield distortions observed in the present experiment. The characteristic flow distortions produced by a tab at the nozzle exit were demonstrated to be due to a pair of streamwise vortices having a sense of rotation such that ambient fluid was ingested into the core of the jet. The mechanism producing these vortices could be described on the basis of azimuthal pressure gradients. The stagnation of the flow caused by the tab created a high-pressure region directly upstream of the tab. This "pressure hill" was primarily responsible for generating the counter-rotating streamwise vortex pair. The observations made in the present study can be reconciled from this viewpoint.

Static pressures were measured both upstream and downstream of a tab located inside the nozzle. For these measurements a single line of pressure taps at $x/t = -1.5$ was utilized. A tab was placed at $x/t = -1.0$ for the upstream data and at $x/t = -2.7$ for the downstream data. For both tab locations, the ejection effect was observed for the supersonic condition. Figure 3 shows the measured azimuthal pressure variations. As expected, a pressure hill forms upstream of the tab; however, a more significant "pressure valley" forms just downstream in the wake of the tab. The absolute magnitude of this pressure valley is approximately two times greater than that of the hill. It is apparent that the tab affects the shock-expansion structure near the nozzle exit such that ambient pressure is impressed only in

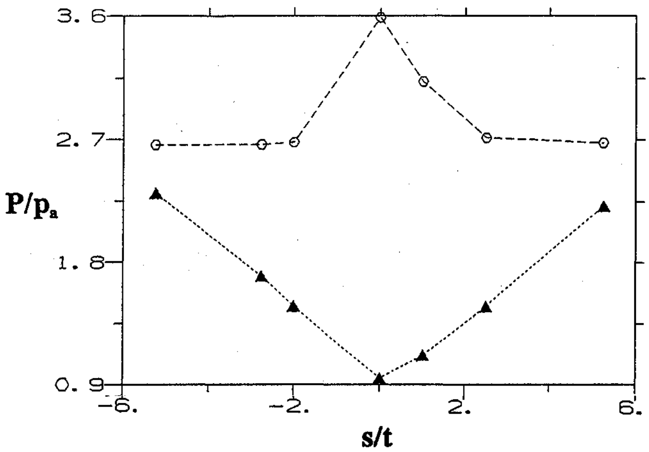

Fig. 3 Azimuthal distribution of static pressure at $x/t = -1.5$, upstream (- - -) and downstream (· · ·) of a cylindrical tab, for an underexpanded jet, $M_j = 1.63$; s denotes azimuthal distance from the tab.

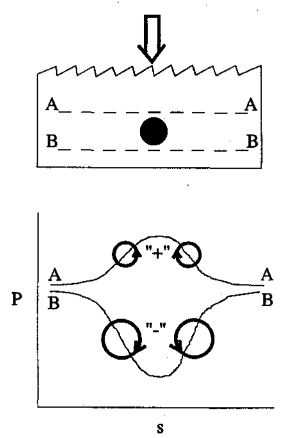

Fig. 4 Sketch of the pressure distributions of Fig. 3 and the sign of each vortex pair generated by the pressure gradients.

the vicinity of the tab wake. Away from the tab the elevated pressure characteristic of underexpanded flows is maintained, resulting in the steep valley. Note that the lowest pressure reading (at $s/t = 0$) within the valley is below that of the ambient, presumably due to streamline curvature.

In the case of a tab at the nozzle exit, there exists only an upstream pressure hill over the nozzle surface that produces a counter-rotating streamwise vortex pair, with a "sign" denoted positive, that ingests ambient fluid. When the tab is located upstream of the nozzle exit, the pressure valley must generate a streamwise vortex pair with an opposite or negative sense. This premise is sketched in Fig. 4 along with the denoted sign of the vortex pairs corresponding to the tab shown in Fig. 1. Since the amplitude of the valley is large for the underexpanded case, the vortex pair with the negative sense is expected to dominate. This vortex pair results in the observed ejection of core fluid and provides a rationale for the new observations of the flowfield distortions. As discussed in Ref. 6, there exists a corresponding pressure valley for subsonic conditions due to streamline curvature. However, in that case the magnitude of the valley is much smaller than that of the upstream hill, which explains why the ejection was not observed at the subsonic condition.

Conclusions

As part of an effort to increase mixing and reduce noise, the effect of tabs on the evolution of free jets was further investigated. A striking contrast in the resultant flowfield of underexpanded jets has been shown when the streamwise location of a tab is varied. Although a tab located at the nozzle exit produces a dramatic ingestion of ambient fluid, a tab located slightly upstream of the nozzle exit causes an ejection of core fluid at the same azimuthal position. The measured static pressure field around the tab suggests that the pair of streamwise vortices produced in the two cases are of opposite signs, explaining the opposite effects. In regard to the noise field generated by underexpanded jets, while screech was eliminated when a tab was located at the nozzle exit, a tab inserted inside the nozzle had little effect on the screech.

Acknowledgment

We gratefully acknowledge Mo Samimy of the Ohio State University for valuable input throughout the study.

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Flow Oscillation over an Airfoil Near Stall

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Introduction

IN a study of acoustic excitation of the flow over a low-Reynolds-number airfoil Zaman et al.[1] encountered a low-frequency flow oscillation. The study was conducted on an LRN (1)-1007 airfoil at Reynolds numbers between 4×10^4 and 1.4×10^5, and the Strouhal number was approximately 0.02. Here Strouhal number is defined as $fc \sin \alpha / U$ where f is the frequency of the flow oscillation, c the airfoil chord, α the angle of attack, and U the freestream velocity. A detailed study of the phenomenon was later conducted by Zaman et al.[2] The experimental and computational study confirmed that the phenomenon was fluid dynamic in origin, not due to any peculiarity of the facility, and involved a quasiperiodic switching between stalled and unstalled conditions. The corresponding force oscillations were extremely large with C_l fluctuations at $\alpha = 15$ deg of approximately 50% of the mean C_l. The computational study, using a thin-layer Navier–Stokes code with the Baldwin–Lomax turbulence model, produced the flow oscillation when transition was placed near the leading edge.

Received July 2, 1994; revision received March 29, 1995; accepted for publication April 20, 1995.

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