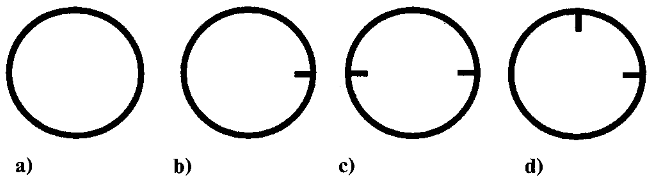

Fig. 2 View of jet nozzle looking upstream showing locations of disturbance generators, cases 1, 2, 3, and 4.

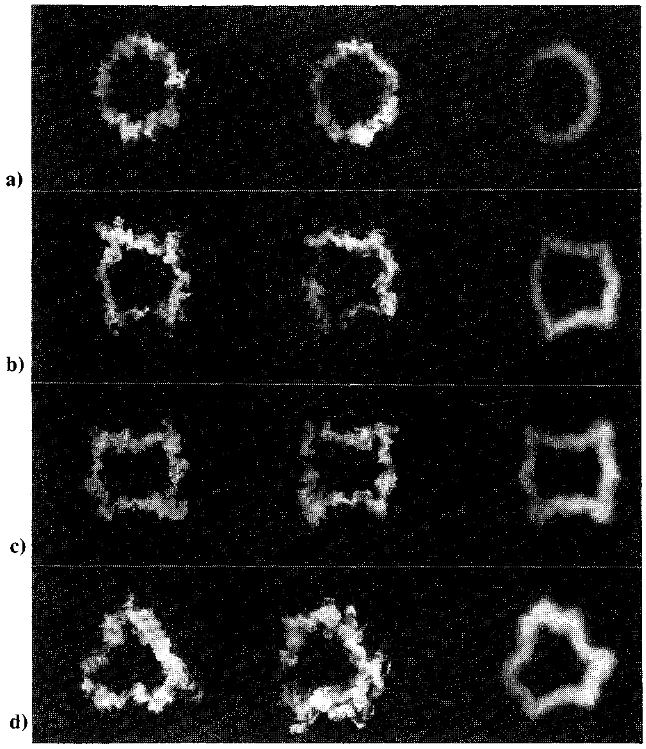

Fig. 3 Upstream views: a) case 1, no disturbances; b) case 2, one disturbance; c) case 3, two symmetric disturbances; and d) case 4, two nonsymmetric disturbances. The first two pictures on the left-hand-side correspond to instantaneous views of the shear layer, and the third picture corresponds to an average.

turbances were also at different upstream locations, there is an additional lack of symmetry of the jet as can be seen by careful examination of the ensemble average. We conclude from these results that azimuthal location as well as axial location are variables that control the final jet appearance.

These results suggest that single point disturbances launched from within the supersonic nozzle are indeed able to produce significant changes to the jet shear layer; the present results appear consistent with the earlier findings[7] for the two-dimensional supersonic mixing layer. These results also appear similar to the larger body of work on jet tabs and the more recent work on delta-tabs.[6] However, a notable difference between the delta-tab work and the present is that the delta-tab is applied externally to the jet lip and also appears to maintain its effectiveness in subsonic jet flows. The present approach relies upon the wave nature of supersonic flows both to create and to propagate the disturbance, and so is not expected to be active in subsonic flows. Finally, we note that although mechanical disturbance generators (rods) were used in the present study, we believe that the same effect can be obtained by the use of fluid-mechanical disturbances such as a jet in a crossflow. Such an approach would also lead to possibilities of active control.

Conclusions

We report here some preliminary results on the use of point disturbances on supersonic jet development. The disturbance generators are located on the supersonic nozzle wall between the throat and the jet exit plane; the resulting fluid mechanical disturbances are felt at the intersection of the disturbance cone and the jet lip. It is shown that a single disturbance generator leads to a polygonal jet appearance; two symmetric disturbances lead to a symmetric, rectangular jet shape; and two nonsymmetric disturbances lead to a star-like appearance; in all cases significant cusps are formed. It would appear from these results that it is possible to contour the jet shape via the number and location (axial and azimuthal) of disturbances. Further investigations of these and related phenomena such as jet noise, mixing efficiency, and thrust loss appear warranted.

Acknowledgment

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Low-Frequency Flow Oscillation over Airfoils near Stall

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Introduction

IT is well known that airfoils, at angles of attack well beyond stall, and bluff bodies experience flow oscillation at the nondimensional shedding frequency or Strouhal number St of approximately 0.20. However, many airfoils also exhibit a low-frequency flow oscillation at or near stall where St=0.02. This Note briefly reviews what is known about this flow phenomenon and presents new measurements at higher Reynolds numbers. In a study of

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acoustic excitation of the flow over a low Reynolds number airfoil, Zaman et al.[1] encountered a low-frequency flow oscillation. These tests were conducted on a LRN(1)-1007 airfoil at Reynolds numbers between 4×10^4 and 1.4×10^5. Here the Strouhal number, based on airfoil projected height and freestream velocity $St=fc\sin\alpha/U$ was 0.02. This oscillation occurred at an angle of attack of 15 deg and could be suppressed by high-frequency acoustic excitation of the flow. A review of the literature revealed that, although no detailed study of this flow oscillation could be found, similar low-frequency oscillations had been reported on a few occasions by other researchers.

Jones[2] reported "violent fluctuations" of lift and drag of airfoils occurring around the angle of maximum lift. The oscillations were of very low frequency and could be estimated from Jones' data to correspond to $St=0.006$. Jones also classified the stall of airfoils into three types: trailing-edge stall, thin-airfoil stall, and leading-edge stall. He observed that this low-frequency flow oscillation occurred for the first two stall types. In addition, he noted that the large fluctuations occurred at maximum lift for the thin-airfoil stall airfoils, but occurred a few degrees above maximum lift for trailing-edge stall airfoils. Farren,[3] using a fast response balance, observed a low-frequency oscillation on an RAF 28×1.07 airfoil at $\alpha=14$ deg and $Re=10^6$. The observed Strouhal number corrsponded to $St=0.019$.

Subsequently, Zaman et al.[4] reported an experimental and computational study of this phenomenon conducted at low Reynolds number, $Re<3\times10^5$. The oscillation was found to be hydrodynamic in nature and involved a quasiperiodic switching between stalled and unstalled conditions. The corresponding force oscillations were extremely large with ΔC_l of approximately 0.50. The Strouhal numbers observed were usually between 0.02 and 0.03. For $Re<10^5$, the oscillation did not occur naturally in the tunnel which had a freestream turbulence level of 0.1%. Either a turbulence generating grid, which raised the freestream turbulence level to 0.4%, or a high-frequency acoustic excitation was required to "excite" the flow oscillation. This, coupled with other evidence, suggests that a transitional boundary layer at separation is required to produce the phenomenon. The computational study, using a thin-layer Navier-Stokes code with the Baldwin-Lomax turbulence model, produced a flow oscillation at $St=0.03$ only when transition was placed near the leading edge.

The bulk of data from Zaman et al.[4] was taken on a LRN(1)-1007 airfoil at low Reynolds number. It was not clear whether this low-frequency flow oscillation would persist at higher Reynolds number. However, recent experimental evidence indicated that the oscillation does occur on other airfoils at higher Reynolds numbers. Bragg and Khodadoust[5] observed a flow oscillation near stall

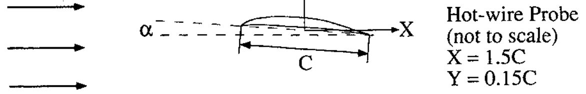

Fig. 1 LRN(1)-1007 airfoil mounted in the UIUC subsonic wind tunnel.

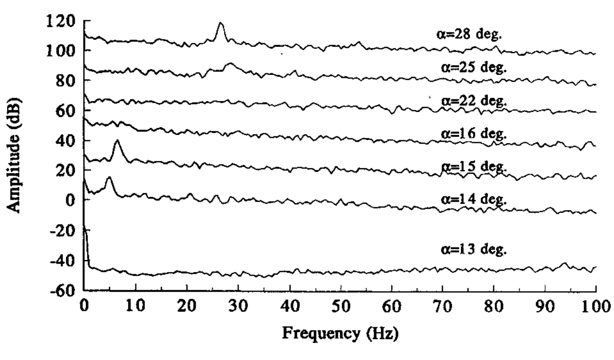

Fig. 2 Spectral intensities for the $c=10$-in. airfoil at $Re=0.3\times10^6$. The traces are staggered successively by one ordinate division.

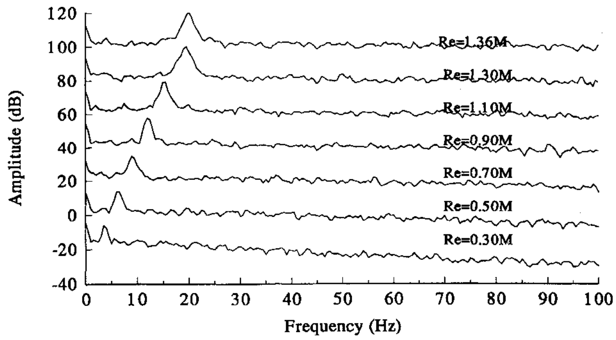

Fig. 3 Spectral intensities for the $c=12$-in. airfoil at $\alpha=14$ deg.

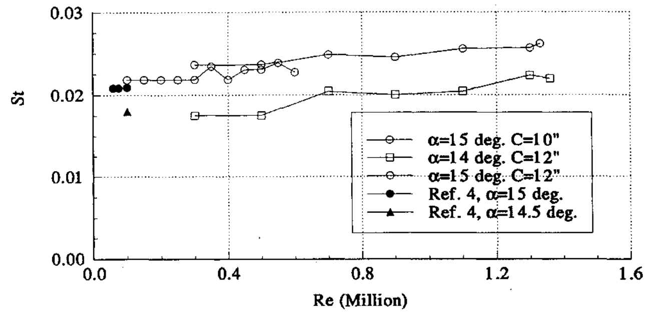

Fig. 4 Strouhal number for peak fluctuation intensity vs Reynolds number.

observed using hot-wire anemometry. Reda[6] observed a similar phenomenon when using liquid crystal flow visualization on a SAND 0018/50 airfoil at $Re=10^6$. He described the flow as "a quasiperiodic switching of the flow between separated and attached states over large portions of the airfoil lee surface." Using frame-by-frame analysis of the flow visualization, an oscillation frequency corresponding to a Strouhal number of 0.005 was estimated.

Results and Discussion

The experiment was conducted in the 2.8-×4-ft subsonic wind tunnel at the University of Illinois at Urbana-Champaign (UIUC) to attempt to extend the results of Zaman et al.[4] to higher Reynolds number. The UIUC subsonic tunnel is an open return tunnel with four screens and honeycomb for flow conditioning which produces a test section turbulence level less than 0.1%. Figure 1 shows the experimental setup, identical to that of Ref. 4. A single hot-wire probe was used one chordlength downstream of the trailing edge and $0.15c$ above the airfoil midchord point to sense the flow fluctuations. A standard spectrum analyzer was used to process the analog hot-wire signal.

Two different airfoil models were used in the test. The wooden model of 10-in. chord, used as one of the models in the test of Zaman et al.,[4] was modified to span the 2.8-ft height of the tunnel. A larger aluminum 12-in. chord model, built specifically for this test, was also used. Both airfoil models were of the LRN(1)-1007 section.

The wake velocity spectra taken on the 10-in. chord wood model at $Re=3\times10^5$ with varying α are shown in Fig. 2. A dominant frequency is not found in the wake as the angle of attack is increased until $\alpha=14$ deg is reached. At 14- and 15-deg angle of attack the low-frequency flow oscillation is easily seen in the data. These frequencies convert to a Strouhal number of approximately 0.02. Note that no excitation of the flow was required in this experiment to produce the low-frequency oscillation. This was also the case in the experiment of Zaman et al.[4] for the high end of the Reynolds number range covered. At Reynolds numbers under 10^5, they used a turbulence grid to raise the test section turbulence level to 0.4% to excite the oscillation. At very low Reynolds number, $Re=2.5\times10^5$, the turbulence grid together with acoustic excitation was required to excite the low-frequency oscillation. Since it is thought that a transitional boundary-layer state is required to have a low-frequency flow oscillation, it is consistent that as the freestream Reynolds number increases, less excitation would be required to produce the oscillation.

As the angle of attack is increased further, a higher frequency oscillation around 27 Hz is identified. This corresponds to a Strouhal number of 0.173 and is recognized as bluff body shedding. This frequency first became distinguishable at $\alpha=25$ deg and is clearly visible at 28 deg. The angle of attack when the bluff body shedding first occurred in the experiments of Zaman et al.[4] was much lower, about 18 deg, but their Reynolds number for the corresponding data was only 10^5.

Figure 3 presents the spectral intensities measured in the wake of the 12-in. chord aluminum model at several Reynolds numbers from 3×10^5 to 1.4×10^6. Here the spectra at $\alpha=14$ deg are shown, but the data at 15 deg are very similar. The frequency of the spectral peak is seen to increase with Reynolds number, although the Strouhal number remains nearly constant. Over the Reynolds number range shown, the magnitude of the peak appears to increase with Reynolds number. The spectra suggest that the low-frequency flow oscillation will continue to be present on this model at even higher Reynolds numbers.

A plot of Strouhal number vs Reynolds number for the present data and selected data from Ref. 4 are shown in Fig. 4. The present data taken at 15-deg angle of attack compare well to the earlier data[4] and seem to be a smooth extrapolation to the higher Reynolds numbers. Because of the magnitude of the forces induced by the flow oscillations and structural considerations, the wooden 10-in. chord model could only be used up to $Re=6\times10^5$. The 12-in. chord aluminum model was built to extend the data to the maximum tunnel speed and, therefore, Re, while still maintaining a low tunnel wall interference. Two trends are clearly seen in these data. The Strouhal number of the flow oscillation increases with model angle of attack and with increasing Reynolds number.

The increase in Strouhal number in these data is about 0.0034/10^6 Reynolds number. However, it should be noted that the phenomenon occurs over a small α range. Stepping in 1-deg increments in α, a clear peak in the u' spectra is only seen at $\alpha=14$ and 15 deg. Data from Ref. 4, shown in Fig. 4, also show a similar trend with angle of attack. The small increase in Strouhal number with Reynolds number seen in the present data was not apparent in the earlier data.[4]

Tunnel wall interference appears to affect the measured frequency of flow oscillation. Using exactly the same wooden 10-in. chord model, but in a much smaller tunnel, Zaman et al.[4] measured a Strouhal number of 0.033 at a Reynolds number of 3×10^5. The angle of attack at which the flow oscillation occurred was also higher at $\alpha=17$ deg. Considering only solid body and wake blockage, the increase in flow velocity at the model would only be about 5%,[7] not nearly enough to account for the discrepancy. An explanation of the discrepancy is not currently available.

Summary

A low-frequency flow oscillation on airfoils which occurs near the angle of maximum lift has been discussed. The frequency was measured with a hot-wire probe in the wake and was analyzed using a spectrum analyzer. Data available from Ref. 4 on a LRN(1)-1007 airfoil up to a Reynolds number of only 3×10^5 was extended to over 1.3×10^6. The frequency converts to a Strouhal number of approximately 0.02, which, from these data, appears to increase slightly with Reynolds number and more significantly with angle of attack.

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Mach Disk of Dual Coaxial Axisymmetric Jets

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Nomenclature

D_i, D_m = diameter of the inner nozzle and Mach disk, respectively
P_a = ambient pressure
P_i, P_0 = inner and outer flow blowing pressures
X_m = axial location of Mach disk

Introduction

ONE of the distinctive features in the near-field shock wave structure of supersonic jets issuing from moderately/highly underexpanded nozzles is the normal shock or Mach disk existing in such flows. Extensive studies have already been carried out on Mach disk structure.[1–5] These studies are of importance in aerospace propulsion technology because sizable (in comparison to the nozzle exit diameter) Mach disks may appear in the flow issuing from nozzles of rocket/airbreathing engines when operating at very high altitudes or under highly underexpanded conditions. In the laboratory, such large sized Mach disks can be obtained only in high altitude test facilities using moderate to high pressure ratios.

Mach disks using two streams have been generated prior to this work,[6,7] but most of these studies have been confined to asymmetric Mach disks, generated by transverse injection of highly underexpanded flows into a supersonic stream. While conducting experiments on mixing of two coaxial axisymmetric, supersonic flows, the authors observed the existance of a large sized Mach disk even at relatively low pressure ratios across the main nozzle. Such a low pressure system of generating Mach disks should result in a simpler test setup compared to the existing high pressure, altitude simulation facilities. Therefore, some experiments were carried out to determine the effect of blowing pressures of the two streams on the size and location of the Mach disk. These experiments yielded some interesting results which are presented in this Note.

Description of Test Setup

The basic test setup shown in Fig. 1 was built to conduct studies on mixing of two high speed streams. It consisted of 1) an inner airstream with a convergent-divergent nozzle and 2) an outer, coaxial, annular airstream with a convergent nozzle. The outer stream makes an angle of about 26 deg with the axis of the inner stream. The inner nozzle was designed for a critical pressure ratio of 5:1. Both of the nozzles exit to the atmosphere. The diameter and axial location of the Mach disk was determined from shadowgraph of the freejet flowfield. Mach number was obtained from total and static pressure measurements along the axis.

Results

Shadowgraphs

Figure 2 shadowgraphs show that, for a constant value of P_i, as P_0 increases the Mach disk grows in size and shifts downstream.

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