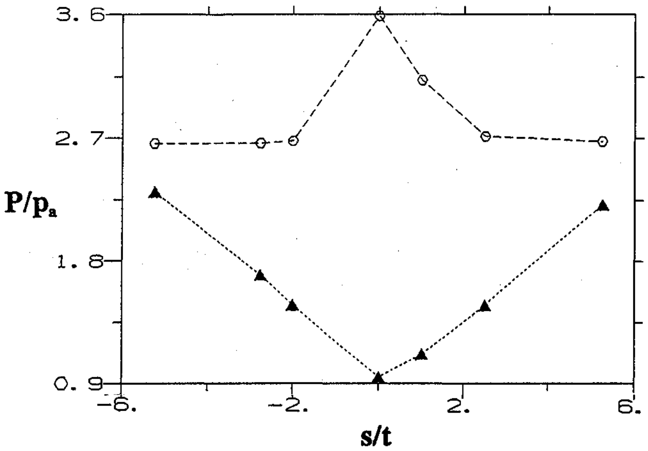

Fig. 3 Azimuthal distribution of static pressure at $x/t = -1.5$, upstream (- - -) and downstream (· · ·) of a cylindrical tab, for an underexpanded jet, $M_j = 1.63$; s denotes azimuthal distance from the tab.

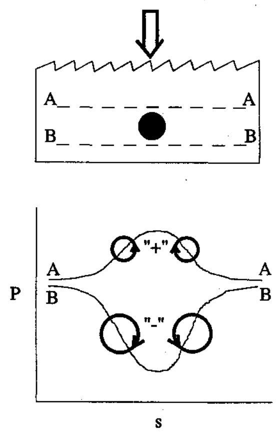

Fig. 4 Sketch of the pressure distributions of Fig. 3 and the sign of each vortex pair generated by the pressure gradients.

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

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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.

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Bragg et al.[3] used a model of the LRN(1)-1007 airfoil in a larger wind tunnel and covered Reynolds numbers to 1.4×10^6. The oscillation persisted up to this value of Reynolds number, and the Strouhal number was found to increase slightly with increasing Reynolds number. Experimental evidence indicated that the oscillation occurred on other airfoils as well. Reference 2 reported a similar oscillation on a NACA 0012 airfoil. Bragg and Khodadoust[4] observed similar low-frequency flow oscillations on a NACA 0012 airfoil with a simulated glaze ice accretion near the leading edge at $Re = 1.5 \times 10^6$. Reda[5] reported 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."

Thus the low-frequency flow oscillation on airfoils near stall has been observed on several airfoils over a range of Reynolds numbers. However, the mechanism of selection of the long time scale involved in the oscillation remained far from clearly understood. This provided motivation to continue to pursue the topic. In the present investigation, efforts were made to further document the characteristics of the phenomenon and gain additional insight into the flow mechanisms. Results obtained so far indicate the phenomenon is most likely linked to the occurrence of a separation bubble near the leading edge. Also, systematic trends have been established on the dependence of the Strouhal number on the Reynolds number as well as the angle of attack. The purpose of the present Note is to describe these results.

Results and Discussion

The LRN(1)-1007 airfoil was tested in the Reynolds number range of $0.3 \times 10^6 < Re < 1.25 \times 10^6$ and the angle of attack range of $0 < \alpha < 28$ deg. Flow visualization studies were performed at $Re = 0.8 \times 10^6$ using surface oil flow and 0.075×10^6 using laser sheet illumination. Hot-wire spectra measurements were taken in the airfoil wake to determine the flow oscillation frequencies.

By examining the frequency content of the hot-wire signals, the low-frequency oscillation was determined to occur in the α range of 14.4–16.6 deg. Within this range, the Strouhal number varied significantly with α. For a given α, the Strouhal number also increased with Reynolds number. These trends are shown by the data of Fig. 1. The value of the Strouhal number can be seen to increase slightly with Reynolds number, but significantly with α. At $Re = 0.8 \times 10^6$, the Strouhal number increased almost linearly from 0.02 to 0.029 when α was increased from 14.4 to 16.6 deg, the corresponding slope being 0.00458/deg. The change in Strouhal number with Reynolds number, dSt/dRe, was 0.0035 per million Re at $\alpha = 14.4$ deg and 0.0015 at $\alpha = 16$ deg.

Surface flow visualization revealed that a large laminar separation bubble existed near the leading edge of the airfoil during the flow oscillation.[6] These results of these experiments are summarized in Fig. 2. The bubble appeared at the airfoil leading edge at approximately $\alpha = 6$ deg, at the same time turbulent separation was observed on the aft portion of the airfoil upper surface. The bubble grew rapidly as the angle of attack was increased over 12 deg, and only these data are shown in Fig. 2. For angles of attack above 14.6 deg, the flow was very unsteady and thus the uncertainty in the mean bubble reattachment location was large. Evidence of the low-frequency flow oscillation was present in the wake velocity spectra at angles of attack as low as 13.2 deg. However, a resonantlike oscillation ensued around 14.4 deg. Between these two values of α, the bubble grew from 8 to 23% chord in length. Above 14.4 deg the bubble growth with α slowed. At higher values of α the mean turbulent separation location on the aft of the airfoil could no longer be determined.

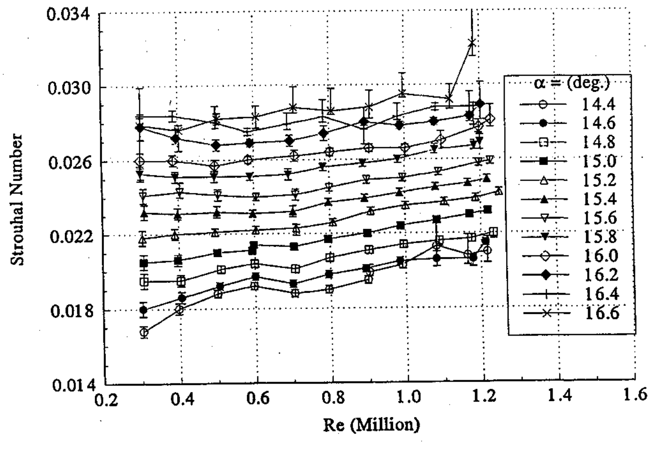

Fig. 1 Strouhal number of the low-frequency oscillation as a function of α and Re($\alpha \pm 0.1$ deg and $Re \pm 1\%$).

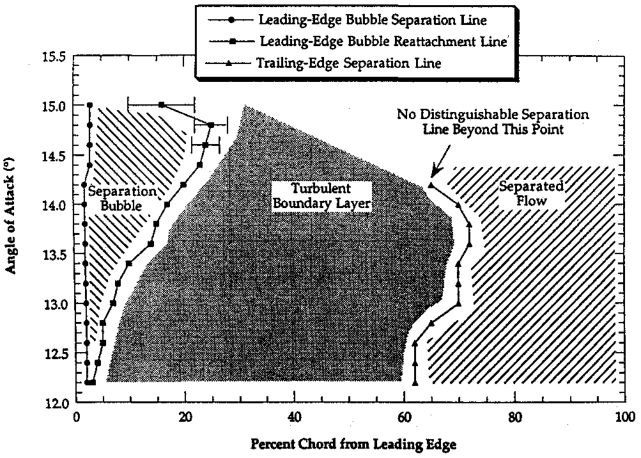

Fig. 2 Airfoil upper surface boundary-layer state from surface oil flow visualization (chordwise position ±2% for data without error bars and $\alpha \pm 0.1$ deg).

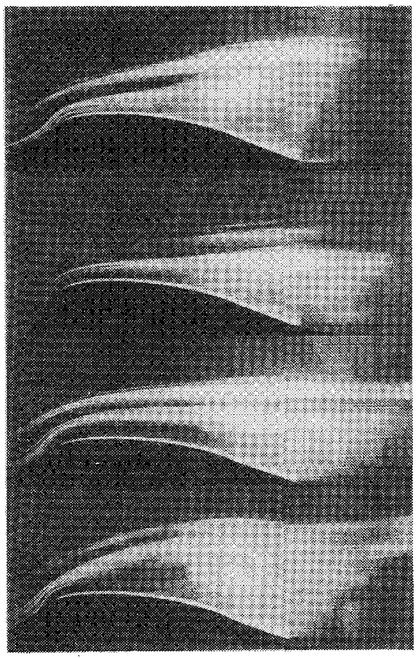

Fig. 3 Laser sheet flow visualization on the upper surface at $Re = 0.075 \times 10^6 \pm 1\%$ and $\alpha = 15 \pm 0.1$ deg; successive photos are 0.225 ± 0.05 s apart (flow from left to right).

In Fig. 3 laser sheet flow visualization reveals the basic characteristics of the unsteady separation phenomena. A sequence of photos are shown with the flow seeded with 1-μm particles and the tunnel at about 12 ft/s ($Re = 0.075 \times 10^6$). The flow is from left to right, and the airfoil upper surface is seen as the thin white line formed by the intersection of the laser sheet and the model. The photos were taken with 0.225 s between frames, the low-frequency oscillation being about 1 Hz. The flow appears to be reattaching in the top photo and has attached over most of the upper surface in the second photo. An

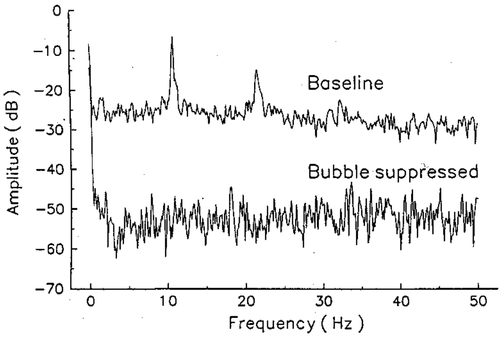

Fig. 4 Wake velocity spectra with and without the leading-edge bubble present (frequency ± 0.125 Hz and amplitude ± 0.1 dB).

inspection of these photos, aided by the surface oil flow visualization experiments, reveals the presence of the separation bubble near the leading edge. The bubble is relatively small in the top photo. By the third photo it has grown substantially and appears to have burst in the fourth. The bursting is accompanied by a complete separation of the flow and the appearance of a stall-vortex-type structure on the upper surface. The sequence of events described in the foregoing qualitatively agrees with the computational as well as experimental results presented in Ref. 2.

Figures 2 and 3 suggest that the low-frequency oscillation is related to the occurrence of the leading-edge separation bubble. This idea is supported by the data shown in Fig. 4. Wake velocity spectra at $\alpha = 15$ and $Re = 0.8 \times 10^6$ are shown with and without "zig-zag" tape placed near the leading edge. In the upper trace an oscillation frequency of 11 Hz and its first harmonic are clearly seen. In the second trace the bubble was eliminated by the zig-zag tape, which acts as both boundary-layer trip and vortex generators.[7] Not only are the low-frequency oscillation peaks gone, but also the overall energy in the wake was reduced by 30 dB. No evidence was seen of the low-frequency oscillation over the entire α range with the zig-zag tape in place and the bubble eliminated.

The unsteady behavior of separation bubbles is well known.[8–10] When nondimensionalized by the bubble length, the characteristic oscillation frequency typically corresponds to a Strouhal number of about 0.6. However, much lower frequency unsteadiness has also been reported in several references. For example, Driver et al.[9] also documented an unsteady phenomenon in their backward-facing step flow at frequencies less than 1/6th the characteristic frequency. This phenomenon, referred to as shear layer flapping, involved a momentary disorder of the shear layer where a vortex was shed, the bubble collapsed and then grew in size until another vortex was shed. This was characterized by large changes in the reattachment location and a corresponding vertical motion of the shear layer. The frequency and the flow characteristics of the phenomena considered in the present study appear to agree with those of shear layer flapping. The flow oscillation in the present case, however, is much more pronounced and symptomatic of a resonance. What completes a possible feedback loop to produce the resonance-like oscillation remains unclear and is the subject of the ongoing investigation.

Acknowledgment

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Use of Drag Probe in Supersonic Flow

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I. Introduction

THE purpose of this research was to develop an instrument that could provide dynamic flow parameters in supersonic propulsion research.[1] The parameters of interest are the velocity, velocity head, Mach number, and mass flow rate.

The drag probe functions by measuring the drag on a flat cantilever beam exposed transversely to a flowfield.[2–5] This process is shown schematically in Fig. 1. The drag is measured indirectly with strain gauges attached on opposite sides of the beam's base—a layout that makes the probe inherently temperature compensated. The frequency response of the probe can be extended to 100 kHz, which rivals the frequency response of hot wires, yet it is rugged enough to survive the harsh environments often encountered in aerospace applications. Its associated electronics are as simple as those of strain-gauge pressure transducers, and it is easy to calibrate. It gives the velocity-head measurement directly and yields the velocity readily.

Use of the drag-force anemometer has been limited to subsonic-flow applications. Such use and the anemometer design are discussed by Krause and Fralick.[2] The drag force induced by the flow impinging on the probe's cantilever beam may be found from fluid-mechanics principles.[6] The coefficient of the drag imparted to the plate, C_D, has been characterized[6] as being affected by flow parameters such as the Reynolds number Re and the Mach number M. This Note focuses on demonstrating that the relation between a subsonic and a supersonic velocity head are the same for each drag probe. The supersonic flow impinging on the drag probe is assumed to be unidirectional. Krause and Fralick[2] have analyzed drag probes for the purpose of determining the flow direction. The shock region directly in front of the drag probe is assumed to be normal and two dimensional, as verified by photographs.

II. Analysis

In a supersonic flow, the force sensed by the drag probe is proportional to $(\rho u^2)_2/2$. The drag probe still senses the subsonic conditions immediately surrounding it and not the supersonic conditions

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