Experimental Results on Edge-Tone Oscillations in High-Speed Subsonic Jets

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A well-controlled investigation of the feedback phenomenon that occurs when a probe is inserted into a jet potential core was carried out for a subsonic jet. The recently incorporated capability of conditional sampling into the Lockheed laser velocimeter was used for this type of investigation. The major aspects investigated were the path of the feedback loop and the effect of the edge tone on the jet fluid dynamics. The analysis of the experimental results indicates that for our particular experimental arrangement the feedback loop is completed within the jet itself and not by sound traveling outside the main jet. Furthermore, it was found that the potential-core region between the nozzle exit and the probe acts similar to a wave guide, and hydrodynamic standing waves are set up in this region.

Nomenclature

D	= main jet diameter
f	= edge-tone frequency
$I(U), I(W)$	= axial and radial components of turbulence intensity, respectively
L_I	= axial distance between spike vertex and nozzle exit plane
L_s	= sound pressure level (relative 2×10^{-5} Pa)
M	= Mach number
R	= main jet radius, $=D/2$
U	= mean axial velocity
u	= instantaneous axial velocity, $=U+u'$
u'	= fluctuating axial velocity
W	= mean radial velocity
w	= instantaneous radial velocity, $=W+w'$
w'	= fluctuating radial velocity
X,Z	= axial and radial distances, respectively
ψ	= relative phase angle

Subscripts

j	= main nozzle exit plane
p,r	= large and small scale, respectively
t	= total
0	= secondary nozzle exit plane

Introduction

MUCH has been discussed in the open literature about the flow-excited acoustic resonance of edge-tone feedback phenomenon.[1-10] When a probe is inserted into a jet, such a phenomenon is often referred to as the edge-tone effect. Although there is a wealth of experimental evidence of the edge-tone feedback phenomenon, the understanding of the fluid dynamics involved is still of a superficial nature. Most of the published experimental results were acquired either at super slow velocities[1-3] ($U_j<3$ m/s) or at small velocities[4-7] (15 m/s $<U_j<$ 46 m/s). Only few experiments were made in high-speed subsonic jets.[8,9] Thus, the need for further detailed experimental investigations in a high-speed subsonic region still exists.

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The objective of the present work was to carry out an experimental study of the edge-tone phenomenon with state-of-the-art equipment, and to resolve some of the important questions. The study was planned to answer the following two particular questions.

1) Is the feedback loop in subsonic jets completed wholly within the jet, or does part of it lie outside the jet?

2) What are the effects of the feedback phenomenon on the large-scale turbulence structures in the jet and its subsequent effects on the small-scale turbulence, and on the fluid dynamics of the jet, in general?

Experimental Facility and Test Procedure

Jet-Flow Facility

All of the experiments were conducted in Lockheed's Jet-Flow Facility.[11,12] The facility is designed to produce parallel, low-turbulence coaxial flows. It has two plenums arranged coaxially. The inner or main nozzle is a 50.8-mm-diam convergent nozzle, the outer or secondary nozzle has a diameter of 254 mm. The impingement probe consisted of a 6.4-mm B&K microphone fitted with a nose cone and mounted on a suitably faired support. A photographic view of the experimental arrangement is given in Fig. 1.

Velocity and Turbulence Measurement

The mean velocities and turbulence intensities were measured by Lockheed's two-color, four-channel laser velocimeter. The laser velocimeter was arranged in a forward-scatter mode with collecting optics placed 30 deg off-axis. Transmitting and collecting optics were firmly mounted on a robust frame free to move along all three axes. Inasmuch as the measurement volume was fixed with respect to the transmitting optics, it was possible to traverse the flowfield by moving the frame. The effective length of the measurement volume was 1 mm and the diameter was 0.15 mm. The velocimeter has built in frequency shifting for both velocity components to avoid a velocity ambiguity.

Large-Scale Turbulence Structure Measurement

Recently developed data acquisition and reduction techniques have been incorporated into Lockheed's laser velocimeter system. These techniques enable the use of the laser velocimeter for conditional sampling and ensemble averaging and thus make it possible to resolve the contribution of organized (periodic) and random changes of the instantaneous flow velocity to the total unsteadiness level of the flow and express these contributions in terms of large- and small-scale turbulence intensity. The conditional sampling, described in detail in Refs. 13 and 14, was accomplished by synchronizing the beginning of the repetitive data acquisition interval of the laser velocimeter with respect to the periodic flow oscillations measured by a microphone probe.

Feedback-Loop Path

Sound generated at the immersed probe travels outside or inside the main jet and interacts at the nozzle exit to generate an eddy that travels downstream to the probe to complete the feedback loop. A simple experiment was set up to test if the feedback-loop path is completed inside or outside the main jet. A coannular nozzle system consisting of 50.8-mm main and 254-mm secondary nozzles was used. The microphone probe, fitted with a 6.4-mm-diam nose cone, was located inside the jet of the main nozzle at that axial station where acoustic feedback tone was quite intense. At first, with secondary flow switched off, the velocity of the main flow was varied. Then, for a given velocity of the main jet ($M_j = 0.79$), the velocity of the secondary flow was varied. The results are shown in Fig. 2. A strong dependence of the acoustic feedback frequency on the main jet velocity is clearly seen. The velocity of the secondary jet, however, had no significant effect on the feedback frequency, at least for a given range of test conditions. If the feedback loop is completed outside the main jet, then the feedback frequency should change if a secondary stream is added. The independence of the feedback frequency on secondary velocity indicates that in the case of a small impingement probe the feedback loop is wholly completed within the main jet.

Edge Tone and Jet Fluid Dynamics

A laser velocimeter was used to study the fluid dynamics of the jet under the acoustic feedback phenomenon with the impingement probe—a 6.4-mm B&K microphone fitted with a nose cone in this case. The signal from this microphone also served as a triggering signal for conditional sampling of the velocity measurements. The impingement probe was located at the jet centerline at the axial distance $L_I/D = 2.09$. The feedback phenomenon was very well defined at this axial distance with a single, dominant tone of frequency equal to 2888 Hz.

Centerline Distributions

The distributions of both the axial and radial components of the mean velocity and turbulence intensity were measured first. The axial distributions along the jet centerline for $M_j = 0.79$ are shown in Figs. 3 and 4. As seen in Fig. 3, the feedback phenomenon produces drastic changes in the axial-velocity and turbulence-intensity distributions along the jet centerline. The mean velocity tends to decrease stepwise starting very close to the nozzle exit plane, while the constant-velocity potential core of a free jet at this Mach number reaches up to $X/D = 5$.

The distribution of the axial turbulence-intensity component is very nonuniform. In general, the axial turbulence levels have increased significantly, in comparison with those in the free jet. In addition, the distribution is characterized by repeated rise and fall of turbulence intensity. In the present measurements four local maximums and five local

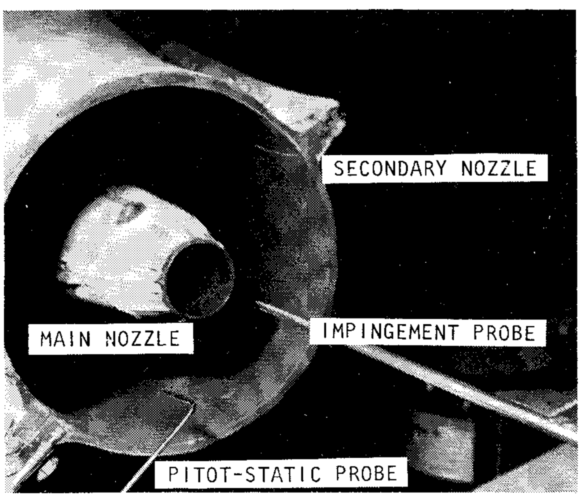

Fig. 1 Test nozzle and impingement probe.

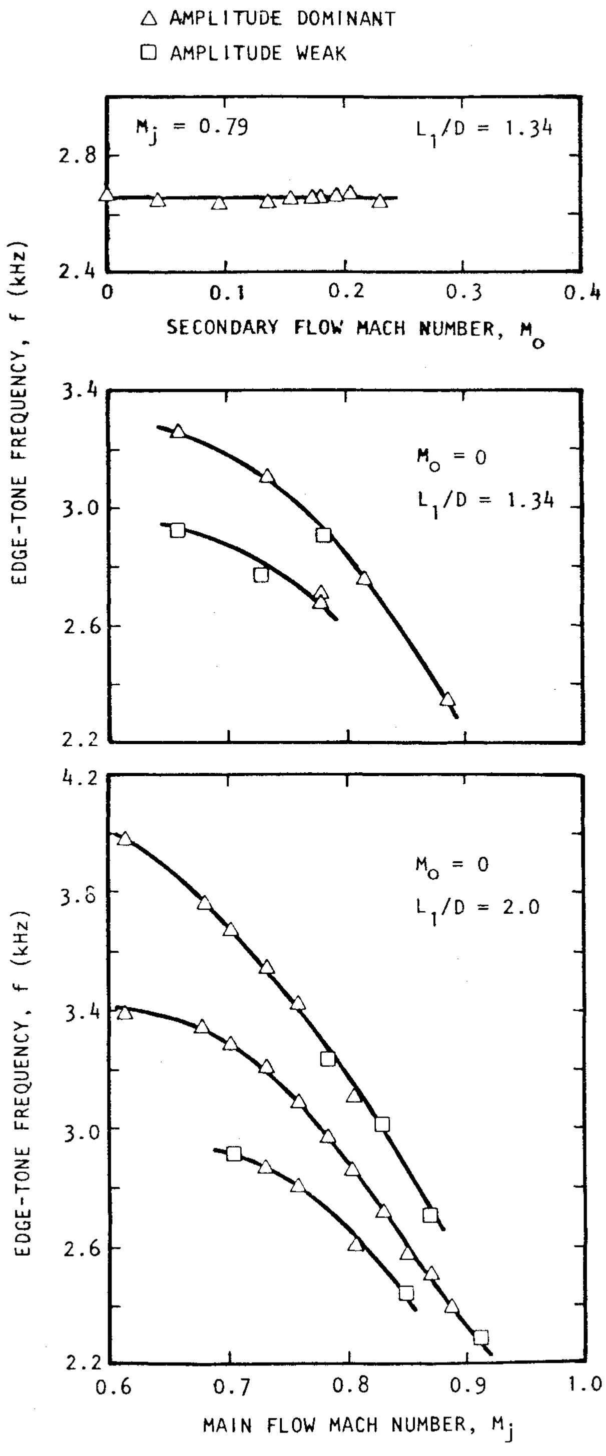

Fig. 2 Dependence of edge-tone frequencies on main-flow Mach number M_j and secondary-flow Mach number M_0.

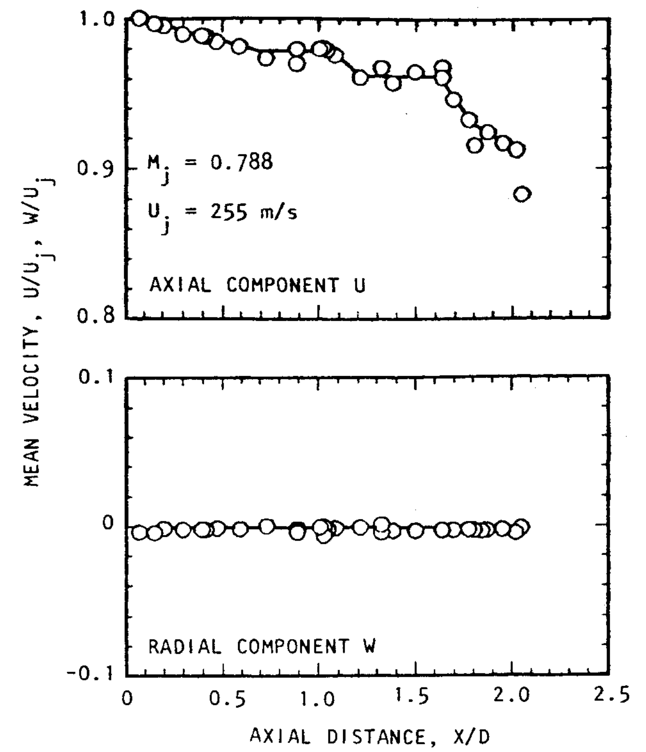

Fig. 3 Centerline distributions of mean velocities with impingement probe at $L_l/D = 2.09$.

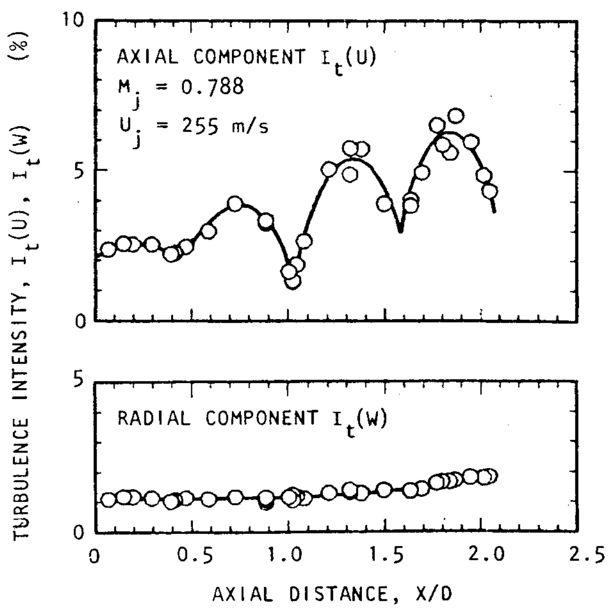

Fig. 4 Centerline distributions of turbulence intensities with impingement probe at $L_l/D = 2.09$.

minimums are clearly detectable. The local extremities, including the minimum at the nozzle exit plane and the minimum at the impingement probe tip, are distributed uniformly between the nozzle exit and the impingement probe.

The centerline distributions of the radial velocity and turbulence intensity shown in Figs. 3 and 4, however, did not appear to be affected by the acoustic feedback presence.

Radial Profiles

Radial profiles were measured at three axial stations: 1) $X/D = 1.02$, where the axial turbulence intensity has its local minimum at the jet centerline; 2) $X/D = 1.32$, where the axial turbulence intensity reaches its local maximum, and 3) $X/D = 0.89$. These radial profiles are plotted in Figs. 5-8. Measured and interpolated corresponding radial profiles of the mean velocities and turbulence intensities of a free jet for $M_j = 0.79$ without the impingement probe are also shown in Figs. 5-8. The acoustic feedback affects the axial velocity and axial turbulence intensity in a manner similar to upstream discrete tone acoustic excitation.[11] The jet plume widens in comparison with a free jet without acoustic feed-

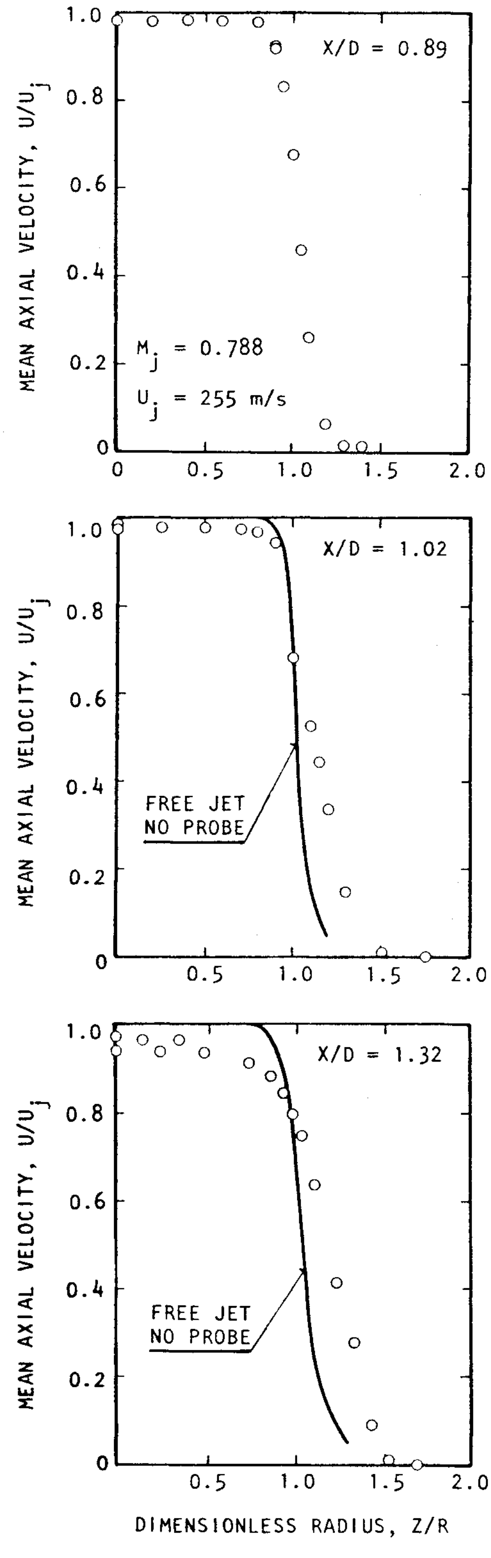

Fig. 5 Radial profiles of axial mean velocity with impingement probe at $L_l/D = 2.09$.

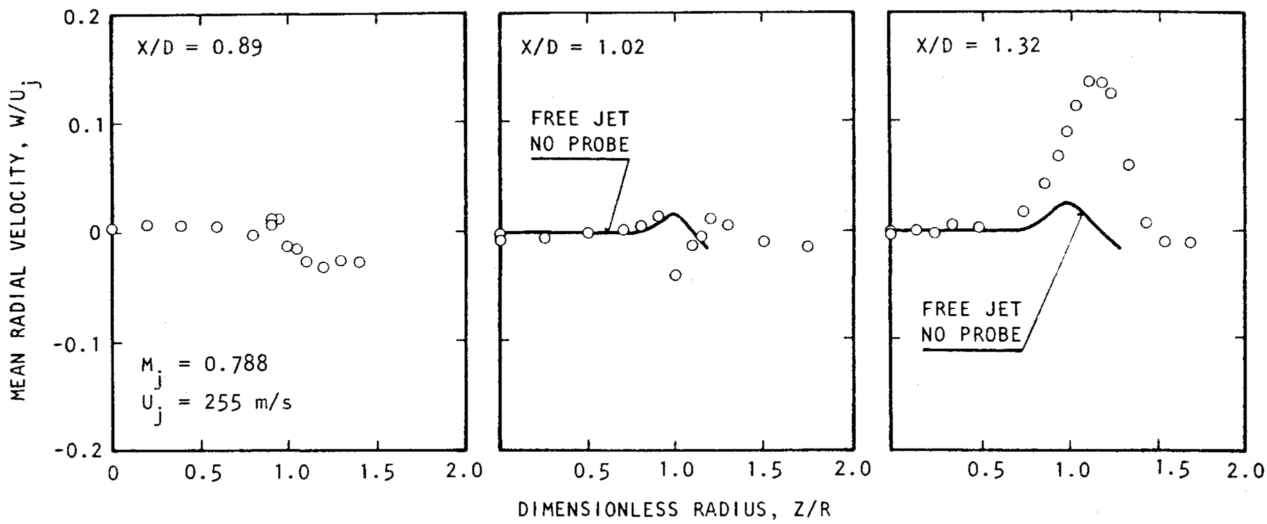

Fig. 6 Radial profiles of radial mean velocity with impingement probe at $L_I/D=2.09$.

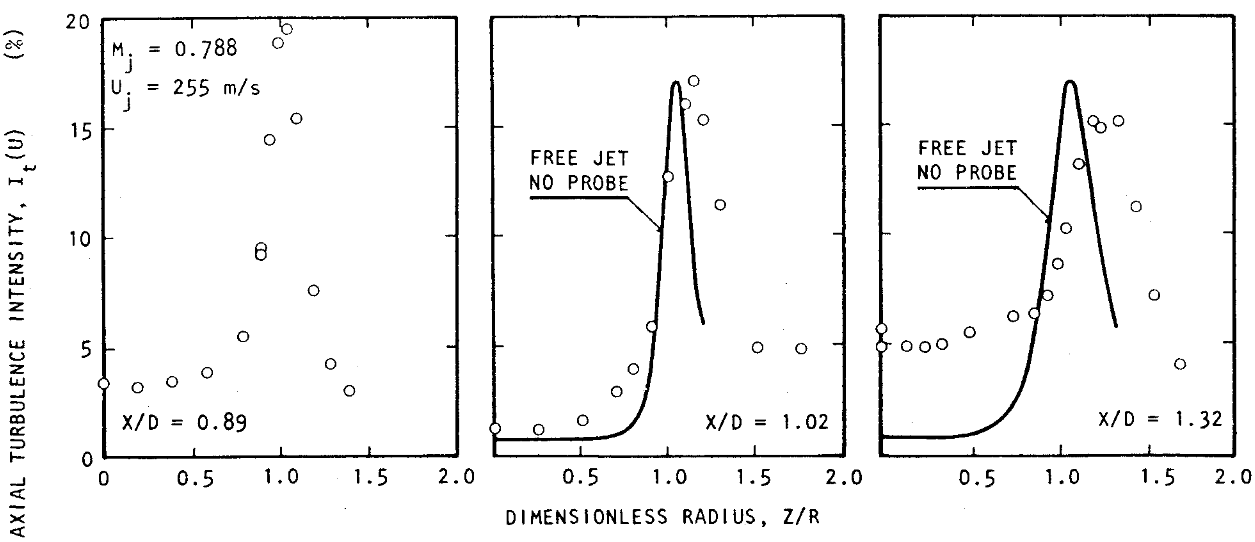

Fig. 7 Radial profiles of axial turbulence intensity with impingement probe at $L_I/D=2.09$.

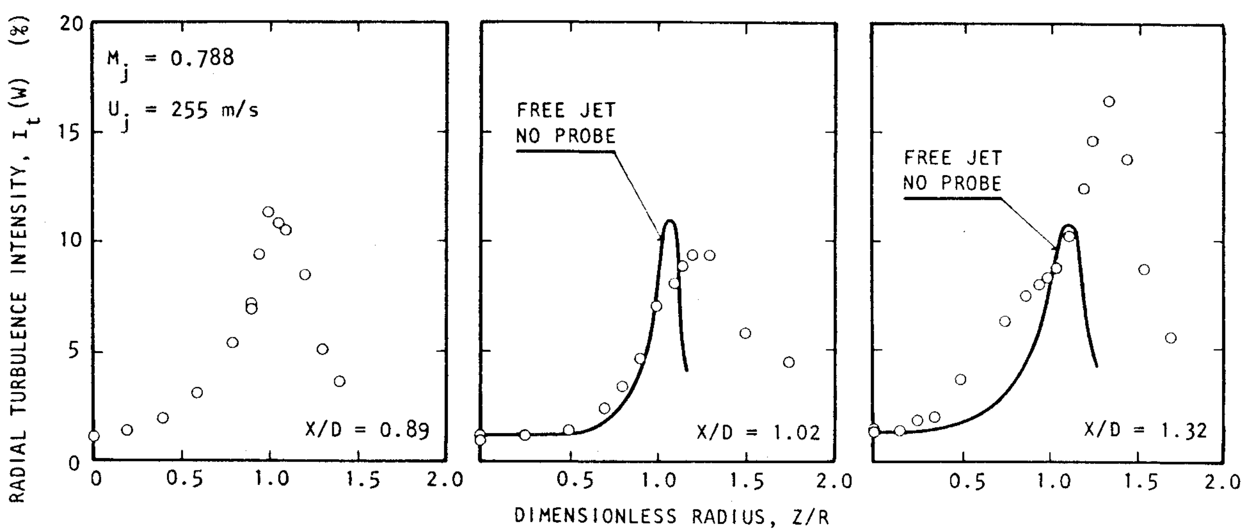

Fig. 8 Radial profiles of radial turbulence intensity with impingement probe at $L_I/D=2.09$.

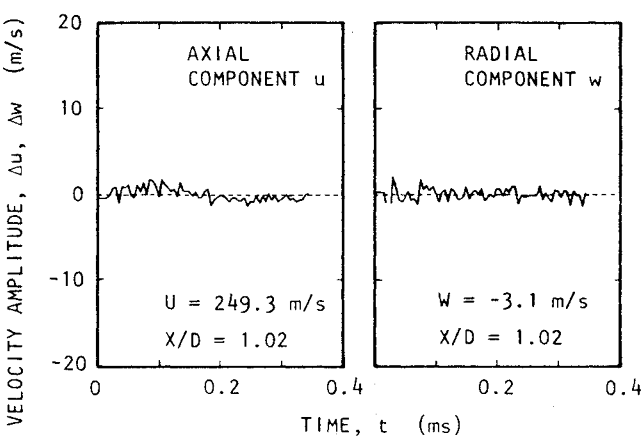

Fig. 9 Ensemble-averaged velocity histories at $X/D=1.02$ with impingement probe at $L_I/D=2.09$.

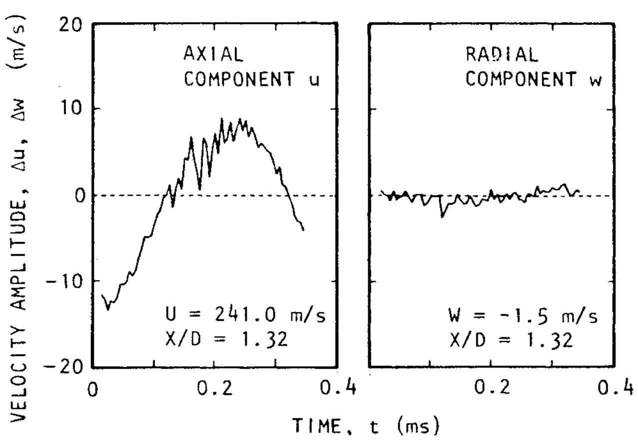

Fig. 10 Ensemble-averaged velocity histories at $X/D=1.32$ with impingement probe at $L_I/D=2.09$.

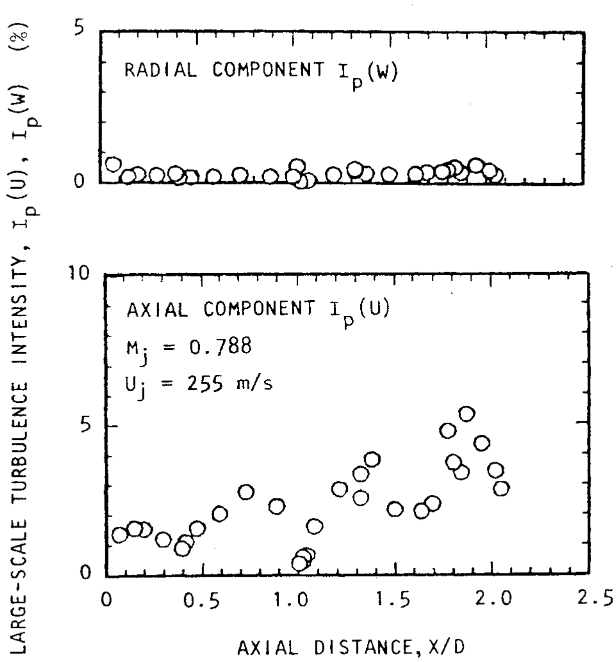

Fig. 11 Centerline distributions of large-scale turbulence intensities with impingement probe at $L_I/D=2.09$.

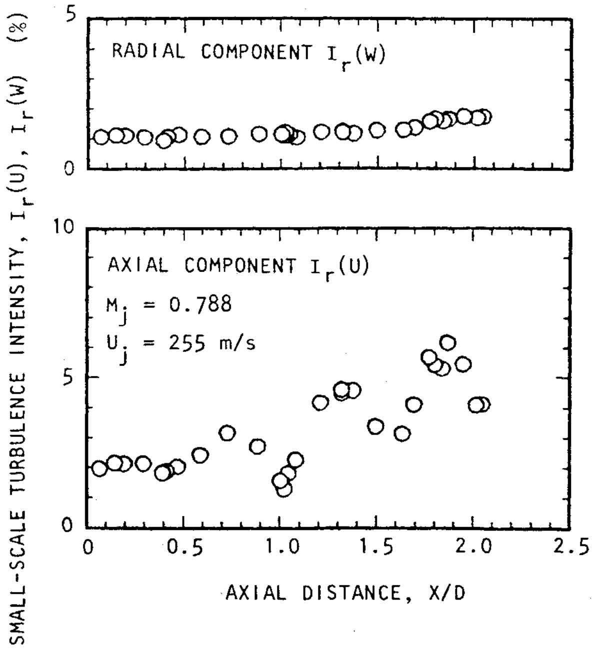

Fig. 12 Centerline distributions of small-scale turbulence intensities with impingement probe at $L_I/D=2.09$.

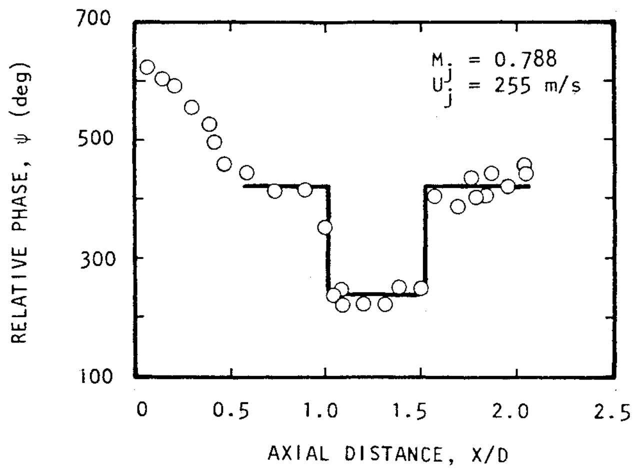

Fig. 13 Relative phase centerline distribution of large-scale structure with impingement probe at $L_I/D=2.09$.

back and the jet mixing is enhanced as indicated by the thicker shear layer. The maximum axial turbulence intensity in the shear layer decreases steadily with increasing axial distance from the nozzle.

The profiles of the radial components of velocity and turbulence intensity, however, show slightly different behavior. The radial velocity component (Fig. 6) is close to zero in the jet inner region and differs from zero in the shear layer, particularly in the lipline vicinity. However, the radial velocity is not unidirectional at all axial stations along the lipline. Direction and magnitude of the radial velocity along the lipline seem to be related to the centerline distribution of the axial component of turbulence intensity. At those axial stations where the axial turbulence intensity reaches its local maximum at the centerline, the radial velocity is large and in the outward direction at the lipline. On the other hand, where the axial turbulence intensity has its minimum at the centerline, the radial velocity is small and even in the inward direction.

The radial turbulence intensity in the shear layer also seems to be related to the centerline distribution of the axial turbulence intensity. When the axial turbulence intensity has its maximum/minimum at the centerline, the radial turbulence intensity has its maximum/minimum at the lipline.

Large- and Small-Scale Turbulence

The velocity histories over one time period of the edge tone were obtained by employing the ensemble-averaging technique for reduction of conditionally sampled data.[13] The time histories for both velocity components at two axial stations are shown in Figs. 9 and 10.

The standard deviation of the time history over the edge-tone period can be considered a measure of the large-scale turbulence level or large-scale turbulence intensity if it is normalized by the jet exit velocity.[14] The centerline distributions of the axial and radial components of the large-scale turbulence intensity are plotted in Fig. 11. The corresponding distributions of the small-scale turbulence intensity are plotted in Fig. 12. As seen from these figures, the variations of small-scale turbulence intensity are directly controlled by the local large-scale turbulence-intensity level. The centerline distribution of the radial small-scale turbulence is very uniform (Fig. 12), probably because no organized velocity fluctuations in the radial direction are present (Figs. 9-11). However, in the case of the axial small-scale turbulence-intensity centerline distribution, a significant enhancement of the small-scale turbulence intensity occurs due to the presence of the organized axial-velocity fluctuations. The axial small-scale turbulence follows the large-scale turbulence distribution with a large enhancement at the local maximum of the large-scale turbulence intensity and a small one at the local minimum.

Standing Hydrodynamic Waves

The nature of the axial turbulence-intensity distribution along the jet centerline (Fig. 4) indicates the presence of hydrodynamic standing waves in the inner jet. Indeed, the time history of the axial-velocity component measured at the nodal point ($X/D=1.02$, Fig. 9) and one at the antinode ($X/D=1.32$, Fig. 10) support this finding.

The presence of standing hydrodynamic waves is further confirmed by the phase measurements of the large-scale structure. Phases of the large-scale structure are relative phases between the triggering signal, measured by a nose-cone microphone located at $L_l/D=2.09$ and the ensemble-averaged axial-velocity fluctuation measured by a laser velocimeter along the jet centerline; results are shown in Fig. 13. The phase, with respect to a fixed observer, changes by 180 deg every half-wavelength of the hydrodynamic wave, with the exception of the region close to the nozzle exit. Different behavior in this region was already indicated by turbulence-intensity measurements (Figs. 4, 11, and 12), where there is a small difference in turbulence level between the nodal and antinodal points in comparison with the flow region farther from the nozzle exit.

Conclusions

A detailed study of acoustic feedback phenomenon has been carried out to answer two specific questions stated in the Introduction. For our particular test arrangement, the experimental results indicate that, for subsonic jets, the feedback loop is completed within the jet itself and not by sound traveling outside the main jet.

The effect of the edge tone on the jet dynamics is somewhat similar to that of exciting a jet by upstream discrete tone sound. The jet plume is widened and the mixing rate is increased significantly. The major difference between the two cases is that standing hydrodynamic waves exist in the jet with the impingement probe and not without it.

Acknowledgments

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