smaller scale motions than the shear stress. Now, the larger the scale of an eddy the longer will be its survival time and thus the greater its contribution to convective transport. We may thus conclude that the approximation for C_{ij} should allow a *preferential* transport of off-diagonal Reynolds stresses. This feature is readily achieved by combining elements of both Eqs. (1) and (2)

$$C_{ij} = C_k [(1+\alpha) (\overline{u_i u_j}/k) - \alpha \tfrac{2}{3} \delta_{ij}] \tag{6}$$

where α is a positive coefficient. We adopt a precisely parallel representation of diffusive transport

$$D_{ij} = D_k [(1+\beta) (\overline{u_i u_j}/k) - \beta \tfrac{2}{3} \delta_{ij}] \tag{7}$$

Introduction of Eqs. (6) and (7) into Eq. (3) leads to the following implied formula for the coefficient c_μ

$$c_\mu = \tfrac{2}{3} \frac{(1-c_2)(c_1 + (1+\alpha)(\lambda - 1) + (\alpha - \beta)\Lambda - (1-c_2)\lambda)}{(c_1 + (1+\alpha)(\lambda - 1) + (\alpha-\beta)\Lambda)^2} \tag{8}$$

where $\Lambda \equiv D_k/\epsilon$, the ratio of the rates of diffusive gain of turbulence energy to viscous loss.

The choice $\beta = \alpha$ produces the simplest stress-strain relation and, indeed, with these coefficients taken as 0.9 and retaining the above values for c_1 and c_2, the variation of c_μ with λ is very close to the *mean* experimental correlation (Fig. 1). This choice, however, exacerbates the problem of too high viscosities near a jet axis. Now, it must be said that no algebraic approximation is particularly satisfactory for representing diffusive transport—the use of Eq. (7) is justified mainly by the resulting overall success of the ASM formulation. If, therefore, β and α are adjusted to allow Eq. (8) to match as well as possible the experimental behavior in the far round wake and in the jet, β needs to be negative because such a choice helps prevent c_μ from rising excessively on the axis. Table 1 shows the values of c_μ emerging for these two flows with $\alpha = 0.3$ and $\beta = -0.8$ with values of λ and Λ taken from experiments cited by Rodi.[1] Clearly Eq. (8) is more successful than Eq. (5) in capturing the observed variation of c_μ in different flows. Further refinement in the choice of α and β must await extensive numerical computations of these flows.

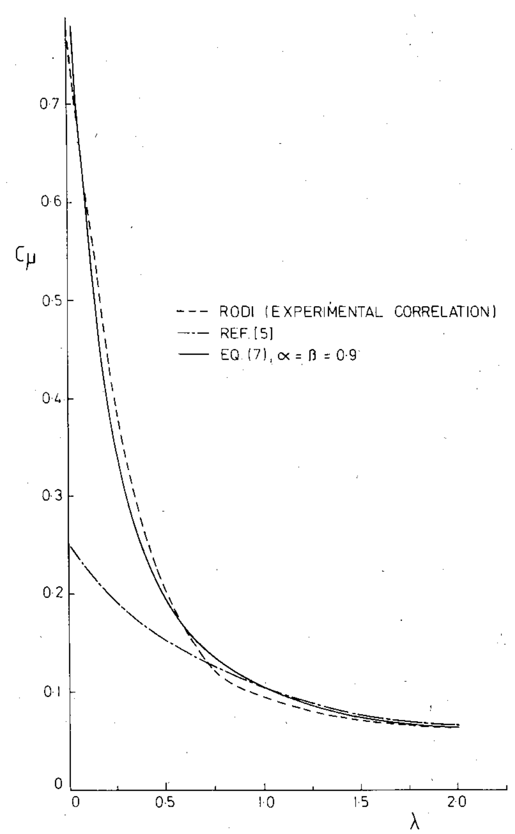

Fig. 1 Dependence of c_μ on λ.

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AIAA 82-4068

Effect of Thickness on Airfoil Surface Noise

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Introduction and Discussion of Existing Theory

THE noise radiated from the fixed and rotating surfaces of an aircraft is a matter of concern. The experimental results of this paper can be applied in these areas through appropriate theories describing the noise from an airfoil (e.g., fan, helicopter rotor, flap, and wing noise).

The early airfoil noise theories (e.g., Ref. 1) were for incompressible flow about a thin, small-chord airfoil. The thin airfoil does not disturb the straight mean flow streamlines. Goldstein and Atassi[2] accounted for the real airfoil effects of thickness, camber, and angle of attack for a small-chord airfoil in incompressible flow. These real airfoil effects modify the straight mean flow streamlines which thereby distorts the incident turbulent gusts. They suggest that this distortion will affect the radiated noise, especially at high frequency. Goldstein also formulated fundamental theories that account for the major effects of transverse mean velocity gradients (e.g., jet noise in Ref. 3, and the noise from the leading and trailing edges of a thin infinite plate in Ref. 4). These theories were shown by Olsen to be quite accurate.[5-7] Goldstein also showed (Ref. 1, pp. 137-145) that the early airfoil theory (incompressible flow over a small chord-thin airfoil) is easily modified to include the effect of compressibility. According to Ref. 1, this compressible theory can also be used to predict the spectra at 90 deg (i.e., normal to plane of airfoil) for airfoils of finite chord immersed in a mean velocity gradient. Olsen[8] demonstrated experimentally that this theory predicts the spectra at 90 deg for finite-chord

Received July 2, 1981. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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airfoils with excellent accuracy; in contrast, incompressible theory was only applicable to extremely small chord airfoils.

There is no fundamental theory that accounts for all of the effects that occur in the experiment reported herein; namely, thickness, oncoming (incident) velocity gradients, and compressibility. Therefore, any theoretical comparisons made in this experimental Note will be with existing theories described above, wherever they apply to this experiment.

Apparatus and Procedure

The apparatus, instrumentation, and data reduction system are the same as that used in Ref. 8. Valve noise was removed by mufflers down to a velocity of about 50 m/s. Figure 1 shows a schematic of the apparatus, and the very small chord and very large chord airfoils tested. The airfoil thickness was varied, but in all cases the leading edge was in the center of the turbulent mixing region of the jet. Figure 1 also defines some of the symbols used herein.

Reference 8 showed that this arrangement with a small jet permits almost the entire noise emission from the airfoil to be studied without the contamination of the jet noise. Furthermore, the axial and spanwise velocity gradients only affect the absolute level of the noise in comparison to theory, because the surface noise source is concentrated in a very small spanwise and axial region of the turbulent jet. However, the velocity gradients across the airfoil thickness must be accounted for, except (according to theory) at 90 deg.

The noise emission was measured with eleven 0.63 cm microphones placed along a horizontal semicircle (4.57 m radius) that was centered on the leading edge of the test airfoil. Acoustical foam was placed on the ground over the circle. This arrangement resulted in far field data that was not subject to ground reflections (i.e., free field) above about 400 Hz. Furthermore, neither the nozzle nor the airfoil supports caused measurable reflections or shielding.

The noise signals were analyzed by an automated spectrum analyzer which yielded ⅓-octave band sound pressure level (SPL) spectra for each microphone. These data were subsequently corrected to remove the small losses due to atmospheric attenuation of the sound. Jet noise, which was measured separately with only the support in place, was also subsequently removed so that the data reported (SPL_c) represent pure airfoil-alone noise. None of the SPL_c data reported required more than a 2 dB correction. Data requiring a greater correction were not plotted; these occurred at very low and high frequencies, and at large θ_i.

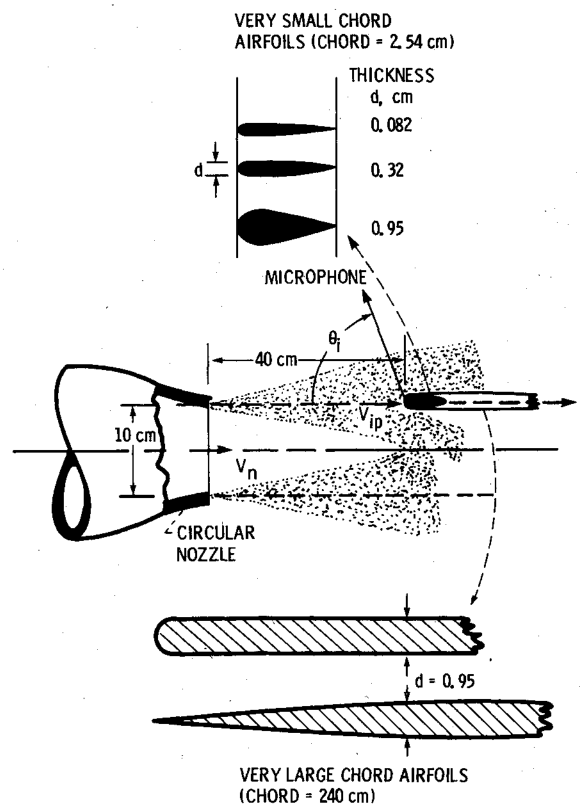

Fig. 1 Test configurations and surfaces tested.

Results and Discussion

Small Chord Airfoil

The effect of airfoil thickness upon the noise spectra at $\theta_i = 90$ deg is shown by the data plotted in Fig. 2a. The airfoil-alone noise spectra for three small-chord airfoils of varied thickness are compared at two velocities, V_{ip}. These three airfoils are of the same chord and all are subject to the same incident velocities and turbulence.

The data clearly show that there is a large thickness effect. The noise level generated by the thick airfoil is much lower than that of the thin airfoils, especially at high frequency. The decrease in the SPL_c from that generated by the thinnest

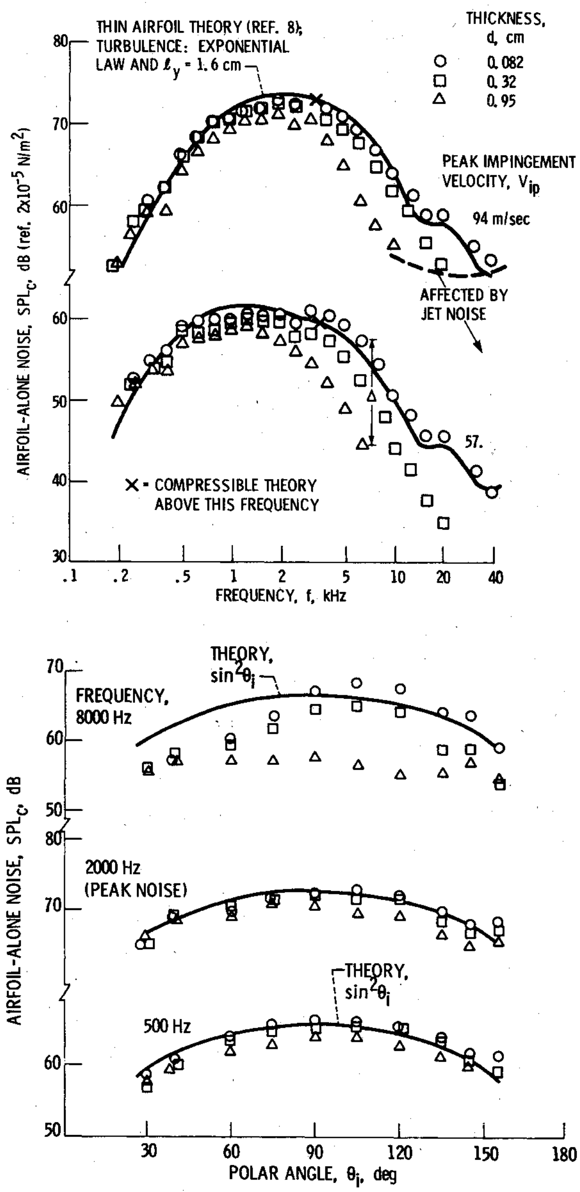

Fig. 2 Effect of airfoil thickness on the noise emitted by a very small-chord airfoil. Airfoil chord, 2.54 cm; freefield lossless data; jet noise and background noise removed: a) spectra at $\theta_i = 90$ deg; b) radiation patterns at constant frequency, $V_{ip} = 94$ m/s.

airfoil ($\Delta = SPL_{c,thinnest} - SPL_{c,thicker}$) increases linearly with frequency and also with increasing thickness.

The theoretical spectra at $\theta_i = 90$ deg for a thin airfoil, which accounts for compressibility[1] are also shown in Fig. 2a as solid curves. According to the theory, frequencies to the right of the X on the curves are where compressible effects are important. The wiggles in the theoretical spectrum at very high frequency are due to the Fresnal integral term in the compressible theory.

The theory and data for the thin airfoil are in excellent agreement over the whole spectrum, including the wiggles. Only the absolute level of the set of theoretical spectra was adjusted for the best overall agreement to the data; all other inputs to the theory (summarized in Ref. 8) were as measured (i.e., transverse turbulence scale length, ℓ_y; peak impingement velocity, V_{ip}; chord length, etc.).

In previous theoretical comparisons with thin airfoils,[8] the thinnest airfoil tested was 0.32 cm. The results shown in Fig. 2a indicate that the airfoil used in Ref. 8 was thin enough for thin airfoil theory to apply, except for very high frequencies. The thinnest airfoil tested in this experiment (0.082 cm) was impractically thin; indeed, special care was taken, and additional experiments were performed to insure that the thinnest airfoil data were not affected by vibration or deflection.

The effect of airfoil thickness upon the radiation patterns of the noise at three frequencies is shown in Fig. 2b for one velocity, $V_{ip} = 94$ m/s. The highest and lowest frequencies were selected to avoid large jet noise corrections, while the middle frequency corresponds to the peak noise of the spectrum plotted in Fig. 2a.

The radiation patterns for the lowest and peak noise frequencies show no sizeable effect of thickness. On the other hand, the patterns for the highest frequency show a large effect of thickness; the thinnest airfoil is much noisier than the thick airfoil.

The theoretical pattern for a thin, small-chord airfoil in uniform turbulent flow ($\sin^2\theta_i$) is put through the data at each frequency. The agreement is excellent at the low and peak frequencies, but the agreement is poor at high frequencies, even for the thinnest airfoil. This discrepancy with the thin airfoil data is probably due to the transverse velocity gradient across the airfoil thickness. There is no theory at this time to account for the effect of velocity gradients on the radiation pattern from a small airfoil. Existing theories that account for the effect of velocity gradients are for jet noise[3] and for edge noise from infinite plates.[4] These theories show that there is no effect of velocity gradients at $\theta_i = 90$ deg; we took advantage of this fact in the spectral comparisons made in Fig. 2a.

The radiation pattern for the thick airfoil seems to curl up at large and small θ_i, especially at high frequency. This effect is probably due to the "drag dipole," which was shown more clearly for thick airfoils in the data of Ref. 8. Fluctuating drag forces were neglected in the thin airfoil theory that produced the $\sin^2\theta_i$ pattern.

Similar thickness-effect comparisons were also made (not shown) for the very large chord airfoils shown in Fig. 1. The agreement between the prediction from compressible-thin airfoil theory and the spectral data at 90 deg was again excellent. The effect of thickness on the spectra and radiation pattern was similar to that shown in Figs. 2a and 2b.

Conclusions

This experiment expanded upon the thickness-effect aspect of the airfoil experiments performed in Ref. 8. The results show that the effect of thickness is large and must be accounted for in any fundamental airfoil noise theory that attempts to describe the noise emitted from real airfoils. Incident mean velocity gradients and compressibility must also be taken into account. The effect of thickness increases with frequency, with thick airfoils being quieter than thin ones.

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AIAA 82-4069

Active Attenuation of Acoustic Disturbances in Pulsed, Flowing Gas Lasers

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Introduction

In pulsed, flowing gas lasers, only a small fraction of the pump energy is converted to laser output. Most of the energy goes into heat and acoustic waves which, until they eventually die out, distort the optical medium unacceptably. The laser pulse rate, which is limited by the acoustic relaxation time, can be increased by employing sidewall mufflers to speed up the damping process. In CO_2 lasers, the required attenuation can be achieved with reasonable muffler volumes.[1] However, the order of magnitude more stringent density homogeneity needed for excimer lasers necessitates that very large, costly mufflers be used to meet the required 40 dB attenuation in sound power.[2]

For typical cavity dimensions of 0.50-1 m in the flow direction, most of the acoustic power is concentrated in the frequencies below a few hundred hertz.[3]

The effects of the lowest-frequency disturbances can be eliminated by fixed optical corrections.[4] The muffler volume is then driven by the need to attenuate the frequencies from a few ten to a few hundred hertz, which is the range over which active attenuation has been demonstrated.

The application of active attenuation[5] to the control of sound in laser ducts is best understood by an eigenmode[6]

Received May 14, 1981; revision received Aug. 31, 1981.

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