Effect of Initial Condition on Subsonic Jet Noise

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The initial boundary-layer state can significantly affect the radiated noise from an axisymmetric jet. Jets with initially laminar boundary layers are found to emit more noise. Thus, "cleaner" far-field noise characteristics are achieved in tripped jets. Data suggest that the additional noise in the initially laminar case partly originates from the first stage of pairing of the coherent shear-layer vortices.

Introduction

ALTHOUGH there have been several investigations studying the effect of the initial condition on the turbulence structure of jets and mixing layers,[1-3] few studies addressed the corresponding effect on jet noise. Those that addressed this question typically involved noise measurements with and without a trip in the boundary layer, but without detailed documentation of the initial condition. In general, from results at high Mach numbers, the effect of tripping on the far-field noise has been assumed to be insignificant.[4] However, remarkable effects were observed, mostly at lower Mach numbers, in a set of present experiments.

The initial condition of a jet can be expressed in terms of several parameters at the jet exit. For a top-hat mean velocity profile, the most important parameter is the efflux boundary-layer state. This state can be suitably characterized by the measured profiles of mean velocity (U) and turbulence intensity (u') along a radial line at the exit plane. These, for a nozzle ending into a straight (cylindrical) section, should agree with flat-plate boundary-layer characteristics, provided that the thickness of the layer is small compared to the diameter of the jet. Thus, for fully laminar state, the $U(y)$ profile should agree with the Blasius profile, but for fully turbulent state, it should exhibit clearly discernible logarithmic and wake regions in a relatively thicker boundary layer. The shape factor (δ_l/Θ) should change from 2.59 to about 1.4 from laminar to turbulent state[5]; δ_l and Θ are the displacement and the momentum thicknesses, respectively. $u'(y)$ for the laminar state remains low and constant throughout the exit plane, into the boundary layer, until dropping to zero near the wall. In contrast, a sharp rise, to about $0.10\ U_e$, occurs near the wall in the fully turbulent layer; U_e is the exit velocity in the core of the jet.

Besides the above two well-defined asymptotic states of the efflux boundary layer, there may exist several transitional states,[6] which can be divided into two broad categories: nominally laminar and nominally turbulent. While $U(y)$ tends to agree with the Blasius profile, large fluctuation intensity is encountered, say, over but close to $0.01\ U_e$ in the former category and around $0.10\ U_e$ in the latter. In practice, the two asymptotic states are hard to achieve while the transitional states generally exist in typical model jets. It is shown in the following that when a fully or nominally laminar boundary layer is tripped to obtain at least a nominally turbulent state, the far-field noise is reduced.

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Procedures

The experiments were carried out in an anechoic facility of NASA Langley Research Center. The jet flow was obtained by passing air through a vertical settling chamber (20-cm diameter), and then through a contoured, convergent, detachable nozzle that ended in a short cylindrical section of diameter (D) of 2.54 cm. Further details of the facility can be found in Ref. 7. Standard hot-wire anemometry was employed for boundary-layer measurements. Standard microphone measurements were done for the far-field noise, at different angle θ from the downstream jet axis, measured at 120 D from the jet exit. Tripping was done by 100-grit carborandum particles (0.15-mm nominal size) sprinkled over a thin coat of clear lacquer painted on the inside surface of the nozzle. The area tripped was a 1.25 cm wide strip, 1.25 cm inside from the nozzle exit; the particle density used was approximately 1 per 1.5-mm^2 area.

Data for a number of U_e were obtained with the trip on (or off), and these data trends were then compared with the corresponding data for the other initial condition obtained subsequently. However, it was noted that the data repeatability was

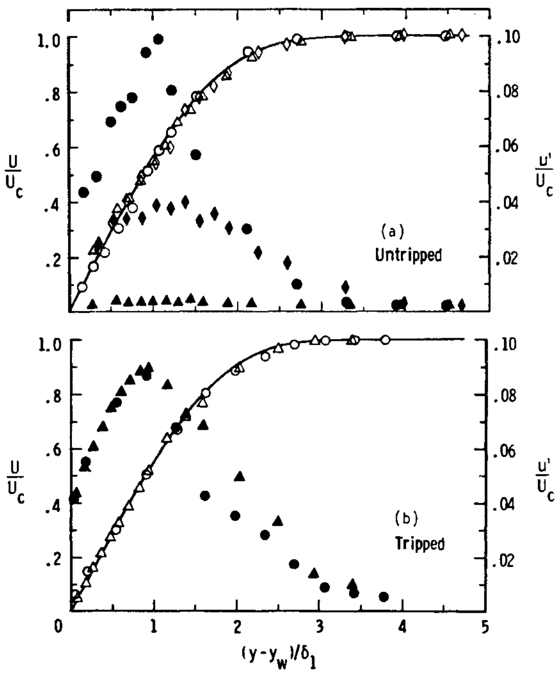

Fig. 1 Profiles of longitudinal mean velocity (U, open symbols) and rms fluctuation intensity (u', closed symbols) in the exit boundary layer of the jet; y_w is location of nozzle wall, δ_l the displacement thickness. a) Untripped jet: △, $U_e = 60\ ms^{-1}$; ◇, $U_e = 90\ ms^{-1}$; ○, $U_e = 148\ ms^{-1}$. b) Tripped jet: △, $U_e = 62\ ms^{-1}$; ○, 140 ms^{-1}.

poor, especially at low speeds, presumably due to small changes in the facility every time the nozzle was remounted.[7] Only after comparison of several data sets, it became apparent that there were certain repeatable features of the noise spectra which were affected by the tripping.

Results and Discussion

Typical exit boundary-layer characteristics, measured about 0.5 mm downstream of the exit plane, are shown in Fig. 1. While $U(y)$ for the untripped cases agreed with the Blasius profile, the fluctuation intensity increased rapidly above a Reynolds number (Re_D) of about 10^5. For the tripped jet, even at the high speed, $U(y)$ agreed with the Blasius profile. This indicated that tripping did not produce a fully turbulent state; limited trials with various grit size and density did not make a difference. However, in the range $Re_D \lesssim 2.5\times10^5$, tripping significantly thickened the boundary layer as well as increased the turbulence intensity, as should be clear from the discussion of Fig. 2.

Figure 2 shows the variations of the peak intensity (u'_{max}) and the momentum thickness (Θ) with Re_D and the Mach number ($M=U_e/a_0$, a_0 being ambient sound speed), for the untripped jet. For $Re_D \lesssim 10^5$, the intensity is low and essentially uniform across the jet exit; thus, the boundary layer can be considered fully laminar in this range. (Re_Θ corresponding to $Re_D=10^5$ is 300; note that boundary-layer theory[8] predicts a critical Re_Θ of 200 and a transitional Re_Θ has been found to be anywhere up to 1200). The solid line through the data of Θ/D represents the equation $\Theta/D=1.02/\sqrt{Re_D}$; marked deviation occurs at high Re_D. According to the criteria discussed before, the boundary layer in the present (untripped) jet becomes nominally laminar above $Re_D \simeq 10^5$ and then nominally turbulent above $Re_D \simeq 2.5\times10^5$. For the tripped jet, u'_{max}/U_e as well as Θ/D remained constant at about 0.09 and 0.009, respectively, over the entire measurement range. Thus, for $Re_D \lesssim 2.5\times10^5$ ($M \lesssim 0.45$), tripping undoubtedly changed the fully or nominally laminar state into a nominally turbulent state. It is in this range that tripping was also found to make a difference in the far-field noise.

The far-field (total) sound intensity (L, dB re 2×10^{-5} N/m^2), for $\theta=30$ and 90 deg, is shown in Fig. 3. It is observed that in the range $0.5 \lesssim M \lesssim 0.9$, the intensity varies as $U_e^{9.2}$ at $\theta=30$ deg, and as $U_e^{7.5}$ at $\theta=90$ deg,[7] and that tripping does not have any noticeable effect. But, for lower M, tripping reduces the noise levels. A deviation from a M^E-power law for the intensity at low M, has been observed in most previous studies, and attributed to internal or other parasitic noise sources. The present data demonstrate that the deviation is more for laminar initial conditions and that

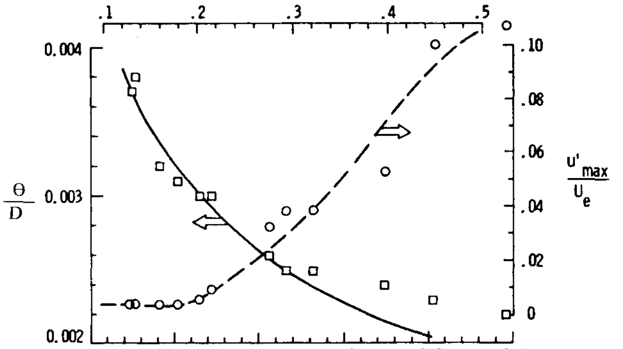

Fig. 2 Variations of exit boundary-layer momentum thickness (square symbols) and maximum turbulence intensity (circles) with Re_D and M for the untripped jet.

tripping results in cleaner noise characteristics. Note that for a given M (i.e., U_e) the reduction in the jet thrust due to a thicker boundary layer in the tripped case is insignificant; at $M=0.2$, it is estimated to be about 0.3 dB when the reduction in L is about 4 dB.

The normalized power spectral density (psd) of the far-field noise is shown in Fig. 4a for several low M for the untripped jet. Here

$$P^* = \left(\frac{p'}{\rho U_e^2}\right)^2 \left(\frac{R}{D}\right)^2 \left(\frac{U_e}{\Delta f \cdot D}\right)$$

where p' is the rms sound pressure in the bandwidth Δf.[7] One observes that with decreasing M, the normalized psd amplitude increases and the traces are characterized by certain high-frequency peaks. Inspection reveals that the dominant peaks, indicated by the arrows, correspond to a narrow St_Θ range of 0.005-0.007; St_Θ is the Strouhal number based on the exit boundary-layer momentum thickness. Similar high-frequency peaks in the same St_Θ range have also been observed by Bridges and Hussain.[9]

The natural roll-up frequency for the laminar initial shear layer in various investigations has been found to correspond to $St_\Theta \simeq 0.012$.[10] This was verified in the present jet by hot-

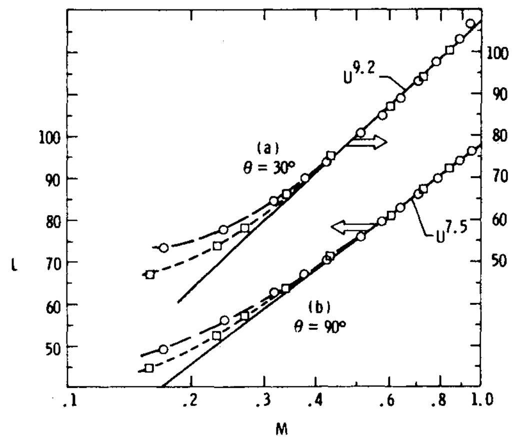

Fig. 3 Variation of the sound intensity, L(dB re 2×10^{-5} N/m^2) with Mach number M. ○, untripped jet; □, tripped jet.

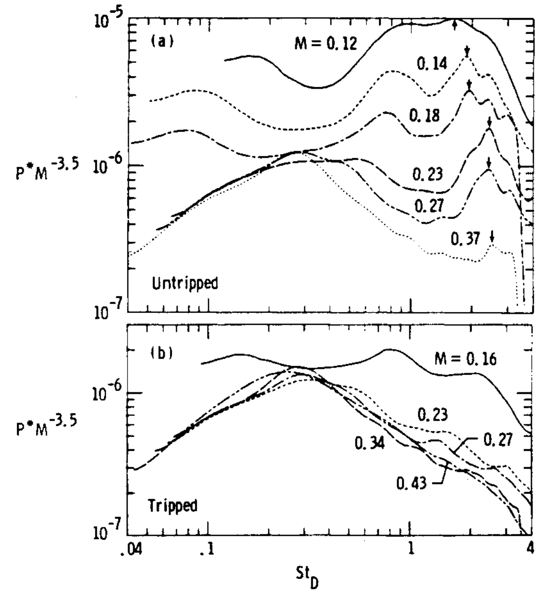

Fig. 4 Far-field noise psd at $\theta=90$ deg for different M.

wire measurements via the method of probe interference.[11] Thus, the dominant high-frequency peak in the far-field noise spectra corresponds to half the initial roll-up frequency. Therefore, it is reasonable to believe that the first stage of pairing of the shear-layer vortices causes these high-frequency peaks. [Note that similar high-frequency spectral peaks are also observed in trailing-edge noise from airfoils.[12] However, trailing-edge noise, and various classes of similar phenomena, occur at the vortex shedding frequency rather than at the subharmonic(s).]

It has also been found previously[10] that stronger, laminar-like coherent structures dominate the flow, in the first few diameters, for the cases of laminar initial condition. The interaction and evolution of these stronger structures are also believed to contribute to the higher noise level. These notions are substantiated by the fact that tripping removes the high-frequency peaks as well as brings down the psd levels to an asymptotically lower level observed for high Mach numbers. This is shown by the psd traces for the tripped jet in Fig. 4b. A similar observation is also made at $\theta = 30$ deg, for which data are shown in Figs. 5a and 5b. Note for the tripped jet that at the lowest speed, a return to the trend for the untripped case occurs, probably due to relaminarization of the boundary layer. Note also that since the jet at higher speeds has a transitional or turbulent boundary layer, the effect of tripping is observed only at low speeds.

The observed initial condition effect sheds new light on the excess, or internal, noise from low M jets.[13] The excess noise dominating over the jet mixing noise, even for model jets, had been typically thought of as originating from upstream sources, e.g., due to unsteady flow separation, valve noise, fan noise, etc. This notion changed considerably with the discovery of broadband noise amplification by excitation,[4,14] which clearly emphasized the role of jet instability mechanism in these processes. The present experiment further emphasizes this point and traces at least part of the excess noise to physical processes, like pairing of the votices, in the flow.

A few sets of data were found in the literature dealing with the effect of initial condition on jet noise. These generally supported the present observations; some, however, were in apparent disagreement. Figure 6a shows data obtained by Maestrello and McDaid,[15] on radiated sound psd (integrated over the sphere of radiation), for a short nozzle having laminar exit boundary layer (solid line), and for a longer nozzle having partially turbulent boundary layer (dashed line). These data are in qualitative agreement with the present results showing that a turbulent initial condition reduces the noise levels. (A reviewer has pointed out that similar observations were also made in Refs. 16 and 17.) The solid trace in Fig. 6a does not exhibit the high-frequency peaks; this should be partly because of one-third octave analysis, which smoothes out details on the high-frequency end. (Present measurements are based on narrowband spectral analysis.) Figure 6b shows data on the noise source measurements by Grosche[18]; these data represent the overall sound radiation from different axial locations obtained from the far field by elliptical mirror technique. The effect of tripping shown by these data is also in excellent qualitative agreement with the present inference, in that the additional noise is shown to originate from the region $0 \lesssim x/D \lesssim 2.5$, where pairing of the shear-layer vortices takes place. Grosche's data also demonstrate the effect of tripping on the radiated noise for as high a Mach number of 0.7.

Figure 6c shows far-field noise psd at $\theta = 25$ deg reported by Mollo-Christensen[19]; these data have been normalized to present in the same format as in Fig. 5. The tripped vs untripped jet data for the 2.54-cm jet show the same trend as in

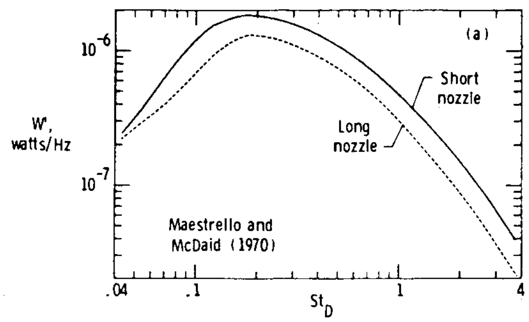

Fig. 6a Data from Ref. 15. Radiated acoustic power from 6.2-cm-diam jets at $M = 0.71$.

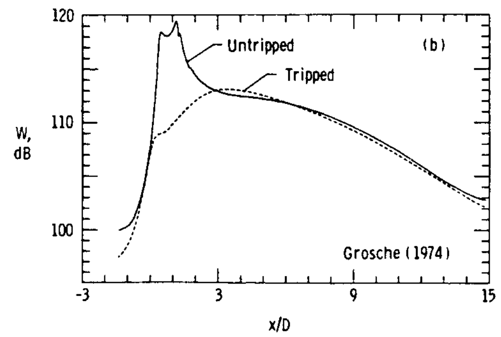

Fig. 6b Data from Ref. 18. Variation of overall sound source intensity with downstream distance from the nozzle exit, measured by elliptical mirror technique. Data for 2-cm-diam jet at $M = 0.7$.

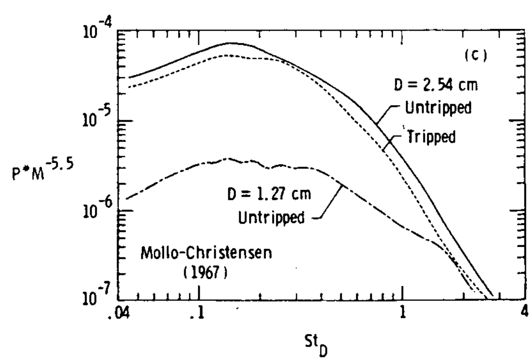

Fig. 6c Data from Ref. 19 and presented as in Fig. 5. All data are for $\theta = 25$ deg and $M = 0.6$.

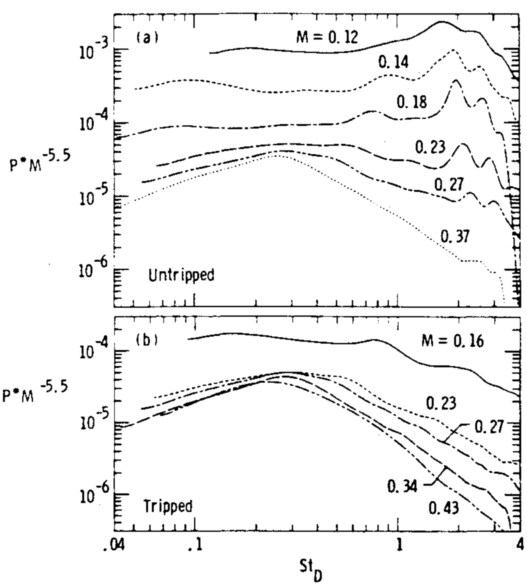

Fig. 5 Far-field noise psd at $\theta = 30$ deg corresponding to the data of Fig. 4.

Fig. 6a. However, data from the untripped 1.27-cm jet, presumed to have a laminar boundary layer, show a remarkably lower amplitude. A similar low psd amplitude in low Re_D jets has also been observed in Ref. 20. It is reasonable to presume that the low Re_D jets would have laminar boundary layers. Thus, these data would imply lower noise level for laminar initial condition, in apparent conflict with the present observation. An explanation for this is not clear. It is possible that some peculiarity in the large-scale structure (instability) characteristics of the low Re_D jets in question could explain this. Since higher order mode, large-scale structures are inefficient noise radiators,[21] one could speculate that such structures, instead of the more common axisymmetric structures, dominated these jets, causing the observed lower noise levels. If this were true, a new avenue for investigation of jet noise suppression through large-scale structure control would appear prospective.

Conclusion

If the efflux boundary layer is fully or nominally laminar, an axisymmetric jet emits more noise. There is evidence tracing part of the excess noise to physical processes in the flow, namely, to the pairing of the initial vortices and to the evolution of stronger coherent structures characteristic of jets with initially laminar boundary layers.

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