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Turbulence suppression in free turbulent shear flows under controlled excitation. Part 2. Jet-noise reduction

By A. K. M. F. HUSSAIN AND M. A. Z. HASAN†
Department of Mechanical Engineering, University of Houston, Texas

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It is shown that reduction of broadband (even total) far-field jet noise can be achieved via controlled excitation of a jet at a frequency in the range $0.01 < St_\theta < 0.02$, where St_θ is the Strouhal number based on the exit momentum thickness of the shear layer. Hot-wire measurements in the noise-producing region of the jet reveal that the noise suppression is a direct consequence of turbulence suppression, produced by early saturation and breakdown of maximally growing instability modes.

1. Introduction

The reduction of turbulence intensity in the near field of an axisymmetrically excited circular air jet at the Strouhal number St_D ($\equiv fD/U_e$) ≈ 1.6 at low subsonic Mach numbers (Hussain & Zaman 1975) puzzled us for a long time because the then-fresh data of Crow & Champagne (1971) in an excited circular jet showed no turbulence suppression; here f is the excitation frequency, D is the jet diameter and U_e is the jet exit velocity. It became subsequently known to us that Vlasov & Ginevskiy (1974) and Petersen, Kaplan & Laufer (1974) also independently noticed turbulence suppression at excitation Strouhal numbers $St_D \approx 2.75$ and 3.0 respectively. However, neither of these groups attempted to explain this interesting phenomenon or even emphasized the suppression effect. Our detailed investigations revealed that reduction of jet centreline turbulence due to excitation was unavoidable, at least for some range of frequencies.

The fact that the St_D values of excitations causing turbulence suppression varied considerably between three experiments suggested to us (Zaman & Hussain 1981, hereinafter referenced as ZH) that the observed phenomenon was neither a tailpipe effect (Crow 1972; Crighton 1975, 1981*b*; Crighton & Gaster 1976), nor a result of superposition of acoustic and hydrodynamic waves in the jet near field (Pfizenmaier 1973; Rockwell & Schachenmann 1982) and that St_D was not the appropriate characterizing parameter. ZH were able to produce turbulence suppression in a number of flow configurations (viz circular and plane jets and plane mixing layers) via different excitation techniques. Both circular and plane jets were excited via settling-chamber cavity resonance, the plane jet and the plane mixing layer were excited by electromagnetically driven vibrating ribbons, and all facilities were also exposed to acoustic excitation with a loudspeaker located downstream of the lip and external to the flow. In Part 1 of this study, ZH documented in detail the suppression effect and showed that turbulence suppression occurred for all these

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† Present address: Department of Mechanical Engineering, The Catholic University of America, Washington, D.C. 20064.

kinds of excitations at frequencies corresponding to the Strouhal number St_θ ($\equiv f\theta_e/U_e$) ≈ 0.017, where θ_e was the initial momentum thickness of the shear layer. The explanation provided by them was that, this being the maximally unstable St_θ (Michalke 1965; Freymuth 1966), excitation at this frequency produced, as compared with the unexcited case, more rapid growth of the instability waves and their earlier saturation, precipitating an earlier roll-up and transition (breakdown). In the absence of the excitation, the shear-layer instability is dominated by waves which receive maximum amplification at $St_\theta \approx 0{\cdot}011$ (Freymuth 1966; Hussain & Zaman 1978). At this lower St_θ, the disturbance wavelength being longer, the rolled-up vortical structures are larger, and their interactions and evolutions are consequently more energetic. The excitation-induced earlier saturation and breakdown of the shear-layer structures (also visualized as well as educed by ZH) resulted in a decrease in the turbulence intensities, Reynolds stress and shear-layer spreading. Based on these hydrodynamic data, ZH speculated that such reduction might be associated with a reduction in the radiated jet noise.

The objective of the present investigation was therefore to determine experimentally if there existed a narrow range of St_θ over which controlled excitation produced reduction of far-field jet noise. It was decided to use acoustic excitation for this purpose. Since excitation introduced additional sound into the jet, it would be especially interesting if reduction of overall sound-pressure level (OASPL) could be achieved this way. It should be noted that Moore (1977) reported a small reduction in the far-field noise level of an initially turbulent circular jet for excitation at $St_D > 1.5$ and for Mach numbers M up to 0.7. However, this reduction was only *after* the subtraction of the energy peaks at the excitation frequency and its harmonics (see also Kibens 1980). In fact, we are not aware of any study that has shown reduction in OASPL (including these peaks) by excitation.

Another objective of this study was to examine the validity of Crighton's (1981 *a*) Reynolds-number barrier hypothesis. In brief, a review of experimental data suggested to him that broadband amplification would in general occur for $Re_D > 10^5$ and reduction would occur for lower Re_D. Apart from the point of view of validity of Reynolds-number similarity, this suggestion should raise serious question about the typical practice of extrapolating characteristics of low-Reynolds-number laboratory jets to practical jets.

2. Apparatus and procedure

The experiments were carried out in a 4 cm air jet located in the University of Houston anechoic chamber (figure 1). The chamber, of size 7.6 m × 5 m × 5 m between wedge tip and wedge tip, is a well-ventilated concrete box of 27 cm wall thickness supported on air bearings. The box is lined with closely packed fibreglass wedges 61 cm long and spaced 20 cm apart, which make the chamber anechoic down to 75 Hz with a background OASPL level of 45 dB. The jet is provided with air from a d.c. motor-driven seven-stage centrifugal blower, which is connected to the supply pipe via mufflers and vibration-isolating couplings. The entire 70 m length of the supply pipe is free from any valve or flow separation and is of the same diameter (15 cm) as that of the settling chamber, and all bends are of large-radius type. Thus the jet flow is virtually free from any noise from the blower or noise generated within the pipe. The 5 m long settling chamber is fitted with a number of screens (9 and 40 meshes/cm) so that the flow at the end of the settling chamber (before the nozzle) is uniform in the mean velocity and fluctuation intensity. The shape of the nozzle

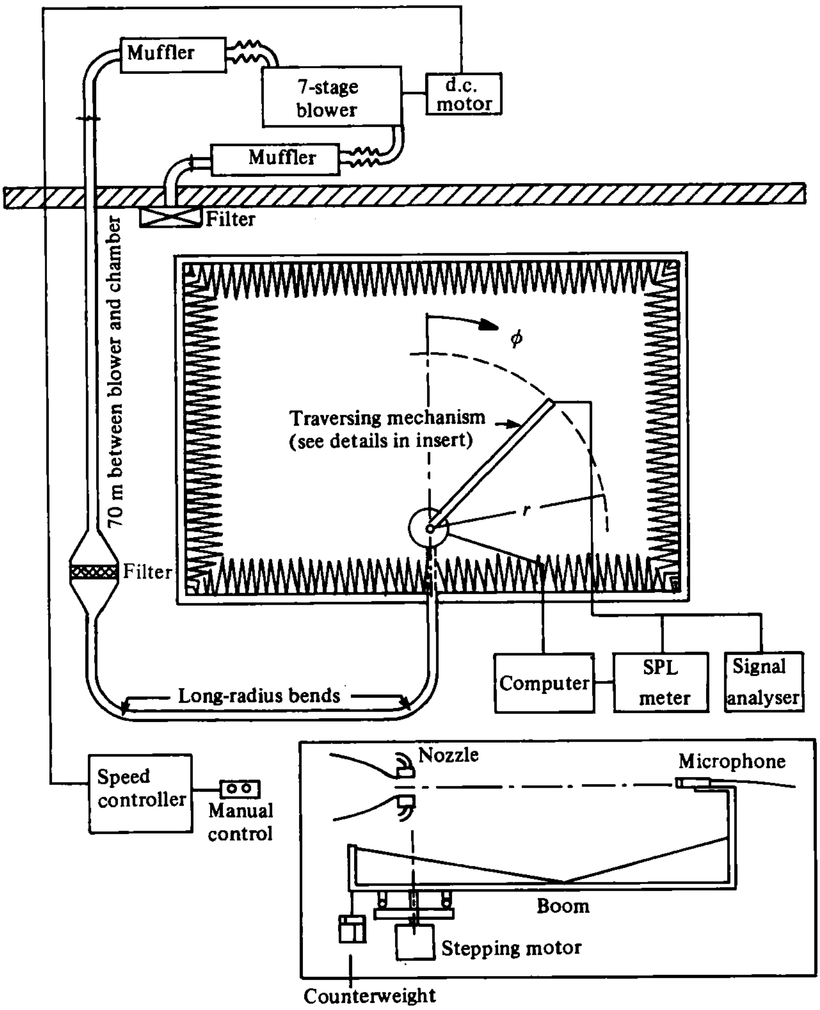

FIGURE 1. Schematic of the anechoic chamber and flow facility.

(of contraction ratio 16:1) is a compromise between the Batchelor–Shaw and cubic-equation profiles. The nozzle exit flow is found to be axisymmetric with a top-hat profile and free from swirl. The excitation is introduced via a 1 mm slit all around the lip of the nozzle (see insert in figure 1). This slit leads out of a thin axisymmetric jacket outside the nozzle, to which disturbances are fed from a tweeter via 24 equal-length tygon tubes of 1.6 mm inner diameter. Somewhat similar excitation techniques were employed by Petersen *et al.* (1974) and Kibens (1980).

Far-field sound-pressure level (OASPL) and spectra were measured with a 1.27 cm condenser microphone (B & K 4133) fitted with a preamplifier (B & K 2619). The microphone, mounted on top of a vertical rod at the end of a horizontal boom, was traversed in a circular arc (of a meridian circle) in the horizontal plane through the jet axis (see insert in figure 1). The true axis was determined from the far-field OASPL data as a function of the emission angle ϕ.

The facility was qualified by recording OASPL and spectral data taken along an arc or radius $57D$ for M up to 0.69. The OASPL data as a function of ϕ for

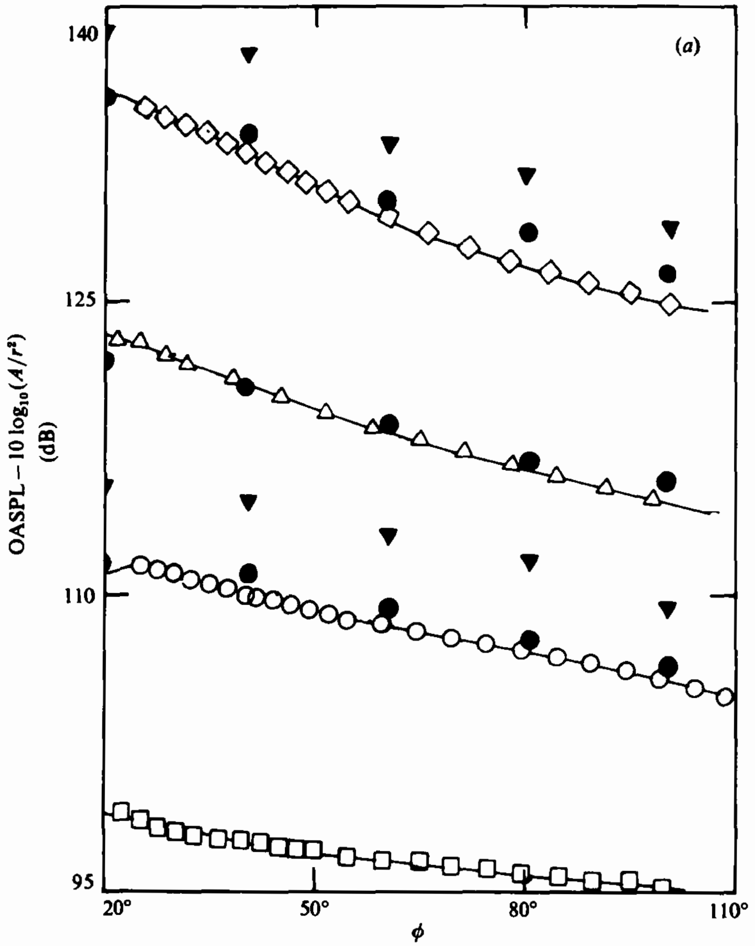

FIGURE 2 (*a*). For caption see facing page.

different M are shown in figures 2(*a*, *b*). In figure 2(*a*) the data have been plotted as OASPL $-10\log_{10}(A/r^2)$ as a function of the emission angle ϕ; here $A = \frac{1}{4}\pi D^2$ and $r = 57D$. These data are in reasonable agreement with the data of Moore (1977), but are about 3–4 dB lower than the data of Ahuja (1972). The data of Lush (1971) are not shown here, because his data are within ± 0.5 dB of Moore's data. In figure 2(*b*) the OASPL data are compared with theoretical curves using the convection factors $(1-M_c\cos\phi)^{-5}$ and $\{(1-M_c\cos\phi)^2+(\alpha M_c)^2\}^{-\frac{5}{2}}$ proposed by Lighthill (1952) and Ffowcs Williams (1963) respectively; M_c is the convection Mach number. The values used for M_c and α in figure 2(*b*) are 0.62 and 0.5 respectively. The levels of the theoretical curves are adjusted to go through the experimental data at 90° from the jet axis, where the convection effect is small. The data suggest Ffowcs Williams' prediction to be more accurate than Lighthill's, particularly at higher Mach numbers. The cumulative acoustic power as a function of ϕ also agreed with that predicted with Lighthill's theory. Both sound-pressure spectrum and the $\frac{1}{3}$-octave OASPL as a function of St_D at different ϕ showed very good agreement with data reported in the literature (see Goldstein 1976). These, along with hot-wire measurements within the near field of the jet, proved that the jet did not display any irregular behaviour either acoustically or hydrodynamically.

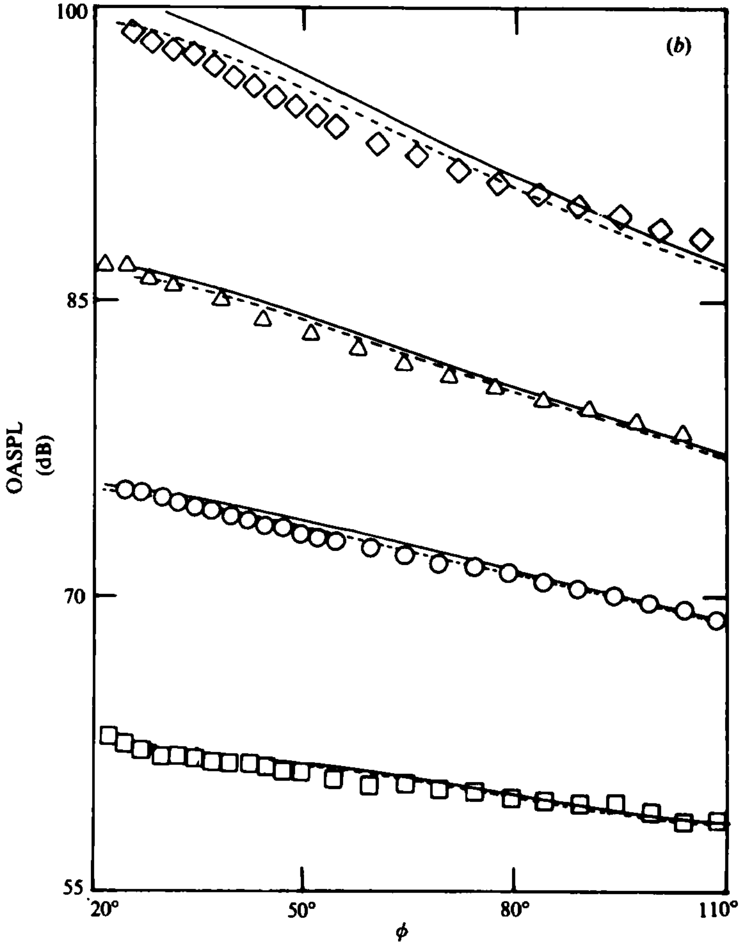

FIGURE 2. (*a*) Comparison of OASPL directivity with others' data: ●, Moore (1977); ▼, Ahuja (1972); □, $M = 0.25$; ○, 0.37; △, 0.50; ◇, 0.69. (*b*) Variation of OASPL with ϕ: ———, Lighthill's (1952) theory with Doppler factor 5; ----, Ffowcs Williams (1963).

Further details of the facility and measurements are reported by Hasan (1983).

In order to introduce excitations corresponding to St_θ values around 0.017 as well as of sufficient amplitude (limited by frequency responses of the excitation port and tweeter), the noise-suppression study had to be limited to low Mach numbers ($M = 0.1$, 0.15 and 0.2 only). However, at these low M, the sound level at $57D$ being near the background OASPL of the anechoic chamber, data were taken along a circular arc $30D$ away from the jet exit.

3. Results and discussion

The nozzle exit-velocity profile was measured with a single hot wire. For all the measurements reported in this paper, both mean and r.m.s. fluctuating longitudinal velocity profiles indicated that the exit boundary layer was laminar. The mean profile with a shape factor of about 2.6 agreed well with the Blasius profile.

Figures 3(*a*, *b*) show the sound-pressure spectra at $\phi = 45°$ and 90° respectively. Each of these represents an ensemble average of 100 spectra obtained via FFT with

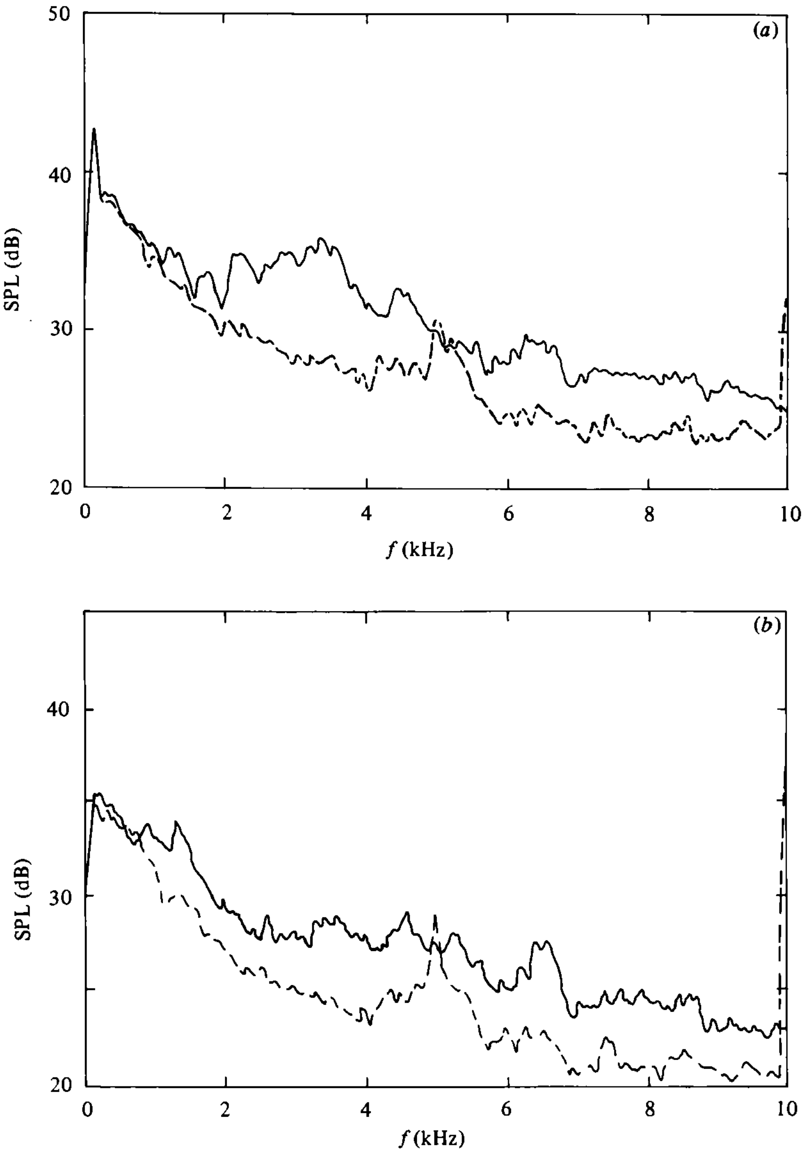

FIGURE 3. (a) Pressure spectrum at $\phi = 45°$ for $M = 0.15$ and $r = 30D$: ——, unexcited; -----, excited at $St_\theta = 0.0155$ ($St_D = 7.74$). (b) Same data as in figure 3(a) for $\phi = 90°$.

the help of a digital signal analyser (HP 5420A), which computed spectral values at 256 equispaced lines. Data closer to the axis were not recorded owing to interference of the microphone with the flow. Each of these two figures compares the unexcited spectrum with that excited at $St_\theta = 0.0155$ (corresponding to $St_D = 7.74$). Note that there is reduction in SPL everywhere, except at the excitation frequency at 10 kHz and its subharmonic. However, in contrast with Kibens' (1980) data, note that the subharmonic is relatively weak, and lower subharmonics like $\frac{1}{4}f$, $\frac{1}{8}f$, etc. are absent. This is consistent with the hot-wire data of ZH showing that turbulence suppression is associated with elimination of at least some stages of pairings.

The noise suppression is rather uniform over the entire spectral range, except for

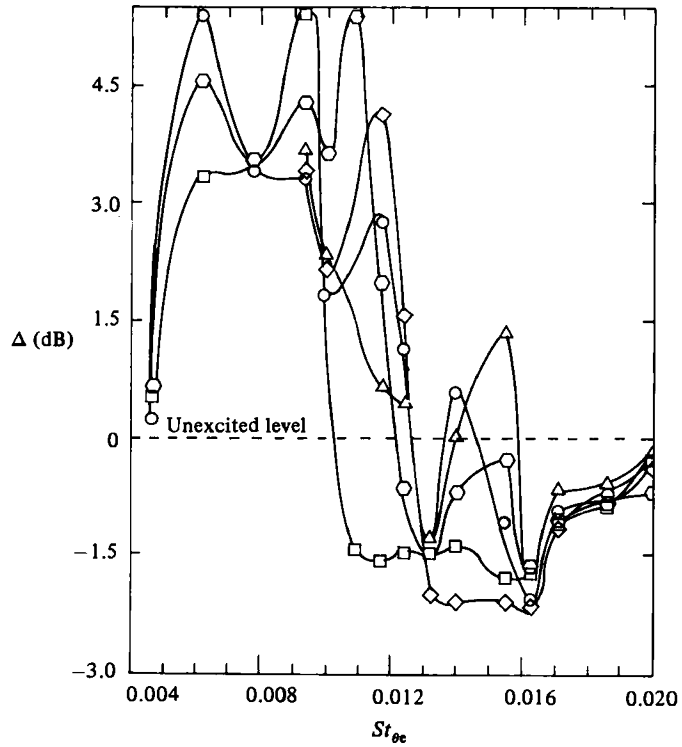

FIGURE 4. Relative change in OASPL with St_θ at $M = 0.15$: □, $\phi = 45°$; ⬡, 60°; △, 75°; ○, 90°; ◇, 105°.

$\frac{1}{2}f$ and, of course, the excitation frequency. Since the initial roll-up is organized by the excitation, the first pairing is also organized, producing a $\frac{1}{2}f$ peak. Kibens (1980) suggests that most noise is due to pairing, which usually occurs randomly in space and time, producing a broadband far-field noise signature. Controlled excitation can spatially localize these pairings, and thus the far field will show peaks at $\frac{1}{2}f$, $\frac{1}{4}f$, $\frac{1}{8}f$, etc. resulting in broadband suppression. The broadband noise reduction without any significant subharmonic peak, as observed in the present experiments, raises doubts about Kibens' proposition. Independently, we have argued (Hussain & Zaman 1981; Hussain 1983) that pairing in general cannot be the dominant contributor to noise in practical jets where toroidal pairing is rare, even though claims to the contrary have received widespread support (Laufer 1973; Ffowcs Williams & Kempton 1978; Crighton 1981*a*).

Figure 4 shows the change in the OASPL at different emission angles as a function of the excitation Strouhal number St_θ. The OASPL is the integral of the energy under each spectral curve. The ordinate is the OASPL with excitation minus the OASPL without excitation. It is clear that excitation, while typically producing a net increase of the OASPL, can also produce a net decrease. The decrease in the OASPL is maximum at $St_\theta \approx 0.016$.

Since data in figure 4 also contain acoustic energy in the excitation frequency and the subharmonic, it was considered more meaningful to examine broadband modification of the SPL by excluding these peaks. Bechert & Pfizenmaier (1975) and Moore (1977) examined broadband amplification by subtracting power in the peaks via rejection filters. Figure 5 shows the data in figure 4 after the peaks are subtracted.

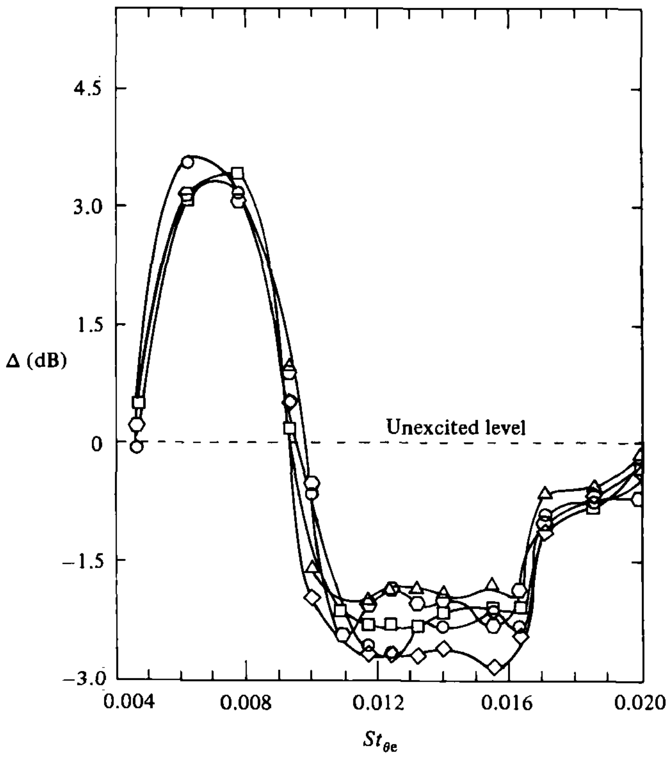

FIGURE 5. Broadband noise modification at $M = 0.15$. For symbols see figure 4.

Note that the irregular variations in OASPL (figure 4) have disappeared, and data at different angles show reasonable collapse. The positive values of the ordinate indicate broadband noise amplification, and the negative values indicate broadband noise reduction. It is clear that broadband reduction of far-field jet noise occurs over the range $0.010 < St_\theta < 0.02$.

The increase in the SPL over the range $0.004 < St_\theta < 0.009$ is due to broadband amplification. Excitation within this lower-frequency range forces the instability wave (of longer wavelength) to persist longer and thus grow to larger amplitudes before breakdown. The resulting higher turbulence level (confirmed by our hot-wire measurements) produces the enhanced far-field noise.

Figure 6 shows the corresponding suppression data (similar to the data in figure 5) at $M = 0.1$ for the same excitation amplitude. Note that the data at St_θ values lower than 0.008 could not be obtained because of the lower-frequency limitation of the tweeter used. It should be noted that the broadband noise reduction at $M = 0.1$ (by about 6 dB) is considerably larger than that (about 2 dB) at $M = 0.15$. This reduction decreases further at $M = 0.2$. For higher values of M no suppression could be obtained with the same excitation amplitude. In fact, excitation at higher M produced broadband amplification. At $M \approx 0.25$ the jet Reynolds number is about 2×10^5. Thus, the trends in our data are in agreement with the Reynolds-number barrier proposed by Crighton (1981*a*).

It has been our opinion that the Reynolds-number and Mach-number effects on jet noise as well as the effects of excitation on turbulence and noise reduction/amplification of a jet at different Reynolds numbers and Mach numbers *are indeed*

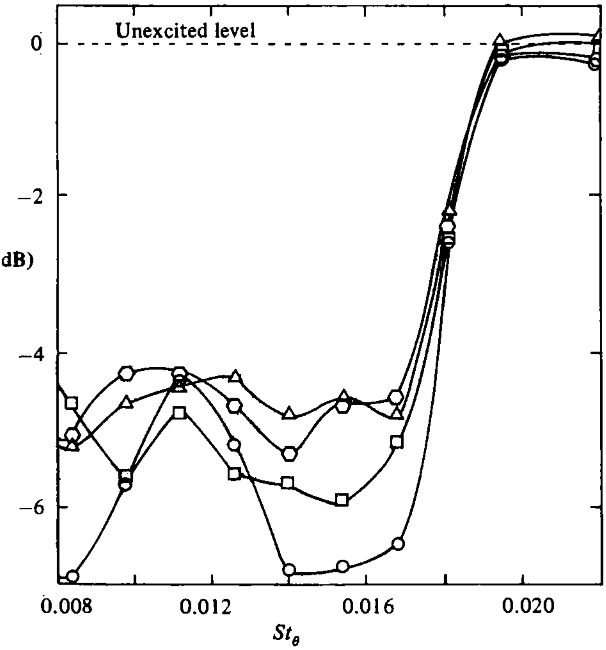

FIGURE 6. Broadband noise modification at $M = 0.1$. For symbols see figure 2.

initial-condition effects. In most laboratory jets, the exit boundary layer is laminar at low *Re* (say, below 10^5) and *M* (say, below 0.25) but turbulent at much higher *Re* and *M*.

Even though it is known that initially fully turbulent mixing layers also undergo roll-up, failure of excitation to induce turbulence suppression at high *M* or *Re* suggests a lack of coupling of the excitation with the turbulent-layer instability. This is because the background turbulence is both high-amplitude and three-dimensional. We believe that excitation should produce a corresponding modification of the initially turbulent shear layer also if the excitation amplitude and wavelength are sufficiently large compared with turbulence scales. Sufficiently higher excitation amplitudes were not available in our facility to test this conjecture.

The jet near field over the range $0 < x/D < 12$ was documented in detail with an X-wire by measuring the spatial distributions of longitudinal and lateral mean velocities U, V, fluctuation intensities u', v' and Reynolds stress $\overline{uv}$ for both excited and unexcited situations. The intensities and the Reynolds stress showed decreased peak values in the presence of the proper excitation. The excitation also produced a decrease in the width of the shear layer and of the jet as revealed by the contours of U, V, u', v' and $\overline{uv}$. However, the extent of the decrease in the peak values as well as the width is considerably smaller (see Hasan 1983) than that reported by ZH for low *M*. This correspondence between decreased turbulence suppression at higher *M* with decreased noise suppression at higher *M* is consistent with our claim that there is a direct dependence of the far-field noise on the near-field turbulence – both in amplitude and in frequency. The details of the mechanism underlying this dependence are far from being understood.

Therefore either broadband amplification or broadband reduction of the far-field acoustic noise of a jet is a direct consequence of near-field turbulence amplification or reduction respectively. The actual hydrodynamic mechanism for turbulence reduction was proposed and verified by ZH. The mechanism for broadband noise amplification, involving vortex breakdown and cut-and-connect interactions proposed by Hussain (1983), is very hard to verify and remains a conjecture.

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Note Added in proof: Professor Roger Arndt (private communication) has recently observed jet-noise reduction by excitation.

REFERENCES

AHUJA, K. K. 1972 M.Phil. thesis, London University.

BECHERT, D. & PFIZENMAIER, E. 1975 *J. Sound Vib.* **43**, 581.

CRIGHTON, D. G. 1975 *Prog. Aero. Sci.* **16**, 31.

CRIGHTON, D. G. 1981*a* In *The Role of Goherent Structures in Modelling Turbulence and Mixing* (ed. J. Jimenez). Lecture Notes in Physics, vol. 136, p. 340. Springer.

CRIGHTON, D. G. 1981*b* *J. Fluid Mech.* **106**, 261.

CRIGHTON, D. G. & GASTER, M. 1976 *J. Fluid Mech.* **77**, 397.

CROW, S. C. 1972 Acoustic gain of a turbulent jet. (Private communication.)

CROW, S. C. & CHAMPAGNE, F. H. 1971 *J. Fluid Mech.* **48**, 547.

FFOWCS WILLIAMS, J. E. 1963 *Phil. Trans. R. Soc. Lond.* A **225**, 469.

FFOWCS WILLIAMS, J. E. & KEMPTON, A. J. 1978 *J. Fluid Mech.* **84**, 673.

FREYMUTH, P. 1966 *J. Fluid Mech.* **25**, 683.

GOLDSTEIN, M. E. 1976 *Aeroacoustics*. McGraw-Hill.

HASAN, M. A. Z. 1983 Ph.D. thesis, University of Houston.

HUSSAIN, A. K. M. F. 1983 *Phys. Fluids* **26**, 2816.

HUSSAIN, A. K. M. F. & ZAMAN, K. B. M. Q. 1975 In *Proc. 3rd Interagency Symp. on University Research and Transportation Noise, University of Utah*, p. 314.

HUSSAIN, A. K. M. F. & ZAMAN, K. B. M. Q. 1978 *J. Fluid Mech.* **87**, 349.

HUSSAIN, A. K. M. F. & ZAMAN, K. B. M. Q. 1981 *J. Fluid Mech.* **110**, 39.

KIBENS, V. 1980 *AIAA J.* **18**, 434.

LAUFER, J. 1973 *Bull. Am. Phys. Soc.* **18**, 1478.

LIGHTHILL, M. J. 1952 *Proc. R. Soc. Lond.* A **211**, 364.

LUSH, P. A. 1971 *J. Fluid Mech.* **46**, 477.

MICHALKE, A. 1965 *J. Fluid Mech.* **23**, 521.

MOORE, C. J. 1977 *J. Fluid Mech.* **80**, 321.

PETERSEN, R. A., KAPLAN, R. E. & LAUFER, J. 1974 *NASA Contr. Rep.* 134733.

PFIZENMAIER, E. 1973 Doctor-Ingenieur thesis, Technische Universität Berlin.

ROCKWELL, D. O. & SCHACHENMANN, A. 1982 *J. Fluid Mech.* **117**, 425.

VLASOV, Y. V. & GINEVSKIY, A. S. 1974 *NASA* TTF-15, 721.

ZAMAN, K. B. M. Q. & HUSSAIN, A. K. M. F. 1981 *J. Fluid Mech.* **103**, 133.