Reynolds Number Dependence in Supersonic Jet Noise

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An experimental study of the noise production by high speed jets over a wide range of Reynolds numbers has been performed. Two jets of nominal Mach numbers 1.5 and 2.3 were run over a Reynolds number range from 5300 to 107,000. Microphone measurements of the radiated noise and hot-wire measurements of the flow fluctuations demonstrate that at low Reynolds numbers coherent flow instabilities produce a dominant portion of the noise. In the nominal Mach number 2.3 jet these instability waves convect downstream supersonically with respect to the ambient air. In the nominal Mach number 1.5 jet the instabilities convect downstream subsonically. In both cases however, sound pressure level amplitude contours show that the low Reynolds number jets radiate noise comparable to intermediate and high Reynolds number jets. These measurements constitute substantial evidence that a flow instability model of the dominant noise generators may be appropriate for conventional high Reynolds number supersonic jets.

Nomenclature

a_o = speed of sound outside jet
C = wavespeed in the downstream direction
D = diameter of the jet
d = effective diameter of the jet
M = Mach number of the jet at the exit
$\tilde{m}$ = normalized mass velocity fluctuations $= (\rho u)'_{\rm rms}/(\overline{\rho u})$
n = azimuthal mode number
r = radial distance from jet centerline
Re = Reynolds number $= \rho U d/\mu$
St = Strouhal number $= fd/U$ (f is frequency)
u = local velocity
U = mean centerline velocity of the jet at the nozzle exit
x = downstream distance from nozzle exit
β = angle from jet axis
θ = azimuth angle
ϕ = relative phase
ρ = local density
μ = viscosity
λ = wavelength of fluctuation
$(\bar{\ })$ = time averaged quantity
$(\ )'_{\rm rms}$ = root mean square of fluctuating quantity

I. Introduction

THERE is currently considerable interest in evaluating the function of large-scale organized fluctuations in the generation of noise from high speed air jets. A number of experimental observations[1-4] have indicated that a dominant portion of the jet noise may be generated by these large scale disturbances. However, direct measurements of these fluctuations in high Reynolds number jets are both difficult to obtain and to interpret.

Although the fraction of energy contained in the coherent fluctuations may be small it has been suggested that these large scale disturbances play an important role in the distribution of the total fluctuation energy[5] as well as in the growth of the shear layer.[6] Also, it seems quite reasonable that a coherent periodic disturbance will be a much more efficient noise generator than the random turbulent flucutations (see discussion in Refs. 7 and 8).

Presently there is extensive debate over the description of the large scale disturbances. Laufer and his co-workers[3,9] visualize these disturbances as a regular pattern of concentrated vortices which tend to pair or interact as they convect downstream. Several other researchers have attempted to formulate the organized fluctuations in terms of a wave model using hydrodynamic stability theory. At the present time the leading researchers in the analysis of instability waves in turbulent jet-like flows are Chan,[10,11] Tam[8,12] and Liu.[13,14]

Chan's instability analyses are the most extensive; however, he has not carried his analyses very far in the prediction of noise production. On the other hand Tam has developed an extensive supersonic jet noise production theory using a quasilinear instability computation as a starting point. He then combines the effects of unsteady entrainment and large scale jet vibrations (resulting from the instability) to calculate a predicted noise radiation field produced by the jet. His predictions of noise field amplitude levels and directivity agree reasonably well with the experimental results of Dosanjh and Yu.[15] Based upon this agreement, his theory must be regarded as the most advanced work to date for supersonic jet noise analysis. However, there are several places in the theory where improvements should be made. The most serious criticism of Tam's analysis concerns its inability to accurately predict the spectrum of either the instability waves, or the radiated noise.

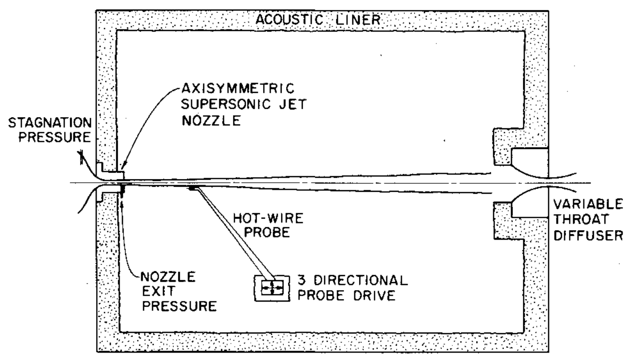

Fig. 1 Schematic of the anechoic vacuum chamber test facility.

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The major goal of our research is to provide the experimental framework upon which more accurate supersonic jet noise theories can build. We are therefore investigating the behavior of the coherent fluctuations in the jet and their role in noise production. To enable the properties of the coherent fluctuations to be more easily identified and measured we operate our jets in a low to intermediate Reynolds number range ($5300 < Re < 107{,}000$).

At the lowest Reynolds numbers the jet flow and radiated noise spectra are found to be dominated by discrete modes. We believe these modes to be instabilities of the laminar jet (Tollmein-Schlichting waves). It is also our belief that these flow instabilities generate noise in a manner similar to the major noise generators (the large scale organized fluctuations) in conventional high Reynolds number jets.

The objective of this paper is to present evidence to demonstrate that a study of low to moderate Reynolds number jets can yield information which is helpful in providing understanding of the dominant noise generation mechanisms in conventional high speed jets.

II. Description of the Experiments

The experiments were performed in our new anechoic vacuum chamber test facility shown schematically in Fig. 1. The overall dimensions of the chamber are approximately $0.7 \times 0.8 \times 1.2$ meters. The chamber is lined with 5 cm thick acoustic absorption material to dampen the reverberant sound field. All noise measurements presented in this paper are corrected for the effect of the reverberant pressure field. (The correction was always less than 2 dB.) It should be noted that this anechoic vacuum chamber is approximately 10 times larger than the facility used in our earlier investigations.[16, 17] However, no major results of our earlier papers have proven to be in error as a result of using the much smaller facility.

The downstream vacuum pump is isolated from the test facility by 15 meters of piping and a 30 cubic meter vacuum storage tank. The extraneous noise produced by the pump was measured and found to be negligible compared to the presented measurements.

Two supersonic axisymmetric de Laval nozzles of design Mach numbers $M=1.5$ and $M=2.3$ were used. The exit diameters of the nozzles are 8.03 mm and 6.35 mm respectively. The stagnation temperature of the air jets was room temperature (approximately 294 K) and the air was dehumidified before being used in the facility.

The inlet to the jet was a 15 cm diameter stilling section with a 5 cm section of foam rubber and six fine screens. By controlling both the stilling chamber stagnation pressure and the test chamber pressure (the jet back pressure) perfectly expanded jets over a wide range of Reynolds numbers can be obtained. The Reynolds number of the present experiments ranged from 5300 to 107,000. For comparison, a cold $M=2$ jet of exit diameter 8 mm exhausting to atmospheric pressure will have a Reynolds number of about 800,000.

Noise measurements were made using a ⅛ in. diameter Bruel and Kjaer condenser microphone type 4138 and associated B and K preamplifier and power supply. The microphone has ominidirectional response within ±3 dB for frequencies up to 60 kHz. The microphone was calibrated in a low pressure environment using a piston phone, and its calibration constant was determined to be essentially independent of the ambient pressure over the range of pressure levels used in test chamber (down to 1/50 atm).

Sound pressure level data in this paper are presented using a reference pressure scaled to the ambient pressure in the test facility, i.e. $p_{\text{ref}} = (2 \times 10^{-5})\,(p_c/p_a)$ Newtons/m^2 where p_c is the pressure of the test chamber and p_a is standard atmospheric pressure.

Flow fluctuation measurements were made using a Disa 55 M constant temperature anemometer. The hot-wire probes were Disa 55A53 subminiature probes which have been epoxied to the upper edge of slender brass supports. The frequency response of the hot-wire probe and electronics was approximately 60 kHz. However, it can be seen from the microphone measurements, that this frequency response is adequate to obtain the dominant portion of the spectral content of the fluctuations (see "Results").

Both hot-wire and microphone signals were high passed to remove the acoustic resonance effect of the test chamber. The lower cutoff frequency was set at 1 kHz for the hot-wire measurements. The microphone signals were bandpassed using a pass band of 3 kHz to 80 kHz. The upper cutoff eliminates a resonance at 100 kHz which is characteristic of the microphone in low pressure environments.

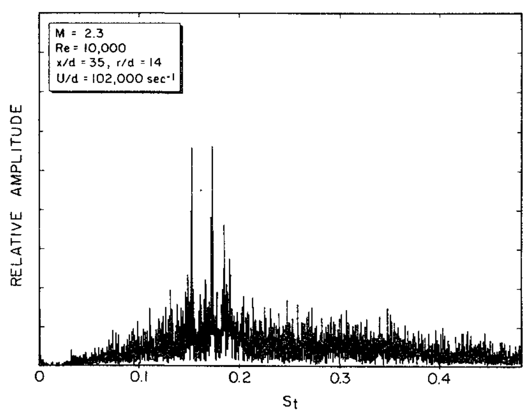

Fig. 2 Spectrum of noise radiated from the low Reynolds number $M=2.3$ jet.

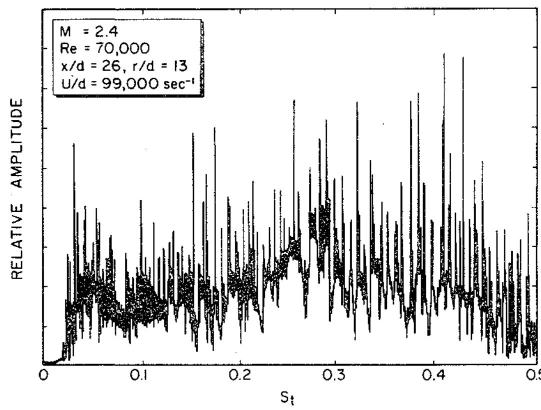

Fig. 3 Spectrum of noise radiated from the intermediate Reynolds number $M=2.3$ jet.

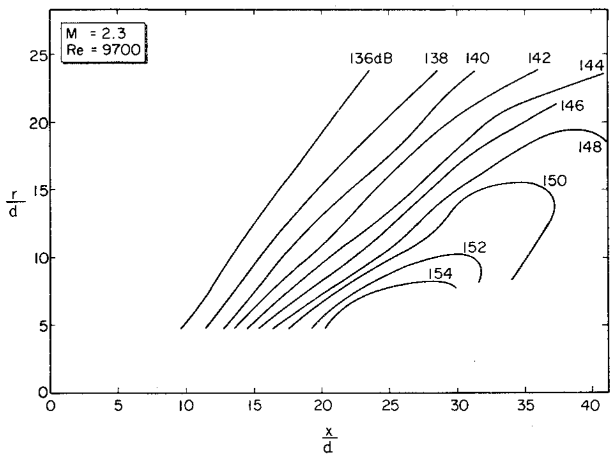

Fig. 4 Sound pressure level contours for the low Reynolds number $M=2.3$ jet.

Reduction of the hot-wire data has been accomplished with a technique which we developed[18] following the original ideas of Kovasznay[19] and Morkovin.[20] The results of the hot-wire fluctuation measurements will be presented in terms of mass velocity fluctuations $(\rho u)'_{rms}$. These are nondimensionalized with the local average mass velocity in the following way: $\tilde{m} = (\rho u)'_{rms}/\overline{\rho u}$. Since $\tilde{m}$ contains both the velocity and density fluctuations and their covariance, values of $\tilde{m}$ are typically two to three times larger in magnitude than $u'_{rms}/\bar{u}$ estimates.[18]

Spectral analyses of the flow fluctuations and noise signals were made with a Hewlett-Packard Model 302 A Wave Analyzer with a constant bandwidth of 6 Hz. The sweep time was typically slow enough to provide an adequate 'analyzing time' in all measurements.

Phase measurements of spectral components of the hot-wire fluctuations were made using a glow discharge excitation technique developed and reported earlier.[16] The glow was set up at a single point tungsten electrode approximately 2 mm from the jet exit. As explained in Ref. 16, the level of excitation of the glow discharge device was very low. Consequently, it had little influence on the naturally developing instability but did provide the crucial phase reference required for the measurements. A dual beam oscilloscope was used to determine the relative phase between the sensor signal and the exciter signal.

III. Experimental Results

The design Mach numbers of the two jet nozzles used in this study are $M = 1.5$ and $M = 2.3$. As expected, the boundary layers on these nozzles are Reynold's number dependent so that the jets have varying "effective" exit diameters and exit Mach numbers depending on the Reynolds number. The values, exit Mach number are determined from pitot pressure and static pressure measurements on the jet centerline as described in Ref. 16. For the range of Reynolds number of the present experiments, the Mach number ranges of the two nozzles are $M = 1.3$ to 1.6 and $M = 2.3$ to 2.4. When analyzing the noise radiation from these jets, the shift in Mach number with jet Reynolds number should be kept in mind.

Since the decrease in the effective diameter of the nozzle exit is substantial at low Mach numbers (over 10%) and effective diameter d is defined to be the physical diameter D, minus twice the displacement thickness of the boundary layer. Most of the data presented in the paper is nondimensionalized using the effective diameter d.

Acoustic Measurements of the $M = 2.3$ Jet

Since the nominal Mach number 2.3 jet experiments experience a smaller percentage change in Mach number, the experimental measurements for this jet will be presented first.

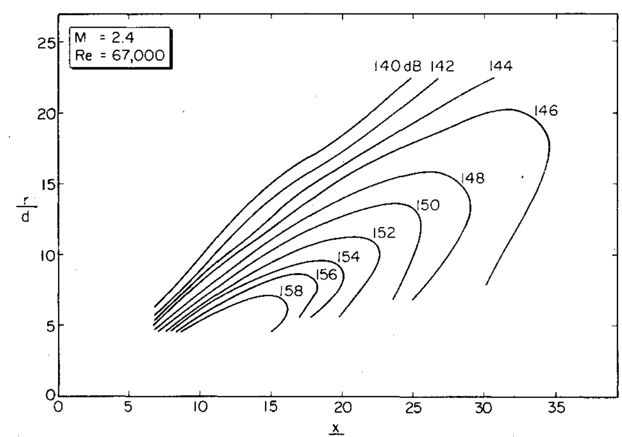

Fig. 5 Sound pressure level contours for the intermediate Reynolds number $M = 2.4$ jet.

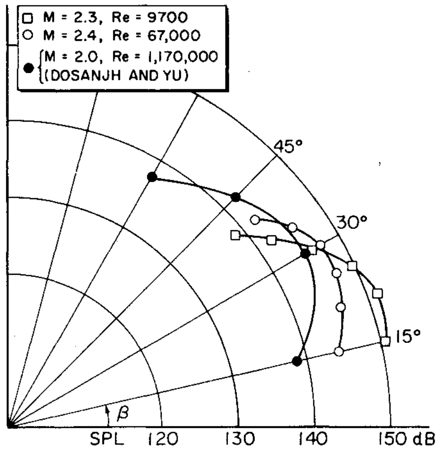

Fig. 6 Sound pressure level directivity distributions for the nominal Mach number 2.3 jets.

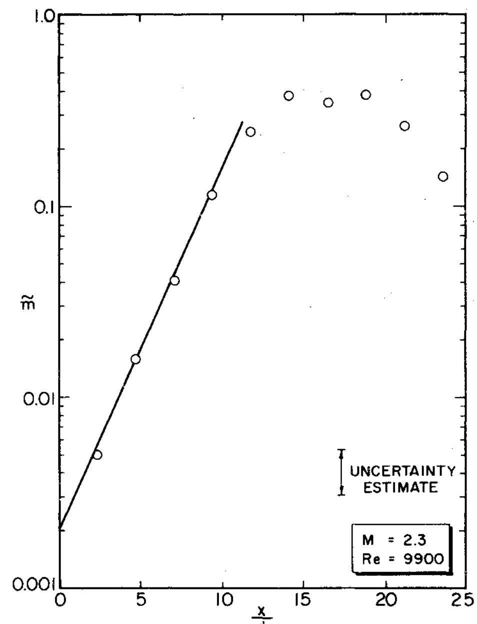

Fig. 7 Axial distribution of peak mass velocity fluctuations for the low Reynolds number $M = 2.3$ jet.

Shown in Figs. 2 and 3 are noise spectra from the nominal $M = 2.3$ nozzle at two Reynolds number conditions. All noise spectra presented are taken at an angle between 20° and 30° from the jet axis. Directivity measurements presented later will show that a dominant portion of the jet noise is propagating in this direction. The low Reynolds number spectrum is dominated by a few discrete modes. We believe these modes to be coherent wavelike instabilities of the laminar jet. The spectrum of the intermediate Reynolds number jet ($Re = 70{,}000$) shows a broad frequency content which is similar to the noise spectra of jets exhausting to atmosphere measured by other researchers.[9,15]

It is our belief that if wavelike instabilities of the fully turbulent jet are responsible for a major portion of the noise generated, then at low Reynolds numbers laminar instability waves should also be efficient noise generators. To determine the relative noise generation from the different Reynolds number jets, sound pressure level (SPL) contours are plotted. Shown in Figs. 4 and 5 are the sound pressure levels measured in the acoustic field of the nominal Mach number 2.3 jet operated at Reynolds numbers of $Re = 9700$ and $Re = 67{,}000$. It is apparent from these figures that the noise produced by the two jets are of comparable levels; although the position of the contours has shifted downstream in the low Reynolds number case. It should be kept in mind that the reference pressures used to calculate the dB levels are scaled to the chamber pressure as explained in Sec. II.

A directivity plot of the noise radiation of these jets is shown in Fig. 6. In this figure the sound pressure levels are determined from the SPL contours over an arc of 36 jet diameters in radius centered at the exit. The sound pressure levels are then plotted as a function of β, the angle from the jet axis. Also included on this plot are data estimated from directivity plots for a $M=2.0$ jet reported by Dosanjh and Yu.[15] The data from the two higher Reynolds number jets are in reasonable agreement with regard to sound level and directivity, both having an angle of maximum propagation of approximately 30° from the axis.

The low Reynolds number data have an apparent angle of maximum amplitude somewhat different from the two higher Reynolds number jets and a slightly higher maximum sound pressure level is indicated. These differences are a result of two factors. First the arc radius is smaller than required to be completely in the far field. (For example Dosanjh and Yu[15] use an arc radius of 180 jet diameters for their directivity measurements.) Second, the maximum noise generators are located farther downstream in the low Reynolds number jet compared to the higher Reynolds number jet as evident in the SPL contours of Figs. 4 and 5.

In view of the acoustic data presented so far and the explanation for the small differences evident in the data of Fig. 6, two major features can be observed. First, the low Reynolds number jet has SPL contours which are similar in shape to the contours at higher Reynolds numbers. Second, scaled noise amplitudes of the low and higher Reynolds number jets are almost equal at corresponding locations in the acoustic field. This physical situation is remarkable in view of the differences in noise spectra of the two jets.

In the low Reynolds number jet a few discrete modes are powerful noise generators. No doubt, the noise generation efficiency of these modes is enhanced because they are coherent flow fluctuations. In the next section hot-wire measurements will be used to show that these fluctuations are the instability modes of the laminar jet.

Flow Fluctuation Measurements, $M=2.3$ Jet

Measurements of the axial distribution of flow fluctuations made with the hot-wire at the radial location of maximum fluctuation amplitude are shown in Figs. 7 and 8 for the two Reynolds number cases presented in the acoustic section. The data have been reduced using the method of Ko, et al[18] as described earlier. From these figures it can be seen that the fluctuation levels grow exponentially in both jets. In the low Reynolds number jet, however, the fluctuations grow more slowly and saturate considerably farther downstream than the higher Reynolds number jet. In the higher Reynolds number jet, saturation of the flow fluctuation amplitudes occurs at approximately 8 diameters downstream. For the low Reynolds number jet the peak amplitude location has moved downstream to $x/d=14$. This shift in location of the maximum fluctuation region corresponds to the shift in SPL contours between different Reynolds number jets mentioned earlier. Apparently, the major noise production areas of the jets are linked to the positions of maximum flow fluctations as sensed by the hot-wire.

We now have enough information to classify the flow fluctuations in the low Reynolds number jet as instability waves. This can be done because the flow fluctuations satisfy three common criteria for a flow instability. 1) The amplitude of the total spectrum of mass velocity fluctuations is less than 0.5% of the local mean mass velocity at the jet exit. This implies that initially the flowfield of the jet is laminar. 2) The initial fluctuations grow approximately exponentially as would be predicted for a quasiparallel flow, linear stability theory. 3) The initial fluctuations display concentrated bands of unstable frequencies. Criteria 1) and 2) are satisfied in Fig. 7 while criterion 3) is satisfied because hot-wire spectra (not presented here) of the flow fluctuations are similar to the

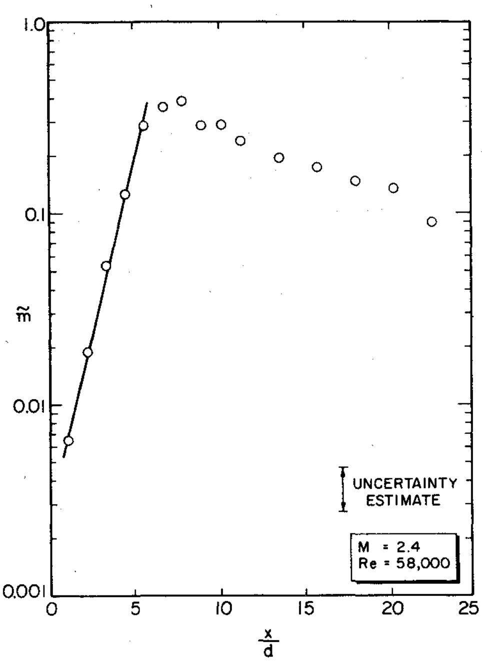

Fig. 8 Axial distribution of peak mass velocity fluctuations for the intermediate Reynolds number, $M=2.4$ jet.

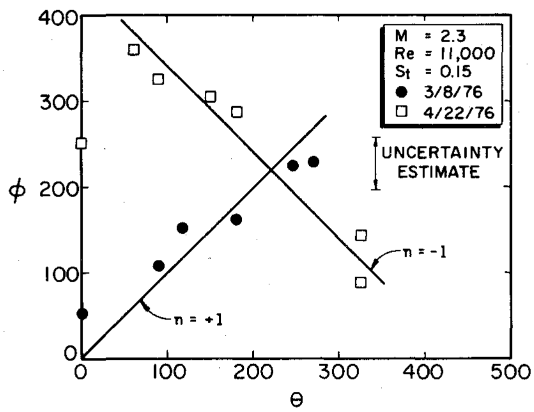

Fig. 9 Azimuthal distribution of hot-wire relative phase for the low Reynolds number $M=2.3$ jet.

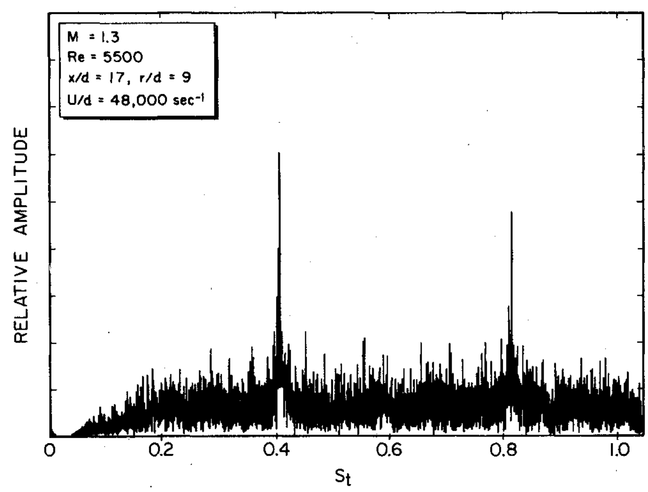

Fig. 10 Spectrum of noise radiated from the low Reynolds number $M=1.3$ jet.

microphone spectra which are dominated by a few discrete modes.

The flow fluctuations of the higher Reynolds number jet also satisfy criteria 1) and 2). However, the broad frequency content of these fluctuations, as evident from the earlier microphone spectrum, preclude our classifying these fluctuations as flow instabilities at the present time.

In an earlier paper[17] we presented the results of instability wavelength measurements for this $M = 2.3$ jet using the phase measurement technique described earlier. From the measured wavelength and frequency it was determined that the instability waves travel supersonically with respect to the ambient air ($C/a_o = 1.13$). Recently we have made azimuthal phase measurements, the results of which are presented in Fig. 9 for two different experimental days. These show that the fundamental instability has a sin $n\theta$ dependence where $n = +1$ on one day and $n = -1$ on another day (right and left hand simple helices). These measurements are representative of similar measurements made on several days. This azimuthal dependence is also similar to results found in other instability flow situations by other experimenters,[21-23] and it is the azimuthal dependence used by Tam in his theory.[8,12]

An important comparison can now be made if we recall that in the hot-wire fluctuation measurements presented in Fig. 8 for the $Re = 58{,}000$ jet, the peak amplitude occurs at approximately 8 jet diameters downstream of the exit. The SPL contours corresponding to this jet also seem to indicate that the dominant noise generators are located around 8 diameters downstream. It is interesting to compare this apparent peak noise source location with the measurements of Laufer et al[9] using a directional microphone system in the far field of a $M = 2.5$, $Re = 4 \times 10^6$ jet. For this jet they determined the peak noise source location to be 10 diameters downstream. This type of agreement (along with the noise spectra comparison made earlier) indicates that the $Re = 67{,}000$ jet and its noise production are almost identical to the $Re = 4 \times 10^6$ jet.

$M = 1.5$ Jet Measurements

In the $M = 2.3$ jet the flow instability modes were found to be traveling at a supersonic convection velocity.[17] As we have seen, these modes are powerful noise generators. It was of particular interest to us to determine if coherent instabilities traveling at a subsonic convection velocity could also be efficient noise generators. If subsonic instability waves are

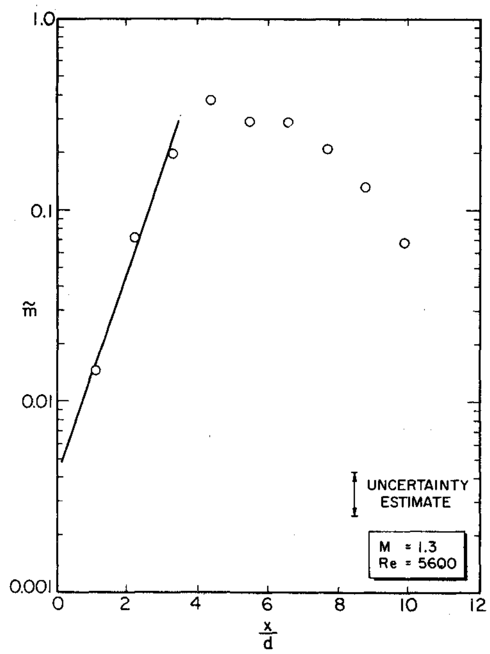

Fig. 11 Axial distribution of peak mass velocity fluctuations for the low Reynolds number $M = 1.3$ jet.

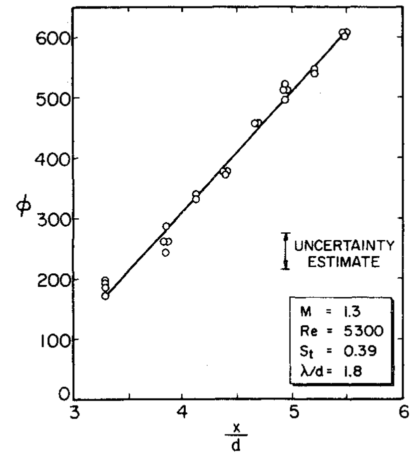

Fig. 12 Axial distribution of the hot-wire relative phase for the low Reynolds number $M = 1.3$ jet.

determined to be strong noise generators, then a reasonable case can be made for the noise generation potential of a large scale, coherent fluctuations in high Reynolds number jets at lower Mach numbers.

To investigate the noise production capability of instability modes traveling subsonically, acoustic measurements as well as hot-wire measurements were performed in a nominal $M = 1.5$ jet. At a Reynolds number of approximately 5500 the noise spectrum shown in Fig. 10 indicates that the flow fluctuations are dominated by a discrete mode and its first harmonic. Hot-wire spectra of the flow fluctuations were similar to this noise spectrum.

Hot-wire measurements of the mass velocity fluctuation amplitudes show a low initial level of fluctuation amplitude with exponential growth for approixmately 4 diameters downstream (Fig. 11).) These measurements demonstrate that the dominant flow fluctuations can be classified as instability waves by the criteria applied to the $M = 2.3$ jet fluctuations.

It should be noted here that the Strouhal number of the dominant instability mode in the $M = 1.3$ jet is considerably higher than the Strouhal numbers of the dominant modes in the $M = 2.3$ jet. This trend of increasing Strouhal number with decreasing Mach number is predicted by Chan's instability analysis.[11]

Choosing the lower mode as the fundamental instability, axial phase measurements of the $St = 0.39$ mode, using the excitation procedure described earlier,[16] were performed. These measurements, shown in Fig. 12, indicate a wavelength

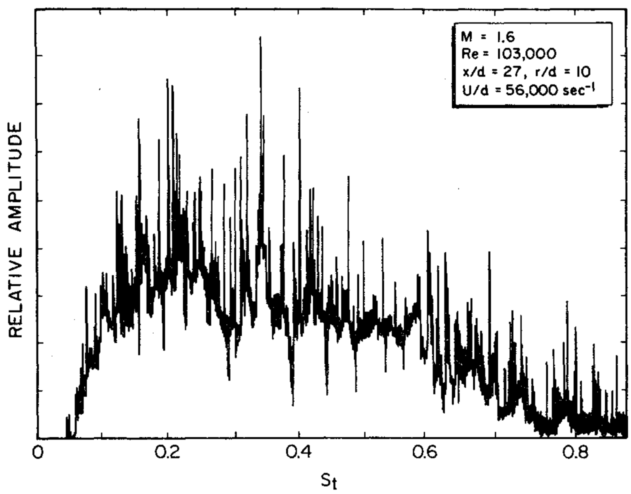

Fig. 13 Spectrum of noise radiated from the intermediate Reynolds number $M = 1.6$ jet.

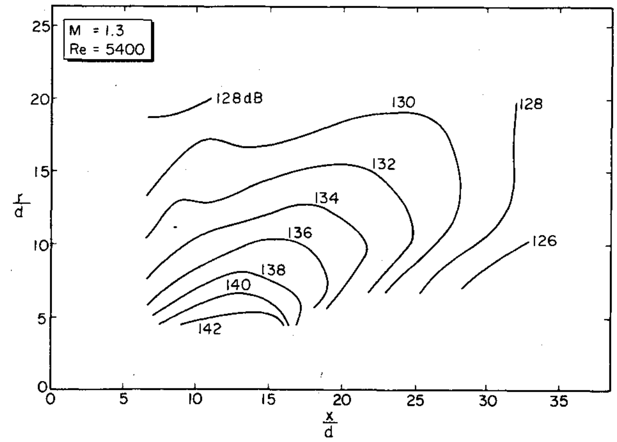

Fig. 14 Sound pressure level contours for the low Reynolds number $M = 1.3$ jet.

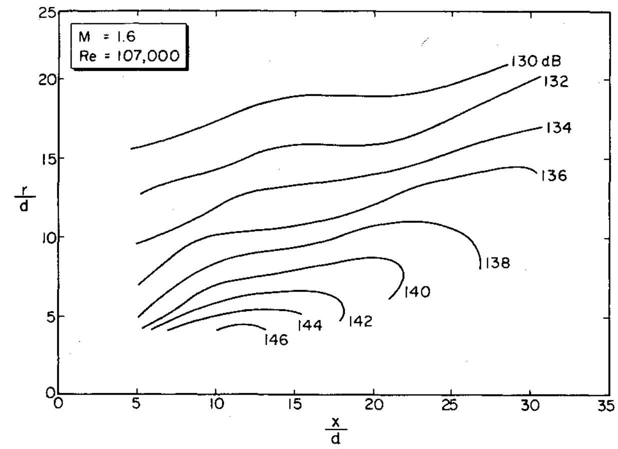

Fig. 15 Sound pressure level contours for the intermediate Reynolds number $M = 1.6$ jet.

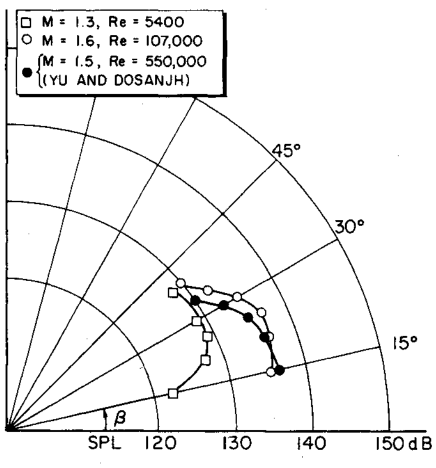

Fig. 16 Sound pressure level directivity distributions for the nominal $M = 1.5$ jets.

of $\lambda/d = 1.8$. The calculated convection velocity from the dispersion relationship gives $C/a_o = 0.72$. Since this instability is traveling subsonically, noise production of the Mach wave type cannot be produced.

To quantify the noise generation ability of this subsonic instability, its noise field was compared to a noise field produced by a higher Reynolds number jet. (The noise spectrum of the $Re = 103{,}000$ jet showing the typically broad frequency content is presented in Fig. 13.) The SPL contours for the two jets are compared in Figs. 14 and 15. Even though the low Reynolds number jet has a substantially lower Mach number than the higher Reynolds number jet ($M = 1.3$ compared to $M = 1.6$) the amplitude and shape of the contours are reasonably similar.

Directivity patterns of the low and intermediate Reynolds number jets are presented in Fig. 16. Included on this figure are data obtained from the measurements of Yu and Dosanjh[24] in the acoustic field of a high Reynolds number $M = 1.5$ jet. An arc of radius 30 diameters centered at the jet exit was used to generate this data. The data for the two higher Reynolds number jets show good agreement, as we found in the intermediate and high Reynolds number data of the $M = 2.3$ jet. The low Reynolds number jet shows a somewhat lower maximum sound pressure level. This is, no doubt, caused by the unavoidable decrease in jet Mach number with decreasing Reynolds number. (An idea of the sensitivity of the noise level to changing Mach number can be obtained by comparing the data of Figs. 6 and 16.) In view of this explanation the conclusion from the acoustic data that the subsonic instability waves are powerful noise generators seems well substantiated.

The noise generation ability of the subsonic instability waves may be attributed to their rapid growth and decay. However, this is a very complicated phenmenonwhich is not well understood at this time (see discussion in Liu[25]).

Azimuthal phase measurements have been performed but the results are too inconclusive to present here. Further measurements must wait for more sophisticated electronic data-acquisition and reduction.

IV. Conclusions

Microphone measurements of the radiated noise and hot-wire measurements of the flow fluctuations of supersonic jets of $M = 1.3$ and $M = 2.3$ demonstrate that at low Reynolds numbers, coherent flow instabilities produce a dominant portion of the noise. In the Mach number 2.3 jet these instability waves convect downstream supersonically with respect to the ambient air. In the Mach number 1.3 jet the instabilities convect downstream subsonically, In both cases, however, sound pressure level amplitude contours show that the low Reynolds number jets radiate noise of comparable amplitude to intermediate and high Reynolds number jets. These measurements constitute substantial evidence that a flow instability model of the dominant noise generators may be appropriate for conventional, high Reynolds number supersonic jets.

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References

[1]Mollo-Christensen, E., "Jet Noise and Shear Flow Instability Seen From an Experimenter's Viewpoint," *Journal of Applied Mechanics,* Vol. 34, 1967, pp. 1-7.

[2]Bishop, K. A., Ffowcs Williams, J. E., and Smith, W., "On the Noise Sources of the Unsuppressed High-Speed Jet," *Journal of Fluid Mechanics,* Vol. 50, pp. 21-31.

[3]Laufer, J., Kaplan, R. E., and Chu, W. T., "On the Generation of Jet Noise," AGARD Conference Proceedings No. 131 on Noise Mechanisms, 1973.

[4]Lau, J. C., Fisher, M. J., and Fuchs, H. V., "The Intrinisic Structure of Turbulent Jets," *Journal of Sound and Vibration,* Vol. 22, 1972, pp. 379-406.

[5]Townsend, A. A., *The Structure of Turbulent Shear Flow,* Cambridge University Press, Cambridge, England, 1956.

[6]Winant, C. D. and Browand, F. K., "Vortex Pairing, the Mechanism of Turbulent Mixing Layer Growth at Moderate Reynolds Number," *Journal of Fluid Mechanics,* Vol. 63, 1974, pp. 237-256.

[7]Mollo-Christensen, E., "Some Aspects of Free Shear-Layer instability and Sound Emission," NATO Report 260, 1960.

[8]Tam, C. K. W., "On the Noise of a Nearly Ideally Expanded Supersonic Jet," *Journal of Fluid Mechanics*, Vol. 51, 1972, pp. 69-95.

[9]Laufer, J., Schlinder, R., and Kaplan, R. E., "Experiments on Supersonic Jet Noise," *AIAA Journal*, Vol. 14, April 1976, pp. 489-497.

[10]Chan, Y. Y., "Spatial Waves in Turbulent Jets," *Physics of Fluids*, Vol. 17, Jan. 1974, pp. 46-53.

[11]Chan, Y. Y., "Discrete Acoustic Radiation From a High-Speed Jet as a Singular Perturbation Problem," *Canadian Aeronautics and Space Journal*, Vol. 21, June 1975.

[12]Tam, C. K. W., "Supersonic Jet Noise Generated by Large Scale Disturbances," *Journal of Sound and Vibration*, Vol. 38, 1974, pp. 51-79.

[13]Liu, J. T. C., "Developing Large-Scale Wavelike Eddies and the Near Jet Noise Field," *Journal of Fluid Mechanics*, Vol. 62, 1974, pp. 437-464.

[14]Merkine, L.O., and Liu, J. T. C., "On the Development of Noise-Producing Large Scale Wavelike Eddies in a Plane Turbulent Jet." *Journal of Fluid Mechanics*, Vol. 70, 1975, pp. 353-368.

[15]Dosanjh, D. S. and Yu, J. C., "Noise From Underexpanded Axisymmetric Jet Flows Using Radial Jet Flow Impingement," AFOSR-UTIAS Symposium on Aerodynamic Noise, Toronto, May 1968.

[16]McLaughlin, D. K., Morrison, G. L., and Troutt, T. R., "Experiments on the Instability Waves in a Supersonic Jet and Their Acoustic Radiation," *Journal of Fluid Mechanics*, Vol. 69, 1975, pp. 73-95.

[17]McLaughlin, D. K., Morrison, G. L., and Troutt, T. R., "Experiments on the Instability Waves in a Supersonic Jet and Their Acoustic Radiation," in *Proceedings of the Second Interagency Symposium on University Research in Transportation Noise*, Raleigh, N.C. June 1974.

[18]Ko, C. L., McLaughlin, D. K., and Troutt, T. R., "Improved Techniques for Hot-Wire Fluctuation Measurements in Supersonic Flows," AIAA Paper 76-398, 1976.

[19]Kovasznay, L. S. G., "Turbulence in Supersonic Flow," *Journal of the Aeronautical Sciences*, Vol. 20, Oct. 1953, pp. 657-675.

[20]Morkovin, M. V., "Fluctuations and Hot-Wire Anemomentry in Compressible Flows," AGARDograph, No. 24, Nov. 1956.

[21]McLaughlin, D. K., "Experimental Investigation of the Stability of the Laminar Supersonic Cone Wake," *AIAA Journal*, Vol. 9, April 1971, pp. 696-702.

[22]Sato, H. and Okada, O., "The Stability and Transition of an Axisymmetric Wake," *Journal of Fluid Mechanics*, Vol. 26, 1966, pp. 237-253.

[23]Kendall, J. M., "Experimental Study of Cylinder and Sphere Wakes at a Mach Number of 3.7," Jet Propulsion Lab, Calif. Institute of Technology, Tech. Rep. No. 32-363, 1962.

[24]Yu, J. C. and Dosanjh, D. S., "Noise Field of a Supersonic Mach 1.5 Cold Model Jet," *Journal of the Acoustical Society of America*, Vol. 51, 1972, pp. 1400-1410.

[25]Liu, J. T. C., "The Large-Scale Wave-like Eddies and Their Near and Far Jet Noise Field," in *Proceedings of the Third Interagency Symposium on University Research in Transportation Noise*, Salt Lake City, Utah, Nov. 1975.