ARTICLE NO. 79-0571R

J80-145

Direct Correlation of Noise and Flow of a Jet Using Laser Doppler

00023
20001

W. G. Richarz*
University of Toronto, Toronto, Canada

Ribner's self and shear noise theory has successfully described many features of jet noise. However, earlier attempts to cross-correlate postulated source terms and jet noise have been only partially successful owing to hot wire-flow interaction. Thus a nonintrusive laser Doppler velocimeter (LDV) has replaced the hot wire. Source strength distributions and far-field self and shear noise spectra are inferred from jet flow (measured with LDV) correlations with jet noise for a model air jet operating at Mach 0.3. Source distributions over slices of jet are unexpectedly somewhat pearshaped. Spectra computed from LDV-jet noise correlations are compatible with corresponding spectra extracted from farfield intensities and with theory.

Introduction

THE generation of noise by turbulent flow is described by a variety of theories. The governing equations differ primarily in the interpretation of certain terms as either source or propagation mechanisms. Measurable properties of the sound field are predicted by summation over all sources, typically a volume integral. These sources are described by an approximate model of the underlying process. Integration over the source region is a smoothing operation; thus predictions tend to be somewhat insensitive to variations of parameters of the assumed model.

It is therefore desirable to eliminate the empiricism of source modeling and to demonstrate a one-to-one correspondence between the postulated source mechanism and the radiated sound. Such relationships are readily measured in terms of cross-correlations in the time domain and cross-spectral densities in the frequency domain. These functions are indicators of the measure of coherence between two signals. Statistically independent functions possess no coherence; input and output of a linear system, on the other hand, are well correlated. The source terms measured herein may be thought of as inputs and the jet noise as the output.

The existence of coherence is not sufficient proof of a definite causal relationship between the assumed source terms and the radiated sound. Both may be the result of an unidentified forcing function. One must also demonstrate that the measured cross-correlations are consistent with the postulated source mechanism.

Consider a collection of independent radiators as a rather heuristic model of jet nosie. The cross-correlation (cross-spectrum) of a single source and the far-field pressure is a measure of the contribution to the far-field pressure autocorrelation (power spectrum). The latter can be constructed by adding the contributions of all sources. Closure occurs only if the source model is a valid description of the physical process.

Jet noise diagnostics combine the measurement of cross-correlations between the postulated source terms and the effect they produce with computation of far-field properties therefrom. Closure tests whether the theory is a self-consistent description of the generation of sound by turbulent flows.

Experimental considerations dictate that the source terms be amenable to measurements, preferably by a single sensor. To date, cross-correlations have been measured only for the pseudosound model[1-3] and source terms based upon far-field solutions of Lighthill's equation.[4-6] The present work is an extension of jet noise diagnostics via jet flow-jet noise correlations which were pioneered at this laboratory.

Ribner's self and shear noise theory,[7] a development of Lighthill's theory of jet noise,[8-10] serves as the source model to be tested. The theory identifies the second time derivative of momentum flux ρv_x^2 in the direction of an observer at $\underline{x}$ as an equivalent sound generator. The velocity v_x is the sum of a mean flow U_x and a turbulent component u_x. This leads to two families of sources which radiate self ($\propto \partial^2/\partial t^2 \rho u_x^2$) and shear noise ($\propto 2U_x \partial^2/\partial t^2 \rho u_x$), respectively.

Using certain mean flow and turbulence models, Ribner computed the basic self and shear noise derivatives and spectra.[7] He found that the self and shear noise spectra have the same shape after an octave shift, the self noise possessing the higher pitch. Peak spectral amplitudes are comparable. The self noise is omnidirectional, whereas the shear noise exhibits a dipole-like directivity. The spectra and directivities are powerfully altered by the effects of source convection and refraction due to mean flow and density gradients.

The model allows for source convection but does not account for refraction. Nevertheless, the predictions were found to be compatible with a large body of jet noise data for field points outside the refraction valley.[11] In particular self and shear noise spectra extracted from farfield data exhibit the key features predicted by theory.

Recently the analysis has been extended to deal with the more general case of two-point far-field pressure correlations.[12] The predicted normalized cross-correlations agree quantitatively with measurements of Maestrello.[13] All this has strengthened the credibility of the self and shear noise theory.

Thus it was rather surprising that early attempts to cross-correlate the self and shear noise sources and jet noise did not appear to conform altogether to expectations. Lee and Ribner[4] pioneered jet flow-jet noise diagnostics and measured cross-correlations of the total momentum flux ρv_x^2 and the far-field pressure at $\underline{x}$. Axial source distributions inferred therefrom were found to be compatible with accepted scaling laws.[14-16]

The farfield spectrum computed from jet flow-jet noise cross-spectral densities, on the other hand, did not agree with direct measurement. The former underestimated the low

Presented as Paper 79-0571 at the AIAA 5th Aeroacoustics Conference, Seattle, Wash., March 12-14, 1979; submitted April 17, 1979; revision received Dec. 3, 1979.

Index categories: Aeroacoustics; Noise.

*Assistant Professor, Institute for Aerospace Studies. Member AIAA.

frequencies (Strouhal<0.3) by a considerable amount. Only the first seven jet diameters were surveyed; one may well argue that neglect of the sources further downstream, which should radiate predominantly low frequencies, is solely responsible for the discrepancy. However, the results are not incompatible with the notion of probe noise, in particular the bias toward the high frequencies. This possibility will be discussed in more detail.

Morris[5] and later Seiner and Reethof[6] extended the measurements of Lee and Ribner and cross-correlated self and shear noise source terms separately with the jet noise. Their data appeared to show that the shear noise dominated the self noise by a factor of 10, whereas theory suggests both to be comparable.

One is faced with a dilemma: the theory is capable of describing many observed properties of jet noise, yet diagnostics via cross-correlations do not demonstrate any reasonable degree of closure. As the self and shear noise model is derived from the equations of fluid motion, it is reasonable to search for a possible common mechanism responsible for the discrepancies before dismissing the theory for lack of self-consistency.

All cross-correlation experiments cited above were performed with hot wire sensors. It is well known that solid surfaces in turbulent flow radiate sound in proportion to the time rate of change of the forces acting thereon.[17] Thus the diagnostic tests were subject to a common mechanism which may have contributed spurious but well-correlated "probe noise."

The problem of probe interference has been studied extensively in connection with pressure measurements in turbulent flows.[18,19] The principal motivation was to devise a scheme which corrects for the presence of the probe. Hot wires do not appear to disturb the probe appreciably, and the possibility of probe noise has been largely ignored when a hot wire probe is placed in a jet flow, perhaps for the absence of a measurable increase in the overall sound pressure level.

Although the noise radiated by a hot wire probe is completely masked by jet noise, it may contribute to the measured jet flow-jet noise correlation nevertheless. A little thought will show that the unsteady forces acting upon the probe are proportional to the velocities measured by it. Therefore the probe noise and the velocity signal are well correlated. The velocity signal is also proportional to the sound emitted by a single turbulent "eddy" which convects past the probe. One may speculate that jet flow-jet noise correlations contain a significant contribution due to probe noise which is an artifact of the measurement.

Richarz[20] has predicted the effects of probe noise on cross-correlations and identified them in measured data. He concludes that the probe noise is a significant contributor to the cross-correlations at low Mach number ($M<0.5$). Dominance at low Mach number is explained by the dipole-nature of probe noise: flow-surface interactions give rise to dipole sources. These are more efficient radiators at low Mach numbers than jet noise sources which are quadrupoles. The spurious probe noise is a higher pitched signal as temporal as well as spatial fluctuations of the turbulence contribute to the forces acting on the probe. This results in a bias toward the high frequencies, as can be observed in the data of Lee and Ribner. The apparent dominance of the shear noise found by Morris and others is also predicted.

To avoid the possibility of probe noise, it is necessary to measure the sources with a nonintrusive device. The laser Doppler velocimeter (LDV) is the ideal tool for such an endeavor, if velocities are to be measured. This novel technique has been refined over the last decade and is in widespread use in major research laboratories. Knott et al.[21] for example, have performed parametric studies of high speed, high temperature turbulent jets via LDV. They also demonstrated that the LDV can be used in cross-correlation measurements of jet flow and jet noise. The cross-correlation was, however, restricted to a single pair of field points on the jet and the far field.

More recently Schaffar[22] measured cross-correlation of a high speed jet flow ($M=0.99$) and the radiated sound via LDV. The results appear to substantiate the conclusions of Seiner and Reethof.[6] However, simplifying assumptions made therein, as well as the vastly different experimental conditions are believed to be largely responsible for the discrepancies with the results reported here.

The present investigation is an extension of the work of Lee and Ribner[4] and others[5,6] in the field of jet noise diagnostics via cross-correlations. A major difference is the replacement of the hot wire, with its spurious noise, by an LDV. The self and shear noise theory has been tested by measuring cross-spectral densities of the assumed sources and the radiated noise and deriving far-field spectra therefrom. The source region was confined to 3-7 jet diameters downstream of the nozzle (truncated jet). Extensive surveys have been perfomed at selected axial positions to provide unprecendented detail of the source distribution over a slice of jet.

Theoretical Considerations

In Ribner's theory[7] the instantaneous far-field sound pressure is given by

$$p(x,t) \approx \frac{1}{4\pi c_0^2 |x|} \int_{\text{jet}} \left[\frac{\partial^2}{\partial t^2} (2\rho_0 \mu_x U_x + \rho_0 u_x^2) \right] \mathrm{d}y \qquad (1)$$

The square brackets indicate evaluation at retarded time $t - c_0^{-1} |\underline{x} - \underline{y}|$. The terms $2\rho_0 \mu_x U_x$ and $\rho_0 \mu_x^2$ are the unsteady components of the momentum flux in the direction of an observer at $\underline{x}$. This particular description neglects fluctuations in density. The assumption of constant density suppresses refraction. Therefore, the solution is expected to be invalid in and near the so-called valley of quiet close to the jet axis.

It follows that the autocorrelation of the far-field pressure can be written as:

$$\overline{p(x,t)p(x,t-\tau)} = \frac{\rho_0}{4\pi c_0^2 |x|} \int_{\text{jet}} \frac{\partial^2}{\partial t^2} 2U_x(y) \cdot \overline{u_x(y,t)p(x,t-\hat{\tau})}\,\mathrm{d}y + \frac{\rho_0}{4\pi c_0^2 |x|} \int_{\text{jet}} \frac{\partial^2}{\partial \tau^2} \cdot \overline{u_x^2(y,t)p(x,t-\hat{\tau})}\,\mathrm{d}y \qquad (2)$$

if a stationary process is assumed, and $\hat{\tau} = \tau - c_0^{-1} |x-y|$. The autocorrelation of the far-field pressure is constructed from cross-correlations of the assumed sources and the jet noise, evaluated at the correct time delay. Similarly the far-field power spectrum can be shown to be the volume integral of two weighted cross-spectral densities:

$$\varphi_{pp}(x,\omega) = \frac{\rho_0}{4\pi c_0^2 |x|} \int_{\text{jet}} \omega^2 [2U_x \varphi_{u_x p}(x,y,\omega) + \varphi_{u^2{}_x p}(x,y,\omega)]\,\mathrm{d}y \qquad (3)$$

where

$$\varphi_{u_x p}(x,y,\omega) = \frac{1}{2\pi} \int \overline{u_x(y,t)p(x,t-\hat{\tau})}\, e^{i\omega\tau}\,\mathrm{d}\tau$$

$$\varphi_{u^2{}_x p}(x,y,\omega) = \frac{1}{2\pi} \int \overline{u_x^2(y,t)p(x,t-\hat{\tau})}\, e^{i\omega\tau}\,\mathrm{d}\tau$$

Equations (1) and (2) form the mathematical description of the diagnostic procedure employed herein. It reads: given that the jet noise is proportional to the turbulent momentum flux in the direction of the observer, then the far-field jet noise spectrum can be computed from cross-spectral densities of the source terms and the jet noise. The conclusion is correct only if the premise [i.e., Eq. (1)] is a valid description of jet noise generation.

It must be remembered that the source model is not a unique description of jet noise generation. The model is but one of a number of mathematically equivalent formalisms. Only the overall contribution to the far-field is identical.

The far-field spectrum is compounded of two distinct spectra:

$$\varphi_{SE}(x,\omega) = \frac{\rho_0}{4\pi c_0^2 |x|} \int_{\text{jet}} \omega^2 \varphi_{u_x^2 p}(x,y,\omega)\,\mathrm{d}y$$

$$\varphi_{SH}(x,\omega) = \frac{\rho_0}{2\pi c_0^2 |x|} \int_{\text{jet}} \omega^2 U_x(y) \varphi_{u_x}(x,y,\omega)\,\mathrm{d}y \tag{4}$$

The self noise spectrum φ_{SE} is governed by the structure of the turbulent flow. The orientation of the sources is random in space and time. Thus the basic self noise should be omnidirectional, albeit source convection and refraction will effect considerable modification.

The shear noise spectrum φ_{SH} is strongly biased by the mean flow U_x. For example, no shear noise is radiated in the direction normal to the mean flow. For nearly parallel shear flows, such as jets, the basic directivity of the shear noise behaves at least as $\cos^2\theta$ where θ is the angle with respect to the jet axis.

Furthermore, a single frequency component of shear noise, $e^{i\omega t}$ say, has a corresponding self noise image of $e^{2i\omega t}$. This is a rather simplistic argument for the one octave spectral shift. The shift is actually governed by the statistics of the turbulence.[23]

Using a model of homogeneous isotropic turbulence Ribner has shown that the farfield spectrum of the form

$$\varphi_{pp}(x,\omega) = C^{-4}\left[\varphi_{SE}(C\omega) + \cos^2\theta\left(\frac{1+\cos^2\theta}{2}\right)\varphi_{SH}(C\omega)\right]$$

$$C = [(1-M_c\cos\theta)^2 + \alpha^2 M_c^2]^{1/2}, \varphi_{SH}(C\omega) = 2\varphi_{SE}(2C\omega) \tag{5}$$

The convection factor C accounts for source convection at a convection Mach number M_c. The effect is twofold. Source motion enhances the intensity in the downstream direction and increases the pitch of the radiated sound. The increase in pitch is more than offset by the growing contribution of the shear noise, the overall effect being a "reverse Doppler shift." The basic directivities behave as expected. In addition to the frequency shift, the self and shear noise spectra have the same shape. Their peak amplitudes differ by a factor of 2.

Nossier and Ribner[11] found that jet noise data are well correlated with this model. Self and shear noise spectra extracted from farfield spectra by a procedure developed therein serve as reference data for corresponding spectra estimated from measured cross-spectral densities.

LDV System

The experiments were performed with the UTIAS 0.75 in. (19 mm) model air jet installed in a $4.2\times2.9\times2.1$ m^3 anechoic chamber. An LDV replaced the traditional hot wire to eliminate the possibility of probe noise.

The LDV detects the Doppler shift suffered by light scattered from a moving object. The "Doppler signal" generated by a particle traversing the region of intersection of two laser beams (probe volume) is proportional to the projection of the instantaneous particle velocity on the difference of the incident wave vectors. This allows the measurement of an arbitrary velocity component. The frequency to velocity conversion was performed by a Disa 55L90 LDV counter processor.

The LDV depends upon light scattered from objects suspended in the fluid. The scattering agents are microscopic

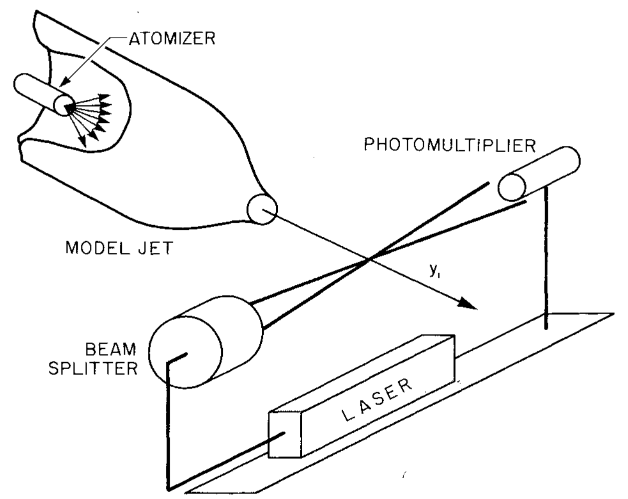

Fig. 1 General arrangement of laser Doppler velocimeter (LDV).

particles capable of following the flow even at high frequencies (~20 kHz). The velocity information available at the output of the processor is updated at a rate proportional to the number of particles that cross the probe volume.

To ensure a virtually continuous velocity signal, the flow had to be seeded. After considerable experimentation a very quiet seeding generator based upon the atomizer principle was installed in the settling chamber of the model jet. The working fluid of the atomizer was water. The air in the settling chamber does work in accelerating the water droplets; this reduces the jet exit velocity. However, careful measurements of near-field/far-field pressure correlations and spectra indicated no detectable adverse effect on sound generation due to the injection of water droplets.

The optical arrangement of the LDV, shown in Fig. 1, consists of a 15 mW He-Ne laser on an aluminum channel which supports the beam splitter optics and the photomultiplier. The probe volume is formed by the intersection of the two laser beams. Light scattered from water droplets is focused on the photomultiplier and detected as a "Doppler signal." The entire optical assembly can be rotated about the vertical axis of the probe volume, thus permitting the measurement of v_x.

The performance of the LDV was validated by comparison with hot wire measurements of the jet flow. Mean velocity and turbulence measurements such as illustrated in Figs. 2 and 3 are indicative of the good agreement of the two methods. Turbulence spectra measured with the LDV and hot wire respectively were found to collapse onto a common curve. This suggests that the data rate and the particle size have no influence on the LDV measurement in the frequency range of interest (0-20 kHz).

Cross-spectral densities of jet flow and jet noise were computed on a Spectral Dynamics DSP 360 FFT analyzer. A ½ in. Bruel and Kjaer condenser microphone placed at 40 deg to the jet axis served as the observer in the farfield. This position is the best compromise between the detectability of shear noise and minimal errors due to refraction effects. The latter alter jet noise directivity and spectra near the jet axis and are not accounted for by the present model. All experiments were perfomed at a jet Mach number of 0.3. The atomizer as well as the air supply system were found to have no measurable effect on the radiated jet noise. The experimental procedure and some aspects of data handling and analysis are described in detail in Ref. 24.

Results

As expected the cross-spectral densities are quite weak. Normalized cross-spectral densities are of the order of 5×10^{-3}. Such low levels are difficult to detect, and despite

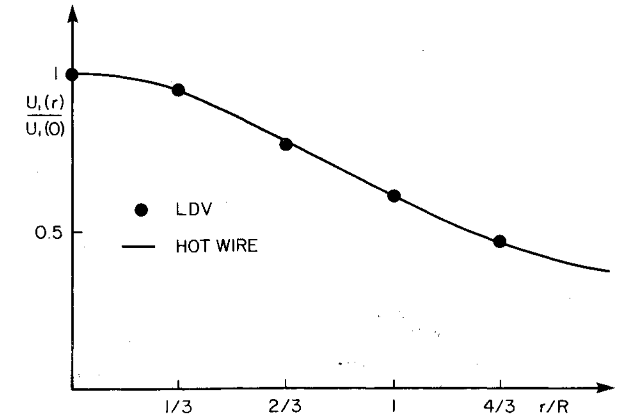

Fig. 2 Comparison of mean velocity profile measured with LDV and hot wire.

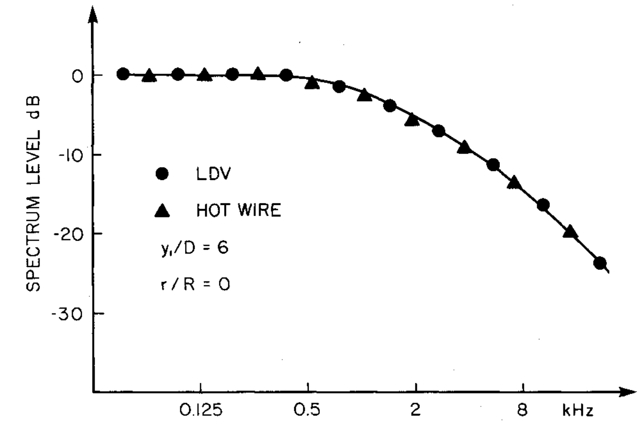

Fig. 3 Comparison of turbulence spectrum derived from LDV and hot wire measurements.

averaging some spurious high frequency noise may still be present. The low levels of coherence suggests that there must be a large number of uncorrelated sources. The cross-spectral densities are converted to contributions from unit volume to the far-field spectrum by multiplication with $0.25\ \rho_0\pi^{-1} c_0^{-2}\,|\underline{x}|^{-1}\omega^2$ [see Eq. (3)]. The contributions are normalized by a common reference level for convenience. As all scale factors are known, it is possible to construct farfield spectra after summing over all source location.

Measured self and shear noise contributions per unit volume possess a rather broadband spectrum (Figs. 4 and 5). The peak frequencies are functions of axial position. Self noise spectral contributions are always of a higher pitch, the average peak frequency ratio being 1.54. The inverse proportionality of frequency and axial position is also demonstrated.

The strength of the sources (proportional to the area under the curves) is found to decrease with distance from the jet nozzle. This effect is offset to some degree by the increasing jet diameter. All these features are consistent with scaling laws.

The shape of the spectral contribution per unit value is invariant over a slice of jet. This behavior has been postulated in many computational models of jet noise. The concept appears to be valid at least in the region of intense turbulence ($r/R \leq 1.5$).

Whereas the spectral shape is invariant over a slice of jet, the contribution per unit volume is not. In order to map the effective distribution of sources, a detailed survey was performed at three jet diameters downstream in the mixing region and at six jet diameters in the transition region. Contours of equal relative contribution to the farfield spectra are plotted in Fig. 6.

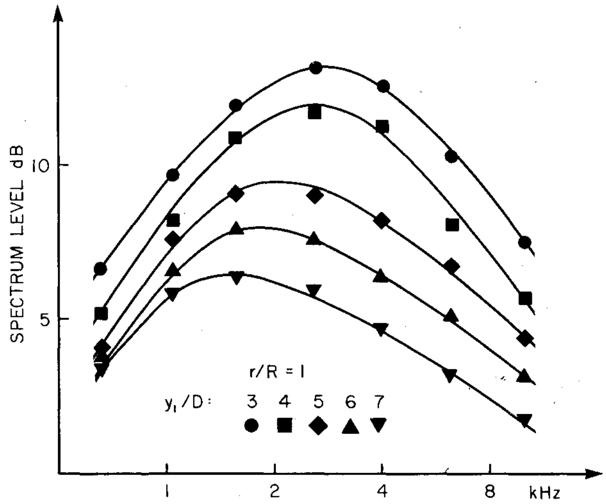

Fig. 4 Relative contribution to shear noise spectrum from unit volume of jet.

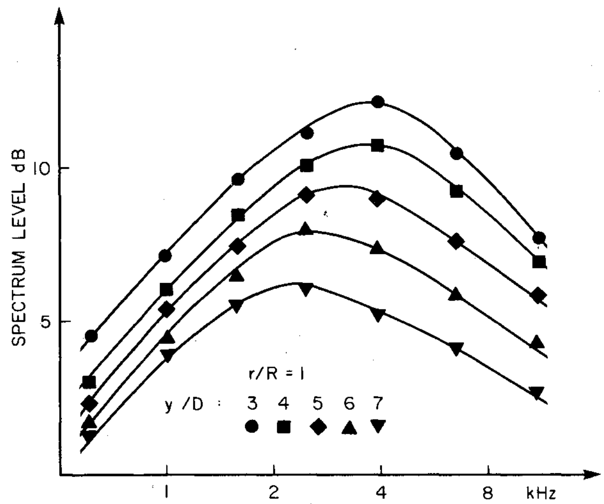

Fig. 5 Relative contribution to self noise spectrum for unit volume of jet.

The contours are somewhat pearshaped, the small end of the pear pointing toward the observer. Source patterns in the self and shear noise format are fixed to the vector x and move with the observer; therefore the axisymmetry of the jet will insure that the mean square pressure is axisymmetric. The quadrants of the jet nearest the observer appear to be the strongest contributors to the sound heard by the observer.

Diagnostic tests performed with a pure tone injected in the jet flow show that refraction and turbulence scattering are too weak to cause such a bias toward the observer. It can be argued that the shape of the contours are in part governed by the RMS turbulent momentum flux. Contours of equal relative momentum flux were found to behave in a similar fashion (Fig. 7). There is no one-to-one correspondence for the sound is emitted from moving correlation volumes ("eddies") rather than stationary point sources.

The contours suggest that the turbulence is not isotropic. This together with the radial mean flow explains a bias toward the observer. In the mixing region one can identify the potential core. For a given azimuthal angle the most energetic sources are near $r/R = 1$, where the turbulence intensity is greatest.[25] The mean flow shifts this locus toward the jet axis for the case of the shear noise distribution.

The contours do not define a correlation volume. In fact source points on the same contour are uncorrelated, if they are sufficiently far apart a typical correlation length is about $0.1\ y_1/D$.[26] It is also misleading to evaluate azimuthal and

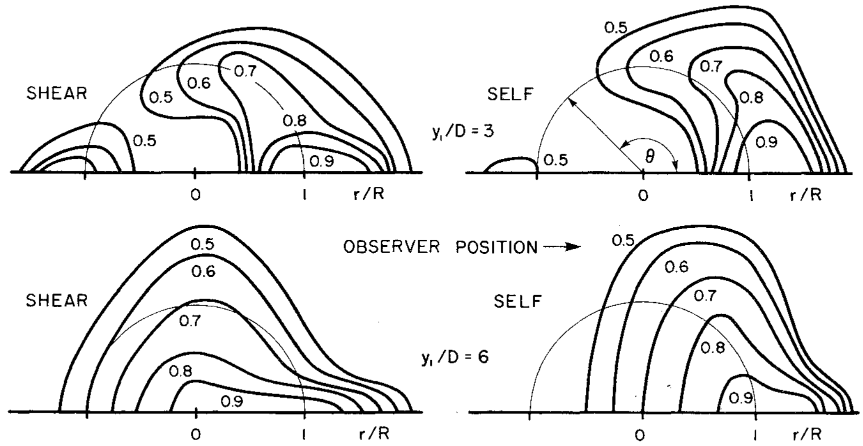

Fig. 6 Contours of equal relative contribution per unit volume to overall self and shear noise for slice of jet. Reference point is at $r/R=1$, $\phi=0$ deg, observer is at 40 deg to jet axis.

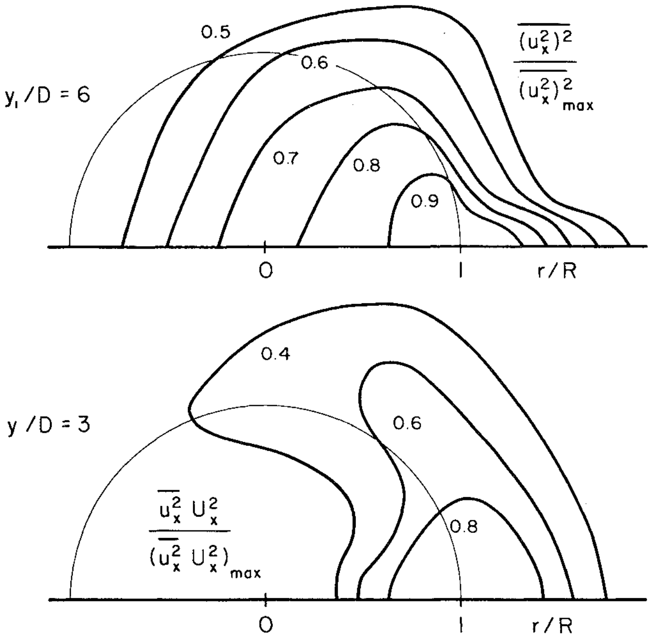

Fig. 7 Contours of mean square turbulent momentum flux in the direction of observer at $\underline{x}$.

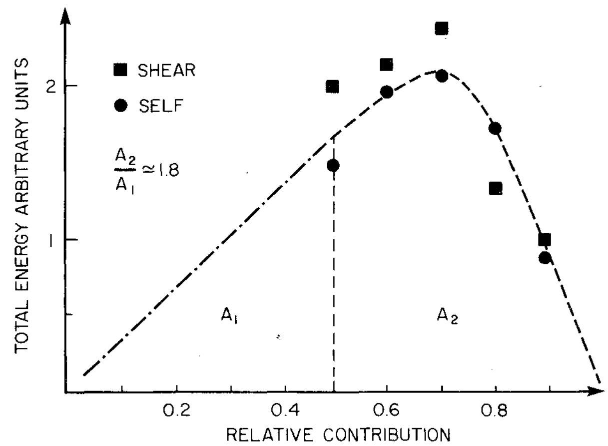

Fig. 8 Total energy of sources of equal relative contribution per unit volume for slice of jet at $y_1/D=6$.

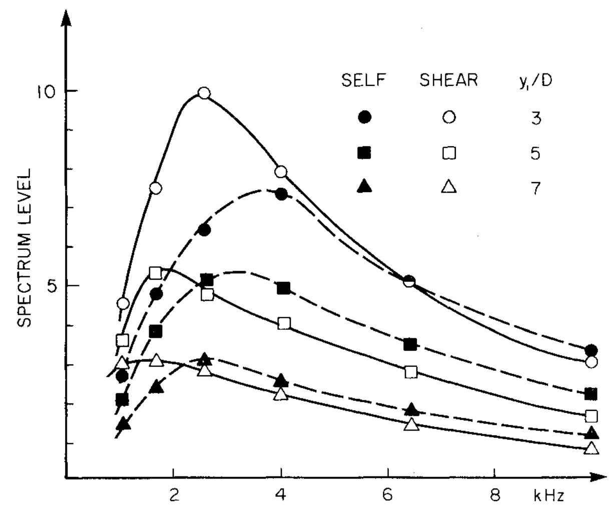

Fig. 9 Contributions to self and shear noise spectra from slices of jet.

radial modes for the contours and interpret them as coherent source distributions. The reader is referred to Appendix A of Ref. 12 where a related problem of the directivity of randomly oriented quadrupoles is discussed.

The contours merely define regions of equal relative contribution to the farfield spectra due to the postulated self and shear noise sources. One must keep in mind the parts of the coherent source volume not measured by the LDV contribute to the cross-spectral density as well. This is equivalent to the space average over the coherent source volume, and can be readily shown when $p(x,t)$ in Eq. (2) is replaced by the volume integral given in Eq. (1). It follows that any detailed information about the spatial coherence of the sources is lost.

The contours are boundaries of regions that contribute comparable energy to the farfield. The product of the relative contribution and the area enclosed by neighboring contours is a measure of the total contribution of the particular region. Sources contained within the contours of 0.8 to 0.6 radiate most of the energy (Fig. 8). A similar result is found for the slice in the mixing region. It is reasonable to assume that the total energy is a monotonically increasing functions for values of relative contributions less than 0.5. A linear relationship is thought to be a conservative estimate; whence one concludes that on the average sources contained within the 0.5 contour radiate at least 60% of the total acoustic energy.

Summation over a single slice yields an estimate of the contribution per unit length (Fig. 9). Theory predicts that at 40 deg from the jet axis the shelf and shear noise spectra (including directivity) have virtually identical peak amplitudes. Contributions per unit length confirm this assertion. The contribution per unit bandwidth appears to be inversely proportional to axial position. The decay rates are frequency dependent, low Strouhal numbers suffering the least decay (Fig. 10).

These curves do not agree with measurements of Fisher, et al.[27] although the trends are similar. The polar correlation

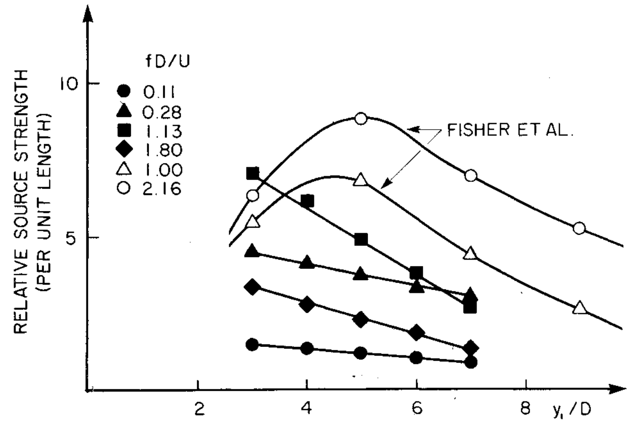

Fig. 10 Mean square source strength distribution per unit length. Source strength distributions inferred from polar correlation techniques[27] are shown for qualitative comparison.

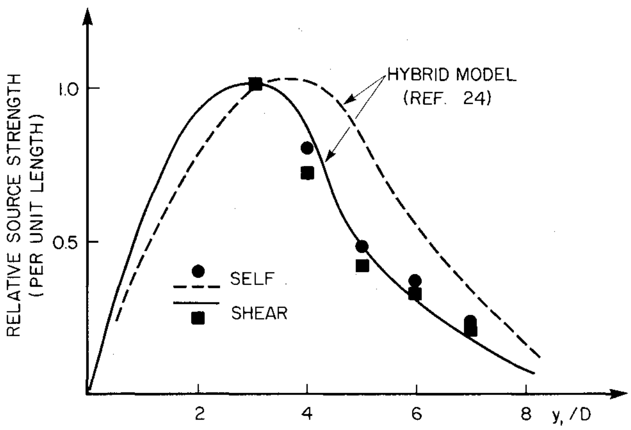

Fig. 11 Self and shear noise contributions to mean square jet noise per unit length.

technique, however, does not rely on a realistic jet noise model. Rather a source distribution along the jet centerline is adjusted for best fit of the farfield data.

As a final test the far-field self and shear noise spectra have been derived from the cross-spectral density measurements. Only a finite portion of the jet volume, namely $y_l/D = 3$-7, has been surveyed. It is anticipated that the spectra will be underestimated. From a plot of relative power radiated per unit length (derived by integrating corresponding spectra shown in Fig. 9), one may infer that the truncated source region is responsible for about 40% of the overall jet noise (Fig. 11). A hybrid model proposed in Ref. 24 is shown for comparison. The model combines measurements of RMS turbulent momentum flux over a slice of jet with postulated frequency scaling. The qualitative fit lends support to jet noise prediction schemes such as employed by Balsa and Gliebe.[28]

Figures 12 and 13 compare self and shear noise spectra extracted from the farfield and predicted from measured cross-spectral densities. The self noise spectrum derived from the cross-spectral densities differs from the reference spectrum by about 4 dB. This is compatible with the estimates discussed above. There is however some discrepancy in the case of the shear noise. It is believed that neglect of phase information is responsible. Analysis suggests that the shear noise cross-spectrum is more susceptible to phase errors. A major factor is the mean flow which tends to distort the region of shear noise source coherence toward the centerline of the jet. The shape of the spectrum should be unaltered, although a decrease in amplitude is expected.

That is why the similarity of the self and shear noise spectra can be demonstrated. Ribner has predicted that peak nor-

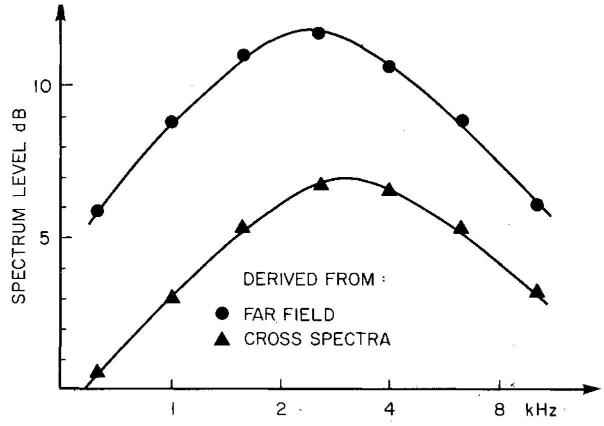

Fig. 12 Comparison of farfield self noise spectrum computed from cross-spectral densities with one extracted from farfield jet noise data.

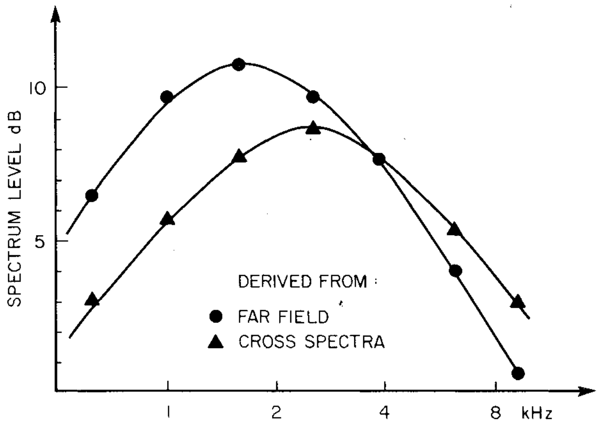

Fig. 13 Comparison of farfield shear noise spectrum computed from cross-spectral densities with one extracted from farfield jet noise data.

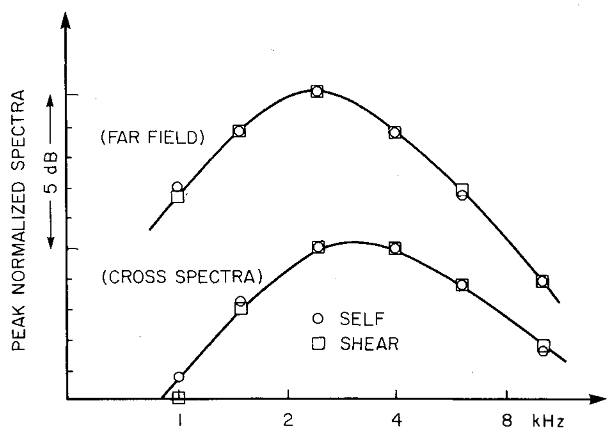

Fig. 14 Test of similarity of peak normalized self and shear noise spectra after frequency shift, shear noise spectra have been shifted in frequency by factor of 1.6.

malized spectra should have the same shape after about an octave shift. It was found that the peak normalized self and shear noise spectra extracted from the field measurements collapsed onto a common curve after a shift of 1.6. Application of the identical shift to the spectra derived from cross-spectral densities results in a similar fit (Fig. 14). The two sets of data exhibit the same behavior, although they have been derived from vastly different experimental procedures.

Conclusion

Over the years Ribner's self and shear noise model, an extension of Lighthill's theory of jet noise, has been demonstrated to describe the major features of jet noise, but direct measurement of the postulated source terms via cross-correlations has met only limited success. The spurious "probe noise" generated by hot wire-turbulence interactions is believed to be the major source of error. In the investigation described herein the sources, which are proportional to certain rates of momentum flux, have been measured with an LDV, thus eliminating the possibility of probe noise.

Cross-spectral densities of the postulated self and shear noise source terms and the radiated sound have been measured. For radiation to a field point 40 deg to the jet axis, the effective source distributions, as derived from the cross-spectra, show a marked deviation from axisymmetry.

Self and shear noise spectra predicted from an aggregate of cross-spectral densities are compatible with corresponding spectra extracted from farfield measurments by a method due to Nossier and Ribner. Both sets of spectra do match very nearly inshape and exhibit a common frequency shift. Both sets have comparable absolute spectral amplitudes. All this is predicted by theory. The compatibility suggests that the theory is internally consistent and lends it further credibility.

Acknowledgments

This paper is based upon the author's Ph.D. thesis. The author is indebted to H. S. Ribner, who initiated and supervised this research. His continued interest, stimulating discussions, and numerous suggestions are gratefully acknowledged.

The research was supported by funds from the National Research Council of Canada and the U.S. Air Force Office of Scientific Research under Grant AF-AFOSR 75-2808B.

References

[1] Rackl, R., "Two Causality Correlation Techniques Applied to Jet Noise," Ph.D. Dissertation, Dept. of Mechanical Engineering, University of British Columbia, 1973.

[2] Hurdle, P. M. and Meecham, W. C., "Investigation of the Aerodynamic Noise Generating Region of a Jet Engine by Means of the Simple Source Fluid Dilatation Model," *Journal of the Acoustical Society of America*, Vol. 56, No. 6, 1974, pp. 1708-1721.

[3] Jones, B. G., Adrian, R. J., Withianandan, C. K., and Hammersley, R. J., "Prediction of Sound Emitted from Co-Annular Subsonic Jet Flows," AIAA Paper 77-1265, 4th Aero-Acoustics Conf., Atlanta, Ga., 1977.

[4] Lee, H. K. and Ribner, H. S., "Direct Correlation of Noise and Flow of a Jet," *Journal of the Acoustical Society of America*, Vol. 52, No. 5, 1972, pp. 1280-1290.

[5] Morris, P. J., "Hot Wire-Microphone Cross-Correlations Based on Ribner's Source Terms," University of Toronto, Institute for Aerospace Studies, unpublished, 1972.

[6] Seiner, J. M. and Reethof, G., "On the Distribution of Source Coherency in Subsonic Jets," AIAA Paper 74-4, 12th Aerospace Sciences Meeting, Washington, D.C., 1974.

[7] Ribner, H. S., "Quadrupole Correlations Governing the Pattern of Jet Noise," *Journal of Fluid Mechanics*, Vol. 38, 1969, pp. 1-24.

[8] Lighthill, M. J., "On Sound Generated Aerodynamically, I—General Theory," *Proceedings of the Royal Society*, No. A211, 1952, pp. 564-587.

[9] Lighthill, M. J., "On Sound Generated Aerodynamically, II—Turbulence as a Source of Sound," *Proceedings of the Royal Society*, No. A222, 1954, pp. 1-32.

[10] Proudman, I., "The Generation of Noise by Isotropic Turbulence," *Proceedings of the Royal Society*, No. A214, 1952, pp. 119-132.

[11] Nossier, N.S.M. and Ribner, H. S., "Tests of a Theoretical Model of Jet Noise," AIAA Paper 75-436, Hampton, Va., 1975.

[12] Ribner, H. S., "Theory of Two-Point Correlations of Jet Noise," NASA TN D8330, 1976; also, "Two-Point Correlations of Jet Noise," *Journal of Sound and Vibration*, Vol. 56, No. 1, 1978, pp. 1-19.

[13] Maestrello, L., "Two-Point Correlations of Sound Pressure in the Far Field of a Jet: Experiment," NASA TM X-72835, 1976.

[14] Ribner, H. S., "On the Strength Distribution of Noise Sources Along a Jet," University of Toronto, Institute of Aerophysics, UTIA Rept. 51, 1958; abridged in *Journal of the Acoustical Society of America*, Vol. 30, No. 9, 1958, p. 876.

[15] Powell, A., "Similarity Considerations of Noise Production from Turbulent Jets, Both Static and Moving," Douglas Aircraft Co., Rept. SM-23246, 1958; abridged in *Journal of the Acoustical Society of America*, Vol. 31, No. 6, 1959, pp. 812-813.

[16] Lilley, G. M., "On the Noise from Air Jets," Aeronautical Research Council, United Kingdom, ARC 20, 376-N40-FM2724, 1958.

[17] Curle, N., "The Influence of Solid Boundaries Upon Aerodynamic Sound," *Proceedings of the Royal Society*, No. A231, 1955, pp. 505-514.

[18] Siddon, T. E., "On the Response of Pressure Measuring Instrumentation in Unsteady Flow," University of Toronto, Institute for Aerospace Studies, UTIS Rept. 136, 1969.

[19] Planchon, H. P. and Jones, B. G., "A Study of the Local Pressure Field in Turbulent Shear Flow and Its Relation to Aerodynamic Noise Generation—A Study of the Mixing Region of the Round Jet," *Proceedings of 2nd Interagency Symposium on University Research in Transportation Noise*, Raleigh, N.C., June 1974, pp. 20-35.

[20] Richarz, W. G., "Jet Noise Diagnostics: Spurious Sound Generated by Hot Wire-Turbulence Interaction," *Journal of the Acoustical Society of America*, Vol. 64, Suppl. 1, 1978.

[21] Scott, P., Ahlgrisi, F., and Knott, P., "In-Jet/Far-Field Cross-Correlation Experiments. Supersonic Jet Exhaust Noise Investigation, Vol. 11, General Electric Co., Technical Rept. AFARL TR-76-68, 1976, pp. 417-457.

[22] Schaffar, M., "Direct Measurement of the Correlation Between Axial In-Jet Velocity Fluctuations and Far Field Noise Near the Axis of a Cold Jet," *Journal of Sound and Vibration*, Vol. 64, No. 1, 1979, pp. 73-83.

[23] McCartney, J. R., "Ratio of Peak Frequencies of Jet Self and Shear Noise," *Journal of Sound and Vibration*, Vol. 39, No. 2, 1975, pp. 269-272.

[24] Richarz, W. G., "Direct Correlation of Noise and Flow of a Jet Using Laser Doppler," University of Toronto, Institute for Aerospace Studies, UTIAS Rept. 230, 1978.

[25] Bradshaw, P., Ferriss, D. H., and Johnson, R. F., "Turbulence in the Noise Producing Region of a Circular Jet," National Physical Laboratory, Aerodynamics Division, Rept. 1054, 1963.

[26] Chu, W. T., "Turbulence Measurements Relevant to Jet Noise," University of Toronto, Institute for Aerospace Studies, UTIAS Rept. 119, 1966.

[27] Fisher, M. J., Harper-Bourne, M., and Glegg, S.A.L., "Jet Engine Noise Source Location: The Polar Correlation Technique," *Journal of Sound and Vibration*, Vol. 51, No. 1, 1977, pp. 23-54.

[28] Balsa, T. F. and Gliebe, P. R., "Aerodynamics and Noise of Coaxial Jets," *AIAA Journal*, Vol. 15, Nov. 1977, pp. 1550-1558.