AIAA JOURNAL
Vol. 38, No. 2, February 2000

Readers' Forum

Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the AIAA Journal *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment on "Jet Mixing Noise from Fine-Scale Turbulence"

H. S. Ribner*
University of Toronto,
Downsview, Ontario M3H 5T6, Canada

I STRONGLY disagree with the concepts and theoretical foundations of Ref. 1. The major points are as follows: 1) Their two-component model of jet noise is largely invalid. 2) The reinvented pressure-based source term and its space–time correlation are both untenable. 3) The theoretical framework of this semi-empirical prediction formalism,[1] being based on point 2, is faulty. 4) Contrary to the Abstract, jet noise theory based on "first principle(s)" is alive and well.

With regard to the Abstract, Ref. 1 draws on two others.[2,3] An empirical two-component model of jet noise was introduced in Ref. 2 and given as a premise.[1] One component, G, "has a relatively uniform directivity."[1] The other component, F, "radiates principally in the downstream direction."[1] In arbitrary oblique directions, the F and G spectra are superposed: If empirical choices of relative amplitude and peak frequency are chosen, measured spectra can be fitted.[2] However, the G spectrum is very broad and flat, whereas the F spectrum is much narrower. Is it surprising that spectra of intermediate shape can be fitted by adjustable superposition? There is no real physical significance to such a fit.

A more rational explanation of spectral shape has long been available. Theory predicts two similar basic spectra, one with a figure-of-eight pattern (except where cut by the refractive cone of silence) aligned with the jet axis and the other omnidirectional (G?) and of double frequency. Convective amplification elongates these basic patterns (downstream beaming). At an angle just outside the cone, both are comparable, but at 90 deg only G survives. These two spectra may be extracted from experimental measurements at the two angles by solving a pair of simultaneous equations. The predicted two-to-one collapse is beautifully confirmed (Fig. 2 of Ref. 4, with cited references).

The authors' remarks about spectrum F place it within the cone of (relative) silence in the jet noise. The silence is due to the turning of sound rays out of the jet by the refractive effect of mean velocity gradients. Figure 3 of Ref. 4 shows how the sound intensity near the axis attenuates with increasing frequency. The figure is experimental, but patterns calculated from refraction theory (see later) show the same behavior. This behavior accounts directly and very physically for the faster high-frequency rolloff of the type F spectra. By contrast, Tam and Auriault[1] and Tam et al.[2] unconvincingly attribute the spectra to large-scale structures/instability waves, citing a similarity to their predicted spectral shape. Refractive rolloff is, in fact, implicit in the analysis of Tam.[5]

Received 16 May 1999; revision received 23 July 1999; accepted for publication 9 August 1999.

*Professor Emeritus, Institute for Aerospace Studies, 4925 Dufferin Street; also Distinguished Research Associate, NASA Langley Research Center, Hampton, VA 23681-0001. Fellow AIAA.

Further using heuristic arguments, the authors[1,2] attribute their G spectrum (that implied in Ref. 1) to fine-scale turbulence. However, the (preceding) theory and measurements include all scales: The qualification "fine-scale" should be removed from the title.

Contrary to the Abstract, there are first principle theories of jet noise; there is lacking only a first principle theory of the turbulence on which the theories depend. Given the turbulence, the theories can predict the noise. The accuracy in the past has been degraded by relatively crude approximations to the turbulence, for example, simple scaling laws, and/or to the formidable mathematics (cf. Ref. 4). With realistic spatial modeling of turbulence and mean flow properties, predictions of spectra and directivity have approached measurement; for example, see Ref. 6. Also implementation of recent refinements[4] to the theory should yield fairly close agreement.

With regard to the main text, the following points are made:

1) The authors[1] rediscover the dilatation theory of jet noise; for example, see Ref. 7: the sound source is expressed in terms of the turbulence pressure perturbation p_{turb}. However, by using a heuristic gas kinetic analogy, they get it wrong. In place of the correct source term $-c^{-2}\,\mathrm{D}^2 p_{\text{turb}}/\,\mathrm{D}t^2$, they deduce $\mathrm{D}p_{\text{turb}}/\,\mathrm{D}t$.

2) They assume a mostly Gaussian (bell-shaped) from for its two-point space–time correlation. This is physically impossible for a source that is a time derivative: The correlation must have the form of a double derivative with respect to time delay. These two errors, in the source term and in its correlation function, would be expected to yield substantial error in jet noise prediction. In particular, the convective amplification would be severely underestimated (cf. Ref. 7, pp. 36 and 37).

3) The Green's function that ". . .accounts for refraction effects of the mean flow. . ." is evaluated by a method of the authors[3] of Ref. 1. This is, however, antedated by Schubert[8] and by Mungur et al.[9] (not cited), both using full wave acoustics. Schubert[8] makes extensive comparisons with experiments of Atvars et al.[10]; although these are cited in Ref. 3, comparisons are not made. Moreover, the plots of Ref. 3 do not suggest any improvement in accuracy over the much earlier work.

4) The integrand of the final Eq. (35) may be interpreted as the spectrum emitted to point $\boldsymbol{x}$ from unit volume of the jet. Examination seems to indicate that this spectrum is finite at both zero and infinite frequency. This is quite unrealistic. By contrast, prior theory, for example, Ribner,[11] predicts a relatively narrowband bell-shaped spectrum. (When summed over all volume elements, the result is the characteristic broadband spectrum of the complete jet.)

References

[1]Tam, C. K. W., and Auriault, L., "Jet Mixing Noise from Fine-Scale Turbulence," *AIAA Journal*, Vol. 37, No. 2, 1999, pp. 145–153.

[2]Tam, C. K. W., Golebiowski, M., and Seiner, J. M., "On the Two Components of Turbulent Mixing Noise from Supersonic Jets," AIAA Paper 96-1716, 1996.

[3]Tam, C. K. W., and Auriault, L., "Mean Flow Refraction Effects on Sound Radiated from Localized Sources in a Jet," *Journal of Fluid Mechanics*, Vol. 370, Sept. 1998, pp. 149–174.

[4]Ribner, H. S., "Effects of Jet Flow on Jet Noise via an Extension to the Lighthill Model," *Journal of Fluid Mechanics*, Vol. 321, 1996, pp. 1–24.

[5]Tam, C. K. W., "Jet Noise Generated by Large Scale Coherent Motion," *Aeroacoustics of Flight Vehicles: Theory and Practice*, edited by H. H. Hubbard, Vol. 1, RP-1258, NASA, 1991, pp. 311–390.

[6]Moon, L. F., and Zelazny, S. W., "Experimental and Analytical Study of Jet Noise Modeling," *AIAA Journal*, Vol. 13, 1975, pp. 387–393.

[7]Ribner, H. S., "Aerodynamic Sound from Fluid Dilatations: A Theory of Sound from Jets and Other Flows," Inst. for Aerospace Studies, Univ. of Toronto, UTIA Rept. 86, Downsview, ON, Canada, 1962.

[8]Schubert, L. K., "Numerical Study of Sound Refraction by a Jet Flow II. Wave Acoustics," *Journal of the Acoustical Society of America*, Vol. 51, No. 1, 1972, pp. 447–463.

[9]Mungur, P., Plumblee, H. E., and Doak, P. E., "Analysis of Acoustic Radiation in a Jet Flow Environment," *Journal of Sound and Vibration*, Vol. 36, No. 1, 1974, pp. 21–52.

[10]Atvars, J., Schubert, L. K., and Ribner, H. S., "Refraction of Sound from a Point Source Placed in an Air Jet," *Journal of the Acoustical Society of America*, Vol. 37, No. 1, 1965, pp. 168–170.

[11]Ribner, H. S., "The Generation of Sound by Turbulent Jets," *Advances in Applied Mechanics*, Vol. 8, Academic, New York, 1964, pp. 103–182.

M. Samimy
Associate Editor

Reply by the Authors to H. S. Ribner

Christopher K. W. Tam* and Laurent Auriault†
Florida State University, Tallahassee, Florida 32306-4510

IT is no secret that our proposed semi-empirical theory[1] is totally different from Ribner's own jet noise theories.[2,3] Because of the fundamental difference in approach, we are prepared to justify our assumptions and explain any points that need clarification. However, a scientific theory must, in the end, be judged by its physics, prediction capability, and accuracy. We most certainly believe that our theory has a firm physical foundation, although it is definitely not following the traditional approach and concepts.

Earlier, as reported by Tam et al.[4] and Tam,[5,6] an unexpected discovery was made that all measured jet noise spectra from circular, elliptic, and rectangular high-speed jets, regardless of Mach number, jet temperature, and direction of radiation (as long as one noise component is dominant in that direction), appeared to fit two seemingly universal spectra: the F and G spectra. It is relevant to point out that, in a recent investigation, Dahl and Papamoschou[7] found that the F and G spectra also fitted their coaxial jet noise data. In addition, Wat et al.[8] in their analysis of flight jet noise data found the two spectra fitting their measured data well. To provide a physical meaning to the two empirical spectra, it was noted in Refs. 4–6 that during the past 25 years there was overwhelming experimental evidence that jet turbulence consisted of both large and small scales. For high-speed jets, optical observations and theoretical analysis indicated that the large turbulence structures of the jet flow, behaving like traveling wavy walls, emitted intense Mach wavelike radiation in the downstream direction. In the downstream direction, all of the noise spectra were observed to fit the empirical F spectrum[4–6] well. Based on this, it was proposed that the F spectrum was a distinctive characteristic of large-turbulence structures noise. Tam et al.[4] and Tam[5,6] also recognized that the fine-scale turbulence was more isotropic and emitted noise without a strong directivity. Because there was little large-turbulence structure noise in the sideline and upstream directions, the noise in these directions was that from the fine-scale turbulence. In the sideline and upstream directions, the noise was found to fit the G spectrum well. Thus, it was proposed that the G spectrum was a feature of fine-scale turbulence noise.

Experimental support for the suggestion that the F spectrum is the noise from the large-turbulence structures and the G spectrum is the noise from the fine-scale turbulence is provided in a recent experiment by Zaman (see Ref. 9). In Zaman's experiment, nozzles with a variety of geometries but equal exit area were used. One of the nozzles had a six-lobe configuration. Because of the lobed geometry, the jet fluid came out of the nozzle in thin sheets. The thickness was much smaller than the equivalent diameter of the baseline nozzle, so that this jet could not support large-turbulence structures that existed in the baseline circular jet. In other words, the six-lobe nozzle effectively eliminated the large-turbulence structures. In the absence of large-turbulence structures, the noise spectrum of the jet should fit only the G spectrum in all directions, even in the downstream direction close to the jet axis, where the large-turbulence structure noise is usually dominant. This was, indeed, the unambiguous experimental result. Thus, there should be no doubt as to the existence of two mixing noise components; one generated by the large-turbulence structures and the other by the fine-scale turbulence of the jet flow.

In Ref. 10, it is suggested that there are first principle theories of jet noise; there is lacking only a first principle theory of turbulence on which the theories depend. Presumably, Ref. 2 is one of the first principle jet noise theories. Note that turbulence research has gone on since the beginning of the century. However, progress has been slow and tortuous. The prospect of having a first principle turbulence theory in the foreseeable future is rather remote. Because the first principle jet noise theories depend on the availability of a first principle turbulence theory to provide the necessary input before any accurate prediction can be made, we are effectively without a first principle jet noise theory despite any claims to the contrary.

We strongly object to the suggestion of Ribner[10] that we rediscover the dilatation theory. In Ref. 10, he claims that our theory has a wrong noise source term because ours is different from the correct source term of his own dilatation theory. Theories with different source terms are definitely different. Our theory has absolutely nothing to do with the dilatation theory. We disagree with the proposition that our noise source term is wrong. It we were wrong, how is it possible that our predictions match so well with experimental measurements over such a large range of Mach numbers and temperature ratios, whereas the dilatation theory, having the correct source term, could not?

We are unable to find any physical basis for the following assertion of Ref. 10: "This is physically impossible for a source that is a time derivative: The correlation must have the form of a double derivative with respect to time delay." Clearly, the dilatation theory requires a double derivative with respect to time delay, and hence, all jet noise theories should have this feature; otherwise they are wrong and physically impossible.

The author of Ref. 10 appears to suggest that, because we use the Green's function in our theory, we should give more credit to his associates. We believe we have. However, we would like to point out that we use the adjoint Green's function and not the direct Green's function. Perhaps the author of Ref. 10 has overlooked that an adjoint Green's function is not the same as the Green's function in a non-self-adjoint problem. We use the adjoint Green's function because it has many important advantages. These advantages have been carefully elaborated in Ref. 11.

The author of Ref. 10 further states that, on examining Eq. (35) of Ref. 1, the formula for the noise spectral density $S(\boldsymbol{x}, \omega)$, he finds that it has a finite value at infinite frequency. We would like to request him to recheck his calculation. It is elementary to show that the high-frequency limit is zero; i.e., $\lim_{\omega \to \infty} S(\boldsymbol{x}, \omega) \to 0$.

In summary, we firmly believe that the criticisms of Ref. 10 on our work are unjustified and without any physical basis.

Received 21 June 1999; revision received 4 August 1999; accepted for publication 9 August 1999.

*Distinguished Research Professor, Department of Mathematics. Associate Fellow AIAA.

†Graduate Student, Department of Mathematics.

References

[1]Tam, C. K. W., and Auriault, L., "Jet Mixing Noise from Fine-Scale Turbulence," *AIAA Journal*, Vol. 37, No. 2, 1999, pp. 145–153.

[2]Ribner, H. S., "Effects of Jet Flows on Jet Noise via an Extension to the Lighthill Model," *Journal of Fluid Mechanics*, Vol. 321, Nov. 1996, pp. 1–24.

[3]Ribner, H. S., "Aerodynamic Sound from Fluid Dilatations: A Theory of Sound from Jets and Other Flows," Inst. of Aerospace Studies, Univ. of Toronto, UTIA Rept. 86, Downsview, ON, Canada, 1962.

[4]Tam, C. K. W., Golebiowski, M., and Seiner, J. M., "On the Two Components of Turbulent Mixing Noise from Supersonic Jets," AIAA Paper 96-1716, May 1996.