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Reply by the Authors to H. S. Ribner

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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.

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

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IN a recent paper, Tam and Auriault[1] describe a semi-empirical theory for the prediction of the spectrum, intensity, and directivity of the fine-scale turbulence noise from jet mixing layers. The turbulence information is supplied by a $k-\varepsilon$ turbulence model. The authors conclude that "By comparison with experimental measurements over a wide range of jet velocity and temperature ratios, it is found that the theory can provide very accurate noise predictions."

An examination of those comparisons reveals that only Fig. 6 deals with a hot jet case. The combination of a Mach number of 2.0 and a stagnation temperature ratio of 1.8, however, yields a fully expanded jet temperature precisely equal to ambient temperature; the significance of this observation will become apparent next.

The extensive and systematic database from Tanna et al.[2] includes hot subsonic jets; it was apparently considered for comparison but "Only the jet data at supersonic Mach numbers are considered of good quality to be included for comparison."

One can only presume that this apparent lack of quality results from the observation that at subsonic jet Mach numbers the measured noise level, for a given jet velocity, increases with jet temperature instead of decreasing, as appears to be universally predicted by the current model.

However, the fact that subsonic jet mixing noise increases with jet exit temperature is well known and has been extensively described in the literature. An early report is contained in Ref. 3, where the authors went to considerable lengths to demonstrate that the effect was indeed a genuine feature of the jet mixing process and not associated with combustion or other noise production upstream of the jet nozzle. The first definitive attempt to model this component of mixing noise appears to be that from Morfey.[4] In brief, after rewriting Lighthill's acoustic analogy in the form

$$\frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}-\nabla^2 p=\frac{\partial^2 \rho u_i u_j}{\partial x_i \partial x_j}-\frac{\partial^2}{\partial t^2}\left(\rho-\frac{p}{c_0^2}\right)$$

he argued that the second term on the right-hand side constituted an additional source, which would be zero only when the density in the source region was identical to that of the ambient fluid. Otherwise an additional dipole source, which in heated air jets scales as $U^6(\Delta T/T_s)^2$, where T_s is the temperature in the source region, must be considered in addition to the traditional quadrupole source, which scales as the eighth power of the jet exit velocity U. It follows that at lower velocities the dipole source will become progressively more apparent, reducing the velocity dependence from U^8 to U^6.

In a subsequent paper, Tester and Morfey[5] tested this model against an extensive database with convincing results. Perhaps of more importance in the current context was the consistency demonstrated between the Lockheed data[2] and that from the (then) National Gas Turbine Establishment and Institute of Sound and Vibration Research facilities in the United Kingdom and the Société Nationale d'Etude et de Construction de Moteurs d'Aviation in France.

The following is respectfully submitted:

1) The data of Ref. 2 should not be rejected on the basis of quality. They are consistent with quality data from other sources.

2) The model proposed in Ref. 1 includes only the quadrupole term in the preceding equation. It is suited, therefore, only to the prediction of noise from unheated jets or to jets of sufficiently high velocity that the dipole term is negligible. The single heated jet spectral comparison (Fig. 6) happens to correspond to a case where the fully expanded jet temperature, and hence density, is precisely equal to the ambient value.

3)Although it is an achievement to predict cold and isothermal jets to the accuracy demonstrated, the model will fail to predict jet mixing noise for subsonic exit velocities at practical jet temperature ratios.

Recent references to temperature effects on jet noise production may also be found in Refs. 6 and 7 in the context of coaxial jet noise prediction.

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PROFESSOR Fisher's comments on our paper[1] center on the effect of temperature on jet noise. He points out that in the

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