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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 "Acoustic Analogy and Alternative Theories for Jet Noise Prediction"

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IN Ref. 1, Morris and Farassat discussed and compared the Mani–Gliebe–Balsa–Khavaran (MGBK)[2–4] model theory and the Tam–Auriault[5] theory for predicting jet noise spectra. The MGBK model was developed following the Lighthill[6,7] acoustic analogy approach. The Tam–Auriault theory was formulated in an independent way. As Morris and Farassat stated, "... it is shown in this paper that, for the same RANS solution, jet noise predictions made with the Tam and Auriault model give much better agreement with experimental measurements at 90 deg to the jet axis than methods based on the acoustic analogy. However, it will also be shown that this is not due to any inherent flaw in methods based on the acoustic analogy; rather, it is associated with the assumptions made concerning the statistical properties of the turbulence sources. Both approaches yield identical noise predictions at 90 deg to the jet axis if consistent descriptions of the turbulent sources are chosen." The last two sentences of the preceding statements are incorrect. There are fundamental differences between the noise sources of the MGBK model theory and the Tam–Auriault theory.

There are now other published works beyond that of Ref. 5 showing that for cold to moderate temperature jets the Tam–Auriault theory predicts noise spectra that are in good agreement with experimental measurements. Tam et al.[8] applied the theory to jets in simulated forward flight and found good agreement with measured data for both subsonic and supersonic jets. In another work, Tam and Pastouchenko[9] investigated the noise from nonaxisymmetric jets. They were able to demonstrate that the theoretical predictions based on the Tam–Auriault theory matched well with experiments. The Tam–Auriault theory not only can predict far-field noise spectra, but it is also capable of predicting the noise source distribution inside a jet. In a recent work, Tam et al.[10] calculated the noise source distributions of supersonic jets at Mach 1.46, 1.96, and 2.46 according to the Tam–Auriault theory. Their theoretical results on the noise source intensity distributions as well as on noise source distributions at selected Strouhal numbers were in favorable agreement with experimental measurements.

The issue in question is whether the noise source model of the MGBK model is fundamentally different from that of the Tam–Auriault theory. If they are indeed different, then regardless of the assumptions made of the statistical properties of turbulence, the two theories are different. They will not yield identical noise predictions.

The MGBK model relies on the Lighthill acoustic analogy theory[6,7] to identify the noise sources of turbulent jets. Recently, Fedorchenko[11] expressed the view that the acoustic analogy theory had fundamental flaws. Tam,[12] on the other hand, pointed out two basic ambiguities inherent in the acoustic analogy theory. He provided a number of examples showing that the acoustic analogy theory failed to identify the correct noise sources. In simple terms, the examples demonstrated that the so-called quadrupole noise source terms of the theory were wave-propagation terms. They had nothing to do with the physical noise sources.

In Ref. 1, Morris and Farassat provided a detailed description of the modeling of the noise sources of the MGBK model. According to this model, the noise source is T_{ij}, the Lighthill stress tensor. To predict the far-field noise spectra, one would require the two-point space-time correlation of T_{ij}, which could be manipulated to $\langle T_{xx}^{(1)} T_{xx}^{(2)} \rangle$, where x is in the direction of radiation and $\langle\,\rangle$ is the ensemble or time average. However, the prediction gives a spectrum, for 90 deg radiation, that is too narrow when compared with measurements. In the Tam–Auriault theory, physical reasoning was used to identify how fine-scale turbulence generated noise. For predicting far-field noise spectra, their formulation leads to the conclusion that the noise source is the two-point space-time correlation of $\mathrm{D}q/\mathrm{D}t$, namely,

$$\left\langle \frac{\mathrm{D}q}{\mathrm{D}t_1} \frac{\mathrm{D}q}{\mathrm{D}t_2} \right\rangle$$

where q is the kinetic energy of turbulence per unit volume and $\mathrm{D}/\mathrm{D}t$ is the convective derivative. In other words, the noise source is the time fluctuation of the turbulence intensity in the moving frame of the turbulence. (Note that the source is not the turbulence intensity q, but $\mathrm{D}q/\mathrm{D}t$.) The predicted noise spectra of the Tam–Auriault theory agreed well with experimental measurements.

In Sec. V of Ref. 1, Morris and Farassat suggested to replace the noise source correlation function

$$\left\langle \frac{\mathrm{D}q}{\mathrm{D}t_1} \frac{\mathrm{D}q}{\mathrm{D}t_2} \right\rangle$$

in the Tam–Auriault theory by $\langle q_1 q_2 \rangle$ and modeled $\langle q_1 q_2 \rangle$ by the same model function they used for $\langle T_{xx}^{(1)} T_{xx}^{(2)} \rangle$ of the MGBK model. They then showed that this immediately yielded the same prediction as the MGBK model. Again the half-width of the predicted noise spectrum was too narrow compared with measurements. Based on this, Morris and Farassat concluded that "both the Acoustic Analogy theory and the Tam and Auriault's model yield identical noise prediction formulas at 90 deg to the jet axis if consistent assumptions are made in the statistical description of the turbulent sources." It is the author's contention that this conclusion is erroneous and misleading. Replacing the noise source of the Tam–Auriault theory with an incorrect noise source would naturally lead to inaccurate predictions. The noise source of the Tam–Auriault theory is not T_{ij} or q but $\mathrm{D}q/\mathrm{D}t$. The noise source space-time correlation function

$$\left\langle \frac{\mathrm{D}q}{\mathrm{D}t_1} \frac{\mathrm{D}q}{\mathrm{D}t_2} \right\rangle$$

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is surely not the same as $\langle T_{xx}^{(1)} T_{xx}^{(2)} \rangle$ or $\langle q_1 q_2 \rangle$ either physically or mathematically. On the other hand, the exercise performed by Morris and Farassat may have a different interpretation. It demonstrates that the noise source T_{ij}, identified by the acoustic analogy theory and adopted by the MGBK model, would not give correct prediction of the radiated noise spectrum. Furthermore, the noise source that gives good predictions is Dq/Dt.

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Reply by the Authors to C. K. W. Tam

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THE prediction of noise generation and radiation by turbulence has been the subject of continuous research for over 50 years. The essential problem is how to model the noise sources when one's knowledge of the detailed space-time properties of the turbulence is limited. In Ref. 1 we attempted to provide a comparison of models based on acoustic analogies and recent alternative models. Our goal was to demonstrate that the predictive capabilities of any model are based on the choice of the turbulence property that is modeled as a source of noise. Our general definition of an acoustic analogy is a rearrangement of the equations of motion into the form $\mathcal{L}(u) = Q$, where $\mathcal{L}$ is a linear operator that reduces to an acoustic propagation operator outside a region $\mathcal{V}$, u is a variable that reduces to acoustic pressure (or a related linear acoustic variable) outside $\mathcal{V}$, and Q is a source term that can be meaningfully estimated without knowing u and tends to zero outside $\mathcal{V}$. There should be no dispute that if the details of the turbulence were known in sufficient detail, then an acoustic analogy, or any other method, could be used to predict the radiated noise.[2] It should also be noted that models based on the acoustic analogy provide excellent predictions of rotorcraft and propeller noise[3,4] as well as broadband airfoil noise.[5] In addition, the acoustic analogy yields very good predictions of statistical properties, such as the two-point cross correlation of the noise radiated by jets, outside the region where refraction effects are important.[6] What is at issue here is whether an acoustic analogy, in whatever form, is capable of describing the noise radiated by turbulence when the details of the turbulence are not known completely.

In Ref. 7, addressing our paper, as well as in Ref. 8, it is argued that an acoustic analogy is unable to provide a description of the physical sources of aerodynamic noise; however, the Tam–Auriault[9] theory can. However, Lighthill's acoustic analogy was formulated on the basis that "we never know a fluctuating fluid flow very accurately."[10] An acoustic analogy, as its name indicates, formulates the aerodynamic noise generation problem in terms of equivalent sources that give "the effect of a fluctuating external force field, known if the flow is known, acting on the said uniform acoustic medium at rest, and hence radiating sound in it according to the ordinary laws of acoustics."[10]

The concept that the gradients of the instantaneous Reynolds stress, or a vortex force,[1] provide an unsteady force on the fluid that results in noise generation and radiation seems to us to be one very viable picture of how turbulence generates noise. The force associated with the Reynolds stress gradient is an important feature of other fluid dynamics problems and models. These include acoustic streaming[11] and, of course, turbulence modeling in the Reynolds-averaged Navier–Stokes (RANS) equations. The key question is how to model this effective force.

The issues raised in Ref. 7 go far beyond anything contained in our original paper. So, our response will only try to address a few specific issues; however, we hope that this response will highlight open issues that should be the subject of continued constructive debate.

Reference 8 provides three examples of the application of the acoustic analogy to problems with either exact or numerically exact solutions. The first example is the initial value problem of sound initiated by a pressure pulse with a Gaussian spatial distribution, and the second is a boundary value problem of sound radiation from a sphere whose surface temperature oscillates in time. Both of these cases are ones in which an acoustic analogy is not needed, because the problems (equations and initial and boundary conditions) are defined exactly. However, whether the problems are solved directly or by a solution of a formulation based on Lighthill's acoustic analogy, the correct answer for the radiated noise is obtained. On the basis of these examples, in Ref. 8 the question is posed "whether the Acoustic Analogy is a reliable way to identify the true sources of noise in real practical aeroacoustics problems, especially in turbulent flows?" Because the acoustic analogy was never formulated to identify the "true sources" of noise, a more pertinent question would be "whether the acoustic analogy is a useful way to identify the effective sources of noise in real practical aeroacoustics problems where the details of the flow are not known precisely, especially in turbulent flows."

In a third example in Ref. 8, it is argued that the acoustic analogy is unable to obtain the weak solution to the nonlinear Euler equations. The example given is the propagation of a normal shock into a stationary gas in one dimension. The gas conditions behind the shock are known to be given by the Rankine–Hugoniot relations.

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