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Model for Radiated Sound from High-Reynolds-Number Turbulence Source

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I. Introduction

THE MGB code is a well-established tool developed by Mani et al.,[1] which has become an industry standard for jet-noise prediction. It is based on Mani's theoretical analysis, which was among the earliest attempts to analyze flow-acoustic interactions in the general context of Lighthill's theory[2] of quadrupole sound sources. As in Lighthill's original theory, the sound source for the MGB code is a fourth-order product of velocity fluctuations, which is closed in terms of the second-order space-time correlation by assuming quasi-normality. Following Proudman's analysis[3] of sound radiation by isotropic turbulence, the MGB code uses the special form for the second-order space-time correlation[4]

$$\langle v_i(\boldsymbol{x}, t) v_j(\boldsymbol{y}, s)\rangle = K(z)\left\{f(r)\delta_{ij} + h(r)r_i r_j \mid r^2\right\}e^{-(t-s)/\tau(z)}$$

In this equation the kinetic energy K and timescale τ are evaluated at the point $z = (\boldsymbol{x} + \boldsymbol{y})/2$; f and h are the longitudinal and lateral correlation functions. The argument r is defined by

$$r = |\boldsymbol{x} - \boldsymbol{y}|$$

The plausible assumption is that the timescale is given in MGB code by

$$\tau(z) = C[K(z)/\epsilon(z)]$$

with C as a model constant and $\epsilon(z)$ as the turbulence dissipation rate.

The second-order space-time correlation consists of two major simplifications: first, the correlation function is assumed to be isotropic; and second, the correlation function has the property of spatial and time separation. Recently, Khavaran and Krejsa[5] addressed the first issue by investigating the impact of sound source anisotropy on aerodynamic mixing noise from fine-scale turbulence. An axisymmetric turbulence model was presented with the axis of symmetry aligned with the jet axis. They found that anisotropy increases the overall noise level.

In this Note we focus on the second major simplification: the assumption that the correlation function is the product of a function of space and a function of time. Indeed, the temporal part of the space-time correlation function is scale dependent. In general, the velocity correlation function should be given by

$$\langle v_i(\boldsymbol{x}, t) v_j(\boldsymbol{y}, s)\rangle = K(z)\left\{f(r)\delta_{ij} + h(r)r_i r_j \mid r^2\right\}e^{-R[(t-s),r,z]}$$

where

$$R(0, \boldsymbol{r}, z) \equiv 1$$

The goals of this paper are two-fold. First, we would like to assess the implications of using the more realistic correlation function model in the MGB noise calculations. Second, we would like to suggest an improved choice of the spatial correlation function f (therefore, function h from the isotropic relationship). As long as one can distinguish the sound source from the scales of turbulent fluctuations, a physical space formulation is simpler than a spectral space formulation. This simplicity is obviously very appealing, and the extension of Batchelor's work[6] to include the effects of shear by Kraichnan[7] is restricted to physical space correlation function representation. Several recent treatments[8,9] of sound generated by isotropic turbulence, based on the Lighthill's analogy, use the physical space correlation function.

In the following section we present brief descriptions of the MGB code and our new formulations. Numerical results and conclusions are presented in the following sections.

II. Sound Source

The sound source in the MGB code is written as

$$I_{ijkl} = \int \frac{\partial^2}{\partial \tau^2}\overline{(\rho v_i v_j)(\rho' v'_k v'_l)}\,\mathrm{d}x \tag{1}$$

so that if we define

$$S_{ijkl} = \overline{v_i v_j v'_k v'_l}$$

then

$$I_{ijkl} = \rho^2 \int \frac{\partial^2}{\partial \tau^2} S_{ijkl}\,\mathrm{d}x$$

The quasi-normal approximation leads to

$$S_{ijkl} = S_{ik}S_{jl} + S_{il}S_{jk} + S_{ij}S_{kl}$$

where the second-order correlation function is given by $S_{ij} = \overline{v_i v_j}$.

The second-order correlations are assumed to be separable function of x and τ, i.e.,

$$S_{ij}(r, \tau) = R_{ij}(r)g(\tau, r)$$

But the temporal correlation function g now has a scale dependence through the dependence on the separation variable r. The tensor R is defined in terms of the longitudinal correlation function f by

$$R_{ij}(x) = (u')^2\left[\left(f + \tfrac{1}{2}xf'\right)\delta_{ij} - \tfrac{1}{2}f'x_i x_j \mid x\right]$$

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III. Spatial Correlation Function Models for High-Reynolds-Number Flows

Traditionally, the spatial-correlation function has been assumed to be either Gaussian or exponential.[7] The Gaussian function is

$$f(r) = \exp(-\sigma^2 r^2) \tag{2}$$

whereas the exponential function is

$$f(r) = \exp(-\sigma r) \tag{3}$$

Kraichnan[7] remarked that the numerical factors of pressure correlations are sensitive to the assumed correlation function. We would like to mention that the exponential form is not correct because its derivative is not zero at the origin.

The Gaussian function is used in the MGB code. The sound generated from high-Reynolds-number turbulence, which is of interest here, obviously cannot be represented correctly by the Gaussian distribution. Hence, we suggest a change of the spatial correlation function f based on recent advancement of turbulence research. In particular, the structure function, which is related to the velocity distribution function

$$2u^2(1 - f) = (\nu\varepsilon)^{\frac{1}{2}} B(y/\eta) \tag{4}$$

should exhibit the $\frac{2}{3}$ scaling law in the inertial range. Batchelor[6] derived an expression based on his high-Reynolds-number structure function

$$B(z) = \frac{z^2/15}{(1 + \alpha z^2)^{\frac{2}{3}}} \tag{5}$$

where $z = r/\eta$ with η as the Kolmogorov length. The constant $\alpha = 15^{-3/2}$. As shown recently by Benzi et al.[10] and Lohse and Muller-Groeling,[11] the Batchelor structure function compares well with high-Reynolds-number experimental and numerical simulation data.

IV. Spatial Dependence in the Temporal Correlation Function

The time Fourier transform of I_{1111} is defined by

$$I_{1111}(\Omega) = \left(\frac{1}{\pi}\right) \int \mathrm{d}\tau I_{1111}(\tau) \exp(i\Omega\tau)$$

and the results are substituted

$$I_{1111}(\Omega) = \left(\frac{1}{\pi}\right) \Omega^4 \int \mathrm{d}\tau\, \mathrm{d}x \exp(i\Omega\tau) R_{11}(x) R_{11}(x) g^2\left(\frac{V\tau}{x}\right)$$

In this equation the temporal correlation function could be determined by the sweeping[12,13] or straining[14] hypothesis. See Refs. 12–16 for a detailed discussion of this important subject. For the Batchelor structure function:

$$I_{1111}(\Omega) \sim \rho u^4 V^{\frac{13}{3}} \Omega^{-\frac{4}{3}} \int \mathrm{d}x x^{\frac{13}{3}} \exp\left(\frac{-x^2}{8}\right)$$

The sweeping-and-straining hypothesis was first introduced into the sound generated from turbulent flows[17] to estimate the total pressure level. It was also argued that the frequency spectrum may be deduced.[18]

There is a critical need for flowfield data at high Reynolds number for providing a definite answer on the temporal correlation function. The information on the scaling of the frequency spectrum should be very helpful for developing a subgrid model for large-eddy simulations in computation aeroacoustics. To the best knowledge of the authors, such diagnostic measurements have not yet been conducted for the jet or other turbulent flowfields.

V. Numerical Experiments

The solution techniques used in the MGB code that are relevant to this note have been described by Kharavan and Krejsa.[4,5] Here we present only a very brief sketch. The mean flowfield and turbulence quantities are calculated by solving Navier–Stokes equations with a K–ϵ turbulence model. The choice of the model coefficients, of course, determines the flowfield. The noise source strength and spectrum are then estimated from computed turbulence quantities using Eq. (5). The MGB model assumes that turbulence is locally isotropic and uses a form of temporal correlation function $g(\tau)$ that is independent of spatial information. This temporal correlation function has the form

$$g(\tau) = e^{-(\tau/\tau_0)^2}$$

where τ_0 is the characteristic time delay factor in a moving reference frame and is expressed as $\tau_0 \sim k/\epsilon$. The far-field noise prediction includes sound/flow interaction as a result of flowfield, i.e., temperature, velocity gradient, etc. effects on the noise radiated from convecting quadrupole sources. This phase of the computation uses the mean flow computed earlier. High-frequency asymptotic solutions of Lilley's equation are used to develop expressions for the far-field noise from convected quadropoles embedded in parallel shear flow. These expressions are then used to compute noise associated with turbulent eddy volume elements distributed in the jet plume. Various corrections to the far-field noise spectrum are made to account for effects such as Doppler shift, flight speed, etc. Details of the formulation can be found in Kharavan and Krejsa.[4,5]

In Fig. 1 we show the sound pressure level in decibels at different frequencies at a 40-ft (13-m) radius from nozzle for 80 deg from flow direction. Original and new models are compared against observed data. The angle of 80 deg should be a relatively clean location for checking our models for turbulent flows at high Reynolds number, because this is the location with almost minimum interaction between flow and sound. We believe this figure provides the most important support for our suggested model. We indicate in Fig. 2 that our model also provides an improved prediction at

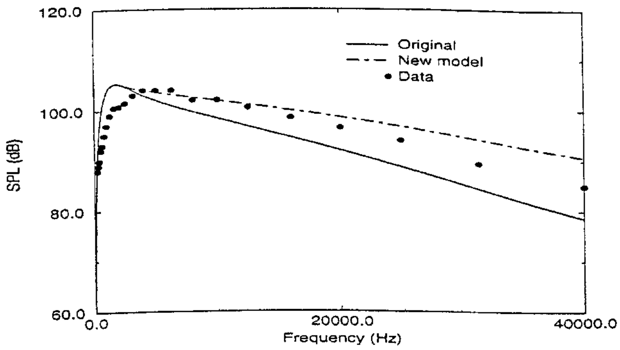

Fig. 1 Sound pressure level (dB) at 80 deg.

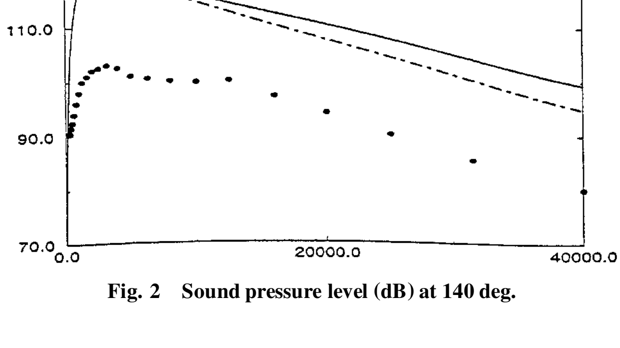

Fig. 2 Sound pressure level (dB) at 140 deg.

140 deg, where the jet noise usually peaks. However, it is important to stress that this can include effects caused by flow and sound interactions.

VI. Conclusions

In this Note we have considered two important improvements that the original MGB code needed for estimating noise generated from high-Reynolds-number turbulent flows. First, we allowed the spatial dependence of the temporal correlation function. Second, we used the Batchelor structure function, which has the appropriate inertial range form. Numerical tests against experimental data and original MGB code calculation demonstrated that significant improvement can be achieved.

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Improved Computational Method for Determining Light Buffet of Flapped Wings

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Introduction

BUFFETING is the response of a transonic aircraft to the fluctuating aerodynamic forces originating from the separated flow regions on its wing. The commonly adopted computational method for predicting light buffet of an aircraft is that developed by Proksch[1] based on the wing area occupied by the separated flow. However, when this method is applied to a flapped wing, unrealistic results might be obtained for large flap-deflection angles.

As an illustrative example shown in Fig. 1, we consider two identical flapped airfoils with different flap-deflection angles δ_a and $\delta_b (> \delta_a)$. The deflection angles are so large that the upper surfaces of both flaps are completely occupied by fully separated flows, whose lengths are equal to the length of the flap. Then, according to Proksch's method, the buffet coefficients for these two airfoils are the same. However, the size of the separation bubble in case b is larger than that in case a, and therefore it is expected to cause a stronger buffeting force on the flap. This simple example indicates that the projected area of the separated flow alone truly cannot represent the buffet intensity of the fluctuating forces originating within the separated flow. The result thus suggests that the vertical dimension of the separation bubble, in addition to its projected area on the wing, is also a characteristic parameter for determining the buffet intensity of wings with strong flow separation.

In this Note, the computational method developed by Proksch[1] for predicting light buffet of a wing is first described, then followed by our proposed method, which takes into account the volume of separated flows. The advantage of using the latter is demonstrated in an example for predicting the light buffet of a model flapped wing utilizing both methods.

All flow computations shown here are carried out using an efficient numerical tool that provides a user-friendly environment for the control of smoothness, clustering, and orthogonality of the grids. The total number of grids is $195 \times 30 \times 49$, with 195 points in the streamwise direction (ξ), 30 points in the spanwise direction (η), and 49 points in the direction normal to the wing surface (ζ). The transonic flow code that solves the thin-layer Navier–Stokes equations using an implicit and approximately factored scheme[2] is based on central differencing in both the η and ζ directions and upwind differencing in the ξ direction. The algebraic turbulent-eddy-viscosity model of Baldwin and Lomax[3] is used to calculate the turbulent shear stress. The code was validated using an unflapped ONERA M6 wing, whose experimental surface-pressure data are available in Ref. 4. Details of the numerical tool and code validation are described in Ref. 5.

Light Buffet Prediction Methods

Method Based on Proksch's Buffeting Coefficient C_{bi}

A numerical procedure for predicting light buffet for finite wings based on the concept of Thomas and Redeker[6] was carried out by

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