Ray tracing methodology for jet noise prediction

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Abstract: A computational aeroacoustics method based on Lighthill's acoustic analogy and geometrical acoustics is presented to calculate the noise arising from the mixing of subsonic turbulent jets. The acoustic source model is based on information available from a standard RANS $k-\epsilon$ turbulence model. Far field propagation, accounting for the effects of sound refraction, is treated using a ray tracing methodology. This implementation makes few simplifying assumptions about the flow field, allowing application of the method to complicated three-dimensional configurations. In future work, we intend to apply this method to compute far field acoustic predictions to the time averaged output of a RANS simulation of a subsonic round jet.

1 Problem Background

While jet noise arising from turbulent mixing remains one of the most significant sources of aircraft noise overall, its calculation remains a significant challenge, both theoretically and computationally. Jet aeroacoustic methods have ranged from low fidelity fitting to empirical databases to expensive FWH calculations based on LES or DNS data. In the context of design optimization, where repeated aeroacoustic evaluations of a flow field are required, it is highly desirable to develop a method that minimizes computational time and expense while retaining the necessary accuracy. In this paper we apply a source model based on Lighthill's acoustic analogy. In order to handle far field propagation, and the refraction of sound by the mean flow field, we apply a ray tracing methodology [1]. The source and propagation models are developed independently and then coupled to form the overall jet noise prediction tool.

2 Methodology

2.1 Source model

The starting point of the source model is Ribner's formulation of the Lighthill equation [2], resulting in the following expression for the far field spectrum:

$$P(\mathbf{x},\omega) = \frac{1}{4\pi r^2}\frac{1}{a_0^4}\bar{\rho}^2 D_f^5 d_{ijkl}\int \Phi F[I_{ijkl}]d^3\mathbf{y} \tag{1}$$

where $\mathbf{y}$ and $\mathbf{x}$ are respectively the source and observer locations, and r is the distance to the far field observer. A model for the Fourier transform of the two-point fourth order velocity correlation tensor $F[I_{ijkl}]$ is required. For this purpose, we assume that the turbulence is isotropic and locally homogeneous. This allows the fourth order correlation to be expressed in terms of individual second order correlations. The resulting spatial and temporal correlations are modeled using Gaussian distributions, giving the following expression for $F[I_{ijkl}] = I(\mathit{\Omega})$, where the modified frequency $\Omega = \omega\sqrt{(1-M_c\cos\theta)^2 + (\alpha k^{1/2}/a_0)^2}$, and the standard length and time scales are calculated from the RANS k and ϵ fields:

$$I(\Omega) = \frac{\sqrt{\pi}}{4} \frac{c_l^3}{c_\tau^3} k^{7/2} \rho^2 \tau_0^4 \Omega^4 \exp\left(-\frac{\tau_0^2 \Omega^2}{8}\right) \tag{2}$$

2.2 Propagation model

The refraction of sound by the non-uniform medium is accounted for by calculation of the flow factor Φ in equation 1. We make a high frequency approximation in order to use geometrical acoustics. A large number of rays are launched at different initial polar angles from each of the acoustic source points placed in the core of the jet. The path of each ray is then tracked through the jet flow and assigned to one of several far field bins corresponding to an observer location $\mathbf{x}$.

The full derivation of the ray tracing equations is presented by Pierce [3]. The following system is integrated forward in time for each ray:

$$\frac{dx_i}{dt} = U_i + \frac{a s_i}{1 - U_j s_j} \qquad \frac{ds_i}{dt} = -\frac{1 - U_j s_j}{a} - s_j \frac{U_j}{x_i} \tag{3}$$

where $\mathbf{x}$ is a position on the wave front with normal vector $\mathbf{n}$, and the wave slowness vector is $\mathbf{s} = \mathbf{n}/(a + \mathbf{v}.\mathbf{n})$. We then make use of the Blokhintsev invariant along each ray to calculate the change in far field acoustic pressure amplitude as a result of flow refraction effects. The ratio of ray tube areas is approximated by calculating the number of rays intersecting a given far field observer location for both the jet flow and quiescent cases, and taking the inverse ratio.

2.3 Go4Hybrid round jet test case

The mean flow RANS calculation is performed using the $k - \epsilon$ turbulence model and flow solver built into the open-source SU2 code [4]. In this work, we simulate an isothermal round jet at a Mach number of $M_j = 0.9$. This test case was previously studied in the framework of an EU Project Go4Hybrid (G4H) and simulated with hybrid RANS/LES methods. Previous base flow simulation results for this test case using SU2 compare favorably against corresponding experimental results.

3 Future Work

In the complete paper, we will apply our implementation to the time averaged output of the RANS round jet simulation, and compare the resulting far field acoustic predictions with experimental noise measurements.

References

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