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A Numerical Study on the Sound Radiation by Turbulent Jets Based on a Wavepacket Sound-Source Model

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Prior to the 1950s, turbulence in jet flow was considered to be entirely composed of stochastic structures characterized by their integral turbulence scales, which led to the assumption of spatially decorrelated and compact sound sources. However, several studies showed that coherent structures in turbulent jets play the role of sound sources producing far-field pressure fluctuations [1–3]. Therefore, a theoretical model relating the hydrodynamic sound source to the generated pressure field was necessary to predict the features of the sound radiated by turbulent jets and conceive noise reduction strategies. The key to develop a sound radiation model was the observation by Crow and Champagne [4] and Moore [5], among others, that coherent structures in turbulent jets propagate as wavepackets, from which prominent statistical features of the acoustic field, such as cross-spectral density (CSD) and averaged amplitude and phase, can be drawn in good agreement with experimental data.

In this study, turbulent jets are modeled as stochastic systems whose statistical quantities are related to the hydrodynamic near-field, and the associated acoustic far-field is derived from the line-source wavepacket model proposed by Cavalieri and co-workers [6–8]. Linear stability analysis of turbulent mean flow has shown that relevant statistical quantities related to turbulent jets can be obtained from coherent flow structures modeled as wavepackets propagating downstream [4, 5]. However, when the single-point time-periodic wavepacket model was applied to predict the far-acoustic field produced by turbulent jets, satisfactory agreement was limited to supersonic jet flow [7].

The theoretical formulation proposed in [7, 8] is applied to numerically simulate the stochastic wavepacket and the associated far-acoustic field. As the time-dependent random fluctuations characteristics of turbulent jets are ill-defined and not square integrable functions [8], the frequency-domain near-field pressure fluctuations must be evaluated from a two-point statistics approach based the Fourier Transforms of the auto and cross-correlation functions, which in turn decay toward zero for large time delays. Equations (1) and (2) are applied to estimate the far-acoustic field from a numerical model for the pressure power and cross-spectral density, respectively.

$$\langle \hat{p}\left(x,\omega\right)\hat{p}^{*}\left(x,\omega\right)\rangle = \int_{y}\int_{z}\langle S\left(y,\omega\right)S^{*}\left(z,\omega\right)\rangle\; G\left(x,y,\omega\right)G^{*}\left(x,z,\omega\right)dydz \tag{1}$$

$$\langle \hat{p}\left(x_1,\omega\right)\hat{p}^{*}\left(x_2,\omega\right)\rangle = \int_{y}\int_{z}\langle S\left(y,\omega\right)S^{*}\left(z,\omega\right)\rangle\; G\left(x_1,y,\omega\right)G^{*}\left(x_2,z,\omega\right)dydz \tag{2}$$

Equations (1) and (2) represent, respectively, one-point and two-point statistical quantities. $S\left(y/z,\omega\right)$ is the frequency domain stochastic hidrodynamic source fluctuation, at position y/z, driving the far-acoustic field at positions x_1/x_2.

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The operator $\langle \cdot \rangle$ denotes the expected-value operator, which for real data is applied by taking the ensemble average of uncorrelated data blocks (under the ergodicity hypothesis) in the frequency domain. $(*)$ denotes complex conjugates and $(\,\hat{}\,)$ indicates that a physical quantity has been transformed to the frequency domain. x_1 and x_2 are positions of observers measuring the far-acoustic field, y and z are points along the line source. The free-field Green function, which plays the role of a model to propagate pressure fluctuations from a wavepacket line-source element position to a virtual microphone, is defined as

$$G\left(x, y_1, \omega\right) = \frac{1}{4\pi \mid x_1 - y \mid} e^{-ik|x_1 - y|}, \tag{3}$$

where $i = \sqrt{-1}$ and k is the acoustic wavenumber.

A parametric study will be accomplished to fulfill three primary goals: a) verify whether our numerical implementation of the stochastic wavepacket model is capable of revealing some of the most prominent features of the far-acoustic field produced by turbulent jets, b) produce a database to train a neural network to recognize stochastic wavepackets from experimental or numerical acoustic databases, and c) identify the relevant model parameters and set proper ranges of variation to reveal the prominent characteristic of turbulent jet noise based on a reduced experimental database. Following such an approach, we hope to be able to identify the prominent hydrodynamic parameters generating jet noise based on the far-acoustic field measured by virtual microphones.

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