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The prediction of jet noise ground effects using an acoustic analogy and a tailored Green's function

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ABSTRACT

An assessment of an acoustic analogy for the mixing noise component of jet noise in the presence of an infinite surface is presented. The reflection of jet noise by the ground changes the distribution of acoustic energy and is characterized by constructive and destructive interference patterns. The equivalent sources are modeled based on the two-point cross-correlation of the turbulent velocity fluctuations and a steady Reynolds-Averaged Navier–Stokes (RANS) solution. Propagation effects, due to reflection by the surface and refraction by the jet shear layer, are taken into account by calculating the vector Green's function of the linearized Euler equations (LEE). The vector Green's function of the LEE is written in relation to that of Lilley's equation; that is, it is approximated with matched asymptotic solutions and Green's function of the convective Helmholtz equation. The Green's function of the convective Helmholtz equation in the presence of an infinite flat plane with impedance is the Weyl–van der Pol equation. Predictions are compared with measurements from an unheated Mach 0.95 jet. Microphones are placed at various heights and distances from the nozzle exit in the peak jet noise direction above an acoustically hard and an asphalt surface. The predictions are shown to accurately capture jet noise ground effects that are characterized by constructive and destructive interference patterns in the mid- and far-field and capture overall trends in the near-field.

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1. Introduction

An acoustic analogy is developed based on the Euler equations for the prediction of jet mixing noise in the vicinity of an arbitrary geometry surface. The analogy is based on the development by Morris and Farassat [1] but has unique differences. The Euler equations, written in terms of the logarithm of the pressure, are rearranged into a left-hand side operator consistent with the linearized Euler equations (LEE) and right-hand side equivalent sources. The far-field pressure is written in terms of an integral solution of the governing equations. It appears as a volumetric integral of the equivalent sources and the vector Green's function of the LEE. Any adjoint vector Green's function solver for the LEE can be used within the analogy. Equivalent source models are created for both the dilatation and unsteady force per unit volume source terms. The equivalent sources follow the models of Tam and Auriault [2] and Morris and Boluriaan [3]. The model is dependent on steady Reynolds-Averaged Navier–Stokes (RANS) solutions but could easily be based on an empirical flow-field or unsteady

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Nomenclature

A_s	constant associated with dilatation source
B_s	constant associated with unsteady force per unit volume source
c	speed of sound
c_l	constant of integral length scale
c_u	constant of integral velocity scale
c_τ	constant of integral time scale
D	nozzle exit diameter
E	variation of two-point cross-correlation of velocity fluctuations with space and time
F	Rudwick boundary loss factor
f	frequency
f_i	unsteady force per unit volume associated with velocity fluctuations
g	Green's function of the convective Helmholtz equation
g_l	Green's function of Lilley's equation
K	turbulent kinetic energy
l_x	integral length scale in the streamwise direction
l_y	integral length scale in the y direction
l_z	integral length scale in the z direction
M	Mach number
M_j	fully expanded Mach number
p	pressure
R_p	reflection coefficient
R_s	flow resistivity
r	radial direction
S	spectral density
TTR	total temperature ratio
t	time
u	streamwise velocity component in the x direction
u_s	integral scale of velocity
v	radial velocity component in the y direction
w	radial velocity component in the z direction or numerical distance
$\boldsymbol{x}$	observer position
x	streamwise direction
$\boldsymbol{y}$	source position
$\boldsymbol{z}$	vector from source to observer
z_s	surface impedance
γ	ratio of specific heats
δ	Dirac delta function
ε	dissipation rate of turbulent kinetic energy
$\boldsymbol{\eta}$	vector between two source locations (ξ, η, ζ)
θ	dilatation rate or observer angle from nozzle downstream axis
π	logarithm of the normalized pressure
π_g^n	vector Green's function of the linearized Euler equations
ρ	density
τ	retarded time
τ_s	integral time scale
ϕ	azimuthal angle
Ψ	observer angle from the nozzle inlet axis
Ω	specific dissipation rate of turbulent kinetic energy
ω	radian frequency

Subscript

j	jet fully expanded quantity
s	property of turbulence
∞	ambient value

simulation. This allows the nozzle pressure ratio, temperature ratio, and nozzle geometry to be connected directly to the aerodynamic solution and resultant jet noise. A model of the two-point cross-correlation of the unsteady velocity fluctuations within the jet connects the turbulence statistics to the noise prediction. It is based on measurement and the turbulence statistics generated by a two-equation closure of the steady RANS equations.

The refraction of the sound through the mean flow, diffraction by surfaces, or reflection by the ground or airframe, are all handled by the solution of the vector Green's function of the LEE. For simplicity in this investigation, the vector Green's function of the LEE is written in terms of Lilley's [4] equation. An approximate solution of Lilley's equation is formed about Green's function of the convective Helmholtz equation. Analytic forms of the Green's function of the convective Helmholtz equation are used to account for sound reflection on an infinite flat surface which is representative of the ground. The impedance model of Delany and Bazley [5] is used to simulate the damping of the reflected acoustic waves, but can be neglected for an acoustically hard wall. The form of the Green's function of the convective Helmholtz equation is the Weyl–van der Pol [6] formula. The geometry chosen to exercise the model coincides with the experiment by Miles [7].

The methodology presented in this paper is developed to address many of the issues encountered by previous investigators. Experimental measurements conducted near reflecting surfaces pose unique difficulties. These are summarized well by the studies of Seiner et al. [8], Butzel [9], Schlinker et al. [10], Pao et al. [11], Huber and Sogeti [12], and many others, who performed experiments with microphones at or near various surface locations relative to a free jet as well as aircraft flyover experiments. With careful microphone placement and corrections, accurate measurements can be conducted.

A large body of prediction methodologies have been developed to address reflection and impedance effects. In particular, Illston et al. [13] performed a combined theoretical and experimental study on jet noise, erosion, and ground effects. Their methodology used a Harper-Bourne [14] like prediction approach by integrating the source strength per unit length along the jet centerline axis. The Aircraft Noise Prediction Program (ANOPP) (see Zorumski [15] for details) accounts for ground