Journal of Sound and Vibration 372 (2016) 82–104

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Broadband shock-associated noise near-field cross-spectra

Steven A.E. Miller

The National Aeronautics and Space Administration Langley Research Center Aeroacoustics Branch 2 N. Dryden St. MS 461 Hampton, VA 23681, USA

ARTICLE INFO

Article history:
Received 3 June 2015
Accepted 27 January 2016
Handling Editor: P. Joseph
Available online 9 March 2016

Keywords:
Broadband
Jet
Shock
Noise
Spectra
Near-field

ABSTRACT

The cross-spectral acoustic analogy is used to predict auto-spectra and cross-spectra of broadband shock-associated noise in the near-field and far-field from a range of heated and unheated supersonic off-design jets. A single equivalent source model is proposed for the near-field, mid-field, and far-field terms, that contains flow-field statistics of the shock wave shear layer interactions. Flow-field statistics are modeled based upon experimental observation and computational fluid dynamics solutions. An axisymmetric assumption is used to reduce the model to a closed-form equation involving a double summation over the equivalent source at each shock wave shear layer interaction. Predictions are compared with a wide variety of measurements at numerous jet Mach numbers and temperature ratios from multiple facilities. Auto-spectral predictions of broadband shock-associated noise in the near-field and far-field capture trends observed in measurement and other prediction theories. Predictions of spatial coherence of broadband shock-associated noise accurately capture the peak coherent intensity, frequency, and spectral width.

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1. Introduction

The interaction of high speed convecting turbulence with a shock wave results in high intensity acoustic radiation. This radiation is broadband in nature, and it is dependent on the convection velocity and intensity of the turbulence, and strength of the shock wave. Systems of shock waves are present within off-design supersonic turbulent jets. Off-design supersonic jets are created by propulsion systems of flight vehicles that include rockets, missiles, aircraft, and by some natural phenomenon. Coherent turbulence in the jet shear layer interacts with the shock cells and produces broadband shock-associated noise (BBSAN). The radiation from subsequent shock wave shear layer interactions combines constructively and is characterized by multiple broad spectral lobes. This radiation may impinge on the flight vehicle and can also cause observer hearing loss or annoyance. Predicting the cross-power spectral density (CPSD) of BBSAN is beneficial for understanding the physics of the radiating source and also provides mathematical guidance for flight vehicle designers. This paper presents an approach to predict the near-field intensity and coherence of off-design supersonic jets using the cross-spectral acoustic analogy.

In the far-field BBSAN is dominant at mid- to high-frequencies in the upstream and sideline direction relative to the jet flow. Generally, BBSAN is dominated by other noise components in the downstream direction. Harper-Bourne and Fisher [1] proposed that the intensity of BBSAN increases as β^4, where β is the off-design parameter involving the fully expanded Mach number, M_j, and design Mach number, M_d. A general form of the off-design parameter is $\beta = |M_j^2 - M_d^2|^{1/2}$. Norum and Seiner

E-mail address: s.miller@nasa.gov

http://dx.doi.org/10.1016/j.jsv.2016.01.048
0022-460X/Published by Elsevier Ltd.

Nomenclature

A_{ijlm}	coefficient matrix
D	nozzle exit diameter
D_j	fully expanded diameter
c	speed of sound
F_t	far-field term
f_i	equivalent source term
G	cross-power spectral density
I	modified Bessel function
k	turbulent kinetic energy
l_c	turbulent length scale coefficient
l_i	turbulent length scale
M_d	design Mach number
M_t	mid-field term
M_j	fully expanded Mach number
N_s	number of shocks
N_t	near-field term
P_f	constant
p	pressure
p_s	shock pressure
p_t	total pressure
R	gas constant or radiation distance
R_{mn}	two-point cross-correlation
R^v_{ijlm}	two-point cross-correlation of source
S_i	shock wave thickness
St	Strouhal number
$\boldsymbol{r}$	radiation vector
T	temperature
T_j	fully expanded temperature
T_{ij}	lighthill stress tensor
$\boldsymbol{u}$	velocity vector
u_c	convection velocity
u_j	fully expanded jet velocity
$\boldsymbol{x}$	observer vector
$\boldsymbol{y}$	source vector
y_c	jet core length
z	radial cylindrical coordinate
α_i	constant
β	off-design parameter
Γ	coherence
γ	ratio of specific heats
Δ	separation operator
$\boldsymbol{\eta}(\xi,\eta,\zeta)$	source separation vector
ρ	density
θ_i	observer angle relative to downstream nozzle axis
ϕ_i	Azimuthal cylindrical coordinate
Ψ	observer angle relative to upstream nozzle axis
τ	retarded time
τ_c	turbulent time scale coefficient
τ_s	turbulent time scale
ω	radial frequency
$\tilde{\omega}$	modified radial frequency

Abbreviations

BBSAN	Broadband shock-associated noise
CPSD	Cross-power spectral density
PSD	Power spectral density
RANS	Reynolds-averaged Navier-Stokes
SHJAR	Small Hot Jet Acoustic Rig
TTR	Total temperature ratio

[2] showed that the β^4 relationship is invalid when Mach disks form within the jet plume with increasing nozzle pressure ratio (NPR). Generally, the intensity scaling of BBSAN is strongly dependent on NPR and very weakly dependent on total temperature ratio (TTR). Viswanathan et al. [3] noted that when NPR is held constant and TTR increases the BBSAN intensity saturates (ceases to increase). A physical explanation for the saturation of BBSAN was proposed by Miller [4]. The source of BBSAN is the interaction of large-scale coherent turbulence within the jet shear layer interacting with the shock waves. Each of these shock wave shear layer interactions creates outgoing acoustic waves. As the waves propagate from the near-field to the far-field, they constructively interfere to form characteristic broad lobes in the far-field. BBSAN spectra are characterized by multiple broad lobes that decrease in intensity with increasing frequency. Though this noise component is broadband and random, it is highly coherent near peak frequencies due to its constructive nature, and almost entirely incoherent at relatively low and high frequencies. The spatial coherence of BBSAN decreases with increasing observer separation distance and increasing frequency.

A number of experiments were conducted to study the noise from off-design jets. Early measurements of Yu [5] yielded contour plots of BBSAN intensity in the jet near-field. Soon after, Tanna [6] measured far-field auto-spectra for a wide range of jet Mach numbers and temperature ratios from convergent nozzles, and isolated the BBSAN component of the spectrum using the prediction method of Harper-Bourne and Fisher [1]. Tam and Tanna [7] defined β to account for convergent–divergent nozzles and jet stagnation temperature variation. The same year that Tam and Tanna [7] presented their work, Norum and Seiner [2] examined the variation of peak Helmholtz number of BBSAN relative to unheated jets from a convergent nozzle. Norum and Seiner [2] used a near-field microphone array to characterize BBSAN intensity and their results agreed with the early findings of Yu [5]. Seiner and Yu [8] used a near-field linear microphone array located 2.68 jet diameters from the nozzle centerline to confirm measurements of Harper-Bourne and Fisher [1], who showed that the shock-associated noise intensity is proportional to the first power of the fluctuating velocity components within the jet mixing layer.

Bridges and Brown [9] and Bridges and Wernet [10] examined far-field auto-spectra and performed time resolved particle image velocimetry from a large range of off-design jets. Turbulent statistics along the nozzle lip line were shown to