Journal of Sound and Vibration 391 (2017) 95–115

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

A model problem for sound radiation by an installed jet

Petrônio A.S. Nogueira [a],*, André V.G. Cavalieri [a], Peter Jordan [b]

[a] Instituto Tecnológico de Aeronáutica, Divisão de Engenharia Aeronáutica, São José dos Campos, 12228-900 SP, Brazil
[b] Institut Pprime, CNRS - Université de Poitiers - ENSMA, 86000 Poitiers, France

ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form
8 September 2016
Accepted 7 December 2016
Available online 13 December 2016

Keywords:
Aeroacoustics
Jet noise
Jet-wing interaction

ABSTRACT

A model for sound generation by a jet in the vicinity of a flat plate, mimicking an exhaust jet installed near an aircraft wing, is presented. An earlier model (Cavalieri et al. J. Sound Vib. 333 (2014) 6516–6531) is further simplified by considering that the sound source is an axially-extended, cylindrical wavepacket concentrated on the jet lipline, and that this source is scattered by the trailing edge of a semi-infinite flat plate; the model is shown to match earlier results and considerably simplifies the analysis. It is used to evaluate how the parameters of the problem influence sound radiation by subsonic jets. We show that the axisymmetric mode of the source is the most acoustically efficient, similarly to what is seen for free jets; but unlike the latter problem, the sound scattered by the trailing edge is only weakly dependent on the details of the wavepacket envelope and on the two-point coherence of the source, the wavepacket phase speed being the salient feature for installed jet noise. We then use the model to evaluate how geometrical parameters of jet-plate configurations modify the radiated sound. The acoustic radiation is particularly sensitive to the jet-plate distance due to the exponential radial decay of near-field disturbances; the relative axial position of jet and trailing edge is shown to play a comparably minor role. Finally, changes in the angle of attack of the plate and in the sweep angle of the trailing edge considerably modify the radiated sound, leading to significant reductions of the acoustic intensity in some directions. The various properties of installed jet noise are further explored by appealing to the wavenumber transform of the tailored Green's function used to compute the scattered field; insight is thus provided on how jet-wing configurations might be designed so as to reduce installation noise.

1. Introduction

Jet noise continues to be an important aeroacoustic problem. Noise restrictions for aircraft have become progressively more rigid, leading to a need for new strategies to diminish aerodynamic sound; in order to accomplish this, it is important to gain fundamental knowledge on the mechanisms of sound generation by turbulent jets. Recent works have shown substantial evidence that most of the sound radiated at low polar angles by turbulent subsonic jets are related to axisymmetric wavepackets inside the turbulent field [1–3]. Simplified, kinematic wavepacket models, with a limited number of parameters scaled using experimental results [1], reproduce the salient traits of the acoustic directivity of a free jet.

However, new generations of aircraft engine have higher bypass ratios and larger diameters, such that installation effects such as jet-wing interaction can no longer be neglected. When a jet is close enough to a wing, acoustic scattering takes place

---

* Corresponding author.

http://dx.doi.org/10.1016/j.jsv.2016.12.015
0022-460X/© 2016 Elsevier Ltd. All rights reserved.

at the wing trailing edge, significantly enhancing the sound levels in the far-field. A seminal study exploring this phenomenon is that of Ffowcs-Williams and Hall [4], who derived an analytical expression for the Green's function tailored to this problem. The work focused on turbulence in the very near field of the trailing edge, which, when scattered, leads to a U^5 velocity dependence.

Several groups have investigated this phenomenon in recent years. Experimental studies from Mead and Strange [5] qualitatively analysed the interaction between a jet exiting an industrial nozzle and the trailing edge of a rectangular flat plate, a wing platform flat plate and a wing model, obtaining relevant characteristics of the problem such as the dipole-like directivity. Later, a series of works from Mengle et al. focused on the experimental study of installed jets equipped with chevron nozzles; where a modern wing model [6–8] was used. Kopiev et al. carried out experiments that also show the amplification of sound due to scattering by the wing [9]. Finally, an extensive experimental campaign was carried out by Lawrence [10], who analysed both the near- and far-field of the jet. The results revealed the sensitivity of the problem to the trailing edge position, including cases where the jet grazes the plate; the authors also showed the effect of the jet Mach number [10], installation noise being more prominent for lower jet Mach numbers. Finally, Lawrence [11] compared jet-plate and jet-wing measurements, the latter being carried out with realistic wing and jet geometries; the results are remarkably similar, suggesting that the canonical jet-plate interaction problem already displays the relevant features of installation noise.

The experimental studies show numerous trends for the changes of acoustic directivity with parameters of installed jet configurations. Simplified models that capture these trends are useful, as they allow evaluation of other parametric trends; most importantly, they provide information on the underlying physical mechanisms, illuminating the problem such that new sound-reduction strategies might be proposed. Such reduced-order models have been proposed considering that the essential mechanism at work is the trailing-edge scattering of large-scale structures in jets, which in turn can be modelled as linear instabilities of the mean flow. A two-dimensional problem modelling this effect is presented by Kopiev et al. [9], who study the scattering of Kelvin-Helmholtz instabilities by a flat plate using the Wiener-Hopf method; the model captures important features such as the exponential dependence of the scattered sound with the jet-wing distance. The problem of installed circular jets was modelled by Cavalieri et al. [12], where the source, modelled as an axisymmetric wavepacket, is scattered by a flat plate. The model results show good agreement with the experimental sound pressure levels of installed subsonic jets.

In the present work we push forward the analysis of Cavalieri et al. [12], this time with a more comprehensive analysis of the relevant parameters of the problem. We use the same tailored Green's function of Ffowcs Williams and Hall [4], associated with a wavepacket model as a source term, in order to understand the influence of the trailing edge on the sound generated by a jet. Due to the simplicity of this approach, its computational cost is much less than a more general Boundary Element Method, which can be used to evaluate the influence of any solid surfaces on the acoustic field. However, the flat-plate model implicit in the tailored Green's function has been shown to represent the salient sound-generation mechanisms [12,11,13]. In order to perform a more complete analysis of the installed jet problem using this canonical model, we modify both hydrodynamic and geometrical parameters in order to obtain relevant trends, explaining these by means of a Fourier transform of the tailored Green's function. In the present study we focus on relative trends of the radiated sound with the parameters of the problem, in order to explore their effect in the installed jet problem, providing physical explanation whenever is possible.

The paper is organised as follows. In Section 2.1 we present the mathematical model, and details of the numerical solution are given in Section 2.2; the procedure is validated in Section 2.3 by reproducing the results in Cavalieri et al. [12]. Some relevant properties of the tailored Green's function modelling acoustic scattering by the plate trailing edge are explored in Section 3 by analysis of the wavenumber Fourier transform of the Green's function. In Section 4 we study how different parameters of wavepackets alter sound radiation, and in Section 5 a similar analysis is carried out, this time with an evaluation of the effect of geometrical parameters of installed jet configurations; these are related, whenever possible, to the wavenumber-space analysis of the Green's function presented in Section 3. The paper closes with some conclusions in Section 6.

2. Mathematical model and numerical approach

2.1. Mathematical model

Lighthill's acoustic analogy [14] involves rearranging the Navier-Stokes and continuity equations as a wave equation with a forcing term, Lighthill's stress tensor T_{ij}, which is a function of the turbulent flow fluctuations. The corresponding equation in the frequency domain, which is the Helmholtz equation with the Fourier transform of T_{ij} as a source term, can be written as,

$$\nabla^2\hat{p} + k^2\hat{p} = -\left[\frac{\partial^2\hat{T}_{ij}}{\partial y_i \partial y_j}\right], \tag{1}$$

where p is pressure, k the acoustic wavenumber $k = \omega/c_0$, ω being the angular frequency and c_0 the ambient speed of sound.