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Jet noise modelling and control/Modélisation et contrôle du bruit de jet

Wavepacket models for subsonic twin jets using 3D parabolized stability equations

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ABSTRACT

An extension of the classical parabolized stability equations to flows strongly dependent on the two cross-stream spatial directions and weakly dependent on the streamwise one is applied to model the large-scale structures present in twin-jet configurations. The existence of these unsteady flow structures, usually referred to as wavepackets, has been demonstrated in the literature for both subsonic and supersonic round jets, along with their relation to the generation of highly directional noise emitted in the aft direction. The present study considers twin-jet configurations with different separations at high Reynolds number and subsonic conditions. The existing instability modes for the twin-jet mean flow, their dependence on the separation of the two jets, and the interaction between the wavepackets originating from the two jets is investigated here. Arising from the axisymmetric mode for single round jets, two dominant modes are found for twin jets: a varicose one, relatively insensitive to jets' proximity, but likely to be efficient in radiating noise; a sinuous one, whose amplification is strongly dependent on the jets' distance, and which can be expected to produce weaker acoustic signatures.

1. Introduction

Jet noise reduction is a technological problem that has received continuous effort since the appearance of commercial jet airliners in the early 1950s. Modern commercial aircrafts feature very high-bypass-ratio turbofans that are considerably quieter than the early-day jet engines. However, mission requirements and architecture of tactical fighters impose high exhaust speed and limited nozzle cross-section area, demanding alternative noise reduction strategies. In addition to a deep understanding of the underlying physics, the development of noise reduction mechanisms requires efficient and reliable models for noise prediction that could be used in the design and optimization cycle of passive devices, or as reduced-order models for active control devices. With a view of achieving this objective, simple models that relate the properties of the turbulent jet mean flow with the noise radiated to the far-field are sought for here.

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Following the seminal works of Mollo–Christensen [1], the relation between the dominant components of the far-field noise radiated by high-speed jets and large-scale fluctuations in the turbulent mixing region, coherent over several nozzle diameters, has been the subject of growing research [2]. Evidence amassed in the last decades show that, indeed, radiated sound is highly directional for both subsonic and ideally-expanded supersonic jets [3–5]. While temporal intermittency is a characteristic of both far- and near-field pressure fluctuations, the radiated sound is found to be highly correlated with large-scale, low-frequency fluctuations in the mixing region, and with the very few azimuthal modes, for single isolated jets [6–8]. The existence of coherent structures in turbulent jets was first identified by Crow and Champagne [9], and their resemblance to instability waves for harmonically-forced supersonic jets suggested the use of linear instability analysis for modeling them [10,11]. The presence of wavepackets in subsonic natural high-speed jets was finally demonstrated over the last decade [12–14], as well as the ability of linear stability calculations to model them faithfully. In particular, parabolized stability equations (PSE) were demonstrated to deliver a notable agreement with simulation and experimental near-fields for both subsonic and supersonic jets, at a very low computational cost [15,16,13,14,17,18]. Alternative methodologies, based on the comparatively more expensive two-dimensional eigenmode problems, have been used to compute global wavepackets in the time and frequency domains [19–21]. More recently, one-way linearized equations have been proposed as an improved method for modeling the wavepacket using a parabolic integration, which overcomes some of the limitations known for PSE [22].

With few exceptions, most of the tactical fighters developed since the 1960s feature fuselage-embedded twin-jet engines. Additionally, multi-tube nozzles have been investigated as possible jet noise suppressors. Experiments on these configurations showed that twin-jet configurations can result in a reduction of the far-field noise with respect to the equivalent isolated jet [23,24]. By varying the spacing between the nozzles, two different mechanisms leading to noise suppression were identified. The first one is related to the interaction between the turbulent mixing region of each jet, which can modify and reduce the sound sources, and only occurs for closely-spaced nozzles. The second one is due to the acoustic shielding that one jet exerts on the sound emitted from the other one. Although noise reduction occurs at all jet spacings, it is only important in the plane defined by the jet centers.

This paper is concerned with the modeling of the coherent structures present in twin-jet configurations as instability wavepackets. As opposed to single round jets, instability analyses for twin jets are scarce in the literature, which is partially explained by the mathematical complexity of the latter. The mean turbulent flow corresponding to isolated round jets is axisymmetric, which enables the introduction of azimuthal Fourier modes and requires spatial discretization on the radial direction alone. Bipolar coordinates were used by Morris [25] and Green and Crighton [26] to study the inviscid instability of two axially-homogeneous parallel jets. They identified the counterparts of the different azimuthal Fourier modes known for single jets and classified them according to the symmetries about the jet-center plane and the plane normal to it. Jet interactions were found to be important only when the distance between jets was below ~ 3 times the nozzle diameter.

An extension of the standard parabolized stability equations is used in this paper for modeling the wavepackets in subsonic turbulent twin jets. First introduced by Blackburn and Sherwin [27], the three-dimensional parabolized stability equations (3D PSE) are applicable to mean flows with a strong variation of its properties on the cross-stream plane and a mild downstream variation. Separation of scales for the time-periodic disturbances results in a downstream-marching problem analogous to the standard PSE, but allowing disturbances of arbitrary shape along the cross-stream plane. An *ad hoc* locally-parallel stability problem is derived based on the 3D PSE operators to provide the adequate near-nozzle initial conditions. The computed solutions implicitly account for the interaction of the wavepackets on each jet, including the possible mutual stabilization or destabilization. The methodology is applied to a tailored mean flow, constructed by superposition of the axial velocity fields measured experimentally for a single round jet with Mach number $M_j = 0.4$ and Reynolds number $Re = 4.2 \times 10^5$, based on jet exit velocity and nozzle diameter [14,28]. The analyses performed herein are focused on the frequency range in which the highly-directional turbulent-mixing noise was found to be dominant in subsonic single round jets. In terms of the Strouhal number $St = fD/U_j$ defined by the frequency f and the jet exhaust velocity U_j and diameter D, the frequency range is $St = [0.25 - 0.65]$. Additionally, linear stability computations aiming to model the wavepackets recovered maximum amplifications and amplitudes for this range, both for subsonic and supersonic regimes (e.g., [12,13,19,14,2,20,21]).

The rest of the paper is organized as follows. Sections 2.1 and 2.2 introduce the 3D PSE approach and the spatial locally-parallel stability eigenvalue problem associated with it, while 2.3 briefly presents the numerical techniques used. The construction of the mean flows is discussed in section 3.1. Results from the locally-parallel stability at the near-nozzle section and the 3D PSE computations are respectively presented in sections 3.2 and 3.3. Finally, some discussion of the results and conclusions close the paper.

2. Methodology

The total turbulent flow field is separated into a mean (i.e. time-averaged) flow and temporal fluctuations $\mathbf{q}(\mathbf{x}, t) = \bar{\mathbf{q}}(x) + \mathbf{q}'(\mathbf{x}, t)$, where $\mathbf{x} = (x, y, z)^\intercal$ is the vector or coordinates in a Cartesian system, t is the time and $\mathbf{q} = (u, v, w, \rho, p, T)^\intercal$ is a vector containing all the fluid variables of interest: the velocity components u, v, w in the x, y, z directions respectively, density ρ, pressure p and temperature T. Physical quantities are made dimensionless using the jet diameter D, and the free-stream sound speed c_∞ and density ρ_∞. Pressure is scaled with $\rho_\infty c_\infty^2$ and temperature with $(\gamma - 1)T_\infty$, where γ is the ratio of specific heats. The jet Mach number is defined as $M_j = U_j/c_\infty$, with U_j being the exit velocity. The statistical

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