Direct computation of the screech tones generated by a planar underexpanded jet

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Abstract

The screech tones generated by a planar underexpanded jet are computed directly using compressible large-eddy simulation. The numerical method based on explicit high-order filtering, and the jet parameters are first described. The investigation of the numerical results then show that the flow development, the shock cell structure and the screech frequency are well reproduced by the present computation.

Keywords: Computational Aeroacoustics, Large-Eddy Simulation, Planar Jet, Supersonic, Screech Tones

1 Introduction

Under certain operating conditions, supersonic over- and under-expanded jets may produce a discrete tone, referred to as screech, dominating all other noise sources in the forward direction. Powell [5] was the first to observe this phenomenon in the 1950s and to propose that the screech production is controlled by a feedback loop. The coherent vortical structures developing in the shear layer, indeed interact with the regularly spaced shock cell system to give rise to upstream-propagating acoustic perturbations, which are reflected back at the nozzle lip, and excite the jet shear layer, closing the resonant loop.

Former studies have shown the complexity of the mechanisms involved in the screech [6]. Numerical simulations now permit to investigate turbulent flows in details. In particular, compressible Large-Eddy Simulation (LES) allow the computation, within a same run, of the turbulent field and of the radiated acoustic field. The method, referred to as Direct Noise Computation (DNC), may in addition be applied to realistic turbulence configurations. Bogey *et al.* [1] for instance, successfully performed the DNC of a high Reynolds number subsonic jet.

The DNC of a planar supersonic jet is performed in this work using compressible LES. The jet operates at underexpanded conditions so that a quasi-periodic shock cell structure is formed in the jet plume. The Reynolds number based on the fully expanded jet Mach number $M_j = 1.55$, and on the jet height $h = 3$ mm, is equal to 10^5. The computation aims at reproducing the aerodynamic flow development and the features of the screech tones.

The LES strategy and the simulation specifications are first described. Numerical results are then briefly investigated.

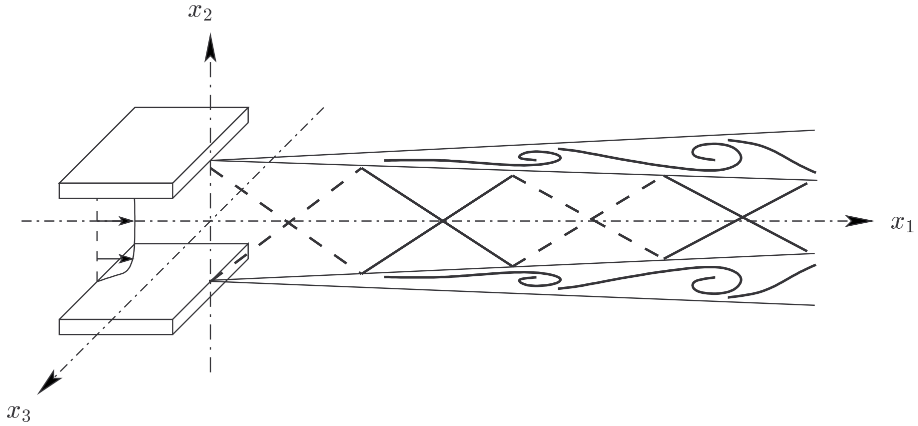

Figure 1: Sketch of the computational domain and of the coordinates system.

2 Numerical procedure

2.1 LES strategy and numerical methods

The filtered compressible Navier-Stokes equations proposed by Vreman *et al.* [8] are solved in this work to perform the LES of a planar underexpanded jet. To take account of the dissipation provided by the unresolved scales, an eddy-viscosity-based model is commonly introduced. This modeling approach may nevertheless introduce excessive dissipation on the resolved scales, leading to a decrease of the effective Reynolds number of the simulation [3]. An alternative to eddy viscosity models is to minimize the dissipation on the resolved scales. Explicit selective high-order filtering of the flow variables is therefore applied to diffuse energy only at the smaller scales, close the grid cut-off wave number. The method has been successfully used in recent applications [1, 3, 7] and is applied here to compute in a same run the turbulent flow development, and the acoustic field of a planar supersonic shocked jet.

The filtered compressible Navier-Stokes equations are solved using low dispersive and low dissipative explicit numerical algorithms developed by Bogey & Bailly [2]. Periodic boundary conditions are implemented in the x_3-direction while non-reflecting conditions are used in the x_1 and x_2 directions so that acoustic perturbations leave the computational domain without the generation of spurious waves. A sketch of the computational domain and of the coordinates system is given in Figure 1.

2.2 Simulation parameters

The jet nozzle is modeled by two adiabatic plates perpendicular to x_2 and separated by a distance $h = 3$ mm defining the jet height. The nozzle lip thickness h_l is such as $h = 4h_l$. The flow inside the nozzle is laminar and sonic. An elevated exit pressure $p_e = 2.09 p_\infty$, where p_∞ is the ambient pressure, is imposed at the nozzle exit so that the jet operates at underexpanded conditions. The fully expanded jet Mach number $M_j = \left\{2/(\gamma-1)\left[\left\{1+M_d^2(\gamma-1)/2\right\}(p_e/p_\infty)^{1-1/\gamma}-1\right]\right\}^{1/2}$ is equal to 1.55, where $M_d = 1$ is the exit Mach number. This value has been observed by Krothapalli *et al.* [4] to correspond to maximum screech sound radiation for a large aspect ratio rectangular jet. The Reynolds number $\mathrm{Re}_h = U_j h/\nu$ is about 10^5, where $U_j = M_j c_j$ with $c_j = 310$ m.s^{-1}.

The computational domain contains $645 \times 195 \times 121 \sim 15 \times 10^6$ points, and has the following dimensions: $25.6h \times 16h \times 5h$, with a nozzle extending over $0.6h$ inside the domain. The time step $\Delta t \sim 2.1 \times 10^{-7}$ corresponds to a $\mathrm{CFL} = (U_j + c_j)\Delta t/\Delta_m$ number equal to 1.5, where $\Delta_m = h/24$ is the smallest mesh size. To ensure mean flow convergence and to compute at least one hundred periods of the screech, the simulation is run over 50,000 time steps.

3 Results

The mean longitudinal velocity $\overline{u}_1/U_j$ in the plane $x_3 = 0$ is plotted in Figure 2. Due to the overpressure at the nozzle exit, five shock cells are visible in the jet plume for $x_1/h < 10$. Average shock cell spacing is found to be about $2.1h$, which is close to the value expected based on experimental and theoretical results [6]. A weakening of the shock strength in the downstream direction is also observed in Figure 2. The interactions between the cells and the shear layer are indeed stronger as the vortical structures develop in the streamwise direction. The velocity and pressure gradients induced by the shocks are consequently smoothed out.

An instantaneous snapshot of isosurfaces of the vorticity modulus $|\omega|$ in the whole computational domain is represented in Figure 3. A large range of turbulence scales, especially the fine scales characterizing high Reynolds number flows, are observed in this simulation. Pressure isocontours in the plane $x_3/h = -2.5$ are also reported in Figure 3. Upstream-propagating wavefronts are clearly visible on either side of the jet. The power spectral density of the pressure measured close to the nozzle at $x_1/h = -0.5$ and $x_2/h = 1$ is now given in Figure 4. Three tones, corresponding to the screech and its first and second harmonics, are observed in the spectrum at the Strouhal numbers 0.11, 0.22 and 0.33, which are in agreement with experimental studies [6].

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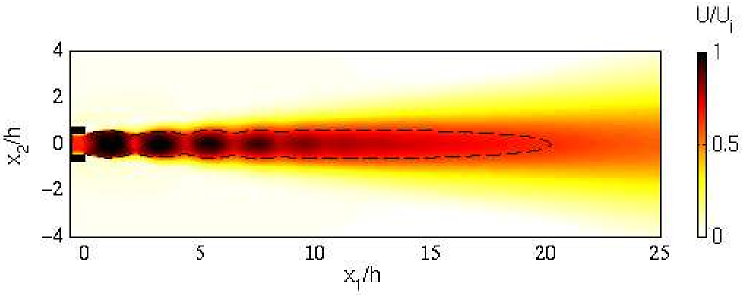

Figure 2: Mean longitudinal velocity $\overline{u}_1/U_j$ in the plane $x_3 = 0$.

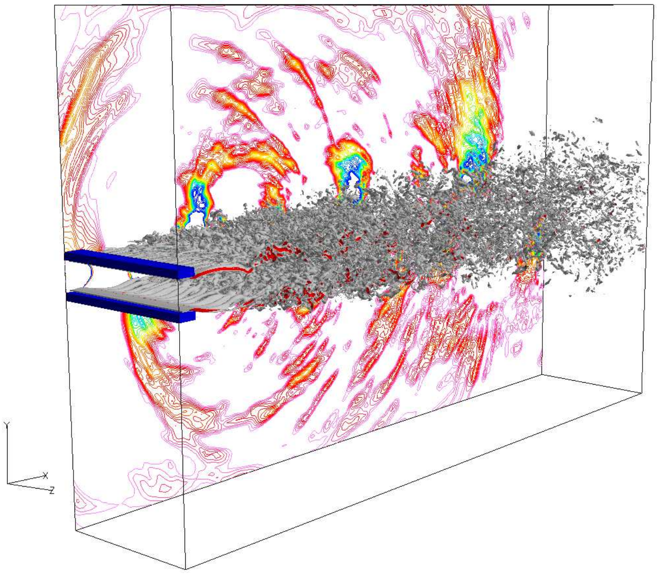

Figure 3: Instantaneous snapshot of vorticity modulus in the whole computational domain and of pressure in the plane $x_3/h = -2.5$. In gray: isosurfaces of $|w| = 5 \times 10^5$ s^{-1}. Colored contours (from blue to red): pressure isocontours ranging from p_∞ to $1.01p_\infty$. The nozzle lips are represented in dark blue.

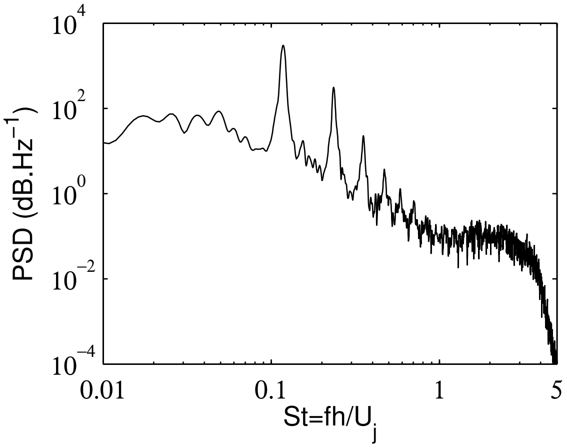

Figure 4: Power spectral density of the pressure signal measured at $x_1/h = -0.5$ and $x_2/h = 1$ as a function of the Strouhal number $\mathrm{St} = fh/U_j$.