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Computation of a Shock Containing Planar Jet and its Screech Tones Using Large-Eddy Simulation

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Abstract

A shock containing planar jet is computed using compressible large-eddy simulation with the aim of simulating both turbulent motions and the generated screech tones. The numerical method based on explicit spectral-like filtering, and the jet parameters are first described. The investigation of the numerical results then shows that the flow development and the screech frequency are well reproduced by the present computation.

INTRODUCTION

Screech tones may be produced in supersonic over- and under expanded jets. The phenomenon, discovered in the early 1950s by Powell [1], is controlled by a feedback loop. Indeed, the interactions of the turbulent motions developing in the shear layer with the shock waves of the quasi-periodic shock cell system, may give rise to upstream-propagating acoustic waves. These perturbations 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 shock-vortex interaction mechanisms involved in the screech [2, 3]. Numerical simulations now permit to investigate turbulent flow in details. In particular, compressible Large-Eddy Simulation (LES) allows the computation, within a same run, of the turbulent flow field, the radiated acoustic field, as well as their interactions. The method, referred to as Direct Noise Computation (DNC) may in addition be applied to realistic turbulence configurations.

In the present work, the DNC of a 3-D planar underexpanded jet is performed using compressible LES based on explicit spectral-like filtering. The simulation aims at reproducing turbulence development in the jet and the features of the generated screech tones.

NUMERICAL PROCEDURE

In the present work, the DNC of a planar supersonic jet is performed using compressible LES. Explicit spectral-like filtering of the flow variables is applied to take account of the dissipation provided by the unresolved scales, while minimizing energy loss at the resolved scales [4]. With this aim in view, the filtered compressible Navier-Stokes equations are solved using low dispersive and low dissipative explicit selective filter and finite differences developed by Bogey & Bailly [5]. Time integration is carried out by a fourth-order six-stage low-storage Runge-Kutta algorithm, whose properties have been optimized in the Fourier space [6]. Periodic boundary conditions are implemented in the spanwise direction to simulate a three-dimensional planar flow.

The jet nozzle, which is known to be necessary for screech tones emergence, is described by two parallel adiabatic plates, separated by a distance $h = 3$ mm defining the jet height. The domain is periodic in the spanwise direction. The flow inside the nozzle is laminar and sonic. An elevated exit pressure is imposed at the nozzle exit so that the jet operates at underexpanded conditions and reaches a fully expanded jet Mach number of $M_j = 1.55$. The Reynolds number is about 10^5. The computational domain contains 15×10^6 points and the simulation time is long enough to compute at least one hundred periods of the screech.

RESULTS

An instantaneous snapshot of spanwise vorticity modulus is represented in Figure 1.a. A large range of turbulence scales, especially the fine scales typical of high Reynolds number flows, are observed.

Pressure isocontours are reported in Figure 1.b. Upstream-propagating wave fronts typical of screech tones are visible on either side of the jet. The power spectral density of a pressure probe located near the nozzle is given in Figure 2.a. Three tones, corresponding to the screech and its first and second harmonics are

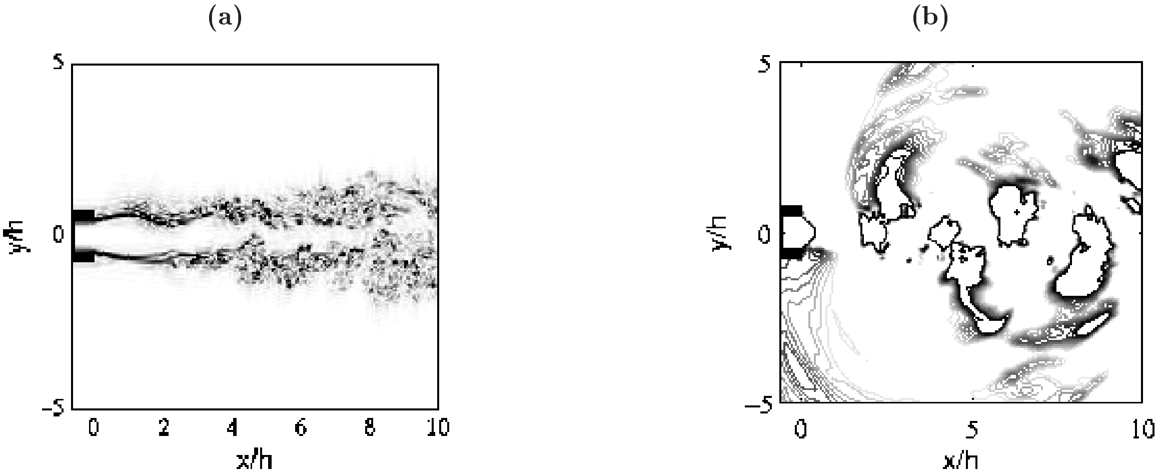

Figure 1: *(a) Instantaneous snapshot of spanwise vorticity modulus $|\omega_z|$ in a plane perpendicular to the spanwise direction. (b) Isocontours of unsteady pressure, from p_∞ to $1.05p_\infty$, in a plane perpendicular to the spanwise direction, where p_∞ is the ambient pressure.*

observed in the spectrum at the Strouhal numbers 0.1, 0.2 and 0.3. Screech Strouhal numbers obtained experimentally by Panda *et al.* [8] and Raman & Rice [9] for large aspect ratio rectangular jets, and analytically by Tam [10] for planar jets, are plotted in Figure 2.b, as a function of the fully expanded jet Mach number M_j. The Strouhal value obtained from the present computation is shown to be in good agreement with those of the literature.

Phase difference between different sides of the jet is also investigated. Cross-spectrum P_{xy} of the pressure measured in $x = -0.5h$ and $y = \pm h$ is calculated. Its amplitude is given in Figure 3.a. The fundamental screech tone and two harmonic peaks are visible. Investigation of the cross-spectrum phase in Figure 3.b shows that the fundamental and the second harmonic are antisymmetric ($\phi_{xy} = \pm\pi$), whereas the first harmonic is symmetric ($\phi_{xy} = 0$). These observations are in agreement with experimental results [9].

CONCLUSION

In the present work, the compressible large eddy simulation of a three-dimensional planar underexpanded jet is performed using explicit selective filtering with spectral-like resolution, and low dispersion and low dissipation numerical methods. The investigation of the numerical results demonstrates that the computation correctly reproduces the screech tone generation phenomenon, which shows the feasibility of the direct noise computation of such a feedback loop with high-order algorithms. In particular, screech frequency and phase difference on either side of the jet are in good agreement with experimental data provided by the literature. These results support that the computation is consistent, and that it may be used to further investigate the screech tone generation mechanisms, and especially the coupling of turbulence with shocks as a noise source.

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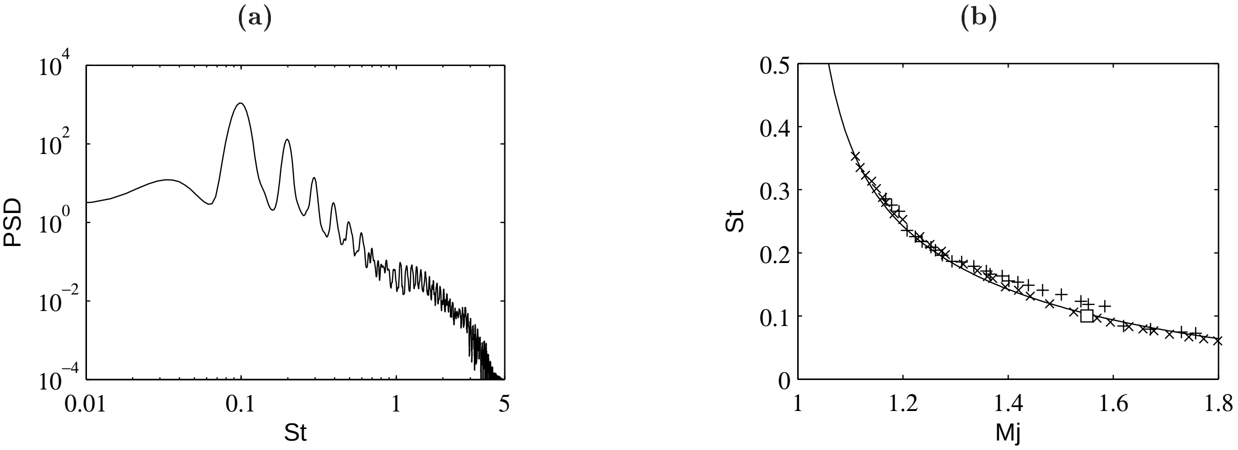

Figure 2: ***(a)*** *Power spectral density of the pressure signal measured near the nozzle exit as a function of the Strouhal number* $St = fh/U_j$. ***(b)*** *Screech Strouhal number* $St = fh/U_j$ *as a function of the fully expanded jet Mach number* M_j. □, *present computation. Measurements:* ×, *large aspect ratio rectangular jets [8];* +, *large aspect ratio rectangular jets [9];* ———, *analytical solution of Tam for planar jets [10].*

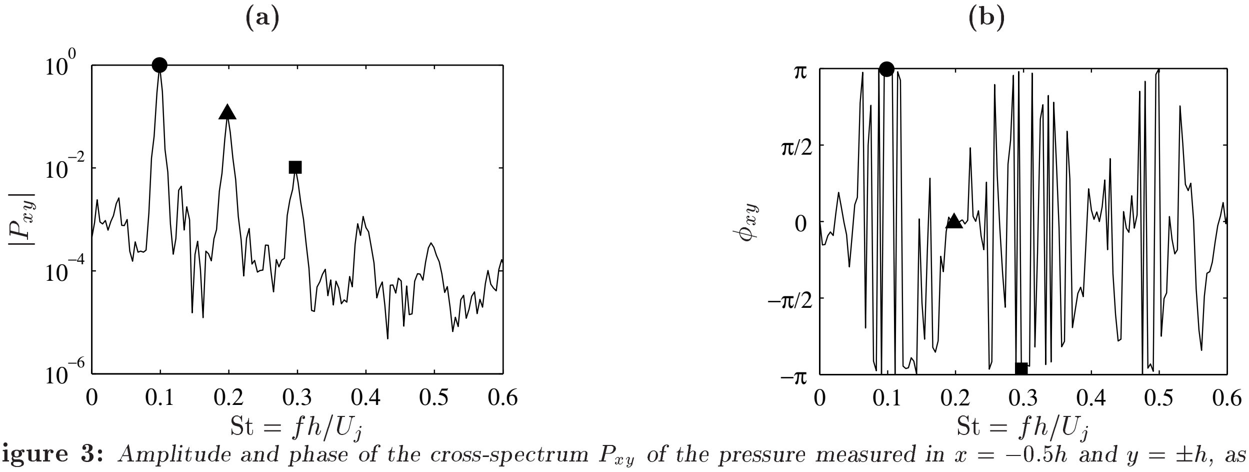

Figure 3: *Amplitude and phase of the cross-spectrum* P_{xy} *of the pressure measured in* $x = -0.5h$ *and* $y = \pm h$, *as a function of the Strouhal number* $St = fh/U_j$. ***(a)****, amplitude ;* ***(b)****, phase.* •, *screech fundamental ;* ▲, *first harmonic ;* ■, *second harmonic.*