Computation of the noise generated by subsonic jets with turbulent exit boundary layers

Sébastien Barré [1] **Christophe Bogey**[1]
`sebastien.barre@ec-lyon.fr` `christophe.bogey@ec-lyon.fr`
Christophe Bailly[1]
`christophe.bailly@ec-lyon.fr`

[1] Centre Acoustique, LMFA, UMR CNRS & École Centrale de Lyon
36 avenue Guy de Collongue, 69134 Ecully, France
http://acoustique.ec-lyon.fr

Abstract

The acoustic field radiated by subsonic jets with turbulent nozzle exit conditions has been investigated, by solving the full compressible Navier–Stokes equations. In the simulations, the nozzle is included in the computational domain, and the flow inside the nozzle is calculated in order to obtain a turbulent boundary layer at the nozzle exit. The influence of the exit turbulence level on the aerodynamic evolution and on the radiated noise is studied. Two jets, with different turbulence levels at the nozzle exit, are computed. The shear layer development is thus found to be strongly affected when the exit fluctuation level is increased: for instance the peak turbulence intensity in the shear layer decreases. The level of the noise generated from the shear layer, in the sideline direction, is also found to be higher. Nevertheless, the flow downstream of the end of the potential core appears not significantly affected by the the exit turbulence level.

Keywords: Jet noise, Direct Noise Computation, Large-Eddy-Simulation, boundary layer

1 Introduction

The control of the acoustic environment near airports is a key topic in the development of new aircrafts. In particular, jet engine manufacturers need to reduce the jet noise of their engines, since it is one of the main acoustic contributions during the lift-off and the landing. However, the underlying mechanisms that generate noise in jets are still not well understood. A good knowledge of the physical phenomena occurring in jets is needed to involve powerful tools of sound reduction. In this study, the noise generated by subsonic jets at high Reynolds number has been computed by solving the compressible Navier–Stokes equations, using Large Eddy Simulation (LES). One of the difficulties of such calculations is the modelling of the incoming perturbations. Thus, in the present simulations, the nozzle body has been included in the computational domain. The turbulent boundary layer inside the nozzle is also calculated, in order to obtain relevant exit conditions at high Reynolds numbers. The influence of the exit turbulence level on the jet development and on the radiated noise is investigated. It is indeed a key issue to obtain accurate computations.

2 Numerical method

In the present work, the turbulent flow field and the radiated acoustic field are computed in the same calculation, by solving the full compressible Navier–Stokes equations. LES is performed using an explicit selective high-order filtering on flow variables, in order to preserve the Reynolds number of the investigated configurations [2]. A high level of accuracy [3] is needed to calculate properly the acoustic fluctuations, which are of very lower amplitude than the aerodynamic fluctuations. This requires specific numerical techniques devoted to the direct computation of aerodynamic noise. In the present work, numerical schemes with low-dispersion and low-dissipation properties developed by Bogey & Bailly [1] are used. The spatial discretization is performed by an eleven-point stencil finite-difference scheme optimized in the wave-number space ensuring accuracy up to four points per wavelength. An optimized explicit six-stage Runge-Kutta algorithm is applied for time integration. To ensure stability, grid-to-grid oscillations are removed thanks to an eleven-point stencil selective filter without affecting the resolved scales, since only the short waves discretized by less than four points per wavelength are damped. Moreover, the non-reflecting boundary conditions developed by Tam & Webb [8] are implemented. This point is crucial for the direct calculation of the acoustic field.

A cylindrical formulation is used in order to have a good description of the geometry of round jets, which also minimizes the number of grid-points. Usual approaches, such as the Hopital's rule, are not accurate enough for direct noise calculations. Therefore, two methods, developed respectively by Mohseni & Colonius [7] and Constantinescu & Lele [4], have been studied. The method based on series expansions proposed by Constantinescu & Lele has finally been chosen. It provides indeed the most accurate solutions and enables the use of a large time-step.

In the present simulations, the computational domain is made of two overlapping blocks. The first one is used to compute the development of the turbulent boundary layer inside the nozzle. The second one includes the lips of the nozzle, the jet plume and the acoustic field. Two simulations with different exit turbulence levels are performed. Practically, random low fluctuations are introduced in the boundary layer, far upstream inside the nozzle. They naturally grow in the boundary layer. Thus, the high level turbulence obtained at the nozzle exit is generated by the physics of the boundary layer and is expected not to be biaised by the artificial excitation.

3 Results

The modelling of the incoming perturbations used in the present work enables the variation of the turbulence level in the boundary layer at the nozzle exit, by adjusting the amplitude of the initial random excitation. To study the influence of the initial shear layer state on the jet development, two configurations have been performed, with a fixed exit momentum thickness and two different exit fluctuation levels of the axial velocity: 8.5% (case A) and 1.3% (case B). Hussain & Zedan [5, 6] have indeed shown experimentally that the initial conditions, and in particular the exit turbulence level, have a notable effect on the evolution of the jet. The Mach number and the Reynolds number are respectively $M_j = 0.9$ and $Re_D = 5 \times 10^5$. The temperature ratio is $T_j/T_\infty = 1$.

Snapshots of the vorticity and pressure fields are displayed in Figure 1 for the two cases. The shear layer near the nozzle exit is visibly turbulent and small structures are created very close to the nozzle. High frequencies are mainly radiated in the sideline direction, and are clearly generated in the shear layer. This is in good agreement with the literature and experiments. Note also that the nozzle and the modelling of the incoming perturbations do not create spurious waves.

The evolution of the fluctuation level of the axial velocity in the shear layer along the line $r = 0.48D$ is shown in Figure 2(a). Just downstream of the nozzle exit, $u_{z\mathrm{rms}}$ suddenly increases to a value of 20% and then slowly decreases. The initial increase is faster and the maximum level is lower when the initial fluctuation level is higher (case A). After the end of the potential core, around $z = 5D$, no significant difference is observed. Thus, the exit fluctuation level seems to affect mainly the development of the shear layer and to have a negligible effect downstream of the potential core. The fluctuation level of the pressure along the line $r = 3.5D$ is also displayed in Figure 2(b). The noise level in the case A is higher than in the case B for $z < 3.5D$. Farther downstream, for $z > 3.5D$, the levels are similar. Thus, a higher exit fluctuation level seems to increase appreciably the radiated noise only in the sideline direction. The fact that the noise emitted in this direction may be generated in the shear layer supports that the variation of the exit fluctuation level affects the shear layer and not

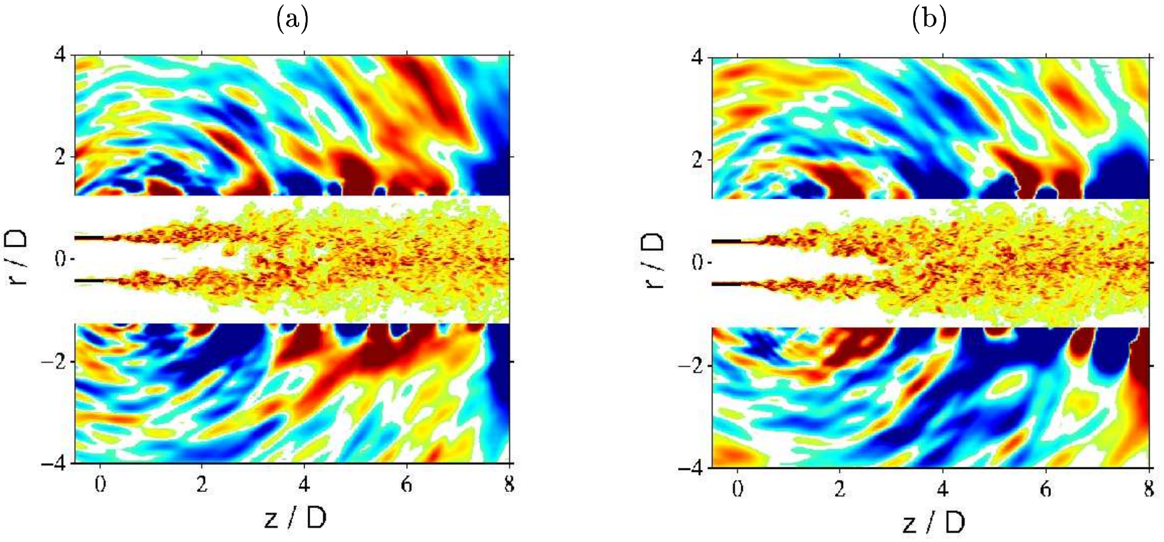

Figure 1: Snapshots of the vorticity field in the flow and of the pressure field outside. (a) Jet with a nozzle exit fluctuation level of $u_{z\mathrm{rms}} = 8.5\%$ (case A). (b) Jet with a nozzle exit fluctuation level of $u_{z\mathrm{rms}} = 1.3\%$ (case B).

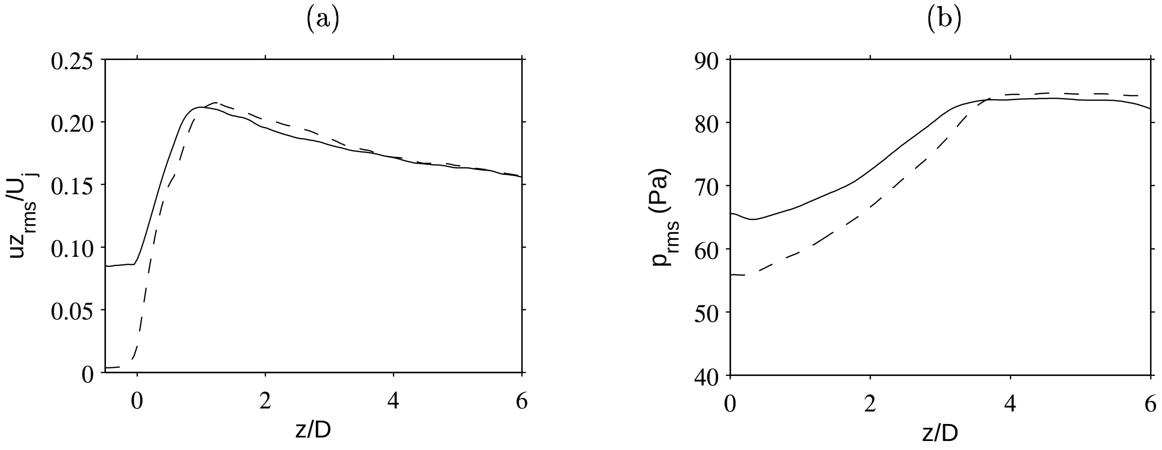

Figure 2: —— jet with a nozzle exit fluctuation level of $u_{z\mathrm{rms}} = 8.5\%$ (case A); - - - - jet with a nozzle exit fluctuation level of $u_{z\mathrm{rms}} = 1.3\%$ (case B). (a) Fluctuation level of the axial velocity u_z in the shear layer, along the line $r = 0.48D$. (b) Fluctuation level of the pressure along the line $r = 3.5D$.

significantly the flow downstream of the end of the potential core. Moreover, it is clearly observed that this level has a notable effect on the sound field and is a crucial parameter for the direct computation of jet noise. The effects on the sound spectra may also be notable, especially for the high-frequency components. This point will be particularly studied in the future.

References

[1] Bogey C., Bailly C., A family of low dispersive and low dissipative explicit schemes for noise computation, *J. Comp. Phys.*, vol. 194(1), pp. 194-214, 2004.

[2] Bogey C., Bailly C., Decrease of the effective Reynolds number with eddy-viscosity subgrid-scale modelling, *AIAA Journal*, vol. 43(2), pp. 437-439, 2005.

[3] Bogey C., Bailly C., Juvé D., Noise investigation of a high subsonic, moderate Reynolds number jet using a compressible LES, *Theoret. Comput. Fluid Dynamics*, vol. 16(4), pp. 273-297, 2003.

[4] Constantinescu G. S., Lele S. K., A highly accurate technique for the treatment of flow equations at the polar axis in cylindrical coordinates using series expansions, *J. Comput. Phys.*, vol. 183, pp. 165-186, 2002.

[5] Hussain A. K. M. F., Zedan M. F., Effects of the initial condition on the axisymmetric free shear layer: Effects of the initial momentum thickness, *Phys. Fluids*, vol. 21(7), pp. 1100-1112, 1978.

[6] Hussain A. K. M. F., Zedan M. F., Effects of the initial condition on the axisymmetric free shear layer: Effects of the initial fluctuation level, *Phys. Fluids*, vol. 21(9), pp. 1475-1481, 1978.

[7] Mohseni K., Colonius T., Numerical Treatment of Polar Coordinate Singularities, *J. Comput. Phys.*, vol. 157, pp. 787-795, 2000.

[8] Tam C. K. W., Webb J. C., Dispersion-Relation-Preserving Finite Difference Schemes for Computational Acoustics, *J. Comput. Phys.*, vol. 107, pp. 262-281, 1993.