Int. Conf. on Jets, Wakes and Separated Flows, ICJWSF-2010
Sept. 27-30, 2010, Cincinnati, Ohio USA

Influence of grid resolution on a tripped subsonic round jet at a Reynolds number of 100,000

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ABSTRACT

Large-Eddy Simulations (LES) of an isothermal round jet at Mach number 0.9 and Reynolds number 100,000 originating from a pipe nozzle are reported. In the pipe, the boundary layers are tripped so that the mean velocity profiles at the exit agree with a Blasius profile for a laminar boundary layer of momentum thickness δ_θ of 0.018 times the jet radius, and that the peak turbulent intensities are around 9% of the jet velocity. Four grids are considered to investigate the effects of the grid resolution on the turbulent development and noise radiation of the present initially nominally turbulent jet.

1.INTRODUCTION

According to experiments [1-6], the development and the noise radiation of subsonic round jets vary significantly with the properties of the nozzle-exit boundary layer. They are especially affected by the state of the exit turbulence, depending on whether the jets are initially laminar or turbulent. At moderate Reynolds numbers, jets with tripped or untripped boundary layers thus exhibit quite different turbulent and acoustical features. Zaman [3, 4] for instance shown that additional noise components are generated by the pairings of coherent shear-layer vortices in untripped, initially laminar jets. More recently, in simulations of initially laminar jets at Reynolds number 100,000 by the present authors [7], flow and sound fields have been found to be strongly modified by the addition of very low random noise in the jet nozzle.

The objective is now to accurately compute tripped, initially turbulent jets as those considered in experiments. With this aim in view, in the present work, a round jet at Mach number 0.9 and Reynolds number 100,000 is calculated by Large-Eddy Simulations based on relaxation filtering (LES-RF) using low-dissipation and low-dispersion schemes. Inside a pipe nozzle, the jet boundary layers are tripped to obtain exit conditions similar to those measured in the tripped jets of Zaman [3]. Four grid meshes are used to investigate the effects of the numerical resolution on the jet turbulent development and noise radiation. The main parameters of the simulations and some preliminary results are provided.

2. PARAMETERS

The simulations are performed by solving the unsteady compressible Navier-Stokes equations in cylindrical coordinates, using low-dispersion and low-dissipation finite-difference schemes [8]. The LES approach is based on the explicit application of a low-pass high-order filtering to the flow variables, in order to take into account the dissipative effects of the subgrid scales by relaxing turbulent energy only through the smaller scales discretized. It has been implemented with success in previous simulations of subsonic round jets [9-11].

Four jets at Mach number 0.9 and Reynolds number 100,000 originating at $z=0$ from a pipe nozzle of length $2r_0$ where r_0 is the pipe radius, are considered. At the pipe inlet, Blasius profiles for a laminar boundary layer of thickness $\delta=0.15r_0$ are imposed. The boundary layers inside the pipe are tripped at $z=-r_0$ by adding vortical disturbances [12, 13] non-correlated in the azimuthal direction. The forcing magnitudes have been adjusted to obtain, at the nozzle exit of the four jets, turbulence intensities around 9% of the jet velocity u_j and laminar Blasius mean-velocity profiles of momentum thickness $\delta_\theta=0.018r_0$, exactly as in the experiments of Zaman [3, 4]. As also clearly evidenced by Hussain and Zedan [14], it is indeed possible to find at the nozzle-exit section of tripped jets high levels of velocity fluctuations together with laminar mean-velocity profiles.

The grids used contain from 50 up to 252 millions of points. In Jetv9ring256, the azimuth is discretized by $n_\theta=256$ points, whereas the mesh spacings at the pipe lip are $\Delta r=0.72\%$ and $\Delta z=1.4\%$ of the jet radius. In Jetv9ring256fine, $n_\theta=256$ is kept in the azimuth, but the mesh resolutions in the radial and the axial directions are twice as fine as previously at the nozzle lip. In Jetv9ring512, $n_\theta=512$ points are then specified in the azimuthal direction, while using the radial and axial discretizations of Jetv9ring256. Given the results obtained from these first four cases, a fourth configuration, Jetv9ring1024, has been studied using a grid characterized by $n_\theta=1024$ points in the azimuth, yielding $r_0\Delta\theta=0.0061r_0$ at $r=r_0$, and by $\Delta r=\Delta z=0.0072r_0$ at the nozzle lip. The physical domain, that is found upstream of an 80-point sponge zone applied at the outflow, finally extends up to $z=32.5r_0$ in the two first jets, but up to $z=25r_0$ in the two other jets computed using higher azimuthal resolutions.

The simulations have been completed: between 81,000 and 110,000 iterations have been done, corresponding to physical times between $325r_0/u_j$ and $475r_0/u_j$. Regarding computational resources, the LES are carried out using NEC SX-8 computers. The simulation Jetv9ring1024 was in particular performed on 7 processors using OpenMP, at a CPU speed around 36 Gflops and required 60 Go of memory.

3.RESULTS

Some illustrations of the jet flow and acoustic fields are provided here. They will also be described in detail in reference [15].

Snapshots of the vorticity norm obtained for the four cases considered just downstream of the nozzle lip over $0\leq z\leq 3r_0$ are presented in Fig.1. In all jets, turbulent structures can first be noticed initially, immediately from the exit section. The developments of the shear layers also seem to be roughly similar, with the presence of both small and large vortical disturbances. A wider range of fine turbulent scales is however observed in the simulations using finer grids, especially in Jetv9ring256fine and Jetv9ringazi1024, whereas coherent structures may be more apparent using coarser grids in Jetv9ring256.

To compare the properties of the mixing layers, the variations over $0\leq z\leq 8r_0$ of the shear-layer momentum thickness and of the *rms* values of the radial fluctuating velocity at $r=r_0$ are shown in Fig.2 and 3. They are very similar in the simulations Jetv9ring256 and Jetv9ring256fine with $n_\theta=256$ in the azimuth. The shear-layer development in the present jets therefore does not appear to vary much with the axial and radial discretizations at the nozzle lip. The results from Jetv9ring512 and Jetv9ring1024 however differ significantly. As the azimuthal resolution becomes finer, the shear layer spreads more slowly, with lower turbulent intensities. The profiles of the *rms* radial fluctuating velocity along the pipe lip are specially modified in a striking way because, while reaching a peak around $z=2r_0$ for $n_\theta=256$, they increase nearly monotonically with the axial distance for $n_\theta=1024$. Note finally that the variations of the shear-layer thickness in~Jetv9ring1024 are in fairly good agreement with measurements provided by Husain and Hussain [14] for an initially turbulent mixing layer.

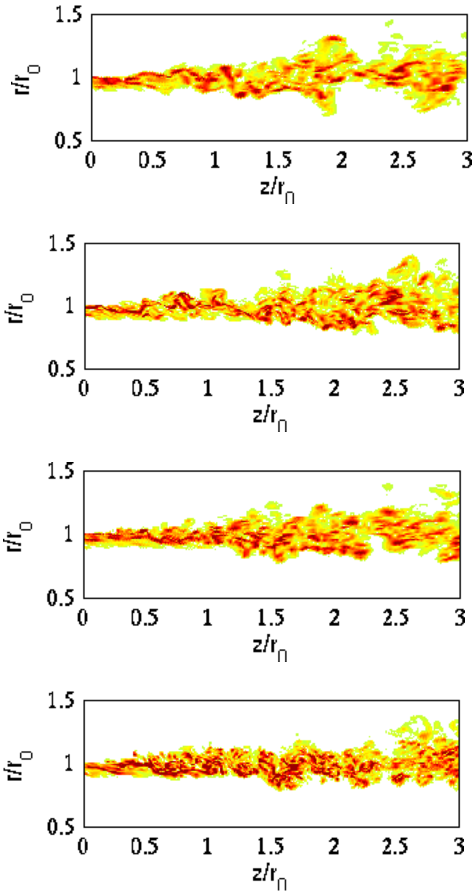

Fig.1. Vorticity norm downstream of the pipe lip, from top to bottom: for Jetv9ring256, Jetv9ring256fine, Jetv9ring512, and Jetv9ring1024. The color scale ranges up to the level of $25u_j/r_0$.

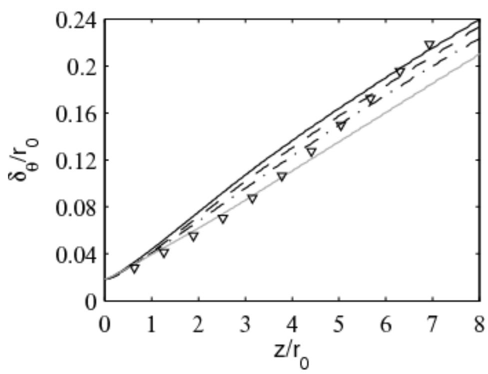

Fig.2. Shear-layer momentum thickness at $r=r_0$ for: Jetv9ring256 (black solid line), Jetv9ring256fine (black dashed line), Jetv9ring512 (black mixed line), Jetv9ring1024 (grey solid line). Measurements for an initially turbulent shear layer: [2].

Snapshots of vorticity obtained up to $z=25r_0$ are now presented in Fig.4. No appreciable change in the jet flows can be distinguished. In all cases for instance, the end of the jet potential core appears to be located around $z=15r_0$.

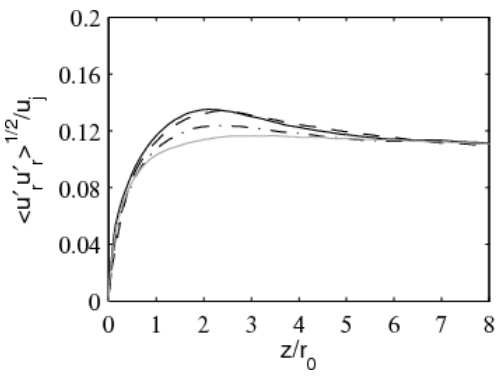

Fig.3. *Rms* radial fluctuating velocity at $r=r_0$. See caption of Fig.2 for line types.

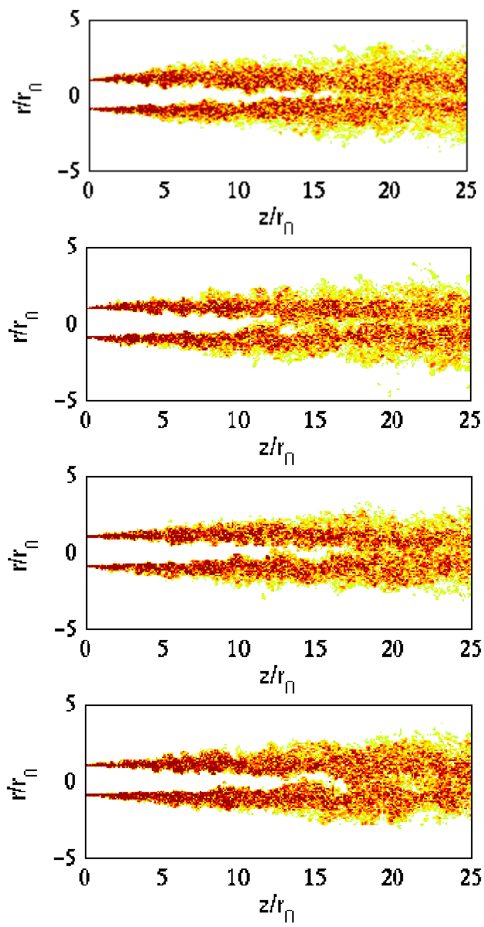

Fig.4. Vorticity norm up to $z=25r_0$, from top to bottom: for Jetv9ring256, Jetv9ring256fine, Jetv9ring512, and Jetv9ring1024. The color scale ranges to the level of $5u_j/r_0$.

To examine the jet developments more closely, the variations of the mean axial velocity and of the *rms* axial fluctuating velocity along the jet centerline are shown in Fig. 5 and 6. They compare favorably with experimental data for jets at high Reynolds numbers. In the four simulated jets, the potential core lengths, the centerline velocity decays, as well as the turbulent intensities do not also differ in an important manner, indicating that both the mean and the turbulent jet flows are fairly similar, regardless of the grid resolution. This is specially the case for the simulations with $n_\theta=256$ in the azimuth, which provided nearly identical results. For $n_\theta=512$ and $n_\theta=1024$, the variations are more significant. In Jetv9ring512, the jet indeed spreads slightly farther downstream, whereas in Jetv9ring1024 the jet development takes place somewhat earlier with higher turbulent intensities.

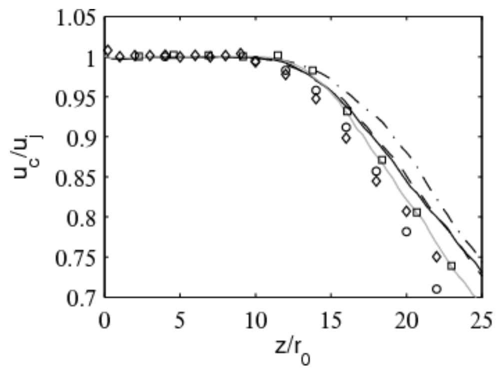

Fig.5. Mean axial velocity for: Jetv9ring256 (black solid line), Jetv9ring256fine (black dashed line), Jetv9ring512 (black mixed line), Jetv9ring1024 (grey solid line). Measurements for Mach 0.9 jets at Reynolds numbers ≥500,000: [16] (circles), [17] (squares), [18] (diamonds).

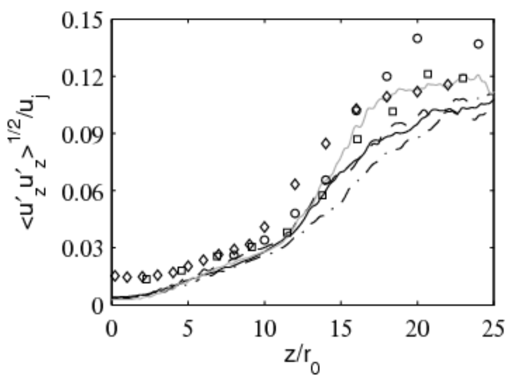

Fig.6. *Rms* axial fluctuating velocity. See caption of Fig.5 for line types and symbols.

As final illustrations of the results, snapshots of the near pressure fields obtained for Jetv9ring256 and Jetv9ring512 are presented in Fig.5. The acoustic waves originating from the mixing layers are of lower amplitude with $n_\theta=512$ points than with $n_\theta=256$ points in the azimuth. More precisely, the increase of the azimuthal resolution seems to significantly reduce the noise generated by the vortex pairings taking place in the shear layers, as expected in an initially turbulent jet.

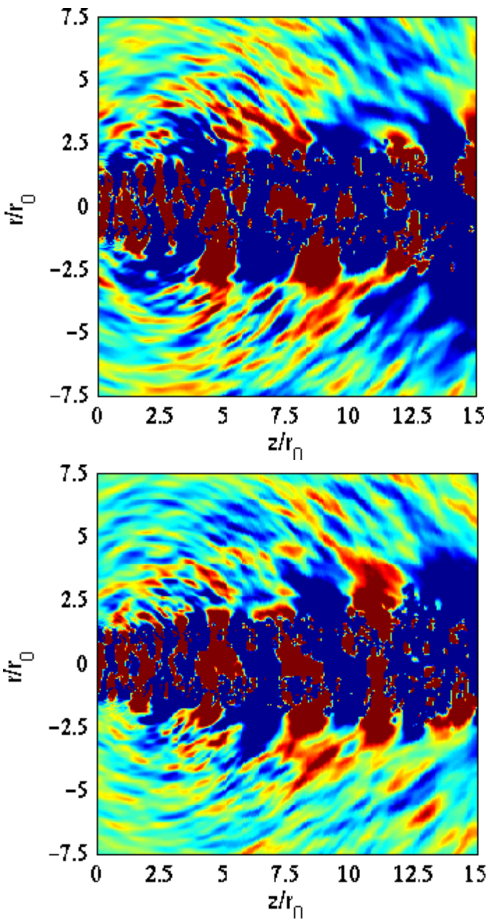

Fig.7. Fluctuating pressure for Jetv9ring256 (top) and Jetv9ring512 (bottom.) The color scale is ±100Pa.

5. CONCLUSION

In the present paper, preliminary results obtained from LES of initially turbulent round jets with tripped nozzle-exit boundary layers are shown. They are found to vary in a negligible way with the grid resolutions in the axial and the radial directions, but strongly with the azimuthal discretization. For the jet considered, it appears indeed necessary to specify $n_\theta=1024$ points in the azimuth to weaken the shear-layer transition so as to obtain turbulent intensities increasing nearly monotonically along the nozzle lip line. Further works will be carried out to characterize the turbulent mechanisms developing in the jets, in particular to discuss the possible presence of pairings of coherent structures in the initially turbulent mixing layers and their effects on noise generation.

ACKNOWLEDGMENTS

This work was granted access to the HPC resources of IDRIS under the allocation 2009-020204 made by GENCI (Grand Equipement National de Calcul Intensif).The authors are especially grateful to Jean-Michel Dupays from the Institut du Développement et des (IDRIS - CNRS) for his technical assistance. They would also like to thank Dr Khairul Zaman for his remarks on the present works.

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