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LARGE-EDDY SIMULATION OF SUBSONIC ROUND JETS WITH TRIPPED EXIT BOUNDARY LAYERS

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Abstract. *In this paper, Large-Eddy Simulations (LES) of five isothermal round jets at Mach number 0.9 and Reynolds number* 10^5 *originating from a pipe nozzle are reported. In the pipe, the boundary layers are tripped so that in all jets the mean velocity profiles at the exit agree with a Blasius profile for a laminar boundary layer of momentum thickness* $\delta_\theta = 0.018$ *times the jet radius, and that the peak turbulent intensities are around 9% of the jet velocity. Two means of tripping the boundary layers and four grids are considered. The effects of the tripping method and of the grid resolution on the turbulent development of initially nominally turbulent jets are thus investigated.*

1 INTRODUCTION

According to experiments [1, 2, 3, 4, 5, 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 10^5 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 in the present work is therefore now to accurately compute tripped, initially turbulent jets as those considered in experiments. With this aim in view, five round jets at Mach number 0.9 and Reynolds number 10^5 are 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 in all jets exit conditions similar to those measured in the tripped jets of Zaman [3]. Two different means of tripping and four grid meshes are moreover used to investigate the effects of the tripping methodology and of the numerical resolution on the jet turbulent development. The main parameters of the simulations and some preliminary results are provided in this paper.

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, 10, 11].

Five jets at Mach number 0.9 and Reynolds number 10^5, originating at $z = 0$ from a pipe nozzle of length $2r_0$ where r_0 is the pipe radius, are considered, as reported in table 1. 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 either velocity disturbances fully random both in time and space in Jetv9noise256, or vortical disturbances [12, 13] decorrelated in the azimuthal direction in the four other cases. The forcing magnitudes have been adjusted to obtain, at the nozzle exit of the five jets, turbulence intensities around 9% of the jet velocity u_j and laminar Blasius mean-velocity profiles of momentum thickness $\delta_\theta \simeq 0.018r_0$, 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.

Reference	trip	$n_r \times n_\theta \times n_z$	$\Delta r(r{=}r_0)$	$r_0\Delta\theta$	$\Delta z(z{=}0)$	L_z
Jetv9noise256	noise	$256 \times 256 \times 768$	$0.0072r_0$	$0.0245r_0$	$0.0145r_0$	$32.5r_0$
Jetv9ring256	ring	$256 \times 256 \times 768$	$0.0072r_0$	$0.0245r_0$	$0.0145r_0$	$32.5r_0$
Jetv9ring256fine	ring	$290 \times 256 \times 992$	$0.0036r_0$	$0.0245r_0$	$0.0072r_0$	$32.5r_0$
Jetv9ring512	ring	$256 \times 512 \times 654$	$0.0072r_0$	$0.0123r_0$	$0.0145r_0$	$25r_0$
Jetv9ring1024	ring	$256 \times 1024 \times 962$	$0.0072r_0$	$0.0061r_0$	$0.0072r_0$	$25r_0$

Table 1: Simulation parameters: boundary-layer trip (noise or ring: addition of random or vortical velocity disturbances in the pipe nozzle), numbers of grid points (n_r, n_θ, n_z), mesh spacings $(\Delta r, \Delta\theta, \Delta z)$, and axial extend L_z of the physical domain.

Some parameters of the grids used for the five jet LES are provided in table 1. The grids contain from 50 up to 252 millions of points. In Jetv9noise256 and 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 Jetv9noise256 and Jetv9ring256. Given the results obtained from these first four cases, a fifth 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 first three jets, but up to $z = 25r_0$ in the two other jets computed using finer azimuthal resolutions.

The simulations Jetv9noise256, Jetv9ring256, Jetv9ring512 and Jetv9ring256fine have been completed: 81,000 and 110,000 iterations have respectively been done in the first three LES and in the fourth LES, corresponding to physical times of $475r_0/u_j$ and $325r_0/u_j$. The simulation Jetv9ring1024 is still running but it provides statistical results, albeit not fully converged, that can be shown in this paper. Concerning computational resources, the LES are carried out using NEC SX-8 computers. The simulation Jetv9ring1024 is in particular performed on 7 processors using OpenMP, at a CPU speed around 36 Gflops and requires 60 Go of memory.

3 RESULTS

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

Snapshots of the vorticity norm obtained for the five cases considered just downstream of the nozzle lip over $0 \le z \le 3r_0$ are presented in figure 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 Jetv9noise256 and Jetv9ring256.

To quantitatively compare the properties of the mixing layers, the variations over $0 \le z \le 6r_0$ of the shear-layer momentum thickness and of the rms values of the radial fluctuating velocity at $r = r_0$ are shown in figure 2. They are very similar in the three simulations Jetv9ring256, 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 tripping methodology or 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 is indeed found to spread 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 monotonically with the axial distance for $n_\theta = 1024$. Note finally that the variations of the shear-layer momentum thickness in Jetv9ring1024 are in fairly good agreement with corrresponding measurements provided by Husain and

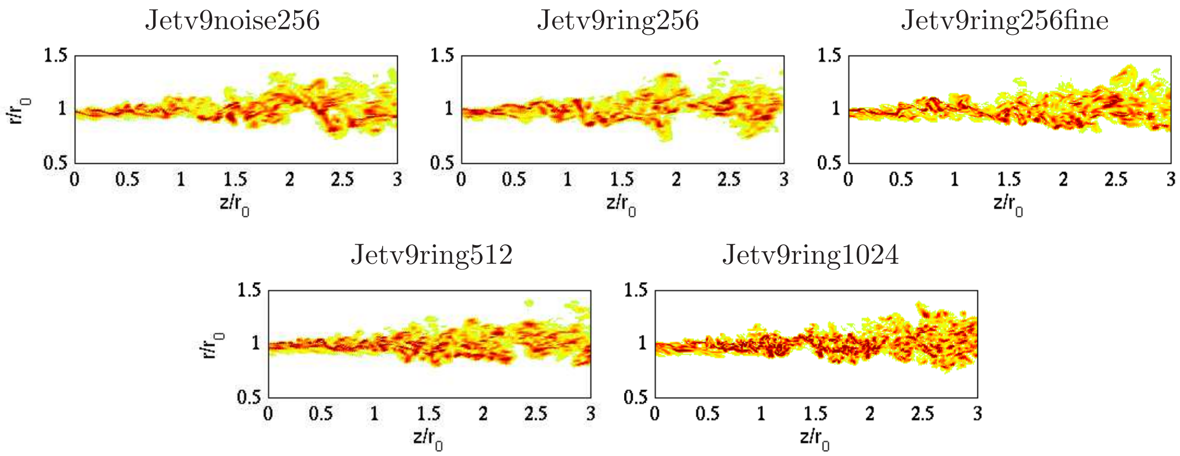

Figure 1: Snapshots in the (z, r) plane of vorticity norm $|\boldsymbol{\omega}|$ just downstream of the pipe lip for the jets. The color scale ranges up to the level of $25u_j/r_0$.

Hussain [14] for an initially turbulent axisymetric mixing layer.

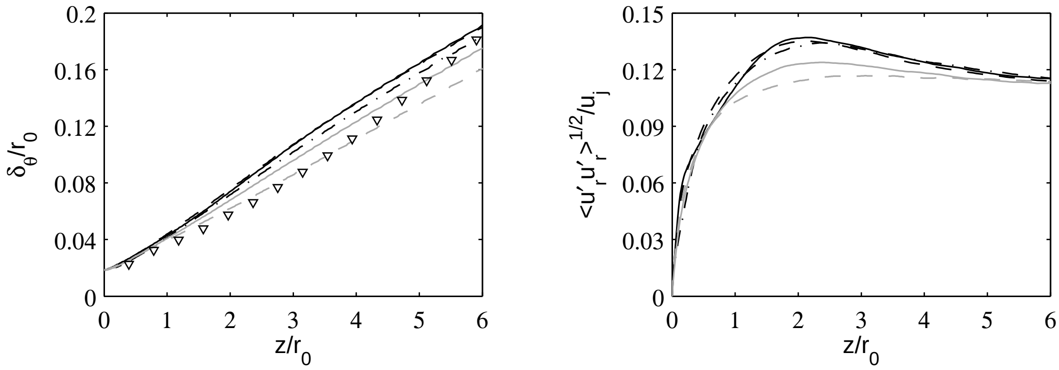

Figure 2: Variations of shear-layer momentum thickness δ_θ and of rms radial fluctuating velocity u'_r at $r = r_0$ for: ——— Jetv9noise256, − − − Jetv9ring256, − · − · Jetv9ring256fine, ——— Jetv9ring512, − − − Jetv9ring1024. Measurements for an initially turbulent axisymmetric shear layer: ▽ Husain and Hussain [2].

Snapshots of the vorticity fields obtained from the five computations up to $z = 25r_0$ are now presented in figure 3. 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 $z = 15r_0$.

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 figure 4. They compare favorably with experimental data for jets at high Reynolds numbers. In the five 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 similar, regardless of the tripping methodology and

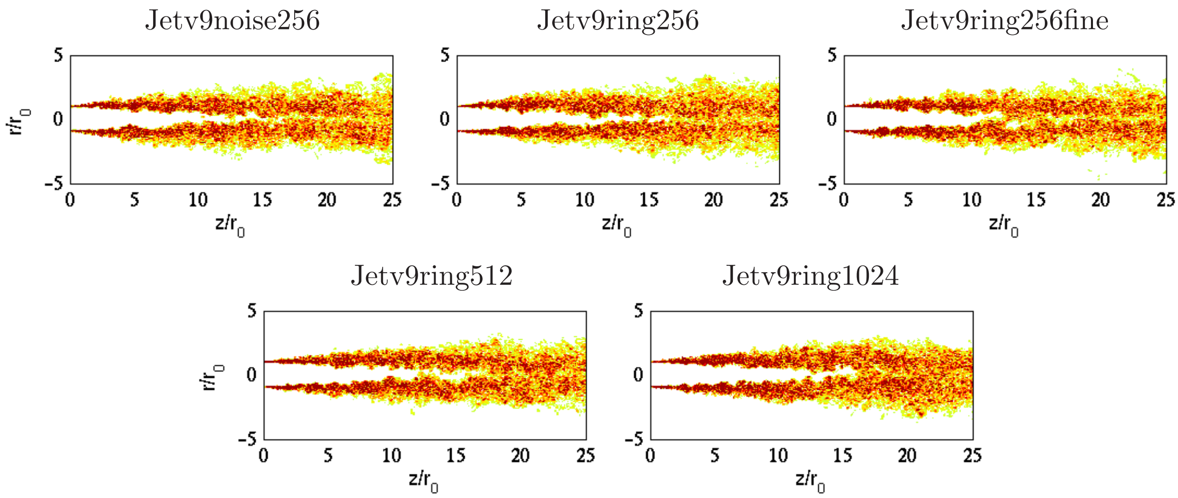

Figure 3: Snapshots in the (z, r) plane of vorticity norm $|\boldsymbol{\omega}|$ for the jet flow fields up to $z = 25r_0$. The color scale ranges up to the level of $5u_j/r_0$.

of the grid resolution. This is specially the case for the three 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. The latter point will be investigated more in depth when the Jetv9ring1024 simulation is completed. More results and analyses, specially regarding the acoustic fields radiated by the jets, will be provided in reference [15].

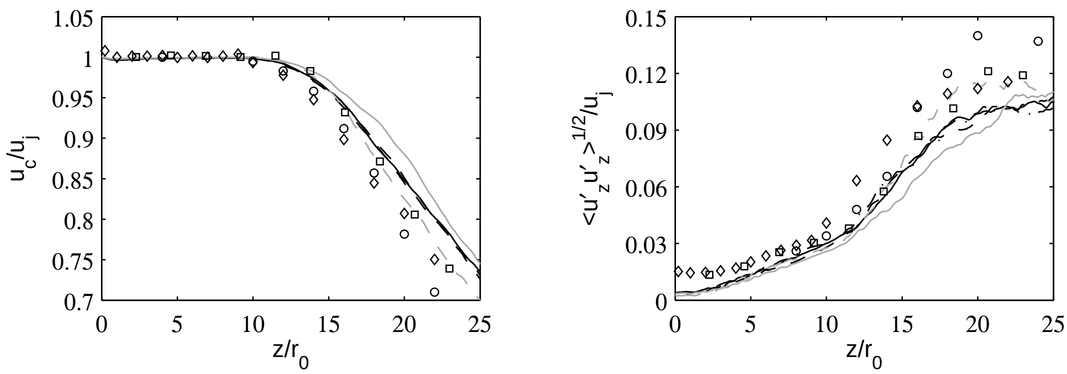

Figure 4: Variations along jet centerline of mean axial velocity u_c and of rms axial fluctuating velocity u'_z for: ——— Jetv9noise256, − − − Jetv9ring256, − · − · Jetv9ring256fine, ——— Jetv9ring512, − − − Jetv9ring1024. Measurements for Mach 0.9 jets at Reynolds numbers higher than 5×10^5: ∘ Lau *et al.* [16], □ Arakeri *et al.* [17], ⋄ Fleury *et al.* [18]

4 CONCLUSIONS

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 tripping methodology or 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 monotonically along the nozzle lip. 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.

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