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On the importance of specifying appropriate nozzle-exit conditions in jet noise prediction

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Abstract

In this paper, the importance of initial conditions on subsonic jet noise is emphasized by showing numerical results obtained by large-eddy simulations for initially laminar round jets at Mach number 0.9 and Reynolds number 10^5. The near and the far sound pressure fields of the jets are found to significantly vary with the flow parameters, namely the boundary-layer thickness and the turbulence levels, at the nozzle exit. With respect to initially turbulent jets, strong additional noise components generated by pairings of coherent vortical structures in the transitional shear layers are in addition observed, in agreement with experiments.

Keywords: jet noise, free shear layer, large eddy simulation

1. Introduction

According to experiments [1, 2, 3, 4, 5, 6], the development and the noise radiation of subsonic round jets depend significantly on 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 exit boundary layers exhibit for instance quite different turbulent and acoustical features. In the works of Zaman [3, 4] and of Bridges & Hussain [5], additional noise components have in particular been found to be generated by the pairings of coherent shear-layer vortices in untripped, initially laminar jets.

In numerical simulations of subsonic jets aiming at providing reliable noise predictions and accurate descriptions of sound sources, the issue of the flow initial parameters is then to be carefully considered. To illustrate this point, some results recently obtained [7] from high-order large-eddy simulations (LES) of subsonic round jets under controlled conditions are reported in this paper. The jets are all initially laminar as in the experiments by Zaman [3], but they are

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characterized by varying boundary-layer thicknesses and turbulence levels at the nozzle exit. In this way, the effects of the exit conditions on the jet far-field noise are shown.

2. Study parameters

The simulations are performed by solving the unsteady compressible Navier-Stokes equations in cylindrical coordinates, using low-dispersion and low-dissipation finite-differences [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].

Round isothermal jets at Mach number $\mathrm{M} = u_j/c_a = 0.9$ and at Reynolds number $\mathrm{Re}_D = u_j D/\nu = 10^5$, originating from a pipe nozzle of radius r_0 and length $1.1r_0$, are computed (u_j is the jet inflow velocity, c_a is the speed of sound in the ambient medium, $D = 2r_0$ is the nozzle diameter, and ν is the kinematic molecular viscosity). The ambient temperature and pressure are 293 K and 10^5 Pa. At the nozzle exit at $z = 0$, the width of the pipe lip is $0.053r_0$. At the inlet, laminar Blasius boundary layers of thickness δ are imposed.

Four jets characterized by inlet boundary-layer thicknesses $\delta = 0.025r_0$, $0.05r_0$, $0.1r_0$ and $0.2r_0$, referred to as JetD0025, JetD005, JetD01 and JetD02 in table 1, are simulated. Two additional jets with initial boundary-layer thickness $\delta = 0.05r_0$ are calculated. In these two cases JetD005p250 and JetD005p2000, unlike the previous jets in which no forcing is applied, random pressure disturbances are introduced in the pipe within the boundary layer between $z = -0.4r_0$ and $z = -0.2r_0$. They are of maximum amplitude 250 and 2000 Pa, respectively.

Table 1: Thickness of the inlet Blasius boundary layer $\boldsymbol{\delta}$, maximum amplitude of random pressure disturbances in the pipe, shear-layer momentum thickness $\boldsymbol{\delta_\theta}$ and maximum intensity of velocity $\boldsymbol{u'_z}$ at the nozzle exit, and line types used.

Reference	δ/r_0	δ_θ/r_0	Inlet noise	u'_z/u_j	Line type
JetD02	0.2	0.0232	0	0.17%	━━━ (thick solid)
JetD01	0.1	0.0116	0	0.23%	━ ━ ━ (thick dashed)
JetD005	0.05	0.0056	0	0.31%	——— (solid)
JetD0025	0.025	0.0025	0	0.36%	– – – (dashed)
JetD005p250	0.05	0.0056	250 Pa	0.32%	——— (grey solid)
JetD005p2000	0.05	0.0056	2000 Pa	1.92%	– – – (grey dashed)

The shear-layer momentum thicknesses δ_θ determined at $z = 0$ at the exit plane of the different jets are given in table 1. They range from $0.0025r_0$ in JetD0025 to $0.0232r_0$ in JetD02. As for the rms levels of velocity u'_z, peaks near the wall are around $0.3\% u_j$ in all jets, except in JetD005p2000 in which the peak is about $2\% u_j$. Therefore, following Zaman [3, 4], the shear layers are initially fully laminar in the four jets without inlet noise and in JetD005p250, and nominally laminar in JetD005p2000.

Finally, to determine the far-field noise generated by the jets, the near fields obtained directly by LES are propagated at 60 radii of the nozzle exit by solving the linear acoustic equations written in cylindrical coordinates, from the fluctuating velocity components and pressure on a control surface at $r = 5.25r_0$.

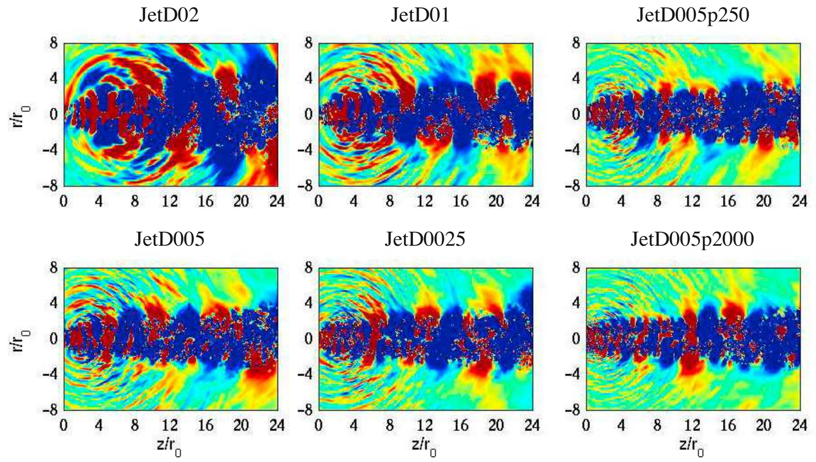

Figure 1: Snapshots in the (z, r) plane of the fluctuating pressure obtained by LES. The color scale ranges for levels from -250 to 250 Pa.

3. Results

As first illustrations of the jet acoustic fields, snapshots of the near pressure fields determined directly by LES are shown in figure 1. In JetD02, JetD01, JetD005 and JetD0025, strong acoustic waves are seen to propagate at wide angles, typically between 60^o and 90^o, relative to the jet direction. These waves visibly come from the transition region of the shear layers. Their apparent origins, which are closer to the jet exit as the initial shear-layer thickness decreases, even correspond roughly to the locations of the first vortex pairing in the mixing layers. Additionally, their associated wavelengths and levels are found both to be significantly reduced when smaller δ_θ is specified at the nozzle exit. Concerning the near pressure fields obtained for JetD005p250 and JetD005p2000, they display features similar to those for JetD005. The acoustic waves radiated by these two jets are however of lower amplitude.

A qualitative comparison of the sound fields computed for the fully initially laminar jets JetD02, JetD01, JetD005 and JetD0025 is made with some experimental results obtained by Zaman [3]. As shown in table 2, this author indeed considered untripped jets at $\mathrm{Re}_D \leq 2.5 \times 10^5$ characterized by nozzle-exit turbulent intensities lower than 1%, and boundary-layer momentum thickness decreasing from $\delta_\theta = 0.0079r_0$ down to $\delta_\theta = 0.0057r_0$ with the Mach number.

Table 2: Experiments on initially laminar jets by Zaman [3]: Mach and Reynolds numbers, initial shear-layer momentum thickness, and maximum intensity of velocity u'_z at the nozzle exit. The arrow indicates the parameter variations.

Reference	M	$\mathrm{Re}_D \times 10^{-5}$	$\delta_\theta / r_0 \times 10^3$	u'_z / u_j
Zaman [3]	$0.12 \rightarrow 0.23$	$0.7 \rightarrow 1.3$	$7.9 \rightarrow 5.7$	$\leq 1\%$

Far-field pressure spectra calculated for JetD02, JetD01, JetD005 and JetD0025 at 60 radii from the nozzle exit and at the angle of 90^o are represented in figure 2(a), while corresponding

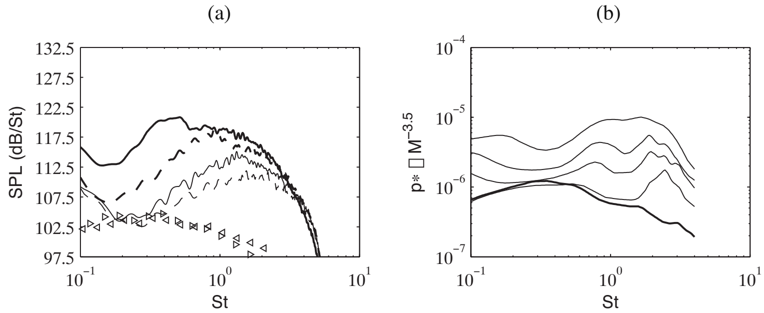

Figure 2: Far-field pressure spectra at a radiation angle of 90°, as functions of Strouhal number St = fD/u_j: (a) ——— JetD02, — — — JetD01, ——— JetD005, — — — JetD0025; measurements: ◃ Tanna [14], ▹ Bogey *et al.* [15]; (b) experimental data by Zaman [3] for ——— untripped jets with exit boundary layers of momentum thickness $\delta_\theta/r_0 \times 10^3$ = 7.9, 7.3, 6.5, 5.7 (from top to bottom), and ——— a tripped jet.

spectra provided by Zaman [3] for four untripped jets are displayed in figure 2(b). A spectacular resemblance can be seen between the simulation and the experimental results. The acoustic spectra similarly exhibit important additional bumps with respect to spectra obtained for M = 0.9 jets at Reynolds numbers around 10^6 in figure 2(a), and for a tripped jet in figure 2(b). In both cases, the amplitude of these noise components moreover decreases and their peak frequency becomes higher with thinner initial shear layer. A good agreement with experiments is thus observed, which supports that the simulations correctly predict noise generation mechanisms in initially laminar jets.

Table 3: Experiments on jets at M ≃ 0.9 and $\mathrm{Re}_D \geq 5 \times 10^5$: Mach and Reynolds numbers.

Reference	M	$\mathrm{Re}_D \times 10^{-5}$
Mollo-Christensen *et al.* [12]	0.9	5.4
Lush [13]	0.88	5
Tanna [14]	0.9	10
Bogey *et al.* [15]	0.9	7.8

The sound pressure levels calculated at $60r_0$ from the jet nozzle exit, for St ≥ 0.1, are represented in figure 3. Compared to measurements provided by Mollo-Christensen *et al.* [12], Lush [13], and Bogey *et al.* [15] for jets at M ≃ 0.9 and $\mathrm{Re}_D \geq 5 \times 10^5$ listed in table 3, they are strongly higher, which indicates the presence of additional noise components. This corresponds accurately to the observations made by Zaman [3, 4] and by Bridges & Hussain [5] concerning the noise radiated by untripped jets at $\mathrm{Re}_D < 5 \times 10^5$. In figure 3, a significant decrease of the acoustic levels when just adding inlet random disturbances of low amplitude in the pipe is also noticed. Furthermore, it can be pointed out that the levels obtained for the jets are much more scattered at an emission angle of 90° than at 30°. At the latter angle, for the jets with thin initial shear layers, they are even rather close to the experimental data. The sensitivity of the sound fields to the jet exit conditions is therefore higher in the transverse direction than in the downstream direction.

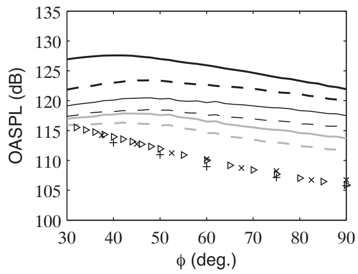

Figure 3: Sound pressure levels obtained at $60r_0$ from the nozzle exit, as functions of the angle relative to the jet direction, for: ——— JetD02, — — — JetD01, ——— JetD005, — — — JetD0025, ——— JetD005p250, — — — JetD005p2000. Measurements: + Mollo-Christensen *et al*. [12], × Lush [13], ▹ Bogey *et al*. [15].

4. Conclusion

The numerical results reported in this paper illustrate the great importance of taking into account the issue of inflow conditions to accurately predict noise generation in subsonic jets. In simulations, it is thus necessary to specify initial conditions as close as possible to the corresponding experimental conditions, when the latter are fortunately known. For practical applications at high Reynolds numbers, vortex pairing noise appears moreover to be attenuated, which has motivated the development of simulations of initially turbulent jets [16, 17].

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References

[1] Hill W.G., Jenkins R.C., Gilbert B.L. Effects of the initial boundary-layer state on turbulent jet mixing. *AIAA J.* 1976;**14**(11):1513–1514.
[2] Husain Z.D., Hussain A.K.M.F. Axisymmetric mixing layer: influence of the initial and boundary conditions. *AIAA J.* 1979;**17**(1):48–55.
[3] Zaman K.B.M.Q. Effect of initial condition on subsonic jet noise. *AIAA J.* 1985;**23**:1370–1373.
[4] Zaman K.B.M.Q. Far-field noise of subsonic jet under controlled excitation. *J. Fluid Mech.* 1985;**152**:83–111.
[5] Bridges J.E., Hussain A.K.M.F. Roles of initial conditions and vortex pairing in jet noise. *J. Sound Vib.* 1987;**117**(2):289–311.
[6] Raman G., Rice E.J., Reshotko E. Mode spectra of natural disturbances in a circular jet and the effect of acoustic forcing. *Exp. Fluids* 1994;**17**:415–426.
[7] Bogey C., Bailly C. Influence of nozzle-exit boundary-layer conditions on the flow and acoustic fields of initially laminar jets. submitted to *J. Fluid Mech.* 2010. See also AIAA Paper 2009-3409 (2009)
[8] Bogey C., Bailly C. A family of low dispersive and low dissipative explicit schemes for flow and noise computations. *J. Comput. Phys.* 2004;**194**(1):194–214.
[9] Bogey C., Bailly C. Large Eddy Simulations of transitional round jets: influence of the Reynolds number on flow development and energy dissipation. *Phys. Fluids* 2006;**18**(6):1–14.
[10] Bogey C., Bailly C. An analysis of the correlations between the turbulent flow and the sound pressure field of subsonic jets. *J. Fluid Mech.* 2007;**583**:71–97.

[11] Bogey C., Bailly C. Turbulence and energy budget in a self-preserving round jet: direct evaluation using large-eddy simulation. *J. Fluid Mech.* 2009;**627**:129–160.

[12] Mollo-Christensen E., Kolpin M.A., Martucelli J.R. Experiments on jet flows and jet noise far-field spectra and directivity patterns. *J. Fluid Mech.* 1964;**18**:285-301.

[13] Lush P.A. Measurements of subsonic jet noise and comparison with theory. *J. Fluid Mech.* 1971;**46**(3):477-500.

[14] Tanna H.K. An experimental study of jet noise. Part I: Turbulent mixing noise. *J. Sound Vib.* 1977;**50**(3):405-428.

[15] Bogey C., Barré S., Fleury V., Bailly C., Juvé D. Experimental study of the spectral properties of near-field and far-field jet noise. *Int. J. of Aeroacoustics* 2007;**6**(2):73-92.

[16] Bogey C., Barré S., Bailly C. Direct computation of the noise generated by subsonic jets originating from a straight pipe nozzle. *Int. J. of Aeroacoustics* 2008;**7**(1):1–22.

[17] Bogey C., Bailly C. Flow and acoustic fields of Reynolds number 10^5, subsonic jets with tripped exit boundary layers. AIAA Paper 2010-3727 (2010)