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# Investigation of the generation of nonlinear waves by a temporal supersonic round jet

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## Résumé :

*Le calcul du développement temporel d'un jet rond supersonique à un nombre de Mach de 2 et à un nombre de Reynolds de 3125 est réalisé par simulation numérique directe afin de caractériser les mécanismes de génération de bruit dans les écoulements cisailés supersoniques. Il est montré qu'à la fermeture du cœur potentiel, des ondes de forte amplitude sont émises. Elles sont composées de compressions rapides suivies de détente progressives. Au même moment, les fluctuations de vitesse dans le jet atteignent un maximum et des vitesses de convection supersoniques sont mesurées sur l'axe du jet. Les coefficients d'assymétrie du champ de pression acoustique et de sa dérivée temporelle sont positifs, ce qui est semblable à ce qui est observé dans les études expérimentales de jets supersoniques rayonnant du bruit de "crackle".*

## Abstract :

*A temporally-developing supersonic round jet at a Mach number of 2 and at a diameter-based Reynolds number of 3125 is computed by Direct Numerical Simulation in order to investigate sound generation mechanisms in supersonic axisymmetric sheared flows. It is found that as the potential core closes, strong, steep pressure waves are radiated. At the same time, high turbulence levels and supersonic convection velocities are found inside the jet. Positive levels of skewness of the pressure fluctuations and of its time derivative are observed in the radiated sound field. This is similar to measurements made in the pressure fields of supersonic jets exhibiting crackle noise.*

**Mots clefs : Bruit de jet ; Crackle ; Simulation Numérique Directe**

## Introduction

It is known that weak shock waves can be found in the sound fields of high speed supersonic jets like those issuing from the nozzles of tactical jet fighters or space launchers [8]. The intermittent presence of these shock waves is responsible for crackle noise, a perception effect that has been described by Ffowcs-Williams et al. [5] as "a startling stacatto of cracks and bangs". Experimental studies, [7] as well as recent numerical simulations of supersonic jets [9] and temporally-developing mixing layers [2] have shown that steepened, positively skewed waveforms are encountered in the near vicinity of the flow. This

suggests that crackle noise cannot only be explained by nonlinear cumulative wave steepening and that it is mainly linked to intermittent compressible events occurring in the jet flow. However, there is presently no consensus on the precise nature of the underlying mechanism.

In order to investigate the generation of weak shock waves in the acoustic near field of high-speed free shear flows, a Direct Numerical Simulation (DNS) of a temporally developing round jet at a Mach number of 2 and at a Reynolds number of 3125 is performed. The present paper is organized as follows. First, the numerical methodology is described. Then, instantaneous representations of the temporal development of the jet are shown and statistics of the flow and sound field are discussed. Last, concluding remarks are given.

## Simulation parameters

In the present study, the simulated jet is isothermal, has a Mach number  $M_j = u_j/a_j$  of 2, and a Reynolds number  $Re_D = 2u_j r_0/\nu$  equal to 3125, where  $u_j$  is the jet initial centerline velocity,  $a_j$  is the speed of sound inside the jet,  $r_0$  is the initial jet radius and  $\nu$  is the kinematic viscosity. At initial time  $t = 0$ , an hyperbolic tangent velocity profile is prescribed and random velocity perturbations are added in the shear layers in order to drive the transition of the initial flow from laminar to turbulent state. The three dimensional compressible Navier-Stokes equations are solved in cylindrical coordinates  $(r, \theta, z)$  using low-dispersion finite difference schemes [3]. Since the present computation is a simulation of a temporally-developing flow, periodic boundary conditions are applied in the axial direction, and radiation boundary conditions are prescribed at the radial boundary. The mesh grid extends up to  $240r_0$  in the axial direction and up to  $13r_0$  in the radial direction. The number of grid points in the axial, azimuthal, and radial directions are respectively  $n_r = 382$ ,  $n_\theta = 256$  and  $n_z = 9600$  and it has been checked from the evaluation of kinetic energy budgets that the present simulation is a fully resolved DNS. Four different runs are performed using different initial velocity disturbances of the shear layers and the results are ensemble averaged to enhance the convergence of the spatial statistics.

## Results

### Snapshots of the flow and acoustic fields

Snapshots of the vorticity norm inside the jet and of the pressure field outside the jet are shown in figure 1 at different times of the jet development. At  $tu_j/r_0 = 40$ , the flow consists in an inner potential core surrounded by thick mixing layers. At this simulation time, the flow in the mixing layers is in a transitional state and elongated Kelvin-Helmholtz vortices can be distinctly seen. In the pressure field, low amplitude Mach waves attached to instability waves are found. At  $tu_j/r_0 = 60$ , the mixing layers merge on the jet axis and a wider range of turbulent scales are present. In the sound field, steep, strong pressure waves can be seen in the near vicinity of the jet.

### Turbulent flow inside the jet

The evolution of the jet centerline velocity is shown in figure 2(a) as a function of time. It remains constant until  $tu_j/r_0 = 45$  and rapidly decreases afterwards. At  $tu_j/r_0 = 49$ , the jet centerline velocity is equal to 95% of its initial value, which corresponds to the closure of the potential core. The time evolution of the root mean square of the axial velocity fluctuations computed on the jet axis and in the shear layers is shown in figure 2(b). The velocity fluctuations peak at  $tu_j/r_0 = 55$  in the shear layers,

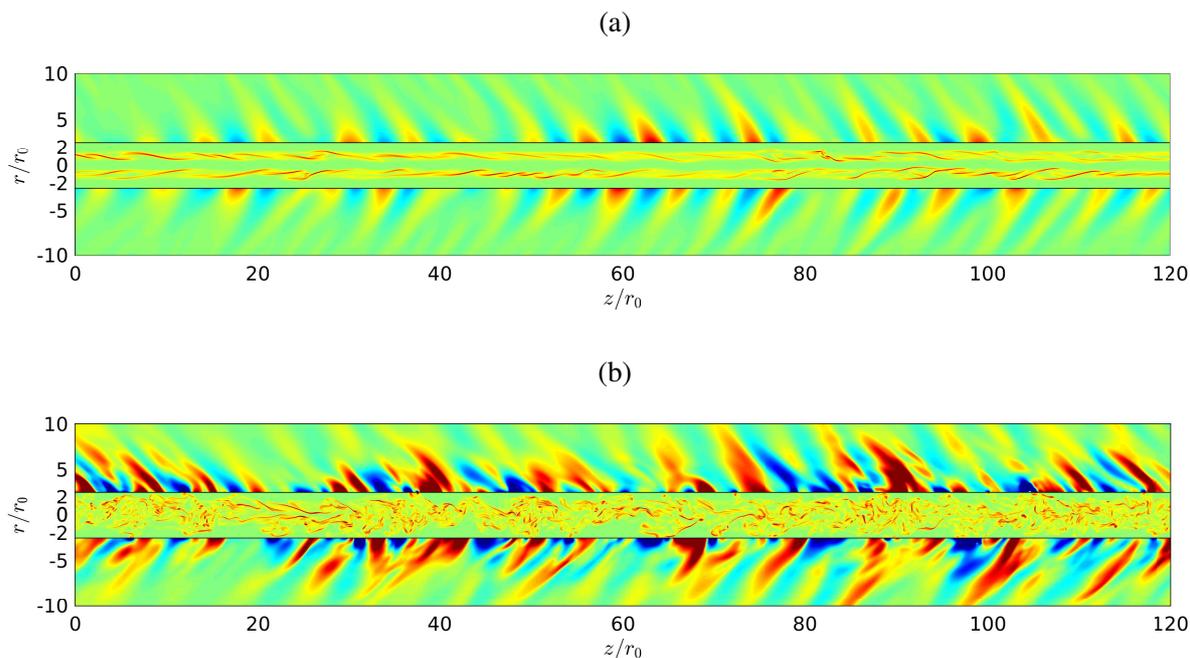


FIGURE 1 – Vorticity norm and pressure fluctuations fields obtained at (a)  $tu_j/r_0 = 40$ , and (b)  $tu_j/r_0 = 60$ . The color scale ranges up to the level of  $5u_j/r_0$  for vorticity and from  $-0.05p_\infty$  to  $0.05p_\infty$  for pressure, where  $p_\infty$  is the ambient pressure.

which is just after the closure of the potential core. On the jet axis, the velocity fluctuations rise rapidly from  $tu_j/r_0 = 40$ , and reach a maximum at  $tu_j/r_0 = 55$ . This quick rise is due to the merging of the shear layers on the jet axis at the closure of the potential core.

The space-time correlation function of the axial velocity fluctuations on the jet axis at  $tu_j/r_0 = 50$  is shown in figure 3(a). Its values are significant over an elongated correlation spot, which indicates that turbulent structures remain coherent as they are convected by the flow. The convection velocity on the jet axis has been estimated by measuring the orientation of the correlation spot and it is shown as a function of time in figure 3(b). It reaches a very clear peak at around  $tu_j/r_0 = 45$ , at the closure of the potential core, then gradually decreases. Between  $tu_j/r_0 = 45$  and  $tu_j/r_0 = 55$ , the convection velocity is roughly equal to  $0.7u_j$ , and is thus higher than the ambient speed of sound.

## Shock structures in the radiated pressure field

Statistical properties of the sound field radiated by the temporal jet are shown in figure 4. The evolution of the root mean square of the pressure fluctuations is represented in figure 4(a). It can be seen that a peak of sound emission occurs between  $tu_j/r_0 = 45$  and  $tu_j/r_0 = 80$ , just after the closing of the potential core. The evolution of the skewness coefficients of the pressure field and of its time derivative are shown in figure 4(b,c). During the peak of sound radiation, high levels of skewness of the pressure fluctuations and of its time derivative are found in the pressure field. They suggest the presence of extreme positive values of the pressure fluctuations, as well as steep, rapid compressions. High levels of skewness of the pressure fluctuations and of its time derivative have been measured in previous experimental studies of high Reynolds number supersonic jets exhibiting crackle noise [1, 5, 8]. They have been attributed to the intermittent presence of weak shock waves in the pressure field. Evidence of such shock structures

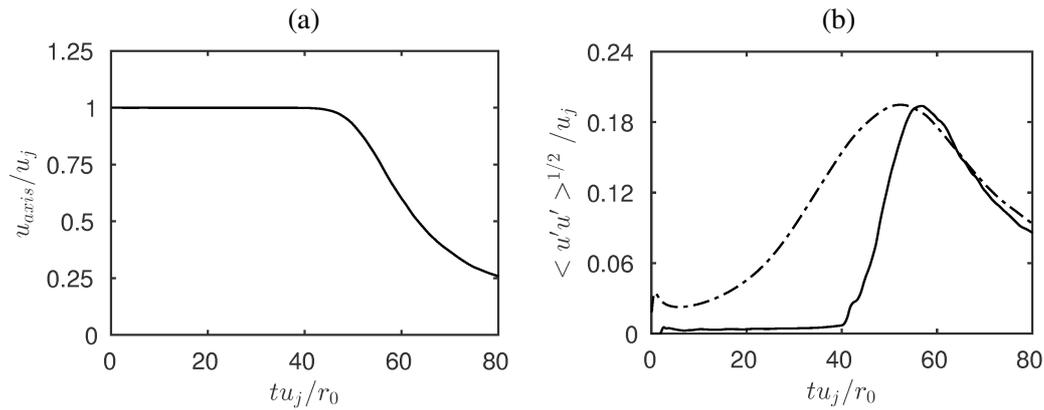


FIGURE 2 – Time evolution of (a) axial velocity at  $r = 0$  and (b) the root mean square of axial velocity fluctuations at — :  $r = 0$ , and - - - :  $r = r_0$ .

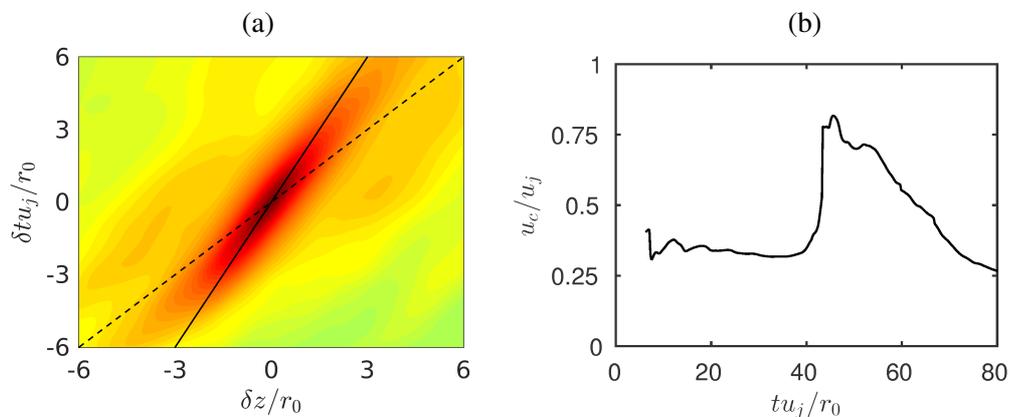


FIGURE 3 – Representation of (a) the space-time correlation function  $R_{zt}(\delta z, \delta t)$  at  $r = 0$  and  $tu_j/r_0 = 50$  and (b) the time evolution of the convection velocity on the jet axis. The dashed line in (a) indicates the jet initial centerline velocity and the continuous line indicates the ambient speed of sound.

can also be seen in figure 5 in the sound field radiated by the present temporal jet. The pressure signal recorded at  $r = 8r_0$  and  $tu_j/r_0 = 70$  exhibits extreme positive values, sometimes exceeding up to three times the standard deviation. These pressure peak are generally made up of fast compressions followed by more gradual expansions.

## Concluding remarks

In this paper, results of a DNS of the flow and sound field radiated by a temporally-developing isothermal supersonic round jet at a Mach number of 2 and a Reynolds number of 3125 are presented. Snapshots of the vorticity and pressure fields show that strong waves are generated after the closing of the potential core. Meanwhile, axial velocity fluctuations on the jet axis and in the shear layers reach a peak and supersonic convection speeds are found on the jet axis. High levels of the skewness coefficients of the radiated pressure fluctuations field and of its time derivative are observed in the immediate vicinity of the jet. They have been attributed to the intermittent presence of strong, positive and steep bursts in the pressure field and they are similar to those found in the sound fields of experimental supersonic jets exhibiting crackle noise.

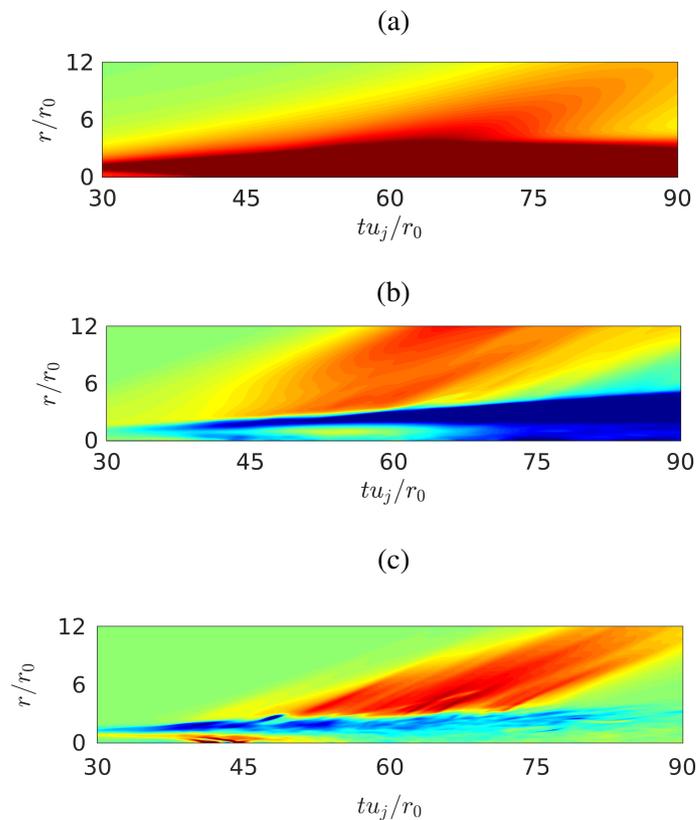


FIGURE 4 – Evolution of (a) the root mean square of the pressure fluctuations, (b) the skewness coefficient of the pressure fluctuations  $p'$  and (c) the skewness coefficient of the pressure time-derivative  $dp/dt$ . The color scale ranges (a) up to  $0.025p_\infty$ , where  $p_\infty$  is the ambient pressure, (b) from -1 to 1 and (c) from -2 to 2.

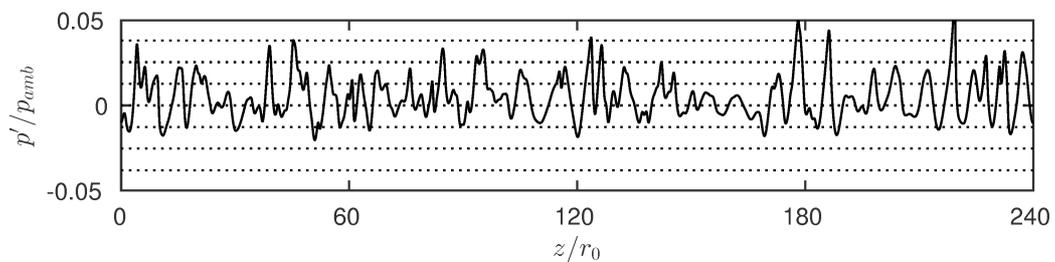


FIGURE 5 – Evolution of the pressure signal at  $r = 8r_0$  and  $tu_j/r_0 = 70$ . The dotted lines indicate integer multiples of the standard deviation of the pressure fluctuations at the same location.

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