INFLUENCE OF INITIAL CONDITIONS ON COHERENT STRUCTURES IN A ROUND JET

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1. Introduction

Coherent structures play a determinant role in several flows including the round jet. According to Lau & Fisher (1975) the structure of the near-field of a round jet consists essentially in a series of vortices moving downstream in the mixing layer of the jet. The regions located between the vortices are characterized by a high shearing which is at the source of the high level of turbulence in the shear-layer. This high level of turbulence leads to the spreading out of the jet. So, the coherent structures play a fundamental role in the expansion process of the jet. This is confirmed by the numerical results of Verzicco & Orlandi (1994). The large scale vortices originate from the shear-layer instability (e.g. Michalke 1984). The Kelvin-Helmholtz instability involves the roll-up of the shear-layer and the formation of vortex rings observed by Liepmann & Gharib (1992) and simulated by Verzicco & Orlandi (1994). According to the review of Ho & Huerre (1984) the roll-up process is predominantly a two-dimensional phenomenon. The vortex rings evolving in the jet shear-layer grow by pairings which have been simulated by Grinstein et al (1987). In a laminar or transitional jet the pairing speeds up the transition to the fully-developed turbulence (e.g. Verzicco & Orlandi 1994).

But the behavior of the round jet depends on the initial conditions of the flow. According to Sahr & Gökäl (1991) a jet with a laminar initially shear-layer has a larger capacity of entrainment than a turbulent one. As the spreading out of a jet is related to the presence of coherent structures, this shows that the behavior of the jet depends on the instability which should occurred. In homogeneous incompressible jets the main parameter to influence instability is the initial shear-layer thickness. According to Michalke (1984)
for homogeneous jets the coherent structures are involved by the induction of the vorticity occurring in the shear-layer. For Cohen & Wygnanski (1986) the increase of the initial shear-layer thickness reduces the number of unstable modes. Therefore, the main objective of this paper is to specify the influence of the inlet conditions on the presence of large scale coherent structures in the flow. Previous numerical investigations allowed the simulation of natural unsteadiness in coaxial jets (e.g. Reynier & Ha Minh 1996) and in compressible round jets (e.g. Reynier 1995) using turbulence models. This method which is an alternative to the LES is chosen for this study to evaluate the influence of the initial conditions on the organized unsteadiness. Finally, the impact of the modelling on the predictions will be investigated using both the classical model proposed by Launder & Sharma (1974) and the model recalibrated by Ha Minh & Kourta (1993).

2. Flow modelling

The main objective of this paper is the evaluation of the influence of inlet conditions on the coherent unsteadiness in a quasi-incompressible round jet. In this flow, the three-dimensional effects are weak up to five diameters (e.g. Grinstein et al 1987). Moreover, three-dimensional instabilities are strongly coupled with the random turbulence which becomes predominantly at the end of the potential core located at four or five diameters (e.g. Sokolov et al 1981). In the near-field of an homogeneous jet, coherent structures originate from the Kelvin-Helmholtz instability. This last involves some fluctuations in the mixing layer which are at the source of the large scale vortices. According to Ho & Huerre (1984), the roll-up of the shear-layer is predominantly a two-dimensional process. Therefore, two-dimensional simulations were executed for this study. As the code works for compressible flows, the mass-weighted average of Favre (1965) is used. The governing equations are the Navier-Stokes equations, a state equation for a perfect gas and the equations of the turbulence model. As the flow to be computed is a round jet the numerical code used axisymmetric coordinates.

The flow pattern studied is characterized by high Reynolds numbers, the DNS and the LES cannot be applied. As a consequence the semi-deterministic modelling (e.g. Ha Minh & Kourta 1993), a method close to the LES, has been chosen for this numerical study. This method allows the simulation of the coherent unsteadiness using turbulence models. The turbulence model used for the predictions is the $k - \epsilon$ model. Two versions
of this model are used for the simulations in order to evaluate the influence of the constant $C_\mu$ on the simulation of the natural unsteadiness. Firstly, the model proposed by Launder & Sharma (1974) with the usual set of constants has been chosen. The second model retained is the version proposed by Ha Minh & Kourta (1993) with a set of constants recalibrated on a backward-facing step to take into account the coherent structures evolving in this flow. If this model has not been recalibrated on a round jet, the low value of the constant $C_\mu$ (which has for value 0.02 in this model and 0.09 in the version of Launder & Sharma) should make easier the simulation of the natural instability. Indeed, a lower value of this constant should involve a less diffusive turbulence model.

3. Computational aspects

The numerical scheme used for the calculations is the finite volume method proposed by MacCormack (1981). This explicit-implicit algorithm uses the prediction-correction step technique and resolved the Navier-Stokes equations in a conservative form. The method is accurate to the second order in time and space. The numerical code has been already successfully applied to the simulation of natural unsteadiness in coaxial jets by Reynier & Ha Minh (1996) and validated with the experimental data of Ribeiro (1972).

An air jet presented in Figure 1 is computed. The exit velocity is 104 m/s, the Mach number of the jet is equal to 0.3 and the Reynolds number is 52240. The pipe diameter D is 7.24 mm. Initially, the temperature at the inlet and in the whole domain is equal to 300°K, the pressure $P_e$ at the exit and in the computational field is 0.101 MPa and the density in all the field is $\rho_o = 1.28$ kg.m$^{-3}$. The computational domain extends over 16.6 diameters
in the streamwise direction and 8.3 diameters in the radial direction. The mesh uses 100 × 93 cells with a coarse grid in the radial direction outside the jet. It is uniform in the streamwise direction.

To investigate the influence of the inlet conditions on the flow unsteadiness several profiles of velocity (see Figure 2) and turbulent kinetic energy (see Figure 3) are applied at the inlet. The different computed cases are reported in the table 1. The initial conditions are derived from the experiment of Durão (1971) for the under-developed turbulence and from the measurements of Chassaing (1979) for the fully-developed turbulence.

Outside the jet, a wall is present (see Figure 1) in the transverse direction, so homogeneous Dirichlet conditions are applied on this boundary for velocity, turbulent kinetic energy and dissipation rate and homogeneous Neumann
Table 1: Computed cases with different inlet conditions and turbulence models

| Mach number | Reynolds number | Inlet conditions | Turbulence model            |
|-------------|-----------------|------------------|----------------------------|
| 0.3         | 52240           | Durão            | Ha Minh & Kourta            |
| 0.3         | 52240           | Chassaing        | Ha Minh & Kourta            |
| 0.3         | 52240           | Chassaing        | Launder & Sharma            |

conditions are applied to density and pressure. The lower boundary is the jet axis, therefore symmetry conditions are assumed. The upper boundary is located far from the flow then homogeneous Neumann conditions are imposed on this boundary. In order to do not perturb the flow, non-reflective conditions are applied at the outlet. They are deducted from characteristic relationships. They originated from the theory of the characteristic analysis and they have been developed for the Euler equations by Thompson (1987). When the flow is subsonic the pressure must be specified at the exit, an homogeneous Neumann condition is applied for this quantity. For the turbulent kinetic energy and its dissipation rate the same condition is used on this boundary.

4. Results

4.1. Influence of inlet conditions on natural instability
To evaluate the influence of initial conditions on the natural instability of the flow, the jet has been computed for fully-developed and under-developed turbulence at the inlet. If the velocity profiles (see Figure 2) are nearly similar it is not the case for the profiles of turbulent kinetic energy. The level of
Figure 5: Spectrum of time-variations of the streamwise velocity in the near-field at $x=1.5D$ and $y=0.5D$

Figure 6: Profiles of the streamwise velocity for four sections located at $x=0.33D$, $x=2D$, $x=5D$ and $x=15D$ for four moments of a pseudo-period $T/4$, $T/2$, $3T/4$ and $T$
turbulence is lower for the under-developed case particularly in the central region of the flow where the level of turbulent kinetic energy is twice smaller that for the fully-developed turbulence. The turbulence model used for these simulations is the semi-deterministic model proposed by Ha Minh & Kourta (1993). The executed computations with the inlet conditions derived from the experimental data of Durão (1971) lead to the simulation of instabilities in the near-field without any flow excitation. The figure 4 represents the time-dependent variations of the streamwise velocity for a point located in the shear-layer at \( x=1.5D \) and \( y=0.5D \). The variations of the streamwise velocity are quasi-sinusoidal. The corresponding spectrum obtained by Fourier analysis over one hundred periods are presented in figure 5. The spectrum puts in evidence the presence of a dominant frequency equal to 5600 Hz. The associated Strouhal number (calculate from the diameter of the inlet pipe and the exit velocity) is equal to 0.39. This Strouhal number is in the range of values contained between 0.3 and 0.4 corresponding to the preferred mode (e.g. Michalke 1984). This preferred mode corresponds to the coherent structures which dominate the shear-layer of a round jet. In figure 6, the unsteady profiles of streamwise velocity are plotted. This figure shows the unsteady variations of the velocity for four sections of the mesh located at \( x=0.33D \), \( x=2D \), \( x=5D \) and \( x=15D \), for four moments of a pseudo-period: \( T/4 \), \( T/2 \), \( 3T/4 \) and \( T \). A high unsteadiness is active in the near region at \( x=0.33D \) and \( x=2D \). This natural unsteadiness originates from the fluctuations in the shear-layer of the jet. The mixing layer becomes unstable near the inlet, due to the Kelvin-Helmholtz instability, then rolls up to form vortex rings. This phenomenon has been largely studied by Liepmann & Gharib (1992) and Verzicco & Orlandi (1994). The present results show the damping of the organized unsteadiness in the far field of the flow (see figure 6). At \( x=15D \) the unsteadiness has disappeared.

The simulation of the flow with a fully-developed turbulence at the inlet leads to the prediction of a steady field of streamwise velocity presented in figure 7. This lack of unsteadiness in the flow is due to a high turbulence level in the center of the jet at the inlet. According to Michalke (1984) the presence of coherent structures is involved by the induction of the vorticity occuring in the shear-layer. When the turbulence is fully-developed the vorticity occuring in the shear-layer is very weak or absent. As a consequence the organized unsteadiness evolving in the shear-layer damps for a fully-developed turbulence at the inlet. The field of radial velocity predicted by the semi-deterministic model shows some residual instabilities in
the shear-layer (see figure 8) but they are very weak. With the inlet conditions derived from the experiment of Durão (1971) the maximum of the radial velocity, scaled by the exit velocity, $|V|/U_0$, is equal to 0.33. With the inlet conditions corresponding to a fully-developed turbulence the maximum of this quantity is equal to 0.07. This low value of the radial velocity in the shear-layer shows a weak entrainment of the jet for the fully-developed turbulence that agrees with the experimental results of Sahr & Gökalp (1991). The weak instabilities can be interpreted as remnants of coherent structures at a great age of turbulence.

4.2. Influence of the modelling on the predictions

The flow has been computed with the initial conditions derived from the measurements of Chassaing (1979) for the two models retained for this study in order to evaluate the impact of the value of the constant $C_\mu$ on the predictions. The computations lead to the prediction of steady fields of streamwise velocity which are represented in figures 7 and 9. The visualizations show that the potential core is shorter for the simulation using the standard set of constants. With the classical model the expansion of the jet is larger than
for the simulation with the recalibrated model. These discrepancies between the prediction of the two models are due to the difference of the value of the constant $C_\mu$. The low value of this constant in the model of Ha Minh & Kourta (1993) involves a lower turbulent viscosity, therefore a less diffusive model. This explains the differences in the prediction of the streamwise velocity field. For the prediction of the radial velocity, the simulation using the classical model of Launder & Sharma (1974) leads to steady results. But the results obtain using the semi-deterministic model (see figure 8) shows some weak unsteadiness in the shear-layer. This is a consequence of the smaller level of diffusion in the semi-deterministic model.

5. Conclusion

This numerical study shows that the coherent structures simulated with under-developed turbulence at the inlet are not found with fully-developed turbulence. Therefore the organized unsteadiness appears to be highly dependent on inlet conditions and particularly on the initial level of turbulent kinetic energy. Indeed, the coherent structures are characteristic of a young
Figure 9: Streamwise velocity field predicts with the model of Launder & Sharma and a fully-developed turbulence at the inlet
turbulence. The simulations with fully-developed initial conditions and the two turbulence models chosen for this study puts in evidence that a low value of the constant $C_\mu$ involves a weaker diffusion in the flow. This low diffusion allows the simulation of a weak unsteadiness in the shear-layer for a fully-developed turbulence at the inlet. These weak instabilities are interpreted as representative of remnants of coherent structures at a great age of turbulence.

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