

DYNAMICS OF VORTICAL STRUCTURES IN A LOW-BLOWING-RATIO PULSED TRANSVERSE JET

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ABSTRACT

The steady or unsteady injection of a fluid jet into a cross flow has many engineering applications. Some examples are turbine blade and combustor film cooling, fuel injection for burners/combustors, and pollutant dispersion from smoke stacks and chimneys. The interaction between the cross flow and a jet creates complex, multi-scale vortical structures, especially when this jet is pulsed. Numerical simulations of this flow can help in identifying these vortical structures, and in understanding their formation processes, dynamics and interactions. Results from the simulations are used to better interpret the complexity of a transverse jet under experimental conditions. Fluent software is used to simulate the unsteady, turbulent flow through a Large Eddy Simulation (LES) model which resolves directly the large eddies and models the small eddies via a Smagorinsky sub-grid scale model.

The geometrical domain used for the numerical simulation is a model of the experimental domain. It consists of a rectangular box representing a part of the test-section of the wind-tunnel used in the experiment as shown in Figure 1. The wind tunnel flow is parallel to the longest dimension of the box. A single elliptical hole with a minor axis $D_j=1$ in, which is perpendicular to the flow direction is located on the bottom wall of the box. This hole is created by the intersection of a circular duct feeding the jet inclined at 35° with respect to the horizontal bottom surface of the box so that the major axis of the elliptical hole is parallel to the flow direction. The computational domain representing the part of the wind tunnel test section is $16D_j$ long (x-direction), $8D_j$ wide (y-direction) and $12D_j$ tall (z-direction). The duct feeding the jet is $7.5D_j$ in length and has the same geometry as in the experiment over that length. The jet exit center is located $4D_j$ downstream from the beginning of the box which represents the inlet to the computational domain.

Figure 1 also shows the boundary conditions applied during the simulations. Velocity profiles for the inlet of the computational domain are obtained from the experimental wind tunnel. At the inlet of the jet feeding duct a uniform

velocity is defined so as to equal the volumetric flow rate of the experiment. In the pulsed jet case this velocity is modulated by using the signal of the unsteady volumetric flow measurement from the experiments. The jet and cross flow fluids are maintained at a constant temperature of 330K. The simulation survey is organized in two parts. First, steady-state cases (constant jet inlet velocity) are examined in order to identify the vortical structures resulting from the interaction of the jet with the cross flow in the absence of jet flow modulation. These cases are used as a baseline for the pulsed cases (pulsed jet inlet velocity) investigated in the second part.

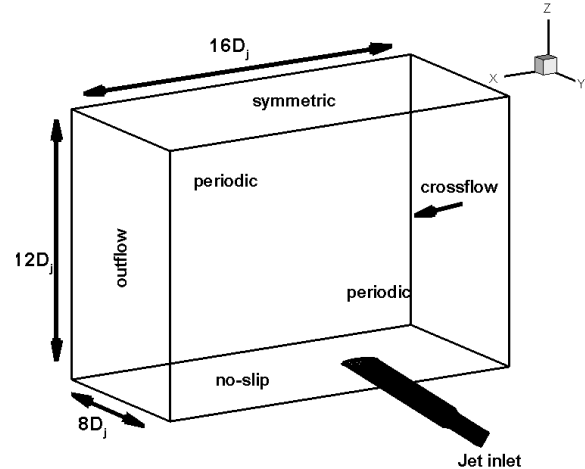


Figure 1: Boundary conditions applied for the simulation

To date, most studies of pulsed transverse jets have been done with a jet injected perpendicularly to the crossflow, while steady jet flow studies abound. Four main vortical structures have been identified in normal transverse jet flow^[1]: horse-shoe vortices, the counter-rotating vortex pair (CRVP), shear-layer vortices and wake vortices. In steady-state cases of inclined jets at relatively low blowing ratios (BR, jet to crossflow mass flux ratio) of 0.39, 0.45 and 0.75, the same structures observed in 90° jets are also present; e.g. horse-shoe vortices, CRVP and hairpin vortices

resulting from the jet shear layers. With the jet fluid existing from the hole, there is an adverse pressure gradient on the windward side of the jet, which causes the crossflow boundary layer to roll up and results in the formation of the horse shoe vortex system. The legs of the horse-shoe vortices extend around the jet. Exiting from the hole, the upstream and downstream interfaces of the jet fluid are exposed to different conditions. The upstream jet shear layer does not roll up due to shear that is too low while the downstream jet interface rolls up. As it is convected downstream, it forms a hairpin vortex. Figure 2 shows a hairpin structure (visualized with iso-surface of Laplacian pressure) whose legs create the counter-rotating vortex. These become closer, with each other, and move upwards due to their mutual induction and interaction with their image vortices. Simultaneously, the head of the hairpin vortex is convected downstream and upward. Once a hairpin is shed a new hairpin vortex starts to form. This formation process occurs periodically and the shedding frequency depends on the BR.

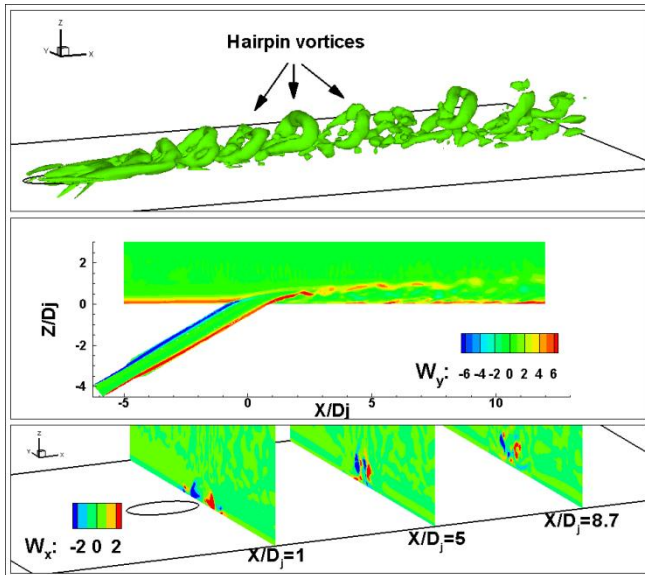


Figure 2: Steady-state case at $BR=0.450$. Top: hairpin vortices visualized with iso-surface of $\Delta P=4500Pa.m^2$. Middle: Y vorticity contours at the center plane. Bottom: CRVP (hairpin vortex) legs visualized by the X vorticity contour at planes $X/D_j=cst$.

The second part of the survey deals with pulsed jet using a predominantly square wave. The characteristic parameters considered in this study are: the average jet to cross-flow mass flux ratio over a cycle (mean blowing ratio – BR_m), the blowing ratios in the high part of the cycle (BR_h) and the low part (BR_l), the forcing frequency (f_f) (in this study 1 and 10 Hz), and the duty cycle (ratio of the high part time to cycle period time – DC, maintained at 50%). The same three principal vortical structures observed in steady-state jets are also observed in pulsed jets for $f_f=1Hz$. At $f_f=10Hz$, the flow structures are not as well defined since

there is no plateau at BR_h or BR_l . The main difference observed in pulsed cases is a ring vortex which appears as the jet switches sharply from BR_l to BR_h .

In the experiment, the jet velocity oscillates around the value of BR_h before reaching a stable value. This is because of acoustic resonance in the jet supply system and is a characteristic present in the application environment (e.g. film cooling flows). The two principal pulses of this damped oscillation are visible on Figure 3 and are associated with a vortex ring created at the exit of the jet with the arrival of each pulse. By pulsing the jet, the upstream and downstream jet shear increase. The jet shear layer rolls up and forms a vortex ring. Simultaneously, the pulse creates a higher adverse pressure gradient compared to the flow configuration at low BR and the upper shear layer is pushed upwards. Having a strong positive vorticity the shear layer rolls up and forms a hairpin vortex as it is convected downstream. As the vortex ring is convected downstream, the upstream side of the ring folds and merges with the jet shear layer. After the plateau of the high part of the cycle is reached, hairpin vortices are shed as in steady-state cases.

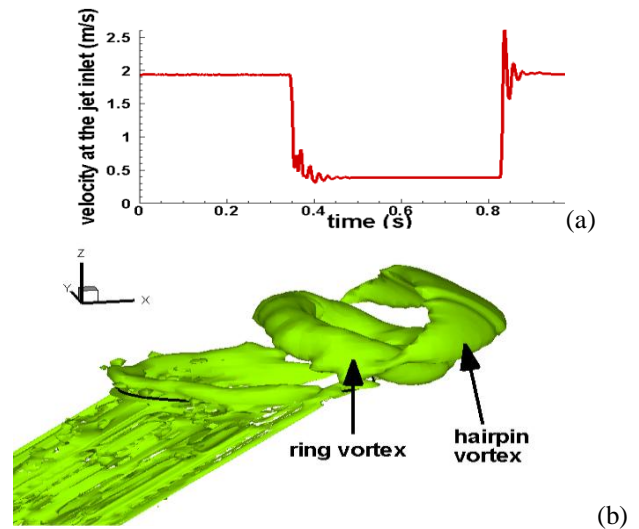


Figure 3: Pulsed jet at $BR_h=0.750$ $BR_l=0.450$ $DC=50\%$ $f_f=1Hz$. Top: Jet inlet velocity over a cycle. Bottom: Visualization of the first hairpin vortex and ring vortex generated by pulsing the jet.

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REFERENCE

1. Fric.T. F. & Roshko, A. 1994 A vortical structure in the wake of a transverse jet. J. Fluid Mech. 279, 1.