INTERACTION BETWEEN THE SHEAR LAYER, SHOCK-WAVE AND VORTEX RING IN A STARTING FREE JET INJECTING INTO A PLENUM

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Abstract While continuous free jets have been investigated and optimised during the last 60 years, the impulsively started jet is still relatively unexplored. We focus here upon the very first stage of a compressible free round jet, when the flow is only few diameters long and the vortex ring generated by the sudden expansion interacts with the shock-waves and the shear layer. Direct numerical simulations with more than $2 \cdot 10^9$ grid points are carried out, discretising the compressible Navier-Stokes equations to compute both the fluid flow and the noise radiated by the interaction of the shear layer, the shock-waves and the vortex ring in a compressible free round jet. As a result of the mentioned interaction, a sound level of 111[dB] at a distance of 100 diameters from the jet has been computed. An interaction between the shear layer, the shock-waves and the vortex ring has been investigated using numerical methods in an impulsively started supersonic free round jet and noise levels of order of the loudest acoustic phenomenon in the continuous jet have been identified and quantified.

INTRODUCTION

Impulsively started free jets have many applications in biology and engineering, ranging from the pulsated trans-aortic flow in the animal heart to the eruption of volcanoes, see figure 1.

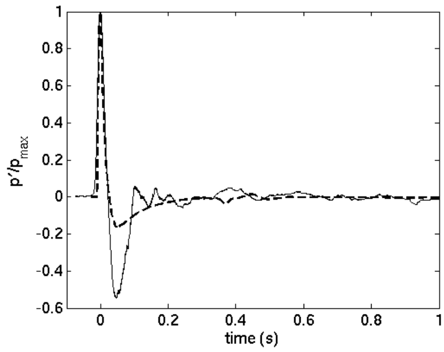


Figure 1: Pressure fluctuation history. The solid line represents experimental data from Mount Etna. The dashed line represent the numerical results.

Since the work of Powell (1953) [2], the continuous free jet has been intensively investigated by both experimental and numerical means, but the starting jet, with as much applications as the continuous jet is still relatively unexplored.

The case under study is a supersonic free round jet flowing through a convergent nozzle in its starting stage, when the fluid flow exiting the nozzle has reached few nozzle diameters in the axial direction.

A box with dimensions $25D \times 15D \times 15D$, where D is the nozzle diameter, is used to perform the numerical simulations. The nozzle is located centred at the plane $x = 0$.

The compressible Navier-Stokes equations are solved in a 6^{th} order finite difference fortran code, [3]. Runge-Kutta 4^{th} order was used to integrate in time. The largest grid used has $2048 \times 1024 \times 1024$ elements in x, y and z directions, respectively. A grid stretching in both transverse directions was used.

The inlet condition is a critical issue when simulating such a fully unsteady flow. In this case a time dependent inlet condition with the form of a hyperbolic tangent: $\frac{p_{\text{exit}}(t)}{p_\infty} = \text{NPR} \cdot \tanh(Kt)$ where NPR is the nozzle pressure ratio, or the pressure ratio between the reservoir and the environment $\frac{p_R}{p_\infty}$ and K is a parameter that controls the rising stage. In this case $K = 60$ was chosen to be the rising stage of the inlet fast enough to have an impulsively starting jet. A jet without decay stage was chosen in order to assure that the inlet condition is long enough in time to generate a trailing jet that leads to the desired interaction, [1].

Due to the sudden expansion through the nozzle, after the first acoustic wave a vortex ring is generated. When this vortex ring reaches few diameters the development of the shear layer and the shock-wave interact with each other because the vortices of the shear layer reach the shock-wave, the former are convected by the flow and the latter is quasi-steady. The result of this interaction is a strong acoustic wave radiated into the outer region with a sound level of order the loudest acoustic phenomenon of the continuous jet.

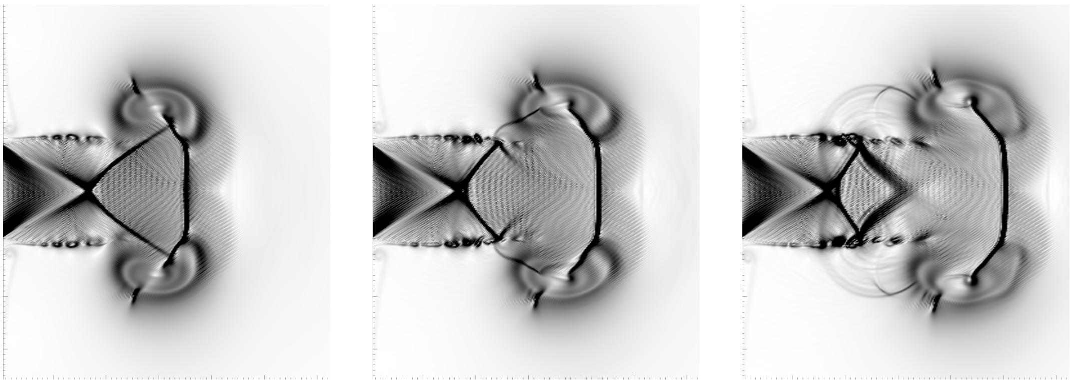
RESULTS

The interaction starts when the flow is few diameters long inside the plenum. The sudden expansion at the nozzle due to the high nozzle pressure ratio generates an acoustic wave that travels with the speed of sound in all directions inside the plenum. After this strong acoustic wave, a vortex ring propagates inside the plenum with a velocity much smaller as the speed of sound. Assuming that the duration of the inlet conditions is large enough to generate a trailing jet, its shear layer and, eventually the shock-cell system are behind the vortex ring, and they are also convected with a similar velocity as the vortex ring inside the plenum. For some time, the flow has a similar appearance as the figure 2a.

When the first vortex from the shear layer reaches the shock-wave, the concentrated vorticity of the shear layer bents the shock-wave in a similar situation as 2b.

When the following vortices from the shear layer reach the shock-wave, they bent more and more the shock-wave and in the end, the part of the shock-wave between the shear layer and the vortex ring is radiated to the outer region as a strong acoustic wave, see figure 2c. A strong acoustic wave is radiated into the outer region with a sound level of 111[dB] at a distance of 100 diameters from the jet axis.

It is also important to notice, that the shock-cell structure of the trailing jet is formed due to reflection of the shock-waves in the shear layer, and before the interaction between the shear layer and the first shock-wave, there was no reflection of the shock-wave, and the shock-wave extends to the core of the vortex ring.



(a) Straight shock (b) Curved and reflected shock (c) Open shock

Figure 2: Stages of the shock cell structure during its interaction with the vortex ring

CONCLUSIONS

A compressible starting free round jet has been simulated using numerical methods to study the interaction of the shock-wave, shear layer and vortex ring. The high resolution of the direct numerical simulation allows us to study in detail the interaction of these three elements. The shock-wave present in the core of the trailing jet is bent by the vortices from the shear layer that reach the shock-wave and as a result a strong acoustic wave is radiated into the outer region.

References

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