Noise radiated by the interaction between the shear layer, shock-wave and vortex ring in a starting free jet

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Introduction

We focus here upon the very first stage of the starting jet, where the flow is few diameters long and the vortex ring produced by the sudden expansion at the lip of the nozzle interacts with the shock-waves and the shear layer. A starting jet emanating from a convergent nozzle in an under-expanded condition was simulated numerically in order to investigate the mentioned interaction.

The continuous jet, and especially its acoustics has been studied since the decade of 1950, but the starting jet remains relatively unexplored. There exist an extensive literature on vortex rings, but only few of them are related to impulsively starting jets.

There is a vast range of applications for starting jets in different disciplines, going from the injection of fuel in engines in engineering, through the aquatic locomotion in biology to volcanoes in geophysics.

The initial state is a high pressure tank connected to a nozzle in a peace surrounding. For $t = 0$ the pressure is released and the tank is discharged through the nozzle into the surrounding, leading to a compressible starting jet. Shortly after, an acoustic wave is generated due to the sudden expansion in the lip of the nozzle. Afterwards, a vortex ring is formed and propagated in the positive axial direction and after that, a trailing jet is formed. This trailing jet can contain shock-waves if the nozzle pressure rate is large enough. In this case we restrict our study to supersonic flow, with a maximal fully expanded Mach number of $M_j = 1.48$.

The starting jet is a fully unsteady system as opposed to the continuous jet, which is a statistically steady one. This difference is crucial when studying turbulent flows because the fully unsteady system cannot be studied by means of statistics. This makes the starting a very challenging case.

The inlet condition has a very important effect in the starting jet flow. We focus in this study into the impulsively starting jets, this means that the time dependent inlet condition must start impulsively. In figure 1 is shown the time dependent inlet fully expanded Mach number used in the present study. The inlet condition was generated by the product of a hyperbolic tangent with a negative exponential, like the shown in equation 1.

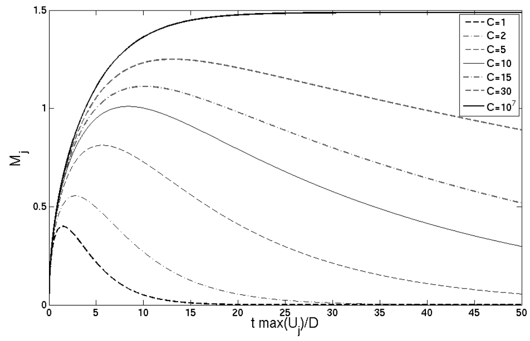


Figure 1: Time dependent inlet condition for the different cases under investigation.

$$\frac{p(x=0,t)}{p_\infty} = \mathrm{NPR} \cdot \exp\Big(\frac{-t}{\underbrace{C\,\frac{D_j}{U_j}}_{\mathrm{T}}}\Big) \cdot \tanh(Kt) \qquad (1)$$

where NPR is the nozzle pressure ratio (NPR = 1.90 for all cases) and K is a constant that controls the slope of the starting stage. In this study a value of $K = 60$ was used in all cases in order to have an impulsively starting inlet condition. C is the constant that controls the duration of the starting jet in comparison with the characteristic time, given by $\tau = \frac{t}{D_j/U_j} = \frac{t}{T}$. C is the only parameter in this study, the used values are in table 1.

Table 1: Parameters used for the different cases in this study.

C	$\max(M_j)$
1	0.40
2	0.55
5	0.81
10	1.01
15	1.11
30	1.25
10^7	1.49

Methodology

In this study, direct numerical simulations (DNS) were performed discretising the compressible Navier–Stokes equations with a spectral-like 6^{th} order finite difference method following Lele (1992) [2]. The compressible Navier–Stokes equations are written in characteristic form following Sesterhenn (2000) [1]. The time discretisation was performed using a Runge–Kutta 4^{th} order algorithm. The time-step has been calculated taking a constant CFL number of 0.6 which gives a $dt = 1.559 \cdot 10^{-5}$ s.

On the one hand, the physical domain is defined by a box with dimensions $25D \times 15D \times 15D$ in x, y, z-directions, respectively. On the other hand, the computational domain contains $2048 \times 1024 \times 1024$ hexaedra elements. The number of elements in this simulations is chosen to be able to resolve all scales of turbulence for a Reynolds number of $5000 - 10000$ and therefore to have a direct numerical simulation.

The boundary condition in the lateral faces of the computational domain were set to non-reflecting, this is a particular advantage from the characteristic formulation of Sesterhenn (2000) [1]. At the outlet face, a sponge region was set. At the inlet face, the inlet condition shown in figure 1 was set while the rest of the inlet face was set to non-reflecting.

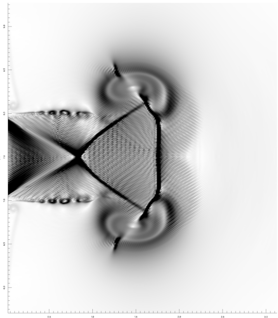
The simulations were run in the Leibniz Supercomputing Centre (LRZ) using Intel Xeon Sandy Bridge-EP processors. Up to 8192 processors were used in a single run using a hybrid paralellization MPI-OpenMP.

Results

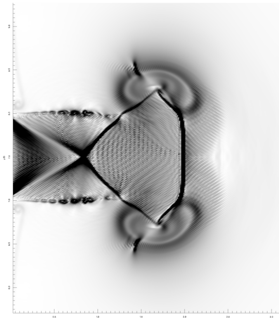
Shortly after the release of the high-pressure a vortex ring and a trailing jet are formed. When the vortex ring is formed and has propagated few diameters the fluid flow is like the one shown in figure 2a. In this condition, the oblique shock-wave follows a straight line extended to the core of the vortex ring, and the vortices of the shear layer did not met yet the shock-wave. Shortly after, the first vortex of the shear layer meets the shock-wave and bents it, see figure 2b, this is where the interaction takes place. The following vortices of the shear layer bent the shock-wave further, like in figure 2c until the part of the shock-wave between the shear layer and the vortex ring is radiated in the form of a strong acoustic wave 2d and 2e.

A probe was placed at 5D from the jet axis and pressure fluctuations of 999 Pa were recorded as a result of the interaction between the vortex ring, the shear layer and the shock-wave. This leads to an equivalent sound pressure level at 100D of 128[dB].

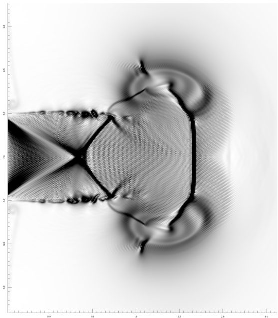
The classical three noise sources of the continuous jet are the TMN (turbulent mixing noise), BBSN (Broadband shock noise) and screech tones, see Tam (1995) [3]. The sound pressure level at 100D was computed for the case with $C = 10^7$ in the statistically steady regime (not the starting jet) and it was plotted in figure 3. It can be seen that maximal sound pressure levels of $120 - 130$[dB] are present in the continuous jet.



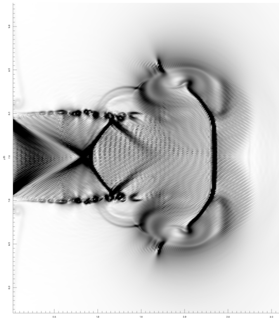
(a) Straight oblique shock.



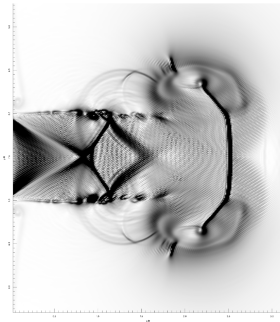
(b) Bent shock.



(c) Bent and reflected shock.



(d) Radiated shock.



(e) State after the interaction.

Figure 2: Phases of the interaction between the shear layer, shock wave and vortex ring.

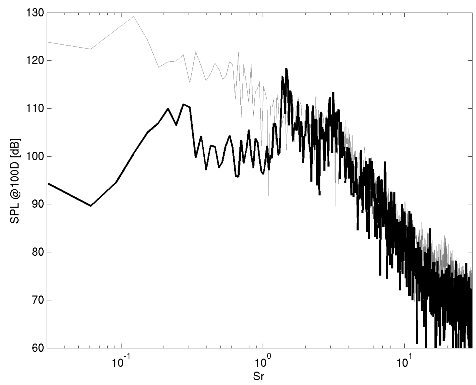


Figure 3: Sound pressure level of the jet under investigation in the continuous regime.

Taking into account, that the sound pressure level radiated by the interaction between the shear layer, the first shock-wave and the vortex ring was 128[dB] at 100D and that the loudest noise sources of the analogous continuous jet at 100D are of the order 120 – 130[dB] depending on the direction of observation it is clear that the interaction between the shear layer, the shock-wave and the vortex ring produces a sound pressure level as large as the loudest continuous jet noise source.

As it can be seen in figure 4 that the origin of the acoustic waves radiated due to the interaction shear layer - shock-wave have their origin in the point where the shock-wave meets the shear layer. This noise source is known in the literature as broadband shock noise (BBSN). Examining the shear layer in detail and the evolution of the vortices with the time when passing by the point in which the shock-wave meets the shear layer it has been found that the frequency with which the vortices passed by the shock-wave – shear layer interaction point was not fixed. This together with the several number of shock-cells leads to the broadband characteristic of the broadband shock noise.

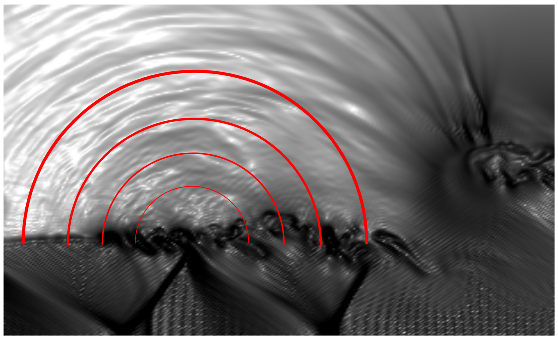


Figure 4: Density gradients plotted in a logarithmic colorscale showing the origin of the broadband shock noise waves.

It can be seen, once more, that the dynamics of the vortices lead to a global characteristic of the acoustic properties of the starting jet.

Conclusion

Direct numerical simulations were performed for a compressible impulsively starting free jet. Using a time dependent inlet condition, starting jets with different durations were simulated successfully. The aim of this study is the interaction between the shear layer, the shock wave and the vortex ring, and it has been seen that a very strong acoustic phenomenon is radiated as a result of the mentioned interaction. This acoustic wave is as loud as the loudest noise source in the continuous jet. It was computed that this interaction has an acoustic effect of 128[dB] at 100D. In this study is shown how the dynamics of the vortices generated by the turbulence of the fluid flow have a direct effect in the acoustic properties of the waves generated, therefore, direct numerical simulations are a great tool to investigate such phenomena.

The studied interaction takes place only in the first acoustic shock-wave, due to the closeness of the vortex ring and due to the fact that the first shock wave is the only one that extends until the vortex ring core, the rest of the shock-waves are just reflected in the shear layer and in the jet axis.

The broadband characteristic of the BBSN is due to the not fixed frequency with which the vortices pass by the shock-wave and the several number of shock-cells radiating this noise at the same time.

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