NUMERICAL INVESTIGATION OF THE SMALL SCALES IN A JET

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Abstract The focus of this investigation is on the isotropy of small scales in a turbulent jet. The aim is to get a better understanding of the structures in the jet and to see wether scale similarity arguments can be employed for LES modelling. Therefore the invariants of the anisotropy tensor are used and a new variable is introduced which measures the departure from isotropy and is used to visualize the results.

DESCRIPTION OF NUMERICAL METHOD

For large-eddy simulations it is assumed that the small scales of the flow exhibit universal scale similarity. Close to the wall, within shear layers or in shock cells this is far from true. The aim of this investigation is to analyse these small scales in respect of the isotropic state and eventually come up with adapted models.
As a testcase with different flow situations an underexpanded jet at $Re = 1000$, $M = 0.96$ and a pressure ratio of $p/p_\infty = 2$ at the inlet with a resolution of $1024 \times 512 \times 512$ is run. The aim is to localise areas with similar behaviour. This information shall be used to get a better model for large-eddy simulations.
To analyse the data of the direct numerical simulations we use the anisotropy tensor

$$a_{ij} = \frac{\overline{u_i u_j}}{2k} - \frac{1}{3}\delta_{ij} \tag{1}$$

with the fluctuations of the velocity u_i, u_j and $k = 0,5\overline{u_i u_i}$. The invariants II_a and III_a are defined in [1] as

$$II_a = a_{ij}a_{ji} \tag{2}$$

$$III_a = a_{ij}a_{jk}a_{ki} \tag{3}$$

The first invariant is zero by definition. With these three invariants it is possible to describe the state of a turbulent flow. These invariants are calculated locally. To look at the flow in every point of the field it is easier to have just one variable. We define

$$l_a = \sqrt{II_a^2 + III_a^2} \tag{4}$$

to characterise the distance of the local state to the isotropic one on the anisotropy invariant map.
The compressible Navier-Stokes equations are solved in characteristic form [6] on a cartesian grid which can be refined in both stream-wise and transverse direction. To accurately capture sound propagation, 6th order compact finite-difference schemes with spectral-like resolution of wavenumber are used, [2]. For time integration classical low-storage Runge-Kutta 4th order are used.
The validity of the NSF code for acoustic and flow simulations of supersonic and subsonic jet noise has been extensively tested and validated, [4, 5], partly using simulations done in the HLRN and LRZ supercomputing centres. The code has also been successfully validated for LES computations of turbulent channel flow using an approximate deconvolution model [3].
The parallelization of the code has been performed with both MPI and OpenMPI. and all the routines work perfectly with this parallelization. The code has reached an ideal linear speedup until 4096 cores in the main Supercomputing centres of Germany, like HLRN, HLRS and LRZ.

RESULTS

Some first results are shown in figure 1. The left figure shows the anisotropy invariant map (see [1]) with the grayscale as legend for the right one. So the darker areas are closer to the isotropic state than the lighter ones.
To get an overview of the states figure 3 (left) shows again the anisotropy invariant map with the additional information of the second and third invariant. All points are close to the right border for axisymmetric turbulence.
Plotting the distance l_a it is possible to identify isoropic and anisotropic reagions cleary within the jet and link these locations to the flow structures. The shockcells and the shear layer at the edge of the jet can be observed. Downstream there is a flow separation that is also seen in figure 2 (left) as a bubble with higher entropy than the outer region. The darkest regions are in the shear layer and inside the shockcells. But this does not mean that the shocks are isotropic. Figure 3 (right) shows a comparison of the distance l_a and the density gradient in an extract of the jet. The latter is a good method to visualise the shocks. This shows that the isotropic parts in the shockcells are not at the shockpositions but rather in the middle between two shocks and on the edge of the cell.

In comparison with the pressure in figure 2 (right) the new plot shows some more structures in the shockcells. These have to be investigated in the following time but it is clear that the distance to the isotropic state is a good possibility to visualise structures in a jet.

Two first conclusions of these results are that the jet is only isotropic in the shear layer and in some structures in the shockcells and that there is stuctural similarity in all shockcells. This means that the scale similarity assumptions for LES are not global but can be used in some flow situations.

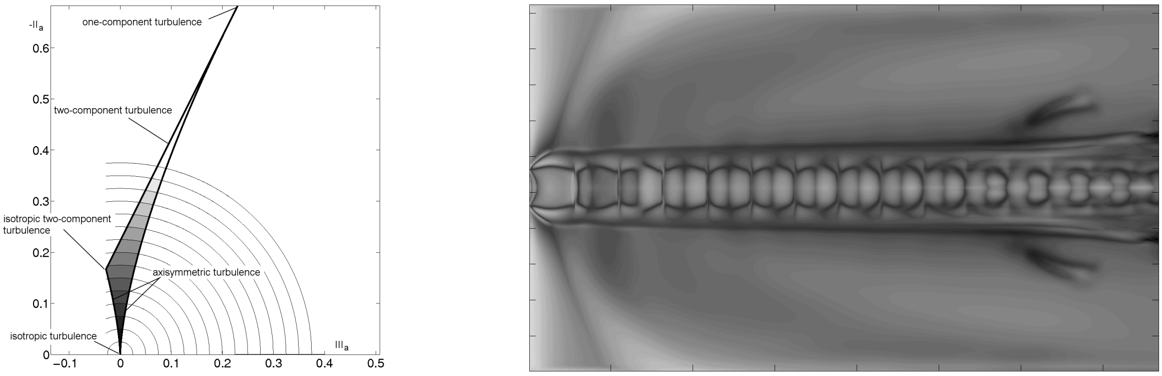

Figure 1. left: Anisotrophy invariant map of a_{ij} with grayscale legend for the right figure; right: Distance l_a of the local state to the isotropic one for a jet ($Re = 1000$, $M = 0.96$)

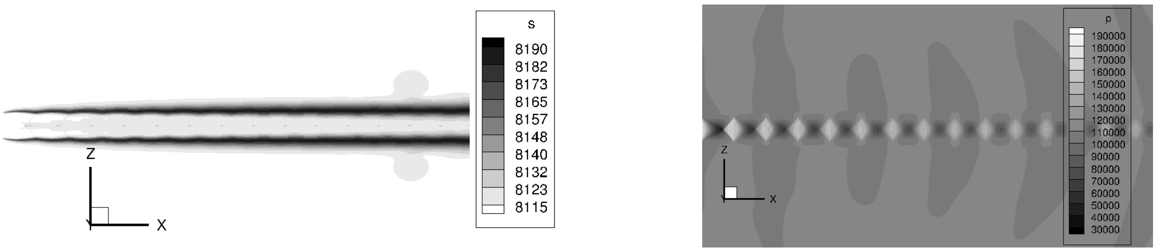

Figure 2. Entropy (left) and pressure (right) of the jet, slice in the middle of the jet

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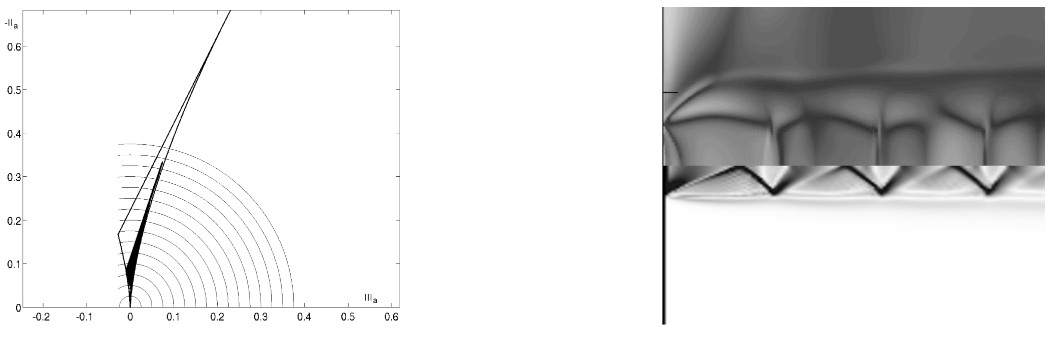

Figure 3. left: anisotropy invariant map with the second and third invariants of the jet; right: comparison of l_a (above) and the density gradient (below) mirrored at the jet axis