In Situ Segmentation of Turbulent Flow with Topology Data Analysis

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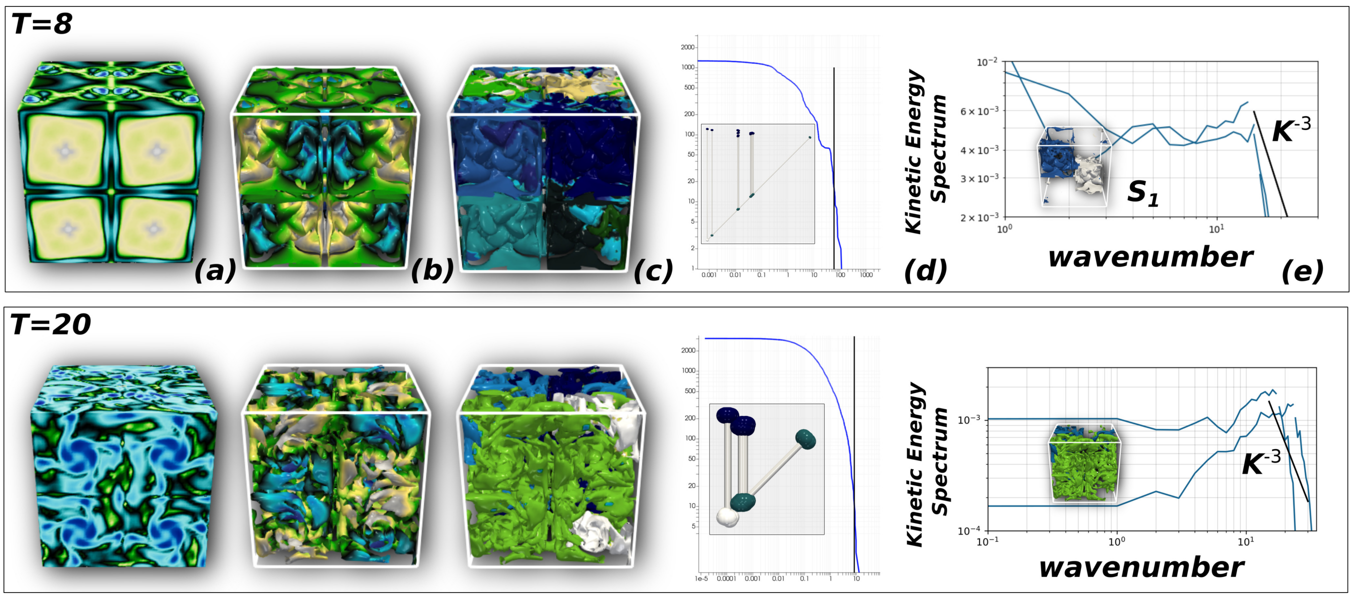

Figure 1: Persistence diagram and curve (d) for an enstrophy scalar field for the Taylor Green Vortex (a: surface visualization, b: iso-contour of enstrophy, c: segmentation view) at time $t = 8$ and $t = 20$. Energy spectrum for different vortices ensembles S_1 (e).

KEYWORDS

topological data analysis, turbulent flow, in situ visualization

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1 INTRODUCTION

The design of complex vehicles for atmospheric reentry requires running massive 3D calculations generating a set of important and complex data that must be analyzed to understand the physical phenomena involved. We focus on turbulent hydrodynamic flows in 2D, and viscous flows in 3D in order to study the areas of influence of the most important vortices. Topological data analysis methods are used for the segmentation of vortices in turbulent data, we show that the vortices describe a physical solution by looking at its energy spectrum. This study would have been more difficult to perform with traditional methods due to the complexity of the turbulent flows and the finer-grained mesh required. This study of turbulence is conducted by using in situ analysis methods.

2 BACKGROUND

2.1 Numerical method

In this study, the three-dimensional compressible unsteady Navier-stokes equation flows are solved. The system can be written as (see e.g. [8] for more details):

$$\mathbf{U}_t + \mathbf{F}_x + \mathbf{G}_y + \mathbf{H}_z = 0, \tag{1}$$

where the subscripts indicate differentiation, $\mathbf{U}$ is the vector of conservative dimensionless variables and $\mathbf{F}$, $\mathbf{G}$ and $\mathbf{H}$ represent the inviscid fluxes in $x-$, $y-$ and $z-$ direction respectively. To run the calculation, we use the Hyperion (HYPERsonic vehicle design with Immersed bOuNdaries) code discussed in [2], with the TENO 5^{th} order scheme [4] and the AUSM^{+}-up Riemann solver [6],[7]. The 2D simulation was run on Kelvin-Helmholtz instabilities (see [9]) on a grid of 512*512 cells. The 3D simulation was run using Taylor Green Vortex initial conditions (see [9]) on a grid of 64*64*64 cells. To emulate turbulence in a infinite medium, all boundary conditions are set as periodic. We use a common quantity to describe turbulence in two and three dimensions, the local enstrophy, defined locally as the square of the flow vorticity : $\mathcal{E} = 0.5\,|\nabla \times \mathbf{u}|^2$.

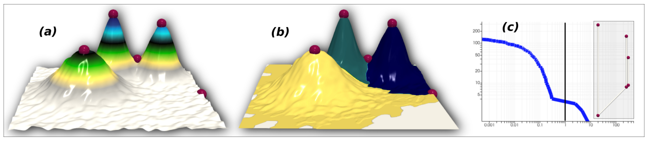

Figure 2: Critical points (spheres, maxima), persistence diagram and curve (c) for a noisy scalar field (a, b: segmentation visualization).

2.2 Topological Data Analysis

Topological Data Analysis (TDA) is a recent set of techniques [10] which focus on structural features in data. Thanks to advanced concepts such as persistent homology [3], TDA provides tools for the multi-scale representation of the structural features of interest such as the turbulence in a flow (see Figure 2). In this work, we used several established techniques, readily available in the "Topology ToolKit" (TTK) [11].

2.3 In situ analysis

Running simulations at the exascale level means computing is getting cheaper while data transfer and storage is increasingly expensive. As a consequence, we replace the post-processing step – analysis and visualization of the simulation results in traditional scientific computing workflows – with in situ analysis. This approach minimizes the data transfer bottlenecks as all analyses are done in line with the simulation. In our work, the ParaView pipeline set up by a user and normally run on data saved on disk is transposed to a Python script generated by ParaView. An adaptor is implemented in the simulation code to map the simulation data structures to the Catalyst [1] data model.

3 CONTRIBUTIONS

The segmentation was first applied to 2D hydrodynamic turbulent flow simulations, where satisfactory results were obtained. The segmentation was then applied to a 3D viscous flow simulation. Our method of separating different ensembles of connected vortices together gives accurate results and is easy to apply.

4 SIMULATION STUDY

4.1 Protocol Description

Our study relies on the enstrophy using Catalyst and TTK. From persistence curves, we set a threshold value on the enstrophy to keep the most important vortices. Then we use a Morse-Smale Complex [10] to segment the enstrophy scalar field. Finally we analyze the vortices ensemble with its energy spectrum [5].

4.2 Interpretation

Thanks to topological tools such as persistence curves, we easily identified the areas of influence of large vortices. This allowed us to verify the segmentation on the enstrophy scalar field with energy spectra for each vortices ensemble. We notice that the energy transfer of vortex ensembles evolves in $K^{5/3}$ for 2D simulations and in K^{-3} for 3D simulations (see Figure 1 and Figure 3).

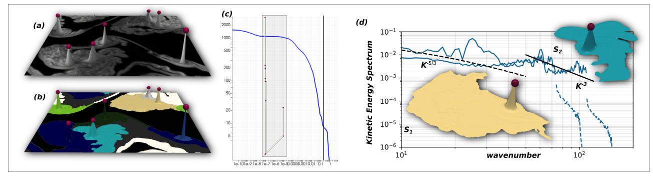

Figure 3: Persistence diagram and curve (c) for an enstrophy scalar field of the Kelvin-Helmholtz instability (a, b: segmentation visualization). Energy spectrum for vortices ensembles S_1 and S_2 (d).

5 CONCLUSION

In this work we have shown that using topological methods, it is possible to segment and analyze a set of vortices connected to each other through a turbulent flow. With the help of in situ methods it is possible to check the progress of a calculation. The proposed method is more accurate and helps us verify that the turbulence reconstruction describes a physical solution during the simulation. In future works, we plan to apply this protocol to Kelvin-Helmhotz and Taylor Green Vortex simulations with finer resolutions. With a finer grid resolution (1024^2 for the Kelvin-Helmholtz simulation and 512^3 for the Taylor Green Vortex one), we would have obtained results describing the correlation between small and large vortices more accurately. Next step is to transpose this turbulence analysis to the atmospheric reentry simulation of a hypersonic vehicle.

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