Survey and Analysis of Multiresolution Methods for Turbulence

J. Pulido, pulido@lanl.gov
D. Livescu, livescu@lanl.gov
J. Woodring, woodring@lanl.gov
J. Ahrens, ahrens@lanl.gov
B.Hamann, hamann@cs.ucdavis.edu

This work compares the effectiveness of various multi-resolution representation methods, such as B-spline, Daubechies and Coiflet wavelets, curvelets and surfacelets, to capture the structure of fully developed turbulence using a truncated set of coefficients [1]. The turbulence dataset is obtained from a Direct Numerical Simulation of buoyancy driven turbulence on a 512^3 mesh size, with an Atwood number, $A = 0.05$, and turbulent Reynolds number, $Re_t = 1800$, and the methods are tested against quantities pertaining to both velocities and active scalar (density) fields and their derivatives, spectra, and the properties of constant density surfaces. The comparisons between the algorithms are given in terms of performance, accuracy, and compression properties. The results should provide useful information for multi-resolution analysis of turbulence, coherent feature extraction, compression for large datasets handling, as well as simulations algorithms based on multi-resolution methods.

Background and Motivation

One of the avenues being explored for simulating, with feasible meshes, flows with large range of scales, as encountered in most practical applications, explores coherent/incoherent decompositions allowed by multi-resolution geometric representations . This approach relies on the ability of such methods to represent the coherent part of the flow with a significantly reduced set of coefficients (e.g. $1-5\%$ of the coefficients to represent the whole flow) and model the incoherent part using simplifying models (e.g. assume Gaussian statistics).

In addition, there is a significant cost associated with the storage of the data generated by turbulence simulations. Efficient lossy algorithms can take advantage of the coherent/incoherent decompositions of the flow field and significantly reduce the archival requirements. Data retrieval can be optimized by extracting only the coherent structures in the data for faster data visualization and analysis at multiple levels of resolution. By reducing the retrieval and transmission cost, projects such as the Johns Hopkins Turbulence Database (JHTDB) can be improved by reducing the amount of data processed and transmitted to a client.

Description/Impact

The focus of this work is the extensive comparison of new and existing methods used in analysis (feature identification, extraction, and analysis) and simulations (based on coherent / incoherent decompositions) of turbulence.

A list of recommended methods for each test is provided in Table 1. In general, any method is superior to Haar wavelets considering our series of tests. These results show that increasing the family order is not always the ideal solution towards higher accuracy. At 3% coefficients, large structures within the flow are well preserved and at that percentage it is not necessary to go to the highest order method. Since the results are very similar across the higher orders of B-splines, it is not recommended to go above cubic B-splines, sacrificing more compute time and questionable accuracy gains. Daubechies wavelets are generally overshadowed by B-splines so their use is not recommended unless orthogonal properties must be preserved. Although Coiflets have a few advantages to Daubechies in derived surface quantities and preservation of Kinetic energy, their representations of curved surfaces and scalar quantities are not ideal. Based on their overall performance, the cubic B-spline wavelet is recommended as the general method for the turbulence data applications considered here. Surfacelets

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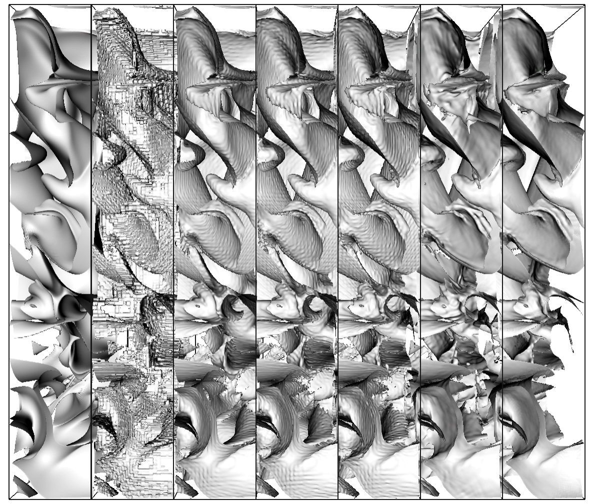
Test Type	Best Method	Runner-up
Velocity PDF	Cubic B-spline	Daubechies-5
Vorticity PSNR and MSE	Cubic B-spline	Quadratic B-spline
Vorticity PDF	Cubic B-spline	Quadratic B-spline
Strain rate tensor	Quadratic B-spline	Cubic B-spline
Density visualization	Surfacelets	Cubic B-spline
Density PSNR and MSE	Cubic B-spline	Quadratic B-spline
Density PDF	Cubic B-spline	Daubechies-5
Density power spectrum	Quintic B-spline	Quartic B-spline
Isosurface Visualization	Surfacelets	Curvelets
Curvature quantities	Cubic B-spline	Surfacelets
Surface signatures	All methods except Haar	—-
Performance	Surfacelets	Haar

***Summary**. Compilation of the best respective methods for each test performed.*

and curvelets have specific applications and advantages where they are able to identify specific features at different scales in turbulence, taking full advantage of the multi-scale interface of these methods but further analysis is required. Both surfacelets and curvelets provide superior representation of smooth surfaces compared to any other method for general applications in turbulence, as seen in Fig. 1. Surfacelets are recommended over curvelets since they are much more efficient in computation, reconstruct more accurately at the same number of coefficients, and capture curved surfaces closest to the original data even compared to all the methods tested.

Anticipated Impact

The selection process described in this work should be useful in several areas, including multi-resolution analysis of turbulence, coherent feature extraction, compression for large datasets handling, as well as simulations algorithms based on multi-resolution methods. While some of the algorithms discussed have already been used for simulations algorithms based on multi-resolution methods, while others for multi-resolution analysis of turbulence, with the continuous increase in the computational platform speed and size, we would like to stress the emerging importance of compression algorithms for large dataset handling.



Isosurfaces representing the pure light fluid are constructed using the largest 3% coefficients. From left to right: original, Haar, cubic B-spline, Daubechies-5, Coiflet-12 wavelets, curvelet, and surfacelet transforms.

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References

[1] Jesus Pulido, Daniel Livescu, Jonathan Woodring, James Ahrens, and Bernd Hamann. Survey and analysis of multiresolution methods for turbulence data. *Computers and Fluids*, 125:39 – 58, 2016.