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Survey and analysis of multiresolution methods for turbulence data

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ABSTRACT

This paper compares the effectiveness of various multi-resolution geometric representation methods, such as B-spline, Daubechies, Coiflet and Dual-tree wavelets, curvelets and surfacelets, to capture the structure of fully developed turbulence using a truncated set of coefficients. 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. The final section provides recommendations for best decomposition algorithms based on several metrics related to computational efficiency and preservation of turbulence properties using a reduced set of coefficients.

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1. Introduction

Most datasets encountered in physical applications, similar to most natural images, present lower dimensional structures whose detection, extraction, and characterization are active areas of research. The search for more efficient algorithms to detect and manipulate such structures has led to the development of a multitude of multi-resolution geometric representations, such as curvelet and surfacelet transforms. The curvelet [1] and surfacelet [2] transforms perform spatial partitioning in Fourier space at multiple resolutions by creating bands using discrete frequency tiling that store localized directional coefficients.

One area which has seen significant interest in the application of such methods is fluid turbulence. While turbulence is a strongly multi-scale phenomenon with a large range of dynamically relevant spatio-temporal scales, coherent structures are almost always present, due to initial or boundary conditions, injection mechanisms, or arising from internal dynamics. The characterization of these structures, which interact nonlinearly as they are advected by the background flow and significantly alter the local topology, is one of the fundamental open questions in the study of turbulence. One of the earliest applications of compression algorithms to turbulence is done in Ref. [3]. The focus was on comparing the coherent vortex simulation (CVS) decomposition based on a orthogonal wavelet basis with the Proper Orthogonal Decomposition or Fourier filtering, as applied to a forced homogeneous isotropic turbulence Direct Numerical Simulations (DNS) dataset. It is shown that CVS filtering, which is local in both physical and spectral spaces, can separate the coherent vortex tubes from the incoherent background flow. The latter is structureless, has an equipartition energy spectrum, a Gaussian velocity probability distribution function (PDF), and an exponential vorticity PDF. On the other hand, the Fourier basis does not extract the coherent vortex tubes cleanly and leaves organized structures in the residual high wavenumber modes whose PDFs are stretched exponentials for both the velocity and vorticity.

More recently, curvelets have been briefly evaluated by Ma et al. [4] in comparison to the classical wavelet transform. In their work, multi-scale geometric analysis is systematically applied to turbulent flows in two and three dimensions using curvelets. The analysis is based on the constrained minimization of a total variation functional representing the difference between the data and its representation in the curvelet space. Constrained multi-scale minimization results in a minimum loss of the geometric flow features and the extraction of the coherent structures with their edges and geometry properly preserved, which is significant for turbulence modeling. The results of this work show that curvelets are very effective in edge and geometry preservation in turbulence data when compared to traditional

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wavelets under a specific series of tests and wavelet coefficient numbers. One goal of the present paper is to expand those tests to the full range of coefficients for reconstruction of turbulence data as well as include tests for quantities dependent on an active scalar field.

These methods have been primarily applied to the quantities directly related to the velocity fields although, recently, the curvelet transform has been used to examine the multi-scale structure of scalar fields, such as mass concentration [5]. These fields are, in general, rougher than the advecting velocity and can present unmixed patches in many practical applications (e.g. non-premixed combustion). Thus, representation methods which are designed to capture surfaces or edges, such as surfacelets or curvelets, appear naturally more suited to capture these fields. For example, Ref. [5] introduces a curvelet-based multi-scale methodology for the study of the non-local geometry of eddy structures in turbulence data. The dataset is from a 512^3 DNS of passive scalar mixing in isotropic turbulence and the curvelet transform is used to extract, characterize and classify structures pertaining to the passive scalar. The classification is based on differential-geometry properties, such as shape index, curvedness, and stretching parameter, which define the geometrical signature of the surfaces of constant scalar value. These properties are discussed with respect to their relation to the dynamical behavior of passive scalar stirring and mixing. Another goal of the present paper is to compare the curvelet transform with other representation methods for their ability to preserve these properties with a reduced set of coefficients.

Accurate simulations of turbulent flows require solving all the dynamically relevant scales of motions. This technique, called DNS (see above), has been successfully applied to a variety of simple flows, however most practical flows would require mesh sizes outside the range of the most powerful supercomputers for the foreseeable future. The resolution requirements can be improved, especially in problems with localized features, by employing an adaptive mesh strategy. However, such approaches often introduce directional bias and use lower order discretization methods, which decreases the accuracy. Adaptive mesh strategies based on wavelet decompositions have been proposed with explicit error control and higher order discretization schemes [6–8]. While these methods extend the range of DNS applicability, accurately solving all the flow scales still imposes severe limitations on the flows which can be simulated.

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 [3,4,9,10]. 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). For such applications, the accuracy and computational efficiency of the algorithms are both important. So far, only the curvelet, Dual-tree, and orthogonal wavelet transforms have been used in this context and no comprehensive comparison between these transforms has been made. Classical large eddy simulation (LES) approaches for computing turbulence represent the flow on a coarse mesh in either real or spectral spaces and model the sub-grid contributions. While finding an optimal function set basis to represent turbulence remains an outstanding open question, the representation methods discussed in this paper may offer a better framework for modeling the sub-grid terms in an LES type approach than spectral or physical space based filters, due to their localization in both spectral and real spaces. Here, we rely on this locality to denote the coherent/incoherent decomposition as applied directly to the primary variables, as opposed to CVS-type decompositions. This is along the lines of the SCALES approach [9] and offers easy generalizations to complex flows and direct connection to LES-type approaches.

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 [11]. By only sending structures at a resolution relevant for analysis, the reduced cost can allow for real-time remote data visualization and analysis of large datasets.

The focus of this paper is the comparison of new and existing methods used in analysis (feature identification, extraction, and analysis) and simulations (based on coherent/incoherent decompositions) of turbulence. These methods include second-generation wavelets such as Haar, biorthogonal B-spline, Daubechies, Coiflets, Dual-tree, and newer methods such as curvelets and surfacelets. In order to make the comparisons as comprehensive as possible, a flow has been selected in which the turbulence is accompanied by mixing between initially segregated different density materials (see description below) which are subjected to a constant acceleration. The large scales of the flow are anisotropic and the interfaces between the two materials become highly corrugated. The methods considered are compared in their ability to capture the structures of both velocity and density fields. It is hoped that this analysis will help both the simulations of turbulent flows using multi-resolution geometrical representations as well as further the study of turbulence physics using such methods.

1.1. Direct numerical simulation dataset

The dataset used in this paper is from a DNS of homogeneous buoyancy driven turbulence on a 512^3 periodic grid. The simulation used the variable-density version of the petascale CFDNS code [12] to solve the incompressible Navier–Stokes equations for two miscible fluids with different densities, in a triply periodic domain. These equations are obtained from the fully compressible Navier–Stokes equations with two species with different molar masses in the limit $c \to \infty$ (c is the speed of sound) such that the individual densities of the two fluids remain constant [13–15].

The two fluids are initialized as random blobs, consistent with the homogeneity assumption. The flow starts from rest, with only a small amount of dilatational velocity necessary to satisfy the divergence condition and turbulence is generated as the two fluids start moving in opposite directions due to differential buoyancy forces. However, as the fluids become molecularly mixed, the buoyancy forces decrease and at some point the turbulence starts decaying. For comparison between the different compression algorithms, density and velocity fields are used at the time when the turbulent kinetic energy is maximum. At this time, the turbulent Reynolds number is $Re_t = 1800$and the turbulence is fully developed. The rest of the non-dimensional parameters characterizing the flow are Atwood number, $A = 0.05$,Schmidt number, $Sc = 1$and Froude number, $Fr = 1$. A similar dataset [16], on a 1024^3mesh, covering the whole range of turbulence evolution, from buoyancy driven increase in turbulent kinetic energy to buoyancy mediated turbulence decay, has been recently added to the Johns Hopkins Turbulence databases [11].

The rest of the paper is organized as follows. In Section 2, a background is given of the geometric representation methods considered in this paper. Section 3 summarizes the software used, thresholding techniques, and properties for all of the different methods. The testing methodologies are described and the results are quantified in Section 4. Finally, Section 5 presents the conclusions with the recommendations of the best schemes suited for the representation and

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