Adaptive Large Eddy Simulation

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Summary

This project is focused on development of a novel approach, called Stochastic Coherent Adaptive Large Eddy Simulation (SCALES) for modeling and simulation of turbulent flows. The approach comes from the realization of the deficiency of the current Large Eddy Simulation (LES) approach, which resolves only the large-scale motions instead of coherent energy containing flow structures. The SCALES approach addresses the shortcomings of LES by using a dynamic grid adaptation strategy that is capable to resolve and track the most energetic coherent structures in a turbulent flow field. Similarly to classical LES the effect of the unresolved motions is modeled in SCALES. A number of localized dynamic subgrid scale models utilizing wavelet multi-resolution analysis have been developed and successfully tested for freely decaying homogeneous turbulence with initial Re_λ=72. It has been shown that the SCALES results obtained with less than 0.4% of the total non-adaptive computational nodes closely match reference data from direct numerical simulation. In contrast to classical LES, where the energetic small scales are poorly simulated, the agreement holds not only in terms of global statistical quantities but also in terms of spectral distribution of energy and, more importantly, enstrophy up to the dissipative wavenumber range.

Although turbulence is common in engineering applications, a solution to the fundamental equations that govern turbulent flow still eludes the scientific community. Due to the prohibitively large disparity of spatial and temporal scales, direct numerical simulation (DNS) of turbulent flows of engineering interest are impossible, even with the aid of the fastest supercomputers that exist or will be available in the foreseeable future. Large eddy simulation (LES) is often viewed as a feasible alternative for turbulent flow modeling. The main idea behind LES is to resolve only the large-scale motions, while modeling the effect of the unresolved subgrid scale (SGS) eddies. When dealing with complex turbulent flows, current LES methods rely on, at best, a zonal grid adaptation strategy to minimize the computational cost. While an improvement over the use of regular grids, these methods fail to resolve the high wavenumber components of the spatially and temporarily intermittent coherent structures characteristic of turbulent flows, thus neglecting valuable physical information. At the same time, the flow is over-resolved in regions between the coherent structures, which wastes computational resources.

These shortcomings have been addressed in this research by the introduction of a novel approach, called Stochastic Coherent Adaptive Large Eddy Simulation (SCALES). The basic idea is to solve only for the most energetic coherent eddies in a turbulent field, while modeling the effect of

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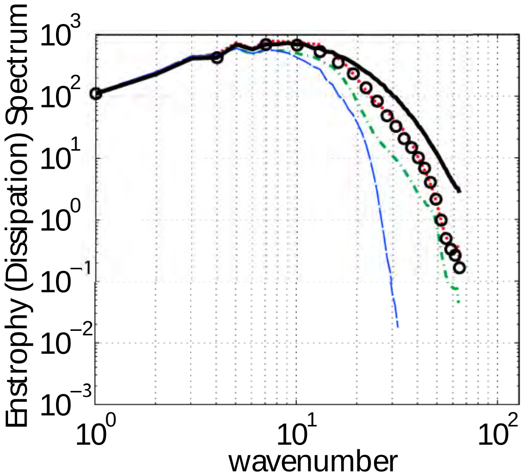
the less energetic (unresolved) motions. A wavelet thresholding filter is employed to perform the dynamic grid adaptation that allows to identify and follow the structures of significant energy in the flow.

Similarly to LES, the SCALES method is supplied with a closure model for the residual stress term that is mainly required to mimic the energy transfer between the resolved and the unresolved motions. In order to realize the full potential of the dynamic adaptability of SCALES approach, a number of fully localized dynamic subgrid scale models that do not rely on homogeneous direction averaging are developed. All the developed models have been assessed by performing SCALES of incompressible isotropic freely decaying turbulence in a triply periodic cubic box with initial $Re_\lambda=72$. Though these localized models are specifically designed to simulate complex non-homogeneous turbulent flows, it is nevertheless enlightening to test them for a case for which well known theoretical and experimental results exist.

One of the most crucial features of the SCALES approach is its ability to match the DNS energy and enstrophy density spectra up to the dissipative wavenumber range using very few degrees of freedom as cleary seen in the figure below. It is important to emphasize that for all localized models the close match is achieved using less than 0.4% of the total non-adaptive nodes required for a DNS with the same wavelet solver. To highlight the significance of such a close match, it is interesting to compare these results with those of an LES with the global dynamic Smagorinsky model. Despite the fact that LES uses almost four times the number of modes (1.56%), it fails to capture the small-scale features of the spectrum.



Enstrophy density spectra for SCALES with two different models (······ and – · ·). Spectral DNS (——), wavelet filtered DNS (oo), and LES (– –) are shown for comparison.

As to future work, SCALES formulation will be extended to include spatially variable wavelet thresholding filter based on physical constrains such as the ratio between SGS and resolved kinetic energies or resolved and SGS dissipations.

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