Wavelet decomposition of turbulent velocity and its application to subgrid scale modeling

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Abstract: The paper presents principles, modeling issues, algorithmic details and numerical results from a discrete wavelet decomposition [1] applied to subgrid-scale modeling. The WALES (Wavelet Adapted Large Eddy Simulation) model introduced in earlier work [2, 3, 4] for simple flow cases, is applied here to a complex swirl flow in a complete combustion chamber, in which length scales and velocities differ by two orders of magnitude. Optimization is required to achieve a compromise between the accuracy of the wavelet decomposition and the information exchange between block boundaries of the structured numerical grid.

Results show that the chosen implementation of the WALES model is robust, accurate and is capable of adequately handling the complexity of combustion chambers. The CPU-time and the algorithmic complexity to carry out the explicit wavelet decomposition are comparable to that of the classical Smagorinsky model. The model needs no special treatment of near-wall regions and in some simple laminar flows naturally returns zero eddy viscosity.

Keywords: discrete wavelet decomposition, large eddy simulation, subgrid scale model, combustion in flow with swirl

1 Introduction

Numerical algorithms based on consecutively finer grid resolutions – multiresolution techniques - are widely employed for solving the Navier-Stokes equations. An example for this can be found in multigrid methods for accelerating the convergence of large sets of algebraic equations. Two further examples present the Coherent Vortex Simulation [2] which uses adaptive grids to resolve all turbulent eddies without modeling, and the Stochastic Adaptive LES which additionally requires appropriate subgrid-scale modeling. Wavelet decompositions naturally contain the idea of multiple resolutions on consecutive grids and are used for analyzing turbulent flows and coherent structures.

The present work also applies consecutively finer grids integrated in a wavelet decomposition, but their application differs from the above methods. The main idea behind the present work is that wavelet details which result from a wavelet decomposition, would have a larger value, if the turbulent signal possesses higher irregularity. Therefore, these wavelet details present a principal measure for the degree of irregularity of the turbulent flow which allows linking them directly to the eddy viscosity in a LES. This idea is embodied in a subgrid scale model referred here as WALES (Wavelet-Adapted LES). It is briefly described in the following.

2 Description of the WALES model and its features

In the WALES model the discrete wavelet decomposition of [1] is applied first. The resolved turbulent signal from the LES (the velocity components *u*, *v* and *w*) constitutes the fine grid (or, the fine level) of the decomposition; a two times coarser grid is also composed. After the wavelet decomposition is explicitly calculated, the values of the details for each velocity component on the fine grid are obtained. Denoting these wavelet details by $d^W\{\ldots\}$, the the eddy viscosity for the respective time-step can be calculated by:

$$\nu_t = C_{WALES} \cdot \Delta \cdot \sqrt{\left(d^W\{u\}\right)^2 + \left(d^W\{v\}\right)^2 + \left(d^W\{w\}\right)^2} \,,$$

where Δ is obtained from the cell volume on the fine grid and the model constant C_{WALES} is 0.02.

One attractive feature of the WALES model is its ability to return exactly zero eddy viscosity in some laminar cases like pipe flows or Couette flows. It is a direct consequence of the properties of the wavelet decomposition which calculates zero wavelet details, if the velocity distribution is linear or parabolic in space. Another advantage of the model is that no special near-wall treatment is necessary – as shown in our earlier test cases [2, 3] and confirmed by the present results.

3 Results from the flow in a combustion chamber

Results obtained on a curvilinear block-structured grid with 6.2 million control volumes and 620 numerical blocks on 120 processors are obtained and analyzed. First, they are compared with available experimental measurements in the regions with largest gradients showing a good quantitative agreement. Second, the WALES results are compared with results from the classical Smagorinsky model. The latter utilizes wall functions and Van Driest near-wall damping while the WALES model was applied with no-slip conditions only. Surprisingly, despite the principal differences in the modeling approaches, the two models show results which are quite close to each other.

In a further postprocessing analysis, dynamic vortex structures of the flow have been obtained and analyzed. The precessing vortex core computed with the WALES model is shown in Fig. 1. Good correlation between the axial velocity component and the pressure fluctuation has been found close to the exit from the swirl inducing device.

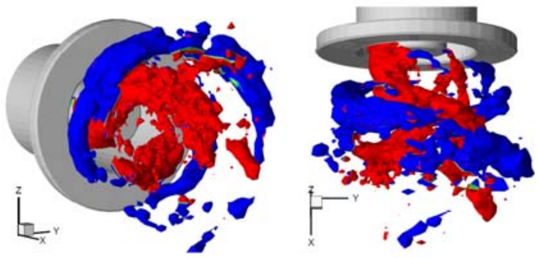

Fig. 1 Large-scale coherent structures near the exit of the swirl-inducing device (gray colour). Structures are presented by iso-surfaces of the pressure fluctuations. Red colour shows the precessing vortex core and blue colour – the surrounding outer structures.

4 Conclusions

The present work discusses principles and algorithmic issues for the application of a wavelet decomposition to subgrid scale modeling in large eddy simulations. It confirmed that the WALES model is accurate and robust and is mature for handling complex engineering problems. Despite principal differences in modeling, results obtained with the WALES and the Smagorinsky model appear to be quite close.

References

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