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A SUBGRID-SCALE MODEL FOR LES BASED ON THE PHYSICS OF INTERSCALE ENERGY TRANSFER IN TURBULENCE

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Abstract

The scale-similarity model in large-eddy simulation (LES) leads to an attractive, functionally simple expression for the subgrid-scale (SGS) stress tensor. It is well known, however, that it does not accurately predict the subgrid-scale dissipation leading to its failure in actual LES. In the present work, considerations of interscale energy transfer have been used to identify sources of the observed deficiencies of the similarity model, allowing to develop a new interscale transfer model with favorable characteristics of SGS dissipation. The proposed model maintains the functional simplicity of the similarity model, consisting of test-filtered velocities and their products, but offers clear improvements in predictions of mean flow quantities and the global energy flux from the resolved to subgrid scales without the need for additional eddy viscosity terms to augment SGS energy dissipation. The application of the interscale transfer model in LES of wall-bounded flows leads to predictions of mean and RMS flow quantities comparable to those obtained for other, established SGS models.

FORMULATION OF THE INTERSCALE TRANSFER MODEL

The proposed interscale transfer model has been formulated using concepts of interscale energy transfer, specifically noting that the model should counteract the effect of the nonlinear energy transfer among resolved scales depositing energy near the LES cutoff [1]. These concepts offer a tool to parse the nonlinear transfer present in LES and formulate expressions capable of removing (or reducing) terms that deposit energy near the LES cutoff. The present formulation is such that a fraction of the nonlinear terms leading to energy production in the the smallest resolved scales of turbulence are removed by the model. The derived expression for the SGS stress tensor is

$$\tau_{ij} = \widehat{\widehat{\overline{u}}_i \overline{u}_j} - \widehat{\widehat{\overline{u}}}_i \widehat{\widehat{\overline{u}}}_j - \widehat{\overline{u}}_i \overline{u}'_j, \tag{1}$$

where an overbar denotes full LES quantities, a hat signifies a test filter, and $\overline{u}'_i = \overline{u}_i - \widehat{\overline{u}}_i$.
The strength of the test filter has been used to define the fraction of these terms removed by the model. The filter strength along with implicit factors such as mesh resolution and Reynolds number determine the model's collective effect on energy transfer. Tuning of the test filter strength was required initially but numerical simulations at various Reynolds numbers and mesh resolutions have demonstrated that good performance can be obtained without additional changes to the once selected filter.

MODEL RESULTS

A solver with spectral-order accuracy is ideal for testing LES models due to the method's inherently low artificial dissipation. All numerical simulations were conducted using the pseudo-spectral flow solver developed by Diamessis *et al.*[2]. This code has been used to simulate wall-bounded channel flows at three Reynolds numbers: $Re_\tau = 180,\ 950$ and 2000. A fundamental feature of a SGS model is its ability to accurately predict mean and RMS velocities at various flow conditions and thus predictions of these statistical quantities were emphasized in testing of the present model. The model has been tested and the results are compared with those obtained from implementations of the similarity model (in the form proposed by by Liu *et al.*[3]) and the dynamic model [4]. The predictions from LES are compared against DNS results provided by del Alamo and Jimenez[5, 6], and del Alamo et al.[7].
As an example we show in Fig. 1 comparison for the mean velocity profiles for Re_τ=180. The observed underprediction of mean velocity by the under-resolved DNS simulations was fairly consistent for all Reynolds numbers considered. The similarity model also greatly under-predicts the DNS results while the dynamic model performs rather poorly in this case, giving an overprediction of the mean velocity in the logarithmic region. The present model performs well in both the inner and outer regions of the boundary layer. In Fig. 2 comparison for the mean velocity profiles for $Re_\tau = 2000$ is shown. The similarity model again fell short of the DNS profiles and consistently gave an underprediction of the mean velocity. The dynamic model gave overpredictions of the DNS results, but overall this model's predictions provided improvements throughout the boundary layers. The predictions obtained from the present model were quite good, overlapping considerably with the DNS, deviating only slightly in the buffer region. Similar conclusions were drawn from results for rms velocities. Overall, the proposed model has demonstrated considerable improvements when compared with predictions of the similarity model and has also demonstrated a predictive capability that easily rivals that

of the dynamic model. The model is relatively simple in its formulation and lacks any obvious drawbacks in terms of its general applicability.

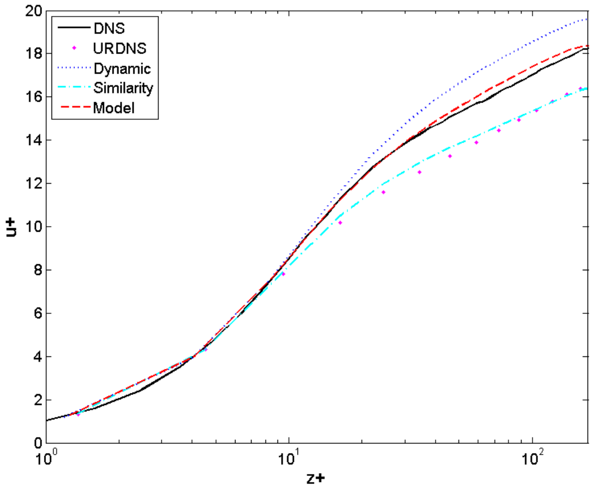

Figure 1. Mean velocity profiles for Re_τ=180 obtained using DNS, under-resolved DNS, similarity model, dynamic model, and the present model

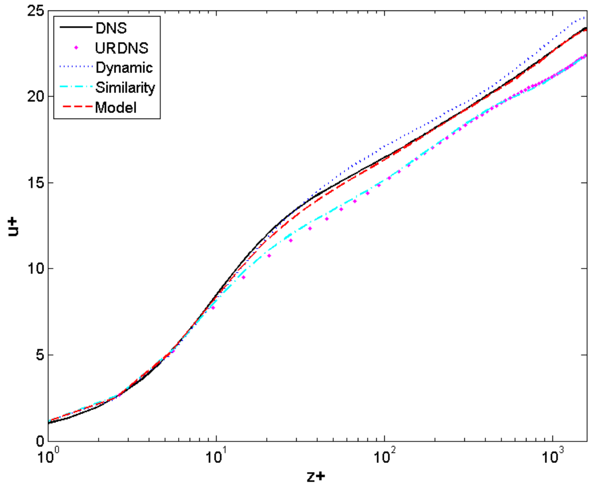

Figure 2. Mean velocity profiles for Re_τ=2000 obtained using DNS, under-resolved DNS, similarity model, dynamic model, and the present model

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