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A framework for the assessment and creation of subfilter-scale models for large-eddy simulation

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Abstract: Most practical turbulent flows cannot be computed directly from the Navier-Stokes equations, because not enough resolution is available to resolve all relevant scales of motion. We therefore turn to large-eddy simulation (LES), in which the large scales of motion in a flow are explicitly computed, whereas effects of small-scale motions have to be modeled. The question is how to model these effects. This question can partly be answered by looking at the wealth of existing turbulence (or subfilter-scale) models. The question remains, however, what defines a well-designed model. Some authors have therefore taken a systematic approach of finding constraints for the construction of subfilter-scale models, based on the idea that models should be consistent with important mathematical and physical properties of the Navier-Stokes equations and the turbulent stresses [1, 2, 4, 5] (also see our previous work [3]). With the current work we aim to consolidate this systematic approach and provide a framework for the assessment of existing and the creation of new subfilter-scale models for large-eddy simulation.

To that end, we discuss several fundamental properties of the Navier-Stokes equations and the turbulent stresses, such as symmetries [1], exact solutions, near-wall scaling behavior, realizability [5] and dissipation behavior [2, 4]. We then focus on the constraints that subfilter-scale models have to satisfy to preserve these properties. In this fashion, a framework consisting of model constraints arises, which can be used to perform a systematic analysis of existing subfilter-scale models. The results of this exercise are illustrated in Table 1, where it can be seen that existing subfilter-scale models do not satisfy all the desired properties. We subsequently show how this framework can be used to create new subfilter-scale models. An example of such a model, an eddy viscosity model that is based on the local velocity gradient [3], has been tested and shows promising results in simulations of decaying homogeneous isotropic turbulence (refer to Fig. 1). Ultimately, this work will lead to a better understanding of the desirable properties of subfilter-scale models and of the fundamental properties of turbulent flows.

References

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Note: This conference paper is followed up by a book chapter that appeared in *Progress in Turbulence VII: Proceedings of the iTi Conference in Turbulence 2016.* Ed. by Örlü, R., Talamelli, A., Oberlack, M., Peinke, J. Springer International Publishing, pp. 133–139 and can be found at http://dx.doi.org/10.1007/978-3-319-57934-4_19.

Table 1: Summary of the properties of several subfilter-scale models. The properties considered are S1–4: time, pressure, generalized Galilean, and rotation and reflection invariance; S5: scaling invariance; S6: two-dimensional material frame-indifference; S7: time reversal invariance; N: the proper near-wall scaling behavior; R: realizability; P1a: zero subfilter dissipation for laminar flow types; P1b: nonzero subfilter dissipation for nonlaminar flow types; P2a: zero subfilter dissipation for two-component flows; P2b: zero subfilter dissipation for the pure axisymmetric strain; P3: consistency with the second law of thermodynamics; P4: sufficient subfilter dissipation for scale separation. * The dynamic procedure may restore these properties [1]. † Result depending on the value of the model parameter or the implementation. Adapted from our previous work [3]

	S1–4	S5*	S6	S7*	N*	R	P1a	P1b	P2a	P2b	P3	P4
Smagorinsky	Y	N	Y	N	N		N	Y	N	N	Y	Y
WALE	Y	N	N	N	Y		N	Y	N	N	Y	Y
Vreman [4]	Y	N	N	N	N		N	Y	N	N	Y	Y
σ	Y	N	Y	N	Y		Y	N	Y	Y	Y	N
QR	Y	N	Y	N	N		Y	N	Y	N	Y	N
S3PQR	Y	N	Y†	N†	Y		Y†	Y†	Y†	N	Y†	Y†
AMD [2]	Y	N	Y	N	N		Y	N	Y	N	Y	Y
Gradient	Y	N	N	Y	N	Y	Y	N	Y	N	N	
EASSM	Y	N	N	N	N	Y	N	Y	N	N	Y	
Example [3]	Y	N	Y	N	Y		Y	N	Y	Y	Y	N

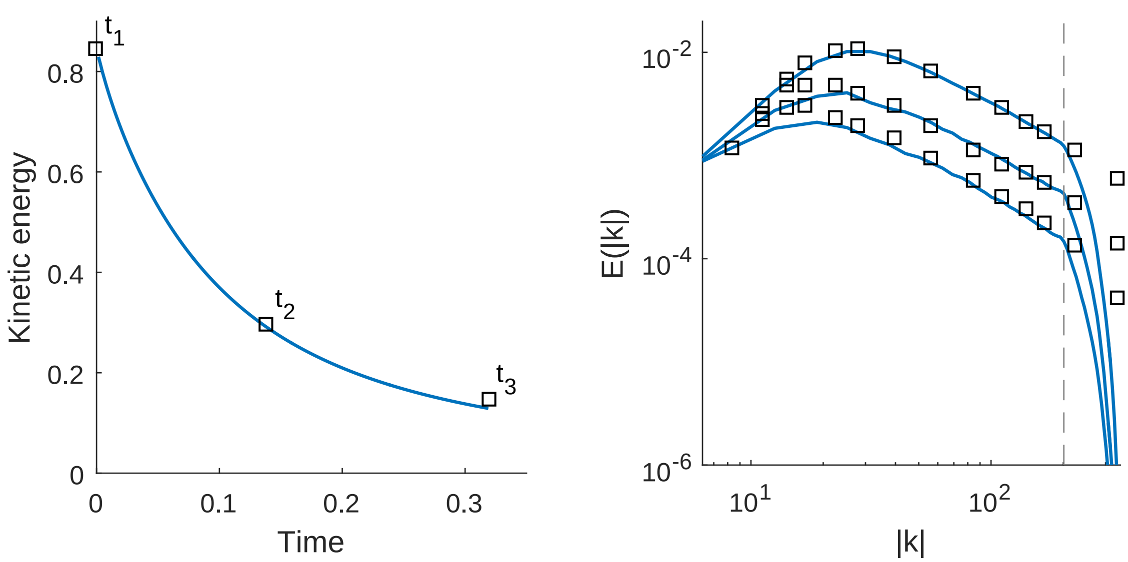

Figure 1: Results of a large-eddy simulation of decaying homogeneous isotropic turbulence using the example eddy viscosity model referred to in the text [3] on a 64^3 uniform Cartesian grid with periodic boundary conditions. Decay of the total kinetic energy of the flow (left). Energy spectra at three different time instances (right). Squares represent experimental data from the 1971 experiment by Comte-Bellot and Corrsin. The dashed line in the right figure indicates the grid cutoff (point-to-point oscillation).