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On the Characteristic Length Scale for the Synthetic Turbulence Based on the Spalart-Allmaras Model

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Abstract. In the hybrid RANS-LES simulations, proper turbulent fluctuations should be added at the RANS-to-LES interface to drive the numerical solution restoring to a physically resolved turbulence as rapidly as possible. Such turbulence generation methods mostly need to know the distribution of the characteristic length scale of the background RANS model, which is important for the recovery process. The approximation of the length scale for the Spalart-Allmaras (S-A) model is not a trivial issue since the model's one-equation nature. As a direct analogy, the approximations could be obtained from the definition of the Prandtl's mixing length. Moreover, this paper proposes a new algebraic expression to approximate the intrinsic length scale of the S-A model. The underlying transportation mechanism of S-A model are largely exploited in the derivation of this new expression. The new proposed expression is employed in the generation of synthetic turbulence to perform the hybrid RANS-LES simulation of canonical wall-bounded turbulent flows. The comparisons demonstrated the feasibility and improved performance of the new length scale on generating synthetic turbulence at the LES inlet.

AMS subject classifications: 76F40, 76F55, 76D99

Key words: Length scale, synthetic turbulence, hybrid RANS-LES, Spalart-Allmaras model.

1 Introduction

Hybrid Reynolds Averaged Navier-Stokes (RANS)-Large Eddy Simulation (LES) methods have been kept improving during the last decades. They have combined the high-efficiency of RANS method and the capability of LES method to resolve large scale turbulent structures. In the hybrid methods, LES is only employed in the region where the large scales need to be resolved, and RANS method is used to model the mean flow in the rest regions. There are many strategies to operate the hybridization in the literature.

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Frohlich and von Terzi [1] summarized the basic concepts, the classification and the limitations of the hybrid RANS-LES methods. When the hybrid methods are applied in a zonal/embedded way, there always exist some artificial interfaces between the regions of both methods. The coupling boundary conditions on such interfaces are important since the performance of the LES on the downstream of the interface would greatly depend on the features of upstream unsteady flows. Proper turbulent fluctuations should be added at the interface, otherwise there would exist a large adaptation region contained in the LES region for building a physically resolved turbulence. An oversized adaptation region can degrade the accuracy of the solution in the whole downstream LES region.

The RANS methods based on the statistical averaging of the Navier-Stokes (N-S) equations only solve the mean flow and compute the influence of the turbulence statistics by semi-empirical models. The approximated mean flow and low-order statistics can be used to synthesize the turbulent fluctuations for the LES inlet. A common fundamental principle for synthesizing the fluctuations is that the statistical information based on the RANS results must approximate the real physical turbulence as close as possible. The statistical information given by RANS can be employed through various methods such as the synthetic turbulence generator (STG) [2,3], the synthetic eddy method (SEM) [4,5], the synthetic Fourier modes methods [6,7] and the dynamic forcing method [8]. Comprehensive reviews have been given by Tabor and Baba-Ahmadi [9], Dhamankar et al. [10], and Wu [11].

Recently, Probst et al. [12] evaluated the performances of SEM and STG as the grey area mitigation tools in the wall-bounded turbulent flow with mild separation. It is shown that such synthetic fluctuations are indeed helpful for improving the accuracy of the hybrid RANS-LES computation. Patterson et al. [13] studied the bias and temporal convergence errors of STG when used to generate the inflow of direct numerical simulation (DNS). An explicit method to measure these errors introduced by the random number arrays is developed, which can be employed to obtain an optimized selection of the random numbers with minimized errors. Generally, the basic input for this kind of methods are the limited statistical information obtained from the RANS computation. To this end, the two-equation RANS models are naturally superior to the one-equation RANS models since they contain the modeling for the independent transportations of two characteristic scales, which allows approximating the second-order statistics without any ambiguity. But for the one-equation RANS models, only one single transport equation is directly solved for representing one characteristic scale. Thus, the proper approximation of the second-order statistics relies on supplementing proper algebraic expression for the other characteristic scale (usually the characteristic length scale). Hence, it is not straightforward to use the one-equation models in cooperation with the SEM or the STG. Indeed, we can find that the background RANS models in the literatures are mostly the two-equation models [2–5].

In the community of aerospace engineering, the one-equation model proposed by Spalart and Allmaras [14], referred as S-A model hereafter, has been one of the most successful turbulence models in the last decades. Therefore, there exists a strong potential