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Improved version of LeMoS hybrid model for ambiguous grid densities

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Abstract

Application of the LeMoS hybrid (LH) URANS/LES method for the wake parameters prediction is considered. The wake fraction coefficient is calculated for inland ship model M1926 under shallow water conditions and compared to results of PIV measurements. It was shown that due to lack of the resolved turbulence at the interface between LES and RANS zones the artificial grid induced separations can occur. In order to overcome this drawback, a shielding function is introduced into LH model. The new version of the model is compared to the original one, RANS $k-\omega$ SST and SST-IDDES models. It is demonstrated that the proposed modification is robust and capable of wake prediction with satisfactory accuracy.

Keywords: Hybrid RANS/LES; Shallow water; Wake prediction; Wake unsteadiness

1. Introduction

Scale resolving computational fluid dynamics (CFD) methods are becoming a useful tool for solution of practical ship hydrodynamics and ocean engineering problems. They are necessary for prediction of flow induced unsteady effects such as unsteady loads on propellers, vibrations in the ship stern area, oscillations of different devices in cross flows with massive separations, etc. Large eddy simulation (LES) is the most advanced approach among all scale resolving methods. However, its application for high Reynolds numbers, which are typical for practical problems, faces severe limitations due to a very fine temporal and spatial resolution, needed for proper simulation of thin boundary layers. The hybrid methods based on the combination of URANS (Unsteady Reynolds Averaged Navier Stokes Equations) and LES is a feasible alternative to LES for flows at high Reynolds numbers. According to the idea of the hybrid methods, the boundary layer region is treated using URANS whereas the flow far from wall is calculated using LES. Both solutions should be matched at the interface. A proper transition of the solution from the URANS zone with weak oscillations to highly unsteady LES zone (taking place in so-called "grey area") is still remaining a challenge. There are a few ways of approaching this issue. The first one is to apply some kind of forcing momentum source terms at the RANS/LES interface Piomelli et al. (2003); Davidson and Billson (2006), which will compensate the lack of momentum transport between the regions Rajamani and Kim (2010). The second way is the introduction of shielding functions of phenomenological nature, which do not combat the source of the problem, but allow for suppression of undesired effects, caused by the "grey area" such as grid induced separation Spalart et al. (2006). Yet another alternative is to use explicit averaging procedure (in time or in homogeneous directions) in order to determine the actual level of resolved turbulent stresses and adapt the RANS/LES zones accordingly (see, for example, Bhushan and Walters (2012), Kniesner et al. (2007)). To authors knowledge this procedure is not widely used because of the complexity of explicit averaging operations for practical applications.

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A few years ago we proposed a hybrid model, referred further to as LeMoS[1] Hybrid (LH) Kornev et al. (2011). It is similar to SST-DES Strelets (2001): both methods use SST model on the RANS branch, in both of them the interface is not prescribed and is instead determined dynamically, depending on the integral length scale and local cell size. However, there are some significant differences. The first of them is the way, how the models switch between RANS and LES modes. In the SST-DES the destruction term in k equation is changed accordingly, whereas the LH swaps the definitions of the turbulent viscosity. The second distinction is the behaviour of the models in the LES mode. SST-DES, analogously to original SA-DES Spalart et al. (1997), turns into the constant coefficient Smagorinsky SGS model at a distance from the wall. On the contrary, LH utilizes the dynamic procedure for the determination of the constant on the LES branch.

The approach mentioned above was implemented in OpenFOAM® CFD package Weller et al. (1998) and successfully validated for various naval hydrodynamics applications Abbas et al. (2015); Abbas and Kornev (2016a, b). During the recent CFD workshop on ship hydrodynamics in Tokyo the results obtained using LH method for the turbulence kinetic energy behind the JBC ship benchmark test case Kornev and Abbas (2017) were among the best ones. One of the important peculiarities of the simulations Abbas et al. (2015); Abbas and Kornev (2016a, b) and Kornev and Abbas (2017) is that they were performed on block structured grids with moderate cell numbers, where the DES applicability constraint ($\Delta x/\delta > 1$) was satisfied. However, as shown below, the performance of the LH model worsened when grids with local refinements were used. When $\Delta x/\delta$ was less than or equal to unity the model performance deteriorated. The aim of this paper is to present the modification of the LH model, which is also applicable on the ambiguous grids Spalart et al. (2006), and to compare its performance to other models.

2. Formulation of the LH model

The momentum equations written in terms of URANS and LES formulations can be represented in a general form:

$$\frac{\partial \overline{u}_i}{\partial t} + \overline{u}_j \frac{\partial \overline{u}_i}{\partial x_j} + \frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \tau^h_{ij}\right] + \overline{f}_i. \tag{1}$$

where u_i is the velocity component, p is pressure, ρ is density, ν is the kinematic viscosity and f_i is the source term. For LES the overline means the filtering and the turbulent stress is the sugrid-scale stress $\tau^h_{ij} = \tau^{SGS}_{ij}(\Delta, \overline{u}_i, C)$, where Δ is the characteristic cell size and C is a model constant. For URANS the overline stands for the time averaging and the turbulent stress is the Reynolds stress $\tau^h_{ij} = \tau^{RANS}_{ij}(\overline{u}_i, k, \varepsilon, C)$, where k is the turbulence kinetic energy, ε is the dissipation rate and C is a set of model constants. Although this similarity is purely formal, this form is very convenient for implementation, allowing one to easily blend URANS and LES approaches by changing the τ^h_{ij}. Eq. (1) is accompanied by the continuity constraint.

Introducing a blending function $f(\mathbf{x}, t) \in [0, 1]$ which is 1 in the RANS region and 0 in the LES one, the blended (hybrid) stress τ^h_{ij} can be represented as a weighted sum of the RANS and LES components:

$$\tau^h_{ij} = f\tau^{RANS}_{ij} + (1-f)\tau^{SGS}_{ij} \tag{2}$$

Solution of (1) with corresponding hybrid stresses provides a velocity field which is continuous over the whole computational domain. The choice of f is the main challenge in the construction of a robust hybrid method. If the blending function is rapidly changed from 1 to 0, so that the region, where $0 < f < 1$ is thin, the hybridization strategy is called RANS/LES interfacing. If $f = f(\mathbf{x})$, then the interface region is prescribed and called "hard". On the contrary, if the interface dynamically changes its position in time depending on the solution, i.e. $f = f(\mathbf{x}, t)$, then the interface is "soft" Fröhlich and von Terzi (2008), Sagaut et al. (2013). Blending of the RANS and LES models, which both use the eddy viscosity concept (e.g. $k-\omega$ SST model with dynamic Smagorinsky model) is done through the viscosity instead of the stress itself:

$$\begin{aligned}\tau^h_{ij} &= -2\left(f\nu_t\overline{S}_{ij} + (1-f)\nu_{sgs}\overline{S}_{ij}\right) = -2\left(f\nu_t + (1-f)\nu_{sgs}\right)\overline{S}_{ij} \\ &= -2\nu_h\overline{S}_{ij}\end{aligned} \tag{3}$$

with $\overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$ being a strain-rate tensor.

In the LH model computational domain is dynamically decomposed into RANS and LES regions based on the ratio

$$h = h(\mathbf{x}, t) = L(\mathbf{x}, t)/\Delta(\mathbf{x}) \tag{4}$$

where L is the integral length scale, $\Delta = \sqrt{0.5(\Delta^2_{max} + V^{2/3})}$ is the characteristic cell size, $\Delta_{\max} = \max(\Delta x, \Delta y, \Delta z)$ − maximum cell edge length, V − cell volume. The hybrid viscosity is represented as a weighted sum of kinematic turbulent viscosity and subgrid scale viscosity:

$$\nu_h = f\nu_t + (1-f)\nu_{sgs}. \tag{5}$$

The blending function $f = f(\mathbf{x}, t)$ reads:

$$f = \begin{cases} 0, & h > h_2 \\ 1, & h < h_1 \\ \gamma(h), & h_1 \le h \le h_2 \end{cases} \tag{6}$$

$$\gamma(h) = \frac{1}{2} + \frac{1}{\pi}\arctan\left(40\frac{h_1 - h}{(h_2 - h_1)^2} + 10\frac{h_2 + h_1}{h_2 - h_1}\right),$$

where $\gamma(h)$ is an empiric function and h_1 and h_2 are the parameters of the blending function. If a cell has $h > h_2$, the cell

[1] Lehrstuhl fuer Modellierung und Simulation (in German) or Chair of modeling and simulation (in Engl.).

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