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Evaluation of hybrid RANS/LES models for prediction of flow around surface combatant and Suboff geometries

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ABSTRACT

Predictive capabilities of hybrid RANS/LES models are compared for single-phase flow over a surface combatant at $Re = 5.3 \times 10^6$ and an appended DARPA Suboff model at $Re = 1.2 \times 10^7$. The turbulence models used in the study are: k–ω shear stress transport (SST)-URANS; Spalart Allmaras based detached eddy simulation (SA-DDES); k–ω based improved delayed detached eddy simulation (KW-IDDES); and a dynamic hybrid RANS/LES (DHRL) model coupling SST and implicit LES. For the surface combatant case, both SA-DDES and KW-IDDES predicted <1% resolved turbulence, whereas DHRL predicted up to 70% resolved turbulence. The SST-URANS, SA-DDES, KW-IDDES and DHRL predictions compared within 4.23%, 4.14%, 5.88% and 3.88% of the experimental data, respectively. For the Suboff case, both the SA-DDES and KW-IDDES predicted only limited resolved turbulence in the sail wake and downstream of the fins, whereas DHRL predicted resolved turbulence levels comparable to LES. The averaged error for the mean velocity profile at propeller plane for SST-URANS, SA-DDES, KW-IDDES and DHRL predictions was 6.4%, 8.9%, 13.1% and 3.0%, respectively. The corresponding errors for the turbulence variables were 44%, 70%, >100% and 28%, respectively. Overall, the DHRL model performed best among the turbulence models tested, and KW-IDDES performed worst. The study indicates that the DHRL approach has the potential to provide accurate mean flow predictions while resolving small-scale turbulent structures. Results also highlight the importance of the wall function formulation for accurately resolving mean skin friction coefficient, especially over smooth regions of the hull.

1. Introduction

Recent advances in high performance computing now enable highly resolved computational fluid dynamics (CFD) predictions for ship hydrodynamics applications. The largest grid used in the CFD workshop for ship hydrodynamics in Tokyo in 2005 [1] was around 5 million grid points, whereas in the latest workshop in Gothenburg in 2010 [2] there were several submissions using 100s of millions of grid points. Large grid computations are important for ship hydrodynamics, as it involves high Reynolds numbers (Re) of the order of 10^6 for model-scale and 10^9 for full-scale, and is characterized by a wide spectrum of turbulent scales [3,4]. In addition, to make the best use of high-resolution computational capabilities, advanced turbulence modeling such as Large Eddy Simulation (LES) or hybrid Reynolds Averaged Navier–Stokes (RANS)/LES (HRL) is required. Furthermore, RANS or unsteady RANS (URANS) approaches resolve only the large-scale mean motions, and depend heavily on turbulence modeling, while LES or HRL approaches have the ability to resolve a portion of the turbulence scales, and modeling is applied only for the unresolved portion of the turbulence spectrum. Unresolved (subgrid) turbulence scales are expected to be nearly isotropic in nature, therefore LES modeling is expected to be more consistently accurate and generally applicable compared to RANS.

Fureby et al. [5,6] reviewed some important aspects of LES as applied to engineering flows, which included simulation over the DARPA Suboff model at straight ahead and static drift conditions using up to 10 M grid points. They also submitted LES results to the Gothenburg 2010 CFD workshop for flow over a straight ahead surface combatant (5415) using a 70 M grid. The results demonstrated the ability of LES to accurately predict the largest unsteady flow structures. They concluded that for LES the subgrid model is less important than the grid resolution and the near-wall flow modeling. The latter is especially critical for LES, since the resolution of the inner boundary layer is very expensive, requiring $\sim Re^{1.8}$ points or 10^{11} and 10^{16} points for model and full scale, respectively [7]. Fureby et al. [5,6] used a wall-model to bypass the solution in the inner boundary layer, but recognized that an explicit wall treatment cannot accurately depict the boundary-layer separation or the turbulence triggers. They concluded that modeling efforts

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should focus on development and assessment of wall-modeled LES or HRL models.

HRL computations for ship hydrodynamics have been performed using detached eddy simulation (DES) for Athena, surface combatant 5415 and container KVLCC2 geometries on meshes containing up to 300 M grid points [4,8,9]. The DES model showed improved resistance and mean vortex prediction compared to URANS, but performed poorly for the prediction of resolved turbulence structures. The poor turbulence predictions were due to the activation of LES in the lower log-layer, which led to grid induced separation and modeled-stress depletion in the boundary layer, and over-prediction of the wake and turbulent stresses in the free-shear region. The modeled stress depletion issue was extreme for slender bodies, such as surface combatant 5415, for which the resolved turbulence was not triggered at all. The delayed DES (DDES) model helped in alleviating the grid induced separation issue, but did not address issues in the free shear and wake regions.

Grid induced separation and modeled stress depletion issues are common for DES models, as reported in several studies in the literature, e.g., for wing-body junction flows [10] and shock wave/turbulent boundary layer interaction [11]. They are caused by the activation of LES in the attached boundary layer region where resolved turbulent fluctuations are absent or minimal, and are insufficient to match the RANS stresses. Thus on the LES side of the RANS/LES interface, the turbulent eddy viscosity is under predicted resulting in lower turbulent stresses (or model stress depletion).This results in near-laminar flow in the LES region, i.e., negligible turbulent viscosity and resolved turbulence, causing a low momentum flow over the high momentum URANS flow. This makes the boundary layer flow more susceptible to separation under adverse pressure gradients, especially in the LES region. It also leads to the characteristic log-layer mismatch for hybrid models, due to the fact that the total Reynolds stress (modeled plus resolved) is under predicted in that part of the boundary layer in which the model changes from RANS to LES behavior.

The DDES approach is expected to mitigate modeled-stress depletion and grid induced separation by delaying the RANS to LES transition in the model [12]. Improved DDES (IDDES) may further help in addressing the issue, as it increases the modeled stress contribution across the interface [13]. However, it does not address the underlying cause, which is the activation of LES in regions without background resolved turbulence. The poor prediction by DES models in free-shear layer regions could also be due to the inaccuracy of the model formulation in the pure LES mode, which is seldom validated as pointed out by Sagaut and Deck [14].

Overall, the modeling issues in DES can be summarized as being due to the use of: (1) predefined grid scale metrics to identify the transition region between URANS and LES; and (2) a single model stress term in both URANS and LES regions to represent two quantities (Reynolds stress and subgrid stress) that are mathematically and physically distinct. These issues can be addressed by implementing physics based RANS/LES transition modeling [15,16], along with coupling of a RANS model with a well validated LES model such as the Dynamic Smagorinsky model [17]. Bhushan and Walters [18] have recently developed such an approach—referred to as dynamic HRL (DHRL) modeling—that has shown encouraging results in addressing the limitations of the DES approach [19].

The objective of this study is to evaluate the predictive capability of currently available hybrid RANS/LES turbulence models and the recently developed DHRL model for ship hydrodynamics applications. To achieve the objective, the DHRL model was first extended to include wall functions. The DHRL model with wall functions was implemented in ANSYS/Fluent using User-Defined Function subroutines, validated for turbulent channel flow, and applied to single-phase flow over surface combatant 5415 at $Re = 5.3 \times 10^6$ and the DARPA Suboff geometry appended with sail and fins at $Re = 1.2 \times 10^7$. Scalability, grid verification and y^+ sensitivity studies were performed as precursors to the ship flow simulations.

2. Computational methods

The governing equations for ship hydrodynamics simulations are the incompressible Navier–Stokes equations. Turbulence simulations typically assume decomposition of the instantaneous velocity (u_i) into resolved ($\hat{u}_i$) and modeled (u_i') components using a suitable filter, i.e.,

$$u_i = \hat{u}_i + u_i' \tag{1}$$

Applying the filtering operation to the Navier–Stokes equations yields,

$$\frac{\partial \hat{u}_i}{\partial x_i} = 0$$

$$\frac{\partial \hat{u}_i}{\partial t} + \left(\hat{u}_j \frac{\partial \hat{u}_i}{\partial x_j}\right) = -\frac{1}{\rho}\frac{\partial \hat{p}}{\partial x_i} + \nu \frac{\partial^2 \hat{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

The last term on the right-hand side includes the turbulent stress due to velocity correlations:

$$\tau_{ij} = \widehat{u_i u_j} - \hat{u}_i \hat{u}_j \tag{3}$$

The closure of the above governing equations requires modeling of the turbulent stress tensor.

2.1. Solution algorithm

All simulations presented here were performed using the commercial flow solver ANSYS/Fluent® version 14.0 [20]. Fluent is a finite volume solver which provides a suite of numerical schemes and transition and turbulence modeling options. Herein, transient simulations were performed using the pressure-based solver option, which is the typical predictor–corrector method with solution of pressure via a Poisson equation to satisfy mass conservation. Pressure–velocity coupling was performed using the PISO scheme [21]. The convective terms in the momentum equations were discretized using the Bounded Central Difference (BCD) scheme, a low-dissipation scheme recommended for LES and hybrid model simulations. The URANS turbulence equations were discretized using the 2nd order upwind scheme. Unsteady terms were discretized using a 2nd order implicit (three-point backward difference) scheme. The time-step size for the simulations was chosen such that the convective CFL number is approximately one, based on the freestream velocity and the streamwise grid spacing in the near-wall region.

2.2. Turbulence models

URANS simulations were performed using the k–ω SST model [22]. Hybrid RANS-LES (HRL) simulations were performed using: the delayed DES (SA-DDES) model [23] based on the one-equation Spalart–Allmaras RANS model [24]; improved DDES model based on the k–ω SST RANS model (KW-IDDES) [13]; and the newly developed DHRL model [18]. The k–ω SST, SA-DDES and KW-IDDES models are available in the Fluent solver and have been well validated. The DHRL model was previously implemented into the Fluent solver by the authors, coupling SST-URANS and monotonically integrated large-eddy simulation (MILES) using available User-Defined Function (UDF) subroutines. Readers are referred to Bhushan and Walters [18] for a more detailed description of the DHRL