Ocean Engineering 129 (2017) 133–148

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Verification and Validation exercises for the flow around the KVLCC2 tanker at model and full-scale Reynolds numbers

F.S. Pereira[a,b,*], L. Eça[b], G. Vaz[c]

[a] Maritime Research Institute Netherlands Academy, 2 Haagsteeg, 6708 PM Wageningen, The Netherlands
[b] Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal
[c] Maritime Research Institute Netherlands, 2 Haagsteeg, 6708 PM Wageningen, The Netherlands

ARTICLE INFO

Keywords:
Modelling error
Numerical error
Turbulence modelling
RANS
KVLCC2

ABSTRACT

This paper presents the quantification of numerical and modelling errors for the solution of the flow around the KVLCC2 tanker at model-scale Reynolds number. Numerical errors are also quantified for full-scale Reynolds number simulations to address the numerical accuracy of the prediction of scale-effects. The calculations are performed with the solver ReFRESCO using fourteen distinct Reynolds-Averaged Navier-Stokes (RANS) equations models. The quantities of interest for the Validation exercises at model-scale are the resistance coefficient and the velocity and turbulence kinetic energy fields at the propeller plane. Modelling errors are estimated using the ASME V & $2V20 procedure which requires numerical and experimental data with their respective uncertainties. Numerical uncertainties are dominated by the contribution of the discretization error, which is determined by grid refinement studies. Scale-effects are also assessed for the wake-fraction and form-factor.

The outcome shows that quantifying modelling errors is not a trivial exercise that depends on the quality and details of simulations and experiments. Nonetheless, it is also evident that a quantitative evaluation of modelling errors is more reliable than traditional graphical comparisons of simulations and experiments. Full-scale results show scale-effects larger than numerical uncertainties that are illustrated for the form-factor and wake-fraction.

1. Introduction

Computational Fluid Dynamics (CFD) has become an integral part of the design process of many engineering applications including ship hydrodynamics. Its ability to give detailed information of the flow field at a much faster turnaround time and cheaper cost than Experimental Fluid Dynamics (EFD) made CFD a valuable complement to the traditional model testing. Nonetheless, as for EFD, the credibility of CFD simulations requires the assessment of the modelling (facility quality in EFD) and numerical (measuring instruments quality in EFD) uncertainties to avoid the risk of taking erroneous conclusions.

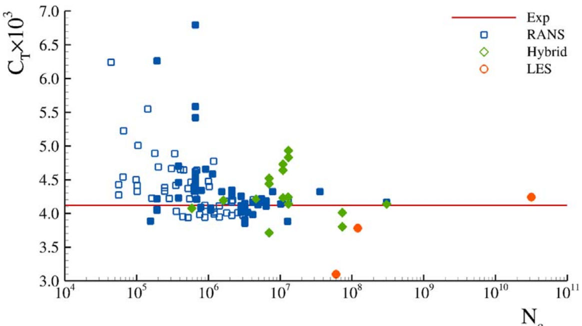
Flows around ships are governed by mass and momentum conservation that are expressed in the incompressible continuity and Navier-Stokes equations. However, ship flows occur at high Reynolds numbers which means turbulent flows exhibiting a wide range of spatial and temporal scales. In such conditions, the direct solution of the Navier-Stokes is not feasible and so alternative mathematical models must be applied in practice.

Nowadays, Scale-Resolving Simulation (SRS) models, as for example Spalart et al. (1997) or Girimaji (2005), are able to solve directly part of the turbulence field, reducing the extra modelling to the smallest scales that tend to be easier to model (isotropic). However, its application to wall bounded flows is substantially more demanding than the Reynolds-Averaged Navier-Stokes (RANS) equations, which are still the most common mathematical model for engineering applications (Larsson et al., 2013; National Maritime Research Institute, 2015). Furthermore, for ships with no drift angle, time-averaged RANS should be able to accurately predict the mean flow field and force coefficients. However, the modelling accuracy of RANS is strongly dependent on the selected turbulence model that provides the

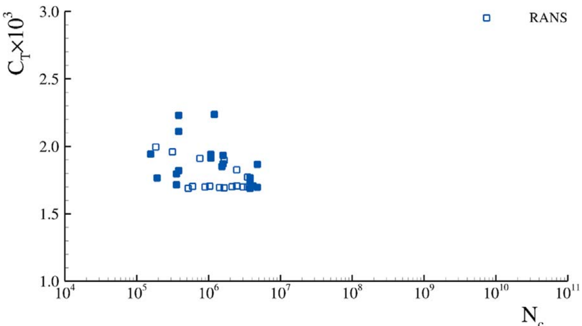
Abbreviations: ASME, American Society of Mechanical Engineers; BSL, Baseline; CFD, Computational Fluid Dynamics; DES, Detached-Eddy Simulation; EARSM, Explicit Algebraic Reynolds-Stresses Model; EFD, Experimental Fluid Dynamics; ITTC, International Towing Tank Conference; KRISO, Korea Research Institute of Ships and Ocean; KVLCC2, KRISO Very Large Crude Carrier 2; LES, Large-Eddy Simulation; MARIN, Maritime Research Institute Netherlands; RANS, Reynolds-Averaged Navier-Stokes equations; ReFRESCO, Reliable and Fast RANS Equations solver for Ships and Construction Offshore; SRS, Scale-Resolving Simulation; SST, Shear-Stress Transport; TNT, Turbulent Non-Turbulent

* Corresponding author at: Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal.
E-mail addresses: filipemsoares@ist.utl.pt (F.S. Pereira), luis.eca@ist.utl.pt (L. Eça), g.vaz@marin.nl (G. Vaz).

http://dx.doi.org/10.1016/j.oceaneng.2016.11.005
Received 3 August 2016; Received in revised form 1 October 2016; Accepted 12 November 2016



(a) Model-scale.



(b) Full-scale.

Fig. 1. Results available in the open scientific literature (Abdel-Maksoud et al., 2000; Beddhu et al., 2000; Chou et al., 2000; Deng and Visonneau, 2000; Hoekstra et al., 2000; Kim, 2000; Kim and Van, 2000; Rhee and Hino, 2000; Svennberg, 2000; Guo and Steen, 2010; Kim et al., 2010; Martio et al., 2010; Schneider, 2010; Xing et al., 2010; Yu et al., 2010; VIRTUE – The Virtual Tank Utility in Europe, 2007a, 2007b; Toxopeus, 2011; Nishikawa et al., 2012, 2013; Abbas et al., 2013; Toxopeus et al., 2014) for the viscous resistance coefficient C_T at model (4.60×10^6) and full-scale (2.03×10^9) Reynolds numbers as a function of the number of grid cells N_c and mathematical model: RANS, Hybrid and LES. Filled symbols represent the best solution obtained in each reference (finest spatial resolution or highest-order convection scheme). Experimental measurement taken from Kim et al. (2001) (estimated experimental uncertainty is 1%).

values of the Reynolds stresses produced by the averaging process. Therefore, the turbulence model is the main source of modelling errors in the solution of the RANS equations for the type of flows addressed in this work.

On the other hand, simulation of ship flows based on the RANS equations requires numerical solutions, which are affected by discretization, iterative and round-off errors (Roache, 1998, 2009; Oberkampf and Roy, 2010; The American Society of Mechanical Engineers, 2009). Therefore, numerical uncertainties must be assessed to properly quantify modelling errors (Roache, 1998, 2009; Oberkampf and Roy, 2010; The American Society of Mechanical Engineers, 2009).

In order to illustrate the relevance of modelling and numerical errors on ship hydrodynamics simulations, a numerical literature review has been performed for a representative and widely studied crude tanker: the KRISO Very Large Crude Carrier 2 (KVLCC2). Fig. 1 depicts the resistance coefficient C_T from 160 results published in the open literature for model (4.60×10^6) and full-scale (2.03×10^9) Reynolds numbers. The data is presented as a function of the mathematical model and number of grid cells. Three groups of mathematical models are considered: RANS with several turbulence models ($k-\omega$, $k-\epsilon$, …), Hybrid models (Detached Eddy Simulation, DES) and Large-Eddy Simulation (LES). In the plot, no distinction is made between domain sizes, grid topologies, turbulence models and boundary conditions, i.e. free surface effects[1] and the use of wall functions (common at full-scale Reynolds numbers). The results are collected from the Gothenburg workshops of Abdel-Maksoud et al. (2000), Beddhu et al. (2000), Chou et al. (2000), Deng and Visonneau (2000), Hoekstra et al. (2000), Kim (2000), Kim and Van (2000), Rhee and Hino (2000), Svennberg (2000) and Guo and Steen (2010), Kim et al. (2010), Martio et al. (2010), Schneider (2010), Xing et al. (2010), Yu et al. (2010), the EU cooperative project Virtue workshops of VIRTUE – The Virtual Tank Utility in Europe (2007a), VIRTUE – The Virtual Tank Utility in Europe (2007b) and some additional studies (Toxopeus, 2011; Nishikawa et al., 2012, 2013; Abbas et al., 2013; Toxopeus et al., 2014). The largest dispersion of C_T values at model-scale is observed for grids with less than one million cells, which suggests a significant influence of discretization errors. For such range of grid resolutions the difference between experiments and simulations (comparison error E_{C_T}) may reach 70%. For grids with more than two million cells[2] the average E_{C_T} obtained from RANS simulations is −0.6% of the experimental value, but the standard deviation is 3.7%, which is more than the desirable 1% accuracy in the prediction of C_T. On the other hand, Hybrid models results do not show any improvement in the standard deviation of E_{C_T}, which is 9% for grids with more than two million cells and the range of values obtained for the three LES solutions exhibits a difference in the predicted C_T of 28%. A similar dispersion of data is also observed in the full-scale results that are depicted in Fig. 1b. This scenario raises a legitimate question: is this spread of data a consequence of modelling errors (turbulence models) or numerical errors (or both)?

The only way to answer this question is to apply available procedures (The American Society of Mechanical Engineers, 2009, 2016) to estimate the modelling error, which require the knowledge of the experimental and numerical uncertainties. To this end, this work presents the quantification of numerical and modelling errors for the flow around the same KVLCC2 tanker at model-scale Reynolds number, i.e. Solution Verification and Validation exercises. On the other hand, numerical errors are quantified for full-scale simulations to address the numerical accuracy of the prediction of scale-effects. Numerical uncertainties are estimated for all flow conditions using grid refinement studies (Eça and Hoekstra, 2014), whereas modelling errors are quantified for the model-scale simulations using the ASME V & $2V20 procedures (The American Society of Mechanical Engineers, 2009, 2016) and the experimental data of Kim et al. (2001) and Lee et al. (2003). The calculations are carried out with the solver ReFRESCO (ReFRESCO, 2016) using fourteen distinct RANS turbulence models:

- Spalart and Allmaras (1992);
- Menter (1997);
- $\sqrt{k}L$ Menter et al. (2006);
- Low-Reynolds $k-\epsilon$ Abe et al. (1994);
- $k-\omega$ Wilcox (1988) and Wilcox (1998) versions;
- $k-\omega$ Turbulent Non-Turbulent (TNT) Kok (2000);
- $k-\omega$ BaSeLine (BSL) Menter (1994);
- $k-\omega$ Shear-Stress Transport (SST) Menter (1994, 2003) versions;
- $k-\sqrt{k}L$ Menter et al. (2006);
- $k-\omega$ BSL Explicit Algebraic Reynolds-Stresses Model (EARSM) Hellsten (2005) (two versions).
- $k-\omega$ TNT EARSM Dol et al. (2002).

The first eleven models are isotropic eddy-viscosity models, while the last three models consider the anisotropy of the Reynolds stresses. Although there are some reviews and studies addressing the role of turbulence modelling and numerical errors for the present test-case (see for instance Larsson et al., 2013; Toxopeus et al., 2013; Guo et al., 2013), the present work compares the former fourteen models under

[1] It must be mentioned that most of the data correspond to simulations neglecting free-surface effects.

[2] Using only the best results of each reference, the average E_{C_T} obtained from RANS simulations is 0.01% and the standard deviation is 3.2%