URANS and Hybrid RANS-LES Simulations of the Flow around a Surface Combatant at 10° Static Drift

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1 Introduction

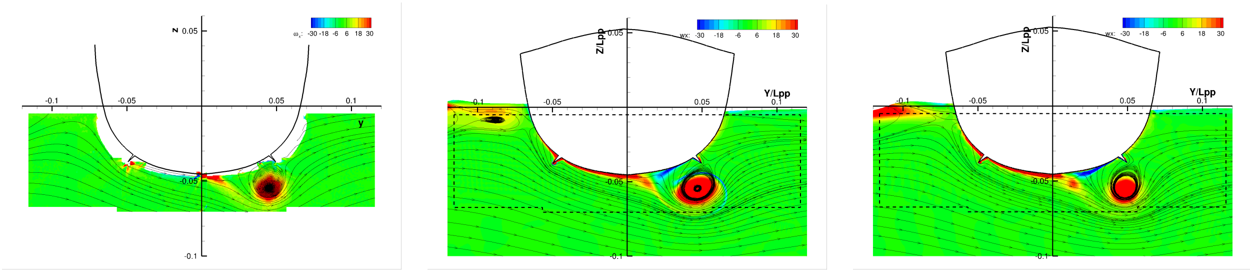
Although ships and submarines are designed to develop attached flow at cruise conditions, they also routinely develop separated flows within their broader operating envelope, such as at maneuver conditions, and occasionally even at cruise. Separated flow effects cause cruise performance penalties, and can often restrict vehicle operating conditions due to such matters as stability and control since propellers and control surfaces operate in a flow field dominated by coherent vortical structures. In previous workshops on numerical ship hydrodynamics Gothenburg 2010 [2] (G2010) and Tokyo 2015 (T2015) or research collaborative studies like NATO/AVT183 and NATO/AVT253 ([3] for IIHR experiments), it was established that the turbulence modelling error was the predominant source of inaccuracy with linear isotropic turbulence models while the use of anisotropic turbulence models like Explicit Algebraic Reynolds Stress (EARSM) or Full Reynolds Stress Transport models might lead to slightly better agreement with the measurements when the flow is not strongly unsteady. However, either for the Japanese Bulk Carrier (JBC) studied during T2015 or for the DTMB5415 studied in NATO/AVT-183 and NATO/AVT-253, it was noticed that the computations failed to reproduce saliant flow characteristics like computed levels of turbulent kinetic energy in the core of the averaged longitudinal vortices four to five times too small than what was measured. The same issue was observed on very different ships (JBC and DTMB5415) for different types of open separation (bilge or sonar dome vortices). This intriguing fact motivated the authors to look deeper into the physical mechanisms characterising the open separation occuring around ship hulls.
The geometry chosen in this paper is the US Navy frigate DTMB5415, Figure 1, a 1:46.6 scale, with a length between perpendiculars L = 3.048 m. The model is un-appended except for port and starboard bilge keels, i.e. not equiped with shafts, struts, propulsors or rudders. The Reynolds number, based on the length L and the velocity U = 1.531 m/s, is Re = 4.65×10^6 and the Froude number is Fr = 0.28. The computational grid, which contains 162.6 million cells, has a wall normal resolution $y^+ \leq 0.2$.

Figure 1: Photographs of DTMB model 5415. The top view highlights the bilge keels.

Simulations are performed with the ISIS-CFD (aka FINE/Marine) unstructured face-based finite-volume solver developed in our group [1]. This second order accurate solver uses a free-surface capturing approach to compute the flow both in air and water with dedicated compressive discretization schemes. Turbulence is modelled with the Menter k-ω SST model, EARSM or variants of hybrid RANSE-LES approaches (DES-SST, IDDES).

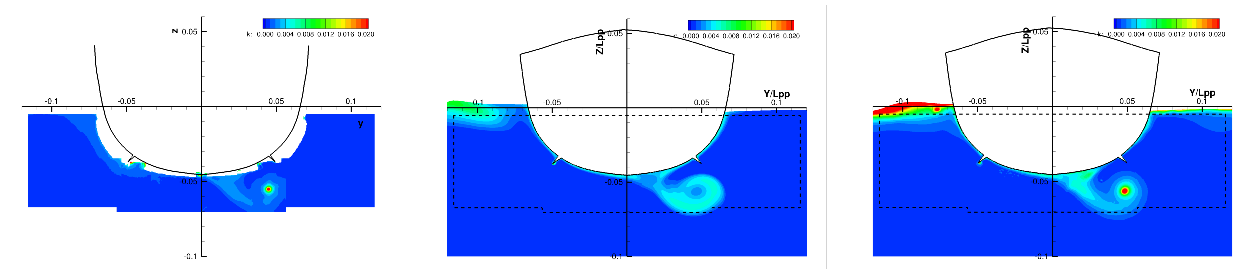
2 Results

The local flow measurements performed by IIHR ([3]) provide very accurate and rich tomographic PIV (TPIV) information at several stations and, in particular, in the close vicinity of the sonar dome of the surface combatant DTMB 5415. They offer a unique opportunity to understand the local characteristics of a turbulent open separation and identify what is missing in the statistical turbulence models to explain the differences between the measurements and computational models. Figures 2 and 3 show comparisons of planar cuts, at X/L = 0.4, between IIHR experiments and numerical results for the longitudinal vorticity and the turbulence kinetic energy, respectively. On this global view, the agreement between computations and experiments appears quite satisfactory for the longitudinal vorticity whatever turbulence closure used. However, k-ω SST fails to reproduce the high level of tke in the core of the vortex observed in the experiments while DES-SST captures accurately this flow characteristic.



(a) Experiments (b) k-ω SST (c) DES-SST

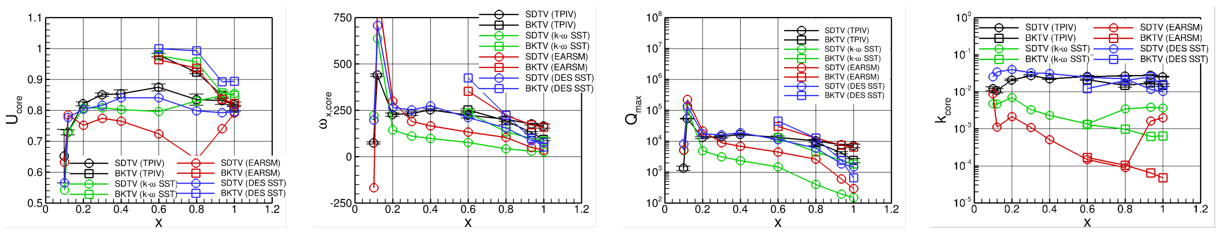
Figure 2: Comparison of the longitudinal vorticity, ω_x, at X/L = 0.4.



(a) Experiments (b) k-ω SST (c) DES-SST

Figure 3: Comparison of the turbulent kinetic energy, k, at X/L = 0.4.

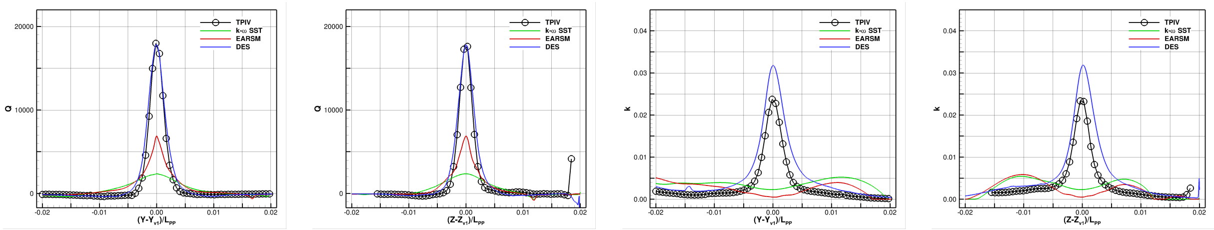
Figure 4 provides a comparison between the IIHR measurements and the numerical results of vortex core variables along the core of the sonar dome tip vortex (SDTV) and the bilge keel tip vortex (BKTV). Large differences between the turbulence modelling approaches can be observed on the prediction of the second invariant Q but the most striking difference between the statistical and hybrid RANS-LES turbulence models is provided by the comparison on the longitudinal evolution of the turbulence kinetic energy at the core of the vortices. DES-SST is clearly the only approach able to predict the right level of turbulence kinetic energy in the core of SDTV and BKTV while k-ω SST and EARSM strongly underestimate by one or two orders of magnitude this quantity. Figure 5 shows a detailed comparison between IIHR experiments and computations of the



(a) Longitudinal velocity, U (b) Longitudinal vorticity, ω_x (c) Second invariant, Q (d) Turbulent kinetic energy, k

Figure 4: Comparison of longitudinal evolution of the longitudinal velocity component U, longitudinal vorticity ω_x, second invariant Q and turbulence kinetic energy k along the cores of the sonar dome tip vortex (SDTV) and the bilge keel tip vortex (BKTV).

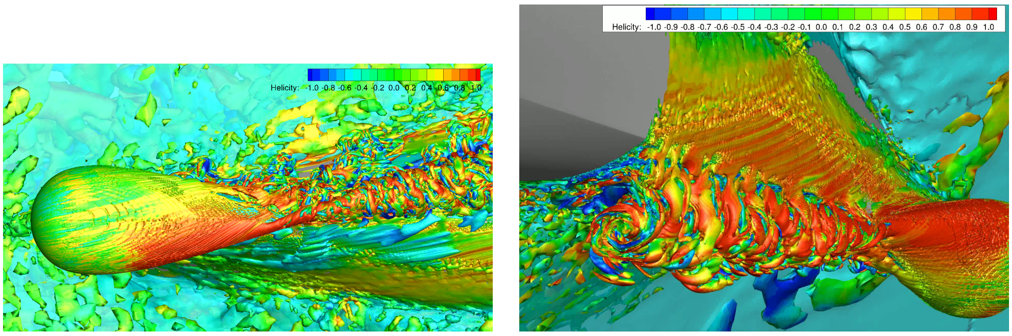
transversal distribution of the turbulence kinetic energy across the core of the SDTV vortex. It illustrates the remarkable agreement reached by the hybrid RANS-LES formulation. To explain this observation, Figure 6(a) shows an instantaneous view close to the trailing edge of the sonar dome of the $Q^* = 50$ isosurfaces colored by helicity obtained with the DES-SST approach. One can see a population of ring-shaped transversal vortices which result from the instability of the longitudinal vortex after its onset and flow separation initiated on the leeward side of the sonar dome. These ring-shaped vortices are shed periodically and are rotating around an axis of revolution roughly aligned with the axis of the initially stable longitudinal vortex. The population of these rotating transversal vortical structures form, once time-averaged, a longitudinal vortex (named SDTV) emanating from the surface of the sonar dome and progressing along the hull. The succession of these secondary vortical structures creates a temporal variation of the velocity in the core of the vortex, which explains the high



(a) Evolution of Q along y (b) Evolution of Q along z (c) Evolution of k along y (d) Evolution of k along z

Figure 5: Comparison of transversal evolutions of the second invariant Q and turbulence kinetic energy k at X/L = 0.4 across the core of the sonar dome tip vortex (SDTV).

level of turbulence kinetic energy (tke) observed in the time-averaged experiments. Contrary to what is often claimed, this high level of tke is not associated to vortex meandering since the vortex-meandering concept refers to low-frequency motions of a coherent longitudinal vortex. On the contrary, the present eddy-resolving simulation reveals a succession of self-sustained higher-frequency transversal vortices rotating around an unsteady core, which provides a more convincing explanation of the high level of turbulence kinetic energy encountered in the core of these vortices (see 6(b) which shows a cross section of the sonar dome vortex).



(a) Instantaneous bottom view at the trailing edge of the sonar dome (b) Instantaneous sectional view in the core of the sonar dome longitudinal vortex

Figure 6: Views of Q^* iso-surfaces obtained by DES and colored by the helicity

3 Conclusions

A systematic investigation of RANS and hybrid RANS-LES models for the DTMB 5415 at 10° static drift will be conducted in the final paper with a detailed flow physics analysis in the core of the main SDTV vortex, comprising tke budget, Lumley anisotropy maps, anisotropy indicators, etc. It will be shown that the use of a hybrid RANS-LES model offers a significant advantage over RANS models, particularly for the prediction of the turbulence kinetic energy in the core of the vortices, which come essentially from the resolved eddies contribution.

References

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