TIME-DOMAIN NUMERICAL EVALUATION OF SHIP RESISTANCE AND MOTION IN REGULAR WAVES BY USING THE CFD URANS METHOD

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ABSTRACT

Taking into account the International Maritime Organisation's (IMO) strategy to radically reduce the GHG emitted by the shipping industry towards zero emission operation, today's assessment of ship behaviour in waves, its seakeeping characteristics and resistance and their interrelation with fuel consumption and emissions are one of the most attended research subject. There are three methods to conduct this analysis, which are Experimental Fluid Dynamics (FED), numerical methods e.g. Computational Fluid Dynamics (CFD) and empirical analysis. This study shows the results of time-domain analysis of ship motions and resistance in head sea waves by using the CFD method, which is then verified using the experimental results. The tests were run for different wavelengths for a KCS model. Numerical results, which are based on solving Unsteady Reynolds-Averaged Navier-Stokes equations (URANS) show that the CFD method applied by using STAR CCM+ can be reliable for evaluating the ship seakeeping characteristics and resistance in waves.

1 INTRODUCTION

To reduce air pollutants and Greenhouse Gases (GHG), recently the International Maritime Organization (IMO), has required all vessels to provide solutions to increase energy efficiency by mandating EEDI (Energy Efficiency Design Index), EEXI (Energy Efficiency Existing Ship Index), CII (carbon intensity indicator) and SEEMP (Ship Energy Efficiency Management Plan) as the adoption of amendments to MARPOL Annex VI. Among different solutions reduction of fuel consumption plays a fundamental role. In this relation, International Towing Tank Conference (ITTC) has recently initiated a deep investigation into the added resistance induced by waves. Understanding and analysis of the instantaneous values of the total resistance in waves in combination with the interaction of hull, propeller and engine can make a clear picture of the fuel consumption profile and pave the road for elaborating better control strategies for ship motion to reduce the emissions.

The three approaches for analysing the added resistance in waves are Experimental Fluid Dynamics (FED), numerical methods e.g. Computational Fluid Dynamics (CFD) and empirical analysis. So far, many studies and research have been done in the field of testing and calculating the added resistance in the head sea wave. One of the first researchers were Storm-Tejsen et al., who identified effective parameters in the added strength of 60 series ships by EFD method [1].

For the S175 container ship, Fuji and Takahashi, [2], and Nakamura and Naito, [3], conducted additional resistance tests at different speeds. Kashiwagi et al., [4], and Kashiwagi, [5], calculated the added resistance for several different ships.

Since the KVLCC2 ship is a model with available results, many researchers have used it for further resistance tests. Guo and Steen, [6], evaluated the added resistance of KVLCC2 in short waves. Park et al., [7], studied the uncertainty of added resistance tes~~ting~~ results in seafaring conditions. Lee et al., [8,9], conducted a series of experiments to understand how different hull shapes affect the added resistance in waves. Other tests have been done on the KCS model to estimate the added resistance, [10-12].

The majority of the above-mentioned studies analyse the added resistance in head waves. The findings show that the number and the range of studies conducting the oblique sea condition are much less than those studies that address the head sea condition. In this regard, Fuji and Takahashi, [2], investigated the added resistance of a ship ~~at~~ in a range of incident wave angles with 30° increment. Kashiwagi et al., [4], investigated the experimental results of added resistance for a model in oblique waves. Recently, Valanto and Hong, [13], measured the added drag in an HSVA cruise ship wave and discussed the effect of Parametric Roll (PA) on the added drag. Stocker, [12], presented data on the added resistance of a KCS vessel in 45° incident waves.

Nowadays, the analysis of added resistance using CFD has become more widespread. The added resistance is defined as subtraction of the calm water resistance from the average of total resistance in waves for a given time length. Orihara and Miyata, [15], solved the Reynolds-averaged Navier-Stokes equation (RANS) using the CFD method and concluded that the added resistance in the wave can be analysed with relative accuracy. Guo et al., [15], studied the added resistance of the KVLCC2 ship using the RANS equation and confirmed the analysis results in general. Sadat Hosseini et al., [16], compared experimental and CFD results of the added resistance under head wave conditions. Yang and Kim, [17], analysed the effective components of the added resistance of KVLCC2 by the Cartesian method. The results of this research show that CFD is satisfactory in estimating the added resistance in head wave condition. However, in oblique sea conditions, it is not straightforward to obtain CFD results due to the computational burden.

As far as empirical analyses are considered, there are many available studies, too. In short waves, Fuji and Takahashi, [2], used some coefficients to derive empirical formulas. Faltinsen et al., [18], developed other empirical formulas. MARIN (Netherlands Marine Research Institute) presented the STAwave method for calculating the added resistance in waves [19]. Also, NMRI proposed an improved formula based on Fuji and Takahashi's formula [20-22], whereby the coefficients were modified using experimental data. Liu and Papanikolaou, [23,24], proposed a new and updated empirical formula to estimate the added resistance. It is stated that in the case of oblique waves, the Faltinsenet al. formula, [18], for short waves may not be appropriate because both diffraction and radiation components are important. A related study can be found in MPEC 70/INF30 (2016), [25], where empirical formulas for radiation and diffraction components in oblique waves have been delivered. Yang et al. (2018), [26], also modified the formula of Faltinsen et al., [18], by considering three aspects in their formulation: the range of the ship's intake, the ship's speed, and the top form of the broken water surface.

It should be mentioned that generally, there are two groups of formulae for calculating the added resistance. The first one, Far-Field Formula (FFF), uses the conservation of momentum and the second one, the Near-Filed Formula (NFF), is based on pressure integration. FFF was developed by Maruo, [27], and was further developed by Newman, [26]. NNF was ~~used~~ employed by Faltinsen et al., [18]. Both formulas were then developed using Narrow-Body Theory (NBT).

By improving the computing ability and capacity of new computers, both FFF and NFF were implemented in software using the 3D Panel Method (3DPM). A comparison between the results by using FFF or NFF can be found in Joncquez, [29]. He studied the added resistance using both methods based on the RANKIN panel method. Kim and Kim, [30], and Kim et al., [31], also used both methods to evaluate the added resistance. Sadeghi and Zeraatgar [32], investigated the ship behaviour in regular and irregular waves to assess the effect of anti-pitch fins on sea-keeping parameters.

In this study, a CFD tool (SRAR CCM+) is utilized by applying URANS equations in combination with free surface modelling by the Volume of Fluid (VoF) method to evaluate the added resistance of a KCS model in four different wavelengths. Next, to validate the results, they have been compared with the experimental results in the time domain. The results include the pitch and heave motion, and time-series of total resistance in waves. The main difference between this work with other similar works is to focus more on the time series ship resistance in different wavelengths.

2 METHODOLOGY

The concept of the study is using implemented URANS equations in a CFD tool to numerically analyse the added resistance of a model ship in head regular waves with different wavelength, and then the results are compared with the EFD results to make a general conclusion about the extent of capability of CFD method to predict the instantaneous added resistance. Here, the ship's motion is described by heave and pitch. The other ship's motion components are not relevant. Such a conclusion will help to a better understanding of the interaction of hull-propeller-engine leading to the elaboration of new strategies for ship control in waves and consequently reduction of fuel consumption. In this regard, a CFD software called STAR CCM+ was utilized to assess the added resistance of a KCS model under various conditions. The URANS equations were applied in conjunction with a Volume of Fluid (VoF) method for free surface modelling.

2.1 Governing Equations

The URANS equations that can be found in Pletcher, [33], are applied here considering viscous incompressible flow for a ship in waves. Additionally, the Reynolds decomposition of turbulent quantities is considered [34]. For modelling the turbulence $k-\omega$ SST (Shear Stress Transport) model is used. This model calculates the stress Reynolds in laminar and turbulent flows and its solver is changeable between them as the flow regime. Also, this model has an extra term which makes the waves do not be dissipated, [35-37]. It combines the standard $k-\varepsilon$ and $k-\omega$ models by rewriting both k and ω equations in terms of ω, [38]. The argument for combining both models is that the $k-\omega$ model is superior to the $k-\varepsilon$ model in the boundary layer, but it fails for flows with pressure-induced separation. In addition, the ω equation is sensitive to the free stream outside the boundary layer [39]. Thus, by combination, the best qualities of each model are used.

2.2 The Case Study

In this study, the KCS model is utilized to assess the time series of resistance, heave and pitch motion. The parameters of the KCS model are presented in Table 1.

Table 1
KCS model parameters

Parameters (unit)	**Value**
Overall length (LOA) (m)	2.500
Waterline length (L_{wl}) (m)	2.325
Breadth (m)	0.322
Draught (m)	0.108
Displacement (kg)	52.03
Block coefficient (-)	0.644
Midship section coefficient	0.953
LCG from aft waterline perpendicular (m)	1.132
VCG from draught (m)	-0.005
Pitch radius of Gyration (%L)	25

The accuracy of the numerical results depends on the mesh, time step and inner iteration. In addition, the dimension of volume controls and related boundary conditions are another effective parameter in the CFD method. The dimensions of domains are selected based on the ITTC recommendation [40]. In this study to simulate better ship dynamics and control the meshes, the overset technique is utilized. In this technique, there is a background domain in which waves are generated there and overset domain which is around the model to record better dynamics of the model and resistance. To control the grids of volume control, background and overset regions being gridded by trimmer mesh. Trimmer mesh is a controllable gridding technique which divides the control volume into small cubical regions. For comparing the effect of the number of grids, heave and pitch and resistance in waves are compared for coarse, medium and fine meshes. Figure 1 shows the heave and pitch motion, as well as resistance in waves for these three cases of meshing.

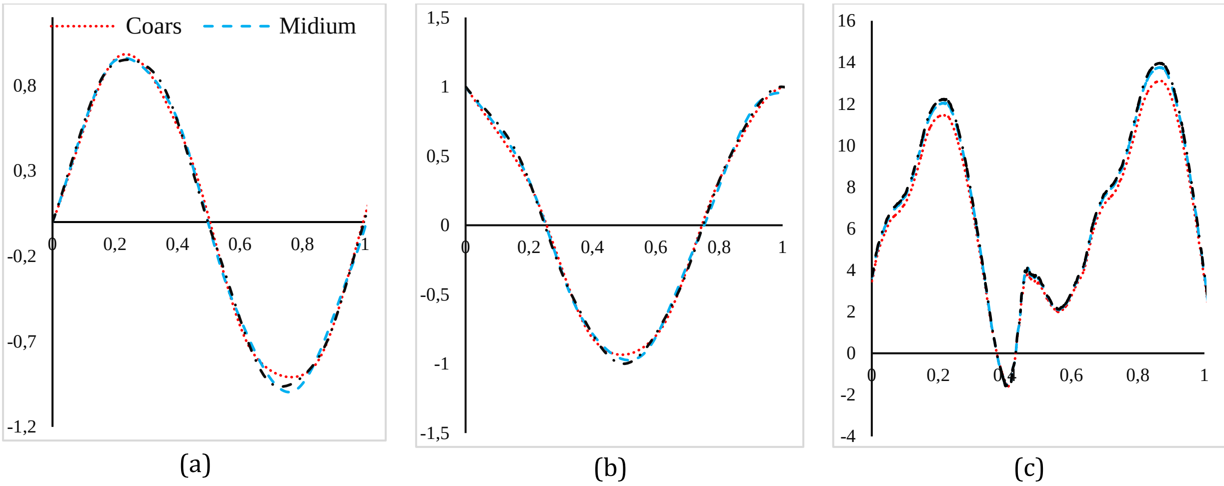


Figure 1 Non-dimensional heave (a), pitch (b) motion, and resistance in waves (c) (results for three meshing modes: coarse, medium and fine)

3 RESULTS AND DISCUSSION

To determine the added resistance in waves the calm water resistance is subtracted from the averaged time series of total resistance in waves at the same forward speed. Table 2 shows the resistance of the KCS model both for EFD and CFD at Fn=0.26. The acceptable range for Y+ is 30-60, and Figure 2 shows that Y+ is acceptable for this simulation.

Table 2
Calm water resistance of KCS model (Fn=0.26)

EFD	CFD	%Difference
3.177 (N)	3.106 (N)	2.6

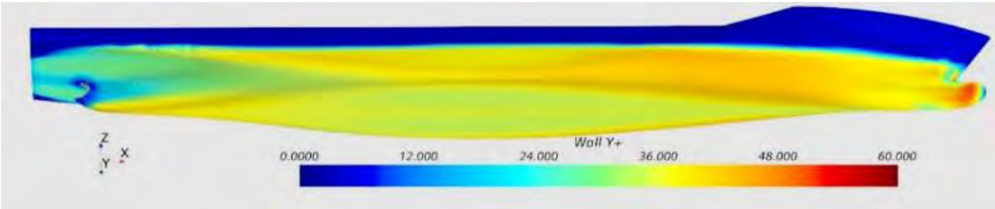


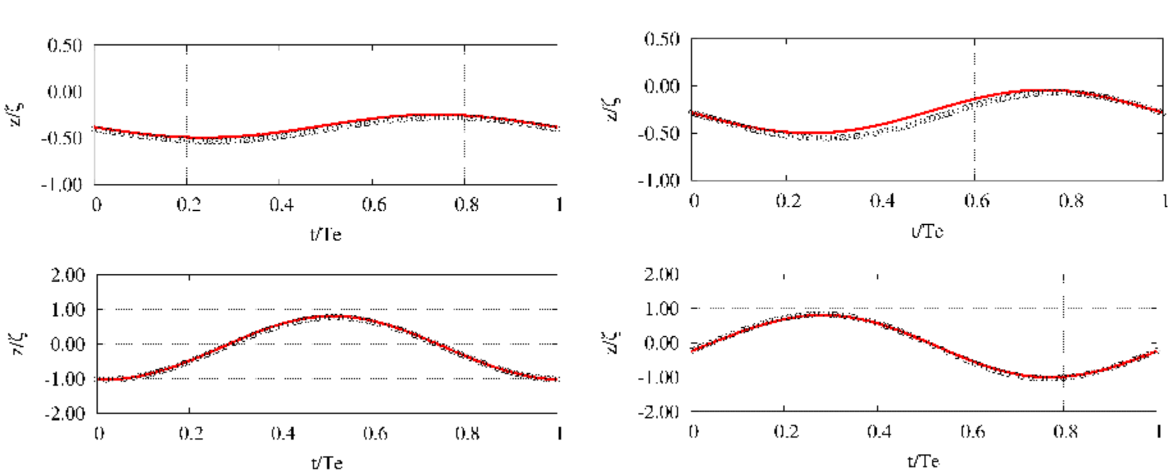
Figure 2 Distribution of Y+ on the KCS hull skin

Table 4 shows the regular wave parameters which are used in the present study. All tests are conducted at Fn=0.26.

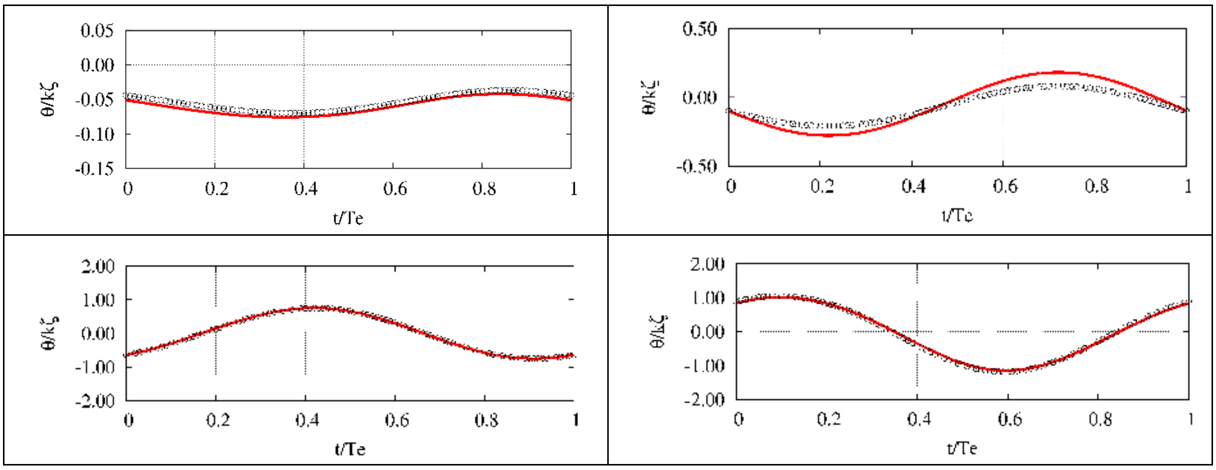
Table 3
Wave parameters for 4 different options

Option	Wave period (s)	Wavelength/L_{wl}	Wave height (mm)
C1	0.858	0.49	56
C2	1.051	0.74	56
C3	1.302	1.14	56
C4	1.695	1.93	56

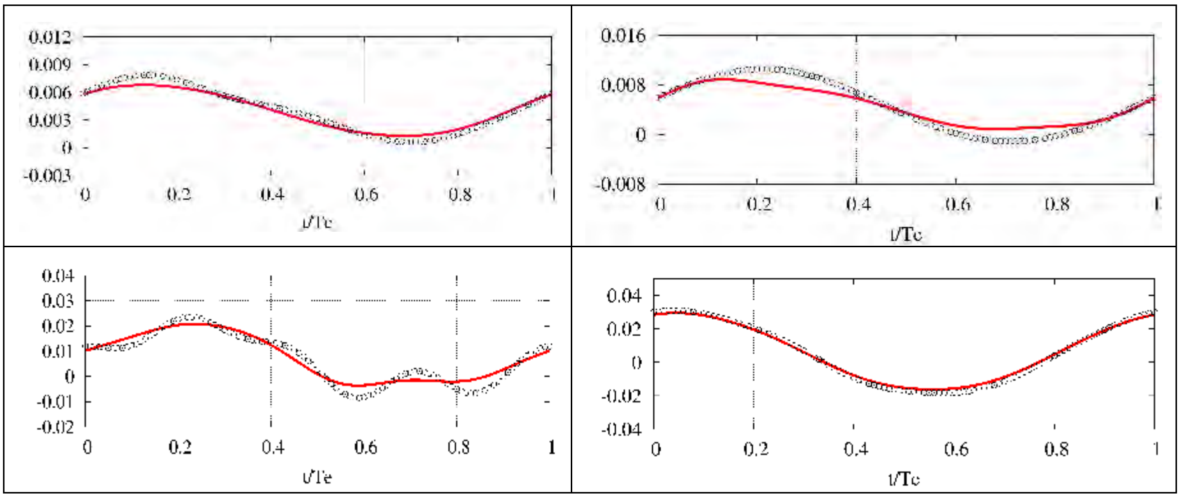
Figure 3 shows the time series of CFD analysis in comparison to the EFD results for options C1 to C4 for heave and pitch motion, and the resistance, respectively.



(a) CFD and EFD results of heave motion for options C1 to C4



(b) CFD and EFD results of pitch motion for options C1 to C4



(c) CFD and EFD results of ship's resistance for options C1 to C4

Figure 3 CFD and EFD results of ship's motion and resistance for different options

Finally, Table 4 shows the non-dimensional heave and pitch amplitudes, and added-resistance in waves, where the CFD and EFD results are compared and the relative difference between them are given.

Table 4
Non-dimensional results

Variable	λ/L_{wl}	EFD	CFD	%Difference
z/ζ	0.49	0.1475	0.1147	-22.22
	0.74	0.2622	0.2295	-12.5
	1.14	0.8688	0.9180	5.66
	1.93	0.9344	0.9016	-3.50
$\theta/k\zeta$	0.49	0.0196	0.0295	50.14
	0.74	0.1475	0.1762	19.7
	1.14	0.7475	0.7573	1.31
	1.93	1.1114	1.0721	-3.53
$R/\rho g\zeta^2 B^2/L_{wl}$	0.49	2.812	2.126	-24.23
	0.74	3.217	2.969	-7.70
	1.14	9.968	8.963	-10.08
	1.93	2.617	2.561	-2.14

4 CONCLUSIONS

In this study, CFD tools have been employed to numerically investigate the ship motion (heave and pitch) and resistance in head wave condition in four different wavelengths, and the results are compared with EFD results for validating purposes. As far as the requirement for CFD analysis is considered, the numerical results are acceptable and the CFD tool is properly applied for solving the problem. Additionally, comparing the CFD and EFD results show that the generally estimated added resistance by using the CFD tool is lower than the values predicted by EFD by 2.1% to 24.2%, depending on the wavelength ratio (λ/L_{wl}). In the case of heave motion, the range of difference between CFD and EFD results is almost the same, from 3.5% to 22.2%, but not necessarily the CFD results are lower for all wavelengths. For pitch motion, the range of difference is even higher up to ac. 50%. However, it should be mentioned that for wavelength higher than unity, the agreement between the CFD and EFD results is acceptable and the relative difference does not exceed 10%. The present~~ed~~ study and the results pave the road for a wider parametric analysis of added resistance and ship motion in waves in the time domain and consequently provide an initial picture of ship behaviour in waves leading to a better understanding and investigating fuel consumption and GHG emissions.

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