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Linear and Nonlinear Based Ship Motion of a Naval Combatant Model

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Abstract: Seakeeping is a very complex problem in Maritime problems involving at least 3 degree-of-freedom (3-DOF) motion of the hull and until commercialized CFD softwares became widely used, the problem was approached by linear approaching applying potential theory. With this motivation, two kinds of numerical methods are employed to study the vertical motions for one encounter frequency where experimental results are available in the literature. While the first method is widely known linear "strip theory", the other one is the fully non-linear U-RANS solver. DTMB 5415 ship form is selected for the computational work. In the first method, the hydrodynamic coefficients in the motion equations are determined and ship responses are found. In the second method, ship responses are found by solving Newton's Motion Law after calculating forces/moments acting on the ship hull via the FVM (Finite Volume Method). Computational study is carried out for Fn=0.41 only. Results are validated with experiments and comparisons are made between the two numerical approaches.

*Keywords**:** Seakeeping, Strip Theory, URANS, ship motions*

1 Introduction

Investigation of ship motions in waves is one of the most challenging topics in the field of hydrodynamics. The difficulties originate the nature of seakeeping calculations because waves are playing a significant role on the ship's response. Viscous flows are highly nonlinear and the Reynolds numbers covered in ship motions are usually high in which turbulent effects are unavoidable. Gravitation complicates the problem even more because waves in nature are not in sinusoidal form as in regular waves. Additionally, the complex geometry of ship hulls majorly affect the restoring terms in the equations of motion. Linear theory regards the restoring terms as constant and this approach fails especially at higher wave amplitudes.

URANS equations which are discretized with the Finite Volume Method are introduced to obtain 6DOF motion of a ship in regular and irregular waves. The inclusion of viscosity with several turbulence models in this approach increases the robustness of the method and its applicability in many cases.

Salvesen et al. presented the original strip theory by using 2-D hydrodynamic coefficients which are obtained by Frank's method [1, 2]. With the strip theory, it was possible to get transfer functions for vertical motions of any 3-D ship form in regular waves. Strip theory is currently a common method to perform seakeeping analyses of a ship and there are many studies implementing the theory.

Beck and Reed advises that the best option to solve for maritime problems are 3D URANS methods [3]. Sato et al. studied on coupled vertical motions for Wigley and Series 60 hull forms at head waves. They compared their results with experimental data. They concluded that CFD analyses are in good accordance with experiments for the Wigley hull but not Series 60 hull form [4]. Weymouth et al. also carried out seakeeping simulations by implementing URANS. Their results are compatible with experiments and they advised the best methods to be implemented in a wide Froude number range [5]. However, in this study the motions are investigated only for a low wave slope range. High wave slope ranges are investigated by Deng et al. and they investigated the vertical motions of a benchmark container ship form. Their study also included numerical uncertainty analyses [6]. Bhushan et al. performed seakeeping analyses for both the model and the full scale of DTMB 5415 ship hull. They also predicted maneuvering derivatives for full scale hull [7]. Simonsen et al. prepared a comprehensive study by using URANS for many different types of ships for seakeeping calculations [8, 9]. Wilson et al. carried out CFD simulations to obtain TF's of vertical responses of the S-175 ship in regular head waves [10].

In this study, as a first step, the ship resistance computations are carried out in calm water and compared with experimental data. Then, Salvesen's strip theory is used to obtain pitch and heave responses for one encounter frequency which is accepted to be around resonance region. Finally, FVM which enables to discretize the URANS equations is used to obtain the pitch and heave responses of the hull.

2 Geometric Features and Physical Conditions

In this study, a $1/24.83$ scaled model of the DTMB 5415 hull given by Figure 1 is used for numerical simulations. The experimental results are given in the reference report [11]. The main particulars of the model hull are given in Table 1. All values are presented for the static case. The numerical simulations were performed for the bare hull case only without any appendages.

Table 1. Main particulars of the model

Main parameters	**Units**	**Value**
L_{WL}	m	5.720
B_{WL}	m	0.768
T	m	0.248
LCG (from aft)	m	2.924
Displacement	kg	549.0
I_{yy}	$kg\,m^2$	1123.2
V	m/s	3.07
Fr	-	0.41

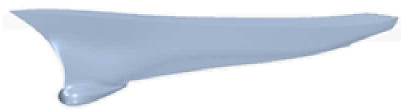

Figure 1: 3D representation of the DTMB 5415 INSEAN Model.

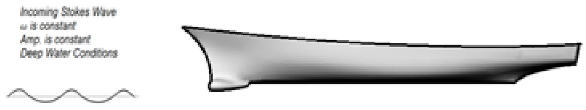

Figure 2: Schematic physics.

An Earth-fixed Cartesian coordinate system xyz is selected for the solution domain. xy plane represents the calm free water surface and z is defined as the vertical axis. The model is moving in the positive x direction with 2DOF including heave and pitch motions only as indicated in Figure 2. A new local coordinate system is created for the ship to obtain 2DOF motion. The URANS and strip theory calculations were performed at ω= 2.488 rad/s and Fn=0.41 as shown in Table 2. All calculations are performed at regular head waves.

Encounter frequency for head waves is defined as below:

$$\omega_e = \omega + \left(\frac{\omega^2}{g} V\right) \tag{1}$$

where g denotes gravity, ω denotes frequency of the wave, V denotes velocity of the ship in Equation 1. Small amplitude waves ($A * k = 0.025$) are selected for numerical simulations to be consistent with the experimental procedure [11] where A denotes the wave amplitude and k denotes the wave number. The generated regular wave for case 2 is given in Figure 3.

Table 2: Defined Cases for strip theory and URANS Calculations

Case no.	Methods	Fn (-)	A*k	ω (rad/s)	ω_e (rad/s)	λ/L_{wl} (-)	H/λ (-)	Time step size
0	**URANS**	0.41	N/A	N/A	N/A	Calm water	N/A	$0.005*V/L_{WL}$
1	**Strip Theory**	0.41	-	2.488	4.427	1.740	-	-
2	**URANS**	0.41	0.025	2.488	4.427	1.740	1/125	$T_e/2^9$

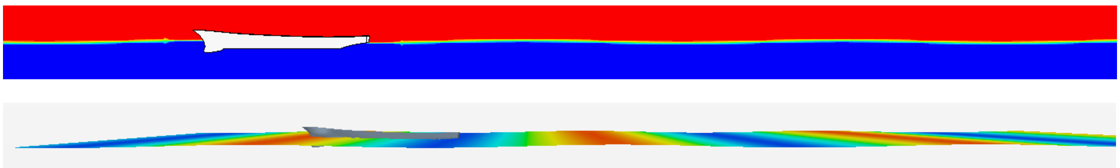

Figure 3: Regular wave representation for case 6 (5th-order Stokes waves).

3 Salvesen's Strip Theory (ST)

In this theory, heave, pitch, sway, roll and yaw motion is predicted for a ship advancing constant speed with arbitary heading in regular waves. Frank-Close Fit method is used to determine hydrodynamic coeeficients in the equation. The 6DOF equation of motions which are based on Newton's second law of dynamics are given Eq.2. Since ship is symmetric, the equations are reduced two uncoupled sets which are vertical and transversal. In a right-handed co-ordinate system, taking the origin to the ship's centre of gravity, these equations are compiled as below [2]:

$$\sum_{j=1}^{6} \left\{ (M_{ij} + A_{ij})\ddot{x}_j + B_{ij}\dot{x}_j + C_{ij}x_j \right\} = F_i \tag{2}$$

for i=1,2…6

where i=1,3,5:Coupled surge, heave and pitch motions (vertical)

i=2,4,6: Coupled sway,roll and yaw motions (transversal)

$\ddot{x}_j$ Acceleration of harmonic oscilation in direction j

$\dot{x}_j$ Velocity of harmonic oscilation in direction j

x_j Displacement of harmonic oscilation in direction j

F_i Harmonic exciting wave force or moment in direction i

M_{ij} Solid mass or inertia coefficient

A_{ij} Added mass or inertia coefficient

B_{ij} Damping coefficient

C_{ij} Restring coefficient

In this study, only vertical motions of the ships are considered and surge motion is neglected because surge amplitudes are very small compared to heave and pitch motions.With only vertical 2DOF assumption, one can express differential form of equation of vertical motion as Eq.3 and Eq.4.

$$\left(M + A_{33}\right)\ddot{x}_3 + B_{33}\dot{x}_3 + C_{33}x_3 + A_{35}\ddot{x}_5 + B_{35}\dot{x}_5 + C_{35}x_5 = F_3 e^{iw_e t+\beta_3} \quad (3)$$

$$\left(I_5 + A_{55}\right)\ddot{x}_5 + B_{55}\dot{x}_5 + C_{55}x_5 + A_{53}\ddot{x}_3 + B_{53}\dot{x}_3 + C_{53}x_3 = F_5 e^{iw_e t+\beta_5} \quad (4)$$

For head waves and two ship speeds, solution of these differential equation sets gives heave and pitch amplitudes and phases for varying encounter frequencies and it allows to draw RAO graphs for both vertical motions. According to Salvesen’s strip theory, heave added mass can be calculated as follows:

$$A_{33} = \int_0^L a_{33}\, dx - \frac{U}{\omega^2} b_{33}^A \quad (5)$$

$$B_{33} = \int_0^L b_{33}\, dx + U a_{33}^A \quad (6)$$

The calculation of other coefficents can be found in Salvesen’s paper [2].

4 URANS EQUATIONS AND MODELING

The averaged continuity and momentum equations can be written for incompressible flow in cartesian coordinates and tensor form as indicated Equation 7 and 8:

$$\frac{\delta U_i}{\delta x_i} = 0 \quad (7)$$

$$\rho(\frac{\delta U_i}{\delta t}+U_j\frac{\delta U_i}{\delta x_i})=-\frac{\delta P}{\delta x_i}+\frac{\delta \tau}{\delta x_j}-\frac{\delta(\rho\overline{u_i'u_j'})}{\delta x_j}+F_i \tag{8}$$

where τ_{ij} are the mean viscous stress tensor components and shown in Equation 9.

$$\tau=\tau_{ij}=\mu(\frac{\delta U_i}{\delta x_j}+\frac{\delta U_i}{\delta x_i}) \tag{9}$$

In this paper, two equation $k-\varepsilon$ turbulence model is used to include the effects of viscosity as it is considered to be one of the most commonly used turbulence model for industrial applications [12]. The employed solver uses a finite volume method which discretizes the Navier–Stokes (N-S) equations for numerical model of fluid flow. Segregated flow model is used in the URANS solver and convection terms in the URANS equations are discretized by applying second order upwind scheme. In the analyses, the URANS solver runs a predictor–corrector SIMPLE-type algorithm between the continuity and momentum equations. A first-order temporal scheme is applied to discretise the unsteady term in the N-S equations. The free surface is dependent on the regular wave properties using Volume of Fluid (VOF) model. In this model, computations are performed for water and air phases. Mesh structure and mesh number in the free surface are significantly important to capture VOF profile accurately and second order convection scheme is used to present results calculated by VOF more precisely. It is also should be noted that all the analyses are performed in deep water conditions.

DFBI (Dynamic Fluid Body Interaction) module in the commercial software STAR CCM+ is used for the motion of body which is free to heave and pitch. The 2DOF motion of the body is obtained by calculating the velocity and pressure field in the fluid domain. For this purpose linear and angular momentum equations, given in Equations 10 and 11 respectively, are solved:

$$\sum\vec{F}=m\vec{a} \tag{10}$$

$$\sum\overrightarrow{M_G}=I_G\overrightarrow{\alpha_a}+\vec{\omega}\times I_G\vec{\omega} \tag{11}$$

where F denotes the total force, m the mass, a the acceleration, M_G the moment taken from the center of gravity, I_G the inertial mass moment, α_a the angular acceleration and ω is the angular speed.

4.1 Selection of time step size

Explicit methods require higher computer memory due to the relatively larger fluid domain demanded by the flow physics of ship hydrodynamic problems. Therefore implicit method is chosen for numerical solution. In the explicit method, CFL condition has to be satisfied for the stability of the method. However in the unsteady implicit problems, the restriction by the CFL condition is not an issue anymore and it relaxes the computer in terms of memory. Time step size is selected as $1/2^9$ of T_e for seakeeping analyses which is more accurate than the value recommended by ITTC [13]. Here T_e denotes encounter period. For calm water resistance predictions, on the other hand, the authors stood by ITTC's recommendation time step size is selected to be $0.005 * L_{WL}/V$ [13].

4.2 Computational domain and boundary conditions

The boundary and initial conditions must be suitable for all numerical and analytical problems to have a well posed problem. These conditions must be usually defined in accordance with the characteristics of the flow. In this study, the computational domain was created in order to simulate the seakeeping behavior of the naval surface combatant in regular waves. The rigid body motion approach was used for representing coupled heave and pitch motions of the ship.

Only half of the body is modeled to decrease the domain size and so computational time. The boundary conditions are shown in Figure 5.

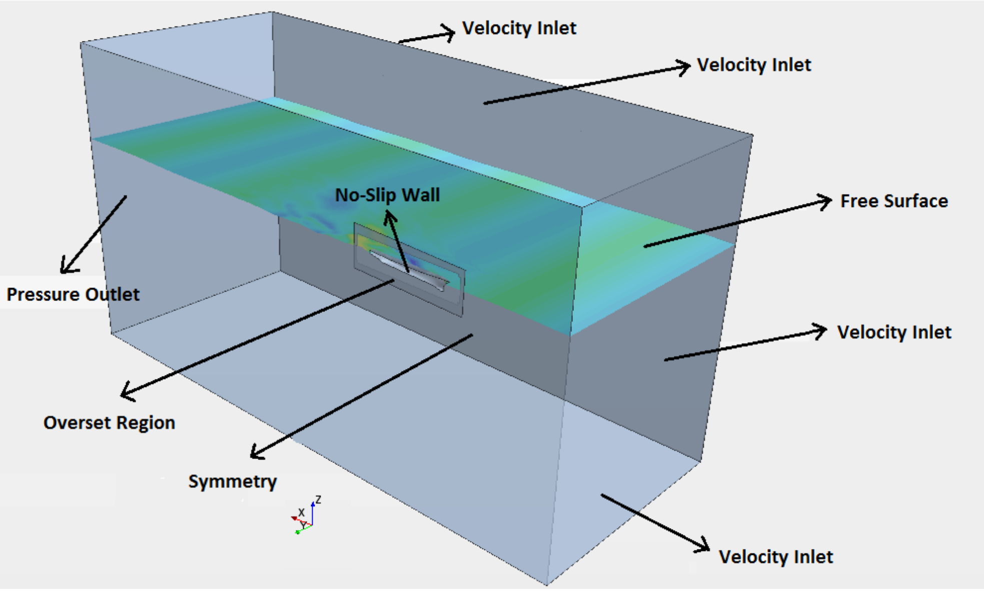

Figure 5: Boundary conditions in the computational fluid domain.

5th-order Stokes waves are used to represent the wavy environment for all URANS analyses as they are shown in Figures 3.

4.3 Mesh structure

The trimmed mesh module in the STAR CCM+ provides an efficient and secured method to generate high quality grid for complex bodies like marine vehicles [14]. The trimmed mesh is mostly hexahedral mesh with a minimal cell skewness.

As it can be seen from Figure 6, the grid system applied in CFD calculations are part of two blocks which are overset and background regions. The background grids are fixed to global coordinate system but the overset grids are moving with the body. The information is passed through the overlap block between overset and background regions. With the overset grid system, any mesh modification or deformation is not necessary which provides great flexibility over the other standard meshing techniques.

The computational domain extends for 1.2L in fro nt of the overset region, 4.8L behind the overset region, and 3L to the side and 2.5L under the boundries of overset region. The air region is 1L above the overset region. The mesh is then refined at five different regions; overset, overlap, vicinity of the hull, around free surface and Kelvin wake regions. Refinement blocks are also built near the ship's bow and stern regions in order to represent pitch motion well. Overlap region ensures the flow of information between overset and backround regions. Three different unstructured hexahedral mesh system are created for all simulations which are coarse, medium and fine. Mesh numbers are given in Table 3. Figure 6 indicates the coarse mesh and refinements at critical zones. Numbers on the Figure 6 show the volumetric controls, respectively:

1. Background region
2. Overset region
3. Overlap region
4. Free surface refinements
5. Bow&Stern refinements

Table 3: Mesh Numbers for $Fn = 0.41$.

Case no.	Coarse Mesh	Medium Mesh	Fine Mesh
0 and 2	Background Mesh 540k	**Background Mesh 1080k**	Background Mesh 2160k
	Overset Mesh 1080k	**Overset Mesh 2160k**	Overset Mesh 4320k
	Total Mesh 1620k	**Total Mesh 3240k**	Total Mesh 6480k

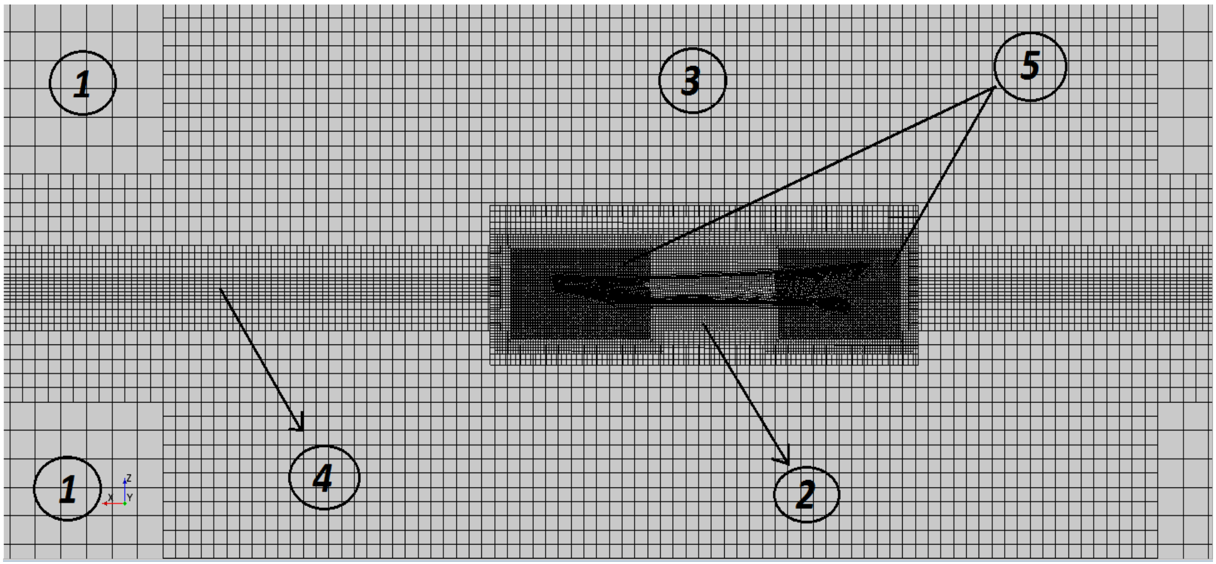

Figure 6. Mesh structure for the coarse grid system in the fluid domain.

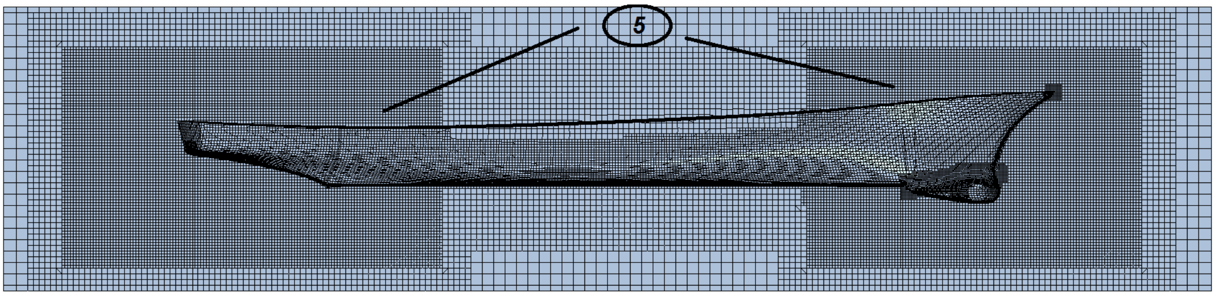

Figure 7. A closer look at the overset mesh structure around the ship.

4.4 Fourier series formulation

The motion results derived from URANS analyses are given in time domain (Case 0 and 2). An example heave and pitch signals obtained for case 2 is given in Figure 8. To transfer the signal from the time domain to the frequency domain, all harmonics of the unsteady signal have to be obtained but only the first harmonic of the signal is required to generate RAO graphs.

Unsteady time histories of the analyzed motions, $\eta(t)$ can be represented by using Fourier series formulation as indicated in Equation 12.

$$\eta(t) = \eta_0 + \sum_{n=1}^{N} \eta_n \cos(\omega_e t + \beta_n)$$
$$n = 1, 2, 3 ... \tag{12}$$

where η_0 is zeroth harmonic amplitude of the unsteady signal which means the average value of the signal.The average total resistance value of the ship is obtained by the help of zeroth harmonic of the total resistance signal (case 0). It can be calculated by Equation 13:

$$\eta_0 = \frac{1}{T_e}\int_0^{T_e} \eta(t)dt \tag{13}$$

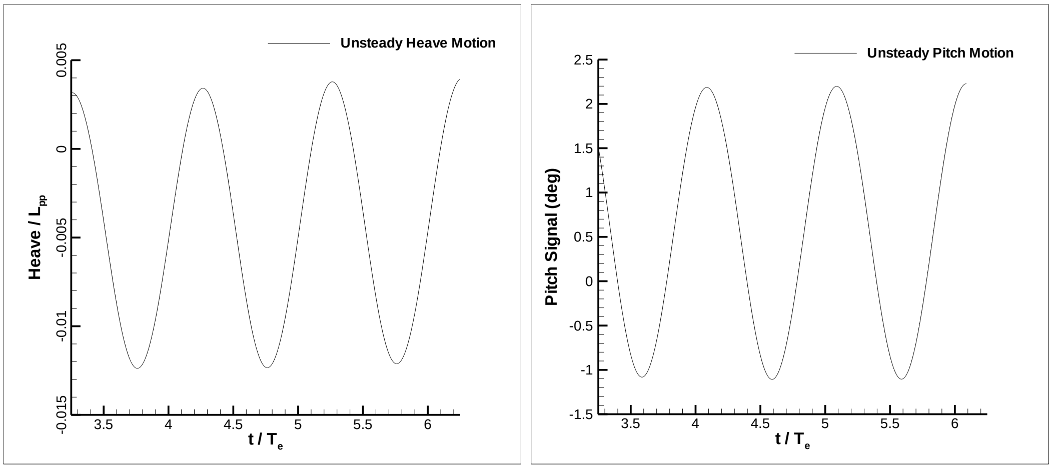

Figure 8: Heave and pitch motions in time domain for case 2.

In Equations 14 and 15, η_n and β_n denotes n_{th} harmonic amplitude and phase angle respectively. These values can be calculated as follows by using a_n and b_n in Equation 16 and 17.

$$\eta_n = \sqrt{a_n^2 + b_n^2} \tag{14}$$

$$\beta_n = \arctan(\frac{b_n}{a_n}) \tag{15}$$

$$a_n = \frac{2}{T_e}\int_0^{T_e} \eta(t)\cos(\omega_e nt)dt \tag{16}$$

$$b_n = -\frac{2}{T_e}\int_0^{T_e} \eta(t)\sin(\omega_e nt)dt \tag{17}$$

In these equations T_e refers to sampling time and it is the encounter period of the given signal. Vertical ship motions, heave and pitch in regular waves can be expressed in terms of RAO'S by the following statements given in Equations 18 and 19 (case 2):

$$RAO_{Heave} = \frac{\eta_{1Heave}}{A} \tag{18}$$

$$RAO_{Pitch} = \frac{\eta_{1Pitch}}{Ak} \tag{19}$$

5 CFD Verification and Validation

Verification and validation (V&V) test [15, 16] is made for computational studies involved in this work to assess numerical uncertainties which is a combination of iterative, grid and time step uncertainties

(U_I, U_G, U_T respectively). Simulation numerical uncertainty U_{SN}, given in Equation 20:

$$U_{SN} = \sqrt{{U_I}^2 + {U_G}^2 + {U_T}^2} \tag{20}$$

The V&V study is made for $Fn = 0.41$ and at a wave frequency of $\omega = 2.488$. Iterative uncertainties in all trials are found to be very low when compared with grid and time step uncertainties; therefore, it is assumed that $U_I \approx 0$. The element numbers for grid uncertainty and time step sizes for time step convergence study is given in Table 4.

Table 4. Element numbers and time step sizes involved in the uncertainty study.

	G3	**G2**	**G1**
Element no.	750,000	1,500,000	3,000,000

	T3	**T2**	**T1**
Time step size	$T_e/2^7$	$T_e/2^8$	$T_e/2^9$

Here, T_e is the encounter period. The results of the grid and time step convergence studies are given in Tables 5 and 6. The number of elements in each grid are twice the previous grid as can be seen in Table 4 and the refinement ratio in grid convergence study is $r_G = 1.2599$. The time steps are increased with a refinement ratio of 2, starting from $\Delta t = T_e/2^7$. The grid uncertainties as a percentage of grid 2 (G2, 1.5M elements) for heave and pitch are 7.47% and 4.07% respectively as it is seen from Table 5. The time step uncertainty as percentage of time step 1 (T1, $\Delta t = T_e/2^9$) for heave and pitch are 10.57% and 11.60% respectively as it is seen from Table 6. The simulation numerical uncertainty for heave is around 13% while it is around 12% for pitch as it is indicated in Table 7.

Table 5. Grid convergence study.

	G3	***G2***	**G1**	$\mathbf{r_G}$	$\mathbf{R_{G2}}$	$\mathbf{U_G}$ **(%$\mathbf{G_2}$)**	**EFD**
Heave	1.1325	*1.1173*	1.0881	1.2599	1.921	7.47	1.0806
Pitch	1.2007	*1.1850*	1.1811	1.2599	0.248	4.07	1.1788

Table 6. Time step convergence study.

	T3	**T2**	***T1***	$\mathbf{r_T}$	$\mathbf{R_{T2}}$	$\mathbf{U_T}$ **(%$\mathbf{T_2}$)**	**EFD**
Heave	0.9690	1.0645	*1.1173*	2	0.553	10.57	1.0806
Pitch	0.9911	1.1188	*1.1850*	2	0.518	11.60	1.1788

Table 7. Validation of heave and pitch.

	Values	U_{SN} (%)	Result range	EFD	Validation
Heave	1.1173	12.94	0.9727-1.2619	1.0806	Yes
Pitch	1.1850	12.29	1.0393-1.3307	1.1788	Yes

6 Results and Discussion

The presented results and discussion on resistance in calm water and vertical motions in regular head waves of DTMB 5415 are shown in this section. Results are compared with experimental data of the same scale model in terms of resistance and seakeeping [11,17].

6.1 Calm water resistance

The total resistance R_T of the ship can be decomposed into two essential components R_R (residuary resistance) and R_F (frictional resistance) as given in Equation 21:

$$R_T = R_R + R_F \tag{21}$$

Resistance is usually given in non-dimesional form as in Equation 22:

$$C_x = \frac{R_x}{\frac{1}{2}\rho S V^2} \tag{22}$$

where x in the subscript may represent any resistance component. Here; ρ denotes the water density, S the wetted surface area and V the ship velocity. R_R and R_F are functions of Froude (Fn) and Reynolds (Re) numbers. For this reason the following statement can be expressed in Equation 23:

$$C_T = C_R + C_F \tag{22}$$

Here, C_T denotes the total resistance coefficient, C_R the residuary resistance coefficient and C_F the frictional resistance coefficient. The flow within the boundary layer has to be solved correctly to accurately calculate the C_F value. Therefore, y^+ values on the hull surface should be appropriate for the $k-\varepsilon$ turbulence model. y^+ values on the hull surface are about 60. This value is considered to be suitable since it remains between the recommended range 30-300 for the selected turbulence model [14].

In the URANS calculation, case 0 refers to the resistance test in calm water. Zeroth harmonic of the given signal gives the averaged value of the predicted total resistance. Hence C_T of the DTMB 5415 in calm water is achieved by implementing Fourier series formulation to time series of the total resistance signal. Wave pattern of the ship at $Fn = 0.41$ for case 11 is given in Figure 9.

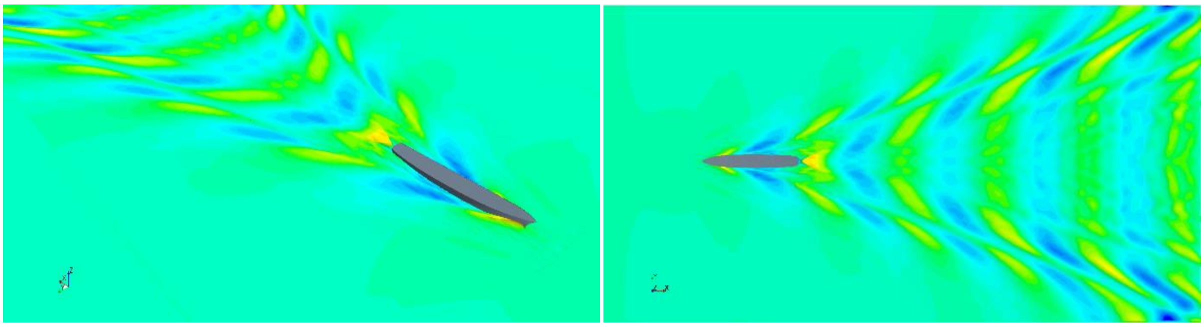

Figure 9: Presentation of the correctly captured Kelvin wave pattern behind the ship.

As it is indicated in Table 8, C_T is predicted with high level of accuracy. The present study underpredicts C_T at around 1% as compared with the experimental data.

Table 8: Experimentally and numerically calculated total resistance coefficients.

Case No.	**URANS**	**Experiment**
Case 0	6.58E-03 (% -1.3)	6.67E-03

6.2 Heave and pitch responses in regular head waves

Heave and pitch RAO graphs for $Fn = 0.41$ which are obtained by applying strip theory and URANS are demonstrated in this part. Results generated by strip theory refers to case 1 while results generated by URANS refers to case 2.

Time histories of the coupled pitch and heave motions are obtained using the medium grid (G3) for all cases. First harmonics are derived by applying Fourier series formulation for case 2. Then RAO value for coupled pitch and heave motions are generated and compared with the experimental RAO value for correspending encounter wave frequency.

The case at $Fn = 0.41$ is considered as high speed for a displacement vessel. The reason why the nonlinear model implementing URANS returns better results compared to the linear strip theory at this speed is because the flow around the ship is highly turbulent and viscous effects are playing a more important role in the vessel's response in waves. Another simplification of the linear model is the absence of the interaction between transversal sections as strip theory takes into account the forces only acting at that specific section. Therefore, it is advised that this case should be investigated with non-linear tools especially when dealing with wave frequencies close to the resonance region where the vessel is making significant motions in the sea.

Table 9: RAO's for both heave and pitch motions at $Fn = 0.41$.

Case No.	**Heave RAO**	**Pitch RAO**
Case 1 (Strip Theory)	1.193 (%9.4)	1,144 (%-2.9)
Case 2 (URANS)	1.117 (%3.3)	1,185 (%0.5)
Experiment	1.081	1,179

As it is indicated in Table 9, Heave and Pitch RAO is predicted with high level of accuracy with the use of URANS. While the present study overpredicts Heave RAO at around 3.3%, overpredicts Pitch RAO at around 0.5% as compared with the experimental data. Although strip theory results (%9.4 for heave and -2.9 for pitch) are worser compared to URANS results it still keeps its availability due to the practicability and quickness of the method.

7 Conclusions

In the present paper, the coupled pitch and heave motions on regular head waves for one case were investigated with linear and nonlinear approaches. The linear approach implemented in this study was the widely used strip theory while for the nonlinear approach URANS was adopted to solve the viscous flow around the ship. Strip theory has proven its worth in time while URANS is still being tested in the last few decades as the nonlinear models are getting more complex and accurate in time. The validity of URANS was tested with a free to sink and trim case of DTMB 5415 hull where experimental results can vastly be found in the literature. Out of the available experiments, DTMB 5415 INSEAN model was chosen as a test case for series of computational studies. The results were compared against the experimental data which involves the resistance in calm water and the vertical motions and heave accelerations on one specified regular head wave. For the resistance test, $Fn = 0.41$ case was considered and C_T value was predicted with high level of accuracy via URANS in comparison with the experiments.

Speaking in terms of motions of the hull in regular head waves, strip theory and RANS are used for high speed case for small amplitudes. For $Fn = 0.41$ covering the cases 0 and 2, the RAO value was calculated by URANS showed a better agreement compared to obtained by strip theory. As a conclusion, the fully nonlinear viscous URANS approach is generally a better option returning closer results to experiments for a high speed case however it does not possess the practicality of the strip theory.

Acknowledgment

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