Unsteady RANSE simulation for ship resistance, heave
and pitch in regular head waves

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Abstract. This study presents an attempt to perform a viscous numerical simulation for ship
advancing in regular head waves. The simulation includes computations for total ship resistance,
heave and pitch responses for the bare hull of the US Navy combatant DTMB 5512 ship model.
The computations are carried out by making use of the commercial software Fine(TM)/Marine
provided by NUMECA, where the discretization in space is based on finite volume method using
unstructured grid. The unsteady Reynolds-Averaged Navier-Stokes equation is solved while the
turbulence is modelled by making use of \( k-\omega \) shear stress transport model. The free-surface is
solved based on volume of fluid method. Results are obtained for ship resistance coefficient,
heave and pitch and compared with experimental results provided in the Gothenburg 2010
Workshop on the Naval Hydrodynamics. The comparison of the computed results showed an
encouraging agreement with the measured results. Finally, a special investigation for the added
resistance in waves is made by comparing the results obtained in this computation with other
results obtained in calm water.

1. Introduction
Ship performance in a seaway presents an importance for the marine engineers from different points of
view. On one hand, the power required to operate the ship economically is increased due to the added
resistance in waves. Some studies considered that the extra power for a ship operating in waves rather
than that performing in calm water is about 15-30% [1]. Obviously, this increment in power is associated
with additional cost and additional fuel consumption. This fuel consumption has to cope with the
requirements for minimum energy efficiency level measured by an Energy Efficiency Design Index
(EEDI) and Energy Efficiency Operational Indicator (EEOI) which are regulated by the International
Maritime Organizations (IMO) and Marine Environment Protection Committee (MEPC). On the other
hand, the ship response in wave is crucially important to be considered for safety reasons; for the ship
asset and for the human lives on board. Many researches have been developed in this scope including
experimental fluid dynamics (EFD), the potential flow methods and lately the computational fluid
dynamics (CFD). The experiments are usually performed for the ship models in regular waves using
wave generators. Seakeeping tests are expensive due to the long waiting periods between tests until the
water has come to rest again. The waiting periods are especially long in conventional towing tanks.
Also, the scope of the experiments is usually large as many parameters need to be varied, e.g. wave
length, wave height, angle of encounter, ship speed, draught and trim, metacentric height etc. [2]. The
potential flow methods either linear or nonlinear were the milestone in the seakeeping for the past five
decades. The linear potential flow seakeeping solvers based on strip theory, source distribution method,
panel method and more recently enhanced unified theory (EUT) were widely used by ship researchers [3]. CFD has proven to be efficient in predicting added ship resistance and motion in waves including the viscous effect; yet, it is more expensive compared to potential flow methods. Viscous CFD tools based on unsteady Reynolds-averaged Navier–Stokes (URANS) computations are becoming more common for seakeeping computations according to ITTC seakeeping committee report [4]; however, their accuracy requires more investigation.

The majority of seakeeping computations conducted nowadays is held based on URANSE solvers, with a few simulations based on Large Eddy Simulations (LES) and Detached Eddy Simulations (DES). The capturing of free-surface is made based on Volume of Fluid (VOF) method or level set method. Incoming waves are mainly assumed linear and are imposed at the domain boundaries. Structured or unstructured multi-block or overset grids are used for motions. Numerical methods mainly use second order discretization schemes for spatial and temporal terms. The High Performance Computations (HPC) methods are used in almost all simulations allowing for small grid sizes at the free surface and boundary layer and small time steps to capture the motions in waves accurately [5]. In the Tokyo 2005 Workshop on the Naval Hydrodynamics, only one case was presented for a speed diffraction problem including no motion [5], while in the Gothenburg 2010 Workshop on the Naval Hydrodynamics, numerous cases were studied including speed diffraction and ship surge in head waves including heave and pitch motion [6]. The level of accuracy for seakeeping computations was promising; however, some significant errors were recorded for the 0th and 1st harmonics of the forces as well as the phase for computed results. Three ships were analysed including; the modified Korean tanker (KVLLC2), Korean Container Ship (KCS) and the US Navy surface combatant (DTMB). There average error for the all the computations was about 23% compared to measured values from tank tests [7]. In the Tokyo 2015 Workshop on the Naval Hydrodynamics, the computations were performed for the KCS in head waves, plus six degrees of freedom motion for the ONR tumblehome [7].

This study is an attempt by the author to predict the capability of the URANSE solver to predict the seakeeping performance of the ship surging in head waves as an initial step for further investigation that will be carried out by the author in the very near future for six degrees of freedom simulation in waves. This attempt stands as an intermediate step for a previous investigation for the bare hull resistance and free-surface simulation that was performed by the author and presented in [8]. The case study is the DTMB 5512 ship model, a geosim of the DTMB 5415 that was conceived as a preliminary design for a Navy surface combatant in 1980. The bare hull geometry includes both a sonar dome and transom stern. Ship particulars are tabulated in table 1, while the geometry is depicted in figure 1.

| Parameter                              | Value     |
|----------------------------------------|-----------|
| Length between Perpendiculars, $L_{pp}$ [m] | 3.048     |
| Beam, $B$ [m]                          | 0.409     |
| Draft, $T$, [m]                        | 0.132     |
| Displacement [m$^3$]                   | 0.0826    |
| Block coefficient, $C_B$               | 0.506     |
| Wetted surface area at rest, $S/L_{pp}$ | 0.1476    |
| Froude number, $Fn$                    | 0.28      |
| Reynolds number, $Re$                  | 4.86x10$^6$ |
| Longitudinal C.O.G. position from F.P., $x_{CG}$ | 1.536      |
| Vertical C.O.G. from calm water, $z_{CG}$ | 0.3       |

Table 1. Particulars of DTMB 5512 ship model.
2. Mathematical model

The computations are performed using the ISIS-CFD solver of the FineTM/Marine commercial software provided under the NUMECA suite. The solver is using unstructured grid technique to build the spatial discretization to solve the Unsteady Reynolds-Averaged Navier-Stokes Equation (URANSE). Closure to the turbulence is achieved by making use of the $k-\omega$ SST. Free-surface is captured in an air-water interface based on the VOF method. The ship axis is set for the computation whereas the forward perpendicular (F.P.) lies at $x = 0$ and the after perpendicular (A.P.) lies at $x = L_{pp}$, while the free-surface at rest is set at $z = 0$.

The simulations include two different studies; the first is for forces computation where the ship is set in a fixed condition for heave and pitch, while the second is with a free heave and pitch simulation. Validation of results is made according to the case 3.5 presented in [6] and including only one wave simulation corresponding to wave steepness $Ak = 0.025$. The wave length $\lambda = 1.5L_{pp}$, wave steepness $Ak = 0.025$, wave frequency $f_w = 0.584$ Hz, encounter frequency $f_e = 0.9189$ Hz and encounter period $T_e = 1.0882$ seconds. For the fixed ship case, two extra computations are performed for $Ak = 0.05$ and 0.075.

2.1. Mathematical formulation

The averaged continuity and momentum equations for incompressible flow in Cartesian coordinates and tensor form can be written as, equation (1) and equation (2):

$$\frac{\partial U_i}{\partial x_i} = 0$$  \hspace{1cm} (1)

$$\rho \left( \frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} \right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau'_i}{\partial x_j} + \frac{\partial (\rho u'_i u'_j)}{\partial x_j} + F_i$$  \hspace{1cm} (2)

where $\tau'_i$ are the mean viscous stress tensor components and can be expressed as, equation (3):

$$\tau'_i = \tau_{ij} = \mu \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right)$$  \hspace{1cm} (3)

For the wave formulations, a wave can be described by wave length $\lambda$ or wave number $k$ and wave period $T$ or circular frequency $\omega$ such that $k = 2\pi/\lambda$ and $\omega = 2\pi/T$, respectively. Wave steepness can be defined based on the wave amplitude $A$ and wave number $k$ as $Ak = 2\pi A/\lambda$.

Frequency of an incidence wave in deep is expressed as, equation (4):

$$f_w = \sqrt{g/2\pi\lambda}$$  \hspace{1cm} (4)

Encounter frequency can be written as $f_e = f_w + U/\lambda$, while the encounter time is $T_e = 1/f_e$.

As a time reference, incident wave height at the forward perpendicular F.P. can be written as, equation (5):

$$\zeta_i(t) = \frac{A}{L_{pp}} \cos(2\pi f_e t + \gamma_i)$$  \hspace{1cm} (5)

where $\gamma_i$ represents the initial phase, which is equal to zero when the wave is at the F.P.
Fourier series for time history of a parameter P ($C_T$, $C_H$, $C_M$, Heave, Pitch, $\zeta_i$); where $C_T$ is the non-dimensional total resistance coefficient, $C_H$ is the heave force coefficient, $C_M$ is the pitching moment coefficient and $\zeta_i$ represent the incident wave height, can be defined as, equation (6):

$$P(t) = \frac{P_0}{2} + \sum_{n=1}^{N} \cos(2\pi f_e t + \Delta \gamma_n)$$

$$\Delta \gamma_n = \gamma_n - \gamma_i$$

$$a_n = \frac{2}{T} \int_0^T P(t) \cos(2\pi f_e t) \, dt$$

$$b_n = \frac{2}{T} \int_0^T P(t) \sin(2\pi f_e t) \, dt$$

$$P_n = \sqrt{a_n^2 + b_n^2}$$

$$\gamma_n = \tan^{-1}\left(-\frac{b_n}{a_n}\right)$$

where $P_n$ is the n-th harmonic amplitude and $\gamma_n$ is the corresponding phase.

2.2. Computational grids
The computational grid is generated by the unstructured hexahedral grid generator Hexpress$^{\text{TM}}$ available in the Fine$^{\text{TM}}$/marine package. Considering the symmetry of the hull, and the roll motion is not included in this computation, only the half ship was used to reduce the computational effort. The computational domain is having a rectangular configuration extended in $xyz$-directions corresponding to the wave length as $2.0\lambda < x < 5.0\lambda$, $0 < y < 2.0\lambda$, $2.0\lambda < z < 2.0\lambda$. The computational domain is depicted in figure 2 showing the domain configuration and the boundary conditions.

![Figure 2. Computational domain configuration and boundary conditions.](image_url)
zones based on the cell size chosen for each zone. The first zone starts at the inlet and extends about one wave length behind the ship, the cell size was chosen for this zone to provide (60 grid cells/\(\lambda\)) in x-direction, (15 grid cells/\(\lambda\)) in y-direction and (16 grid cells/\(H\)) in z-direction. The cell size in x-direction was doubled consequently for the next three zones such that the last refinement zone near the outflow boundary is having a grid spacing about 8 times the cell size in x-direction for the first zone, while the cell size in y and z-direction is kept unchanged.

The computational grid consists of 8.176 million cells. The discretization grid is depicted in figure 3 showing the mesh on the hull and the wave refinement zone.

![Numerical Damping Zone](image)

**Figure 3.** Grid configurations showing the hull mesh (top) and the wave refinement zone near the hull.

The computation is performed in an unsteady approach; the flow is accelerated within one second to reach the corresponding velocity. Discretization in time is made to provide 200 time steps per wave period for the free condition, and reduced to 150 time steps per wave period for the fixed condition. The integration in time is done based on fourth order convergence criteria using combined upwind discretization scheme and centred discretization scheme with twenty nonlinear iterations per time step. Motion is predicted based on the weighted deformation method. The simulation is performed on HPC concept, considering the fact that this type of simulations is difficult and requires a significant computational time. The CPU cost per time step is 88.0 second using 120 processors.

3. Results and discussion

3.1. Results validation

The results are compared with the provided EFD results that were presented in [9] and the result presented in the Gothenburg 2010 Workshop on the Naval Hydrodynamics [6]. The comparison for the total ship resistance coefficient between CFD and EFD is depicted in figure 4 and 5 in time and frequency domain, respectively; while the quantitative comparison for the 0\textsuperscript{th} and the 1\textsuperscript{st} harmonic of the total resistance coefficient is tabulated in table 2. The comparison between measured results for the \(C_T\) is presented in figure 4.a for the fixed condition showing a promising agreement with the experimental results; though the average of the total resistance coefficient \(C_T\) is seemingly under predicted, while the amplitude is slightly over predicted. The error between computed results and measured ones can be computed based on the simple differencing \(E\%D = 100 \times \frac{EFD-\text{CFD}}{EFD}\). Figure 4.b shows the
comparison between the two computed $C_T$ for the fixed and free condition showing that the motion of the ship tends to damp the wave amplitude and distorting the signal. A significant phase shift is also noticeable, though no phase analysis was taken into consideration. The error between the two cases is significant and is about 18.71% for the $C_T0^{th}$ harmonic and 8.355% for the 1\textsuperscript{st} harmonic, a fact that will require further analysis to enhance the accuracy of the results.

![Graphs showing comparison between computed $C_T$](image)

**Figure 4.** Time history for the results for: (a) total resistance coefficient $C_T$ (line) compared to the EFD results (circles) [11], (b) $C_T$ comparison based on simulation condition, (c) heave/$L_{PP}$ and (d) Pitch [deg].
Figure 5. Fourier analysis for: (a) $C_T$, (b) heave and (c) pitch.

Table 2. $C_T$ compared to EFD [11], heave and pitch harmonics.

| Variables | $C_T$ | Heave | Pitch [deg] |
|-----------|-------|-------|-------------|
| Value     | 0th Amp. | 1st Amp. | 0th Amp. | 0th Amp. | 0th Amp. |
| EFD [10]  | 0.00462 | 0.00608 | -        | -        | -        |
| CFD G1    | 0.0045398 | 0.005741 | 0.00556 | 1.54334 |
| E%D       | 1.736   | 5.576  | -        | -        |

The result comparison for $C_T$, $C_H$ and $C_M$ based on $Ak$ is depicted in figure 6 for $Ak = 0.025$, $Ak = 0.05$ and $Ak = 0.075$.

Figure 6. Time history of the; (a) $C_T$, (b) $C_H$ and (c) $C_M$, compared based on the wave steepness $Ak$. 
The analysis of the heave and pitch for the two cases where \( Ak = 0.05 \) and 0.075 were not presented due to the complexity of predicting their significant responses based on weighted deformation method. From the author’s point of view, to predict the response in those conditions; an overset grid technique might be necessary to capture the response of the ship without affecting the stability of the solver.

The free surface elevation is obtained and compared for the three cases as plotted in figure 7. The quantitative free-surface elevation is presented in figure 7.a while the free-surface topology is presented in figure 7.b. The results are presented for the actual computational time of 20 seconds, which is corresponding to the instance between \( v/T_e = 0.75 \) and \( v/T_e = 0 \). The wave elevation shows a relative increase according to the wave height. Besides, a fore and aft radiation due to the wave-hull interaction can be noticed. For the lowest wave height, it can be noticed that the wave signal is distorted after interfering with the hull. Although the wave height at \( Ak = 0.075 \) is representing the most significant amplitude, the peak at the F.P. seems to be less significant than that in case of \( Ak = 0.05 \). Nevertheless, the trough afterwards seems to be adjusted. This might be related to the wave reflection at the ship flare due to the stagnation effect.

\[ R_{aw} = \bar{R}_{aw} - R_{calm} \]  
\[ (7) \]

where \( \bar{R}_{aw} \) is the average of the computed resistance in wave, as illustrated in figure 8. The added resistance can simply be extracted from the \( C_T \) diagram by finding the average value and comparing it with the calm water resistance. The difference is simply representing the added resistance in wave. For a qualitative definition of the results, the average of the computed resistance coefficient in wave for \( Ak = 0.025 \) is 0.0045398, while the computed value for the resistance coefficient in calm water is 0.004140, as obtained for the finest grid in [9]. The difference between the two results is 0.0003998, which means that the added resistance in wave for this computation represents about 9.65% of the computed result in calm water. This can be considered as a significant value though the wave height is not so significant.
Figure 8. Added resistance in wave computed based on resistance results in calm water.

The free-surface prediction for $Ak = 0.025$ at different instances is brought to attention in figure 9, where the time evolution of the wave is depicted for four different moments; first when the wave crest is at the F.P. defined as $t/T_e = 0$ and the rest are related to the quartering wave period.

![Wave Elevation](image)

Figure 9. Free-surface topology at different encountering instance for $Ak = 0.025$ for the free condition.

4. Conclusions

The unsteady RANSE simulation for the DTMB 5512 ship model advancing with the design speed in head wave is presented and computed for two different conditions; the fixed ship condition and the free have and pitch condition. The computations are presenting an attempt to investigate the capability of the viscous URANSE solver to predict ship response in waves to set the pace for a further investigation in this scope. Computation is performed with the commercial software Finetm/Marine provided by NUMECA.

The validation of results showed an encouraging agreement with EFD for the total resistance coefficient. For the fixed condition simulation, an error about 1.736 and 5.576% for 0th and 1st harmonics, respectively were obtained, while for the free heave and pitch condition, the error was significant with an error about 18.71 % for the $C_T$ 0th amplitude and 8.355 % for the 1st harmonic compared to the fixed case. Besides, the phase shift was apparently significant and the $C_T$ signal was seemingly distorted. Heave and pitch were also computed and presented for the case where $Ak = 0.025$. 
Results comparison based on the wave steepness were presented for total resistance coefficient, heave force coefficient, pitching moment coefficient and free-surface elevation for $Ak = 0.025$, $0.05$ and $0.075$, respectively. The results showed the effect of the wave height change on the aforementioned parameters. While and extra investigation is required for the free-surface elevation on a different finer mesh to predict the F.P. wave height accurately.

The ship response for the higher wave cases were not successful due to the associated instability of the solver resulted from the weighted deformation approach. A further investigation with an overset grid approach is necessary to overcome this problem.

The added ship resistance in wave was computed based on the analysis of forces for the current study and a previous study that was performed by the author in calm water. The value for the added resistance was computed about $9.56\%$ of the one computed in calm water.

The free-surface was computed based on VOF method and presented for the four-wave quartering period with respect to the encountering wave period. The study showed that the computational effort is quite significant for these types of simulations, though it was performed on an HPC concept. Despite the fact that the prediction of hull-wave interaction seem to be encouraging, for a commercial purpose, this type of computation might not be considered feasible. Yet, for a research purpose, it is quite promising.

The overall conclusion on the study cannot be taken for granted. More computations are required to study the stability and the accuracy of the solver. Beside, a verification study is required for investigating the computational uncertainties, plus extra computational cases are important to be considered in the future.

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