Study on the behavior of benchmark container ships in regular waves

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Abstract. The study of the behaviour of ships in the real sea has become a real challenge in recent years due to climate change, especially in the European sea basin. One of the main categories of types of ships that cross these waters are transport ships. The development of the economy and trade have a major influence on this type of ships, which must be studied and improved in order to be fully exploited. Investigating the ship's behavior is not a new topic, but the changing environment of the transport ship's specifications requires continuous study. An alternative to model testing is the use of numerical simulation through which performance can be fully evaluated using only computers, without the need to produce a scale model for testing. Due to improved computer performance, but also the disadvantages of towing testing, numerical simulations have become increasingly popular for determining ship characteristics. The shorter time in which results can be obtained, as well as the ease of controlling and changing the input parameters, contributes to the preference to use numerical simulations, to the detriment of basin tests. In this paper, the behavior of a Post-Panamax benchmark container ship in regular waves was studied. Numerical simulations were performed using SHIPFLOW MOTIONS, a solver that treats potential nonlinear flows for regular waves and provides accurate results by the free surface potential flow panel method. For our case, the simulations were performed for a range of six speeds corresponding to Froude numbers ranged between 0.174 and 0.218, for five nondimensional wavelengths (λ/Lpp) and for four wave heights. Because body discretization is one of the main factors for obtaining accurate results, an additional study was conducted in calm waters on body refinement and the influence that the mesh has on results, for a range of ten grids with different densities.

1. Introduction
Climate change has become more pronounced in recent years, which is a real challenge to counteract its effects. Evaluation of the climate change impact on the sea state conditions and on the safe design of ship structures were also performed [1, 2]. Navigation in Europe's maritime areas is affected by extreme weather conditions [3]. Maritime traffic is dominated by transport vessels (figure 1), especially general cargo ships [4], which provide maritime transport in Europe but also outside Europe. Since this type of ship is of great interest, but also due to the need to adapt the ship's performances to the ever-changing navigation conditions, these types of ships have been studied in order to improve their particulars, characteristics, and their hulls shape.
Over the years several transport ships have been studied using numerical simulations, such as numerical and experimental analysis of added resistance of ships in waves [5] with Reynolds-Averaged Navier – Stokes methods, the examination of speed performance for various types of commercial ships [6] also based on RANS methods, comparative seakeeping analysis [7] using different methods, etc.

One of the biggest challenges is predicting the behavior of ships in the real sea. Prediction of seakeeping performances is essential from an early design stage, to ensure that the ship will be able to meet the operation requirements and fulfill its mission in real sea conditions. But studying the behavior of a ship involves several problems to solve, such as: nonlinearities induced by fluid viscosity and hydrodynamic pressure, interference between ship’s body and waves, and time-domain procedures for analysing the ship’s response to oscillations [7]. Mathematical models can be solved numerically, offering approximate solutions to very complex problems that are most of the time impossible to treat analytically. Because of this numerical approach are becoming increasingly popular and this is also supported by the enhanced accuracy due to the increase of computing capabilities. The use of CFD (Computational Fluid Dynamics) methods is constantly increasing due to its advantages compared to towing testing. The main advantages of numerical simulations are lower costs, there is no need for a ship model, the configuration parameters can be changed very easily, and the results can be obtained in a much shorter time. But to use these methods we need a high-performance computer with multiple processors with which we can significantly reduce the computation time.

In this paper, a grid convergence test for three grids with panels of different densities was performed to demonstrate that the results did not depend on the fineness of the discretization grid. A series of simulations in calm water were performed to validate the results obtained with those of the experimental method. Also, a numerical approach of the seakeeping performance of a container ship in regular waves, for a range of six speeds, five wavelengths and four wave heights using a 3D fully nonlinear time-domain Boundary Element Method (BEM) implemented in the commercial software SHIPFLOW Motions is presented.

Figure 1. Maritime traffic in Europe [8].
Regarding this hull, results for model test basin are available only for resistance, propulsion performances and roll decay. In a previous study, the experimental results were compared with different numerical approach results [9]. The mean difference over the speed domain, obtained with SHIPFLOW was 2.011%.

2. Computing strategy

For this study the hull of a benchmark container ship was studied. The hull is a typical container ship developed at Institute of Ship Technology, Ocean Engineering and Transport Systems (ISMT) [10] and presented in figure 2.

![Figure 2. Benchmark container ship hull.](image)

The container ship, also known as Duisburg Test Case, is a modern 14000 TEU Post-Panamax vessel with a bulbous bow, large stern, and a single screw. Bare hull, without rudder and propeller has been considered for the numerical simulations. In table 1 are presented the main characteristics of the vessel in design loading condition, both for model and full scale [9, 10].

| Main particulars                  | Full scale | Model |
|-----------------------------------|------------|-------|
| Length between perpendiculars    | L<sub>pp</sub> [m] | 355   | 5.976 |
| Waterline breadth                 | B<sub>WL</sub> [m]  | 51    | 0.859 |
| Draught midship                   | T<sub>m</sub> [m]  | 14.5  | 0.244 |
| Trim angle                        | U [°]       | 0     | 0     |
| Volume displacement               | V [m³]      | 173467| 0.827 |
| Block coefficient                 | c<sub>B</sub> [-] | 0.661 | 0.661 |
| Wetted surface                    | S<sub>w</sub> [m²] | 22032 | 6.243 |
| Design speed                      | v<sub>d</sub> [m/s] | 12.86 | 1.668 |

The prediction for ship motions and additional resistance in waves is presented in this paper. In waves, ships develop a much higher resistance than resistance in calm water, which is called additional resistance and is generated by energy dissipation due to ship motions and due to the reflection of incident waves [11].

The purpose of this paper is to investigate the behaviour of the Duisburg Test Case container ship (DTC) in regular waves at six speeds, from 1.335 m/s to 1.668 m/s for several nondimensional wave lengths and nondimensional wave heights presented in table 2. The simulations were performed for regular head waves based on the 5th order Stokes wave theory and ran until the convergence was reached.

Simulations were performed on a desktop computer with four cores of 3.1 GHz. Additionally, simulations were performed to study the discretization grid, for a panel density range from 0.2 to 1.2, with a step of 0.1, on a desktop computer with 10 cores. The time of the simulations for the discretization grids was from 42 minutes to 8 hours, and the time of the simulations on regular waves lasted around 4-6 hours per case. The total number of simulations was 129.
Table 2. Test cases.

| v [m/s] | Method | λ/L | H/L  |
|---------|--------|-----|-----|
| 1.335   |        | 0.50| 0.0056|
| 1.401   |        | 0.75| 0.0133|
| 1.469   | BEM    | 1.00| 0.0169|
| 1.535   |        | 1.25| 0.0225|
| 1.602   |        | 1.50|     |
| 1.668   |        |     |     |

The 3D fully nonlinear time-domain boundary element method was used in this study. This method was used through commercial software SHIPFLOW Motions, a product of FLOTECH International AB, developed to compute ship motions in regular and irregular waves. The BEM, or so-called panel method, deals with potential boundary value problems. This method has the advantage of considering any nonlinearity of body geometry and making it possible to perform viscous and extraneous simulations. Another advantage is the short time through which results can be obtained, compared to other methods.

3. Grid convergence test
When dealing with number simulations, the discretization of the ship's body is an essential factor in obtaining accurate results. Therefore, before performing the simulations for seakeeping analysis, a study of the convergence of the discretization grid was performed, based on Richardson extrapolation [12] in order to investigate the numerical simulation error.

Numerical simulations on calm water at maximum speed were performed for three grids: coarse (corresponds to a panel density factor with the value 0.9), medium (corresponds to a panel density factor with the value 1.0) and fine (corresponds to a panel density factor with the value 1.1).

In Table 3 are presented the number of panels and the number of nodes distributed on hull and free surface for the grids used for grid convergence test. The simulations were performed on desktop machines with ten cores.

Table 3. Computational grids.

|                | Coarse | Medium | Fine |
|----------------|--------|--------|------|
| Density factor | 0.9    | 1.0    | 1.1  |
| c_w *1000      | 0.676  | 0.721  | 0.792|
| R_w [N]        | 5.677  | 6.060  | 6.651|
| No. of panels  | 32446  | 40882  | 49301|
| No. of nodes   | 33266  | 41800  | 50311|

The refining grid parameter (r_G) was considered 1.26. S1, S2 and S3 correspond to the solution returned by the simulation for the grids used in this calculation. With the help of these parameters we calculated R_G which represents the convergence ratio and has the following expression:

\[ R_G = \frac{\varepsilon_{12}}{\varepsilon_{12}} \]

where \( \varepsilon_{12} = S_2 - S_1 \) and \( \varepsilon_{12} = S_3 - S_2 \).

Depending on the value R_G, three convergence conditions are possible [12]: monotonic convergence when R_G is between 0 and 1, oscillatory convergence when R_G is less than 0 and divergence when R_G is greater than 1. The value of R_G is 0.647 for c_w and 0.646 for R_w. The value is between 0 and 1, which means that we are in the case of monotonic convergence.
The next step is to apply the generalized Richard extrapolation [12] which estimates the error \( \delta_G \) and the order of precision \( p_G \).

\[
p_G = \frac{\ln(\varepsilon_{21})}{\ln(r_G)}
\]

(2)

\[
\delta_G = \frac{\varepsilon_{21}}{r_G^{p_G}}
\]

(3)

The last step is to calculate the correction factor and with its help the uncertainty. For the calculation of the correction factor, the theoretical order of the network convergence (\( p_{th} \)) was considered equal to two.

\[
c_G = \frac{r_G^{p_{th}} - 1}{r_G^{p_{th}} - 1}
\]

(4)

\[
U_G = \left| c_G \right| + \left| 1 - c_G \right| \left| \delta_G \right|
\]

(5)

According to the results presented, we can conclude that the solutions obtained after running in SHIPFLOW are grid independent. For the regular wave simulations performed in this paper, the fine grid was chosen.

4. Results and Discussion
This section presents the results of regular wave simulations over the full range of speeds, heights, and wavelengths, as well as the influence of wave height, wavelength, but also speeds. To validate the results obtained by numerical simulations, a comparison of the model resistance with the CFD resistance was made. The results of the towing tests used in this paper come from the model tests performed in the SVA Potsdam model test tanks and are available to the public [10].

In table 4 are presented the results obtained from the calm water simulations for the entire speed range, as well as the results of the towing tests. Figure 3 shows the comparison between the model test resistance and the total resistance obtained in SHIPFLOW. The total resistance in the simulations consists of the wave resistance \( R_w \) added with the friction resistance \( R_F \). We can see that the values of the results are almost equal, the mean error difference being 3.36%. In the last column of table 4, the percentage difference between the resistance obtained on the model and the one in SHIPFLOW was calculated, for each speed.

| \( v \) [m/s] | \( R_w \) – calm water [N] (CFD) | \( R_F \) – calm water [N] (CFD) | \( R_T \) – calm water [N] (CFD) | Percentage Difference [%] |
|---------|-----------------|-----------------|-----------------|-----------------|
| 1.335   | 1.33            | 17.56           | 18.89           | 7.39            |
| 1.401   | 1.86            | 19.19           | 21.06           | 4.65            |
| 1.469   | 2.56            | 20.96           | 23.51           | 2.63            |
| 1.535   | 3.71            | 22.74           | 26.45           | 0.03            |
| 1.602   | 5.30            | 24.61           | 29.91           | 3.13            |
| 1.668   | 6.06            | 26.53           | 32.59           | 2.35            |
Numerical simulations were performed for a range of speeds from 1.335 m/s to regime speed, 1.668 m/s, for a range of nondimensional wavelengths from 0.5 to 1.5 with a step of 0.25, and for a range of nondimensional wave heights from 0.0056 to 0.0225. Figure 4 and figure 5 illustrates the effect of wavelength at regime speed (1.668 m/s) on the coefficient of additional resistance in waves and on the wave resistance on regular waves when the wave height is constant. The coefficient of additional resistance in waves was calculated as follows:

$$C_{aw} = \frac{R_w}{\rho g \cdot \zeta_A^2 \cdot B^2 / L_{pp}}$$

where:
- $R_w = R_{aw} - R_{w0}$; $R_w$ [N] represents the wave resistance in regular waves, $R_{aw}$ [N] represents the total wave resistance and $R_{w0}$ [N] represents the wave resistance in calm water;
- $\rho$ [kg/m$^3$] is the water density;
- $g$ [m/s$^2$] is the gravitational acceleration;
- $\zeta_A$ [m] is the wave amplitude; $\zeta_A = H/2$. 

**Figure 3.** Comparison between model resistance and numerical simulation resistance.

**Figure 4.** Influence of wavelength at regime speed on the coefficient of additional resistance.

**Figure 5.** Influence of wavelength at regime speed on the wave resistance.
The influence of the wave resistance on the total resistance is presented as a percentage in table 5 (with green are represented the lowest values and with red the highest values). As the wave height increases, the contribution of the wave resistance increases, from 11.64% at the lowest wave height and lowest wave length to 67.41% at the highest wave height and wave length 5.976 m. Another observation would be that the percentage increase is slightly lower at higher speeds.

Table 5. Influence of wave resistance.

| v[m/s] | λ/L | H/L          | 0.0056 | 0.0133 | 0.0169 | 0.0225 |
|-------|-----|--------------|--------|--------|--------|--------|
| 0.5   | 0.75| 1.335        |        |        |        |        |
|       |     | 1            | 11.64% | 28.12% | 35.93% | 47.72% |
|       |     | 0.75         | 15.40% | 40.34% | 49.19% | 60.38% |
|       | 1   |              |        |        |        |        |
|       | 1.25| 21.35%       | 47.79% | 57.16% | 67.41% |
|       | 1.5 | 16.87%       | 38.44% | 47.49% | 57.34% |
|       | 1.5 | 13.06%       | 29.57% | 36.28% | 46.43% |
|       | 0.5 | 13.28%       | 27.48% | 35.19% | 46.59% |
|       | 0.75| 16.02%       | 38.77% | 47.53% | 58.40% |
| 1.401 | 1   |              |        |        |        |        |
|       | 1.25| 21.02%       | 47.55% | 57.12% | 67.34% |
|       | 1.5 | 17.21%       | 39.03% | 47.53% | 57.40% |
|       | 1.5 | 13.30%       | 29.85% | 36.69% | 46.17% |
|       | 0.5 | 14.97%       | 27.26% | 34.14% | 44.75% |
|       | 0.75| 17.68%       | 37.49% | 46.12% | 56.83% |
| 1.469 | 1   |              |        |        |        |        |
|       | 1.25| 22.34%       | 47.84% | 56.84% | 67.02% |
|       | 1.5 | 18.10%       | 39.51% | 47.91% | 57.68% |
|       | 1.5 | 14.79%       | 29.95% | 37.01% | 46.56% |
|       | 0.5 | 16.55%       | 28.37% | 35.04% | 45.29% |
|       | 0.75| 19.71%       | 36.98% | 45.30% | 55.54% |
| 1.535 | 1   |              |        |        |        |        |
|       | 1.25| 23.64%       | 47.32% | 56.06% | 65.63% |
|       | 1.5 | 20.49%       | 40.67% | 48.84% | 58.25% |
|       | 1.5 | 17.25%       | 30.59% | 37.86% | 47.16% |
|       | 0.5 | 19.78%       | 29.95% | 35.87% | 45.25% |
|       | 0.75| 22.14%       | 37.49% | 45.51% | 55.19% |
| 1.602 | 1   |              |        |        |        |        |
|       | 1.25| 26.35%       | 47.92% | 56.25% | 65.86% |
|       | 1.5 | 23.47%       | 42.18% | 49.23% | 58.95% |
|       | 1.5 | 20.57%       | 31.83% | 39.01% | 47.38% |
|       | 0.5 | 21.27%       | 30.09% | 35.30% | 44.85% |
|       | 0.75| 23.23%       | 36.98% | 44.49% | 54.16% |
| 1.668 | 1   |              |        |        |        |        |
|       | 1.25| 27.25%       | 48.13% | 56.28% | 65.62% |
|       | 1.5 | 24.84%       | 42.81% | 50.04% | 59.10% |
|       | 1.5 | 21.92%       | 32.62% | 39.74% | 47.64% |

The influence of the wave generated by the ship is shown in figure 6(a) where the pitch RAO for variable wave lengths is illustrated. The distance between pitch curves calculated for the H/L=0.0056 and the other curves plotted for higher wave hight, emphasise the non-linear effect of the wave generated by the ship on the pitch especially for higher speed. One can see that with the increase of the length, the influence of the wave also increases. Figure 6(b) shows the wave resistance in the case of variable wave heights, which increases with the increase of the ship-wave meeting frequency.

Figure 7 shows the free surface for the lowest studied wave height (H/L = 0.0056) and the highest studied wave height (H/L=0.0225), for the entire speed range, at the wavelength λ/L =1.
Figure 6. Influence of wavelength on pitch RAO (a) and influence of wave height on wave resistance (b).
5. Conclusions

The behavior of ships on waves is a topical issue in continuous research and development, so that ships will be able to sail at full capacity, regardless of changing weather conditions. CFD methods have advanced with the increased performance of computers, and in the future, it is desired to replace expensive towing tests with numerical simulations, which are easier to perform.

In this paper, a series of numerical simulations were made to see how a benchmark container ship behaves on regular waves, at different wave heights and lengths. A total of 129 numerical simulations were performed, of which 3 for grid testing, 6 for validation of results in calm water and 120 for the study of behavior on regular waves.

A convergence study was performed for three grids: coarse, medium and fine. According to the grid convergence test, the convergence ratio value is in the case of monotonic convergence, and the
solutions obtained are grid independent.

The results in calm water were validated by comparing them with the results of the towing tests. The average error across the entire speed range was 3.36%.

The study of regular waves was performed to identify the influence of wave height, wavelength, but also the speed of the ship. As expected, with the increase of the wavelength, it was possible to observe the increase of the wave contribution, which has an influence on the total resistance from 11% to 67%. The lowest influence was found for the case $\lambda/L = 0.5$ and $H/L = 0.0056$, and the highest influence was found for the case $\lambda/L = 1$ and $H/L = 0.0225$. Influences of 65-67% were also found for the entire speed range in the case of $H/L = 0.0225$ for $\lambda/L$ from 0.75 to 1.25. Also, as the height of the waves increases, another factor that affects the wave resistance is the increased frequency of the ship-wave encounter.

Studying the behavior of ships on waves is necessary to be able to study the effect that waves have on the movements of the ship, as well as the effect of the ship's wave. As expected, with the increase of the height of the waves, another factor that affects the wave resistance is the increased frequency of the ship-wave encounter.

The study of regular waves was performed to identify the influence of wave height, wavelength, but also the speed of the ship. As expected, with the increase of the wavelength, it was possible to observe the increase of the wave contribution, which has an influence on the total resistance from 11% to 67%. The lowest influence was found for the case $\lambda/L = 0.5$ and $H/L = 0.0056$, and the highest influence was found for the case $\lambda/L = 1$ and $H/L = 0.0225$. Influences of 65-67% were also found for the entire speed range in the case of $H/L = 0.0225$ for $\lambda/L$ from 0.75 to 1.25. Also, as the height of the waves increases, another factor that affects the wave resistance is the increased frequency of the ship-wave encounter.

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