

## Trim optimisation in waves

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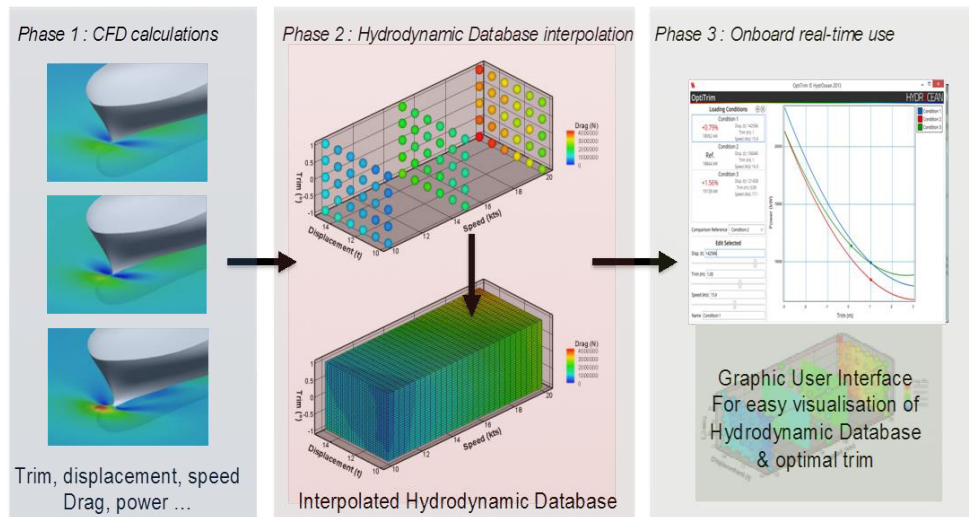
**Summary:** *The trim optimisation is nowadays a common practice for all ship owners. Reduction of fuel consumption and improvement of ship energy efficiency concern all sectors of the maritime industry. The trim optimisation consists in finding the best trim angle with regards to the lowest power - i.e. fuel consumption - for a given operating condition (loading condition and speed). Although the operational efficiency of trim optimisation based on calm water resistance computations databases could be proven at sea, it is well known that added resistance due to wave can significantly impact fuel consumption. The increase of cluster computing power make it today possible to evaluate the added resistance in waves using state of the art free surface RANSE solvers. This study of the optimal trim depending on the sea-states show that taking into account the waves could have a significant impact on the optimal trim that have been identify on still water. Although the optimal trim angle trends are the same on still water and in waves for low sea-states, for highest sea-states the trends can be the perfect opposite. This study shows that the optimal trim mainly depends on the draft and the sea-state. The speed seems to have an effect on the gains / losses amplitude but not on the best trim value. The in waves databases will enable operators to predict their ship efficiency with better accuracy, taking into account weather predictions. The trim needs to be therefore adapted regularly depending on the weather conditions the ship encounter during her voyage.*

### 1. INTRODUCTION

The trim optimisation is nowadays a common practice for all ship owners. Reduction of fuel consumption and improvement of ship energy efficiency concern all sectors of the maritime industry. Even though the oil price is low, ship owners are still asking for more economical ships. Regulation now also imposes that ship owners reduce air emissions (NOX, SOX) of their ships. The trim optimisation is considered as one of the most easily achievable and cost effective fuel saving practices, as it requires no ship modification. The trim optimisation consists in finding the best trim angle with regards to the lowest power - i.e. fuel consumption - corresponding to a given operating condition (loading condition and speed). The ship trim is then set by changing the location of the centre of gravity issued from the deadweight weight distribution or issued from ballasting. The trim optimisation databases provided by HydrOcean

are generally generated from 100 free surface RANSE computations combining speed, displacement and longitudinal position of the centre of gravity (directly linked to the static trim). They are routinely based on calm water resistance simulations for CPU cost effectiveness.

HydrOcean has developed and distributes a dedicated trim optimisation Database and Software (figure 1) that enables a ship's crew to determine the optimal trim at given ship displacements and speeds. It has shown its efficiency in terms of return of investment. As an example, for a container ship with a consumption of 25 000t / year, about 1.0 % of Heavy Fuel Oil (250t / Year / Vessel) are saved thanks to the trim optimisation.



**Figure 1:** HydrOcean's trim optimisation Database and Software

Although the operational efficiency of trim optimisation based on calm water resistance computation databases could be proven at sea, it is well known that added resistance due to wave can significantly impact fuel consumption. The increase of cluster computing power make it possible today to evaluate the added resistance in waves using state of the art free surface RANSE solvers.

This paper presents a comparison between a trim optimisation carried out on calm water with one performed in waves. The methodology and the numerical parameters are firstly presented and then the results and conclusions.

## 2. METHODOLOGY

This part presents the methodology used in order to compute the mean drift forces according to a given irregular sea-state. The mean drift forces could be evaluated using direct computations on an irregular sea-state or using post-processing based on added resistance transfer function called further ARTF. Although the first solution is more accurate, the requested CPU time are too long for this kind of application since the mean drift forces need to be evaluated for a large amount of sea states which require one computation by sea-state. The second solution was therefore chosen since the computation of ARTF enable to determine the mean drift forces for many sea-states just by post-processing and without requiring new CPU time. This second methodology is described hereafter.

The estimation of mean drift forces is divided into 4 main steps:

1. Modeling the ship with a forward speed for various frequencies in 1m regular waves (CFD computations).
2. Building an added resistance transfer function issued from step 1 results.
3. Combination of an added resistance transfer function and a wave spectrum
4. Determination of the mean drift force in irregular waves for a given sea-state.

Please note that for the second point, the ARTF depends on the ship speed and displacement.

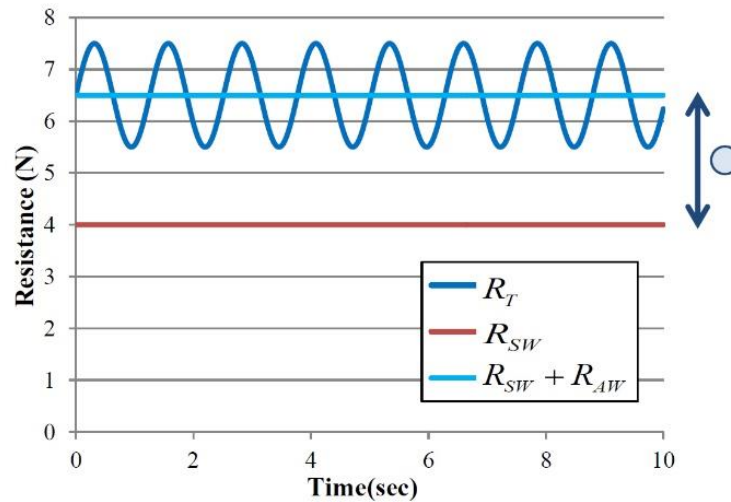
The estimation of added resistance in regular waves is issued from ITTC recommendation [6]. The mean added resistance in waves is obtained by the subtraction of the still water resistance from the total resistance in waves (equation 1 and figure 2).

$$R_{AW} = \overline{R_T} - R_{SW}$$

$R_{AW}$  : Mean added wave resistance  
 $R_{SW}$  : Still water resistance  
 $R_T$  : Total resistance in waves

(1)

The estimation of the added resistance in regular waves therefore requires a preliminary still water resistance computation.



**Figure 2:** Mean added resistance in waves definition

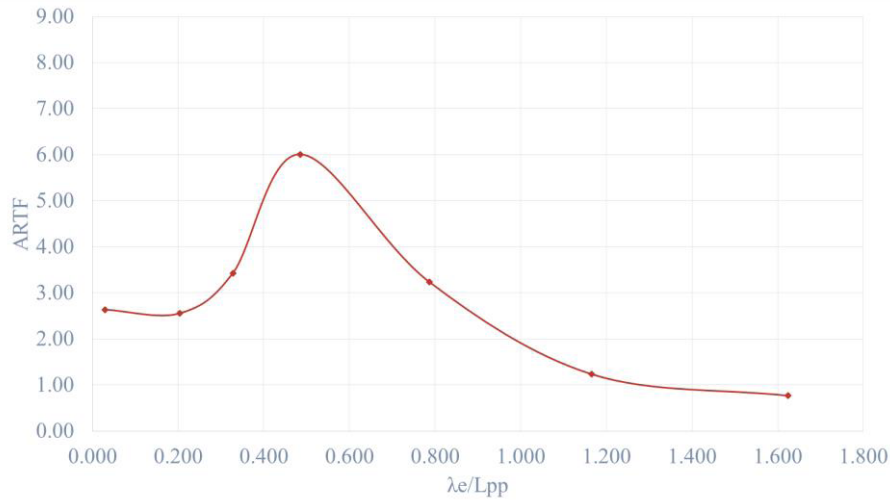
The mean added resistance in waves is computed for 1 m regular waves for a range of wave length (generally from  $0.2L_{pp}$  to  $2.0$ ) that enables to reproduce all physical phenomena (diffraction, radiation, motion resonance ...) that appears depending on the wave length. The added resistance transfer function is then computed by the following dimensionless equation.

$$ARTF = \frac{R_{AW}}{\rho g A^2 B^2 / L_{pp}}$$

With:

- $R_{AW}$  : Mean added wave resistance
- $\rho$  : water density
- $A$  : Wave amplitude
- $B$  : Ship beam
- $L_{pp}$  : Ship length between perpendicular

The figure below show an example of ARTF.



**Figure 3:** Example of ARTF

Although the wave spectrum chosen for the whole study is Pierson-Moskowitz other kinds of spectra such as Jonswap or Bretschneider-Mitsuyau could have been used for this methodology. This choice was made according to the typical commercial route of the container ship. Depending on the weather condition the ship will encounter during his voyage, the wave spectrum parameters will be adapted with regards to  $H_s, T_p$ .

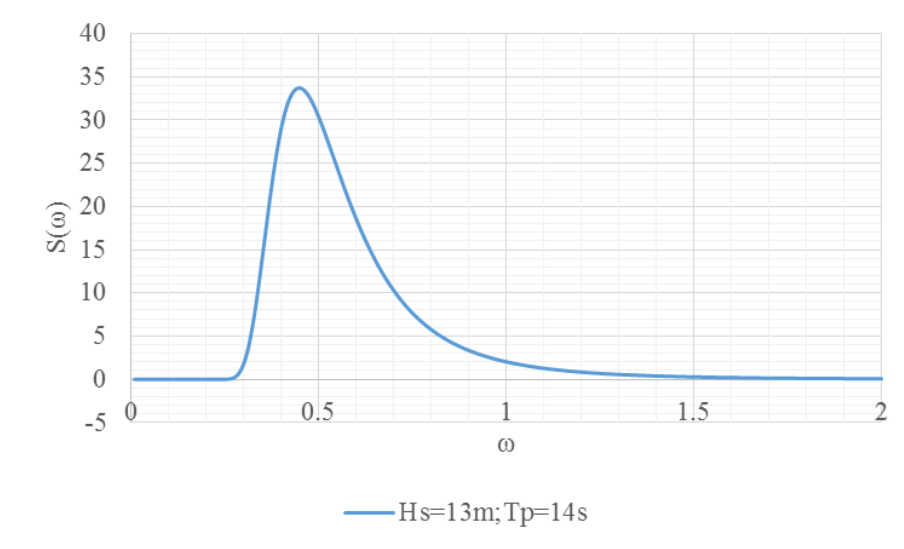
The Pierson-Moskowitz wave spectrum is given by the following equation [5].

$$S(\omega) = 5\pi^4 \frac{H_S^2}{T_P^4} \cdot \frac{1}{\omega^5} \exp \left[ -\frac{20\pi^4}{T_P^4} \cdot \frac{1}{\omega^4} \right]$$

With:

- $H_S$  : significant wave height
- $T_P$  : peak wave period
- $\omega$  : Wave pulsation

An example of Pierson-Moskowitz wave spectrum with  $H_s=13m$  and  $T_p=14s$  is presented on the following graph.



**Figure 4:** Pierson-Moskowitz wave spectrum with  $H_s=13\text{m}$  and  $T_p=14\text{s}$

Once the ARTF and the wave spectrum are defined, the last step is the mean drift forces computation using the following formulae.

$$\overline{R_{AW}} = 2 \int_0^{\infty} \frac{R_{AW}}{A^2} S(\omega) d\omega$$

With:

$R_{AW}$  : Mean added wave resistance

$A$  : Regular wave amplitude used to compute the ARTF

$S(\omega)$  : Wave spectrum

(4)

### 3. NUMERICAL PARAMETER

This part presents the numerical parameters of the CFD computations.

#### 3.1. Coordinate systems

The coordinate system is described below:

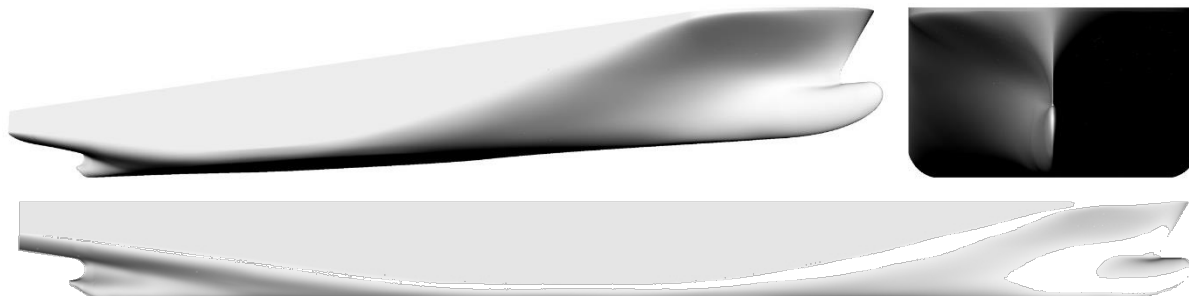
- Origin is located at the intersection of symmetry plane, rudder axis, keel line
- X axis is oriented toward ship bow
- Y axis is oriented port side
- Z axis is oriented up



**Figure 5:** Coordinate system definition

### 3.2. Geometry

The geometry of the container ship used for the trim optimisation study is presented on the figure below. For confidentiality reasons, the hydrostatic particulars and main dimensions are not provided.



**Figure 6:** Container ship geometry

### 3.3. Simulation parameters

The simulation were carried out with ISIS-CFD solver (described in the next paragraph) at full scale using the  $k-\omega$  SST (Menter) turbulence model. A fixed velocity is imposed to the hull from rest to the target speed. Simulations are unsteady, with free heave and pitch. Water characteristics are for salt water (15°C) issued from ITTC [9] (Density 1026.0210 kg/m<sup>3</sup>, Dynamic viscosity: 0.001220 Pa.s). LCG is calculated to reach the required static equilibrium position corresponding to each trim condition. VCG is assumed to be at free surface. The displacement is fixed when varying the trim.

### 3.4. Solver description

ISIS-CFD flow solver developed by ECN (Ecole Centrale de Nantes) uses the incompressible unsteady RANSE (Reynolds Averaged Navier-Stokes Equations) as the governing equations. The equations of  $k-\omega$  SST turbulence model are used for the closure of RANSE.

ISIS-CFD solver is based on the finite volume method to build the spatial discretization of the transport equations. The velocity field is obtained from the momentum conservation equations and the pressure field is extracted from the mass conservation constraint, or continuity equation, transformed into a pressure equation. In the case of turbulent flows, additional transport equations for modelled variables are solved in a form similar to those of the momentum equations and they can be discretized and solved using the same principles. Incompressible and non-miscible flow phases are modelled through the use of conservation equations for each volume fraction of phase [1].

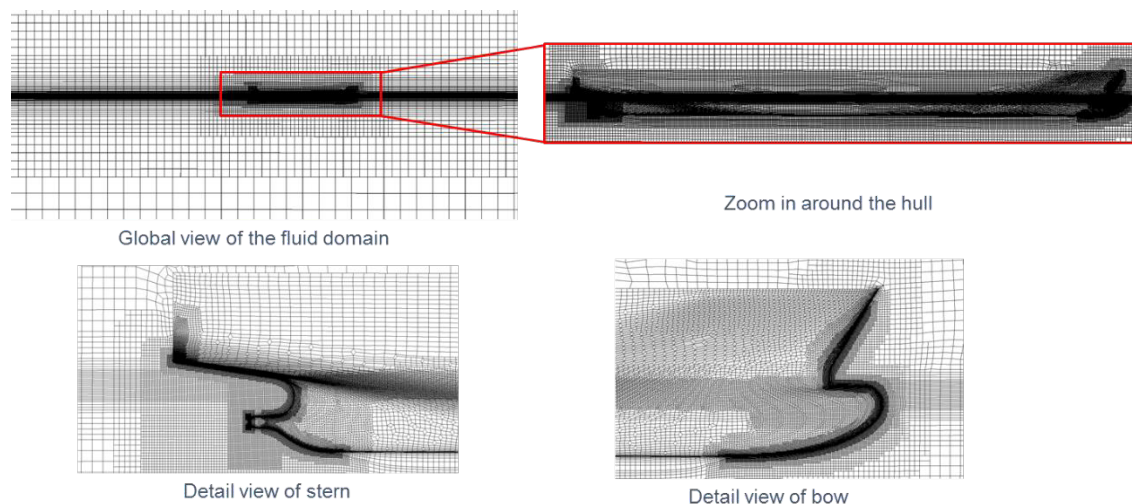
ISIS-CFD solver has been validated through lots of benchmark cases by comparing with towing tank model test. It ensures the accurate estimation of ship hull hydrodynamic performance. It is also possible to propagate regular waves from boundary conditions.

### 3.5. Matrix of computations

In order to be able to compare the trim optimisation in waves with the trim optimisation in still water the scope of work is divided into two parts corresponding respectively to still water resistance computations and added wave resistance computations. The trim optimisation was carried out with regards to 2 drafts and 2 speeds. For each operating condition 4 trims were evaluated. 7 wave periods will be computed in order to build the ARTF corresponding to each condition. To sum up, 16 still water resistance and 112 added resistance in waves simulations were performed.

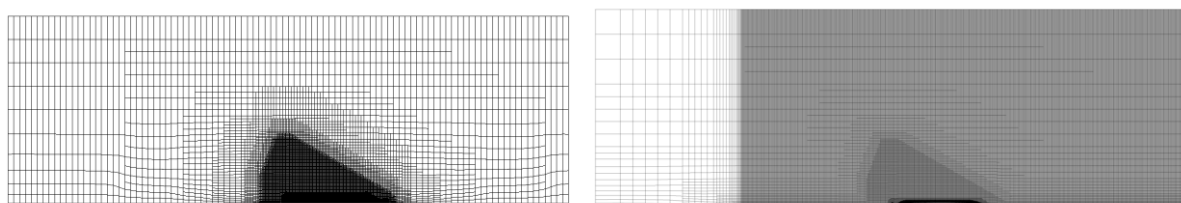
### 3.6. Grid characteristics

This part presents the grid characteristics of the calm water grids and then the special parameters of the grids used for added resistance in waves simulations. The calm water grids are unstructured and composed of 3.5 million cells per grid. 16 grid was generated, one per combination of draft and trim. Wall function were used with  $30 < Y^+ < 300$  corresponding to ITTC recommendation [7,8]. Some grid views for the 11.0 m draft even keel are presented hereafter.



**Figure 7:** Grid views for the 11.0 m draft even keel

Some additional refinement are used into the grids used for added resistance in waves simulations because of the wave propagation. The main criteria to be respected concern the ratio between the wave amplitude with the vertical cell size where  $H/dz \geq 8$  and the ratio between the horizontal cell size with the vertical cell size where  $dx/dz < 8$ . The grid is therefore finer for wave propagation with about 5 million cells per grid.



**Figure 8:** Comparison between resistance grid refinement (left) and in waves grid refinement (right).



## 4. RESULTS

This part presents firstly the analysis of the calm water resistance results computed for different combination of speed, draft and trim. The analysis of the added resistance in waves results with regards to the optimal trim on the same operating condition as the still water resistance is then presented and compared to the still water results.

### 4.1. Still water resistance

The tables below show the differences in terms of resistance with regards to the even keel configuration for four operation conditions issued from the combination of speeds drafts.

**Table 1:** Differences in terms of ship resistance with regards to the even keel configuration, 4 operating conditions

T(m)	Trim (m)	V (kn)	Diff Rts (%) / Trim 0
11.0	-2.0	15.0	1.03%
11.0	-1.0	15.0	0.91%
11.0	0.0	15.0	0.00%
11.0	1.0	15.0	-1.14%

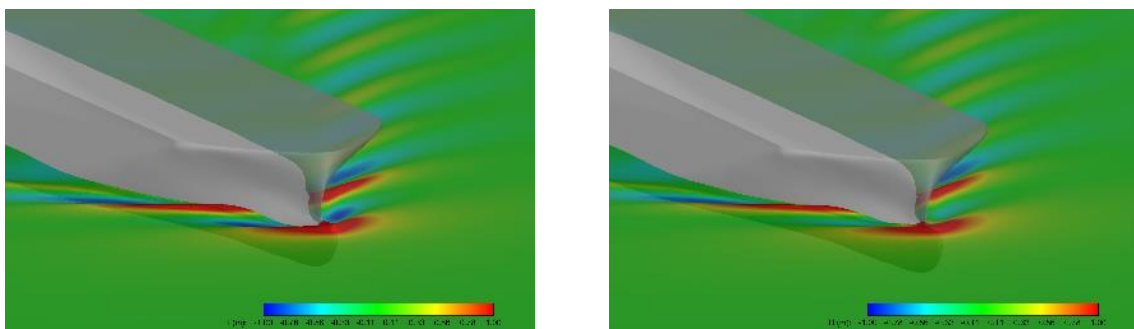
T(m)	Trim (m)	V (kn)	Diff Rts (%) / Trim 0
11.0	-2.0	18.0	4.22%
11.0	-1.0	18.0	2.90%
11.0	0.0	18.0	0.00%
11.0	1.0	18.0	-2.76%

T(m)	Trim (m)	V (kn)	Diff Rts (%) / Trim 0
14.0	-2.0	18.0	3.19%
14.0	-1.0	18.0	0.40%
14.0	0.0	18.0	0.00%
14.0	1.0	18.0	-0.34%

T(m)	Trim (m)	V (kn)	Diff Rts (%) / Trim 0
14.0	-2.0	21.0	2.77%
14.0	-1.0	21.0	0.42%
14.0	0.0	21.0	0.00%
14.0	1.0	21.0	-0.23%

Although the trend is the same (bow down is better), the amplitude of gains / losses is different between the operating conditions with gains varying from 0.2% to 2.76% and losses varying from 2.77% to 4.22% for the same trim range. Depending on the trim configuration, the bow and stern contributions to the resistance are different and therefore lead to gains or losses with regards to the even keel configuration.

The figures below illustrate the differences in terms of interactions between the water surface and the bulbous bow when changing the trim.

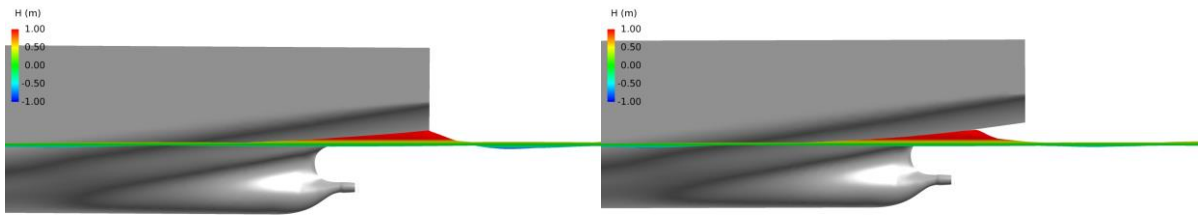


**Figure 9:** Interactions between the water surface and the bulbous bow different when changing the trim

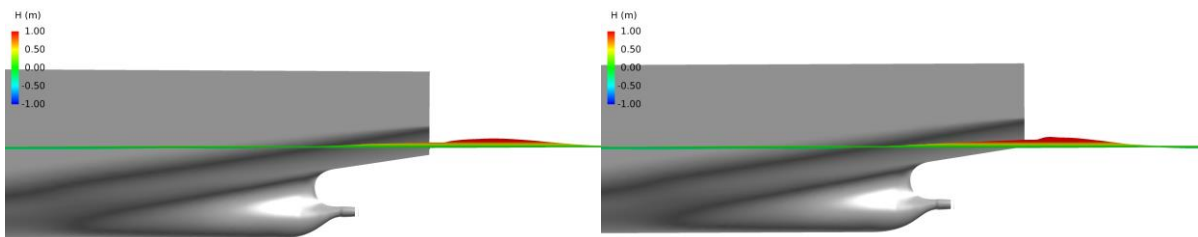
These interactions are among the origins of the trim optimisation gains or losses. The second main factor is the stern immersion, as shown on the figures below. There are three main



phenomena that contribute to the ship resistance around the stern: the stern slope, the wetted length, and the transom immersion.



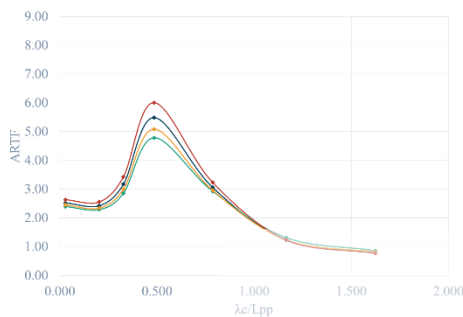
**Figure 10:** Differences in terms of stern slope, the wetted length when changing the trim



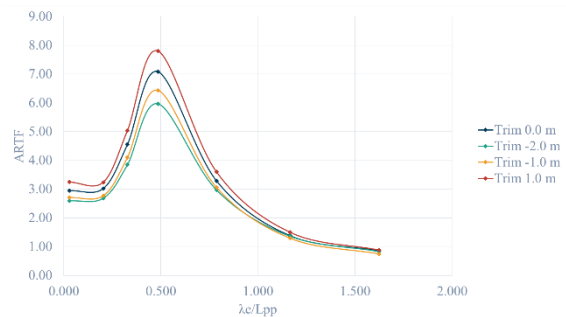
**Figure 11:** Differences in terms of transom immersion / transom wetness when changing the trim

#### 4.2. Added resistance in waves

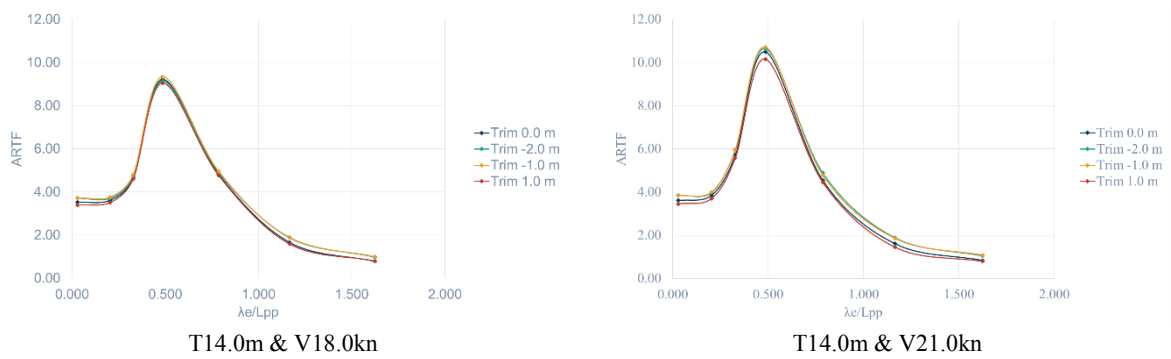
The graphs below show the ARTF computed for the same four operating conditions and four trims simulated in still water resistance. The range of wave length is between  $0.2L_{pp}$  and  $1.6L_{pp}$  and distributed according to 7 values chosen to well describe the different parts of the curve (3 around the peak, 2 around the flat part corresponding to the short periods and 2 in the slope between the peak and the large periods). As expected, all ARTF have the same shape. A horizontal flat shape is obtained for short periods below  $0.2L_{pp}$ . In this part, the motion are very low and the main contribution of forces is due to the wave diffraction generally called drift forces. The peak of added resistance in waves is mainly due to motion radiation. The peak frequency is very close to the ship length which corresponds to the motion resonance frequency of the pitch motion. As far as the wave length increases (to the right of the curve) the wave conditions are closer to the still water and therefore the added resistance in waves is decreasing to zero.



T11.0m & V15.0kn

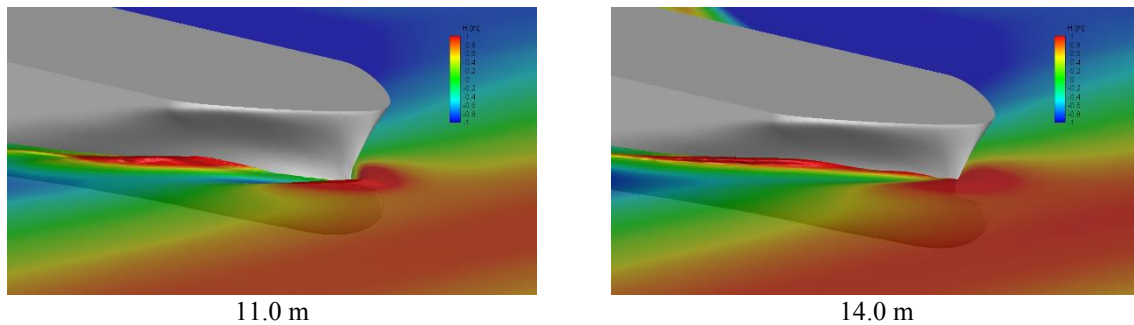


T11.0m & V18.0kn



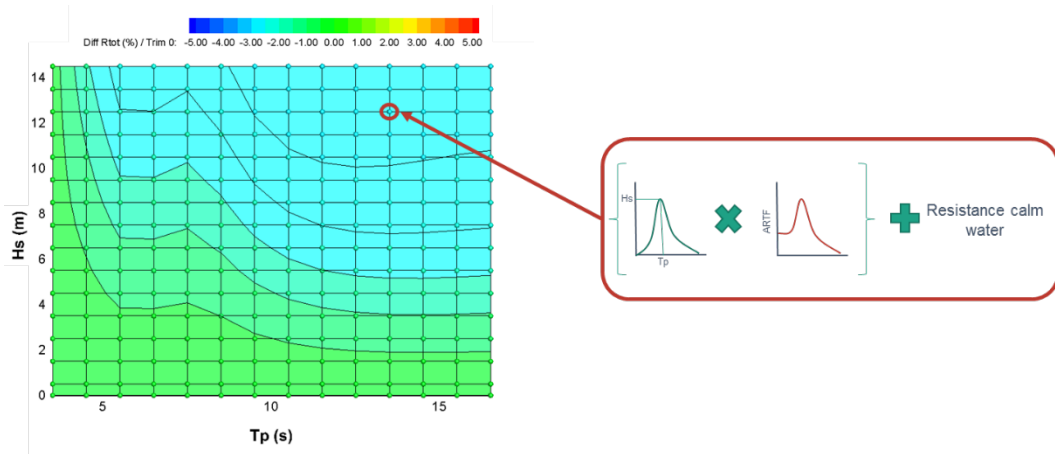
**Figure 12:** ARTF of the four operating conditions

ARTF curves show that as the speed increases, the peak is higher and slightly moved to the left due to the reduction of the encounter periods. The effect of the trim is more visible for the draft 11.0 m than for the draft 14.0 m. This is mainly due to the fact that the bulbous bow is closer to the free surface for the draft 11.0 m and fully immersed for the draft 14.0 m. The figures below illustrate the bulbous bow immersion in waves for the drafts 11.0 m and 14.0 m.



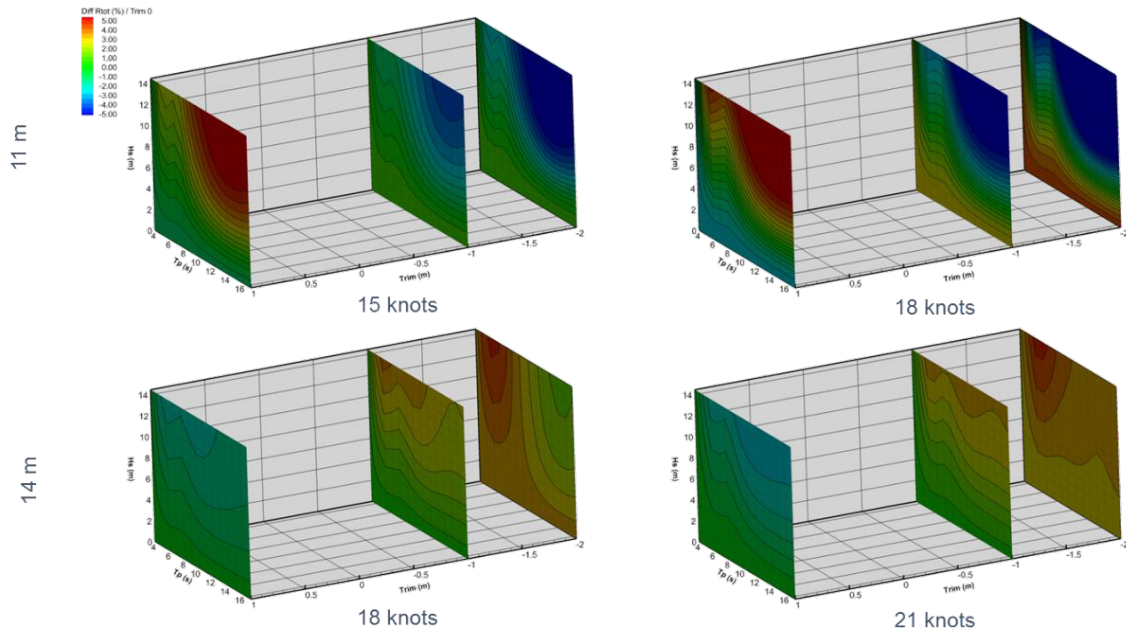
**Figure 13:** Bulbous bow immersion in waves for the drafts 11.0 m and 14.0 m at 18.0 kn.

The trim optimisation in waves depends of the sea-state the ship will encounter during his voyage. In order to have a look on a large range of sea-states, the mean drift forces - computed according to the methodology presented in the paragraph 2 – were estimated for a full matrix composed of 14 peak wave periods from 4.0 s to 17.0 s and 16 significant wave heights from 0.0 m to 15.0 m. The mean drift forces were evaluated also for the 4 trims. A database composed of 896 values of total resistance in waves was therefore determined as post-processing of the CFD computations (ARTF) enabling to study the best trim with regards to a given sea-state. The figure below show an example of the differences in terms of total resistance in waves with regards to the even keel trim configuration for the 224 sea-states. In the following example, the trim is equal to 1.0 to bow. Please note that some of the following sea-states are not realistic.



**Figure 14:** Example of the differences in terms of total resistance in waves with regards to the even keel trim configuration for the 224 sea-states for a trim equal to 1.0m to bow

The figures below illustrates the gains and losses in terms of total resistance in waves with regards to the even keel trim condition for each sea-state evaluated.



**Figure 15:** Gains and losses in terms of total resistance in waves with regards to the even keel trim condition for each sea-state evaluated

The trends highly depend on the considered draft as already discussed because of the interactions between the bulbous bow and the free surface. For low drafts, the optimal trim in waves can be opposite to the one in calm water. For the low sea-states, the trends are close to the still water ones but for the high sea-states in terms of peak wave period and significant wave height, the best trim in terms of total resistance in waves is bow up which is the opposite as the still water optimal trim angle. The trend is the same for the two speeds but the amplitude of gains is larger for the higher speed. For the higher drafts, the optimal trim is less impacted, but the gains are highly linked to the sea-state.

## 5. CONCLUSIONS

This study of the optimal trim depending on the sea-states show that taking into account the waves could have a significant impact on the optimal trim that have been identify on still water. Although the optimal trim angle trends are the same on still water and in waves for low sea-states, for highest sea-states the trends can be the perfect opposite. This study shows that the optimal trim mainly depends on the draft and the sea-state. The speed seems to have an effect on the gains / losses amplitude but not and the best trim value. The in waves databases will enable operators to predict their ship efficiency with better accuracy, taking into account weather predictions. The trim needs to be therefore adapted regularly depending on the weather conditions the ship encounter during her voyage.

These conclusions are based on mean drift forces estimated using ARTF computed for 1.0 regular wave amplitude using the assumption of a linear dependency of the added resistance in waves with the square value of the wave amplitude.

## 6. ACKNOWLEDGEMENTS

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