Investigating Trim Optimisation in Waves for an AFRAMAX Tanker Using CFD

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Abstract

In the world of ever more increasing constraints on fuel consumption, trim optimisation becomes a more attractive option, which is further emphasized by the decreasing cost of CFD analysis. There is no doubt that trim optimisation can be very useful for fast displacement hulls such as container vessels, but can it be useful for full hull forms such as tankers and bulk carriers? Additionally, is the optimal trim in calm water also optimal in waves? We have conducted a trim optimisation study for an AFRAMAX tanker to find out the answers to these questions.

1. Introduction

Trim and draft optimisation are well known terms in shipping, and have been used for decades. They are used on various types of vessels, ranging from faster ships such as Ro-Ro and container vessels to slower, fuller hulls such as bulk carriers or tankers. The savings that can be achieved have been proven over and over again, showing significant efficiency increase for most vessels. For full hull form ships the absolute savings are smaller both due to the smaller total power and smaller portion of the pressure resistance in total resistance. Still, it is economically viable to conduct trim optimisation studies for most of these vessels, especially with today's rise of high fidelity computational methods, and new stricter emission regulations.

While the benefits of trim and draft optimisation in calm sea conditions are well known and fairly well documented, there is little data on the benefits in realistic sea conditions. Ships sailing on long routes can achieve the highest benefit from trim optimisation, but are also often operating in moderate sea conditions. There is very little or no data on whether the trends from calm seas also apply to irregular waves. Kishev et al. (Kishev, Georgiev, Kirilova, Milanov, & Kyulevcheliev, 2014) reported that an experimental study was conducted to investigate trim optimisation in waves, but very little results are reported in the paper, making it difficult to draw conclusions. Ships crossing the north Atlantic for example spend around 65% of their service in wave conditions corresponding to a significant wave height ranging from 2.5 to 5.5 metres (Hogben, Dacunha, & Oliver, 1967). These sea conditions significantly increase the power requirements for most ships, and might in general change the trim-draft-speed-power trends obtained at calm sea.

The aim of this paper is to investigate the applicability of trim optimisation data generated using Computational Fluid Dynamics (CFD) for calm sea for the most common sea condition in the north Atlantic. The ship considered is an Aframax vessel spending most of its service crossing the Atlantic. Only head seas condition are investigated since these have the largest impact on resistance, and since the ship mostly sails in head and following winds when crossing the Atlantic. Calm sea trim optimisation results are also reported in detail, as well as their economic aspect regarding ship operational costs and savings. Software called the Naval Hydro Pack is used for all simulations.

2. Numerical method

The Naval Hydro Pack is a CFD software based on collocated Finite Volume method which uses Level Set for interface capturing. Special discretisation techniques are employed based on the Ghost Fluid Method to guarantee high accuracy of the two-phase flow model (Vukčević & Jasak, 2017).

For trim optimisation, a self-propelled vessel is simulated with two degrees of freedom: heave and pitch. The ship's propeller is modelled using the actuator disc model where a pressure jump is prescribed on a circular surface representing the propeller. The key feature of the algorithm is the ability to assess the undisturbed propeller inflow velocity without the need to perform a separate open water calculation (Jasak, Vukčević, Gatin, & Lalović, 2019). The large number of self-propulsion simulations needed for this study is managed using the automated procedure described in (Gatin, Vukčević, & Jasak, 2019), minimising human effort.

For simulations in waves, irregular seas are generated in CFD using the JONSWAP spectrum. Waves are introduced into the CFD domain and damped out of it using implicit relaxation zones (Jasak, Vukčević, & Gatin, 2015).

3. Vessel characteristics and sailing conditions in calm seas

The subject of the study is an Aframax vessel, with main characteristics shown in Table 1. The ship is simulated with the rudder and a propeller with a diameter of 7.2 m. Figure 1 shows the vessel with the rudder in side view.

Table 1. Aframax vessel main particulars.

L_{PP}, m	233.0
L_{OA}, m	243.5
B, m	42.0
D, m	21.3
$T_{scantling}$, m	14.5

Figure 1. Side view of the vessel.

The sailing and loading conditions for the trim optimisation study in calm seas are selected by observing the operational patterns of the vessel over the years of service. The loading conditions (i.e. drafts) and speeds that are often encountered in service are considered, while having in mind that the most important conditions are the ones corresponding to long voyages. At the same time, the range of the longitudinal static trim of the vessel is selected based on operational limits. Hereafter the positive trim denotes that the ship is trimmed aft with respect to even keel, while trim refers to static trim. The lower limit is mostly dictated by propeller submergence, especially in ballast condition, while the upper limit (bow up trim) depends on operational best practices and crew experience. Setting reasonable limits to the trim conditions that need to be tested reduces the number of overall simulations, lowering the cost of the study.

The list of all drafts, speeds and trims conducted in this study is shown in Table 2. The table shows the list of speeds and trims tested for individual loading conditions, i.e. drafts. Every combination of the draft, speed and trim is tested for individual loading condition, resulting in 64 simulations altogether. In ballast condition, some loading conditions only permitted one trim to be tested due to the requirements on the submergence of the propeller. Loading condition 1 and 2 were tested additionally, after the study showed that bow down trim generally saves fuel for larger speeds, which is why only the minimal trim is tested. At maximum draft of 15.5 metres the ship is only allowed to operate at even keel.

Table 2. Matrix of drafts, speeds and trims tested in calm water.

Load Condition No.	Draft, m	Speeds, kt	Trims, m
1	7.0	10, 12, 14	2.5
2	7.2	10, 12, 14	2.0
3	7.5	8, 10, 12, 14	1.0, 1.5, 2.0
4	7.8	8, 10, 12, 14	1.0, 1.5
5	13.0	8, 10, 12, 14	-1.0, -0.5, 0, 0.5, 1.0
6	14.0	8, 10, 12, 13, 14	-1.0, -0.5, 0.0
7	15.0	8, 10, 12, 14	-0.5, 0.0
8	15.5	8, 10, 12, 14	0.0

4. Trim optimisation results in calm seas

In this section some of the results are shown from the trim optimisation study in calm seas. A few representative load conditions are selected for presentation here in ballast and in fully laden conditions.

Figure 2 to Figure 5 show a few images from the conducted simulations. Figure 3 shows the wave fields for two different velocities and load conditions, where the difference in the geometry of the water-line at the stern can be observed due to a difference in submergence of the transom. On the right image in Figure 3, the wave field generated by the rudder can be seen, since the rudder is not fully submerged (see Figure 2, right image).

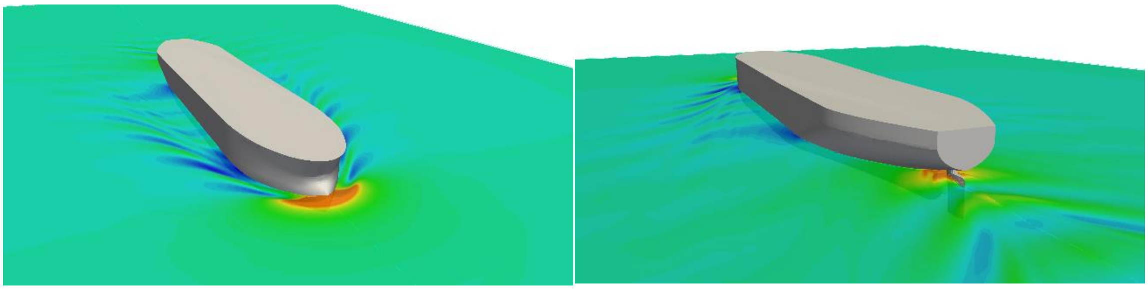

Figure 2. Perspective view of the ship sailing at 14 knots, load condition 3, trim 1.0 metre.

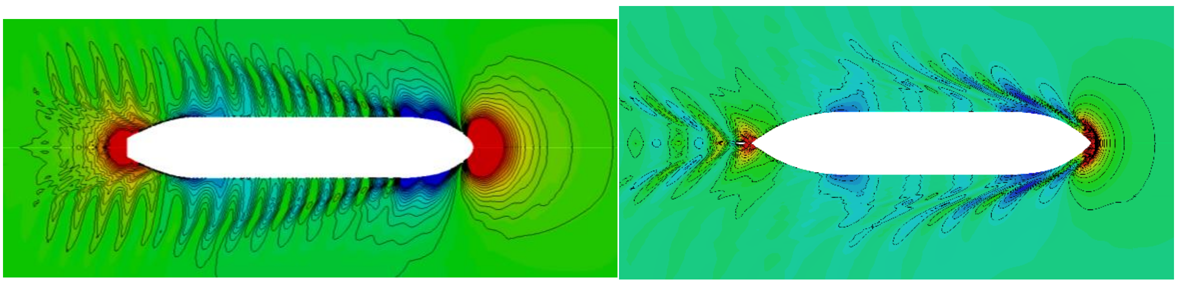

Figure 3. Wave field of the vessel sailing at 10 knots in load condition 8 (left) and in 14 knots in load condition 3 (right).

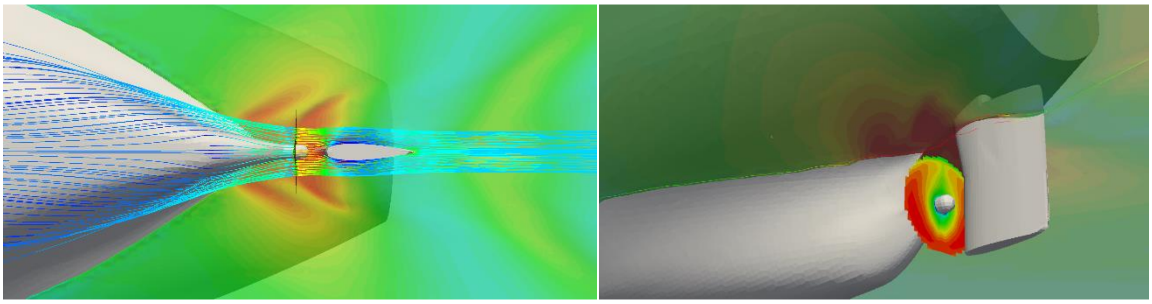

Figure 4. Streamlines showing the flow through the propeller and around the rudder (left), velocity magnitude on the propeller plane (right).

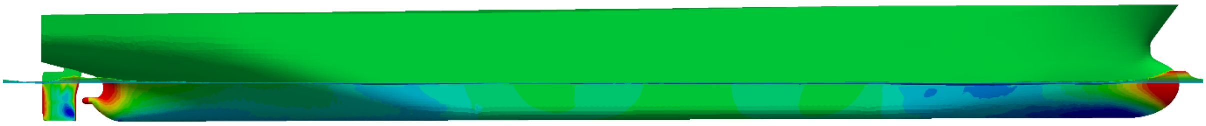

Figure 5. Pressure field along the hull for the ship sailing at 14 knots, load condition 3, trim 1.0 metre.

Figure 6 shows the power and fuel savings in tons per day for load condition 3 (7.5 m), as an example of the CFD output. For speeds 8-12 knots, the power reduces for bow down trim, while the opposite is true for speed of 14 knots. This shows that the trends are not trivial or easily predicted. At 14 knots, as much as 0.8 tons of fuel per day difference can be observed between trim 2.0 and 1.0 metres. Results for load condition 5 are shown in Figure 7, as an example for the laden condition, where the power mostly decreases with decreasing trim, with one exception at 14 knots and -0.5 m trim, where a peak in power is observed. In general, the differences between different trims reach from 0.5 to 1 ton per day of fuel consumption for the largest speed, with similar figures for ballast and laden conditions. At lower speed the differences are significantly smaller: e.g. for 12 knots the maximum differences are typically around 50% of those for 14 knots.

A more relevant representation of these results for the ballast condition is the one where they are compared across different drafts as well as trims, since in ballast it is feasible to change the operating draft. Table 3 and Table 4 show the power and fuel consumption for the ballast conditions, where the differences are represented across trims and drafts for a given speed. The maximum differences for 8 knots are small, around 0.2 tons/day. At 10 knots, up to half a ton/day can be saved. For 12 and 14 knots, differences up to 0.9 tons/day are observed. Note that the savings that can be achieved depend on the current operational practice, with which the optimum conditions need to be compared. This is reported in section 6.

For the laden conditions, a different representation is needed, since the draft is dictated by the amount of cargo. Here, the only freedom is in changing the static trim. For this vessel (and majority of tankers), the usual operational practice is to sail at even keel for laden condition, meaning that any savings compared to even keel are relevant. Table 5 shows relative differences in fuel consumption for laden loading conditions between even keel and the optimum trim, while Table 6Error! Reference source not found. shows the corresponding optimum trims. In general, savings can be expected ranging between 0.1 and 0.3 tons per day.

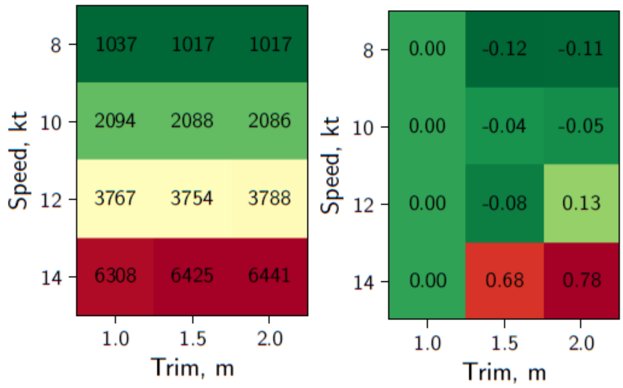

Figure 6. Power in kW (left) and fuel savings in tons per day with respect to trim of 1.0 m (right) for different speeds and trims for Load condition 3.

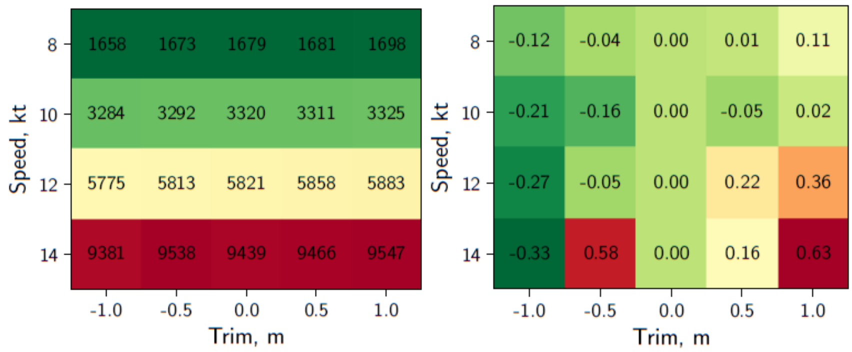

Figure 7. Power in kW (left) and fuel savings in tons per day with respect to even keel (right) for different speeds and trims for Load condition 5.

Table 3. Power in kW for different trims and drafts in ballast condition. Colour indicates the relative difference of power for a given speed (green denotes lower power and red higher).

	Draft, m	7	7,2	7,5	7,5	7,5	7,8	7,8
	Trim, m	2,5	2	1	1,5	2	1	1,5
Speed, kt	8			1037	1017	1017	1059	1044
	10	2022	2033	2094	2088	2086	2121	2122
	12	3680	3689	3767	3754	3788	3867	3856
	14	6264	6361	6308	6425	6441	6463	

Table 4. Fuel consumption in tons per day for different trims and drafts in ballast condition. Colour indicates the relative difference of fuel consumption for a given speed (green denotes lower consumption and red higher).

	Draft, m	7	7,2	7,5	7,5	7,5	7,8	7,8
	Trim, m	2,5	2	1	1,5	2	1	1,5
Speed, kt	8			6,1	5,9	5,9	6,1	6,1
	10	11,4	11,4	11,8	11,7	11,7	11,9	11,9
	12	19,6	19,7	20,1	20	20,2	20,5	20,5
	14	31,6	32,1	31,8	32,4	32,4	32,5	

Table 5. Fuel consumption savings in tons per day for laden loading conditions. Negative values indicate savings.

Speed/Draft	13	14	15	15.5
8	-0.1	-0.1	-0.2	0
10	-0.2	-0.1	-0.3	0
12	-0.2	-0.2	-0.3	0
14	-0.3	0.0	-0.5	0

Table 6. Optimum trims for individual speed/draft combinations in laden conditions

Speed/Draft	13	14	15	15.5
8	-1	-1	-0.5	0
10	-1	-1	-0.5	0
12	-1	-1	-0.5	0
14	-1	0	-0.5	0

5. Trim optimisation in irregular waves

In order to investigate whether the above study can be applied for realistic sailing conditions encountered by the vessel, a representative sea state is selected, and average power requirements are calculated for some of the sailing conditions. Given the relatively high cost of these simulations, the sailing conditions as well as sea condition are selected in a way to maximise the represented operational conditions. The vessel often sails across the north Atlantic, and according to the ships log the most common sea state corresponds to the Beaufort scale values between 4.5 and 5. For the analysis, a mid point is selected, i.e 4.75 Beaufort, which corresponds to the following sea energy spectrum values:

- Significant wave height, H_S = 2.04 m,
- Peak period, T_P = 8.3 s,
- Wind speed = 17.6 kt.

According to the Global Wave Statistics (Hogben, Dacunha, & Oliver, 1967), this sea state has a probability of occurrence of around 6.5%, and it resides in a region of the table surrounded by high probabilities. This verifies the values from the log up to some extent and gives confidence in the selected sea state to represent a realistic and common condition.

In the CFD simulation, the JONSWAP spectrum is used to determine the individual wave components based on the above spectrum characteristics. The simulated conditions are listed in Table 7, while Figure 9 shows a ship sailing in ballast condition. In the simulations, the vessel had a prescribed velocity, and the propeller was instructed to achieve a zero average net force on the vessel. This means that the rotation rate of the propeller varied in the simulation, which is not the exact replication of real-life conditions, where constant RPM is maintained. The reasoning behind this approach is that if a constant RPM was selected, different sailing conditions would differ in ship speed. It would then be difficult to compare different conditions in terms of power, i.e. fuel consumption. In order to minimise statistical errors, all simulations are performed with identical phase shifts of individual wave components, to allow a quasi-deterministic comparison. This might result in an error of absolute added resistance in waves; however, the comparison between different loading and trim conditions is very accurate. To optimise the calculation time the duration of simulated full-scale time is reduced to 15 minutes.

In order to ensure result quality in such a short amount of physical full-scale time, a comparison of total power is performed for a signal averaged after 15 minutes, and after 30. Figure 8 shows a power signal over 1950 seconds of simulated time for Load condition 3, trim 2.0 metres. The black line indicates the entire power signal, the red is the signal from 100 to 1000 seconds (15 minutes), and the blue represents the signal from 100 to 1900 seconds (30 minutes). Note that the first 100 seconds are excluded to prevent any quasi transient effects to influence the results. The average power calculated for 15 minutes is 4377.18 kW, while it is 4387.22 for 30 minutes. The relative difference is therefore 0.2 %, which is acceptable but should be kept in mind when analyzing the results of this study.

Table 7. Matrix of drafts, speeds and trims tested in waves.

Load Condition No.	Draft, m	Speeds, kt	Trims, m
1	7.0	12, 14	2.5
2	7.2	12, 14	2.0
3	7.5	12	1.0, 1.5, 2.0

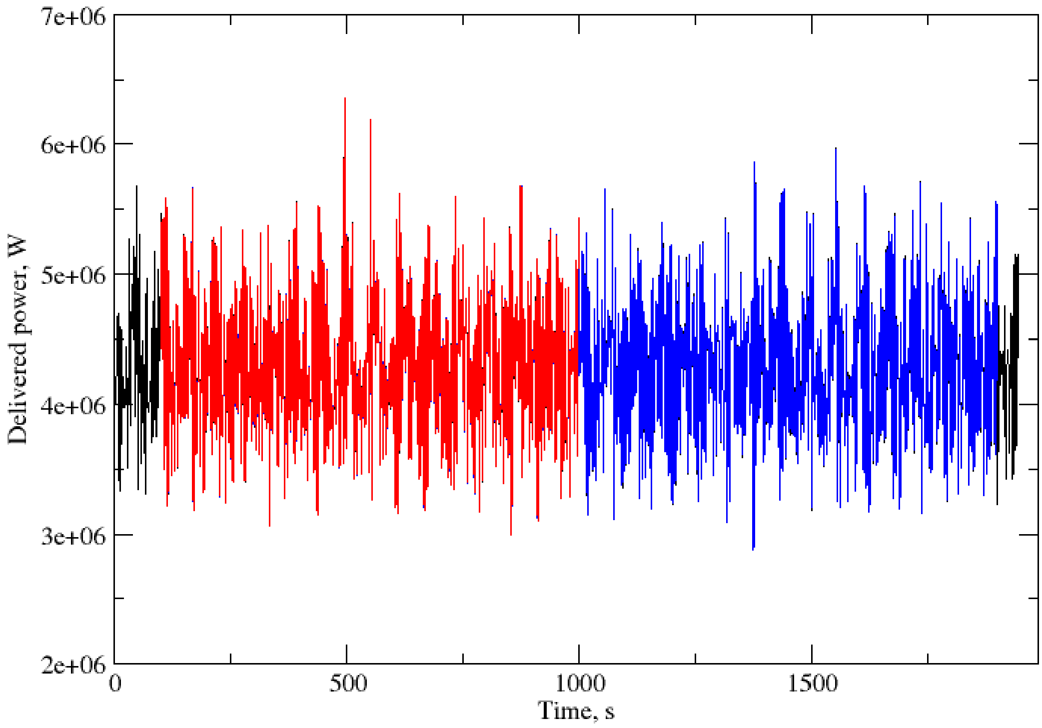

Figure 8. Time signal of the power delivered to the propeller during a simulation in irregular waves for load condition 3, trim 2.0 metres. The black line is the entire simulated signal, the red is the signal from 100 to 1000 seconds, and the blue from 100 to 1900 seconds.

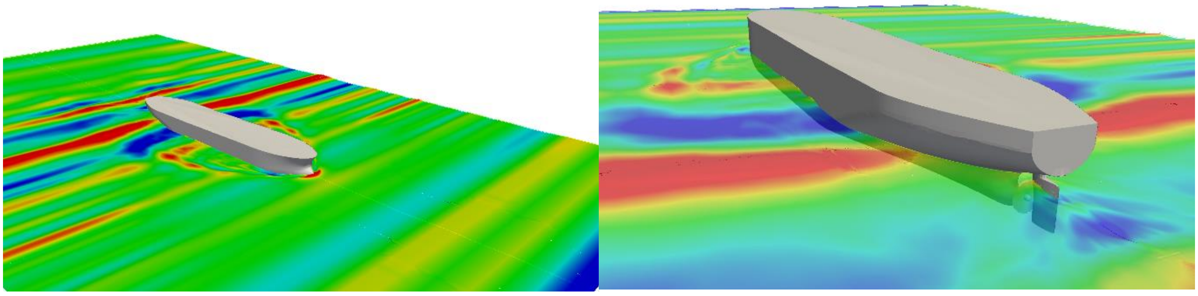

Figure 9. Simulation of a vessel sailing in irregular head waves.

Average power delivered to the propeller and fuel consumption for different sailing conditions is summarized in Table 8 and Table 9, respectively. Overall, the differences in power between different drafts/trims are larger than in calm water. For speed of 12 knots, the largest difference in power is 5.8 % in waves, and 4.95 % in calm seas, or in absolute values, 187 versus 253 kW. Fuel savings also follow this trend, where up to 1.2 tons per day can be saved in waves at 12 knots versus 0.9 in calm seas.
The main purpose of the study in waves is to determine whether the trends of power dependency on speed, trim and draft are equivalent in waves. Table 10 gives a heat map of the calculated power in 12 knots in calm seas and irregular head waves, while Figure 10 shows the same data in a graph. The trend is similar, showing that calm seas results represent the trends in waves very well for this case.

Table 8. Power in kW delivered to the propeller in irregular head waves.

	Draft	7	7,2	7,5	7,5	7,5
	Trim	2,5	2	1	1,5	2
Speed	12	4194	4306	4432	4401	4447
	14	6832	7033			

Table 9. Fuel consumption in tons per day in irregular head waves.

	Draft	7	7,2	7,5	7,5	7,5
	Trim	2,5	2	1	1,5	2
Speed	12	22,1	22,6	23,2	23,1	23,3
	14	34,2	35,1			

Table 10. Comparison of power in calm seas and irregular head waves for 12 knots.

Draft	7	7,2	7,5	7,5	7,5
Trim	2,5	2	1	1,5	2
Condition. No	1	2	3	4	5
Calm seas	3680	3689	3767	3754	3788
Waves	4194	4306	4432	4401	4447

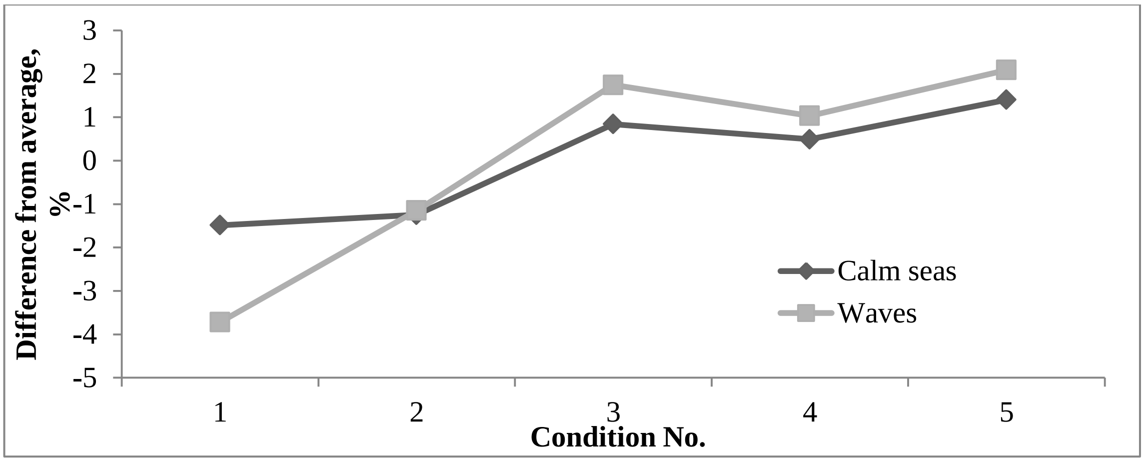

Figure 10. Comparison of power trends in percentages of the average value between calm seas and irregular waves results for speed of 12 knots.

6. Economic aspect – savings in operations, ROI

Based on the actual operational profile of the vessel, and the above results, the actual savings in terms of tons of fuel per year are calculated. For the ballast condition, the current practice is to sail at draft of 7.2 metres and 2.0 metres trim. The optimum condition is to sail at 7.0 metres and 2.5 metres trim. The difference between these two conditions, i.e. the fuel savings in tons per day are shown in Table 11. For 10 knots there are no savings in calm sea, and the data in waves are not available. For the analysis that follows, it is assumed that there are no savings in waves either. Using this data, and applying it to the operational profile of the vessel, the total yearly fuel savings are calculated. Figure 11 shows the distribution of ship speed relative to the total amount of time the ship spends sailing in ballast condition per year.

Similar can be done for every draft in laden conditions. Table 12 summarizes the fuel savings for all loading conditions, where the savings are weighted with the relative frequency of individual loading condition in a year. For ballast, where the trim optimisation data in waves are available, savings in waves are also included. Note that the ship is active 70% of the year. Based on Table 12, the total savings per year range from 44.2 tons to 69.5 tons, depending on the weather conditions during operations in ballast. With the current HFO prices (in Rotterdam), this is equal to approximately 18 500 to 29 000 USD per year.

The vessel in this particular study is one out of seven sister ships, which needs to be taken into account when estimating the Return Of Investment period (ROI). The total cost of the CFD trim optimisation study, without taking into account simulations in waves, is around 22 000 USD, including the generation of the 3D model of the vessel. The simulations in waves cost relatively more, but are not a part of a standard trim optimisation study. This gives a ROI period of less than two months for the more conservative savings of 18 500 USD per ship. The ROI is likely to be even shorter given that the vessel operates in waves a portion of its service. It should be noted here that effects of trim are not investigated in following waves, or other encounter angles, which needs to be kept in mind.

Table 11. Fuel savings in tons per day for ballast condition.

Speed	Calm Sea	Waves
10	0.0	N/A
12	0.1	0.5
14	0.5	0.9

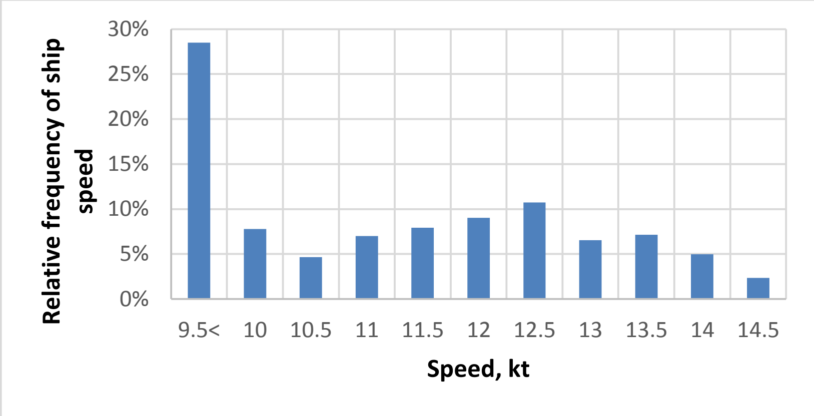

Figure 11. Relative frequency of ship speed in ballast condition.

Table 12. Fuel savings achieved per year given the relative frequency of individual loading conditions, for calm sea conditions.

Loading condition (draft)	Ballast, calm sea/waves	13 m	14 m	15 m	15.5 m
Fuel savings (t/day)	0.12/0.45	0.22	0.16	0.34	0
Relative frequency of the sailing condition per year	21%	13%	19%	11%	1%
Fuel savings per year, t	9.2/34.5	10.1	11.0	13.9	0.0

7. Conclusion

A trim optimisation study for an Aframax tanker vessel is reported in this paper, using a CFD software called the Naval Hydro Pack. In addition to the standard, calm sea trim optimisation study, an investigation of power and fuel savings is extended to irregular waves to assess the applicability of calm sea results to realistic operational conditions.

The study in calm seas showed that moderate savings can be achieved for the Aframax vessel, given the low speeds at which she sails. The fuel differences range from 0.2 to 1.0 tons per day. Larger differences in consumption are observed in the ballast condition due to the larger flexibility of the draft and trim. The investigation in waves showed that similar trends can be expected, at least when it comes to head waves. Moreover, the absolute values of saved fuel increase in waves comparing to calm sea.

For the specific ship considered in this study, it is estimated that around 44.2 tons of fuel per year can be saved, per ship. For a fleet of seven sister ships, this converts to a ROI of less than two months.

In general, it can be concluded that there is an economic benefit in performing trim optimisation studies for full hull forms, at least those sailing on longer routes. The study also indicates that for this particular vessel higher savings can be expected in head waves by using the same data sets obtained in calm seas.

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