A Study on the Relationship Between Ship Resistance and Trim, Supported by Experimental and Software-Based Analysis

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In this study, towing tank experiments have been carried out for a container ship under different trim-draft conditions. Experimental results have been interpreted together with the results of the Holtrop method used in both Maxsurf and Orca to identify reactions to changing trim conditions. The study has shown that towing tank experiment findings differ from other relevant findings. The ship shows different resistance characteristics under different trim conditions, but generally the least resistance without trim. In addition, the total resistance change at ship design speed was found to be up to 18% higher in the trim by aft condition. We believe that study findings will help better understand the constantly changing resistance variable depending on draft, speed, and trim conditions.

KEY WORDS

~ Trim optimization
~ Ship resistance
~ Towing tank experiment
~ Holtrop

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1. INTRODUCTION

The concept of energy efficiency in ships has gained importance in the early 2000s. New regulations/recommendations have been introduced by the International Maritime Organization (IMO) in the form of concepts like Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Design Index (EEDI), and Energy Efficiency Operational Indicator (EEOI) (Polakis et al.,2019). The applications that can save energy onboard ships have been divided into two categories: “technical methods” and “operational methods” (Wang et al., 2016). Technical methods are applications that require more labor and cost. Operational methods, that do not involve any interventions in the ship’s form, relate to changes in ship operation. Trim optimization of operational methods aims to reduce the hydrodynamic resistance of a ship (Tu et al., 2018). Ship trim can be adjusted with simple ballast/bunker movements in tanks and/or small differences in the loading plan (Iakovatos and Others, 2014, Öztürk, 2013). Adjusted trim can reduce the ship’s hydrodynamic resistance and reduce fuel consumption by up to 15% (Hansen and Freund, 2010). To reduce ship resistance, optimum trim conditions for the vessel’s draft and speed need to be identified. An overview of literature shows that researchers working on the concepts of ship energy consumption and resistance draw attention to the importance of trim optimization (Larsen et al., 2012; Reichel et al., 2014; Hansen and Freund, 2010; Sherbaz and Duan, 2014; Perera, Mo, and Kristjansson, 2015; Hansen and Honchkirch, 2013; Reinus, 2014; Wortley, 2013).

Computational Fluid Dynamics (CFD) programs and experimental towing tank test are generally used in trim optimization studies. In Larsen et al. (2012) two different CFD programs based on two different approaches were used in trim optimization. The results were compared with the outcomes of an experimental study carried out for a single draft in towing tank experiments. In this study, it was observed that only one of the CFD program results corresponded to towing tank test results and strong correlation between wave resistance and trim was established. Another study focused on finding the optimal trim conditions by examining the vessel’s log data. The study concluded that ship speed could be increased with the same fuel consumption through trim condition adjustment. In other words, fuel consumption could be reduced by maintaining the same speed by adjusting the trim condition (Perera et al., 2015). The results of another CFD approach for the even keel condition of the KRISO container ship model (KCS) were compared with the experimentally obtained data. Ship resistance was found to increase in trim by bow conditions (Sherbaz & Duan, 2014).

On the other hand, some trim optimization studies proved that ship resistance decreased in trim by bow conditions (Park et al., 2015). In general, ship resistance under trimmed conditions is lower than in no-trim conditions. However, in some cases, the opposite results were obtained. It might mean that changing the trim condition for different ships might increase or decrease ship resistance. A simulation study (The Reynolds-averaged Navier–Stokes / RaNS) on a container ship, carried out by Islam and Soares (2019), revealed that the optimum trim should be identified dynamically depending on speed and draft. The relationship between trim condition and resistance is clearly an essential issue in ship energy efficiency.

2. METHODOLOGY

This study aims to investigate the correlation between trim and hydrodynamic resistance on a 3d container vessel model through towing tank results in calm water. Also, to compare the towing tank test results with the software-based resistance estimation analysis results through Maxsurf and Orca programs that have used the Holtrop method on the 3d digital container vessel model.

The vessel selected for modeling was a sub-Panamax type container vessel used in real life. Three different loading conditions and four different trim conditions were used in the experimental towing tank test. The loading conditions were determined by consulting the ship company’s experts and referring to the loading manual of the container vessel. These loading conditions were the ship’s summer/fully loaded draft (11.40m), loaded draft (10.10m), and partly loaded draft (8.80m) (Table 1).

Conditions (Drafts)	Trim	Trim (Height)	Trim (Degree)
Fully Loaded / 11.40 m Loaded / 10.10 m Partly Loaded / 8.80 m	Trim by aft	-2 m	-0.55 °
	Trim by aft	-1 m	-0.25 °
	Even Keel	0	0 °
	Trim by bow	+1 m	+0.245 °

Table 1. Experiment conditions

The experiments were carried out for the speed range of 8-26 knots (0.09 <Fn <0.3304). The corresponding resistance values have been recorded when the resistance value recorded at each speed run was fixed and re-measured for a new speed. The resistance curve obtained for each condition was examined, and tests were redone when inappropriate curves were observed.

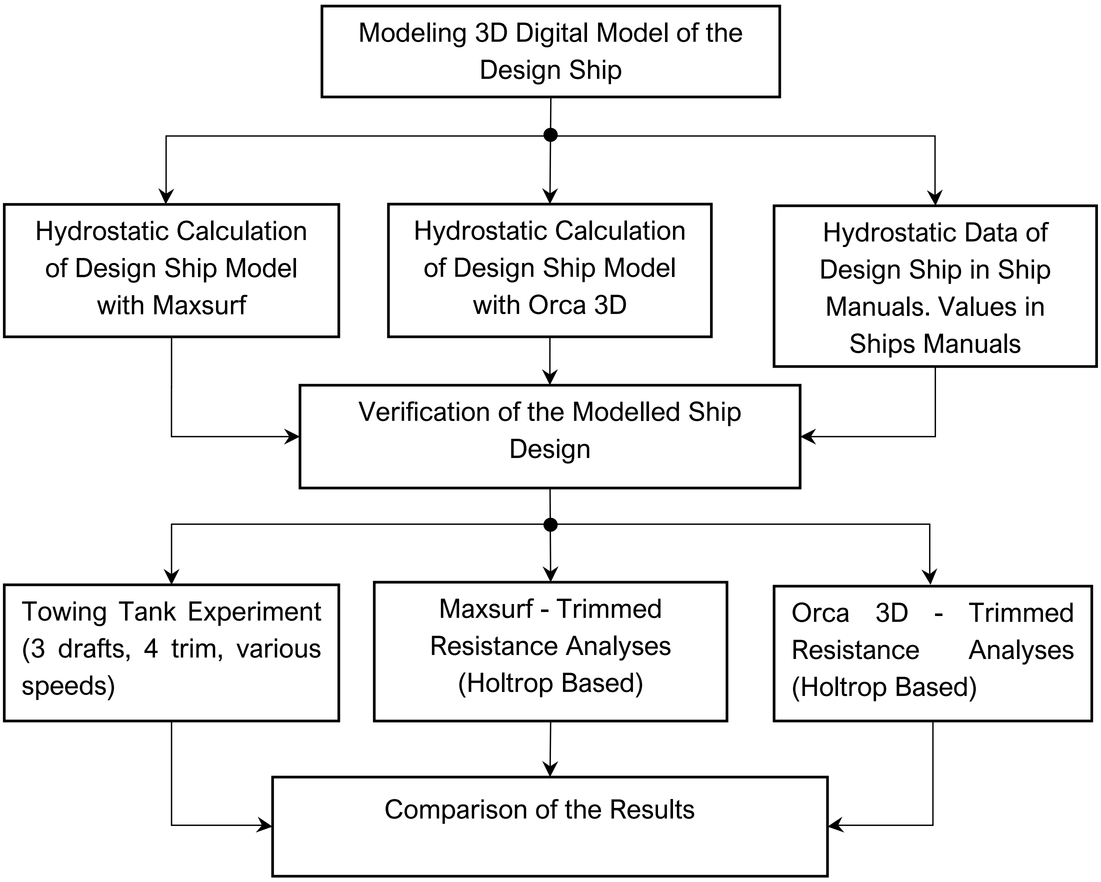

Figure 1. Research process used in the study

The 3d digital model of sub-Panamax type container vessel was modeled with Rhinoceros V.6 software program. The developed model was tested with the Maxsurf and Orca programs in the pre-determined loading conditions and different trims. All these results were evaluated together with the results of the International Towing Tank Conference - 1978 ITTC Performance Prediction Method (Effective date 2017, Revision 04) (ITTC 78), and the resistance characteristics of the designed ship in different trims and displacements determined.

The compatibility of the results of these programs with those of the ITTC 78 method is discussed. The research process of the study is shown in Figure 1.

2.1. Resistance Analysis based on Holtrop Method

One of the first methods that comes to mind when it comes to ship resistance calculation in the shipbuilding industry is definitely the Holtrop method. J. Holtrop and G.G.J Mennen (1982) formulated ship resistance as follows, based on the regression analysis performed on 334 model test trials:

$$R_{Total} = R_F\,(1+k) + R_{APP} + R_W + R_B + R_{TR} + R_A \tag{1}$$

where:

R_F	Frictional resistance defined by ITTC-1957 friction formula
(1 + k)	Form factor describing viscous resistance of a ship in relation to RF
R_{APP}	Resistance of appendages
R_W	Wave-making and wave-breaking resistance
R_B	Pressure resistance of bulbous bow near the free surface
R_{TR}	Additional pressure resistance of wetted transom
R_A	Model – ship correlation resistance

Special experimental pools called “towing tanks” are required for ship model tests trials. A three-dimensional scaled version (ship model) is constructed using the λ scale, which is geometrically similar to the ship whose resistance analysis is being conducted. The model is then dragged in calm water in a special experimental pool to obtain resistance value. Under these conditions, the total resistance RT of the model is divided into frictional resistance RF and residual resistance RR (Froude, 1872). The “M” subscript is used to indicate that the values specified in this section belong to the model, and the “S” subscript will be used to indicate that they belong to the ship.

$$R_{T_M} = R_{F_M} + R_{R_M} \tag{2}$$

$$R_{T_M} = \frac{1}{2} C_{T_M} \rho_M S_M V_M^2 \tag{3}$$

Considering Equation 3, Equation 2 is nondimensionalized and Equation 4 is obtained.

$$C_{T_M} = C_{F_M}(R_{n_M}) + C_{R_M}(F_{n_M}) \tag{4}$$

Rn is the Reynold number and Fn is the Froude number, and they are calculated as follows;

$$R_n = \frac{V.L}{v} \tag{5}$$

$$F_n = \frac{V}{\sqrt{(g.L)}} \tag{6}$$

V: Ship speed
L: Ship length
v: The viscosity of the fluid in which the ship moves.
g: Gravitational acceleration

Froude and Reynold numbers should be equalized between the two to ensure dynamic correspondence between the ship and the model and to make a reliable estimation of resistance. In practice, since the Reynolds number cannot be equalized, incomplete dynamic correspondence is obtained and only the Froude numbers are equalized. This similarity is illustrated by Equation 7.

$$F_{n_M} = F_{n_S} \tag{7}$$

If Equation 7 is interpreted by including Equation 6, the relationship between the model to be tested and ship speeds will be as follows;

$$V_M = \frac{V_S}{\sqrt{\lambda}} \tag{8}$$

Please note that λ is referred to as similarity ratio, scale and calculated as ship length to model length ratio (LS / LM).

Returning to Equation 4, friction coefficient C_F is calculated using the ITTC 1957 formula (Equation 9). Given that it is obtained by nondimensionalizing the R_T value, since the C_T value is also known, it is substituted with Equation 3 and the C_R value is obtained.

$$C_F = \frac{0,075}{(\log_{10} R_n - 2,0)^2} \tag{9}$$

The calculation method for the extrapolation of resistance coefficients introduced by the ITTC in 1957 used in the calculations the real ship was updated by the ITTC in 1978. In the extrapolation method known as ITTC 1957, resistance coefficients are shown in Equation 10.

$$C_{T_S} = C_{F_S} + C_{R_M} + C_A \tag{10}$$

The tolerance coefficient, CA, is a correction coefficient necessitated by the fact that the ship model surface can be manufactured perfectly smooth in contrast to a real ship.

In 1978, ITTC updated the equation used to calculate the total resistance constant shown in Equation 10, as shown in Equation 11.

$$C_{T_S} = (1 + k)\, C_{F_S} + C_{R_M} + C_A + C_{AA} \tag{11}$$

The most important regulation that distinguishes ITTC 1978 from 1957 is the increase of the frictional resistance with the form factor and the addition of the C_{AA} constant, i.e. air resistance. Equation 12 is used to calculate the C_A constant and if the roughness constant ks specified here is unknown, it can be assumed to be150 µm. The C_{AA} constant is calculated as in Equation 13.

$$C_A = [105(\frac{k_s}{L_{WL}})^{1/3} - 0,64]10^{-3} \tag{12}$$

$$C_{AA} = 0,001\frac{A_T}{S} \tag{13}$$

Holtrop (1982) listed the main ship particulars affecting the resistance as follows.

a. Ship speed,
b. Length of waterline,
c. Length between perpendiculars,
d. Breadth molded,
e. Draught molded on Front Peak,
f. Draught molded on Aft Peak,
g. Transverse bulb area,
h. Centre of bulb area above keel line,
i. Displacement volume molded,
j. Longitudinal center of buoyancy,
k. Midship section coefficient,
l. Waterplane area coefficient,
m. Transom area,
n. Stern shape parameter,
o. Wetted area appendages,
p. Propeller diameter,
q. Number of propeller blades,
r. Clearance propeller with keel line

Ship speed (“a”) is the same in all trim and loading conditions, but is used to calculate the ship's trim-independent resistance. Items numbered "b, c & d" vary with trim and loading condition and affect resistance in all conditions. "e and f" are the main elements used to find the trim angle. "g and h" are used to measure the bulb effect. Variables from "i to l" are key factors affecting resistance that change with both loading conditions and trim. “m” and "n" are used to determine the effect of stern form (such as damping effect, Eddy Resistance etc.). "o" is used to establish added resistance. Last listed items (“p, q, r”) are used to estimate propeller efficiency and are not discussed in the study.

On the other hand, Sherbaz (2014) showed that trim change had little effect on the viscous resistance component. The main change occurs in the wave-making resistance component. Viscous resistance and wave-making resistance are a part of another total resistance expression approach described by Froud (1872). Viscous resistance may be described as resistance occurring due to the friction between the ship and the sea. It might therefore be useful to evaluate the variables accordingly when calculating trimmed resistance.

2.1.1. The Design Ship

The data on the original design ship and the permission for their use were formally requested from ARKAS Shipping Company who gave their consent. After obtaining the permission and the approval, interviews were conducted with the experts on the design vessel and information about loading conditions (displacement/draft & trim levels) of the design vessel was obtained. The design ship was a container ship having the capacity of 2478 TEU. The specifications of the ship and the scaled model have been provided in Table 2.

The 3D digital model of the ship was developed using the original ship plans. The form structure and plan of the developed model are shown in Figure 2.

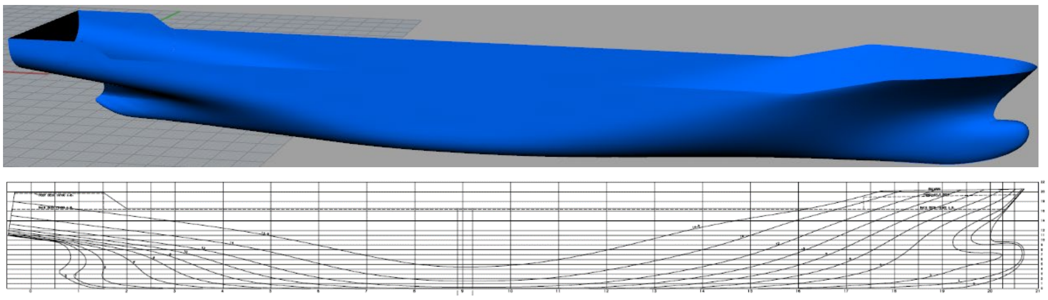

Figure 2. Ship form plan and 3D digital model

Characteristic	Abbreviation	Ship	Model (λ=1/58)
Length over all	L_{OA}	210.54 m	3.630 m
Length between perpendiculars	L_{PP}	198.74 m	3.427 m
Breadth (Molded)	B	29.80 m	0.514 m
Design draft (Molded)	T	10.10 m	0.174 m
Summer draft (Molded)	T_{MAX}	11.40 m	0.197 m
Displacement	Δ	37851.7 t	194 kg
Service speed	V_S	22 knots	1.486 m/s
Main engine power output	P_{ME}	21770 kW	-

Table 2. Main characteristics of the ship & the model

2.1.2. Towing Tank Experiments

The model scale ratio used in the experiment (λ) was 1/58 due to the limitations of the towing tank and Loa of the design ship. This experimental model was constructed by the Computer Numerical Control (CNC) device at the Ata Nutku Ship Model Testing Laboratory, Istanbul Technical University, Faculty of Naval Architecture and Ocean Engineering. Towing tank experiments were carried out in the same laboratory. The photos of the experimental model and experiment scene in the laboratory are shown in Figure 3.

Figure 3. Ship Experiment Model and Experiment Scene

The data obtained from the towing tank experiment were extrapolated using the ITTC 1978 (version 2017 revision 4) (ITTC 78) method. Measured water temperature was 15ºC, while water density and viscosity were determined in keeping with the ITTC Recommended Procedure 7.5-02-01-03. Resistance components considered in the calculation are shown in Equation 14. Value changes such as “waterline length”, “wetted area”, “rudder area” and “wind area” attributable to trim and displacement conditions were considered in the extrapolation process.

$$C_{T_S} = (1 + k)\, C_{F_S} + \Delta C_F + C_{W_M} + C_A + C_{AAS} \tag{14}$$

C_{T_S}	Total resistance coefficient
C_{F_S}	Friction resistance coefficient
ΔC_F	Roughness allowance
C_{W_M}	Wave resistance coefficient
C_A	Correlation allowance
C_{AAS}	Air resistance coefficient (at the air temperature of 15ºC)
1+k	Form factor
M/S	Model or ship

The initial speed in the experiments varied between 8-10 knots in different conditions. The data in a homogeneous speed range (8-26 Knots) were evaluated by fitting a 4th-degree polynomial curve on the data obtained from the experiment. Once the equations for these curves were obtained, resistance values for the 8-26 knots speed range were calculated. In this process, the square of the correlation coefficient (r2) value was examined, and the smallest value observed was r2 = 0.999x.

The findings of towing tank experiments are presented as the total resistance constant of the model scale (C_{Tm}) in Figure 4. C_{TM} values were found by evolving the measured resistance values within Equation 3. The lowest C_{Tm} values were generally obtained with an even keel (0), with the draft of 11.40m. However, when the draft was 10.10m, intertwined curves were obtained. The lowest value is depended on the speed of the vessel. In the last case, with the draft of 8.80m and +1 meter trim by bow condition, the lowest value was found up to a point.

$$R_{T_M} = \frac{1}{2} C_{T_M} \rho_M S_M V_M^2 \quad (3)$$

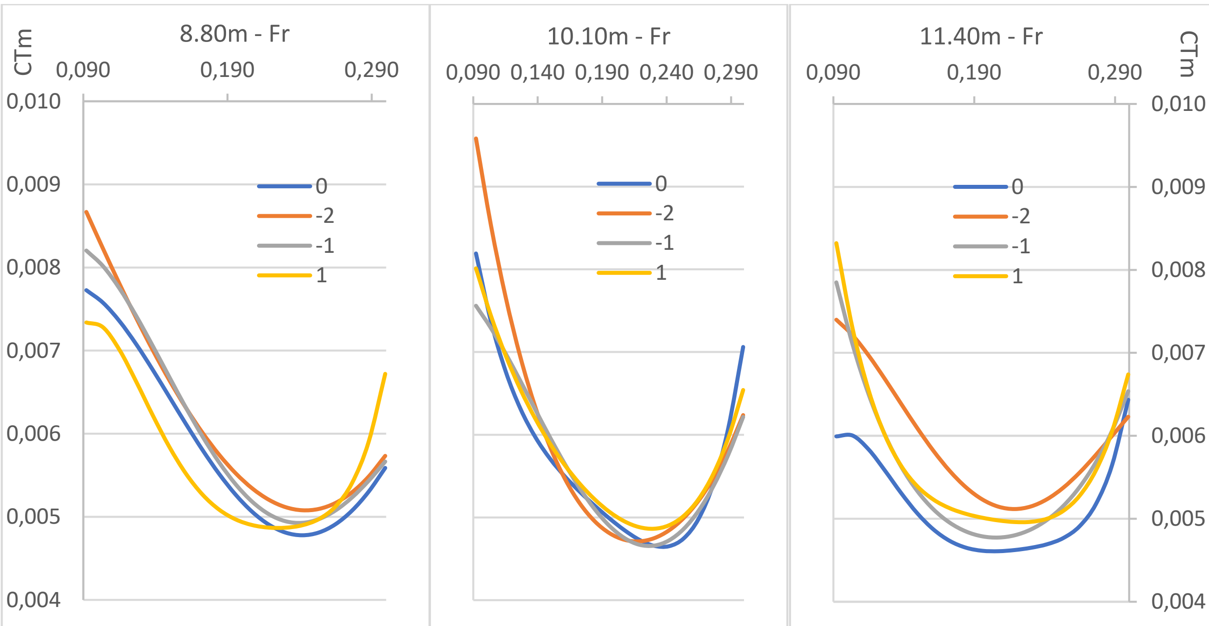

Figure 4. Total drag coefficient (CT) of towing tank trials

2.1.3. Form Factor Calculation

The Prohaska method was used for form factor (1+k) calculations as recommended by ITTC. CTM/CFM vs. F_n^4/CFM curve was calculated using Equation 15 in the range of 0.1 <F_n <0.2 for form factor (1 + k) calculation (Prohaska, 1996). Then, a linear trend line was passed over the curve and found to be 1 + k which is considered to be the place where the vertical axis is cut at "F_n = 0". In the zone selected for the calculation, the trend line slope was observed to be negative. The trend line's negative slope caused the form factor value to be high "F_n = 0". The values obtained were 1.40 <1 + k <1.90. The high form factor coefficient resulted in a negative C_W resistance constant calculated for the model.

$$1 + k = \frac{C_{T_M}}{C_{F_M}} - a\frac{F_n^4}{C_{F_M}} \quad (15)$$

In this process, the ITTC Standard Procedure 7.5-02-02-01 was examined. When the ship's bulb was just below the waterline, half-submerged, or just above the waterline, interventions in the Prohaska method were required. Therefore, form factor value was recalculated for each hydrostatic condition and averaged within each displacement. Extrapolation was performed with this average form factor value. Recalculated (1 + k) form factors are shown in Table 3.

Draft\Trim	-2m	-1m	0m	+1m	Average
11.40m	1.310	1.232	1.238	1.170	1.237
10.10m	1.264	1.190	1.290	1.239	1.246
8.80m	1.318	1.341	1.266	1.293	1.304

Table 3. Calculated form factor (1 + k) for different conditions

2.2. Software-Based Analysis

Two of the most common programs used in ship design and ship-related analysis are Maxsurf and Orca 3D (Chalfant, 2012). These programs are user-friendly and analysis results are obtained much faster than with CFD programs. The towing tank experiment required a digital model of the ship. Once the digital model was developed, hydrostatic calculations were made using the above programs. In this study, the results of the hydrostatic calculations were found to be very close or similar to real ship data. Displacement and LCF (longitudinal center of flotation) values of loading conditions were taken from both ship manuals, Maxsurf & Orca programs, and compared in Table 4. The similarity in hydrostatic conditions required the resistance prediction capabilities of the programs under different loading and trim conditions to be analyzed.

Displacement (ton)							
T (m)	Ship manuals (t)	Maxsurf (t)	Maxsurf error (t)	Maxsurf error ratio	Orca 3D (t)	Orca error (t)	ORCA error ratio
11.40	45569.100	45444.000	125.100	0.00275	45499.926	69.174	0.00152
10.10	38968.300	38855.000	113.300	0.00291	38908.150	60.150	0.00154
8.80	32813.400	32720.000	93.400	0.00285	32766.007	47.393	0.00144

LCF (meter)							
T (m)	Ship manuals (m)	Maxsurf (m)	Maxsurf error (m)	Maxsurf error ratio	Orca 3D (m)	Orca error (m)	ORCA error ratio
11.40	89.42	89.413	0.007	0.00008	89.470	-0.050	-0.00056
10.10	92.97	93.076	-0.106	-0.00114	93.122	-0.152	-0.00163
8.80	96.67	96.735	-0.065	-0.00067	96.791	-0.121	-0.00125

Table 4. Comparison of sample ship hydrostatic data

Maxsurf does not have the resistance calculation option for trim conditions. Therefore, resistance test under different trim conditions was conducted by rotating the ship model at the center of the LCF in a CAD software taking into account trim angles. The calculation of the trim angle is shown in Figure 5 and Equation 16. Rotated and developed models were tested using the Holtrop method in Maxsurf v21.11 with (1 + k) = 1.23. Also, the 19th CA option was ticked. The Holtrop method was developed by J. Holtrop and G.G.J. Mennen. It is based on regression analysis of hundreds of model tests/trials.

Orca 3D (v2.0.10) allows resistance calculation with trimmed condition angle for trimmed vessel. The program calculated the form factor value in the range of 1.225 < (1+k) < 1.237 for different conditions. Again, the Holtrop method was chosen for resistance estimation.

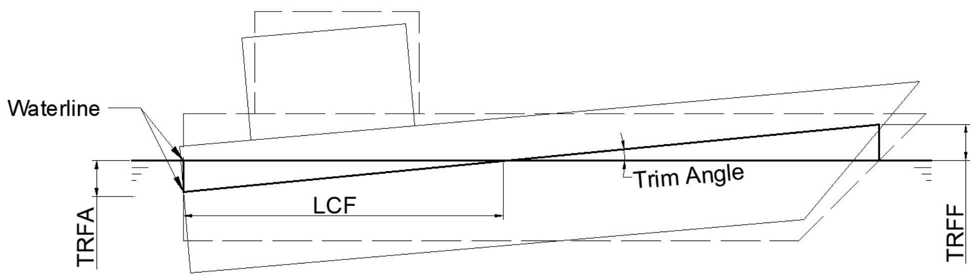

Figure 5. Model constructed to calculate the trim angle of a stern-trimmed vessel

$$\text{Trim Degree} = \sin^{-1}(TRFA/LCF) \times 180/\pi \quad (16)$$

TRFA: Trimmed condition height for aft
TRFF: Trimmed condition height for fore

3. FINDINGS AND DISCUSSION

The loading conditions determined for this study were represented by their corresponding draft values under untrimmed conditions, such as 11.40m summer draft, 10.10m design draft and 8.80m partly loaded conditions. In addition to loading conditions, trim conditions were -2m, -1m, 0m and 1m. Also, the “trim by head” condition is indicated by the (+) sign, while the (-) sign indicates the “trim by stern” condition. The result of towing tank trials at the Istanbul Technical University is referred to as ITU. Since towing tank results were obtained using the ITTC 78 method, they have been designated as ITTC 78 in this study. In Orca 3D, resistance analysis conducted using the Holtrop method is referred to as Orca. Resistance analysis conducted using the Holtrop method in Maxsurf is referred to as Maxsurf.

C_T calculations were made in the even keel condition to compare towing tank trial results in the model scale with Orca and Maxsurf. The C_T comparisons for the scaled model obtained by three methods are given in Figure 6.

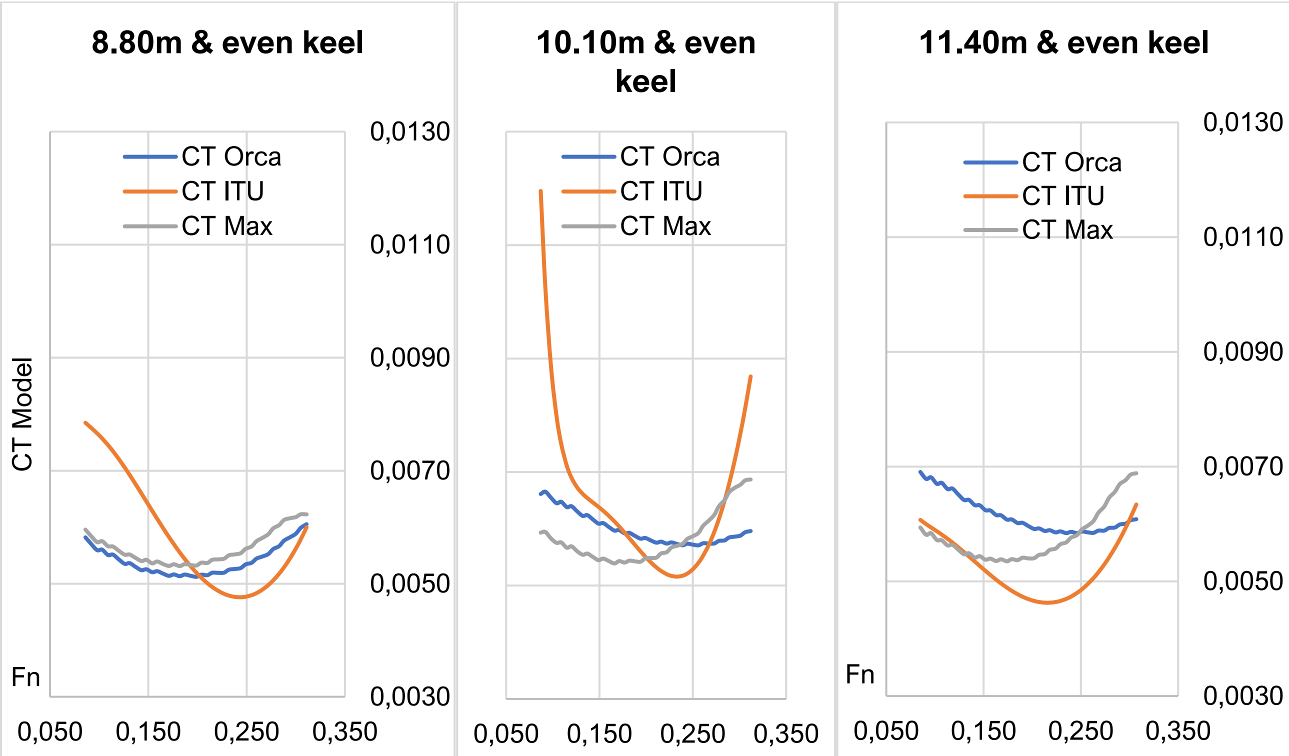

Figure 6. Total drag coefficient (CT) comparison for even keel condition of the scaled model

3.1. Trim Analysis for the Draft of 11.40 m

ITTC 78, Maxsurf and Orca resistance curves under the selected trim conditions were examined. Resistance change results for speeds of 8-26 knots, depending on trim conditions, are presented in Figure 7.

In ITTC 78 and Maxsurf, resistance was the lowest at all speeds under the even keel condition. In Orca, at the speeds of 8-20 knots the lowest resistance was under the +1m trimmed condition. On the other hand, at the speeds of 21-22 knots, the even keel condition had the lowest resistance. Also, at the speeds of 23-26 knots, -1m trimmed condition had the lowest resistance.

Resistance results were compared for all trim conditions and the results of all programs were found to be compatible with each other. Out of all trim conditions, the even keel condition had the lowest resistance value, and -2m trim condition the highest resistance value.

Using the ITTC 78 method, 40% of average resistance value changes were found to be dependent solely on trim condition change at the speeds of 8-12 knots. At the speeds of 13-15 knots, 30% of average changes were obtained, at the speeds of 16-22 knots, 20% of average changes were obtained and at the speeds of 23-26 knots, 15% of average changes were obtained.

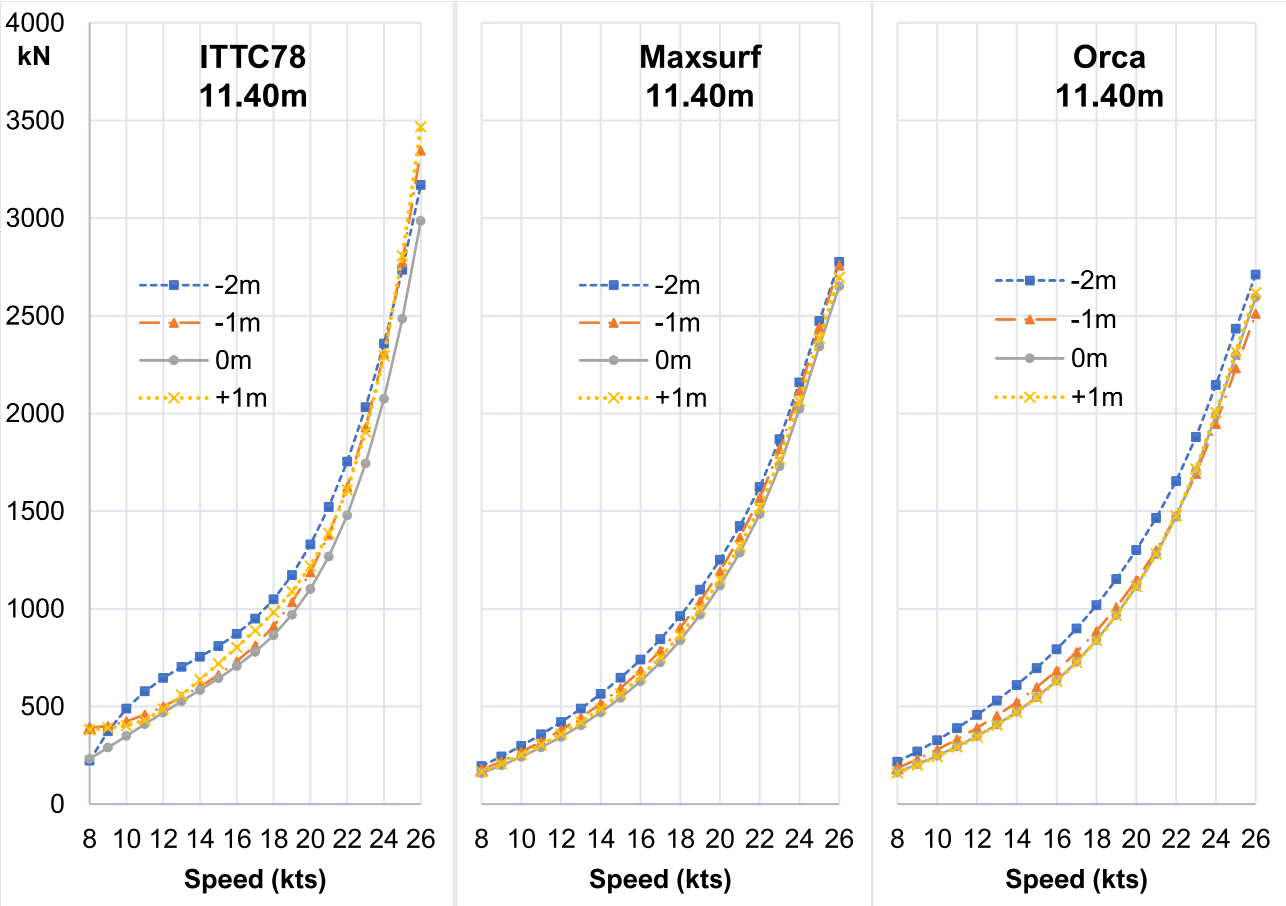

Figure 7. Graphs illustrating resistance (kN) vs speed (knots) at different trim levels. ITTC 78, Maxsurf Holtrop and Orca Holtrop

3.2. Trim Analysis for the Draft of 10.10m

The graphs obtained using the ITTC 78 method for the design draft (10.10m) are given in Figure 8 and examined. In ITTC 78, resistance value was the lowest at 9-14 knots and at 19-23 knots under even keel condition, at 8 knots under -1m trimmed condition. In addition, at 15-18 knots and 24-26 knots, -2m trimmed condition had the lowest resistance. In Maxsurf, the lowest resistance value was measured in the even keel condition at the speed of 8-19 knots. At the speed of 20-26 knots, the -2m trimmed condition had the lowest resistance. In Orca, resistance value was the lowest under the -2m trimmed condition at all speeds. Resistance values obtained using Orca and Maxsurf slightly differed from each other for trimmed conditions as shown in Figure 8.

The comparison of resistance results under all trim conditions obtained using different programs reveals that they slightly differ from each other. As shown in Table 4, these changes are expected due to slight hydrostatic differences. The lowest resistance value was obtained under different trim conditions, at different speed ranges. The highest resistance values were found in the negative trimmed conditions for different speed ranges.

Using the ITTC 78 method, 40% of average resistance value changes were found to be dependent solely on trim condition change at the speeds of 8-12 knots. At the speeds of 13-26 knots, 15% of average changes were obtained.

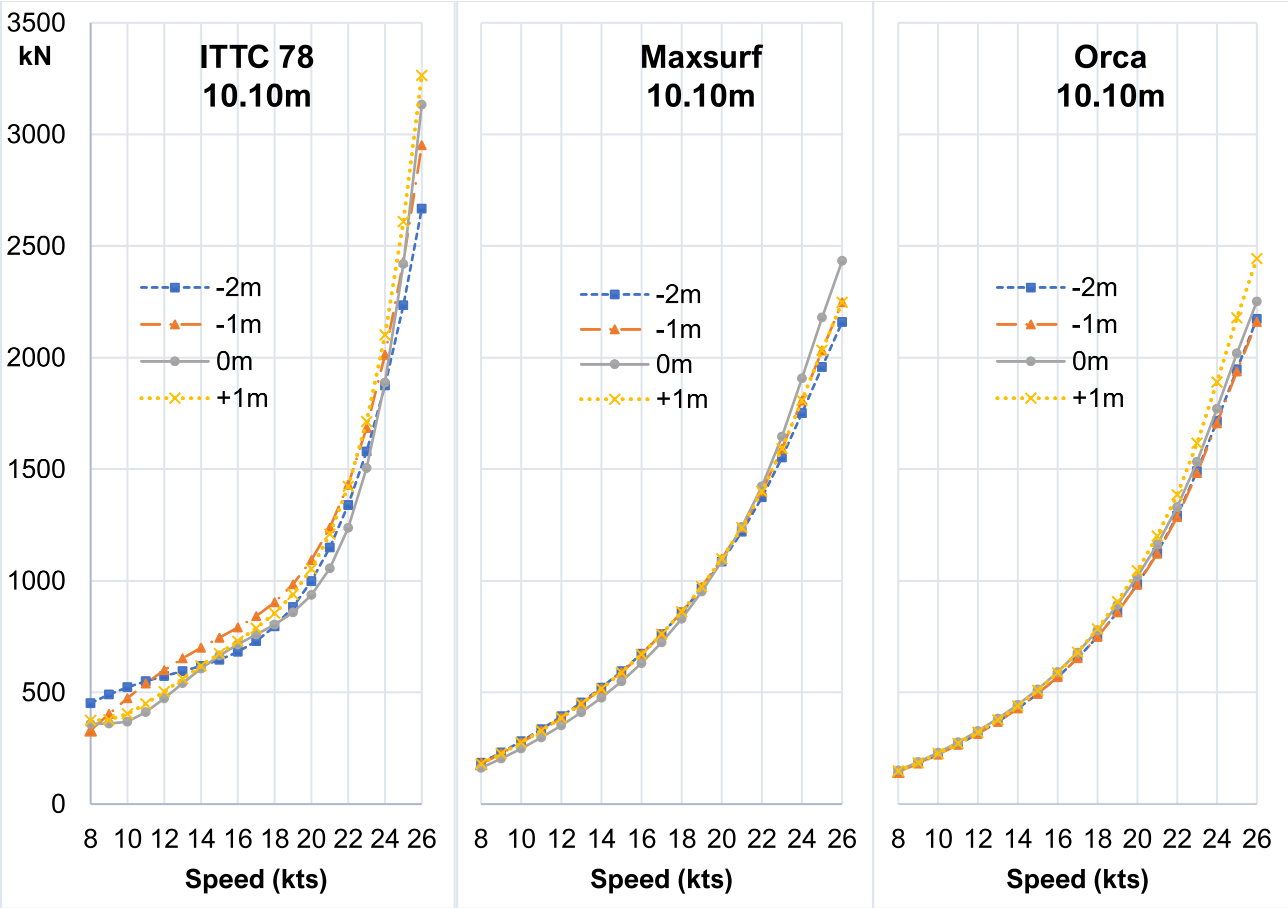

Figure 8. Resistance (kN) vs speed (knots) graphs for different trim levels. ITTC 78, Maxsurf Holtrop and Orca Holtrop

3.3. Trim Analysis for the Draft of 8.80m

When the graphs obtained using ITTC 78 are examined (Figure 9), resistance value is found to be the lowest at 9-14 knots under +1m trimmed condition. The resistance value was the lowest for 8 knots and between 15-26 knots speed range for -1m trimmed condition. In Maxsurf, the lowest resistance value was measured under the -2m trimmed condition at all speeds. In Orca, resistance value was the lowest under the even keel condition at all speeds. There was almost no decomposition of the curves obtained using Orca (Figure 9).

The comparison of resistance results under all trim conditions obtained using different programs reveals that they slightly differ from each other. As shown in Table 4, these changes are expected due to slight hydrostatic differences. The lowest resistance value was obtained under different trim conditions, at different speed ranges. The highest resistance values were found in the negative trimmed conditions for different speed ranges.

Using the ITTC 78 method, 30% of average resistance value changes were found to be dependent solely on trim condition change at the speeds of 8-12 knots. At the speeds of 13-26 knots, 12% of average changes were obtained.

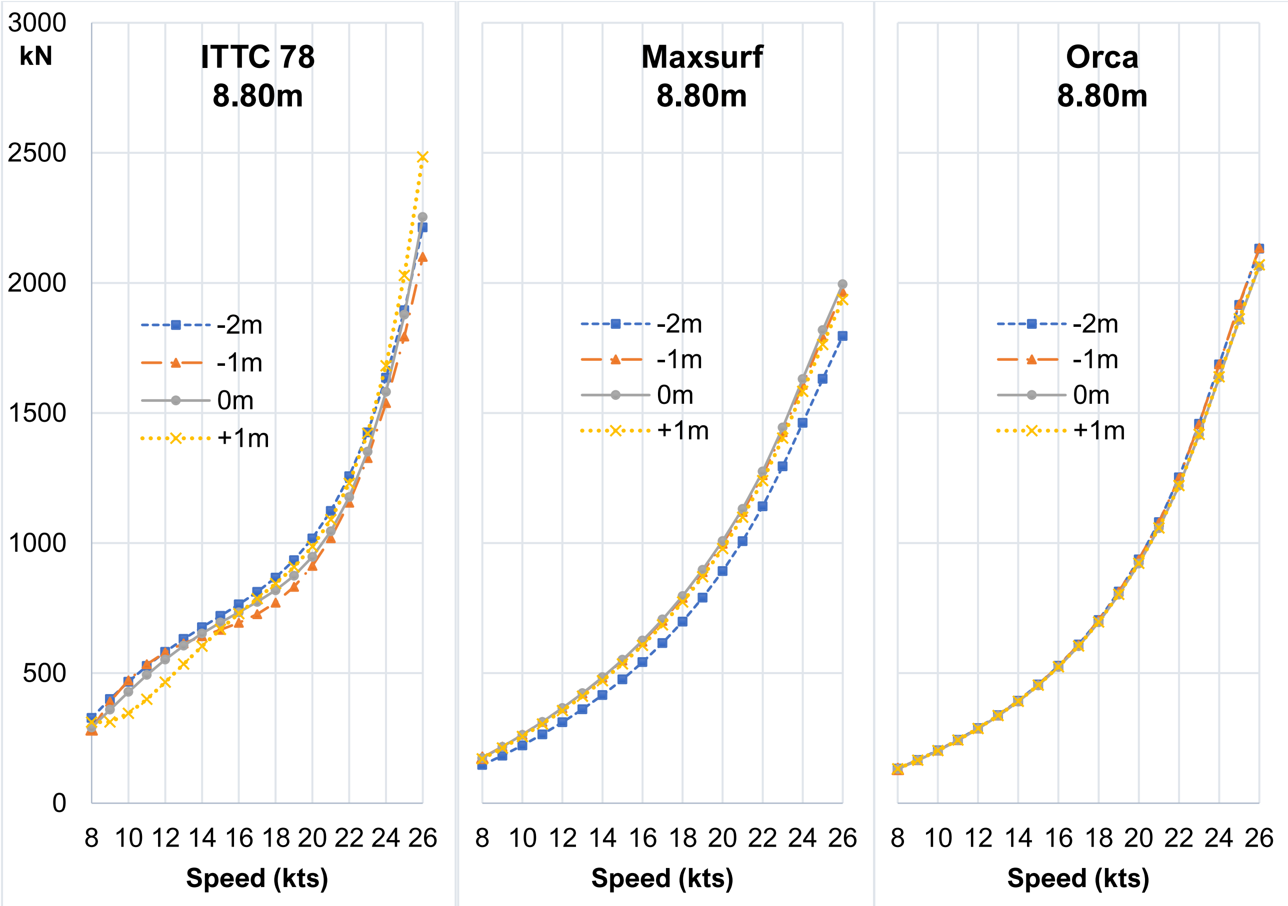

Figure 9. Resistance (kN) vs speed (knots) graphs for different trim levels. ITTC 78, Maxsurf Holtrop and Orca Holtrop

3.4. Comparison of Towing Tank Experiment Findings with Other Methods

The minimum resistance results under different trim and loading conditions obtained with different methods are presented in tables below. Table 5 and Table 6 relate to ship loading conditions and show resistance values calculated by each method in different trim and draft conditions. Table 5 pertains to design speed (22 knots), and Table 6 to economic speed (15 knots). The tables below have been drawn up to evaluate the graphics for the mentioned speeds given in the previous sections.

Resistance change under different trim conditions has been described in Table 5 based on ITTC 78 method results. There is an 18.5% difference between minimum and maximum resistance values in the 11.40m summer draft (fully loaded) condition at the design speed (22 knots), and a 15.7% difference in case of the 10.10m loaded draft. Under the assumption that the ship can float in the specified trim conditions in 8.80m partly loaded condition, the calculated difference between minimum and maximum resistance values is 8.8%.

In recent years, fuel consumption values have been reduced by operating ships in the economical speed range. Takinacı and Önen study (2013) established that even speed reduction by less than 1 knot required approximately 10% less main engine power. Therefore, the second resistance table for 15 knots is given in Table 6.

Draft : 11.40m Speed : 22kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	1760.5	1629.9	1485.1	1615.5	18.5
Orca (kN)	1653.0	1474.8	1470.9	1475.5	12.4
Maxsurf (kN)	1623.0	1567.3	1484.7	1520.1	9.3
Draft : 10.10m Speed : 22kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	1491.3	1414.0	1220.0	1406.3	22.2
Orca (kN)	1292.9	1285.6	1329.9	1385.9	7.8
Maxsurf (kN)	1373.4	1400.8	1423.2	1400.8	3.6
Draft : 08.80m Speed : 22kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	1256.8	1155.4	1176.5	1229.9	8.8
Orca (kN)	1252.5	1250.0	1220.1	1220.9	2.7
Maxsurf (kN)	1141.1	1261.1	1275.3	1239.8	11.8

Table 5. Comparison of calculated resistance values for design speed (22 knots) depending on draft and trim (Dark to white: Maximum to minimum resistance value for each line)

Draft : 11.40m Speed : 15kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	812.3	665.1	646.7	722.7	25.6
Orca (kN)	696.3	598.1	547.1	544.3	27.9
Maxsurf (kN)	646.7	593.5	543.5	564.8	19.0
Draft : 10.10m Speed : 15kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	722.1	737.2	657.2	666.2	12.2
Orca (kN)	494.2	494.3	513.8	508.9	4.0
Maxsurf (kN)	594.4	589.8	549.4	589.8	8.2
Draft : 8.80m Speed : 15kts	-2m	-1m	0m	+1m	% Difference
ITTC 78 (kN)	720.0	666.5	694.4	668.5	8.0
Orca (kN)	456.4	455.1	452.5	453.9	0.9
Maxsurf (kN)	475.7	548.5	551.5	535.8	15.9

Table 6. Comparison of calculated resistance values for economic speed (15 knots) depending on draft and trim (Dark to white: Maximum to minimum resistance value for each line)

3.5. Extra Discussions

Although the ship's wetted area increased with the trim as seen in Table 7, the even keel condition showed less resistance than the trim by bow condition, which has less wetted area than even keel condition. The effect of wetted surface area change is therefore thought to be lesser in the conditions examined. In addition, the hydrodynamic parameters of corresponding drafts were found to change very little under relevant trim conditions. Therefore, as seen in case of wetted surface area, a change in the basic main parameters of ships such as LCB, LWL and B has little effect on the total resistance change. Among other factors, bulb position and the angle of entry into the water are considered to be more critical for the ship.

Draft (m)	Trim condition	Wetted surface area (m^2)	Difference in wetted surface (%)
8.80	Trim by bow (+1)	6693.5	-0.162
8.80	Even keel (0)	6704.4	0.000
8.80	Trim by aft (-1)	6723.6	0.286
8.80	Trim by aft (-2)	6761.7	0.855
10.10	Trim by bow (+1)	7384.3	-0.691
10.10	Even keel (0)	7435.7	0.000
10.10	Trim by aft (-1)	7497.0	0.825
10.10	Trim by aft (-2)	7570.9	1.818
11.40	Trim by bow (+1)	8138.9	-0.647
11.40	Even keel (0)	8191.9	0.000
11.40	Trim by aft (-1)	8232.3	0.493
11.40	Trim by aft (-2)	8269.0	0.941

Table 7. Comparison of wetted surface area and waterplane area

The position of the bulbous bow is important for ships having the draft of 10.10m because it is located just below the waterline. Trim change alters the angle of entry, bulb position changes and it comes into contact with air. In ships with an 8.80m draft, the bulb is in a semi-submerged position. The differences in the results obtained using different methods for these two drafts may be attributable to bulb positions. The high results attributed to bulb position and the intervention made in the form factor calculation according to the Prohaska method should be borne in mind.

4. CONCLUSION

The effect of trim on resistance has been determined for a model ship. In general, resistance was found to increase with increasing stern trim under different loading and speed conditions for the selected model. In literature, ship resistance under trimmed conditions is generally lower than under even keel conditions. However, this study shows that the lowest resistance is generally achieved under the even keel condition. Moreover, the ship's least resistant trim condition varies depending on vessel speed and draft. The trim needs to be adjusted continuously according to these variables. As Takinacı and Önen (2013) stated, using more sensitive trim measuring devices, and looking at trim more frequently will improve our understanding of the trim-resistance relationship.

Some characteristics of the ship, such as wetted area, LCB, LWL, CB, etc., change with trim angle variation. In the Holtrop analysis, these changes have been considered to some extent for each case scenario. The two software-based methods using the same Holtrop analysis, also take these changes into account to some degree. Given that the Holtrop method is statistical, changes in trim conditions might not be realistically reflected in its output, but helped identify some differences in Maxsurf or Orca findings.

As stated earlier, the correspondence of Maxsurf and Orca results with the ship's manuals with respect to hydrodynamic properties has been previously determined. High correspondence between numerical resistance values obtained for speeds of up to 22 knots by the different methods used was established. At higher speeds, the deviations are significantly higher. When the results of the two programs were compared with the results of the towing tank trials, which are considered more reliable in literature, the following results caught our attention. Although Orca has its own trim resistance calculation module, there is almost no divergence in resistance curves under different conditions. In Maxsurf, resistance values vary with changing trim angles. However, these differences are not always meaningful. Resistance results under the same loading, but different trim conditions were found to be incompatible. Although the results of these programs could be used to predict ship resistance values, the selected vessel's testing conditions were insufficient for trim optimization. In addition, the user's role in defining geometry has an effect in Maxsurf. User-made changes in geometry may change the way in which the program handles ship geometry and thus influence resistance calculations. Therefore, ship manuals were carefully followed. As there are discrepancies between experimental and software results, direct software use in final decision-making is risky.

The large divergence in the 10.10m condition curves is thought to be attributable to bulb, as the bulbous bow of the ship is located just below the waterline. In cases with aft trims, the bulb comes into contact with air and waterline length increases. Bulb movements due to model acceleration or trim change may cause a separation. This phenomenon may be the cause of the divergence in related resistance curves.

The total resistance curve was found to increase rapidly at the speed of 22 knots. The operation of the ship considered in Table 5 or Table 6, will cause resistance values to decrease. A 30% reduction in ship speed (from 22 knots to 15 knots) was found to reduce total ship resistance by more than 50%. There is also a linear relationship between the vessel form's resistance values and effective power (PE) required for navigation. Therefore, ship speed and trim optimization will also have a linear effect on fuel economy and natural emission reduction.

RESEARCH LIMITATIONS AND FUTURE STUDY

Towing tank trials took place under the following conditions: calm water, water temperature of 15^0C. Air resistance was calculated, but wind resistance was not considered. Due to testing pool dimensions, the scale of the ship model was very small. Working with a larger pool or smaller-sized real ships would most likely produce more realistic results.

Study results are applicable only to the selected vessel and vessels of very similar geometry.

In real life scenarios, a ship can be operated very differently from the conditions analyzed. Change in trim angle also changes the vessel's maneuvering properties and propeller thrust angle. Furthermore, in general, resistance study with bare hull might not be sufficient to identify optimum trim conditions. Therefore, optimum trim conditions can vary depending on the conditions in which a ship is navigating. In this study, only four different trim conditions have been considered. Optimum conditions may change depending on the ship's conditions and its particular current needs.

The study compares an experimental method with two different regression-based softwares. Softwares are based on the same regression method, the Holtrop. A new study supported by the CFD method can be performed to examine the effects of changing variables on the result during the trim optimization process. ITTC extrapolation method and CFD-based analysis contain some uncertainties due to their natural operation. Hence, a study that would compare the theoretical basis for the Holtrop method, towing tank trials, and CFD analyses without extrapolation would be a valuable contribution to literature.

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CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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