Evaluation of the Optical Towing Tank at Queen's University for use in Model Ship Experiments

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Abstract

An experiment was conducted to evaluate the Optical Towing Tank for Energetics Research as a ship model basin. To this end, resistance tests were carried out on a 1 : 21 scale model of a hard-chine, planing monohull. Both measurement repeatability and accuracy of predicted resistance were investigated. Hull lines, together with hydrostatic and hydrodynamic performance data, were provided by MetalCraft Marine of Kingston, Ontario. The model was constrained to a fixed attitude similar to the known free-running characteristics of the hull, at volume Froude numbers F_∇ of 1.51, 1.62 and 1.72. Variation of measured resistance within test conditions was found to be less than 4% on average. To predict full-scale behaviour, residuary resistance coefficients C_R were calculated for each test condition, according to the guidelines of the International Towing Tank Conference. These were compared to the residuary resistance derived from sea trial data. It was found that, when the Blasius line was used to estimate frictional resistance at model scale, the experimental C_R was within 8% of the range of C_R calculated from sea trials.

1 Introduction

Resistance testing of a 1 : 21 scale ship model was undertaken for the purpose of evaluating the Optical Towing Tank for Energetics Research (OTTER) lab at Queen's University as a viable ship model basin for future research collaboration with MetalCraft Marine Inc. (MetalCraft). An existing hull form built by MetalCraft was tested so that results could be compared to data from sea trials. Geometry and loading conditions for a hard-chine, planing, monohull was provided by MetalCraft. The resistance tests were performed using a captive model, constrained to the known free-running attitude at the Froude-volume F_∇ numbers tested. Calculation of the frictional resistance coefficient C_F by the Blasius and ITTC'57 lines were also compared.

2 List of Symbols

A_p	Projected planing area (m^2)
A_W	Waterplane area (m^2)
B	Beam (m)
B_{px}	Beam over chines (m)
C_A	Model-ship correlation allowance
C_F	Coefficient of frictional resistance
C_R	Coefficient of residual resistance
C_T	Coefficient of total resistance
Fr	Froude number
F_∇	Volume Froude number
$F_{x,z}$	Hydrodynamic forces (N)
g	Gravity constant (m/s^2)
LCG	Longitudinal centre of gravity with respect to centroid of A_p ($\%L_p$)
L	Characteristic length (m)
L_C	Wetted chine length (m)
L_K	Wetted keel length (m)
L_M	Mean wetted length (m)
L_p	Length over chines (m)
L_{WL}	Waterline length at rest (m)
M_y	Hydrodynamic trimming moment (Nm)
R_T	Total resistance (N)
Re	Reynolds number
S	Area of running wetted surface (m^2)
S_0	Area of static wetted surface (m^2)
t_W	Water temperature ($^\circ C$)
V	Velocity (m/s)
$\bar{x}$	Mean of a group
X	Grand mean, or mean of means
Z_{SA}	Static sinkage at aft perpendicular (m)
Z_{VA}	Dynamic sinkage at aft perpendicular (m)
Z^*	Sinkage ratio
β	Deadrise ($^\circ$)
Δ	Displacement (kg)
ϵ	Twist angle ($^\circ$)
η	Combined engine and propeller efficiency
γ	Buttock angle ($^\circ$)
∇	Displacement volume at rest(m^3)
ν	Kinematic viscosity (m^2/s)
ρ	Mass density of water (kg/m^3)
σ	Standard deviation
θ_S	Static trim angle ($^\circ$)

3 Background

A ship model basin is a tank or channel for the testing of scaled models of ships, also known as a towing tank. The most common test is the resistance test, where the amount of force required to tow a model through calm water at a given speed is measured. The method was developed by William Froude during his systematic studies of ship resistance [1]. Best practices for towing tank tests and other predictive techniques for marine hydrodynamics are published by the International Towing Tank Convention (ITTC).

$$C_T = C_R(Fr) + C_F(Re) \tag{1}$$

$$Re = \frac{VL}{\nu} \tag{2}$$

$$Fr = \frac{V}{\sqrt{gL}} \tag{3}$$

Resistance testing is based on Froude's hypothesis (1), that a ship's total resistance C_T is the sum of her frictional resistance C_F and resistance due to wave-making, or residuary resistance C_R. The results of a resistance test are not scaled directly due to the difficulty of matching both the Reynolds number Re (2) and Froude number Fr (3). Instead, C_F is estimated independently for both model and ship, based on Re. At matching Fr the total resistance of the ship can then be calculated by (4), where m and s denote model and ship respectively. The accuracy of predicted C_T is then directly related to the accuracy of C_F.

$$C_{T_s} = C_{T_m} - C_{F_m} + C_{F_s} \tag{4}$$

In this study, C_F was calculated according to two methods, the ITTC'57 model ship correlation line (5), and the Blasius Line (6). The ITTC line is empirical, based on the Hughes flat plate line [2], fitted to towing tank results over $10^6 < Re < 10^{10}$ [3]. The Blasius line is an analytical solution for $Re < 5.3{\times}10^5$ [4].

$$(ITTC'57) : C_F = \frac{0.075}{(log_{10}Re - 2)^2} \tag{5}$$

$$(Blasius) : C_F = 1.328Re^{-0.5} \tag{6}$$

4 Test Parameters

In traditional towing tank testing the ship model is free to heave and trim as the hydrodynamic forces act upon the hull. In this case the model was constrained to a fixed attitude informed by the known free-running attitude. Running trim values were available from full-scale sea trials, and model trim was set at $\theta_S = 6.1°$, Figure 1. Bodily sinkage Z^* (7) was not recorded during sea trials, and instead is informed by the Delft Systematic Deadrise Series (DSDS) [5].

$$Z^* = \frac{Z_{VA}}{Z_{SA}} \tag{7}$$

In order to find an analogous DSDS test case, sea trial resistance data was plotted against the results from DSDS tests at similar hull geometry and loading conditions, Figure 2. The case where the DSDS data most closely matched the sea trial data is referred to as condition α, Table 1. Model sinkage was then based off of the recorded sinkage of α, set at $Z^* = 1.00$, shown in Figure 3.

Table 1: DSDS condition α.

Hull No.	$A_p/\nabla^{\frac{2}{3}}$	β	ϵ	L_p/B_{px}	γ	LCG
188	5.476	25	0	4.09	0	8

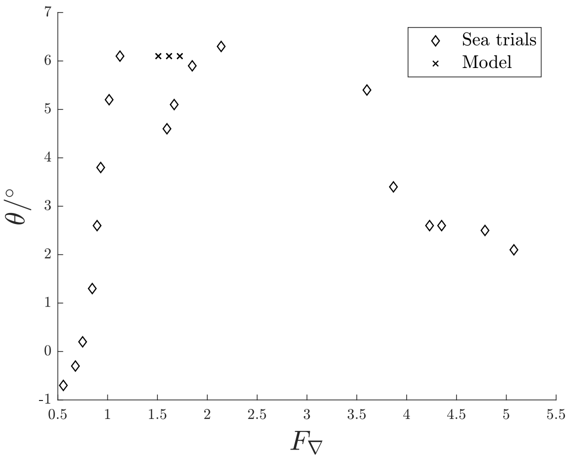

Figure 1: Model trim based on sea trials.

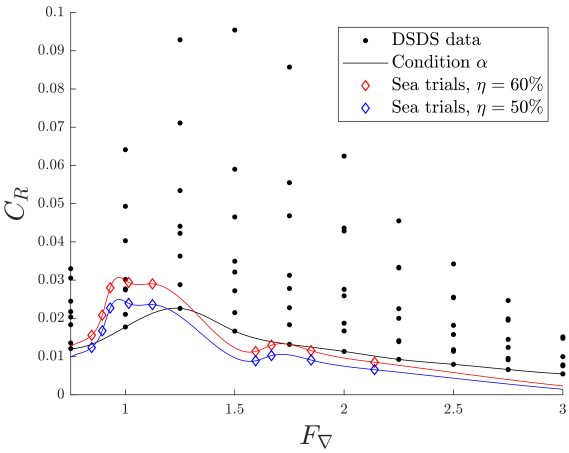

Figure 2: Comparison of sea trials to the DSDS.

5 Model Fabrication

A digital model of the hull was received from MetalCraft in IGS format for processing with SolidWorks. The model was scaled by a factor of 1/21 and exported in binary STL format for 3D printing. Model scale was chosen to maximize the Re of the experiment while achieving a sufficiently high Fr to be in the planing regime, where the towing speed of the tank is limited to

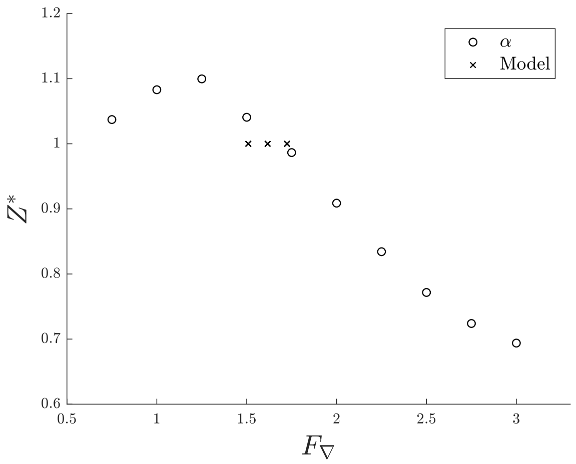

Figure 3: Model sinkage based on the DSDS.

$1.6m/s$. Model size was reduced slightly when it was found that doing so would allow it to be printed as a single piece. Export resolution of the STL file was maximum, with a deviation tolerance of $0.03mm$ and an angular tolerance of $0.5°$. The model was printed in ABS with a layer thickness of $0.254mm$ on a Fortus 380mc printer. The hull surface was hand finished with two layers of epoxy before sanding and painting. Special attention was given to preserving the sharpness of transom, keel, and spray rail edges. Draft and length markings were measured from the keel-transom intersection. The model was a bare hull with no appendages, having a final surface roughness of $1.7 \pm 0.4\mu m$. Model particulars are listed in Table 2.

Following ITTC recommendations [2], turbulence strips were placed on the hull. Though they resulted in an increase in drag, it is difficult to predict how and to what extent they modified flow transition over the hull. Certainly some of the increase can be attributed to additional parasitic drag from the strips, regardless of downstream effects. More detail is given in Appendix D.

Table 2: Principle dimensions and hydrostatics of 1/21 model at design displacement.

L_{WL}/mm	B/mm	Z_{SA}/mm	$\bar{\beta}/°$
386	122	32.5	23

Δ/g	S_0/cm^2	A_W/cm^2
694	484	385

6 Experiment Setup

Testing took place in the OTTER lab. The towing tank dimensions are $15m \times 1m \times 1m$. The width of the tank is greater than 7 times model beam B, and so blockage effects are assumed negligible [6]. The ship model was fixed to the towing post at the required trim θ_S and the tank drained or filled to achieve the required sinkage Z^*. Force data was collected using an ATI Gamma six-component sensor. The testing apparatus is illustrated in Figures 4, 5 and 6. Water temperature was recorded daily. Measurements were biased using the average of $3s$ of at-rest data taken prior to each run, so that only the dynamic component of the forces were considered in subsequent calculations. Readings were averaged over $3s$ at $10kHz$ over a steady running condition. 10 minutes was allowed between each run to let the water surface settle. The running wetted surface was determined from photography of the underside of the hull at steady condition, see Appendix C.

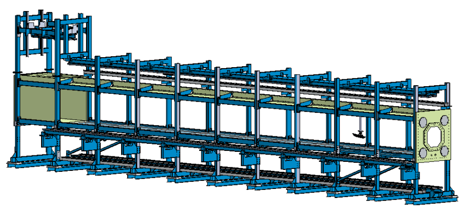

Figure 4: OTTER tank at Queen's University.

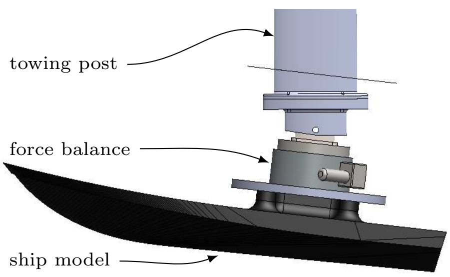

Figure 5: Testing apparatus.

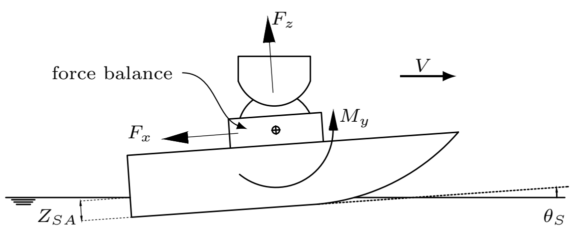

Figure 6: Configuration for fully captive experiment.

7 Data Analysis

The total resistance, R_T (8), was normalized according to (9). The residuary resistance, C_R, was obtained by Froude's hypothesis (1), which is assumed to scale with F_∇, (11). C_F of the model was estimated by both the ITTC'57 model ship correlation line (5), and the Blasius line (6). C_F from sea trials and the DSDS are calculated using the ITTC'57 line.

$$R_T = F_x \cos\theta_S + F_z \sin\theta_S \tag{8}$$

$$C_T = \frac{R_T}{\frac{1}{2}\rho S V^2} \tag{9}$$

Mean wetted length L_M (10) and running wetted surface S are used as the characteristic dimensions for calculating Re and C_T, respectively. However neither of these dynamic values are available from the sea trials, and so the static values are treated as approximately equivalent, so that $L_{WL} \approx L_M$ and $S_0 \approx S$. As is frequently the case with planing craft [7], the volume Froude number F_∇ (11) is used in place of the length based Froude number Fr. Since the at-rest model condition was meant to simulate a running condition, model displacement volume ∇ was calculated from the design displacement. Air resistance and ship appendage resistances are ignored.

$$L_M = (L_K + L_C)/2 \tag{10}$$

$$F_\nabla = \frac{V}{\sqrt{g\nabla^{\frac{1}{3}}}} \tag{11}$$

8 Results

Measurements were on the order of $10^{-1}N$, the low end of the sensor's $120N$ range, and so the repeatability of the tests was investigated. Five trials were conducted at each test condition, averages of the steady-state data for the conditions of interest are listed in Appendix B. However, additional measurements were taken at conditions not relevant to the current analysis, but which provide additional data on the expected variation. Variation is defined here as 2 standard deviations of the means. The average variation was found to be 3.6%. This can be compared to a worldwide study in which 10 towing tanks performed resistance testing on identical 'small' models ($3.048m$) [8]. 10 trials were conducted at each speed, the results for the highest speed, $Fr = 0.41$, are used for comparison since variation decreased with increasing Fr. In this study the average variation was 2.5%. The distribution of the variation is given in Figure 7.

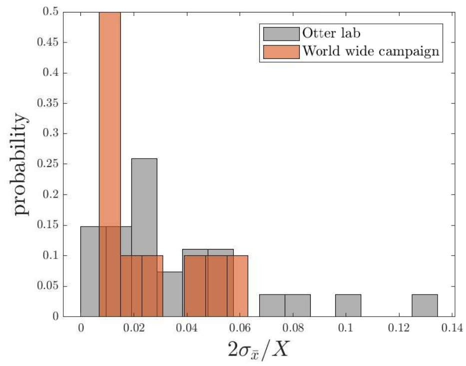

Figure 7: Probability of variation in average resistance measurements $\bar{R}_T$, as determined by standard deviation of the means.

Experimentally determined residuary resistance C_R was compared to sea trial C_R. Resistance from sea trials was determined based on the horsepower at a given engine speed. The thrust produced depended on the combined efficiency of the engine and propellor η, estimated at $0.5 \leq \eta \leq 0.6$. Accordingly, a lower and upper value of C_R is reported. Frictional resistance C_F during sea trials was calculated by the ITTC'57 line, which at matching F_∇ had $Re \approx 5{\times}10^7$.

The frictional resistance coefficient C_F of the model was calculated by both the ITTC'57 and Blasius lines. Though the ITTC'57 line is recommended [2], it is fitted over $10^6 < Re < 10^{10}$, while the OTTER tests took place over $1.29{\times}10^5 < Re < 4.98{\times}10^5$. It was found that the Blasius line led to a more accurate prediction of C_R than the ITTC'57 line, Figure 8. This suggests that, for this hull shape at low Re, the ITTC'57 line overpredicts C_F.

A model-ship correlation allowance C_A was incorporated to calculate the expected C_R from sea trial data (13). The C_A is established on a facility by facility basis and is meant to allow for all effects and uncertainties not covered by the prediction method [2]. In the absence of an established C_A, the ITTC recommends calculation by (12), which is used here.

$$C_A = (5.58 - 0.6\log Re_{ship}){\times}10^{-3} \tag{12}$$

$$C_R = C_T \times \eta - C_F - C_A \tag{13}$$

Using the Blasius line in the calculation of model C_R, the experimental results fell within the expected range when $F_\nabla = 1.51$ and $F_\nabla = 1.62$. At $F_\nabla = 1.72$ it was found that $C_{R_m}/C_{R_{seatrial}} = 0.92$ (compared to the interpolated curve).

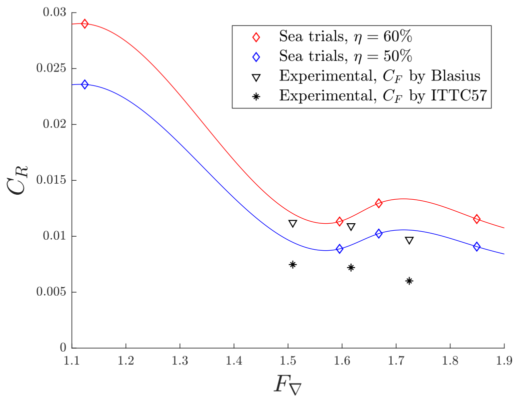

Figure 8: Predicted resistance, comparison of method of calculating C_F. Sea trial lines interpolated by cubic spline.

9 Conclusion

When using the OTTER lab for ship model testing, where forces are expected to occur in the $10^{-1} N$ range, readings of time-averaged, steady-state phenomenon are on average repeatable within 3.6%, suggesting the existing setup can be used for comparative investigations at model scale, when a fixed attitude is appropriate. This can be compared to an average of 2.5% obtained from a world-wide study.

If extrapolating results to full scale, it is recommended to use the Blasius line for estimating model C_F, and to install a towing post where the model is free to pitch and heave; model construction would have to be modified to allow for ballasting. In that case the scaled results should be within 8%. However, due to the limited range of F_∇ tested, as well as the uncertainty in estimating resistance from the sea trials, it would be recommended to further calibrate the tank using a well documented hull form. Further testing could also lead to the determination of a facility specific correlation allowance, improving predictions.

10 Acknowledgments

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References

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Appendices

A Test Parameters

Table 3: Test conditions.

Condition	Date	$V/\frac{m}{s}$	Z_{SA}/mm	$\theta_S/°$	$t_W/°C$
1	2018-07-12	1.5	33	6.1	24.1
2	2018-07-12	1.4	33	6.1	24.1
3	2018-07-12	1.6	33	6.1	24.1

B Data

Table 4: Test results.

Condition	L_C/m	F_x/N	F_z/N	M_y/Nm
1	0.160	0.445	3.287	0.039
2	0.156	0.397	2.905	0.034
3	0.158	0.459	3.785	0.047

C Determining Running Wetted Surface

Model geometry was imported into MatLab for calculation of displacment volume ∇ and running wetted surface S. To calculate S, wetted chine length L_C was estimated from photography of the underside of the hull while underway, Figure 10. The keel-surface intersection is assumed to be the same as the calm-water intersection for $\theta_S < 15°$, and the slight curvature of the spray-root is assumed negligible [9]. Figure 9 shows a visualization of the calculation of S.

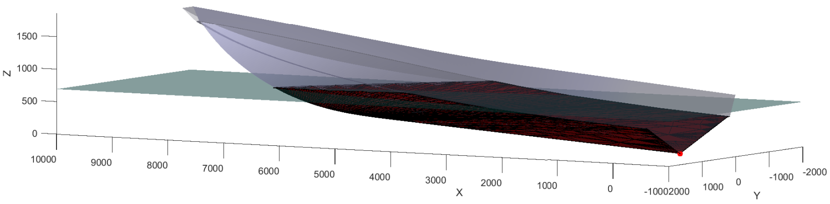

Figure 9: Sample visualization of wetted surface calculation in MatLab.

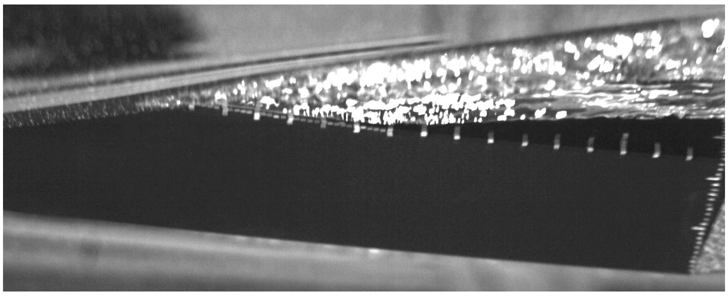

Figure 10: Sample photograph for measurement of wetted chine length.

D Turbulence Strips

Following ITTC guidelines [2], turbulence strips were fitted to the hull, as seen in Figure 11. The strips were self-adhesive, $0.4mm$ thick, $12mm$ wide, and had a $60°$ zig-zag pattern. The use of the strips was compared in one test case and it was found to increase the resistance by $\backsim 15\%$, Table 5, where residuary resistance C_R is calculated using Equation 6. However it is unknown whether this was due to the additional parasitic drag of the strip alone, or in combination with a change in flow transition over the hull. Considering the greater change in C_R by calculation of C_F, it suggests that use of the strips was not sufficient to induce a fully turbulent boundary layer, analogous to the full scale flow.

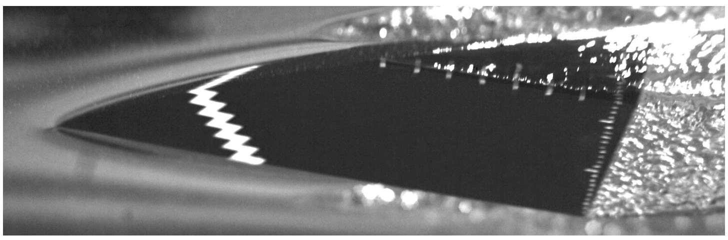

Figure 11: Turbulence strip fitted to hull.

Table 5: Effect of turbulence strips.

turbulence strips fitted?	Z_{SA}	V	θ_S	C_R/C_{R_0}
no	33	1.5	1.5	1
yes	33	1.5	1.9	1.15