Estimating Resistance and Propulsion for Single-Screw and Twin-Screw Ships

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1. Comparison of traditional methods with modern data

Traditional methods to estimate resistance and power in conceptual ship design follow e.g. Holtrop and Mennen *(Holtrop 1984)*, *Guldhammer and Harvald (1974)*, *Danckwardt (1981)* (for trawlers), Lap-Keller *(Lap 1965, Keller 1973)*, *Oortmerssen (1971)*, and Series-60 *(Sabit 1972)*. However, all these methods are based on ship forms which may be considered obsolete, and there has been growing concern regarding the applicability of these methods to modern ship hulls. Therefore the databases of the Vienna Ship Model Basin for the years 1980 to 1995 were used to evaluate the accuracy of these traditional methods. The databases covered 433 models (1218 variants) with protocols of 793 resistance tests and 1103 propulsion tests each for a set of different speeds.

The traditional estimation methods proved to be quite reliable in predicting the resistance of an average single-screw ship, Table I. The result of these methods will be called 'mean resistance' in the following. It is useful to have also formulas for the lower and upper envelope curves of the statistical data which are exceeded by only 5% of the cases. These lower and upper envelopes are called here 'minimum' and 'maximum' resistance. The 'minimum' resistance is taken as an estimate for what may be achieved by excellent lines not subject to severe constraints from the design and found after considerable further computer and model test investigations. The 'maximum' may represent lines subject to unusual constraints from the overall design. These envelopes are not part of the classical prediction methods. The traditional methods are also unsuitable for twin-screw ships except for the methods of Holtrop-Mennen and, to some extent, Guldhammer-Harvald. Lap-Keller and Series-60 methods are only suitable for single-screw ships on design draft. Oortmerssen and Danckwardt Trawler methods are at best suited for small ships, but they show higher standard deviations than other methods.

Table I: Mean values and standard deviation of (model test resistance – estimated resistance)

Method	single-screw		twin-screw	
	mean value	std. deviation	mean value	std. deviation
Holtrop/Mennen	+2.7%	13.4%	+8.4%	17.9%
Guldhammer/Harvald	+4.8%	15.2%	+12.1%	23.0%
Lap-Keller	+2.9%	13.4%	+16.2%	19.7%
Series-60	+2.4%	13.4%	+17.7%	22.4%
Oortmerssen	+5.7%	14.8%	+6.8%	20.2%
Danckwardt Trawler	-4.3%	17.9%	+17.9%	31.5%

2. New estimation method for resistance

Variables not specified explicitly have a meaning according to the ITTC standard. All lengths are taken in [m].

In addition to $L = L_{pp}$ and L_{wl}, which are defined as usual, I define a 'length over surface' L_{os} as follows, Fig. 1:

- For design draft: length between aft end of design waterline and most forward point of ship below design waterline

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- For ballast draft: length between aft end and forward end of ballast waterline (rudder not taken into account)

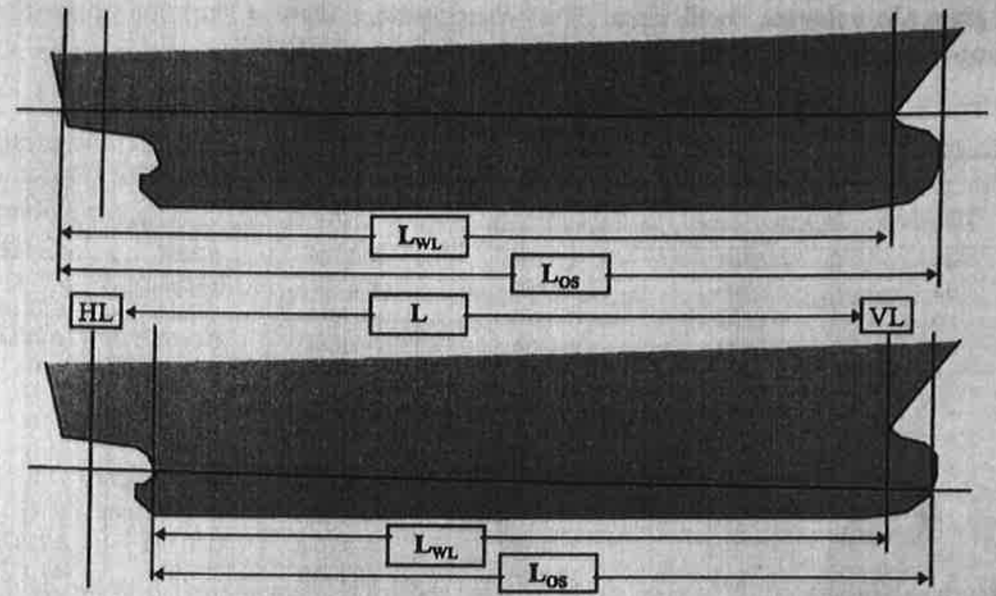

Fig.1: Definition of lengths L, L_{os}, and L_{wl}

The Froude number in the following formulae is based on the length L_{fn}:

$$L_{fn} = \begin{cases} L_{os} & \text{for } L_{os}/L < 1 \\ L + 2/3 \cdot (L_{os} - L) & \text{for } 1 \leq L_{os}/L < 1.1 \\ 1.0667 \cdot L & \text{for } 1.1 \leq L_{os}/L \end{cases} \tag{1}$$

The resistance is decomposed without using a form factor. The residual resistance is given by

$$R_R = C_R \cdot \frac{\rho}{2} \cdot V^2 \cdot B \cdot T.$$

Note that $B \cdot T$ is used instead of the wetted surface S as reference area. The nondimensional coefficient C_R is generally expressed for 'mean' and 'minimum' values as:

$$C_R = C_{R,\text{Standard}} \cdot C_{R,\text{Fnkrit}} \cdot k_L \cdot (T/B)^{a1} \cdot (B/L)^{a2} \cdot (L_{os}/L_{wl})^{a3} \cdot (L_{wl}/L)^{a4} \cdot (D_P/T_A)^{a6}$$

$$\cdot (1 + (T_A - T_F)/L)^{a5} \cdot (1 + N_{\text{Rud}})^{a7} \cdot (1 + N_{\text{Brac}})^{a8} \cdot (1 + N_{\text{Boss}})^{a9} \cdot (1 + N_{\text{Thr}})^{a10} \tag{2}$$

T_A is the draft at AP, T_F the draft at FP, D_P the propeller diameter, N_{Rud} the number of rudders [1 or 2], N_{Brac} the number of brackets [0...2], N_{Boss} the number of bossings [0...2], N_{Thr} is the number of side thrusters [0...4].

$$C_{R,\text{Standard}} = b_{11} + b_{12}F_n + b_{13}F_n^2 + C_B \cdot (b_{21} + b_{22}F_n + b_{23}F_n^2) + C_B^2 \cdot (b_{31} + b_{32}F_n + b_{33}F_n^2) \tag{3}$$

$$C_{R,\text{Fnkrit}} = \max[1.0, (F_n/F_{n,\text{krit}})^{c_1}] \tag{4}$$

$$F_{n,\text{krit}} = d_1 + d_2 C_B + d_3 C_B^2 \tag{5}$$

$$k_L = e_1 L^{e_2} \tag{6}$$

The formulae are valid for Froude number intervals:

$$F_{n,\min} = \min(f_1, f_1 + f_2 \cdot (f_3 - C_B)) \tag{7}$$

$$F_{n,\max} = g_1 + g_2 C_B + g_3 C_B^2 \tag{8}$$

The 'maximum' total resistance is

$$R_{T,\max} = h_1 \cdot R_{T,\mathrm{mean}} \tag{9}$$

Table II gives the relevant coefficients. Test computations showed that the above formulae reflect appropriately the fundamental database of *Hollenbach (1997)*.

Table II: Resistance coefficients

	'mean'			'minimum'	
	single-screw		twin-screw	single-screw	twin-screw
	design draft	ballast draft		design draft	
$a1$	-0.3382	-0.7139	-0.2748	-0.3382	-0.2748
$a2$	0.8086	0.2558	0.5747	0.8086	0.5747
$a3$	-6.0258	-1.1606	-6.7610	-6.0258	-6.7610
$a4$	-3.5632	0.4534	-4.3834	-3.5632	-4.3834
$a5$	9.4405	11.222	8.8158	0	0
$a6$	0.0146	0.4524	-0.1418	0	0
$a7$	0	0	-0.1258	0	0
$a8$	0	0	0.0481	0	0
$a9$	0	0	0.1699	0	0
$a10$	0	0	0.0728	0	0
b_{11}	-0.57424	-1.50162	-5.34750	-0.91424	3.27279
b_{12}	13.3893	12.9678	55.6532	13.3893	-44.1138
b_{13}	90.5960	-36.7985	-114.905	90.5960	171.692
b_{21}	4.6614	5.55536	19.2714	4.6614	-11.5012
b_{22}	-39.721	-45.8815	-192.388	-39.721	166.559
b_{23}	-351.483	121.820	388.333	-351.483	-644.456
b_{31}	-1.14215	-4.33571	-14.3571	-1.14215	12.4626
b_{32}	-12.3296	36.0782	142.738	-12.3296	-179.505
b_{33}	459.254	-85.3741	-254.762	459.254	680.921
c_1	$F_n/F_{n,\mathrm{krit}}$	$10C_B(F_n/F_{n,\mathrm{krit}}-1)$	$F_n/F_{n,\mathrm{krit}}$	0	0
d_1	0.854	0.032	0.897	0	0
d_2	-1.228	0.803	-1.457	0	0
d_3	0.497	-0.739	0.767	0	0
e_1	2.1701	1.9994	1.8319	0	0
e_2	-0.1602	-0.1446	-0.1237	0	0
f_1	0.17	0.15	0.16	0.17	0.14
f_2	0.20	0.10	0.24	0.20	0
f_3	0.60	0.50	0.60	0.60	0
g_1	0.642	0.42	0.50	0.614	0.952
g_2	-0.635	-0.20	0.66	-0.717	-1.406
g_3	0.150	0	0.50	0.261	0.643
h_1	1.204	1.194	1.206		
ship length L [m]	42.0...205.0	50.2...224.8	30.6...206.8	42.0...205.0	30.6...206.8
$L/\nabla^{1/3}$	4.49...6.01	5.45...7.05	4.41...7.27	4.49...6.01	4.41...7.27
C_B	0.60...0.83	0.56...0.79	0.51...0.78	0.60...0.83	0.51...0.78
L/B	4.71...7.11	4.95...6.62	3.96...7.13	4.71...7.11	3.96...7.13
B/T	1.99...4.00	2.97...6.12	2.31...6.11	1.99...4.00	2.31...6.11
L_{os}/L_{wl}	1.00...1.05	1.00...1.05	1.00...1.05	1.00...1.05	1.00...1.05
L_{wl}/L	1.00...1.06	0.95...1.00	1.00...1.07	1.00...1.06	1.00...1.07
D_P/T	0.43...0.84	0.66...1.05	0.50...0.86	0.43...0.84	0.50...0.86

3. Recommendations to estimate propulsive factors

The following formulae can be used to estimate the hull efficiency in model scale:
For single-screw ships on design draft:

$$\eta_{H,\,\mathrm{model}} = 0.948 \cdot C_B^{0.3977} \cdot (R_{T,\mathrm{mean}}/R_T)^{-0.58} \cdot (B/T)^{0.1727} \cdot (D_P^2/(BT))^{-0.1334} \tag{10}$$

For single-screw ships on ballast draft:

$$\eta_{H,\,\mathrm{model}} = 1.055 \cdot C_B^{1.0099} \cdot (L/B)^{0.2991} \cdot (L_{wl}/L)^{-3.2806} \cdot (D_P/T)^{-0.2317} \tag{11}$$

For twin-screw ships:

$$\eta_{H,\,\mathrm{model}} = C \cdot C_B^{0.1262} \cdot (D_P^2/(BT))^{0.0285} \tag{12}$$

The coefficient C for twin-screw ships is $C = 1.125$ for ships with shaft brackets and twin rudders, $C = 1.224$ for ships with twin skegs and twin rudders, $C = 1.086$ for ships with shaft brackets and single rudder, $C = 1.096$ for ships with shaft bossings and single rudder. The formulae are for models of average length 6.5m.

Experimental results showed no correlation between main dimensions and thrust deduction fraction t. This depends instead on local form details and the propeller arrangement. Therefore I recommend to use an average value for t in the preliminary design stage, Table III.

Table III: Recommended estimate for thrust deduction fraction t

single-screw	design draft		0.190
single-screw	ballast draft		0.195
twin-screw	design draft	twin rudder, shaft brackets	0.150
twin-screw	design draft	twin rudder, twin skegs	0.186
twin-screw	design draft	twin rudder, shaft brackets	0.130
twin-screw	design draft	twin rudder, shaft bossings	0.113

The relative rotative efficiency η_R does not correlate to the main dimensions either. η_R increases if the stock propeller of the model has a lower efficiency than the corresponding Wageningen B-series propeller. If for the power prognosis a Wageningen B-series propeller is used, η_R should be taken as

$$\eta_R = \begin{cases} 1.009 & \text{for single-screw ships on design draft} \\ 1.000 & \text{for single-screw ships on ballast draft} \\ 0.981 & \text{for twin-screw ships on design draft} \end{cases} \tag{13}$$

4. Validation against HSVA models

The formulae were validated against test cases of the Hamburg Ship Model Basin HSVA which were not included in the original database. 19 single-screw and 6 twin-screw ships were taken from projects in 1996 and 1997. Table IV suggests the following conclusions:

- The new method shows a similar average error as the traditional methods, but better standard deviation, for single-screw ships on design draft.
- The new method predicts much better the resistance for single-screw ships in ballast condition.
- The new method predicts much better the resistance for twin-screw ships on design draft.

Table IV: Average and standard deviation of error in resistance (model test – prediction)

	single-screw design draft		single-screw ballast draft		twin-screw design draft	
	average	standard deviation	average	standard deviation	average	standard deviation
Holtrop-Mennen	-0.5%	12.8%	6.3%	16.1%	5.8%	18.4%
Guldhammer	0.8%	11.0%	10.5%	17.9%	11.2%	19.2%
Lap-Keller	-0.5%	12.9%	27.9%	32.9%	14.0%	23.4%
Series-60	-1.0%	11.6%	37.3%	42.7%	15.2%	23.3%
Hollenbach	1.0%	9.4%	-0.2%	11.2%	3.5%	13.3%

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