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Comparison between empirical forecast methods of resistance to advance and propulsive design of a container ship

Huascar B. Feijó[1], Jasmim L. C. de Oliveira[2]

[1] *Department of Naval Engineering, State University of Amazonas (UEA), Brazil*
hbf.eng16@uea.edu.br
[2]*Department of Civil Engineering, State University of Amazonas (UEA), Brazil*
jlco.eng@uea.edu.br

Abstract. Estimating the resistance to advancement and the necessary power of ships´ engines has a vital importance in the design and construction of any marine vehicle. However, performing this task is not simple and can be done by different methods. So far, the main ways of predicting ship dragging are restricted to computational fluid dynamics methods (CFD), testing on ship models (small scale), and systematic series. The series, in turn, are empirical approaches originating from tests performed systematically on model ships. In order to verify the applicability of these series, this study presents a comparison between the approach proposed by Holtrop and Mennen and the method proposed by Hollenbach. For this, a container ship was subjected to both methods and the expected resistance values were compared. The second stage of this work consists of the optimization of the propulsive system using the Microsoft Excel Solver tool, which allowed to find parameters in their ideal forms, such as: propeller rotation and maximum propeller efficiency. The Wageningen B-Series propeller series was used in this last stage.

Keywords: Ship resistance. Propulsion design. Systematic series. Optimization.

1 Introduction

The prediction of the force that opposes the advance of ships, known as ship resistance, is a fundamental part of a naval project. Intuitively, it is known that there needs to be a force that overcomes the drag, for the ship to start moving. However, the calculation of this force is not so simple, involving many variables. But, once this first obstacle is surpassed and with the value for the drag in hands, the naval architect will be able to design the propeller with its parameters: diameter, efficiency, number of blades, among others; and, later, will select the necessary engines that will supply the required power.

The methodologies adopted by researchers to obtain ship resistance data originate from tests performed on model ships. With experiments carried out in tanks with ships on a small scale, it is possible to find values and data that can be extrapolated to a ship that will be built on a full scale. This approach provides a more reliable resistance estimate.

However, in the impossibility of carrying out tests on tanks and in view of needing to make quick predictions for preliminary projects, a second option of resistance estimates is available: the systematic series. These series are derived from tests performed on countless small-scale vessels, with variation in the shape of the hulls, and which can be applied to several vessels on a full scale. In this context, the purpose of this article is showing a comparative study of the applicability of the series proposed by Hollenbach and Holtrop-Mennen for the prediction of resistance. These methods use mathematical models to predict the preliminary power of tugs, fishing vessels, cargo ships, bulk carriers, and container carriers.

The first part of this study consists in comparing the results that the two methods will provide when applied to a container ship. The applicability and predictability of these methods for an initial design phase are verified.

Once the total drag of the ship is acquired, the second part of this article consists in propulsive dimensioning. As the main part of the ship's propulsion system, the propeller must be measured in such a way that its interaction with the hull produces maximum propulsive efficiency. The Wageningen B-Series [1] propeller series is used for propulsion forecasting.

The MS Excel program will be used to receive the tables and equations for each resistance forecasting method. The Solver function, present in the program, will be used in the second part of this article as a tool to find optimized data on propulsive efficiency and propeller rotation. With these efficiency and ship resistance values, it will be possible to calculate the required potency value that must be delivered to the propeller by the engines.

2 Theory

2.1 Ship Resistance

The hydrodynamic forces that act against the movement of vessels are called ship resistance or resistance to advance. This resistance is composed by the action of the waters and the winds. In his work, Harvald [2] says that resistance (R_T) is the fluid force that acts on the ship in the opposite way to movement. Mathematically, this statement can be expressed by eq. (1).

$$C_T = \frac{R_T}{0{,}5.\rho V_S^2 S} \tag{1}$$

In which: V_s is the ship's speed, S is the hull's wet area, ρ is the fluid density and C_T is the total resistance coefficient.

According to Bertram and Schneekluth [3] ship resistance of ships in calm waters can be decomposed into several components. These main components are: Friction resistance, Wave resistance and Viscous pressure resistance.

Friction resistance: when the ship moves at a certain speed Vs, a boundary layer is formed along the wet area of the hull. Bertram [4] describes that the water viscosity causes its particles to cling to the hull, forming a film of liquid that moves with the ship. Therefore, with any abrupt change in speed, this boundary layer produces high shear stresses in the hull, thus originating the frictional resistance R_F.

Wave resistance: any body that moves on water creates a typical wave pattern. In ships, the waves generated add a resistance Rw. For the origin of the drag caused by the waves, Birk [5] states that the waves contain and transport kinetic energy and that to maintain and create a wave system, it is necessary to supply energy. Therefore, the part of kinetic energy that is continuously supplied for the formation of waves, is called resistance.

Viscous pressure resistance: The presence of the boundary layer around the ship produces another type of resistance besides frictional resistance. The stern has a thicker layer of fluid that moves with the hull than the bow of the ship. This difference in thickness of the boundary layer creates a region of low pressure at the stern and high pressure at the bow. This pressure difference results in the viscous pressure resistance.

2.2 Systematic series: Hollenbach and Holtrop-Mennen

According to Marzi and Broglia [6], empirical methods to forecast the resistance are traditionally used in preliminary designs due to their simplicity of use and speed. Among the best-known methods are those proposed by Hollenbach [7] and by Holtrop-Mennen [8], [9], [10] and [11]. Hollenbach's approach is modern and used for merchant ships with one or two propulsion axles. The estimates of minimum, mean and maximum resistance are provided for the analysis of the best- or worst-case scenario. On the other hand, the Holtrop´s method is based on regression analysis of tests performed on models, being applicable to several types of vessels. By this method, it is possible to obtain the total drag on components as shown in Fig. 1.

With these methods´ equations, it is possible to reach not only the total ship resistance, but also the following propulsive parameters: thrust deduction fraction (t) wake fraction (w) and relative rotative efficiency (η_R).

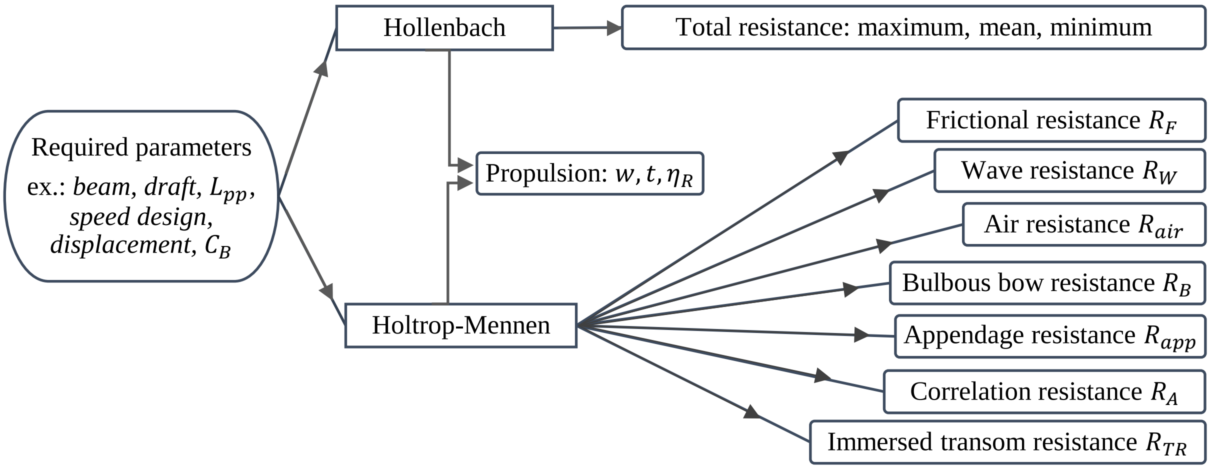

Figure 1. Input and output of systematic series

2.3 Wageningen B-series propellers

This is a systematic series that estimates the initial propellers geometry. The series is based on about 120 propellers that have had their geometry systematically varied. To use this method, the following input parameters are required: number of blades (z), advance coefficient (J), ratio between expanded area and projected area (Ae/Ao) and ratio between pitch and diameter of the propeller (P/D). The series returns the thrust coefficient (K_T) and the propeller´s torque coefficient (K_Q) in the open water condition. With these coefficients, it is possible to calculate the propeller´s efficiency (η_o), the thrust delivered (T_{ent}) and the torque in calm waters (Q_o), as described in eq. (2), (3) and (4).

$$\eta_o = \frac{J}{2\pi}\frac{K_T}{K_Q} \tag{2}$$

$$T_{ent} = K_T \rho n^2 D^4 \tag{3}$$

$$Q_o = K_Q \rho n^2 D^5 \tag{4}$$

The validity field of the series is most effective when it is within the limits described in Tab. 1.

Table 1. Limitations of applicability of the Wageningen B-Series

Number of blades (z)	Blade area ratio (A_E/A_o)	Pitch-diameter ratio (P/D)
2 - 7	0,3 - 1,05	0,5 - 1,4

3 Methods and Results

A container ship with a capacity of 1000 containers, with the dimensions described in Tab. 2, was submitted to the Holtrop and Hollenbach´s empirical methods.

Table 2. Container ship data

Length between perpendiculars	Lpp	145 m	Displacement	∇	18872 m³
Length in front of the bulb	L_{fore}	3,3 m	Design speed	Vs	12-19 knots
Length of water line at the Stern	L_{aft}	2,7 m	Bulb cross sectional area	A_{BT}	14 m²
Waterline length	Lwl	147,7 m	Wetted area of appendages	S_{app}	52 m²
Length over wetted area	Los	151 m	Sail area	Av	383,76 m²
Beam	B	24 m	Lcb	%	1,3067
Draft	D	8,2 m	Number of propeller shafts	Ne	1

The tables and equations were inserted into spreadsheets in Microsoft Excel - the main tool in the formulation of the calculations, so that the task of obtaining results of the ship's resistance is facilitated. Then, with the geometric data of the ship kept constant, it was only necessary to vary the speed of the vessel in the interval in which it operates for the most part of time.

3.1 Results of total resistance

The speed variation interval chosen is between 12 and 20 knots, and for each speed the respective resistances were obtained. According to Hollenbach's approach, the minimum, mean and maximum resistances achieved are detailed in Table 3, as well as Holtrop's predictions. Then, the comparative analysis was performed by constructing the graph in Fig. 2. The resistance curves showed some similarity within the chosen speed range. However, a greater similarity occurs when there is a comparison between Holtrop´s estimates and Hollenbach's mean resistances.

Table 3. Comparison between resistance estimates

Vs		Hollenbach R_T (KN)			Holtrop R_T (KN)
(Knots)	(m/s)	Minimum	Mean	Maximum	
12	6,17	179,16	213,26	256,76	223,23
12,5	6,43	194,53	231,51	278,74	242,62
13	6,69	211,25	251,20	302,45	263,37
13,5	6,94	229,49	272,49	328,08	285,66
14	7,20	249,40	295,55	355,84	309,69
14,5	7,46	271,19	320,56	385,95	335,69
15	7,72	295,05	347,71	418,65	363,86
15,5	7,97	321,19	377,21	454,16	394,50
16	8,23	349,83	409,27	492,76	428,02
16,5	8,49	381,21	444,12	534,72	464,66
17	8,75	415,57	482,00	580,33	504,27
17,5	9,00	453,17	523,16	629,88	546,55
18	9,26	494,27	567,85	683,69	591,60
18,5	9,52	539,17	616,36	742,10	640,50
19	9,77	588,16	668,97	805,44	695,15
19,5	10,03	641,53	730,21	879,17	757,62
20	10,29	699,61	803,06	966,88	829,30

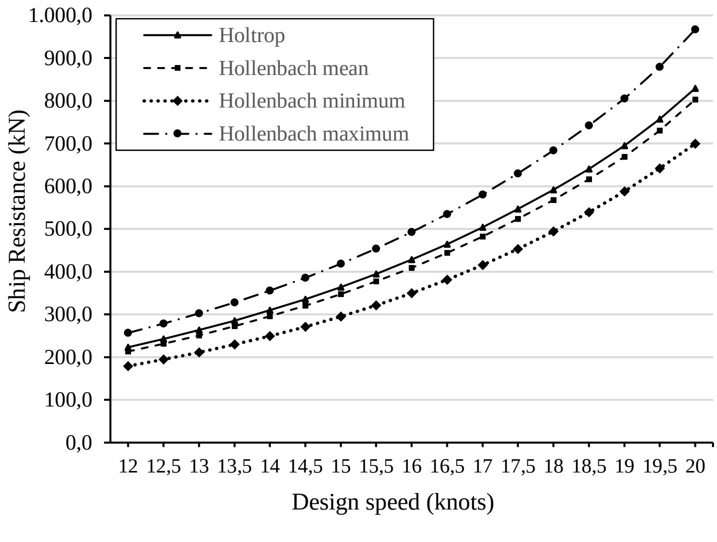

Figure 2. Resistance curves for design speed between 12 to 20 knots

3.2 Propulsive design

After the resistance estimates, the next step is the propulsive design so that the ship's propulsion potency can be determined. For this second task, the Wageningen B-Series is used, and its tables are inserted into spreadsheets in Excel. As previously described, this series of propellers receives input parameters J, $A_{e/}A_o$, P/D and z. These parameters must be varied until an efficient propeller is found. However, the great dilemma of this series is the difficulty of manually varying these parameters and at the same time obtaining the optimized both propeller´s rotation and efficiency, the necessary thrust and respecting the cavitation limit of 5% for merchant ships.

Although there are software and methods to help finding optimized values for the Wageningen B-Series, the purpose of this article is showing an alternative and simple path: Excel's Nonlinear GRG solver tool. Through this tool, it was possible to vary the input values automatically, maximize the efficiency of the propeller and establish restrictions.

In this analysis, some initial constants were defined. The number of blades was fixed at 5 and the diameter of the propeller at 4.9 m. It is important to note that the advance coefficient (J) depends on other variables, as seen in eq. 5; therefore keeping the diameter (D) and the speed of flow in the propeller (V_a) constant, it was necessary to vary only the number of rotations of the propeller (n).

$$J = \frac{V_a}{nD} \tag{5}$$

The next task is the application the Solver command. In the following, the step-by-step is described.

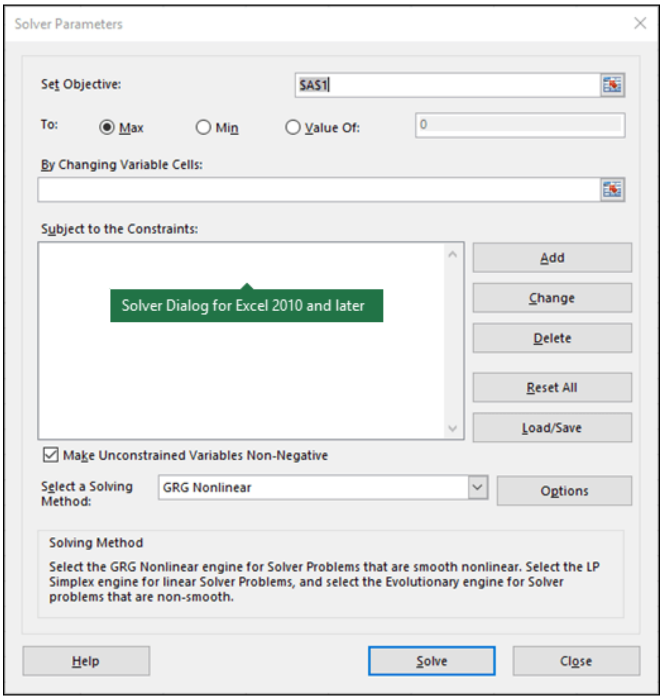

Figure 3. Solver interface

1° step: in the *"Set Objective"* box, the variable to be maximized is chosen, in this case the efficiency cell of the propeller (η_o) is selected.

2° step: in the *"By Changing Variable Cells"* box, it is necessary to select the parameters to be varied to achieve maximum efficiency. The values chosen to vary were:

a) Propeller´s number of rotations per second (n);

b) Pitch-diameter ratio (P/D);

c) Blade area ratio (Ae/Ao).

3° step: Establish restrictions. In the *"Subject to the Constraints"* field, all system restrictions are inserted, which in this study are:

a) (P/D) ≤1,4;

b) $(Ae/Ao) \leq 1{,}05$;

c) Cavitation less than 5% (formulations on this restriction are best understood by reviewing the literature);

d) $T\,delivered \geq T\,effective$ (effective thrust obtained from the drag results).

4° step: select the *"Non-linear GRG"* option in the *"Select a Solving Method"* box. Then it is necessary to click on the *"Solve"* command. The responses obtained will be: thrust delivered, maximum propeller efficiency, ideal rotation rate, areas ratio and ideal ratio between pitch and diameter.

3.2.1 Results of propulsive design

The described steps were applied only to Hollenbach's resistance results. Similarly, the use of the Solver command can be applied to the Holtrop series. However, this topic only aims to exemplify the applicability of this tool and describe the results obtained.

The first step was finding the optimal values of ratio between areas (Ae/Ao) and the pitch-diameter ratio (P/D) for the average speed of 15 knots. This is the vessel's navigation speed most of the time, that is why these geometric parameters have been optimized for this average speed. The values found were: Ae/Ao = 0.6 and P/D = 1. These values were kept fixed for the other speeds.

The propeller rotation rate, however, is a parameter that can be variable during navigation and, therefore, it is possible to obtain an optimized value for each speed. In addition to the rotation rate, the propeller efficiency (or open water efficiency) and quasi-propulsive efficiency (η_D) values were also obtained. Through these efficiencies it is possible to obtain the potency (P_D) that the propulsion system of the container ship must receive.

Table 4. Optimized propulsive parameters

Hollenbach z = 5 Ae/Ao = 0,6 P/D = 1					
Vs (knots)	n_{opm} (rpm)	ηo	η_D	P_D (kW)	Cavitation Criteria
12	84,165	0,602	0,705	1867,23	Cavitation 5%
12,5	87,677	0,602	0,705	2111,42	
13	91,265	0,602	0,705	2383,98	
13,5	94,938	0,601	0,704	2688,59	
14	98,704	0,600	0,703	3029,35	
14,5	102,571	0,598	0,701	3410,90	
15	106,544	0,596	0,699	3838,40	
15,5	110,633	0,594	0,697	4317,63	
16	114,841	0,592	0,694	4854,99	
16,5	126,202	0,564	0,662	5696,18	
17	140,424	0,531	0,623	6765,95	
17,5	159,347	0,490	0,575	8191,83	
18	194,426	0,422	0,496	10606,29	
18,5	137,892	0,575	0,675	8690,41	Cavitation 10%
19	154,474	0,538	0,631	10361,29	
19,5	186,463	0,470	0,552	13281,05	
20	154,489	0,559	0,657	12576,47	Cavitation 20%

It is important to observe that the cavitation limit of 5% was respected up to the speed of 18 knots, as seen in Fig. 4. As expected, the propulsive efficiency values tend to decrease as the speed and ship resistance (or resistance to advance) increase.

After 18 knots, it was no longer possible to keep the percentage of cavitation below 5%. In the range of 18 to 20 knots, cavitation remained between 5 and 20%. Interestingly, the values of propulsive efficiency increase in this range, however it is important to point out that at these speeds the vessel is outside the maximum cavitation limit, which can lead to possible material wear on the propeller.

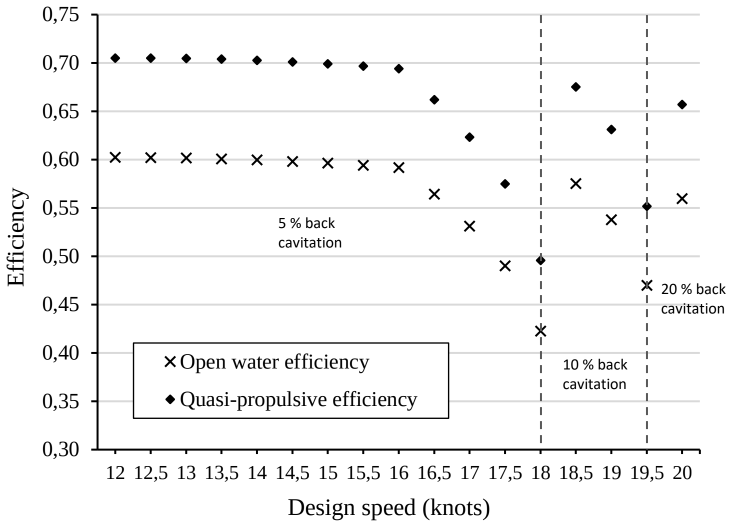

Figure 4. Efficiency points

4 Concluding remarks

The first objective of the work was satisfactorily achieved. When comparing Hollenbach's average resistances to the resistances predicted by Holtrop, the calculated values were approximate for the given speed range (12 to 20 knots). The application of both methods in preliminary projects, can be easily adopted due to the speed and reliability that the approaches present.

In the second part, knowing the required power (P_D), the propulsive efficiency and the propeller rotation rate, were the main objectives of this work. Using the Excel Solver function, it was possible to find these optimized values quickly and effectively, reason by which it was chosen to use this alternative tool, even with more complex softwares available. In addition, it is verified that the propeller rotation rate can be optimized as the design speed is changed.

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References

[1] M. M. Bernitsas, *Wageningen B-Series*, 1981.
[2] S. Harvald, S. R. Turnock and D. A. Hudson. *Resistance and Propulsion of Ships*. John Wiley & Sons, 1983
[3] H. Schneekluth and V. Bertram. *Ship Design for Efficiency and Economy.* Butterworth-Heinemann, 1998.
[4] V. Bertram. *Practical Ship Hydrodynamics*. Butterworth-Heinemann, 2012.
[5] L. Birk. *Fundamentals of Ship Hydrodynamics*. John Wiley & Sons, 2019.
[6] J. Marzi and R. Broglia. "Hydrodynamic Tools in Ship Design". In: A. Papanikolaou. *A Holistic Approach to Ship Design*. Spring, pp. 139-207, 2019.
[7] L. Birk. "Hollenbach's Method". In: *Fundamentals of Ship Hydrodynamics*. John Wiley & Sons, pp. 628-650, 2019.
[8] J. A. Holtrop, "A statistical analysis of performance test results". *International Shipbuilding Progress*, vol 24, n. 270, pp. 23-28, 1977.
[9] J. Holtrop and G. Mennen, "A statistical power prediction method". *International Shipbuilding Progress*, vol. 25, n. 290, pp. 253-256, 1978.
[10] J. Holtrop and G. Mennen, "An approximate power prediction method". *International Shipbuilding Progress*, vol. 29, n. 335, pp. 166-170, 1982.
[11] J. Holtrop, "A statistical re-analysis of resistance and propulsion data". *International Shipbuilding Progress*, vol. 31, n. 363, pp. 272-276, 1984.