Computational and experimental works on ship resistance

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Abstract. Ship engine power is estimated at initial design process to satisfy the required speed. This ship parameter is determined by computation of ship resistance and propulsion parameter from any existing methods or executing ship model test. In fact, the results of ship model tests do not satisfy those of the existing methods. However, for initial design approach this may be used to estimate the engine power. This approach is used in design process for many ships but some methods are not suitable for certain type of ships. Three type of ships were developed and evaluated to prove this issue. They were fishing ship, passenger-cargo coaster and semi-displacement ship. The resistance and propulsion parameters of those ships were determined by the existing methods. Three models of those ships were tested in the towing tank to validate the results of the resistance from existing methods. The results of computation and model test were presented and analyzed. It was found that there were difference between the results of computations and those from model tests for three ships. Some recommendations were stated at this paper concerning the application of the results for such ships.

1. Introduction
The role of seagoing ships is very important in order to transport materials and passengers from one ports to the others. In addition, some ships are doing industrial activities or executing other tasks at sea. The ships need the engine power to travel at the required speeds or to make other jobs. The engine power is one parameter that should be determined at the initial ship design phase. This task can be done by applying some existing statistical methods or executing model tests of ship resistance. Then, the engine power may be estimated by applying additional propulsion parameters. Furthermore, the engine power is evaluated several times following the general ship design procedure. Many design tasks include test model to validate the results from statistical methods. Other procedure is executed by direct model test when the statistical methods are not available.

In fact, the resistance computations are still executed for some kinds of ships though the existing methods are not represented for such ships. This could be accepted at initial design phase. In this paper, the resistance of some ships were evaluated. The approach existing methods were used to compute the ship resistance. Three different ship types were applied to prove this issue. They were semi-displacement passenger boat, pole and line fishing boat and passenger-cargo coaster. The resistance of those ships were computed based on three different methods. Then the results of the resistance were validated by those of test models.

The models were determined based on the scale factor for each ship. Then they were built and set based on the criteria in testing procedures. The standard testing procedures were adapted during the testing. In addition, some external factors were avoided in order to achieve better results. The results of those three models were predicted for the full-scale ships. The prediction procedure was based on the Froude assumption. The results of those three full-scale ships were presented and compared to those from the computation of statistical methods. In fact, the results from those two methods were in good agreement but different in values. Some reasons were explained concerning these differences.
2. Literature Review

2.1. The existing ships

The existence of semi-displacement ships is to transport the passengers in the short routes (Figure 1a). The application of lighter hull material such as Aluminium or composite gives some benefits for such ships. Their speeds are ranging from 19 to 25 knots or Froude number $F_n$ are 0.55 to 0.80. According to the definition by IMO-HSC [1, 2], such ships are classified as High Speed Craft (HSC) or by hydrodynamic point of view those ships are classified as semi-displacement ships as stated by Molland [3] and Nicolaysen [4]. Due to their operational range, those ships are also classified as short-sea ferries [5]. Skipjack pole and line is a kind of fishing vessel that is used to catch skipjack tuna ($Katsuwonus pelamis$). This kind of vessels has been used for long time in the area which is potential in skipjack tuna (Figure 1b). Those vessels are made of wood and recently most of them are made of fiberglass reinforced plastic (FRP). Meanwhile, some ships which serve the coast area are still operating in some routes to transport the passengers and cargoes (coaster). Those ships are made of woods and still operating in some regions.

![Semi-displacement ships](image1)

![Skipjack pole and line](image2)

**Figure 1.** The existing semi-displacement ships

2.2. Resistance of semi-displacement ships

Most of the resistance database for semi-displacement ships are provided for ships with round bilge and double chine hull forms [3, 6]. Two “approach” methods available for the computation of resistance of semi-displacement are Savistsky pre-planing method in Lewis [7] and Mercier [8] and WUMTIA (Wolfson Unit for Marine Technology and Industrial Aerodynamics) method in Molland [3]. Those two methods of WUMTIA and Savitsky pre-planing include both chine and round-bilge hull forms. A general form of resistance equation adopted by Mercier and Savitsky is presented as:

$$R/T/W = A_1 + A_2 X + A_4 U + A_6 XZ + A_8 UX + A_{10} ZU + A_{12} W + A_{14} XW^2 + A_{16} ZX^2 + A_{18} UW^2 + A_{20} WU^2$$

(1)

where:

- $X = \frac{V^{1/3}}{L}$
- $Z = \frac{V^{1/3}}{B}$
- $U = \sqrt{2} \iota E$
- $W = A_r/A_X$
- $V = \text{displacement}$
- $L = \text{length}$
- $B = \text{beam}$
- $\iota_E = \text{angle of entrance}$
- $A_r = \text{transom area}$
- $A_X = \text{midship area}$

The values of the coefficients $A_1$ to $A_{27}$ and correction factors are presented in Lewis [6]. The resistance of full-scale ships were predicted based on Froude method. It is noticed that in order to predict the total resistance for both approach methods, the effects of air and appendage drags are taken into account. The air resistance coefficient $C_{AA}$ is included into the total resistance coefficient ($C_{TS}$) and is computed by the following formula [3, 6, 8]:

$$C_{AA} = 0.001 \times \left(\frac{A_f}{S}\right)$$

(2)

where: $A_f$ is the frontal area of the ship above the water and $S$ is the wetted surface area. The resistance of appendages, as percentages of hull naked resistance is added as much as 8% for the full-scale ship [3].
2.3. Resistance of wooden ships

Two wooden ships were applied in this research also which are KM. Cahaya Bahari (passenger-cargo coaster) dan KM. Zamirun (skipjack pole and line). The hull material of KM. Zamirun was covered by Fibreglass Reinforced Plastic (FRP). The resistance of those two ships were computed based on the statistical methods of Guldhammer and Holtrop [9, 10, 11]. This is the originally ITTC1957 method from the International Towing Tank Committee (ITTC).

The total resistance ($R_T$) of a ship may be computed by this formula:

$$R_T = 0.5 \cdot C_T \cdot \rho \cdot S \cdot V^2$$

$$C_T = C_F + C_A + C_{AA} + C_R$$

where: $C_T$ = total resistance coefficient

$\rho$ = mass density of water

$S$ = wetted surface area of the hull

$V$ = sailing speed

$C_F$ = frictional resistance coefficient

$C_A$ = incremental resistance coefficient

$C_{AA}$ = air resistance coefficient

$C_R$ = residuary resistance coefficient

The frictional resistance coefficient $C_F$, in accordance with the ITTC-57 formula is defined by:

$$C_F = 0.075 / (\log Rn - 2)^3 = R_F / (0.5 \cdot \rho \cdot S \cdot V^2)$$

$Rn = Reynolds number = (V \cdot Lwl) / \nu$

The values of $S$, $C_A$, $C_{AA}$, $C_R$ and their corrections may me found in the references [9, 10]. The residuary resistance coefficient $C_R$ is a function of Froude Number and prismatic coefficient. The value of $C_R$ is presented for each ratio of $L/\sqrt[3]{V}$ which is range from 4.0 to 8.0. That may be found in the references [9, 10]. Meanwhile, the total resistance of ships ($R_{total}$) from the Holtrop statistical method is described as follows [11]:

$$R_{total} = R_F (1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

where: $R_F$ = frictional resistance according to the ITTC-1957 friction formula

$I + k_1$ = form factor describing the viscous resistance of the hull form in relation to $R_F$

$R_{APP}$ = resistance of appendages

$R_W$ = wave making and wave breaking resistance

$R_B$ = additional pressure resistance of bulbous bow near the water surface

$R_{TR}$ = additional pressure resistance of immersed transom stern

$R_A$ = model-ship correlation resistance

The details of total resistance of a ship with their corrections may be found in the reference [11].

2.4. The resistance from experiment model

The procedure in determining full-scale ship resistance from the model test are based on Froude method [a, b, d]. Basic principle of this method is separating the total resistance ($C_T$) into residuary resistance ($C_R$) and frictional resistance ($C_F$). Then Froude assumption stated that the residuary resistance coefficient is the same for model (subscript M) and full-scale ship (subscript S) at the same Froude number:

$$C_{RM} = C_{TM} \cdot C_{FM} \text{ and } C_{RS} = C_{RM}$$

$$C_{TS} = C_{FS} + C_{RS} + \Delta C_F$$

where: $\Delta C_F$ is a roughness allowance coefficient

The full-scale resistance $R_S$ and effective power $P_E$ are computed as:

$$R_S = 0.5 \cdot \rho \cdot C_{TS} \cdot \rho_S \cdot V_S^2 \cdot S_S$$

$$P_E = R_S \cdot V_S$$

The total installed power ($P_I$) or brake power ($P_B$) will consider also a power margin to allow for roughness, fouling and weather. The installed power ($P_I$) is defined as:

$$P_I = (P_B / \eta_B) \times (1 / \eta_T) + \text{margin (roughness, fouling, weather)}$$

where $\eta_B$ = Quasi-propulsive coefficient (QPC)

$\eta_T$ = transmission efficiency
The required power margin for fouling and weather depends on the operation areas of the ship as well as the condition of the sea. The power margin is typically between 15% to 30% of the installed power. The total installed power \( P_i \) will typically relate to the \( MCR \) (maximum continuous rating) or \( CSR \) (continuous service rating) from the main propulsion engines, depending on the practice of the ship operator [12].

3. Methodology
This work consists of some steps which were selection of parent ships, computation of resistance from existing methods, develop the model test, running models and get the results, presenting and discussion the results.

3.1. Selection of ships and models
Three ships were selected for the computations and model test of the resistance. They are semi-displacement passenger ship, skipjack pole and line and passenger-cargo coaster. The semi-displacement passenger ship designed by the author [13]. The ship has the capacity of 254 passengers. The ships were designed to follow the design process for the passenger ships [14, 15, 16, 17, 18, 19]. Those ships have the hard chine hull forms. The hull material of the ship is Aluminium. The scale factors \( \lambda = 27, 10 \) and 20 were set for displacement passenger ship, skipjack pole and line and passenger-cargo coaster respectively to develop the models. The dimensions and other parameters of full-scale ships and models are presented in Table 1.

| Ship parameters         | Unit | \( \lambda = 27 \) | \( \lambda = 10 \) | \( \lambda = 20 \) |
|-------------------------|------|-------------------|-------------------|-------------------|
| Speed                   | knot | 20                | 10                | 12                |
| Length overall, \( L_{OA} \) | m    | 32.00             | 21.60             | 38.00             | 1.185             | 2.16              | 1.90              |
| Length of WL, \( L_{WL} \) | m    | 29.09             | 18.92             | 36.90             | 1.109             | 1.89              | 1.85              |
| Ship beam, \( B \)      | m    | 7.00              | 4.00              | 8.00              | 0.259             | 0.40              | 0.40              |
| Beam of waterline, \( B_{WL} \) | m    | 6.69              | 3.90              | 7.86              | 0.248             | 0.39              | 0.39              |
| Ship draft, \( T \)     | m    | 1.40              | 1.50              | 2.50              | 0.052             | 0.15              | 0.125             |
| Deck height, \( H \)    | m    | 2.60              | 2.05              | 3.10              | 0.096             | 0.21              | 0.155             |
| Ship displacement, \( A \) | t.(kg) | 107.3             | 54.84             | 340.4             | 5.542             | 54.84             | 42.60             |
| Block coefficient, \( Cb \) |       | 0.384             | 0.471             | 0.450             | 0.384             | 0.471             | 0.450             |
| Midship coefficient, \( Cm \) |       | 0.550             | 0.726             | 0.684             | 0.550             | 0.726             | 0.684             |
| Prismatic coefficient, \( Cp \) |       | 0.698             | 0.649             | 0.657             | 0.698             | 0.649             | 0.657             |
| Water plane coeff., \( Cwp \) |       | 0.848             | 0.753             | 0.750             | 0.848             | 0.753             | 0.750             |
| Wetted surface \( A_w \), \( WSA \) | m² | 194.4             | 88.40             | 327.2             | 0.267             | 0.884             | 0.818             |
| Midship area, \( A_L \) | m² | 5.16              | 4.37              | 13.68             | 0.007             | 0.44              | 0.034             |
| \( L_{CB} \) (from midship) | % \( L_{WL} \) | -1.96             | -4.35             | -0.50             | -1.96             | -4.35             | -0.50             |

3.2. Testing procedure
The results of resistance computations from statistical methods were validated by the model tests. The results obtained from the model tests were used to estimate the resistance of full-scale ships based on the Froude method [3, 6, 8]. The ship model of semi-displacement was formed by high-density closed-cell foam and covered by fiber-reinforced plastic (FRP). The model was shaped by multiple-axis cutting machine owned by DN&T (Design Naval & Transports) office, Liege, Belgium (Figure 2a). A sand strip turbulence stimulator was fixed at 5% aft of fore end model waterline [3, 8]. Meanwhile, the other two models were built as seen in Figure 2b and Figure 2c.
a. Semi-displacement ship  

b. Skipjack pole and line  

c. Passenger-cargo coaster  

**Figure 2.** The ship models

The ship model of semi-displacement ship was tested at the towing tank of University of Liege (ULg-ANAST) (Figure 3a). While the models of skipjack pole and line and passenger-cargo coaster were tested at the towing at the towing tank Faculty of Engineering Pattimura University (Figures 3b and 3c). Some external effects were avoided during the tests. The ship parameters measured during the tests are model speed, resistance, trim and sinkage.

**Figure 3:** The ship models test are underway

### 4. Results and Discussion

#### 4.1. Results of ship resistance

The results of ship resistance from statistical methods of computation and model tests are presented in Figures 4 and 5. The computation of ship resistance for semi-displacement ship was based on the Savitsky pre-planing and was executed by using Maxsurf software. While the computation of resistance for two other ships were based on the statistical methods of Guldhammer and Holtrop.

**Figure 4.** Resistance results of semi-displacement passenger ship & skipjack pole and line
The resistance curves of three ship models are in good patterns for the results of computation and model tests. However, there are some differences in values for those three ships which can be described as follows:

- **Semi-displacement ship:** for the speed ranges of 16 to 20 knots, the differences of resistance from experiment model to statistical method (Savitsky pre-planning) are 1% to 2%. At the speed over 21 knots, the experiment model are greater from 3.5% to 10%.

- **Skipjack pole & line:**
  - The difference between Guldhammer method and experiment model: from the speeds of 4 to 7 knots, the difference is 1% to 2% but this values are greater 14% to 27% for the speed of 8 to 11 knots.
  - The difference between experiment model and Holtrop method: from the speeds of 4 to 11 knots, the difference is 47% to 13%.

- **Passenger-cargo coaster:**
  - The difference between experiment model to Guldhammer method: from the speeds of 6 to 10.5 knots, the difference is 60% to 1% and at the speed over 10.5 knots the difference of Guldhammer method to experiment model increases form 1% to 23%.
  - The difference between experiment model and Holtrop method: from the speeds of 6 to 12 knots, the difference is 80% to 43%.

### 4.2. Discussion

During the construction of models and executing the model tests some conditions were kept to be in a proper way. Those conditions included: model precision, calibration of instruments and external effects on models. This may be confirmed that the data obtained from the model tests were valid. The results of resistance of three ships are in good pattern as showed in Figures 4 and 5, although there are differences in values.

The resistance data for semi-displasemen ships may use the Savitsky pre-planning method for the speed ranges of 17 to 21 knots which are favourable speeds for this kind of ships. Above the speeds of 21 knots, the resistance data of Savitsky pre-plaining should be consider again.

In addition, for skipjack pole and line the Guldhammer method is good for the speeds of 5 to 7 knots. Above these speeds there are great difference of the resistance. Meanwhile, for passenger-cargo coaster the application of those statistical methods of resistance is not accepted.

### 5. Conclusions and Future Works

#### 5.1. Conclusion

The investigation of ship resistance was made for three different kind of ships. This work was executed for the computation of the resistance from existing statistical methods and compared to and model tests. The results were presented and compared for for those ships. The conclusions of this work are described as follows:
The resistance curves of three ships are in good patterns for the results of computation from the existing statistical methods and model tests. However, there are great differences in values for certain ships.

Savitsky pre-planning method may be used for semi-displacement ships for the speed range of 17 to 21 knots.

The existing statistical methods used in this works are recommended not to be used for skipjak pole & line or passenger-cargo coaster, perhaps other methods should be investigated more.

5.2. Future works
It is clearly seen from the resistance results of three model tests that there are some differences of ship resistance from the model tests and computations. It was recommended for the future works concerning:

- Several statistical methods should be investigated more to find the correlation to model test.
- Other approach of application CFD should be investigated to find the correlation to the model test and statistical methods.
- Several ship models should be tested more as reference for the resistance.

Acknowledgements
Special thanks are given to:

- The University of Liege (ULg-ANAST) for the towing tank facilities that have been used for the model tests
- DN&T (Design Naval & Transports) office, Liege, Belgium for developing the ship models.
- Faculty of Engineering Pattimura University for the towing tank facilities that have been used for the model tests

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