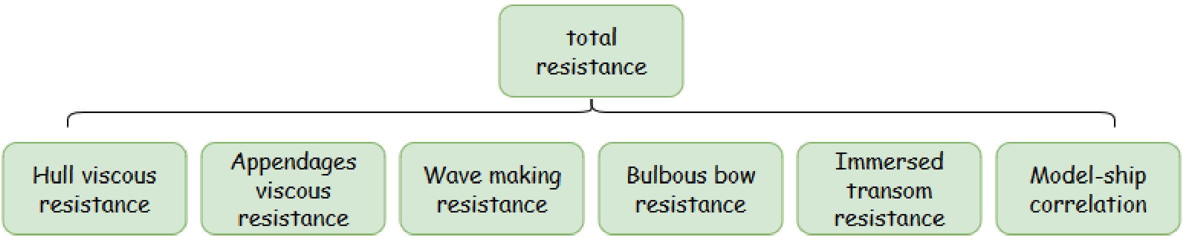
Resistance Analysis

The total resistance of the ship is very complex to directly calculate it. So, it is subdivided into more components to be analyzed and solved. Naval architects used to do model tests to measure ship resistance and then correlate it to the full-scale. Each of the total resistance components has separate equations to solve:



$$R_{total} = R_v + R_{APP} + R_w + R_B + R_{TR} + R_A$$

We discuss each of these components briefly in an example to show the background behind the excel sheet we use in calculations:

Example

Calculate the total resistance of a ship has the following characteristics at a design speed of 25 knots (12.86 m/s):

Item	Value	Unit
L_{PP}	205	m
B	32	m
T	10	m
LCB	2.02 (aft Amidships)	%
C_P	0,583	-
C_B	0.572	-
∇	37500	m^3
C_M	0.980	-
C_{WP}	0.570	-
A_{BT}	20	m^2
C_{stern}	10	-
T_f	10	m
T_a	10	m
h_B	4	m
A_t	16	m^2
S	7205.004	m^2
S_{APP}	50	m^2

Table 1

Other characteristics of the vessel have been assumed or calculated for you to simplify the problem:

Item	Value	Unit
$(1+k_1)$	1.156	-
$(1+k_2)_{eq}$	1.5	-
c_1	1.398	-
c_2	0.7595	-
c_5	0.9592	-
m_1	-2.1274	-
m_2	-0.17087	-
λ	0.6513	-
d	-0.9	-
w	0.2584	-
t	0.1747	-

Table 2

Hull Viscous Resistance

Hull viscous resistance is the component of water resistance due to viscosity; the water particles exert frictional drag on the ship's hull. It comprises the frictional drag due to the surface of the hull and another sub-component due to the local flow field as a result of the ship's form and this is known by the form effect. This component can be solved using the following equations:

$$R_v = 0.5(1+k_1)\rho SV^2 C_F, \quad C_F = \frac{0.075}{(\log(\text{Re})-2)^2}$$

Where C_F is the frictional coefficient according to the IITC 1957 line formula which is a function of the Reynold's number $\text{Re} = \dfrac{VL}{\upsilon}$. $(1+k_1)$ is the form factor multiplied by the frictional drag gives the viscous resistance:

$$\text{Re} = \frac{12.86 \times 205}{1.1897 \times 10^{-6}} = 2215805332$$

$$C_F = \frac{0.075}{(\log(2215805332)-2)^2} = 0.001390$$

$$R_v = 0.5 \times 1.156 \times 1025 \times 7381.45 \times (12.86)^2 \times 0.00139 = 1005.29 \text{ KN}$$

Appendage Resistance

Appendage resistance is the viscous resistance of the appendages attached or fitted to the hull. Appendages include any part that stick out of the bare hull below the waterline (e.g. rudders, thrusters, bilge keel, etc.). It has the same equation as the hull viscous resistance (with separate combined form factor for all the appendages).

$$R_{App} = 0.5\rho S_{App} V^2 (1+k_2)_{eq} C_F = 0.5 \times 1025 \times 50 \times (12.86)^2 \times 1.5 \times 0.00139 = 8.83 \text{ KN}$$

Wave Resistance

The ship when moving in water generates a typical wave system which contribute in the total resistance and known by wave-making resistance. You can imagine it as the energy absorbed in forming such waves. It is given by the following equation:

$$R_W = c_1 c_2 c_5 \nabla \rho g \ \exp(m_1 Fn^d + m_2 \cos(\lambda Fn^{-2}))$$

$$c_1 = fn(L, B, T, i_E),\ c_2 = fn(A_{BT}, B, T, T_F, h_B),\ \text{and } c_5 = fn(A_T, B, T, C_M)$$

$$m_1 = fn(L, T, \nabla, B, C_P),\ m_2 = fn(L/\nabla^{1/3}, C_P, Fn),\ \lambda = fn(L/B, C_P),\ \text{and } d = -0.9$$

To simplify the problem these coefficients have been calculated for you in table (2).

$$R_W = 1.398 \times 0.7595 \times 0.9592 \times 37500 \times 1025 \times 9.81 \times \exp((-2.1274 \times 0.2868^{-0.9})$$
$$+(-0.17087 \times \cos(0.6513 \times 0.2868^{-2}))) = 557.1 \text{ KN}$$

Bulbous Bow Resistance

The bulbous bow is an additional part of the hull at the bow that contributes in reducing wave making resistance by initiating waves that cancel out the waves produced by the hull's pressure points. However, bulbous bow is considered as an additional wetted surface which increase the frictional drag. The additional resistance due to the presence of the bulbous bow is given by:

$$R_B = 0.11 \exp(-3 P_B^{-2}) Fn_i^3 A_{BT}^{1.5} \rho g / (1 + Fn_i^2)$$

Where P_B is a coefficient measures the immersion of the bow and Fn_i is the Froude number based on immersion and are given by:

$$P_B = 0.56 \sqrt{A_{BT}} / (T_F - 1.5 h_B)$$

$$Fn_i = V / \sqrt{g(T_F - h_B - 0.25\sqrt{A_{BT}}) + 0.15 V^2}$$

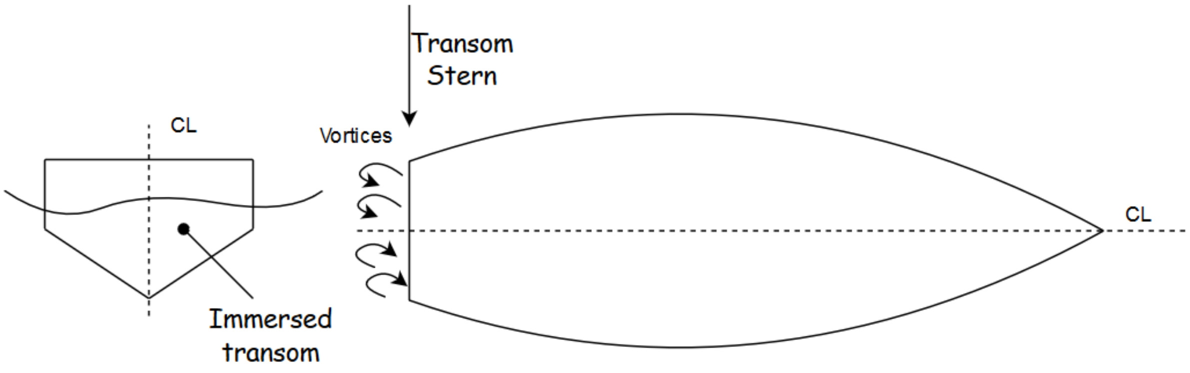
$$\therefore P_B = 0.56 \times \sqrt{20} / (10 - (1.5 \times 4)) = 0.6261$$

$$Fn_i = 12.86 / \sqrt{9.81(10 - 4 - 0.25 \times \sqrt{20} + 0.15 \times (12.86)^2} = 1.5084$$

$$R_B = 0.11 \exp(-3 \times 0.6261^{-2}) \times 1.5084^3 \times 20^{1.5} \times 1025 \times 9.81 / (1 + 1.5084^2) = 0.0491 \text{ KN}$$

Transom Immersion Resistance

Ships are often designed with transom stern for reduced length and wider deck aft. The flow around the transom stern differs from the cruiser(rounded) stern. Transom stern immersion induces some eddies downstream and consequently increases the pressure resistance.



Transom immersion resistance is obtained using the following equations:

$$R_{TR} = 0.5\rho V^2 A_T c_6$$

$$c_6 = 0.2(1-0.2Fn_T) \quad \text{for } Fn_T < 5$$
$$c_6 = 0 \quad \text{for } Fn_T \geq 5$$

$$Fn_T = V / \sqrt{2gA_T / (B + BC_{WP}} = 12.86 / \sqrt{2\times 9.81\times 16 / (32+32\times 0.57)} = 5.144$$
$$\therefore c_6 = 0$$

$$\therefore R_{TR} = 0$$

Model-Ship Correlation Resistance

Mainly, these equations depend on model tests in towing tanks. There must be a correction for the model test resistance values when correlate to the full-scale. The reason behind that is the additional resistance on the full-scale due to the difference in the surface roughness between the model and the ship, and the difference in the still-air resistance. This is given by:

$$R_A = 0.5\rho S V^2 C_A$$

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}C_B^4 c_2 (0.04 - c_4)$$

$$c_4 = T_F / L \quad \text{for } T_F / L \leq 0.04$$
$$c_4 = 0.04 \quad \text{for } T_F / L > 0.04$$

$$T_F / L = 0.0488, \quad \therefore \mathrm{c}_4 = 0.04$$

$$\therefore C_A = 3.525\times 10^{-4}$$

$$R_A = 0.5\times 1025\times 7381.45\times (12.86)^2 \times 3.525\times 10^{-4} = 221 \text{ KN}$$

The total resistance is the summation of the previous components:

$$R_T = 1005.29 + 8.83 + 557.1 + 0.0491 + 221 = 1793 \text{ KN}$$

Propeller-Hull Interaction (Powering Calculations)

The propulsion system interacts with the ship's hull in forming the flow around them. The flow induced to the propeller is changed due to the hull form. On the other hand, the flow around the hull is affected by the propeller existence behind it. The traditional way of dealing with this complex hydrodynamic problem is to consider them separately in analysis, design, and testing, then to introduce some efficiencies to account for this interaction.

The general form of calculating the power: $power = force \times speed$. Now we consider only the hull towed in a tank by some external force, thus, the power required to move the ship at the design speed mentioned above is known by the effective power:

$$P_E = R_{total} \times V = 1793 \times 12.86 = 23058 \text{ KW}$$

Let us consider now the propeller operating in open water without the hull. The power produced by the propeller is the thrust power:

$$P_T = T \times V$$

However, this is not real, as the flow speed directly upstream the propeller differs from the ship speed due to the ship's wake, and the speed directly upstream the propeller(on the suction side) is called the speed of advance V_A and the thrust power is: $P_T = T \times V_A$.

The relation between the ship speed and the speed of advance is connected with a term called the wake fraction, and it indicates how much the wake is affecting the flow velocity directly before the propeller:

$$w = 1 - \frac{V_A}{V}$$

$$V_A = (1 - 0.2584) \times 12.86 = 9.537 \ m/s$$

It can be calculated numerically or by using empirical formulae in preliminary design approaches.

The empirical formula we used to obtain the wake fraction (table 2) is a function of some parameters as shown:

$$w = fn(C_V, L, B, C_P, D, T_A, C_B, C_{stern})$$

On the other hand, the thrust measured when the propeller is behind the hull is higher than the total resistance without the propeller. So, the propeller induces some additional resistance due to some reasons (the propeller increases the flow velocities in the aftbody which increases friction and reduces pressure behind the hull which increases the pressure resistance). The term that connects the relation between the total resistance and the thrust is known by the thrust deduction factor:

$$t = 1 - \frac{R_T}{T}$$

An empirical formula used to obtain the thrust deduction factor: $t = fn(LCB, C_P, L, B, D, C_{stern})$.

The difference between the effective power and the thrust power combines together the wake effects and the thrust deduction effects. The ratio between them is called the hull efficiency:

$$\eta_H = \frac{P_E}{P_T} = \frac{R_T \cdot V}{T \cdot V_A} = \frac{1-t}{1-w} = \frac{1-0.1747}{1-0.2584} = 1.11$$

Noted that this efficiency can be more than unity, that's because those two factors- previously mentioned, can have some beneficial effects on the power.

The power delivered from the shaft to the propeller is expressed by the torque and rpm:

$$P_D = 2\pi \cdot n \cdot Q$$

The losses between the delivered power and the thrust power is expressed in terms of the behind hull efficiency $\eta_B = P_T / P_D$. This ratio is different when the propeller is considered alone without the hull which is known by the open water efficiency (η_o). The factor that accounts for the differences between the case where the propeller is behind the hull and the open water condition is known by the relative rotative efficiency:

$$\frac{P_T}{P_D} = \eta_o \times \eta_{RR}$$

The regression formula gives the relative rotative efficiency as a function of the blade area ratio of the propeller A_E / A_o which is a propeller characteristic:

$$\eta_{RR} = fn(A_E / A_o, C_P, LCB) = 0.9931$$

The delivered power P_D is less than the brake power of the engine due to losses in shafts and bearings. So, the ratio between the delivered power and the brake power represents the shaft efficiency which can be assumed as 98%.

$$\eta_s = \frac{P_D}{P_B} = 98 - 98.5\%$$

The brake power is what you need for your design and it is the main aim of this analysis. Using the brake power, you can select the prime movers of your ship project.

$$P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{R_T \cdot V}{\eta_H \eta_o \eta_{RR} \eta_s}$$

Proplusion Particulars

The final step to calculate the brake power is to obtain the open water efficiency. Usually this needs open water tests. There are some equations used to estimate the open water efficiency and the other propeller characteristics by polynomial representation of the test results. Propeller design is an iterative process and you shall first estimate some main characteristics such as the diameter or the rpm, then calculate the torque coefficient, the thrust coefficient, and the open water efficiency, and finally to compare the thrust produced to the thrust required for your hull. If the thrust produced is lower than the required, you shall start another calculation process. You can find more details in propeller design using methodical series in [2]. For this example, propeller main characteristics are given as follows:

Item	Value	Unit
Number of Blades Z	5	-
Propeller diameter D	8	m
open water efficiency η_o	0.6461	-

Eventually, the brake power $P_B = \frac{P_E}{\eta_H \eta_o \eta_{RR} \eta_s} = \frac{23058}{1.11 \times 0.6461 \times 0.9931 \times 0.98} = 33035.42$ KW

Noted that we assume there is no losses between the shaft and the engine, so the shaft power is equal to the brake power.

References

[1] Holtrop, J. and Mennen, G.G.J, “A statistical power prediction method”, International Shipbuilding Progress, Vol. 25, 1978.

[2] Oosterveld, M.W.C. and Oossanen, P. van, “Further computer analyzed data of the Wageningen B-screw series”, International Shipbuilding Progress, July 1975.

[3] Bertram, Volker, “Practical Ship Hydrodynamics”, Elsevier, 2012.