Innovative Ship and Offshore Plant Design

Part I. Ship Design

Ch. 6 Resistance Prediction

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Ch. 6 Resistance Prediction

1. Object of Resistance Prediction

Object of Resistance Prediction (1/3)

Review) Weight Estimation: Method 4 $LWT = W_s + W_o + W_m$

$$L \cdot B \cdot T \cdot C_B \cdot \rho \cdot (1+\alpha) = DWT + C_s \cdot L^{1.6} \cdot (B+D) + C_o \cdot L \cdot B + C_m \cdot NMCR$$

There are few data available for estimation of the *NMCR* at the early design stage. Thus, *NMCR* can be roughly estimated by 'Admiralty formula'.

C_{ad}: Admiralty coefficient
V_s: Speed of ship [knots]
Δ: Displacement [ton]
NCR: Required power for service speed

Admiralty formula:

$$NCR = f(\Delta, V_s)$$

$$NCR = C_{NCR} \cdot \Delta^{2/3} \cdot V_s^3$$

Define $C_{ad} \equiv \frac{1}{C_{NCR}}$.

C_{ad} is called "Admiralty coefficient".

$$NCR = \frac{\Delta^{2/3} \cdot V_s^3}{C_{ad}}$$

However, *NMCR* should be estimated more accurately based on the prediction of resistance and propulsion power.

Object of Resistance Prediction (2/3)

☑ **Goal: Estimation of NMCR**

At first, we have to predict

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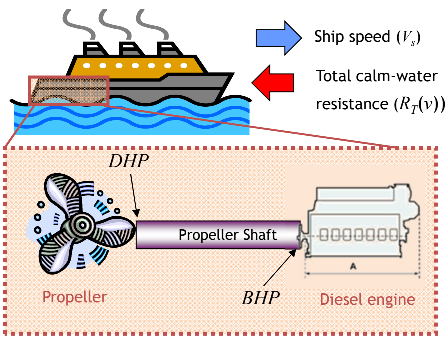


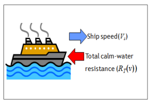
Then, by using the propulsive efficiency, shaft, and sea margin, required propulsive power can be estimated.

Object of Resistance Prediction (3/3)

① EHP (Effective Horse Power)

$$EHP = R_T(v) \cdot V_s$$ (In calm water)

← **Resistance Prediction**



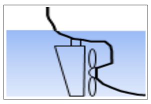
② DHP (Delivered Horse Power)

$$DHP = \frac{EHP}{\eta_D}$$

(η_D : Propulsive efficiency)
$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$
η_O : Open water efficiency
η_H : Hull efficiency
η_R : Relative rotative efficiency

← **Propeller Efficiency**

Thrust deduction and wake (due to additional resistance by propeller)
Hull-propeller interaction



③ BHP (Brake Horse Power)

$$BHP = \frac{DHP}{\eta_T}$$ (η_T : Transmission efficiency)

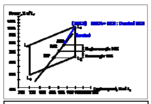
④ NCR (Normal Continuous Rating)

$$NCR = BHP(1 + \frac{\text{Sea Margin}}{100})$$

⑤ DMCR (Derated Maximum Continuous Rating)

$$DMCR = \frac{NCR}{\text{Engine Margin}}$$

→ **Engine Selection**

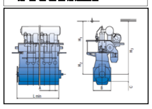


↓

⑥ NMCR (Nominal Maximum Continuous Rating)

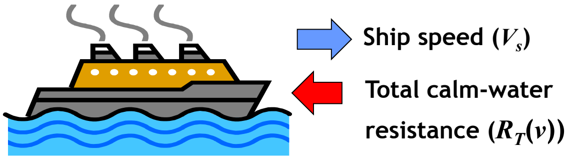
$$NMCR = \frac{DMCR}{\text{Derating rate}}$$

← **Engine Data**



2. Decomposition of Resistance and Methods of Resistance Prediction

Definition of Resistance



☑ Resistance

- The resistance of a ship at a given speed is the force required to tow the ship at that speed in smooth water, assuming no interference from the towing ship.
- This total resistance is made up of a number of different components, which are caused by a variety of factors and which interact one with the other in an extremely complicated way.

* SNAME, Principles of Naval Architecture – Resistance, Propulsion and Vibration, Vol. 2, 1988

Types of Resistance

In order to deal with the question more simply, it is usual to consider the total calm water resistance as being made up of four main components.

(a) , due to the motion of the hull through a viscous fluid.

(b) , due to the energy that must be supplied continuously by the ship to the wave system created on the surface of the water.

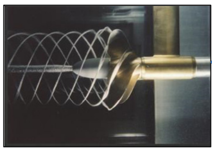
(c) , due to the energy carried away by eddies shed from the hull or appendages. Local eddying will occur behind appendages such as bossings, shafts and shaft struts, and from stern frames and rudders if these items are not properly streamlined and aligned with the flow.

(d) experienced by the above-water part of the main hull and the superstructures due to the motion of the ship through the air.

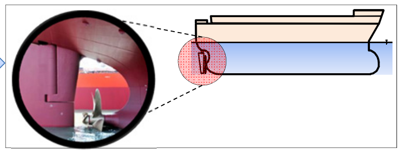
* SNAME, Principles of Naval Architecture – Resistance, Propulsion and Vibration, Vol. 2, 1988

Dimensional Analysis (1/4)

Example) Model propeller test



A model propeller test



A real-ship propeller

▪ Dimensional Analysis

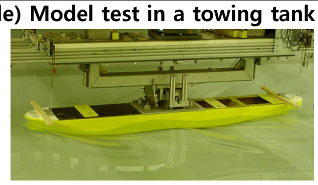
Dimensional analysis is essentially a means of utilizing a partial knowledge of a problem when the details are too obscure to permit an exact analysis.

It has the enormous advantage of requiring for its application a knowledge only of the variables which govern the result.

Dimensional solutions do not yield numerical answers, but they provide the form of the answer so that every experiment can be used to the fullest advantage in determining a general empirical solution.

Dimensional Analysis (2/4)

Example) Model test in a towing tank



Model test

Design ship

▪ Application of dimensional analysis to a ship

To apply it to the flow around ships and the corresponding resistance, it is necessary to know only upon what variables the latter depends.

Applying dimensional analysis to the ship resistance problem, the resistance R could depend upon the following:

(a) Speed, V
(b) Size of body, which may be represented by the linear dimension, L.
(c) Density of fluid, ρ (mass per unit volume)
(d) Viscosity of fluid, μ
(e) Acceleration due to gravity, g
(f) Pressure per unit area in fluid, p

$$R \propto \rho^a V^b L^c \mu^d g^e p^f$$

$$ML/T^2 = \left(M/L^3\right)^a \left(L/T\right)^b \left(L\right)^c \left(M/LT\right)^d \times \left(L/T^2\right)^e \left(M/LT^2\right)^f$$

$$R \propto \rho V^2 L^2 f\left[\left(\frac{\rho VL}{\mu}\right)^{-d}\left(\frac{gL}{V^2}\right)^e\left(\frac{p}{\rho V^2}\right)^f\right]$$

non-dimensional term

Dimensional Analysis (3/4)

It is assumed that the resistance R can now be written in terms of unknown powers of these variables :

$$\frac{R}{1/2 \cdot \rho V^2 L^2} = f\left[\frac{\rho VL}{\mu}, \frac{gL}{V^2}, \frac{p}{\rho V^2}\right]$$

Writing ν for μ/ρ and remembering that for similar shapes the wetted surface S is proportional to L², the equation may be written:

$$\frac{R}{1/2 \cdot \rho S V^2} = f\left[\frac{VL}{\nu}, \frac{gL}{V^2}, \frac{p}{\rho V^2}\right]$$

The 1st term is the Reynolds number R_n.
The 2nd term is related to the Froude number F_n.
The 3rd term is the Cavitation number σ_o.

The left-hand side of the equation is a non-dimensional resistance coefficient. Equation states in effect that if all the parameters on the right-hand side have the same values for two geometrically similar but different sized bodies, the flow patterns will be similar and the value of $\frac{R}{1/2\rho S V^2}$ will be the same for each.

* SNAME, Principles of Naval Architecture – Resistance, Propulsion and Vibration, Vol. 2, 1988

Dimensional Analysis (4/4)

- **Dimensionless number derived by dimensional analysis to a ship**

$$\frac{R}{1/2\rho S V^2} = f\left[\frac{VL}{\nu}, \frac{gL}{V^2}, \frac{p}{\rho V^2}\right]$$

*** Dimensional Homogeneity**

Dimensional analysis rests on the basic principle that every equation which expresses a physical relationship must be dimensionally homogeneous.

Dimensionless Number:

: A dimensionless number that gives a measure of the ratio of inertial forces to viscous forces

$$R_n = \frac{VL}{\nu}$$

V: characteristic velocity of the ship
L: length of the ship at the waterline level
ν : kinematic viscosity

ν : In 10 degree seawater, 1.35X10^{-6}
In 15 degree seawater, 10^{-6}

: A dimensionless number comparing inertial and gravitational forces

$$F_n = \frac{V}{\sqrt{gL}}$$

V: characteristic velocity of the ship
L: length of the ship at the waterline level
g: acceleration due to gravity

* SNAME, Principles of Naval Architecture

Decomposition of Resistance (1/3)

Rn (Reynolds Number) : $R_n = \frac{VL}{\nu}$ Fn (Froude Number) : $F_n = \frac{V}{\sqrt{gL}}$

The concept of resistance decomposition helps in designing the hull form as the designer can focus on how to influence individual resistance components.

Resistance decomposition by Froude

Total resistance (R_T) =

Resistance decomposition by Hughes

Total resistance (R_T) =

Decomposition of Resistance (2/3)

Froude : $R_T=R_F+R_R+\Delta R_F$, Hughes : $R_T=R_V+R_W$

- **Frictional resistance prediction method**

Frictional resistance is assumed to be .

Frictional resistance (R_F):

The frictional resistance is usually predicted taking the resistance of an 'equivalent' flat plate of the same area and length as follows :

$$R_F = 1/2\rho \cdot C_F \cdot S \cdot V^2$$

ρ : density of sea water= 1.025 (Mg/m³)
C_F : frictional resistance coefficient
$V[m/s]$: characteristic velocity of the ship
$S[m^2]$: wetted surface

The 1957 ITTC(International Towing Tank Committee) line is expressed by the formula:

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

R_n (Reynolds Number) : $\frac{VL}{\nu}$

3-dimensionalized form using the form factor

Viscous resistance (R_V): $R_V = (1+k)R_F + \Delta R_F$

k : form factor
ΔR_F : model-ship correlation factor

Decomposition of Resistance (3/3)

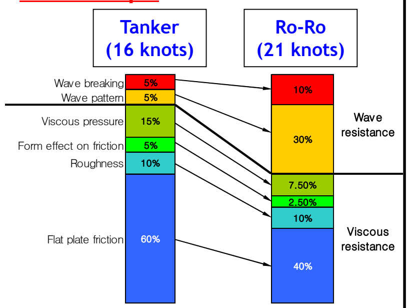
▪ Wave resistance prediction method

The ship creates a typical wave system which contributes to the total resistance. For fast, **slender ships** this component dominates.
In addition, there are breaking waves at the bow which dominate for slow, full hulls, but may also be considerable for **fast ships**.

The interaction of various wave systems is complicated leading to non-monotonous function of the wave resistance coefficient C_w.

The wave resistance depends strongly on the local shape.

$$R_W = f\,(L/B, B/T, C_b, F_n, LCB)$$



Example) Wave resistance formula in the method of Holtrop-Mennen

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

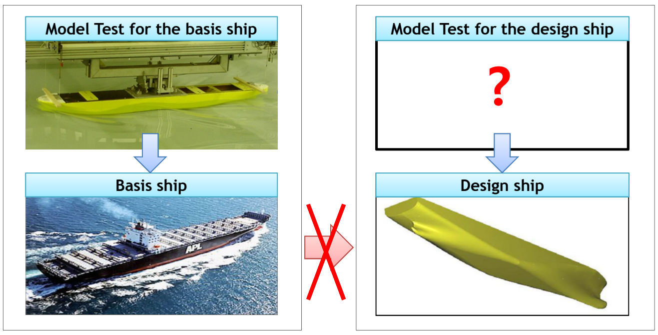
3. Resistance Prediction by Holtrop-Mennen's Method

Types of Ship Resistance Evaluation Methods

- Ship resistance evaluation methods
  - Traditional and standard series methods
    - Taylor, Ayre, Lap, Auf'm Keller, Harvald
    - BSRA series, SSPA series, Series 60, Coaster series
    - ⋮
  - Regression based methods
    - Scott, Holtrop & Mennen
    - ⋮
  - Direct model test
    - 2D extrapolation, 3D extrapolation
    - ⋮
  - Computational Fluid Dynamics (CFD)
    - Advanced Navier-Stokes Solution capabilities For 3D flow around ships
    - ⋮

* John Carlton, Marine Propellers and Propulsion, 3rd Edition, Elsevier, 2012

Resistance estimation by Holtrop-Mennen's Method
- Reason why a statistical method is presented at the initial design stage of a ship (1/2)



As the resistance of a full-scale ship cannot be measured directly, our knowledge about the resistance of ships comes from model tests.

However, at the initial design stage of a ship, the model for the design ship is not provided. Furthermore, the design ship and the basis ship are not preserved geometrical similarity.

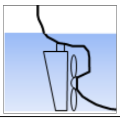
Resistance estimation by Holtrop-Mennen's Method
- Reason why a statistical method is presented at the initial design stage of a ship (2/2)

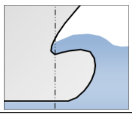
Therefore, a statistical method was presented for the determination of the required propulsive power in the initial design stage.
This method was developed through a regression analysis of random model experiments and full-scale data.

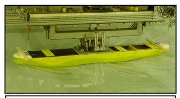
Many naval architects use the method, generally in the form presented in 1984 and find it gives acceptable results although it has to said that a number of the formula seem very complicated and the physics behind them are not at all clear, (a not infrequent corollary of regression analysis).

* Holtrop and Mennen's method, which was originally presented in the *Journal of International Shipbuilding Progress*, Vol. 25 (Oct. 1978), revised in Vol. 29 (July 1982) and again in N.S.M.B. Publication 769 (1984) and in a paper presented to SMSSH'88 (October 1988), meets all criteria with formulae derived by regression analysis from the considerable data bank of the Netherlands Ship Model Basin being provided for every variable.

Formula Proposed by Holtrop & Mennen



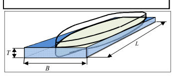


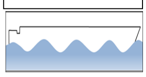


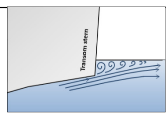
① ③ ⑤ ⑦

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

Total resistance ② ④ ⑥







4. Resistance Prediction by Holtrop-Mennen's Method for a 3,700 TEU Container Carrier

Resistance Prediction by Holtrop and Mennen's Method Example) 3,700 TEU Container Carrier

Item	Value
Main Dimension	
L_{OA}	257.4 m
L_{BP}	245.24 m
L_{WL}	239.26 m
B_{mld}	32.2 m
D_{mld}	19.3 m
Td /Ts (design / scantling)	10.1 / 12.5 m
Deadweight (design / scantling)	34,400 / 50,200 MT(metric ton)
Displacement Volume at Td	49,652.7 m^3
LCB	-0.531% aft of 1/2L_{BP}
Midship section coefficient (C_M)	0.9761
Waterplane are coefficient (C_W)	0.7734
Capacity	
Container on deck / in hold	2,174 TEU / 1,565 TEU
Ballast water	13,800 m^3
Heavy fuel oil	6,200 m^3
Main Engine & Speed	
M / E type	Sulzer 7RTA84C
MCR (BHP × rpm)	38,570 ×102
NCR (BHP × rpm)	34,710 ×98.5
Service speed at NCR (Td, 15% SM)	22.5 knots (at 11.5 m) at 30,185 BHP
DFOC at NCR	103.2 MT
Cruising range	20,000 N.M
Others Complement (Crew)	30 Person

Item	Value
Transverse bulb area	15.2 m^2
Center of bulb area above keel line	5.5 m^2
Transom area	0 m^2
Wetted area appendages	317.74 m^2
Stern shape parameter	V-shaped
Propeller diameter	7.7 m
Number of propeller blades	5
Clearance propeller with keel line	0.3 m

① Frictional Resistance (1/3)

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

3,700 TEU Container Carrier

Item	Value
V	22.5 knots
L_{WL}	239.26 m
ν	1.19×10^{-6}

C_F: Coefficient of frictional resistance (ITTC 1957 friction formula)

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

$$R_n = \frac{V \cdot L}{\nu}$$

R_n is based on the waterline length (L_{WL})

Example 3.700 TEU CTN Carrier)

$$R_n = \frac{V \cdot L_{WL}}{\nu} = \frac{11.8312 \times 239.26}{1.19 \times 10^{-6}} = 2.33 \times 10^9$$

$$C_F = \frac{0.075}{(\log R_n - 2)^2} = \frac{0.075}{(\log 2.33 \times 10^9 - 2)^2} = 1.38 \times 10^{-3}$$

① Frictional Resistance (2/3)

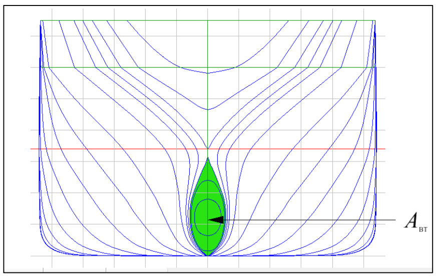
$$R_T = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

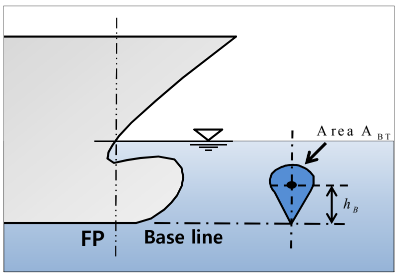
$$R_F = \frac{1}{2}\rho V^2 C_F S_{bh}$$

S_{bh} **: Wetted surface area of the bare hull**

A_{BT} **: Transverse bulb area**

Definition of A_{BT} [L^2]:
The cross sectional area (full section port and starboard) at the fore perpendicular. Where the water lines are rounded so as to terminate on the fore perpendicular A_{BT} is measured by continuing the area curve forward to the perpendicular, ignoring the final rounding (Reference: ITTC).





① Frictional Resistance (3/3)

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

$$R_F = \frac{1}{2}\rho V^2 C_F S_{bh}$$

C_F=0.001378
ρ=1.025 ton/m³

3,700 TEU Container Carrier

Item	Value
L (L_{WL})	239.26 m
T	10.1 m
B	32.2 m
C_M	0.9761
C_{WP}	0.6761
A_{BT}	15.2 m²
C_B	0.6394

S_{bh}: **Wetted surface area of the bare hull**

$$S_{bh} = L(2T+B)\sqrt{C_M}(0.4530 + 0.4425C_B - 0.2862C_M - 0.003467B/T + 0.3696C_{WP}) + 2.38A_{BT}/C_B$$

In this formula, the hull form coefficients are based on the waterline length (L_{WL}).

Example 3.700 TEU CTN Carrier)

$$S_{bh} = L(2T+B)\sqrt{C_M}(0.4530 + 0.4425C_B - 0.2862C_M - 0.003467B/T + 0.3696C_{WP}) + 2.38A_{BT}/C_B$$

$$= 239.26(2\times 10.1 + 32.2)\sqrt{0.9761}(0.4530 + 0.4425\times 0.6394 - 0.2862\times 0.9761 - 0.003467\times 32.2 \div 10.1 + 0.3696\times 0.6761)$$

$$+2.38\times 15.2 \div 0.6394$$

$$= 8,670.24[m^2]$$

$$\therefore R_F = \frac{1}{2}\rho V^2 C_F S_{bh} = \frac{1}{2}\times 1.025\times 11.574^2 \times 1.38\times 10^{-3}\times 8,670.24 = 822.61[kN]$$

② Form Factor of the Bare Hull (1/3)

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

$$1 + k_1 = 0.93 + 0.487118\cdot C_{14}\cdot(B/L)^{1.06806}(T/L)^{0.46106}(L/L_R)^{0.121563}$$
$$\times(L^3/\nabla)^{0.36486}\cdot(1-C_P)^{-0.60247}$$

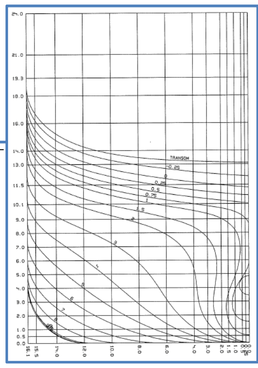
3,700 TEU Container Carrier

Item	Value
After body form	V-shaped

C_{14}: **The prismatic coefficient based on the waterline length**

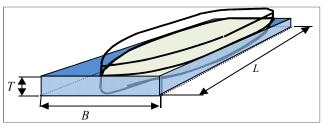
$$C_{14} = 1 + 0.011C_{stern}$$

$C_{stern} = -25$ Pram with gondola
$= -10$ V-shaped sections
$= 0$ Normal section shape
$= 10$ U-shaped sections



Example 3.700 TEU CTN Carrier)

$$C_{stern} = -10$$
$$C_{14} = 1 + 0.011C_{stern}$$
$$= 1 + 0.011\times(-10)$$
$$= 0.89$$



② Form Factor of the Bare Hull (2/3)

Types of stern

(A) Cruiser sterned vessels

(B) Transom sterned vessels

(C) Counter sterned vessels

② Form Factor of the Bare Hull (3/3)

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

$$1+k_1 = 0.93 + 0.487118 \cdot C_{14}(B/L)^{1.06806}(T/L)^{0.46106}(L/L_R)^{0.121563} \times (L^3/\nabla)^{0.36486} \cdot (1-C_P)^{-0.60247}$$

C_{14}=0.89

3,700 TEU Container Carrier

Item	Value
L	239.26 m
B	32.2 m
T	10.1 m
∇	49778
C_p	0.6794
L_{CB}	-0.531 % (aft)

L_R : Length of run

At early design stage, if L_R is unknown, it can be obtained by following formula:

$$L_R / L = 1 - C_P + 0.06 C_P \cdot L_{CB} / (4C_P - 1)$$

L_{CB} : **The longitudinal position of the centre of buoyancy forward of 0.5L as a percentage (%) of L.**

forward : (+), aft : (-)

Example 3.700 TEU CTN Carrier)

$$L_R = L(1 - C_P + 0.06C_P \cdot L_{CB} / (4C_P - 1))$$
$$= 239.26(1 - 0.6794 + 0.06 \times 0.6794 \times (-0.531) / (4 \times 0.6394 - 1))$$
$$= 73.692[m]$$

$$\therefore 1+k_1 = 0.93 + 0.487118 \cdot C_{14}(B/L)^{1.06806}(T/L)^{0.46106}(L/L_R)^{0.121563} \times (L^3/\nabla)^{0.36486} \cdot (1-C_P)^{-0.60247}$$
$$= 0.93 + 0.487118 \times 0.89(32.2/239.26)^{1.06806}(10.1/239.26)^{0.46106}(239.26/73.692)^{0.121563} \times (239.26^3/49778)^{0.36486} \cdot (1-0.6394)^{-0.60247}$$
$$= 1.14$$

③ Resistance of Appendages (1/3)

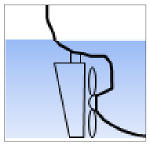
$R_T = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$

$$R_{APP} = 1/2\rho V^2 S_{APP} (1+k_2)_{eq} C_F$$

C_F=0.001378
ρ=1,025 kg/m³

3,700 TEU Container Carrier

Item	Value
V	22.5 knots
Appendages (S_{APP})	82.74 m² (rudder)
	135 m² (bilge keel)



S_{APP} : The wetted area of the appendages
$(1+k_2)$: The appendage resistance factor

- Rudder behind skeg: 1.5~2.0
- Rudder of single screw ship: 1.3~1.5
- Twin-screw balance rudders: 2.8
- Shaft brackets: 3.0
- Skeg: 1.5~2.0
- Strut bossings: 3.0
- Hull bossings: 2.0
- Shafts: 2.0~4.0
- Stabilizer fins: 2.8
- Dome: 2.7
- Bilge keels: 1.4

The equivalent 1 + k_2 value for a combination of appendages is determined from:

$$(1+k_2)_{eq} = \frac{\sum S_i (1+k_2)_i}{\sum S_i}$$

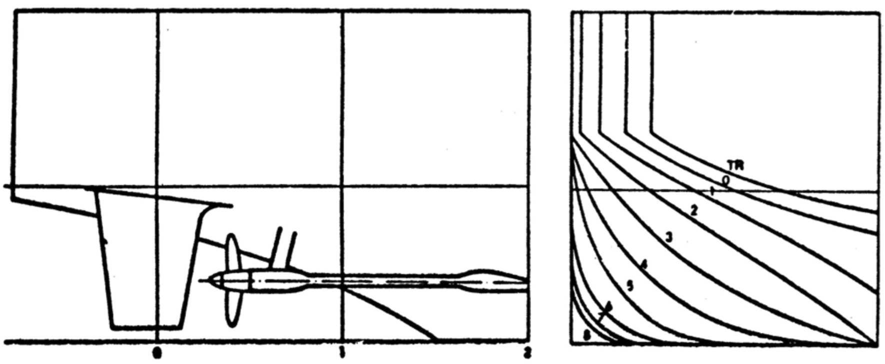
S_i and $(1+k_2)_i$ is the wetted area of the appendages and the appendage resistance factor for the i[th] time.

$$(1+k_2)_{eq} = \frac{\sum S_i (1+k_2)_i}{\sum S_i} = \frac{82.74(1.4)+135(1.4)}{82.74+135} = 1.4$$

$$\therefore R_{APP} = \frac{1}{2}\rho V^2 S_{APP}(1+k_2)_{eq} C_F = \frac{1}{2}\times 1.025\times 11.574^2 \times (82.74+135)\times 1.4\times 1.38\times 10^{-3} = 29.59[kN]$$

③ Resistance of Appendages (2/3)

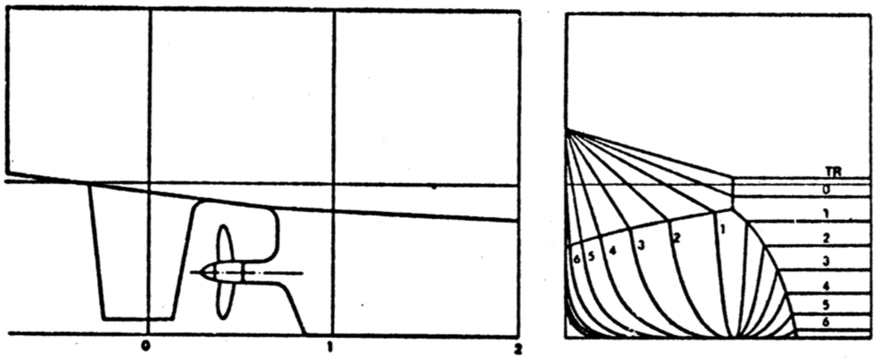
Hull appendage



Conventional twin-screw after body hull form

③ Resistance of Appendages (3/3)

Hull appendage



Twin-screw twin-skeg after body hull form

④ Wave Resistance (Low Speed Range) (1/5)

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

- Low speed range: $F_n \le 0.4$

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

L_R=83.148

3,700 TEU Container Carrier

Item	Value
L	239.26 m
B	32.2 m
T	10.1 m
C_{WP}	0.6761
C_P	0.6794
L_{CB}	-0.531 % (aft)
∇	49,887 m^3

$$C_1 = 2223105 C_7^{3.78613} (T/B)^{1.07961} (90 - i_E)^{-1.37565}$$

$C_7 = 0.229577(B/L)^{0.33333}$: when B/L≤0.11
$C_7 = B/L$: when 0.11≤B/L≤0.25
$C_7 = 0.5 - 0.0625 B/L$: when 0.25≤B/L

i_E : The half angle of entrance in degree

At early design stage, If i_E is unknown, it can be obtained by following formula:

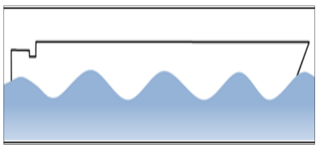
$$i_E = 1 + 89 e^{\left\{ -(L/B)^{0.80856}(1-C_{WP})^{0.30484}(1-C_P-0.0225L_{CB})^{0.6367} \times (L_R/B)^{0.34574}(100\nabla/L^3)^{0.16302} \right\}}$$

$$B/L = 0.135$$

$$C_7 = B/L = 32.2/239.26 = 0.135$$

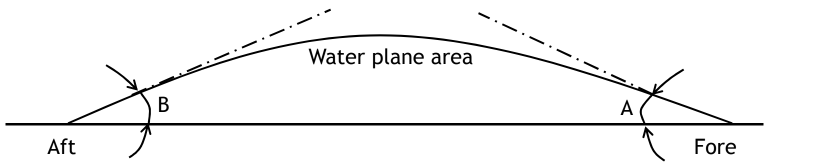
$$\begin{aligned} i_E &= 1 + 89 e^{\{-(L/B)^{0.80856}(1-C_{WP})^{0.30484}(1-C_P-0.0225L_{CB})^{0.6367} \times (L_R/B)^{0.34574}(100\nabla/L^3)^{0.16302}} \\ &= 1 + 89 e^{\{-(L/B)^{0.80856}(1-0.6761)^{0.30484}(1-0.6794-0.0225\times(-0.531))^{0.6367}(73.69/32.2)^{0.34574}(100\times 49887/239.26^3)^{0.16302}} \\ &= 13[\text{deg}] \end{aligned}$$

$$\begin{aligned} \therefore C_1 &= 2223105 C_7^{3.78613}(T/B)^{1.07961}(90-i_E)^{-1.37565} \\ &= 2223105 \times 0.135^{3.78613}(10.1/32.2)^{1.07961}(90-13)^{-1.37565} \\ &= 0.812 \end{aligned}$$



④ Wave Resistance (Low Speed Range) (2/5)

Meaning of a entrance angle



i_E : The half angle of entrance is the angle of the waterline at the bow in degrees with reference to the center plane but neglecting the local shape at the stem.

④ Wave Resistance (Low Speed Range) (3/5)

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

- Low speed range: $F_n \le 0.4$

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

3,700 TEU Container Carrier

Item	Value
B	32.2 m
T	10.1 m
T_F	10.1 m
A_{BT}	15.2 m²
h_B	5.5 m
A_T	0 m²
C_M	0.9761

C_2 : A parameter which accounts for the reduction of the wave resistance due to the action of a bulbous bow

$C_2 = e^{-1.89\sqrt{C_3}}$ If there is not bulb, C_2 is 1.

$C_3 = 0.56 A_{BT}^{1.5} / \{B \cdot T(0.31\sqrt{A_{BT}} + T_F - h_B)\}$ A_{BT} : Transverse bulb area

h_B : The position of the centre of the transverse are A_{BT} above the keel line

T_F : The forward draft of the ship

C_5 : A parameter which accounts for the reduction of the wave resistance due to the action of a transom stern

$C_5 = 1 - 0.8 A_T / (B \cdot T \cdot C_M)$ A_T : The immersed part of the transverse area of the transom at zero speed

$$\begin{aligned} C_3 &= 0.56 A_{BT}^{1.5} / \{B \cdot T(0.31\sqrt{A_{BT}} + T_F - h_B)\} \\ &= 0.56 \times (15.2)^{1.5} / \{32.2 \times 10.1(0.31\sqrt{15.2} + 10.1 - 5.5)\} \\ &= 0.018 \end{aligned}$$

$$\begin{aligned} C_2 &= e^{-1.89\sqrt{C_3}} \\ &= e^{(-1.89\sqrt{0.02})} \\ &= 0.78 \end{aligned}$$

⇨

$$\begin{aligned} C_5 &= 1 - 0.8 A_T / (B \cdot T \cdot C_M) \\ &= 1 \end{aligned}$$

④ Wave Resistance (Low Speed Range) (4/5)

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

- Low speed range: $F_n \le 0.4$

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

3,700 TEU Container Carrier

Item	Value
L	239.26 m
T	10.1 m
C_p	0.6794
∇	49,778 m³
F_n	0.2442

$$m_1 = 0.0140407\, L/T - 1.75254 \nabla^{1/3}/L - 4.79323\, B/L - C_{16}$$

$C_{16} = 8.07981 C_P - 13.8673 C_P^2 + 6.984388 C_P^3$: when $C_P \le 0.8$

$C_{16} = 1.73014 - 0.7067 C_P$: when $0.8 \le C_P$

$$d = -0.9$$

$$m_4 = C_{15} 0.4 e^{-0.034 F_n^{-3.29}}$$

$C_{15} = -1.69385$: when $L^3/\nabla \le 512$

$C_{15} = -1.69385 + (L/\nabla^{1/3} - 8.0)/2.36$: when $512 \le L^3/\nabla \le 1726.91$

$C_{15} = 0.0$: when $1726.91 \le L^3/\nabla$

$$
\begin{aligned}
m_1 &= 0.0140407 L/T - 1.75254 \nabla^{1/3}/L - 4.79323 B/L - C_{16} \\
&= 0.0140407 \times 239.26/10.1 - 1.75254 \times 49778^{1/3}/239.26 \\
&\quad - 4.79323 \times 32.2/239.26 - 1.25 \\
&= -1.832
\end{aligned}
$$

$$
\begin{aligned}
&L^3/\nabla = 275.152 \le 512 \\
&\quad \to C_{15} = -1.694 \\
m_4 &= C_{15} 0.4 e^{-0.034 F_n^{-3.29}} \\
&= -1.694 \cdot 0.4 e^{-0.034 F_n^{-3.29}} \\
&= -0.016
\end{aligned}
$$

④ Wave Resistance (Low Speed Range) (5/5)

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

- Low speed range: $F_n \le 0.4$

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

L_R=83.148
C_1=1.263
C_2=0.778
C_5=1
m_1=-1.860
d=-0.9
m_4=-0.016

3,700 TEU Container Carrier

Item	Value
L	239.26 m
B	32.2 m
C_p	0.6794
∇	49,778 m³
F_n	0.2389

$\lambda = 1.446 C_P - 0.03 L/B$: when L/B≤12

$\lambda = 1.446 C_P - 0.36$: when 12≤L/B

$$
\begin{aligned}
&L/B = 7.43 \le 12 \\
&\to \lambda = 1.446 C_P - 0.03 L/B \\
&\quad = 1.446 \times 0.6794 - 0.03 \times 239.26/32.2 \\
&\quad = 0.702
\end{aligned}
$$

$$
\begin{aligned}
&\therefore R_w = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\} \\
&= 1.025 \times 9.81 \times 49778 \times 0.812 \times 0.78 \times 1 \times \exp\{-1.860 \times 0.2389^{-0.9} - 0.016 \times \cos(0.702 \times 0.2389^{-2})\} \\
&= 406.875[kN]
\end{aligned}
$$

④ Wave Resistance (High Speed Range)

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

- High speed range: $0.55 \le F_n$

$$R_W = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

3,700 TEU Container Carrier

Item	Value
L	239.26 m
B	32.2 m
C_p	0.6794
∇	49,778 m^3
F_n	0.2442

In the high speed, the coefficients C_1 and m_1 are changed

$$C_1 = 6919.3 C_M^{-1.3346} (\nabla / L^3)^{2.00977} (L/B-2)^{1.40692}$$

$$m_1 = -7.2035 (B/L)^{0.326869} (T/B)^{0.605375}$$

④ Wave Resistance (Middle Speed Range)

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

- Middle speed range: $0.4 \le F_n \le 0.55$

$$R_W = (R_W)_{at\,F_n=0.4} + (10F_n - 4) \cdot \{(R_W)_{at\,F_n=0.55} - (R_W)_{at\,F_n=0.4}\} / 1.5$$

3,700 TEU Container Carrier

Item	Value
$(R_W)_{at\,F_n=0.4}$	-
$(R_W)_{at\,F_n=0.55}$	-
F_n	0.2442

$(R_W)_{at\,F_n=0.4}$: The wave resistance prediction for F_N = 0.4 according to the formula in low speed range

$(R_W)_{at\,F_n=0.55}$: The wave resistance prediction for F_N = 0.55 according to the formula in high speed range

⑤ Additional Pressure Resistance of Bulbous Bow near the Water Surface

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

$$R_B = 0.11 e^{(-3P_B^{-2})} \cdot F_{ni}^{\ 3} A_{BT}^{\ 1.5} \rho g / (1 + F_{ni}^{\ 2})$$

3,700 TEU Container Carrier

Item	Value
A_{BT}	15.2 m^2
T_F	10.1 m
h_B	5.5 m
V	22.5 knots
g	9.81 m/s^2
ρ	1.025 ton/m^3

P_B : A measure for the emergence of the bow

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

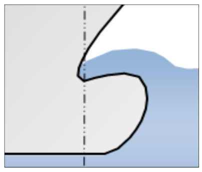
F_{ni}: The Froude number based on immersion of bulbous bow

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

$$P_B = 0.56\sqrt{A_{BT}} / (T_F - 1.5h_B)$$
$$= 0.56 \times \sqrt{15.2} / (10.1 - 1.5 \times 5.5)$$
$$= 1.18$$

$$F_{ni} = V / \sqrt{g(T_F - h_B - 0.25\sqrt{A_{BT}}) + 0.15V^2}$$
$$= 11.574 / \sqrt{(9.81(10.1?5.5?0.25\sqrt{15.2}) + 0.15 \times (11.574)^2)}$$
$$= 1.55$$

$$\therefore R_B = 0.11 e^{(-3P_B^{-2})} \cdot F_{ni}^{\ 3} A_{BT}^{\ 1.5} \rho g / (1 + F_{ni}^{\ 2})$$
$$= 0.11 e^{(-3 \times 1.18^{-2})} \times 1.55^3 \times 15.2^{1.5} \times 1.025 \times 9.81 / (1 + 1.55^2)$$
$$= 8.33[kN]$$



In the recent research, it is assumed that R_B=0[*kN*].

⑥ Additional Pressure Resistance of Immersed Transom Immersion

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

$$R_{TR} = 1/2 \rho V^2 A_T C_6$$

3,700 TEU Container Carrier

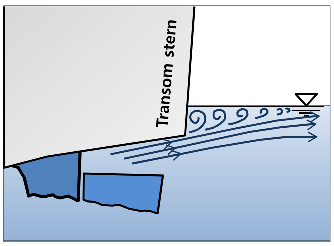
Item	Value
A_T	0 m^2
g	9.81 m/s^2
B	32.2 m
C_{WP}	0.6761
V	22.5 knots
ρ	1.025 ton/m^3

$C_6 = 0.2(1 - 0.2F_{nT})$: when $F_{nT} \le 5$

$C_6 = 0$: when $5 \le F_{nT}$

$$F_{nT} = V / \sqrt{2gA_T / (B + B \cdot C_{WP})}$$

$$\therefore R_{TR} = 1/2 \rho V^2 A_T C_6 \quad \because A_T = 0$$
$$= 0[kN]$$



⑦ Model-Ship Correlation Resistance (1/2)

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

$$R_A = 1/2\rho V^2 S_{total} C_A$$

3,700 TEU Container Carrier

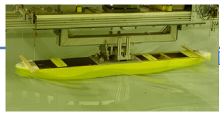
Item	Value
L	239.26 m
C_B	0.6394
T_F	10.1 m
V	22.5 knots
ρ	1.025 ton/m³
S_{total}	9465.74 m²

The model-ship correlation resistance R_A is supposed to describe primarily the effect of the hull roughness and the still-air resistance.

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}C_B{}^4 C_2(0.04 - C_4)$$

$C_4 = T_F / L$: when T_F / L ≤0.04

$C_4 = 0.04$: when 0.04 < T_F / L



$T_F / L = T_F / L$

$= 10.1 / 239.26 = 0.042$

Because 0.04 ≤ T_F/L

$$C_A = 0.006(L+100)^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5}C_B{}^4 C_2(0.04 - C_4)$$

$$= 0.006(239.26+100)^{-0.16} - 0.00205 + 0.003\sqrt{239.26/7.5}0.6241^4 \times 0.629(0.04 - 0.04) = 0.000312$$

$$\therefore R_A = \frac{1}{2}\rho V^2 S_{total} C_A = \frac{1}{2} \times 1.025 \times 11.574^2 \times 9625.74 \times 0.000312 = 202.705[kN]$$

⑦ Model-Ship Correlation Resistance (2/2)

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

3,700 TEU Container Carrier

Item	Value
R_F	822.61 kN
(1+k1)	1.14
R_{APP}	29.59kN
R_W	406.875 kN
R_B	0 kN
R_{TR}	0 kN
R_A	202.705 kN

$$R_T = 822.61 \times (1.14) + 29.59 + 406.875 + 0 + 0 + 202.705 = 1{,}577.21$$

$$\therefore R_{T,basis,Holtrop\,\&\,Mennen} = 1{,}577.21[kN]$$

Resistance Prediction for a Ship (1/3)

Model test of the basis ship

Model test of the design ship

Given

Find

Calculate

Calculate

Resistance of basis ship estimated by Holtrop-Mennen method

Resistance of design ship estimated by Holtrop-Mennen method

Resistance Prediction for a Ship (2/3)

ITTC Standard Prediction

Ship Speed (kts)	Fn	PE (PS)	PD (PS)	S·P Adv (J)	Rate Revs (rpm)	Thrust (kN)	Torque (kN·m)	Model Wake (Wtm)	Ship Wake (Wts)
19.00	.202	11575	14940	.685	80.75	1084	1300	.323	.273
20.00	.212	13716	17914	.677	85.31	1239	1475	.321	.279
21.00	.223	16185	21078	.679	90.21	1380	1641	.315	.273
22.00	.234	18906	24682	.677	94.96	1537	1826	.312	.271
22.50	.239	20386	26635	.676	97.38	1619	1921	.310	.270
23.00	.244	22008	28847	.674	99.83	1713	2030	.309	.270
24.00	.255	26181	34655	.665	105.42	1960	2309	.307	.271
25.00	.266	33202	44312	.652	113.29	2355	2747	.303	.263

Model test of the basis ship

Model test of the design ship

Given

Find

$$\frac{R_{T,basis,modeltest}}{R_{T,basis,Holtrop\ \&\ Mennen}} = \frac{R_{T,design,modeltest}}{R_{T,design,Holtrop\ \&\ Mennen}}$$

Calculate

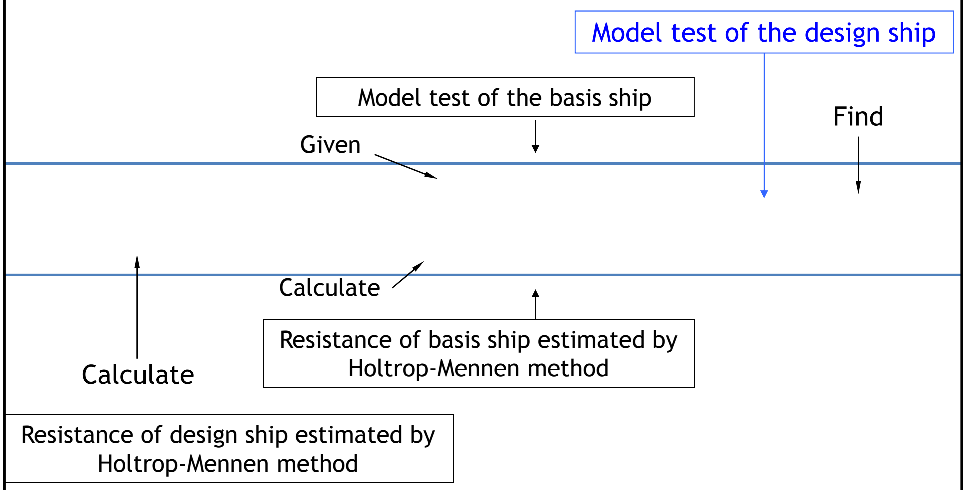
Calculate

Resistance of basis ship estimated by Holtrop-Mennen method

Resistance of design ship estimated by Holtrop-Mennen method

$$R_{T,basis,Holtrop\ \&\ Mennen} = 1{,}557.21[kN]$$

Resistance Prediction for a Ship (3/3)



Resistance Estimation by Holtrop and Mennen's Method - Approximation Formula of the Propeller Efficiency (1/4)

$$\eta_D = \overset{①}{\eta_O} \cdot \overset{②}{\eta_H} \cdot \overset{③}{\eta_R}$$

MCR: Maximum Continuous Rating
NCR: Normal Continuous Rating)
BHP: Brake Horse Power
DHP: Delivered Horse Power
EHP: Effective Horse Power
R_T: Total Resistance
η_T: Transmission Efficiency
η_D: Propulsive Efficiency
η_O: Propeller Efficiency
η_H: Hull Efficiency
η_R: Relative Rotative Efficiency
t: Thrust Deduction Fraction
w: Wake Fraction

① $$\eta_O = [1/(0.97 + 0.14\sqrt{B_P})] \cdot k$$

$$k = [1.11 - 0.11((A_E / A_O)/0.6)] = 1.11 - 0.11(0.731/0.6) = 0.975$$

$$B_P = \frac{n(NCR\eta_T\eta_R)^{0.5}}{V(1-w)}$$

$$C_F = \frac{0.075}{(\log R_n - 2)^2},$$

$$D_P = 15.4 \cdot \left(\frac{MCR}{n_{MCR}^3}\right)^{0.2} \cdot c_1$$
$$= 15.4 \cdot (38570[BHP]/102[rpm]^3)^{0.2} \cdot 1$$
$$= 7.936[m]$$

Beware of Unit

Blade = 5 : C_1=1,
Blade = 4 : C_1=1.05

1PS = 0.73575 kW
1BHP = 0.74556 kW

② $$\eta_H = \frac{1-t}{1-w}$$

③ $$\eta_R = 0.98 \sim 1.03$$

Resistance Estimation by Holtrop and Mennen's Method - Approximation Formula of the Propeller Efficiency (2/4)

$$\eta_D = \overset{①}{\eta_O} \cdot \overset{②}{\eta_H} \cdot \overset{③}{\eta_R} \qquad \eta_H = \frac{1-t}{1-w},$$

$$w = c_9 C_V \frac{L}{T_A}\left(0.0661875 + 1.21756 c_{11} \frac{C_V}{(1-C_{P1})}\right)$$
$$+0.24558\sqrt{\frac{B}{L(1-C_{P1})}} - \frac{0.09726}{0.95-C_P} + \frac{0.11434}{0.95-C_B} + 0.75 C_{stern} C_V + 0.002 C_{stern}$$
$$= 14.55 \times 0.003 \frac{239.26}{10.1}\left(0.0661875 + 1.21756 \times 1.27 \frac{0.003}{(1-0.682)}\right)$$
$$+0.24558\sqrt{\frac{32.2}{239.26(1-0.682)}} - \frac{0.09726}{0.95-0.682} + \frac{0.11434}{0.95-0.6394} + 0.75 \times (-10) \times 0.003 + 0.002(-10)$$
$$= 0.211$$

MCR: Maximum Continuous Rating
NCR: Normal Continuous Rating)
BHP: Brake Horse Power
DHP: Delivered Horse Power
EHP: Effective Horse Power
R_T: Total Resistance
η_T: Transmission Efficiency
η_D: Propulsive Efficiency
η_O: Propeller Efficiency
η_H: Hull Efficiency
η_R: Relative Rotative Efficiency
t: Thrust Deduction Fraction
w: Wake Fraction

$c_8 = BS/(LD_P T_A)$	when $B/T_A < 5$
$c_8 = S(7B/T_A - 25)/(LD_P(B/T_A - 3))$	when $B/T_A > 5$
$c_9 = c_8$	when $c_8 < 28$
$c_9 = 32 - 16/(c_8 - 24)$	when $c_8 > 28$
$c_{11} = T_A / D_P$	when $T_A / D_P < 2$
$c_{11} = 0.0833333(T_A/D)^3 + 1.33333$	when $T_A / D_P > 2$
$C_V = (1+k)C_F + C_A$	
$C_{P1} = 1.45 C_P - 0.315 - 0.0225 LCB$	

$c_8 = BS/(LD_P T_A) = 32.2 \times 8670.24 / (239.26 \times 7.936 \times 10.1) = 14.55$
$(\because B/T_A = 3.19)$
$c_9 = 14.55$
$(\because c_8 = 14.55)$
$c_{11} = 1.27$
$(\because T_A / D_P = 1.27)$
$C_V = (1+k)C_F + C_A = (1+0.975) \times 0.001378 + 0.000312 = 0.003$
$C_{P1} = 1.45 C_P - 0.315 - 0.0225 LCB = 1.45 \times 0.6794 - 0.315 - 0.0224 \times (-0.531) = 0.682$

Resistance Estimation by Holtrop and Mennen's Method - Approximation Formula of the Propeller Efficiency (3/4)

$$\eta_D = \overset{①}{\eta_O} \cdot \overset{②}{\eta_H} \cdot \overset{③}{\eta_R} \qquad \eta_H = \frac{1-t}{1-w},$$

$$t = 0.001979 L / (B - BC_{P1}) + 1.0585 c_{10}$$
$$-0.00524 - 0.1418 D^2 / (BT) + 0.0015 C_{stern}$$
$$= 0.001979 \times 239.26 / (32.2 - (32.2 \times 0.682)) + 1.0585 \times 0.13$$
$$-0.00524 - 0.1418 \times 7.936^2 / (32.2 \times 10.1) + 0.0015 \times (-10)$$
$$= 0.141$$

MCR: Maximum Continuous Rating
NCR: Normal Continuous Rating)
BHP: Brake Horse Power
DHP: Delivered Horse Power
EHP: Effective Horse Power
R_T: Total Resistance
η_T: Transmission Efficiency
η_D: Propulsive Efficiency
η_O: Propeller Efficiency
η_H: Hull Efficiency
η_R: Relative Rotative Efficiency
t: Thrust Deduction Fraction
w: Wake Fraction

②
$$\eta_H = \frac{1-t}{1-w} = \frac{1-0.141}{1-0.211} = 1.09$$

③ If number of shaft = 1
$$\eta_R = 0.9922 - 0.05908 A_E / A_O + 0.07424(C_P - 0.0225 LCB)$$
$$= 0.9922 - 0.05908 \times 0.731 + 0.07424(0.6794 - 0.0225 \times (-0.531))$$
$$= 1.00$$

If number of shaft = 2
$$\eta_R = 0.9737 + 0.111(C_P - 0.0225 LCB) - 0.06325 P_i / D_P$$

$c_{10} = B/L$	when $L/B > 5.2$
$c_{10} = 0.25 - 0.003328402/(B/L - 0.134615385)$	when $L/B < 5.2$

$c_{10} = 0.13$
$(\because L/B = 7.43)$

Resistance Estimation by Holtrop and Mennen's Method - Approximation Formula of the Propeller Efficiency (4/4)

$$\eta_D = \overset{①}{\eta_O} \cdot \overset{②}{\eta_H} \cdot \overset{③}{\eta_R}$$

①

$$\eta_O = [1/(0.97 + 0.14\sqrt{B_P})] \cdot k$$
$$= [1/(0.97 + 0.14\sqrt{28.62})] \times 0.976$$
$$= 0.568$$

$$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$$
$$= 0.568 \times 1.09 \times 1$$
$$= 0.62$$

MCR: Maximum Continuous Rating
NCR: Normal Continuous Rating)
BHP: Brake Horse Power
DHP: Delivered Horse Power
EHP: Effective Horse Power
R_T: Total Resistance
η_T: Transmission Efficiency
η_D: Propulsive Efficiency
η_O: Propeller Efficiency
η_H: Hull Efficiency
η_R: Relative Rotative Efficiency
t: Thrust Deduction Fraction
w: Wake Fraction

$$B_P = \frac{n(NCR\eta_T\eta_R)^{0.5}}{V(1-w)}$$
$$= \frac{1.642[rps](25522[kW] \times 0.98 \times 1)^{0.5}}{11.574(1-0.206)}$$
$$= 28.62$$

Beware of Unit

$MCR: 38,570[PS] \times 102[rpm] \Rightarrow 28,361[kW] \times 1.7[rps]$

$NCR: 34,710[PS] \times 98.5[rpm] \Rightarrow 25,522[kW] \times 1.642[rps]$

Power Prediction by Holtrop & Mennen Method

① EHP (Effective Horse Power)

$$EHP = R_T(v) \cdot V_s \quad \text{(In calm water)}$$

② DHP (Delivered Horse Power)

$$DHP = \frac{EHP}{\eta_D}$$

(η_D : Propulsive efficiency)
$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$
η_O : Open water efficiency
η_H : Hull efficiency
η_R : Relative rotative efficiency

③ BHP (Brake Horse Power)

$$BHP = \frac{DHP}{\eta_T} \quad (\eta_T : \text{Transmission efficiency})$$

④ NCR (Normal Continuous Rating)

$$NCR = BHP(1 + \frac{\text{Sea Margin}}{100})$$

⑤ DMCR (Derated Maximum Continuous Rating)

$$DMCR = \frac{NCR}{\text{Engine Margin}}$$

⑥ NMCR (Nominal Maximum Continuous Rating)

$$NMCR = \frac{DMCR}{\text{Derating rate}}$$

$$EHP = R_T(v) \cdot V_s = 1,577.21 \times 11.574$$
$$= 18,254.7[kW] = 24,484.5[BHP]$$

1PS = 0.73575 kW
1BHP = 0.74556 kW

$$DHP = \frac{EHP}{\eta_D} = \frac{24,484.5}{0.62} = 39,613.5[BHP]$$

$$BHP = \frac{DHP}{\eta_T} = \frac{39,613.5}{0.98} = 40,421.9[BHP]$$

$$NCR = BHP\left(1 + \frac{\text{Sea Margin}}{100}\right)$$
$$= 40,421.9\left(1 + \frac{15}{100}\right) = 46,485.2[BHP]$$

$$DMCR = \frac{NCR}{\text{Engine Margin}} = \frac{46,485.2}{0.9} = 51,650.2[BHP]$$

$$NMCR = \frac{DMCR}{\text{Derating rate}}$$