

Lecture Note of Innovative Ship and Offshore Plant Design

Innovative Ship and Offshore Plant Design

Part I. Ship Design

Ch. 6 Resistance Prediction

Spring 2017

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Ch. 6 Resistance Prediction

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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'.

Admiralty formula: $NCR = f(\Delta, V_s)$

↓

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

↓

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

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

Define $C_{ad} \equiv \frac{1}{C_{NCR}}$.
 C_{ad} is called "Admiralty coefficient".

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

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Object of Resistance Prediction (2/3)

☑ **Goal: Estimation of NMCR**

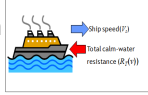
At first, we have to predict

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


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Object of Resistance Prediction (3/3)

① EHP (Effective Horse Power)

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


② DHP (Delivered Horse Power)

$$DHP = \frac{EHP}{\eta_D}$$
← Propeller Efficiency


(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

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

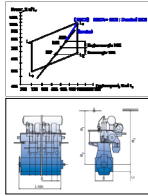
③ BHP (Brake Horse Power)

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

④ NCR (Normal Continuous Rating)

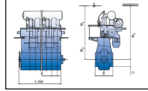
$$NCR = BHP \left(1 + \frac{\text{Sea Margin}}{100}\right)$$

⑤ DMCR (Derated Maximum Continuous Rating)

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


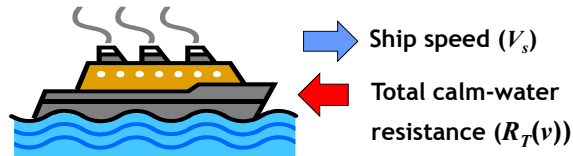
⑥ NMCR (Nominal Maximum Continuous Rating)

$$NMCR = \frac{DMCR}{\text{Derating rate}}$$
← Engine Data


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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.

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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.

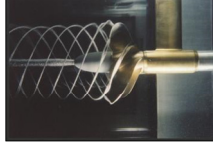
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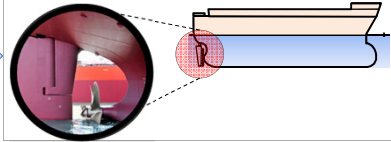
Dimensional Analysis (1/4)

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.

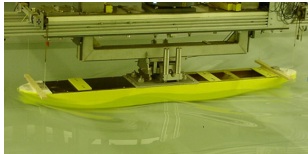
Dimensional solutions do not yield numerical answers, but they provide the form of the answer so that every experiment can be used to the fullest advantage in determining a general empirical solution.

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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**

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


* M: Mass, L: Length, T: Time

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

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

non-dimensional term

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Dimensional Analysis (3/4)

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

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

Writing ν for μ/ρ and remembering that for similar shapes the wetted surface S is proportional to L^2 , the equation may be written:

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

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_c .

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.

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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** non-dimensional term

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 V : In 10 degree seawater, 1.35×10^6
 L : length of the ship at the waterline level In 15 degree seawater, 10^6
 ν : kinematic viscosity

: 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

* Cavitation number: A dimensionless number used in flow calculations. It expresses **the relationship between the difference of a local absolute pressure from the vapor pressure and the kinetic energy per volume**, and is used to characterize the potential of the flow to cavitate.

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Decomposition of Resistance (1/3)

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

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)

$$\text{Froude} : R_T = R_F + R_R + \Delta R_F \quad \text{Hughes} : R_T = R_V + R_W$$

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 [m²]: wetted surface

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

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

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

3-dimensionalized form using the form factor

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

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 $C_{w\lambda}$.

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

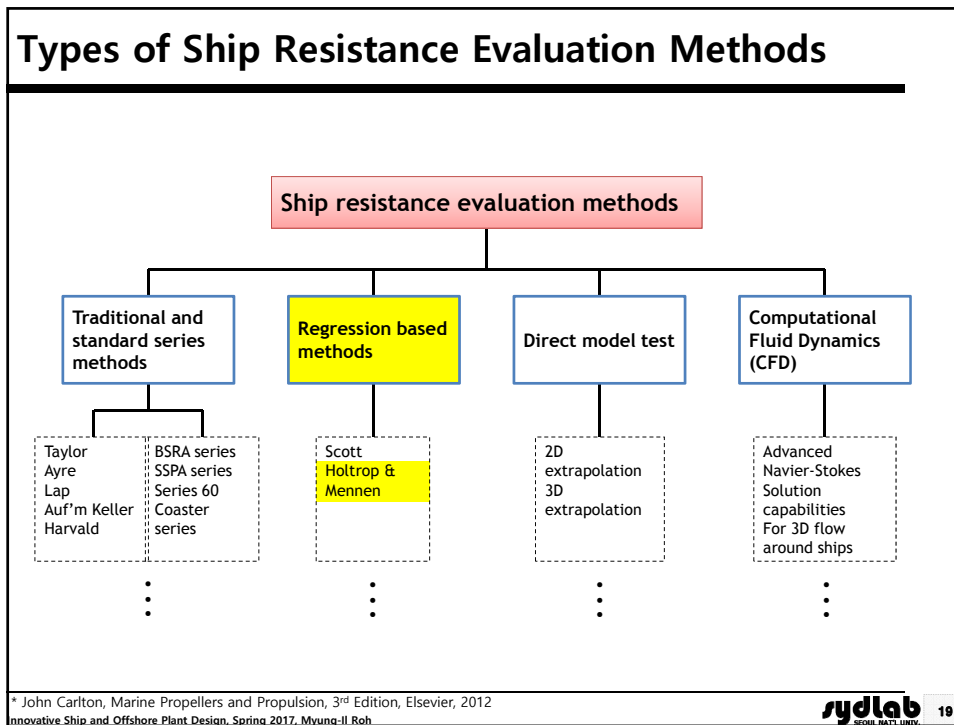
$$R_w = \rho g \nabla C_1 C_2 C_5 \exp\{m_1 F_n^d + m_4 \cos(\lambda F_n^{-2})\}$$

Component	Tanker (16 knots)	Ro-Ro (21 knots)
Wave breaking	5%	10%
Wave pattern	5%	30%
Viscous pressure	18%	7.50%
Form effect on friction	5%	2.50%
Ploughness	10%	10%
Flat plate friction	60%	40%
Wave resistance	25%	50%
Viscous resistance	35%	50%

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3. Resistance Prediction by Holtrop-Mennen's Method

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Resistance estimation by Holtrop-Mennen's Method

- Reason why a statistical method is presented at the initial design stage of a ship (1/2)

Model Test for the basis ship

Model Test for the design ship

Basis ship

Design ship

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.**

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

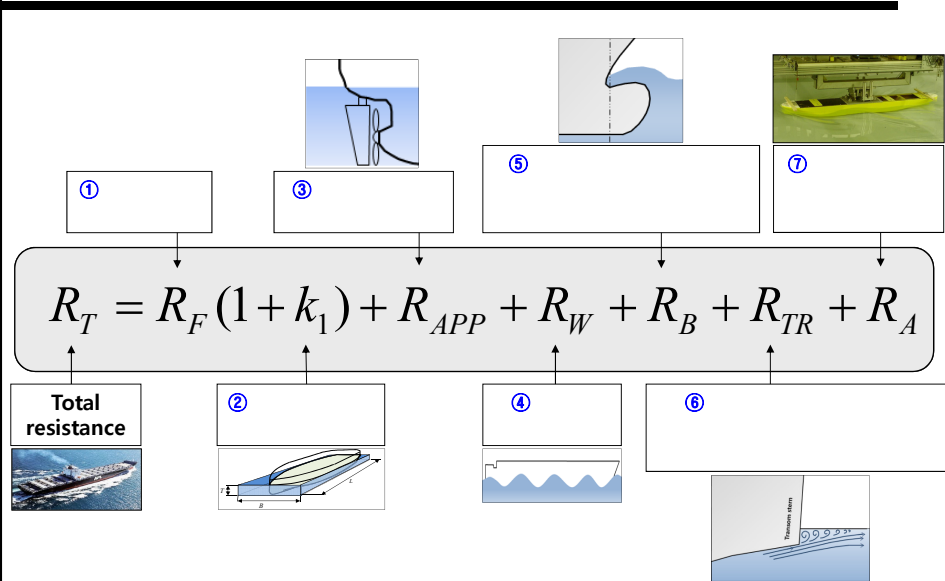
Therefore, [a statistical method was presented](#) for the determination of the required propulsive power at the initial design stage.

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 SSMH'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



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	Item	Value
Main Dimension		Transverse bulb area	15.2 m ²
L _{OA}	257.4 m	Center of bulb area above keel line	5.5 m ²
L _{BP}	245.24 m	Transom area	0 m ²
L _{WL}	239.26 m	Wetted area appendages	317.74 m ²
B _{mid}	32.2 m	Stern shape parameter	V-shaped
D _{mid}	19.3 m	Propeller diameter	7.7 m
Td / Ts (design / scantling)	10.1 / 12.5 m	Number of propeller blades	5
Deadweight (design / scantling)	34,400 / 50,200 MT(metric ton)	Clearance propeller with keel line	0.3 m
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		

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)

$$C_F = \frac{0.075}{(\log R_n - 2)^2} \quad R_n = \frac{V \cdot L}{\nu}$$

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

Example 3,700 TEU CTN Carrier)

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

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

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① Frictional Resistance (2/3)

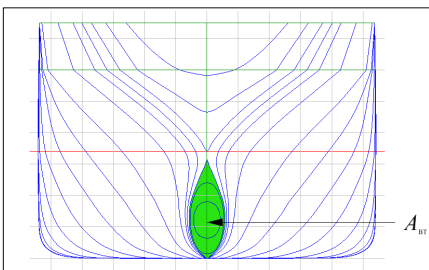
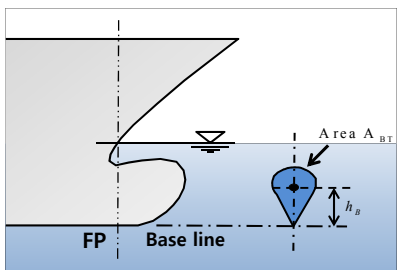
$$R_T = R_F(1+k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A$$

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

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

A_{BT} : Transverse bulb area

Definition of A_{BT} [L²]:
 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).

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① Frictional Resistance (3/3)

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

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

$C_F = 0.001378$
 $\rho = 1.025 \text{ ton/m}^3$

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 m ²
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)

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

$$= 239.26(2 \times 10.1 + 32.2) \sqrt{0.9761} (0.4530 + 0.4425 \times 0.6394 - 0.2862 \times 0.9761 - 0.003467 \times 32.2 \div 10.1 + 0.3696 \times 0.6761) + 2.38 \times 15.2 \div 0.6394$$

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

$$\therefore R_F = \frac{1}{2} \rho V^2 C_F S_{bh} = \frac{1}{2} \times 1.025 \times 11.574^2 \times 1.38 \times 10^{-3} \times 8,670.24 = 822.6 [kN]$$

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② Form Factor of the Bare Hull (1/3)

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

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

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

Item	Value
After body form	V-shaped

C₁₄ : The prismatic coefficient based on the waterline length

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

Example 3,700 TEU CTN Carrier)

$$C_{stern} = -10$$

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

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② Form Factor of the Bare Hull (2/3)

Types of stern

— V-shaped
 - - - U-shaped
 - · - · - Bulbous-shaped

Pram with gondola

Twin gondola stern

(A) Cruiser sterned vessels

(B) Transom sterned vessels (C) Counter sterned vessels

- In the aspect of resistance, V-shaped is better.
 - In the aspect of propulsive efficiency, U-shaped is better.

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② Form Factor of the Bare Hull (3/3)

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

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

$C_{14} = 0.89$

Item	Value
L	239.26 m
B	32.2 m
T	10.1 m
V	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:

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

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

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

$$= 239.26(1 - 0.6794 + 0.06 \times 0.6794 \times (-0.531) / (4 \times 0.6394 - 1))$$

$$= 73.692[m]$$

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

$$= 0.93 + 0.487118 \times 0.89 (32.2/239.26)^{1.06806} (10.1/239.26)^{0.46106} (239.26/73.692)^{0.121563} \times (239.26^3/49778)^{0.36486} \cdot (1-0.6394)^{-0.60247}$$

$$= 1.14$$

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③ Resistance of Appendages (1/3)

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

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

$C_F = 0.001378$
 $\rho = 1,025 \text{ kg/m}^3$

Item	Value
V	22.5 knots
Appendages (S_{APP})	82.74 m ² (rudder) 135 m ² (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

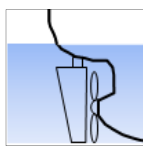
The equivalent $1+k_2$ value for a combination of appendages is determined from:

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

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

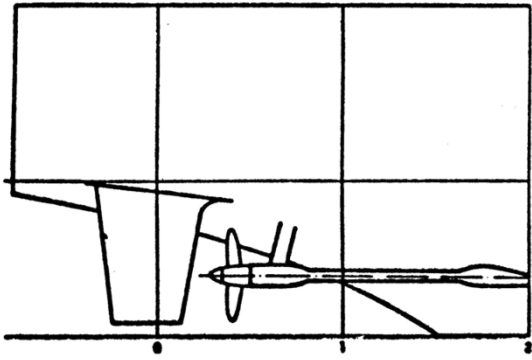
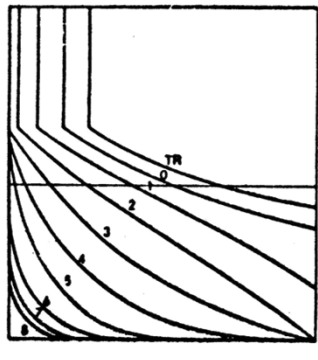
$$(1+k_2)_{eq} = \frac{\sum S_i(1+k_2)_i}{\sum S_i} = \frac{82.74(1.4)+135(1.4)}{82.74+135} = 1.4$$

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



③ Resistance of Appendages (2/3)

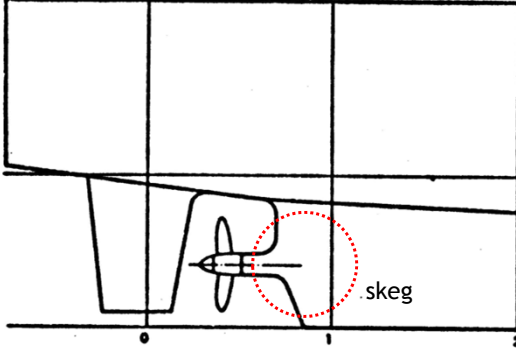
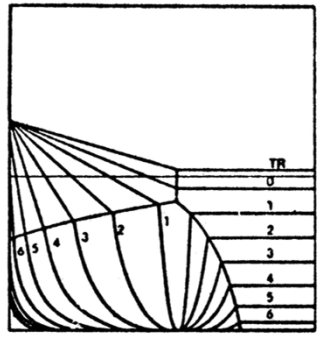
Hull appendage


Conventional twin-screw after body hull form

③ Resistance of Appendages (3/3)

Hull appendage

Twin-screw twin-skeg after body hull form


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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: $F_n \leq 0.4$

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

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

$C_7 = 0.229577(B/L)^{0.33333}$: when $B/L \leq 0.11$

$C_7 = B/L$: when $0.11 \leq B/L \leq 0.25$

$C_7 = 0.5 - 0.0625B/L$: when $0.25 \leq B/L$

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:

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

$L_R = 83.148$ 3,700 TEU Container Carrier

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

$B/L = 0.135$

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

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

= 13 [deg]

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

= 2223105 \times 0.135^{3.78613} (10.1/32.2)^{1.07961} (90-13)^{-1.37565}

= 0.812



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

Meaning of a entrance angle

B: Angle of run of waterline A: Angle of entrance of waterline (i_E)

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.

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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: $F_n \leq 0.4$

$$R_W = \rho g \nabla C_2 C_3 \exp \{ m_1 F_n^d + m_4 \cos(\lambda F_n^{-2}) \}$$

Item	Value
B	32.2 m
T	10.1 m
T_F	10.1 m
A_{BT}	15.2 m ²
h_B	5.5 m
A_T	0 m ²
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 area 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

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

$= 0.56 \times (15.2)^{1.5} / \{ 32.2 \times 10.1 (0.31\sqrt{15.2} + 10.1 - 5.5) \}$

$= 0.018$

$C_2 = e^{-1.89\sqrt{C_3}}$

$= e^{(-1.89\sqrt{0.018})}$

$= 0.78$

$C_5 = 1 - 0.8 A_T / (B \cdot T \cdot C_M)$

$= 1$

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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: $F_n \leq 0.4$

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

$m_1 = 0.0140407 L / T - 1.75254 \nabla^{1/3} / L - 4.79323 B / L - C_{16}$
 $C_{16} = 8.07981 C_p - 13.8673 C_p^2 + 6.984388 C_p^3$: when $C_p \leq 0.8$
 $C_{16} = 1.73014 - 0.7067 C_p$: when $0.8 \leq C_p$

$d = -0.9$

$m_4 = C_{15} 0.4 e^{-0.034 F_n^{-3.29}}$
 $C_{15} = -1.69385$: when $L^3 / \nabla \leq 512$
 $C_{15} = -1.69385 + (L / \nabla^{1/3} - 8.0) / 2.36$: when $512 \leq L^3 / \nabla \leq 1726.91$
 $C_{15} = 0.0$: when $1726.91 \leq L^3 / \nabla$

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

3,700 TEU Container Carrier

Item	Value
L	239.26 m
T	10.1 m
C _p	0.6794
∇	49,778 m ³
F _n	0.2442

$L^3 / \nabla = 275.152 \leq 512$
 $\rightarrow C_{15} = -1.694$
 $m_4 = C_{15} 0.4 e^{-0.034 F_n^{-3.29}}$
 $= -1.694 \cdot 0.4 e^{-0.034 F_n^{-3.29}}$
 $= -0.016$

sydlab 37

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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: $F_n \leq 0.4$

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

$\lambda = 1.446 C_p - 0.03 L / B$: when $L/B \leq 12$
 $\lambda = 1.446 C_p - 0.36$: when $12 \leq L/B$

$L / B = 7.43 \leq 12$
 $\rightarrow \lambda = 1.446 C_p - 0.03 L / B$
 $= 1.446 \times 0.6794 - 0.03 \times 239.26 / 32.2$
 $= 0.702$

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

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	0.2389

$L/B = 7.43 \leq 12$
 $\rightarrow \lambda = 1.446 C_p - 0.03 L / B$
 $= 1.446 \times 0.6794 - 0.03 \times 239.26 / 32.2$
 $= 0.702$

sydlab 38

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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: $0.55 \leq F_n$

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

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

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

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

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

sydlab 39
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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: $0.4 \leq F_n \leq 0.55$

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

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

sydlab 40
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⑤ Additional Pressure Resistance of Bulbous Bow near the Water Surface

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

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

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

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

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

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

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

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

sydlab 41

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⑥ Additional Pressure Resistance of Immersed Transom Immersion

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

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

$C_6 = 0.2(1 - 0.2F_{nT})$: when $F_{nT} \leq 5$
 $C_6 = 0$: when $5 \leq F_{nT}$

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

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

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

sydlab 42

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⑦ Model-Ship Correlation Resistance (1/2)

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

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

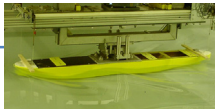

The model-ship correlation resistance R_A is supposed to describe primarily the effect of the hull roughness and the still-air resistance.

Item	Value
L	239.26 m
C _B	0.6394
T _F	10.1 m
V	22.5 knots
ρ	1.025 ton/m ³
S _{total}	9465.74 m ²

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

$$C_4 = T_F / L : \text{when } T_F / L \leq 0.04$$

$$C_4 = 0.04 : \text{when } 0.04 < T_F / L$$





$T_F / L = T_F / L$
 $= 10.1 / 239.26 = 0.042$
 Because $0.04 \leq T_F / L$

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

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

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

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⑦ Model-Ship Correlation Resistance (2/2)

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

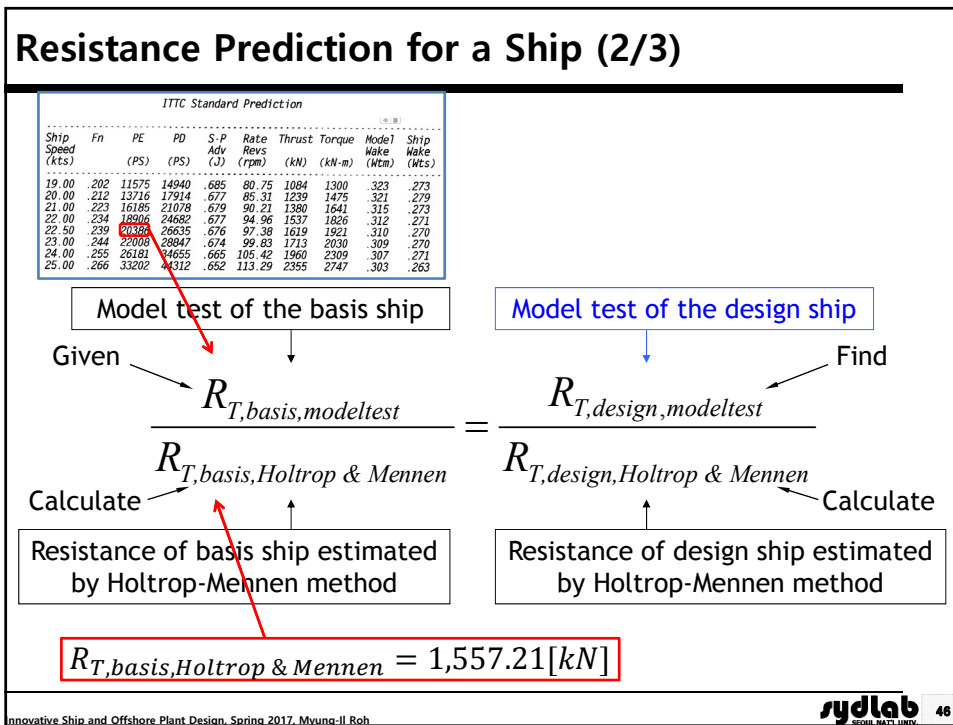
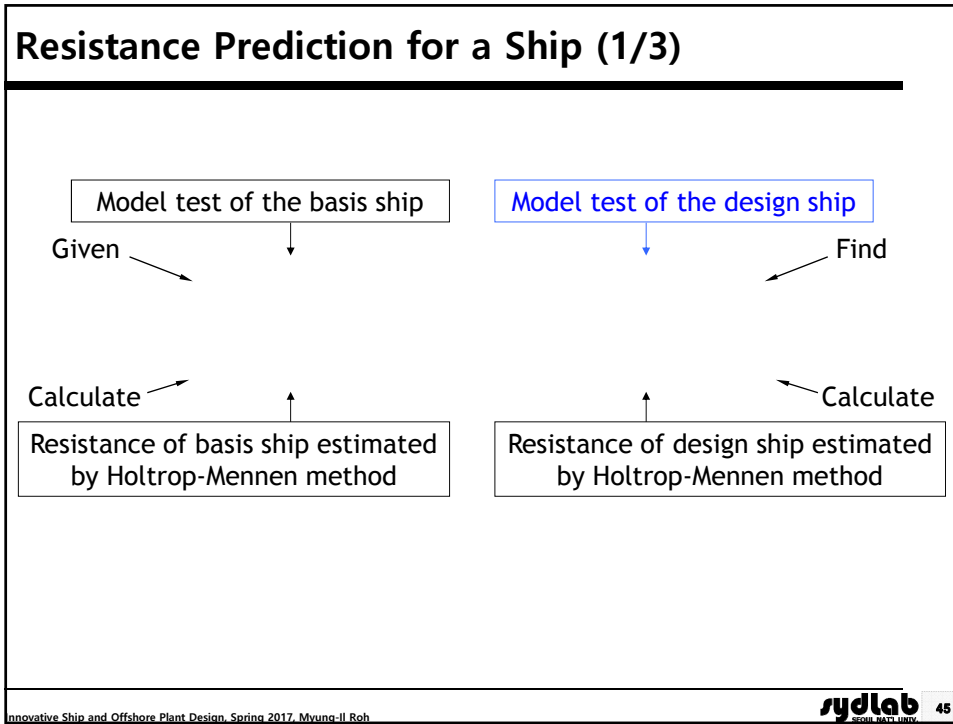
Item	Value
R _F	822.61 kN
(1+k ₁)	1.14
R _{APP}	29.59kN
R _W	406.875 kN
R _B	0 kN
R _{TR}	0 kN
R _A	202.705 kN

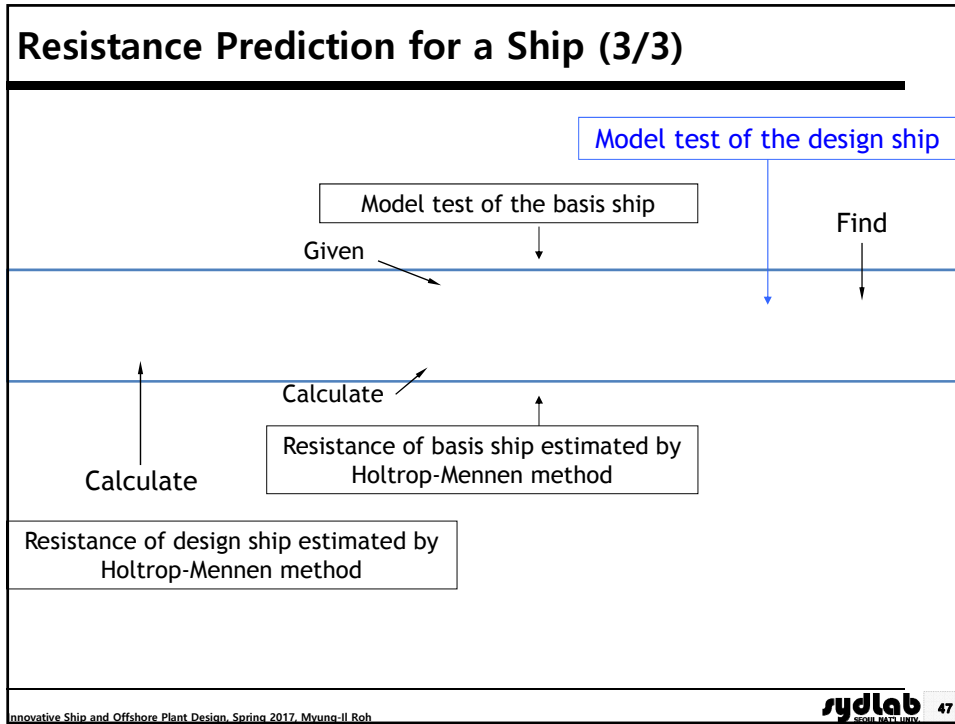
$$R_T = 822.61 \times (1.14) + 29.59 + 406.875 + 0 + 0 + 202.705 = 1,577.21$$

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

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

$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$

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

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

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

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

$D_p = 15.4 \cdot \left(\frac{MCR}{n_{MCR}^3}\right)^{0.2} \cdot c_1$

$= 15.4 \cdot (38570 [BHP] / 102 [rpm]^3)^{0.2}$

$= 7.936 [m]$ **Beware of Unit**

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_O: Propulsive Efficiency
 η_P: Propeller Efficiency
 η_H: Hull Efficiency
 η_R: Relative Rotative Efficiency
 t: Thrust Deduction Fraction
 w: Wake Fraction

Blade = 5 : C₁=1,
 Blade = 4 : C₁=1.05

1PS = 0.73575 kW
 1BHP = 0.74556 kW

$\eta_H = \frac{1-t}{1-w}$

$\eta_R = 0.98 \sim 1.03$

* η_R: The ratio between a propeller's efficiency attached to a ship (η_{OB}) and in open water (η_O), that is, η_R = η_{OB} / η_O

sydlab 48

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

$$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R \quad \eta_H = \frac{1-t}{1-w}$$

$$w = c_w C_v \frac{L}{T_d} \left(0.0661875 + 1.21756 c_{11} \frac{C_v}{(1-C_{p1})} \right)$$

$$+ 0.24558 \sqrt{\frac{B}{L(1-C_{p1})} - \frac{0.09726}{0.95-C_p} + \frac{0.11434}{0.95-C_B} + 0.75 C_{stern} C_v + 0.002 C_{stern}}$$

$$= 14.55 \times 0.003 \frac{239.26}{10.1} \left(0.0661875 + 1.21756 \times 1.27 \frac{0.003}{(1-0.682)} \right)$$

$$+ 0.24558 \sqrt{\frac{32.2}{239.26(1-0.682)} - \frac{0.09726}{0.95-0.682} + \frac{0.11434}{0.95-0.6394} + 0.75 \times (-10) \times 0.003 + 0.002(-10)}$$

$$= 0.211$$

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
η₁₀: Propulsive Efficiency
η₁₀₀: Propeller Efficiency
η_H: Hull Efficiency
η_{RS}: Relative Rotative Efficiency
t: Thrust Deduction Fraction
w: Wake Fraction

c_s = BS / (LD_pT_d) when B/T_d < 5

c_s = S(7B/T_d - 25) / (LD_p(B/T_d - 3)) when B/T_d > 5

c_v = c_s when c_s < 28

c_v = 32 - 16 / (c_s - 24) when c_s > 28

c₁₁ = T_d / D_p when T_d / D_p < 2

c₁₁ = 0.0833333(T_d/D_p)³ + 1.33333 when T_d / D_p > 2

C_v = (1+k)C_v + C_s

C_{p1} = 1.45C_v - 0.315 - 0.0225LCB

c_s = BS / (LD_pT_d) = 32.2 × 8670.24 / (239.26 × 7.936 × 10.1) = 14.55
(∵ B/T_d = 3.19)

∵ c_s = 14.55

c_v = 1.27
(∵ T_d / D_p = 1.27)

C_v = (1+k)C_v + C_s = (1+0.975) × 0.001378 + 0.000312 = 0.003

C_{p1} = 1.45C_v - 0.315 - 0.0225LCB = 1.45 × 0.6794 - 0.315 - 0.0224 × (-0.531) = 0.682

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

$$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R \quad \eta_H = \frac{1-t}{1-w}, \quad t = \frac{T-R_T}{T} = 1 - \frac{R_T}{T} \Rightarrow T = \frac{R_T}{1-t}$$

$$t = 0.001979L / (B - BC_{p1}) + 1.0585c_{10}$$

$$- 0.00524 - 0.1418D^2 / (BT) + 0.0015C_{stern}$$

$$= 0.001979 \times 239.26 / (32.2 - (32.2 \times 0.682)) + 1.0585 \times 0.13$$

$$- 0.00524 - 0.1418 \times 7.936^2 / (32.2 \times 10.1) + 0.0015 \times (-10)$$

$$= 0.141$$

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
η₁₀: Propulsive Efficiency
η₁₀₀: Propeller Efficiency
η_H: Hull Efficiency
η_{RS}: 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

$$\eta_R = 0.9922 - 0.05908A_E / A_O + 0.07424(C_p - 0.0225LCB)$$

$$= 0.9922 - 0.05908 \times 0.731 + 0.07424(0.6794 - 0.0225 \times (-0.531))$$

$$= 1.00$$

If number of shaft = 2

$$\eta_R = 0.9737 + 0.111(C_p - 0.0225LCB) - 0.06325P_i / D_p$$

c₁₀ = B / L when L/B > 5.2

c₁₀ = 0.25 - 0.003328402 / (B / L - 0.134615385) when L/B < 5.2

c₁₀ = 0.13
(∵ L / B = 7.43)

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* Thrust deduction fraction or coefficient (t): Additional resistance on the hull due to the rotation of the propeller
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Resistance Estimation by Holtrop and Mennen's Method - Approximation Formula of the Propeller Efficiency (4/4)

$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$

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

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

Beware of Unit

$$= \frac{1.642[rps](25522[kW] \times 0.98 \times 1)^{0.5}}{11.574(1-0.206)}$$

$$= 28.62$$

MCR : 38,570[PS] × 102[rpm] ⇒ 28,361[kW] × 1.7[rps]
 NCR : 34,710[PS] × 98.5[rpm] ⇒ 25,522[kW] × 1.642[rps]

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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)

$$DHP = \frac{EHP}{\eta_D} \quad (\eta_D = \eta_O \cdot \eta_H \cdot \eta_R)$$

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)

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

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

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

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

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

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

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

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

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