

Innovative Ship and Offshore Plant Design

Part I. Ship Design

Ch. 7 Propeller and Main Engine Selection

Spring 2019

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Ch. 7 Propeller and Main Engine Selection

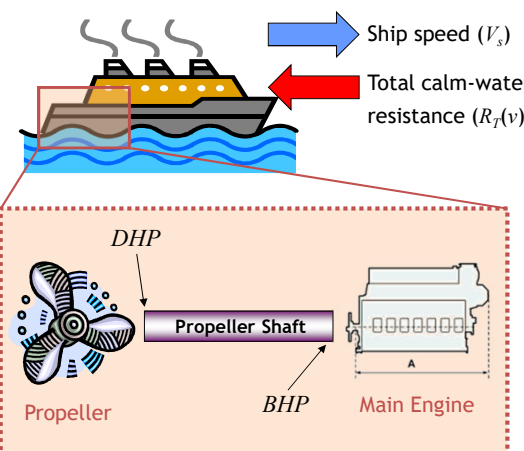
1. Characteristics of Propeller
2. Characteristics of Diesel Engine
3. Procedure of the Determination of Propeller Principal Dimensions and Main Engine Selection

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[Review] Resistance, Power Estimation - Power Prediction of Main Engine



① EHP (Effective Horse Power)

$$EHP = R_T(v) \cdot v \quad (\text{In Calm Water})$$

② DHP (Delivered Horse Power)

$$DHP = \frac{EHP}{\eta_D} \quad \left(\begin{array}{l} \eta_D : \text{Propulsive efficiency} \\ \eta_D = \eta_o \cdot \eta_h \cdot \eta_R \\ \eta_o : \text{Open water efficiency} \\ \eta_h : \text{Hull efficiency} \\ \eta_R : \text{Relative rotative efficiency} \end{array} \right)$$

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 DMCB (Derated Maximum Continuous Rating)

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

⑥ NMCR (Nominal Maximum Continuous Rating)

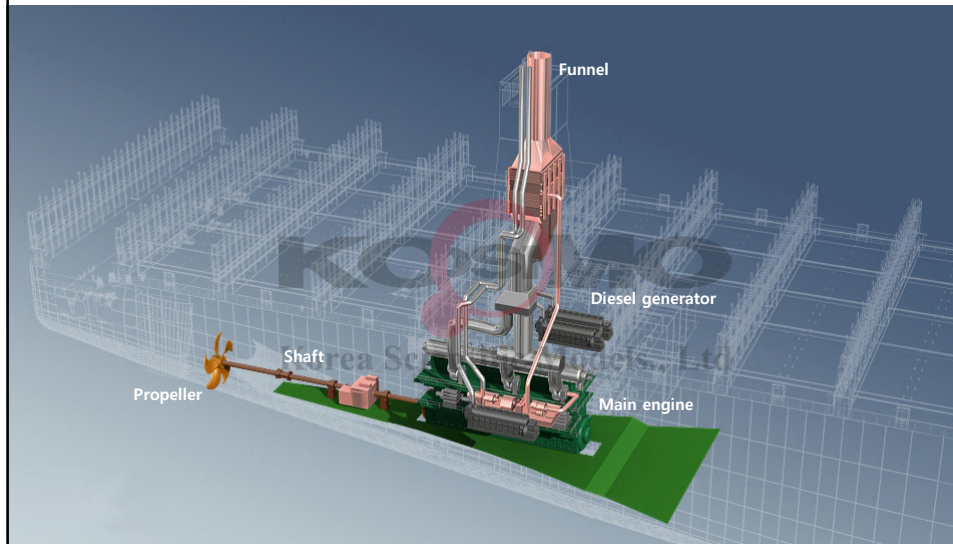
$$NMCR = \frac{DMCB}{\text{Derating rate}}$$

* η_R : The ratio between a propeller's efficiency attached to a ship (η_{oB}) and in open water (η_o), that is, $\eta_R = \eta_{oB} / \eta_o = Q_D / Q_{oB}$

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Example of a Diesel Engine and Propeller



* Reference: Korea Scientific Models
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1. Characteristics of Propeller

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Example of a Propeller

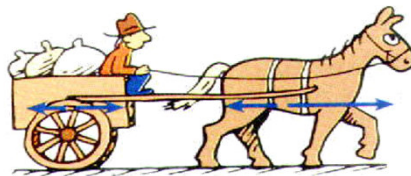


- ☑ Ship: 4,900 TEU Container Ship
- ☑ Owner: NYK, Japan
- ☑ Shipyard: HHI (2007.7.20)
- ☑ Diameter: 8.3 m
- ☑ Weight: 83.3 ton
- ☑ No of Blades: 5

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Concept of the Determination of Principal Dimensions of a Propeller



Wheel design to draw the carriage with cargo by one horse for maximum speed

Given

One Horse = Main Engine
Frictional Force of Wheels =
Resistance of a Ship

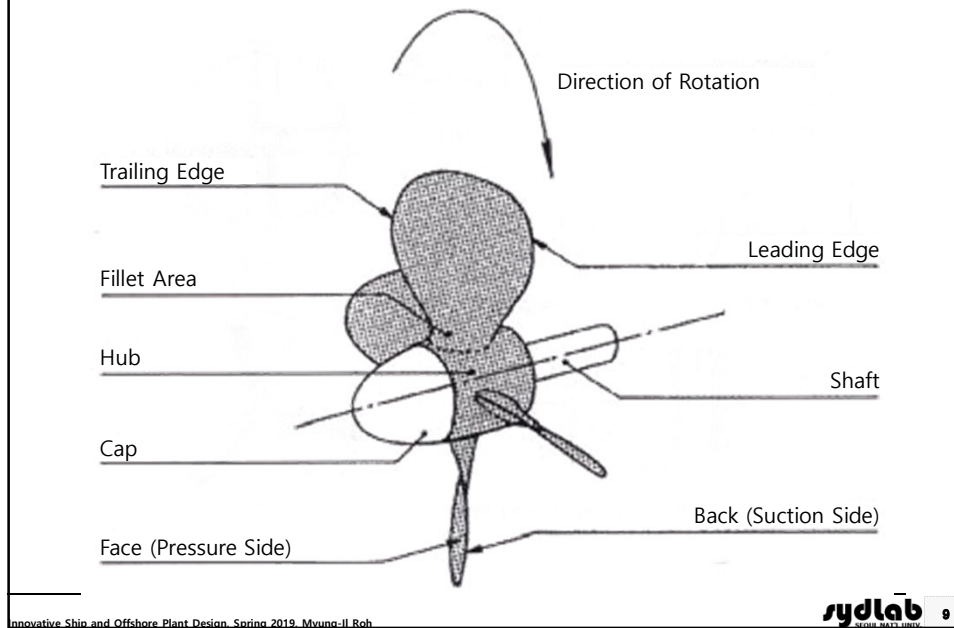
Find

Wheel Design = Propeller Design
Maximum Speed = Maximum Speed of a Ship
Wheel Diameter = Principal Dimensions of a Propeller

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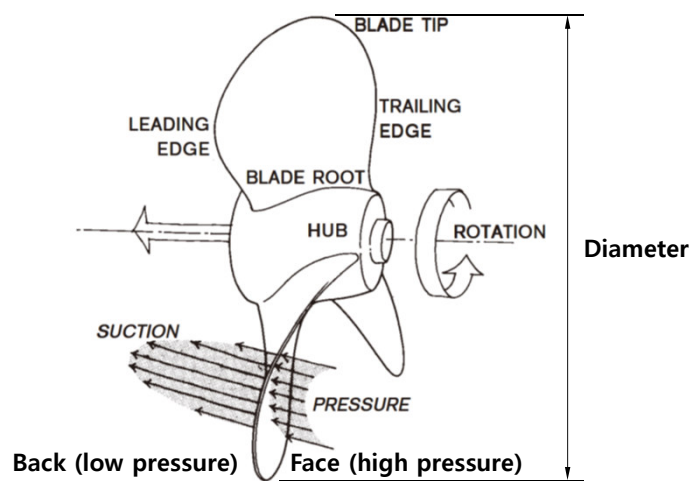
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Propeller Components



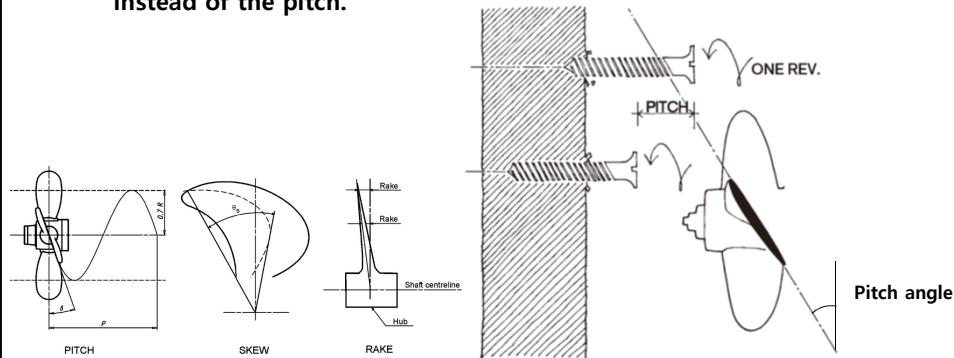
Principal Dimensions of a Propeller (1/4)

☒ Diameter



Principal Dimensions of a Propeller (2/4)

- ☑ Pitch (P_i): Movement forward for one turn of the propeller
 - One turn of the screw results in a movement forward which corresponds to the screw's pitch.
 - Similarly, the propeller has a pitch which can be regarded as the angle of the propeller blades (pitch angle).
 - Sometimes, the ratio of pitch and diameter (P_i/D_p) can be used instead of the pitch.



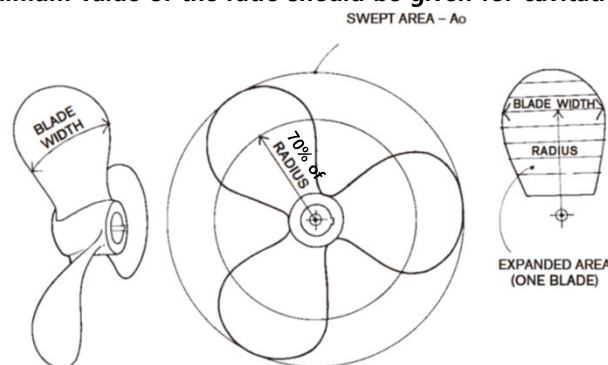
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Principal Dimensions of a Propeller (3/4)

- ☑ Expanded Area Ratio (A_E/A_O)
 - The ratio of the expanded area (A_E) and the swept area (A_O)
 - The smaller ratio is, the higher possibility of cavitation is. ➡ The minimum value of the ratio should be given for cavitation-free.



$$\bullet \text{ RELATIVE EXPANDED BLADE AREA } \frac{A_E}{A_O} = \frac{\text{TOTAL BLADE AREA } A_E}{\text{SWEPT AREA } A_O}$$

$$\text{or } \frac{A_E}{A_O} = 0.43 \times \text{No. of blades} \times \frac{\text{Blade width}}{\text{diameter}}$$

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[Reference] Blade Area Ratio (BAR) (1/2)

☑ Projected Area Ratio (PAR)

- It is the area of the outline as projected onto a surface below. Projected area ratio is the smallest of the three.

☑ Developed Area Ratio (DAR)

- It is the area of the blade outline if it could be untwisted (i.e., as if the whole blade were unattached from the hub and brought to zero pitch).

☑ Expanded Area Ratio (EAR)

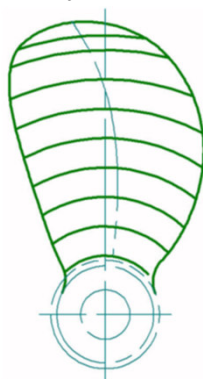
- It is what if the developed area could be flexibly unwrapped on a flat surface so that all sections were parallel. It is what is important to propeller designers, to treat the propeller blade like a wing. In other words, the expanded view converts the propeller from its helix to a flat plane. EAR is typically close in magnitude to DAR, and is often used interchangeably.

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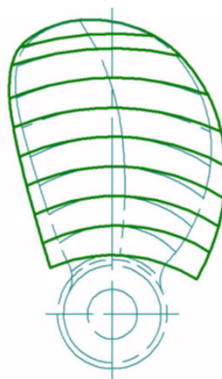
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[Reference] Blade Area Ratio (BAR) (2/2)

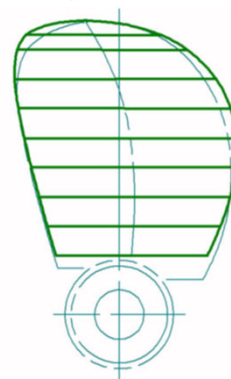
Projected area



Developed area



Expanded area



Conversion between each other

$$\frac{PAR}{DAR} = 1.067 - 0.229 \cdot \frac{P_i}{D_p}$$

$$\frac{EAR}{DAR} = 0.34 \left(2.75 + \frac{DAR}{Z} \right)$$

PAR becomes small if P_i/D_p becomes large.
 $PAR \propto DAR \propto EAR$ ($PAR < DAR < EAR$)
 Thus, high P_i/D_p and small PAR result in high possibility of cavitation.

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Principal Dimensions of a Propeller (4/4)

☑ Ship Speed (V_s)

- Ship speed at which the propeller efficiency (η_D) is to maximized.
- Actually, this speed can be different from the service speed (V_s) required by ship owner.
- The ideal case is that this speed is equal to the service speed (V_s).

[Reference] Advance Speed and Advance Ratio

- ☑ The difference between the propeller's pitch and the real movement is called slip and is necessary in order for the blades to grip and set the water in motion.
- ☑ This means that when the propeller has rotated one turn in the water it has only advanced part of the pitch (usually in the order of 75~95 %).
- ☑ At the same time, the ship will drag water with it, somewhat in front of the propeller. The water's speed reduction which can be 5~15% for pleasure boats is called "wake" and affects the measured value of the slip.
- ☑ **Advance speed:** Speed of advance per unit of time, typically **the water speed of the ship**.
- ☑ **Advance ratio:** The ratio between the distance the propeller moves forward through the fluid during one revolution, and the diameter of the propeller

Advance Speed

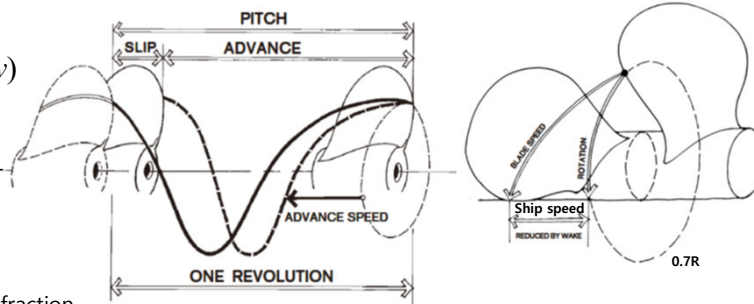
$$V_A = V_s \cdot (1 - w)$$

Advance Ratio

$$J = \frac{V_A \cdot (1/n)}{D_P}$$

$$= \frac{V_A}{n \cdot D_P}$$

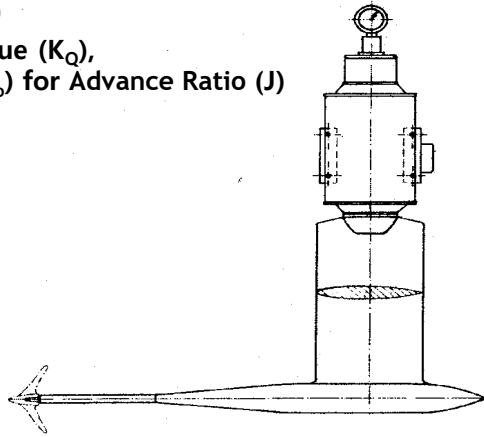
where, w : wake fraction



Propeller Open Water (POW) Test

- ✓ This test is carried out under ideal condition in which the propeller does not get disturbed by the hull.
- ✓ Given: Propeller Dimensions (D_p , P_i , A_E/A_O , z), Propeller RPM (n), Speed of Advance (V_A)
- ✓ Find: Thrust (K_T), Torque (K_Q), Propeller Efficiency (η_o) for Advance Ratio (J)

Uniform flow (V_A)

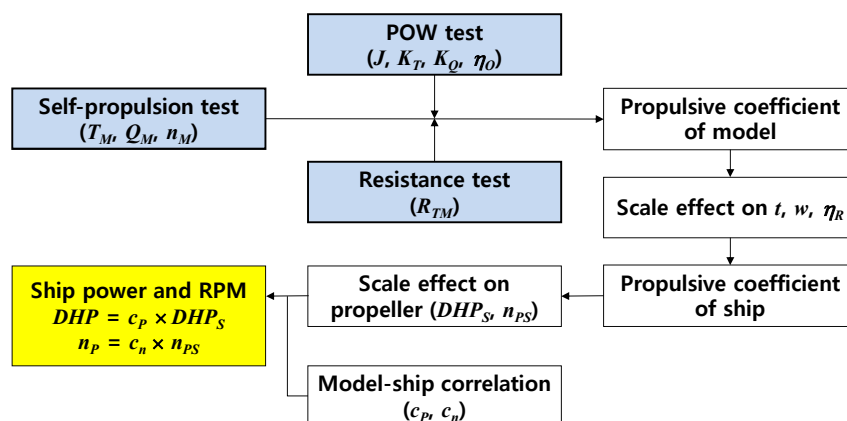


* η_R : The ratio between a propeller's efficiency attached to a ship (η_{OB}) and in open water (η_O), that is, $\eta_R = \eta_{OB}/\eta_O$
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Towing Tank Test



* η_R : The ratio between a propeller's efficiency attached to a ship (η_{OB}) and in open water (η_O), that is, $\eta_R = \eta_{OB}/\eta_O$
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Main Non-dimensional Coefficients of Propeller

From dimensional analysis:

① Thrust coefficient: $\frac{T}{\rho \cdot n^2 \cdot D_p^4} = K_T$

② Torque coefficient: $\frac{Q}{\rho \cdot n^2 \cdot D_p^5} = K_Q$

③ Advance ratio: $J = \frac{V_A}{n \cdot D_p}$
 $V_A = V_s \cdot (1 - w)$

④ Propeller efficiency: $\eta_o = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$
 (in open water)

V_s : Ship speed [m/s]

w : Wake fraction

T : Thrust of the propeller [kN]

Q : Torque absorbed by propeller [kN·m]

n : Number of revolutions [1/s]

D_p : Propeller diameter [m]

P_i : Propeller pitch [m]

V_A : Speed of advance [m/s]

ρ : Density of sea water (1,025) [kg/m³]

* Thrust deduction coefficient: The ratio of the resistance increase due to rotating of a propeller at after body of ship

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Propeller Efficiency (η_o)

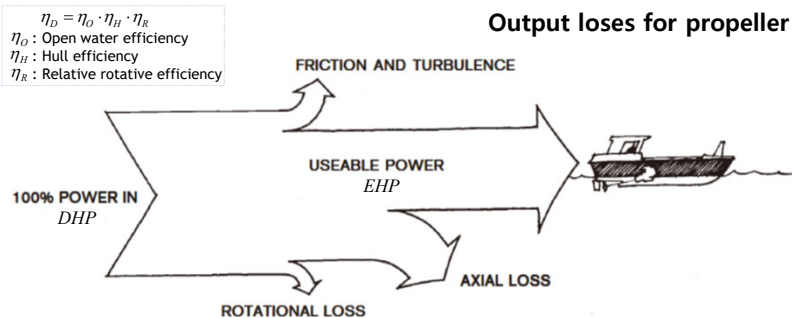
☑ Efficiency of a propeller itself.

☑ One of components of propulsive efficiency (η_D)

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

$DHP = \frac{EHP}{\eta_D}$ (η_D : Propulsive efficiency)

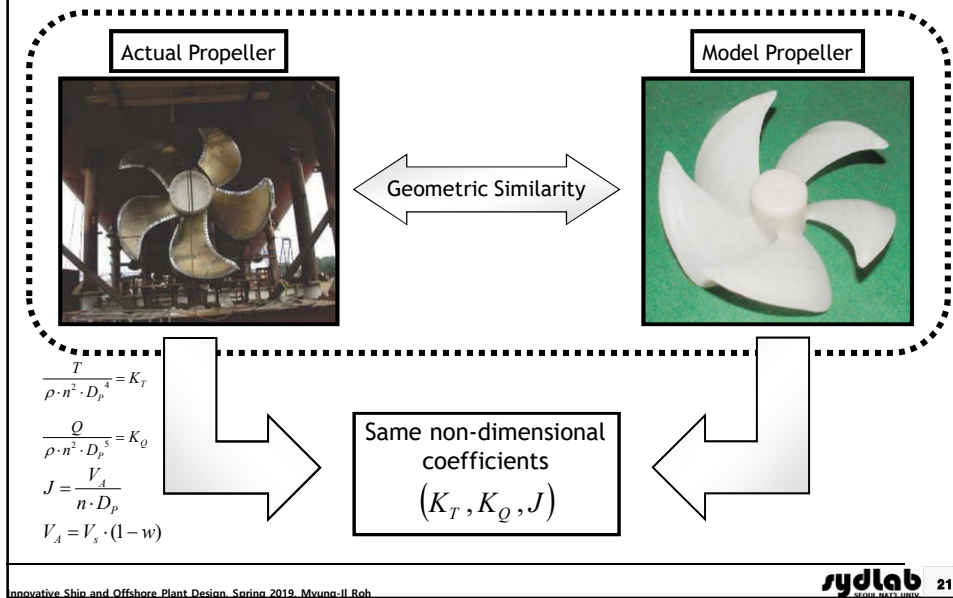
$\eta_D = \eta_o \cdot \eta_H \cdot \eta_R$
 η_o : Open water efficiency
 η_H : Hull efficiency
 η_R : Relative rotative efficiency



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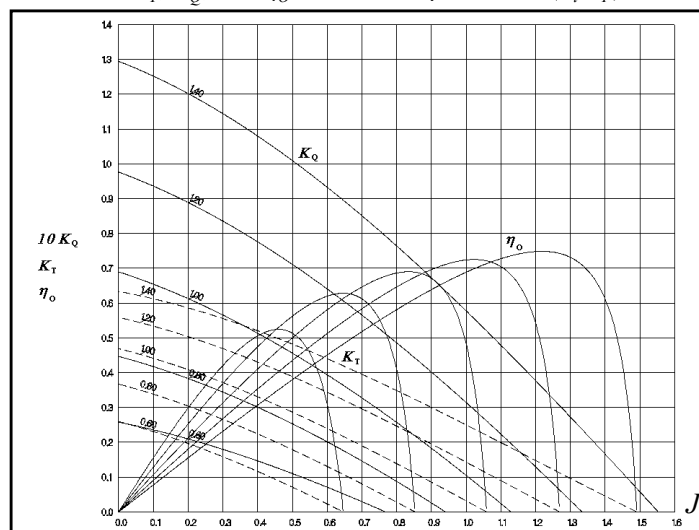
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POW Propeller Model



Propeller Open Water (POW) Curve

- Values of K_T , K_Q , and η_o at different pitch ratio (P/D_p)



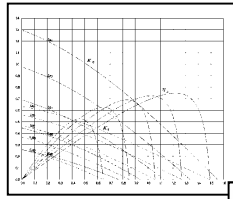
$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_p^4}$$

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D_p^5}$$

$$J = \frac{V_A}{n \cdot D_p}$$

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

Propeller Regression Polynomials for POW Curve



Regression Polynomial

Function of Advance Ratio, Pitch Ratio, Expanded Area Ratio, No. of Blades

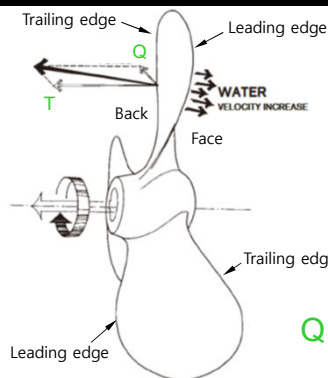
$$K_T \text{ and } K_Q = \sum C_{s,t,u,v} (J)^s (P/D_p)^t (A_E/A_o)^u z^v$$

K_T					K_Q				
$C_{s,t,u,v}$	s (J)	t (P/D_p)	u (A_E/A_o)	v (z)	$C_{s,t,u,v}$	s (J)	t (P/D_p)	u (A_E/A_o)	v (z)
+0.00880496	0	0	0	0	+0.00379368	0	0	0	0
-0.204554	1	0	0	0	+0.00886523	2	0	0	0
+0.166351	0	1	0	0	-0.032241	1	1	0	0
+0.158114	0	2	0	0	+0.00344778	0	2	0	0
-0.147581	2	0	1	0	-0.0408811	0	1	1	0
-0.481497	0	1	1	0	-0.108009	1	1	1	0
\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots	\vdots

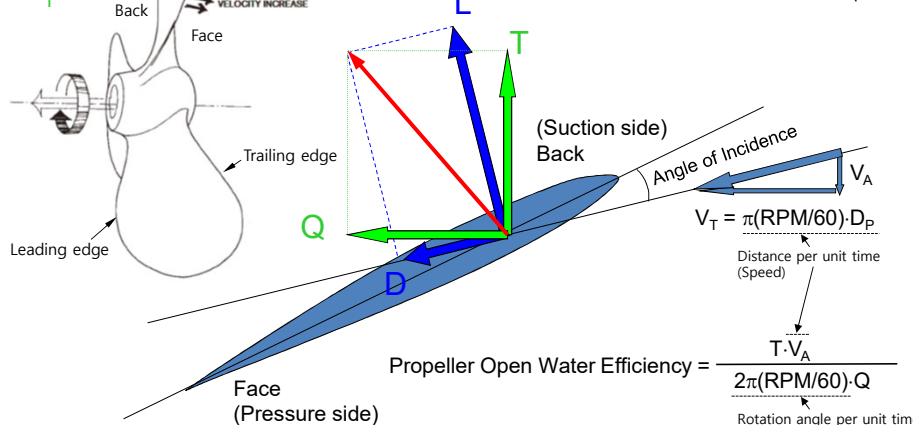
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Forces Acting on Propeller



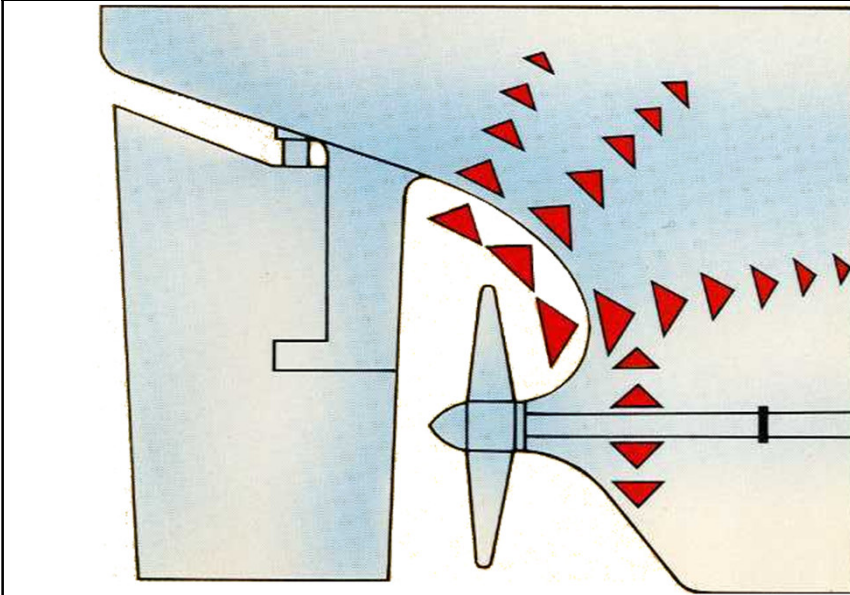
L: Lift force
D: Drag force
T: Thrust
Q: Torque



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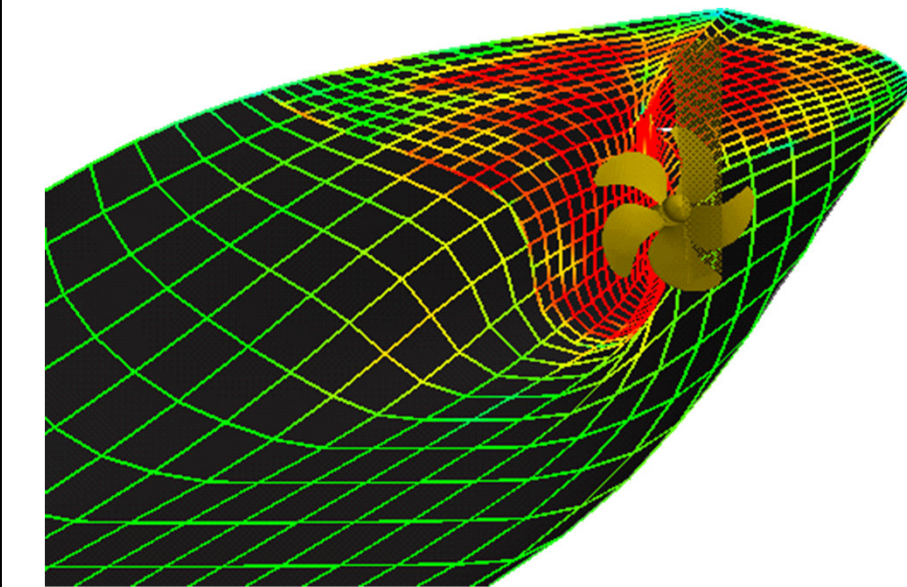
Hull Vibration Due to Propeller Rotation



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Pressure on Hull Due to Propeller Rotation

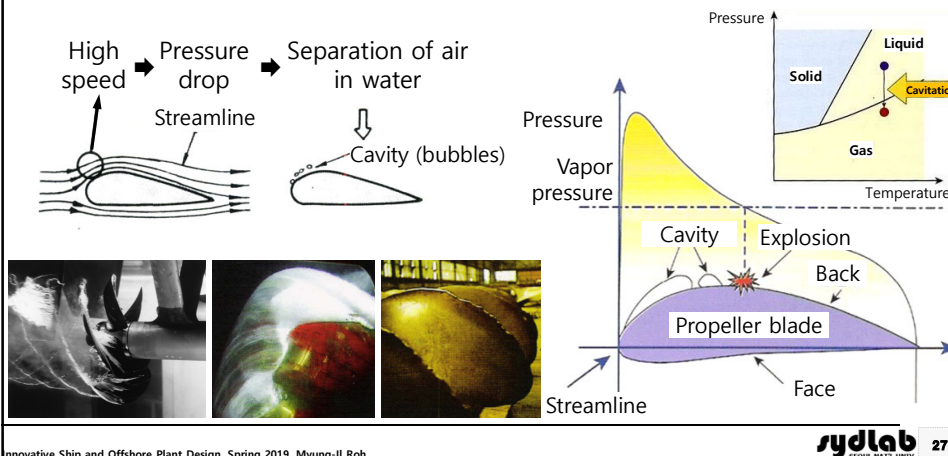


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Cavitation

- ☑ Cavities (small liquid-free zones, "bubble") are generated by
 , that is, rapid change of pressure around blades of
 propeller.
- ☑ Noise and vibration problem, Corrosion at the back of blades



2. Characteristics of Diesel Engine

Example of a Main Diesel Engine of Ship

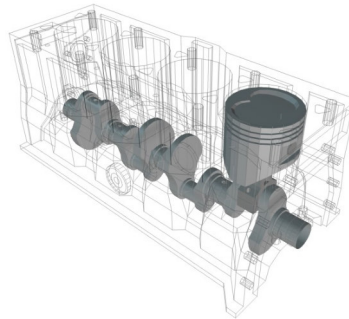
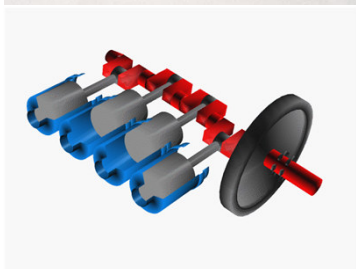


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Crank Shaft in the Main Engine

- ☑ Device to translate linear piston motion into rotation
- ☑ BHP (Brake Horse Power): Power which is delivered to crank shaft from the main engine



Crank shaft for 6-cylinder marine diesel engine



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Characteristics of Diesel Engine

☑ Brake Horse Power (BHP) of Diesel Engine

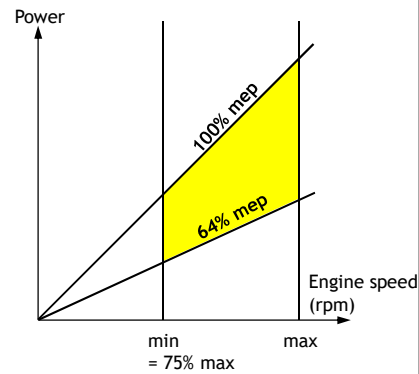
$$BHP = P_{me} \cdot L \cdot A \cdot n \cdot Z$$

Where, BHP: Brake Horse Power(kW)
 P_{me} : Mean Effective Pressure (kN / m^2)
 L : Piston Stroke (m)
 A : Piston Cross-Sectional Area (m^2)
 n : Number of Revolutions ($1 / s$)
 Z : Number of Cylinder

If A and Z are constant,

$$BHP = C_{DE} \cdot P_{me} \cdot n$$

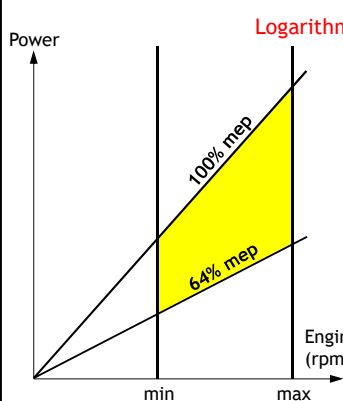
Therefore,



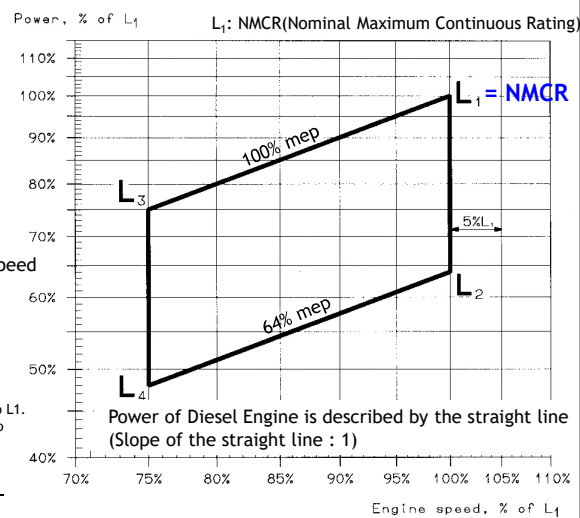
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Diesel Engine Layout Diagram



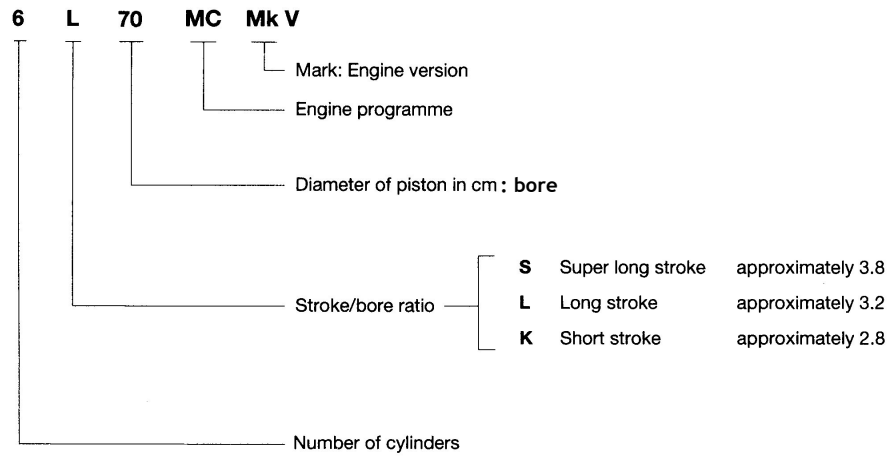
NMCR: Maximum power/speed combination of the chosen engine. This is the criterion of engine size, weight and price.



The NMCR point is the upper right corner of the layout diagram.
 In the case of MAN/B&W engine, the NMCR point refers to L1.
 And in the case of Waertsilae (Sulzer) engine, R1 refers to this point.

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Engine Type Identification of MAN/B&W* Diesel Engine

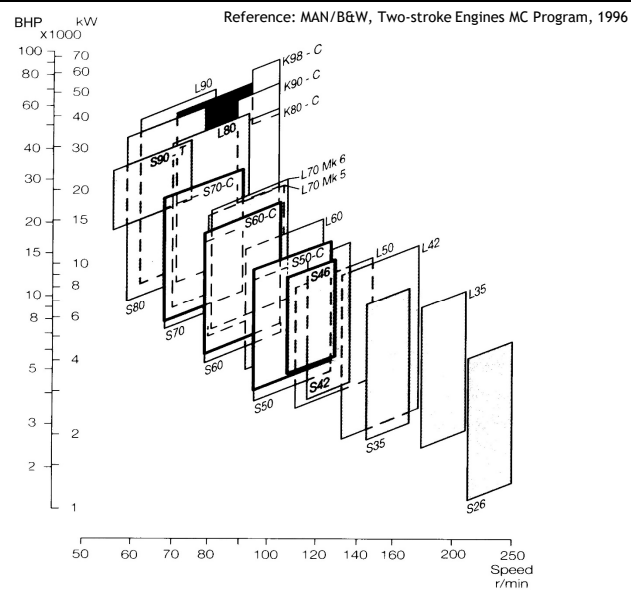


* Currently, MAN Diesel & Turbo

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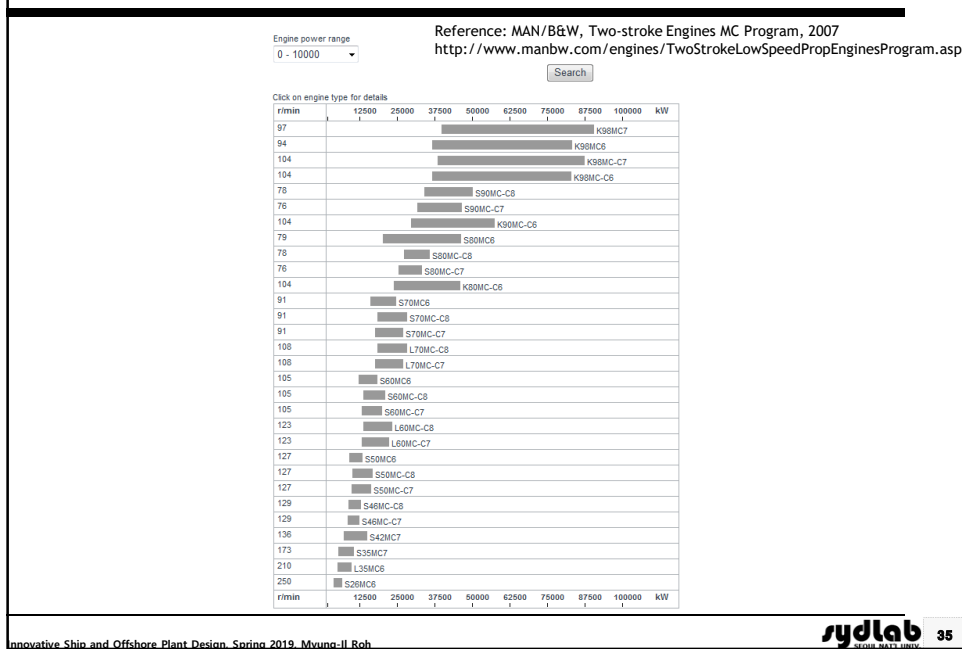
MAN/B&W Diesel Engine (1/2)



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MAN/B&W Diesel Engine (2/2)



MAN/B&W Two Stroke Low Speed Diesel Engine - S80MC6 Engine

Example) S80MC6 Engine: Bore 800 mm, Stroke 3,056 mm

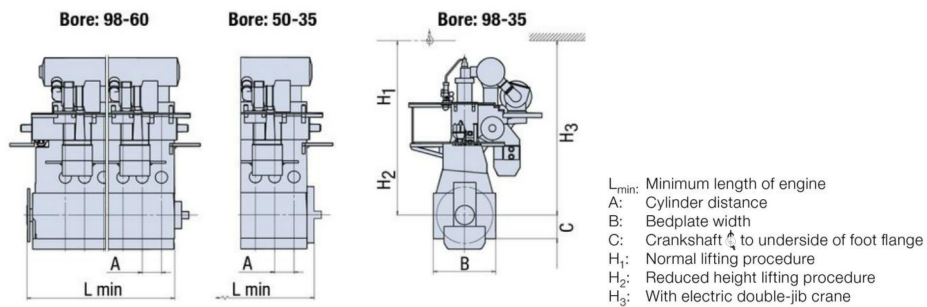
Bore: 800 mm, Stroke: 3056 mm

Main Data					
Layout points		L ₁	L ₂	L ₃	L ₄
Speed	r/min	79	79	59	59
mep	bar	18.0	11.5	18.0	11.5
		kW	kW	kW	kW
5S80MC6		18200	11650	13600	8700
6S80MC6		21840	13980	16320	10440
7S80MC6		25480	16310	19040	12180
8S80MC6		29120	18640	21760	13920
9S80MC6		32760	20970	24480	15660
10S80MC6		36400	23300	27200	17400
11S80MC6		40040	25630	29920	19140
12S80MC6		43680	27960	32640	20880
Specific Fuel Oil Consumption (SFOC)					
g/kWh		167	155	167	155
Lubricating and Cylinder Oil Consumption					
Lubricating oil			0.15 g/kWh		
Cylinder oil			0.7 g/kWh		

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MAN/B&W Two Stroke Low Speed Diesel Engine - S80MC6 Engine



Main dimensions & weights

Cyl. No	5	6	7	8	9	10	11	12
L_{min} mm	9953	11377	12581	14005	16719	18143	19567	20991
H_1 mm	14125	14125	14125	14125	14125	14125	14125	14125
H_2 mm	13250	13250	13250	13250	13250	13250	13250	13250
H_3 mm	12925	12925	12925	12925	12925	12925	12925	12925
A mm	1736	1736	1736	1736	1736	1736	1736	1736
B mm	4824	4824	4824	4824	4824	4824	4824	4824
E mm	1424	1424	1424	1424	1424	1424	1424	1424
Dry Mass t*	777	885	996	1105	1223	1343	1458	1564

*The mass can vary up to 10% depending on the design and options chosen.

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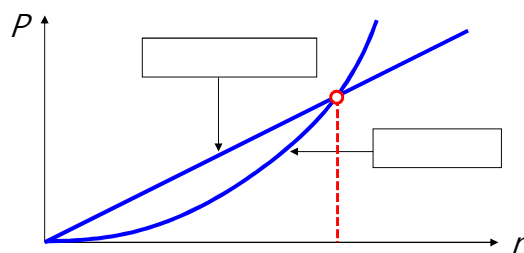
Matching the Powers and RPMs of Propeller and Diesel Engine

Output Power of a Diesel Engine

$$P_{D.E.} = P_{me} \cdot A \cdot L \cdot n \cdot Z$$

Power Absorbed by a Propeller

$$P_{prop.} = 2\pi\rho \cdot n^3 \cdot D_p^5 \cdot K_Q = c_3 \cdot n^3$$



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Sea Margin

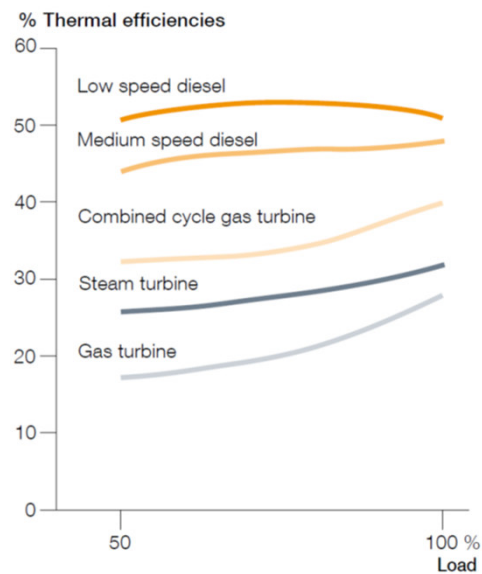
- ☑ If the weather is bad, the resistance will increase compared to that at calm weather conditions. When the necessary engine power is to be determined, it is therefore normal to .
- ☑ Sea margin is not an exact value, but usually expressed by the additional margin determined by shipyard or owner. The so-called sea margin is about of the power at calm water.
- ☑ Note: **Light running propeller** (increase of propeller rpm) refers to the margin of propeller rpm.
 - Light running propeller margin (RPM margin)
 - MAN/B&W Engine: 2.5~5.0%
 - Waertsilae (Sulzer) Engine: 3.5~5.3%

NCR, Engine Margin, DMCR

- ☑ The normal continuous rating (*NCR*) is the power at which the engine is .
- ☑ The owner prefers that engine is operated continuously at **maximum 85~90% of DMCR** to get the margin of speed.

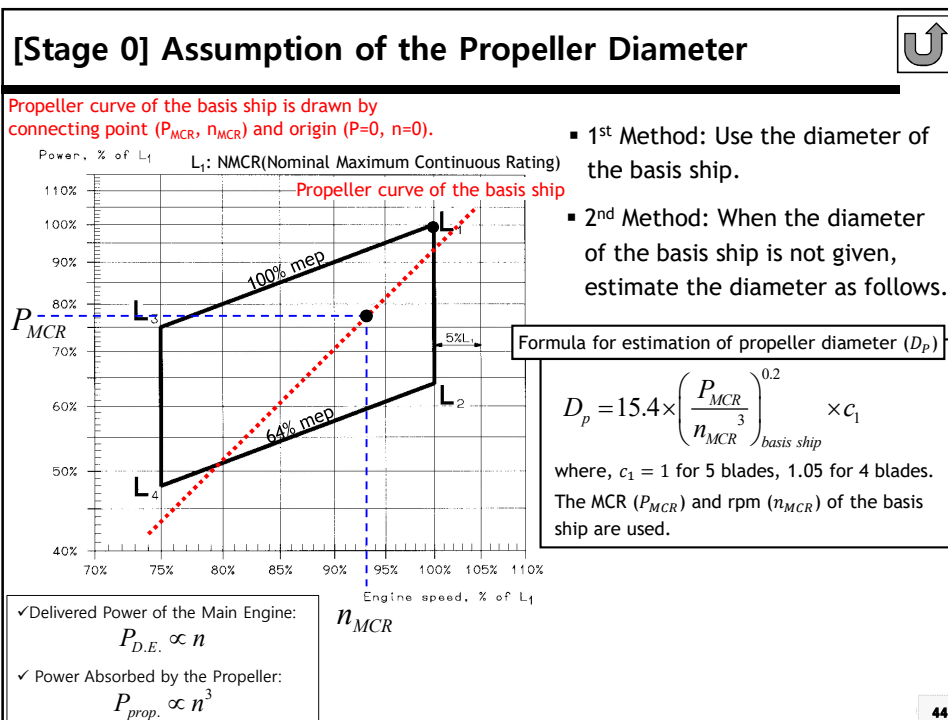
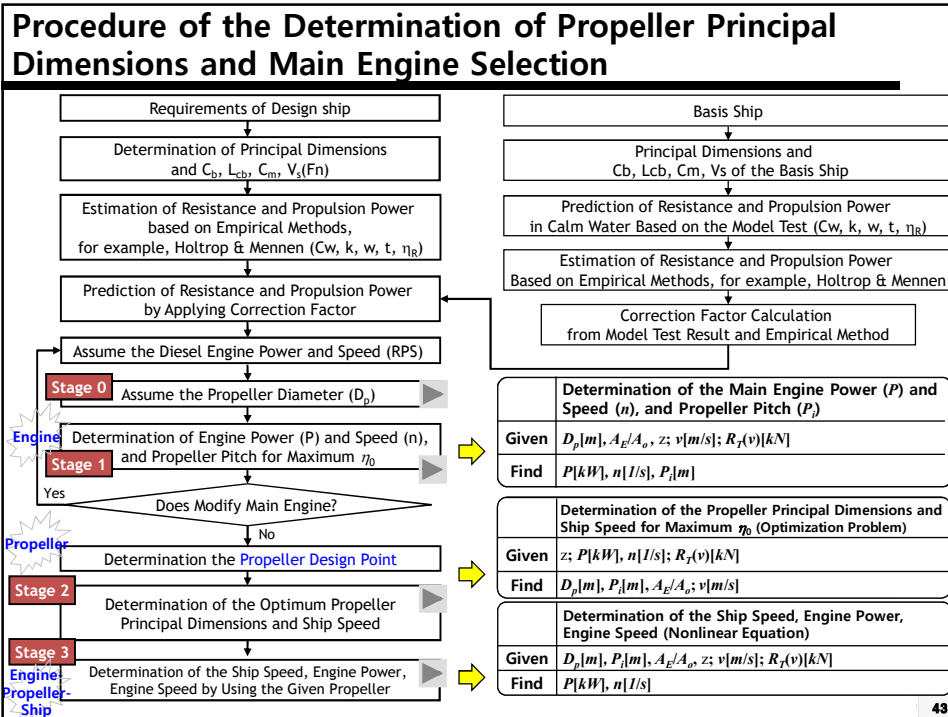
$$DMCR = \frac{NCR}{\text{Engine Margin}}$$

[Appendix] Thermal Efficiency According to Engine Type



* Reference: MAN B&W, Two-stroke Low Speed Diesel Engines for Independent Power Producers and Captive Power Plants, 2009
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3. Procedure of the Determination of Propeller Principal Dimensions and Main Engine Selection



[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (1/10)

Given	D_p [m]: Propeller diameter (from basis ship) A_E/A_O : Expanded area ratio z : Number of blades V_s [m/s]: Ship speed $R_T(V)$ [kN]: Resistance varied with ship speed
Find	P_i [m]: Propeller pitch P [kW]: Delivered power to propeller from main engine ($P=DHP \cdot \eta_R$) n [1/s]: Engine speed

※ η_R should be considered to change the delivered power from after body into the delivered power without hull because the POW curve was generated from propeller in open water.

Flowchart:

```

graph TD
    A[Requirements of Design ship] --> B[Determination of Principal Dimensions and CB, LBP, Cm, VL(Fn)]
    B --> C[Estimation of Resistance and Propulsion Power based on Empirical Methods, for example, Holtrop & Mennen (Cw, ks, w, t,  $\eta_R$ )]
    C --> D[Prediction of Resistance and Propulsion Power by Applying Correction Factor]
    D --> E[Assume the Diesel Engine Power and Speed (RPS)]
    E --> F[Stage 0: Assume the Propeller Diameter (Dp)]
    F --> G[Stage 1: Determination of Engine Power (P) and Speed (n), and Propeller Pitch for Maximum  $\eta_0$ ]
    G --> H{Does Modify Main Engine?}
    H -- Yes --> E
    H -- No --> I[Determination the Propeller Design Point]
    I --> J[Stage 2: Determination of the Optimum Propeller Principal Dimensions and Ship Speed]
    J --> K[Stage 3: Determination of the Ship Speed, Engine Power, Engine Speed by Using the Given Propeller]
  
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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (2/10)

Given	D_p [m], A_E/A_O , z ; V_s [m/s]; $R_T(V)$ [kN]
Find	P_i [m] ; P [kW], n [1/s]

- Condition 1: The propeller absorbs the torque delivered by main engine.

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q \cdots (1)$$

Torque delivered by the
main engine

=

Torque absorbed
by the propeller

where, $P = DHP \cdot \eta_R$

$\eta_R = \frac{Q_a}{Q}$

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

[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (3/10)

Given	D_P [m], A_E/A_{O_P} , z ; V_s [m/s]; $R_T(V)$ [kN]
Find	P_i [m] ; P [kW], n [1/s]

▪ Condition 2:

$$\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_P^4 \cdot K_T \dots (2)$$

The thrust which is required to propel the ship for the given speed

=

The thrust which is produced by the propeller

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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (4/10)

Given	D_P [m], A_E/A_{O_P} , z ; V_s [m/s]; $R_T(V)$ [kN]
Find	P_i [m] ; P [kW], n [1/s]

By Using Optimization Method

3 Unknowns

2 Equations

Nonlinear optimization problem

Objective Function: Maximum η_0

$$\eta_0 = \frac{T \cdot V_A}{DHP} = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$$

Solve the nonlinear optimization problem.
Then the main engine power (P) and the speed of main engine (n) of the design ship are determined.

- Condition 1: The propeller absorbs the torque delivered by main engine.

$$\text{where, } P = DHP \cdot \eta_R$$

- Condition 2: The propeller should produce the required thrust at a given ship speed.

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[Appendix] Optimization by Using Lagrange Multiplier Method (1/2)

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q$$

$$G_1(P_i, n, P) = \frac{P}{2\pi n} - \rho \cdot n^2 \cdot D_p^5 \cdot K_Q = 0 \quad \dots\dots (a)$$

$$\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T$$

$$G_2(P_i, n) = \frac{R_T}{1-t} - \rho \cdot n^2 \cdot D_p^4 \cdot K_T = 0 \quad \dots\dots (b)$$

$$F(P_i, n) = \eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \quad \dots\dots (c)$$

[Appendix] Optimization by Using Lagrange Multiplier Method (2/2)

$$G_1(P_i, n, P) = \frac{P}{2\pi n} - \rho \cdot n^2 \cdot D_p^5 \cdot K_Q \quad (a) \quad G_2(P_i, n) = \frac{R_T}{1-t} - \rho \cdot n^2 \cdot D_p^4 \cdot K_T \quad (b) \quad F(P_i, n) = \eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \quad (c)$$

▪ Lagrange function:

$$H(P_i, n, P) = F(P_i, n) + \lambda_1 \cdot G_1(P_i, n, P) + \lambda_2 \cdot G_2(P_i, n) \quad \dots\dots (d)$$

▪ Stationary point of H: $\nabla H(P_i, n, P, \lambda_1, \lambda_2) = 0$

$$\frac{\partial H}{\partial P_i} = \frac{J}{2\pi} \cdot \frac{\{(\frac{\partial K_T}{\partial P_i}) \cdot K_Q - (\frac{\partial K_Q}{\partial P_i}) \cdot K_T\}}{K_Q^2} + \lambda_1 \cdot (-\rho \cdot n^2 \cdot D_p^5 \cdot \frac{\partial K_Q}{\partial P_i}) + \lambda_2 \cdot (-\rho \cdot n^2 \cdot D_p^4 \cdot \frac{\partial K_T}{\partial P_i}) \quad \dots\dots (e)$$

$$\begin{aligned} \frac{\partial H}{\partial n} = \frac{1}{2\pi} \cdot \frac{\partial J}{\partial n} \cdot \frac{K_T}{K_Q} + \frac{J}{2\pi} \cdot \frac{\{(\frac{\partial K_T}{\partial n}) \cdot K_Q - (\frac{\partial K_Q}{\partial n}) \cdot K_T\}}{K_Q^2} + \lambda_1 \cdot (-\frac{P}{2 \cdot \pi \cdot n^2} - \rho \cdot 2 \cdot n \cdot D_p^5 \cdot K_Q - \rho \cdot n^2 \cdot D_p^5 \cdot \frac{\partial K_Q}{\partial n}) \\ + \lambda_2 \cdot (-\rho \cdot 2 \cdot n \cdot D_p^4 \cdot K_T - \rho \cdot n^2 \cdot D_p^4 \cdot \frac{\partial K_T}{\partial n}) = 0 \quad \dots\dots (f) \end{aligned}$$

$$\frac{\partial H}{\partial P} = \lambda_1 \cdot \frac{1}{2 \cdot \pi \cdot n} = 0 \quad \dots\dots (g)$$

$$\frac{\partial H}{\partial \lambda_1} = \frac{P}{2\pi n} - \rho \cdot n^2 \cdot D_p^5 \cdot K_Q = 0 \quad \dots\dots (h)$$

$$\frac{\partial H}{\partial \lambda_2} = \frac{R_T}{1-t} - \rho \cdot n^2 \cdot D_p^4 \cdot K_T = 0 \quad \dots\dots (i)$$

5 Equations: (e), (f), (g), (h), (i)

5 Unknowns: $P_i, n, P, \lambda_1, \lambda_2$

➔ This can be solved by using numerical method, for example, Newton-Raphson Method.

[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (5/10)

Given	D_p [m], A_E/A_{O_p} , z ; V_s [m/s]; $R_T(V)$ [kN]
Find	P_i [m]; P [kW], n [1/s]

Calculation By Hand

3 Unknowns
2 Equality constraints

Condition 1: The propeller absorbs the torque delivered by main engine.

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q \cdots (1)$$

where, $P = DHP \cdot \eta_R$

Condition 2: The propeller should produce the required thrust at a given ship speed.

$$\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T \cdots (2)$$

Nonlinear indeterminate problem

Objective Function: Find Maximum η_0 .

$$\eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$$

First assume the initial value of the propeller pitch and then determine the main engine power (P) and the speed of main engine (n) by iteration to satisfy the conditions (1) and (2).

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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (6/10)

1	Given	D_p [m], A_E/A_{O_p} , z ; V_s [m/s]; $R_T(V)$ [kN]
	Find	P_i [m]; P [kW], n [1/s]

Calculation By Hand

2 Express the Condition 2 as $K_T = c_2 J^2$.

Condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T$,

Advance Ratio: $J = \frac{V_A}{n \cdot D_p} \Rightarrow n = \frac{V_A}{J \cdot D_p}$

$$K_T = \frac{R_T}{(1-t)\rho D_p^4} \cdot \frac{1}{n^2} \Rightarrow \frac{R_T}{(1-t)\rho D_p^4} \cdot \left(\frac{J \cdot D_p}{V_A} \right)^2$$

$$K_T = \frac{R_T}{(1-t)\rho D_p^2 V_A^2} J^2$$

$K_T = c_2 J^2$, $c_2 = \frac{R_T}{(1-t)\rho D_p^2 V_A^2}$

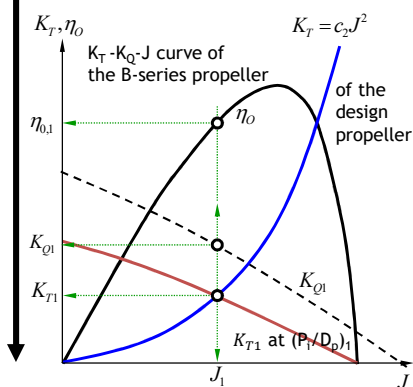
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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (7/10) Calculation By Hand

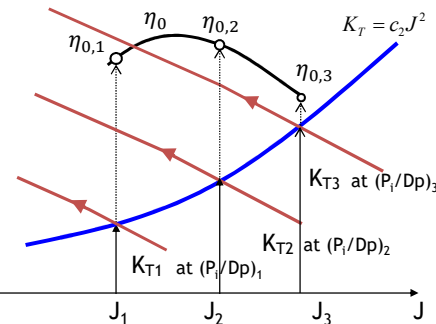
3

By using the POW-Curve (K_T - K_Q - J) of the series propeller data, for example, B-series propeller data, calculate the intersection point (J_1 , K_{T1}) between the $K_T = c_2 J^2$ of the design propeller and the K_T - K_Q - J curve of the B-series propeller at a given pitch/diameter ratio ($P_i/D_p)_1$. And read the K_{Q1} and η_{01} at J_1 .

Repeat this procedure by varying pitch/diameter ratio



P_i/D_p	J	η_0	K_T	K_Q
$(P_i/D_p)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_p)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_p)_3$	J_3	η_{03}	K_{T3}	K_{Q3}



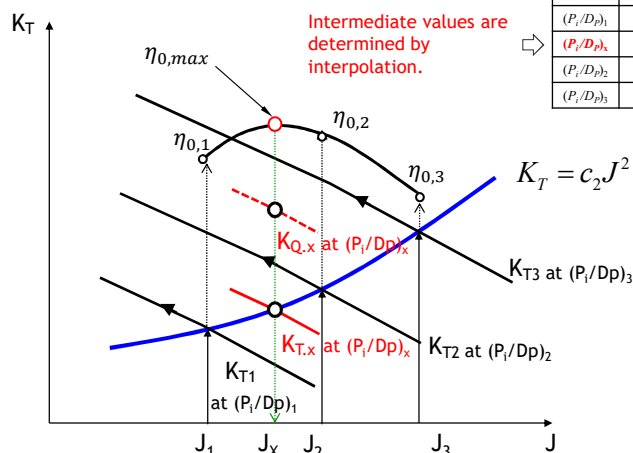
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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (8/10) Calculation By Hand

4

By using the set of K_T , K_Q , η_0 (varied with pitch ratio), determine J_x to maximize η_0 and pitch/diameter ratio $(P_i/D_p)_x$ at J_x .



P_i/D_p	J	η_0	K_T	K_Q
$(P_i/D_p)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_p)_x$	J_x	η_{0x}	K_{Tx}	K_{Qx}
$(P_i/D_p)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_p)_3$	J_3	η_{03}	K_{T3}	K_{Q3}

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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (9/10) Calculation By Hand

5 By using J_x from Step 4, calculate n_x .

$$J_x = \frac{V_A}{n_x \cdot D_P} \Rightarrow n_x = \frac{V_A}{D_P \cdot J_x}$$

6 By using $K_{Q,x}$ from the Condition 1 and Step 4, calculate P_x .

$$\frac{P_x}{2\pi m} = \rho \cdot n_x^2 \cdot D_P^5 \cdot K_{Q,x} \Rightarrow P_x = 2\pi \cdot \rho \cdot n_x^3 \cdot D_P^5 \cdot K_{Q,x}$$

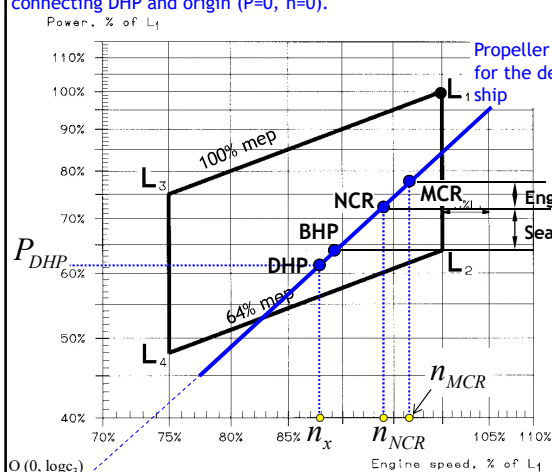
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[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (10/1)

Propeller curve for the design ship is drawn by connecting DHP and origin ($P=0, n=0$).

$P_x (= DHP \cdot \eta_R)$ is determined from optimization.



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

$$NCR = BHP(1 + S.M / 100)$$

$$MCR = NCR / E.M$$

E.M: Engine Margin

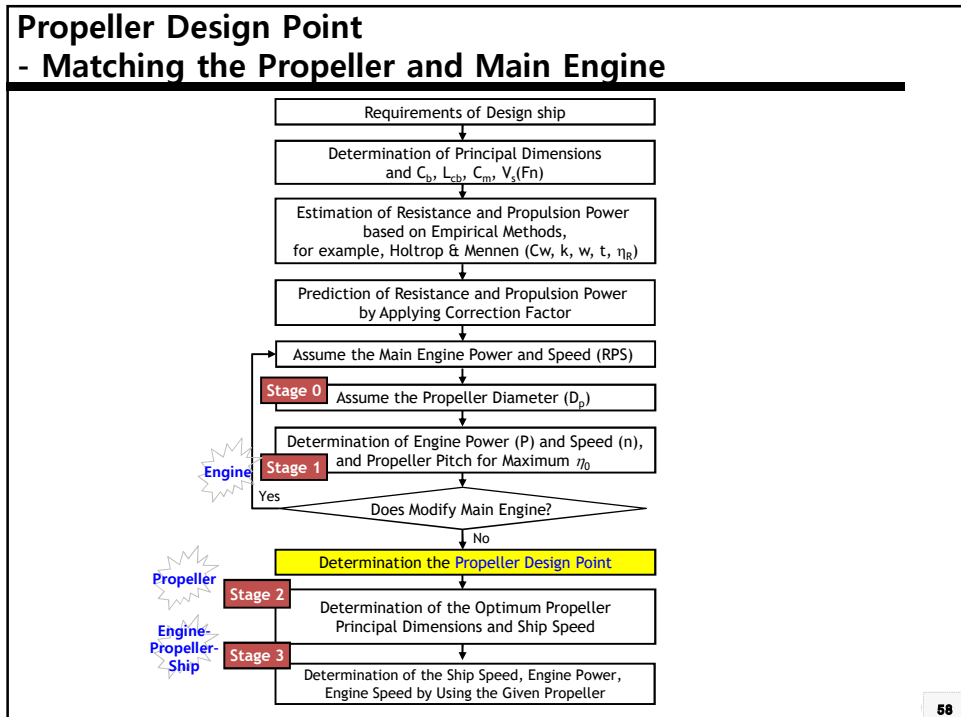
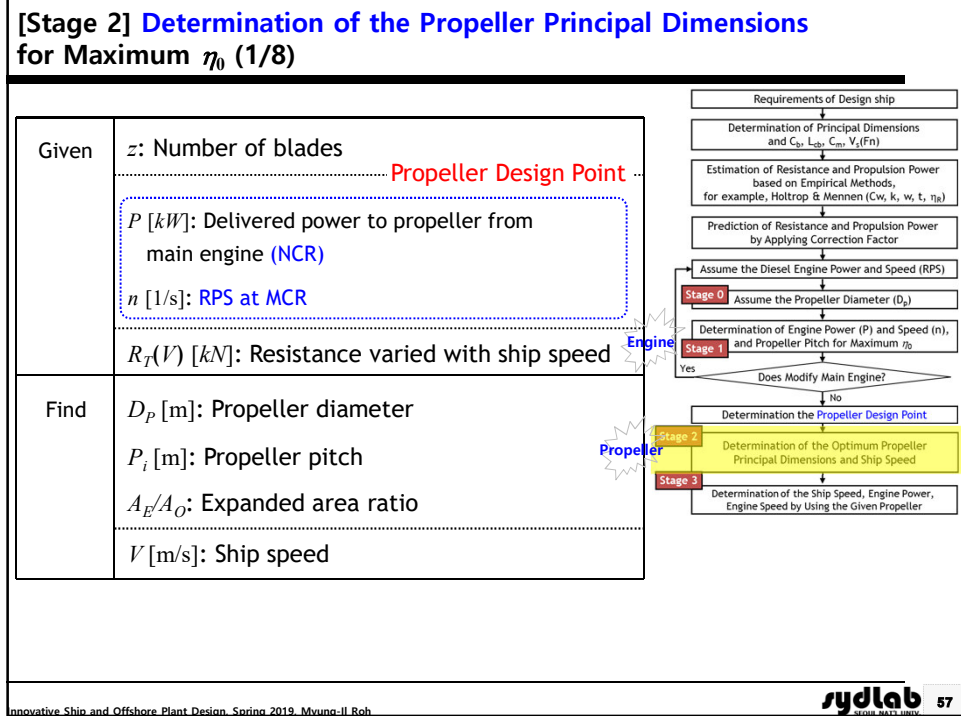
$$n_{NCR} = \sqrt[3]{\frac{NCR}{c_3}}, (P = c_3 \cdot n^3)$$

$$n_{MCR} = \sqrt[3]{\frac{MCR}{c_3}}$$

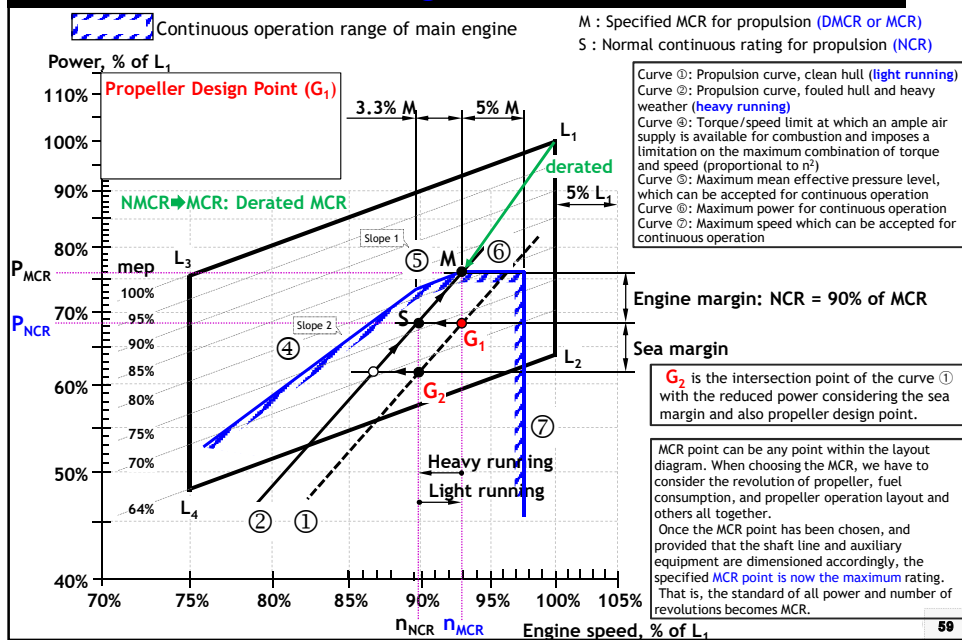
By using P and n required by the propeller, determine the NCR and MCR of the design ship. Check whether the NCR and MCR are in the layout diagram of main engine.

after b

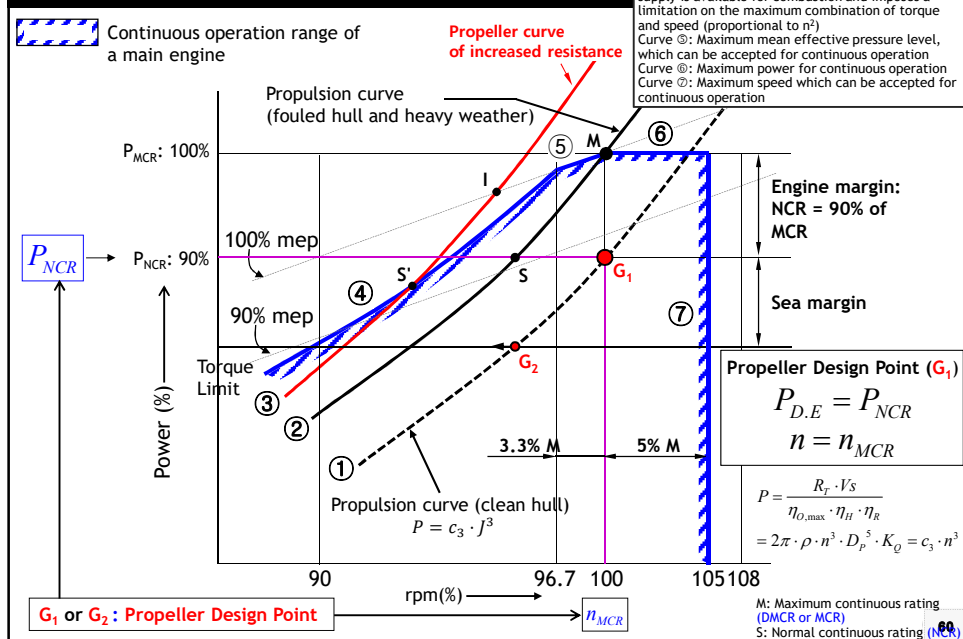
If the NCR and MCR are not in the layout diagram of main engine, select another engine.



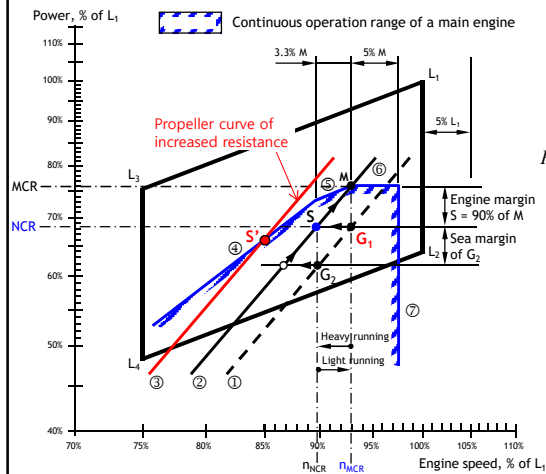
Matching the Propeller and Main Engine in the Load Diagram in Logarithmic Scales



Matching the Propeller and Main Engine in the Load Diagram



Propeller Design Point



$$J = \frac{V_A}{n \cdot D_P} \Rightarrow V_A = n \cdot D_P \cdot J$$

If J is constant, engine speed is proportional to ship speed.

Propeller Design Point (G_1)

$$P_{D.E} = P_{NCR}$$

$$n = n_{MCR}$$

$$P = \frac{R_T \cdot V_S}{\eta_{O,max} \cdot \eta_H \cdot \eta_R} = 2\pi \cdot \rho \cdot n^3 \cdot D_P^5 \cdot K_Q = c_3 \cdot n^3$$

The reason why the propeller design point should be G_1 .

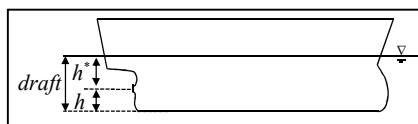
- If the propeller is designed at the point S , the propeller curve is the curve ②. When the resistance of ship increases with time, then the propeller curve will move to the curve ③. Thus the propeller and engine match at the point S' which is not NCR. This means the engine power of NCR cannot be delivered to the propeller, which results in reduction of ship speed.

- If the propeller is designed at the point G_1 , the propeller curve is the curve ①. When the resistance of ship becomes larger with time, the propeller curve ① will move to the curve ② so that the propeller operates at the point S (NCR).

[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (2/8)

- Given: Engine Power, Engine Speed

Given	z ; P_{NCR} [kW], n_{MCR} [1/s]; $R_T(V)$ [kN]
Find	D_P [m], P_i [m], A_E/A_O ; V [m/s]



Condition 3:

calculated by using one of the two formulas.

① Formula given by Keller

$$A_E / A_O \geq K + \frac{(1.3 + 0.3z) \cdot T}{D_P^2 \cdot (\rho_0 + \rho g h^* - p_v)}$$

or ② Formula given by Burrill

$$A_E / A_O \geq F \cdot (\eta_0 / (1/J)^2) / \{1 + 4.826(1/J)^2\} \cdot (1.067 - 0.229 \cdot P_i / D_P)$$

$$F = \frac{\eta_R \cdot B_P^2 \cdot V_A^{1.25}}{287.4(10.18 + h)^{0.625}}$$

$$B_P = n \cdot P^{0.5} / V_A^{2.5}$$

$$v_A = v \cdot (1 - w) [\text{knots}]$$

$$P = DHP \cdot \eta_R [HP]$$

$$n [rpm]$$

can be

K: Single Screw = 0.2, Double Screw = 0.1

$P_0 \cdot P_v = 99.047$ [kN/m²] at 15°C Sea water

h^* : Shaft Immersion Depth [m]

h : Shaft Center Height (height from the baseline) [m]

T : Propeller Thrust [kN]

[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (3/8)

By Using Optimization Method

Given	$z ; P_{NCR} [kW], n_{MCR} [1/s] ; R_T(V) [kN]$
Find	$D_p [m], P_i [m], A_E/A_O ; V [m/s]$

- Condition 1:** The propeller absorbs the torque delivered by main engine.

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q$$
 where, $P = DHP \cdot \eta_R$
- Condition 2:** The propeller should produce the required thrust at a given ship's speed.

$$\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T$$
- Condition 3:** Required minimum expanded blade area ratio for non-cavitating criterion.

$$A_E / A_O \geq K + \frac{(1.3 + 0.3z) \cdot T}{D_p^2 \cdot (p_0 + \rho g h^* - p_v)}$$

4 Unknowns
2 Equality constraints
1 Inequality constraint

Nonlinear indeterminate problem

Objective Function: Maximum η_0

$$\eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q}$$

Propeller diameter (D_p), pitch (P_i), expanded blade area ratio (A_E/A_O), and ship speed are determined to maximize the objective function by iteration.

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[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (4/8)

Calculation By Hand

- 1 Assume the Expanded Area Ratio (A_E / A_O).
 A_O : Swept or disc area ($\pi D_p^2/4$)
 A_E : Expanded blade area
 Assume that the expanded area ratio of the propeller of the design ship is the same as that of the basis ship.
- 2 Assume the ship speed V .
- 3 Express the Condition 1 as $K_Q = c_4 J^5$.

$$\text{Condition 1: } \frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q,$$

$$J = \frac{V_A}{n \cdot D_p} \Rightarrow \frac{nJ}{V_A} = \frac{1}{D_p}$$

$$K_Q = \frac{P}{2\pi n^3 \rho} \cdot \frac{1}{D_p^5} = \frac{P}{2\pi n^3 \rho} \cdot \left(\frac{nJ}{V_A} \right)^5$$

$$= \frac{P \cdot n^2}{2\pi \rho V_A^5} J^5 = c_4 J^5, \quad \left(c_4 = \frac{P \cdot n^2}{2\pi \rho V_A^5} \right)$$

$$K_Q = c_4 J^5$$

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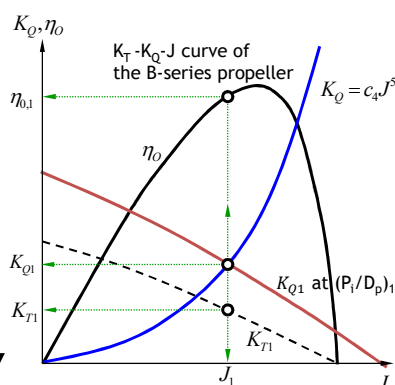
[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (5/8)

Calculation By Hand

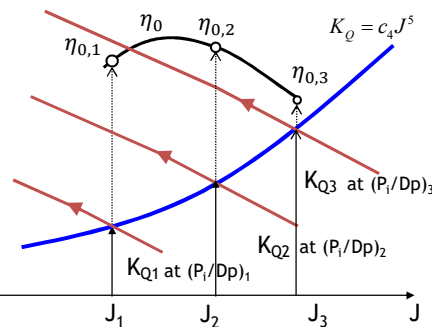
4

By using the POW-Curve (K_T - K_Q - J) of the series propeller data, for example, B-series propeller data, calculate the intersection point (J_1 , K_{Q1}) between the $K_Q = c_d J^5$ of the design propeller and the K_T - K_Q - J curve of the B-series propeller at a given pitch/diameter ratio (P_i/D_p)₁. And read the K_{T1} and η_{01} at J_1 .

Repeat this procedure by varying pitch/diameter ratio



P_i/D_p	J	η_0	K_T	K_Q
$(P_i/D_p)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_p)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_p)_3$	J_3	η_{03}	K_{T3}	K_{Q3}



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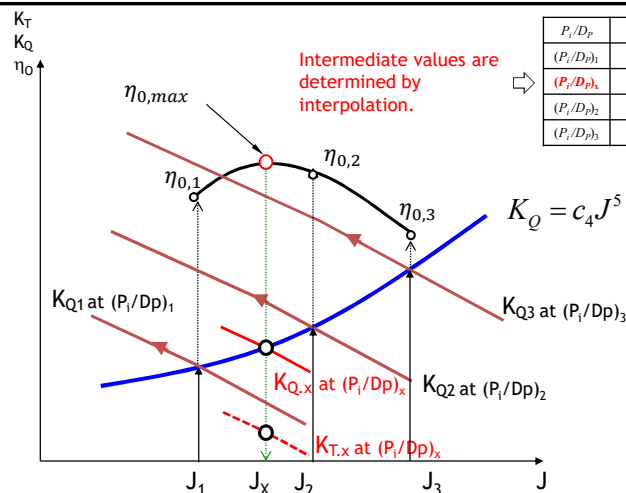
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[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (6/8)

Calculation By Hand

5

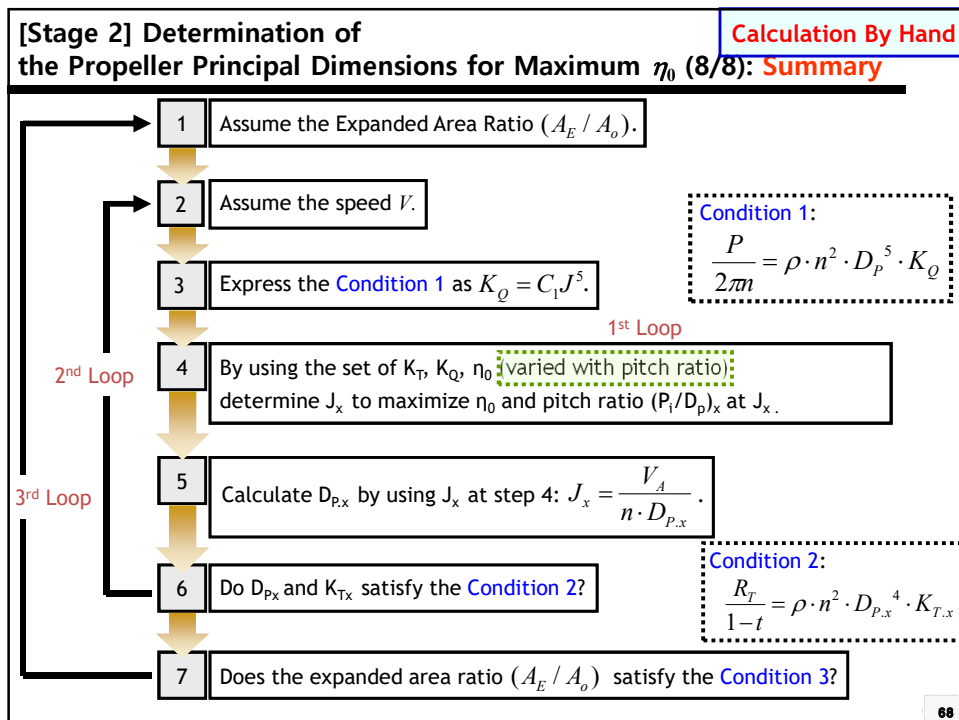
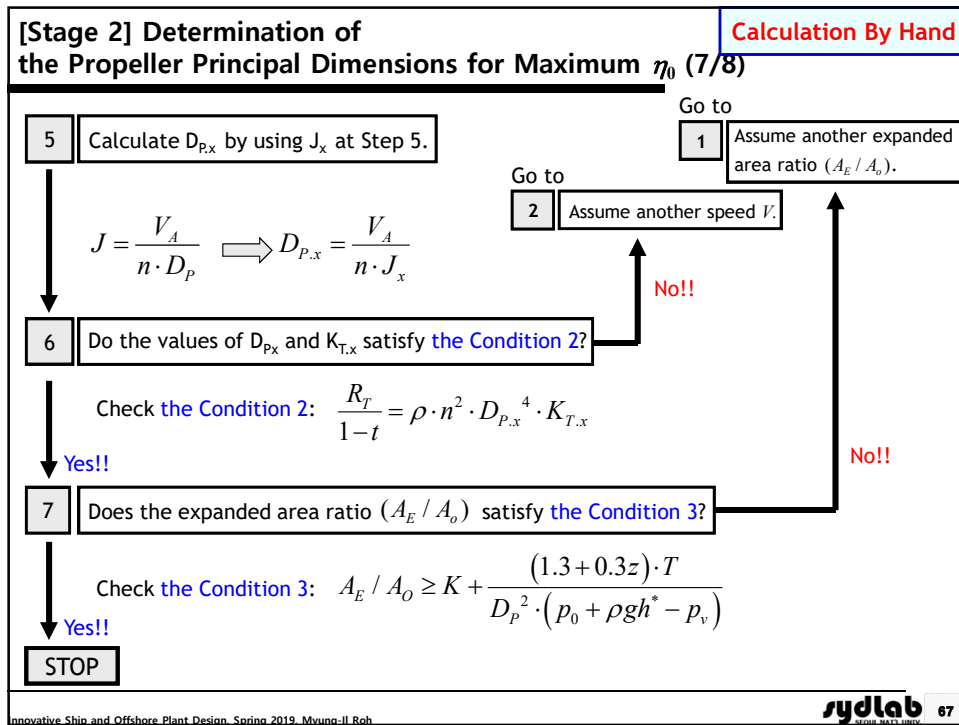
By using the set of K_T , K_Q , η_0 (varied with pitch ratio), determine J_x to maximize η_0 and pitch/diameter ratio (P_i/D_p)_x at J_x .



P_i/D_p	J	η_0	K_T	K_Q
$(P_i/D_p)_1$	J_1	η_{01}	K_{T1}	K_{Q1}
$(P_i/D_p)_x$	J_x	η_{0x}	K_{Tx}	K_{Qx}
$(P_i/D_p)_2$	J_2	η_{02}	K_{T2}	K_{Q2}
$(P_i/D_p)_3$	J_3	η_{03}	K_{T3}	K_{Q3}

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Relations between Propeller and Main Engine

- ☑ The relations between rpm, efficiency of the propeller, and size of the main engine.
 - If the rpm of a propeller decreases, the optimum diameter of the propeller becomes larger, and the efficiency of the propeller increases.
 - If the rpm of a propeller increases, the optimum diameter of the propeller becomes smaller, and the efficiency of the propeller decreases.
 - However, if the rpm of the propeller increases, we can select smaller main engine.
- ☑ Factors considered for selecting main engine
 - Efficiency of the propeller
 - Weight of the engine
 - Arrangement of the engine room
 - Initial investment cost (for large and low-speed diesel engine: about 180 \$/PS in 1998)
 - Operation cost

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_p^4}$$

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D_p^5}$$

$$J = \frac{V_A}{n \cdot D_p}$$

Assume that J is constant.
If n decreases, D_p increases.
Then, K_Q becomes smaller than K_T .
Finally, η_o increases.

$$\eta_o = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} = \frac{TV_A}{2\pi nQ}$$

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[Appendix] Selection of Alternative MCR by Using Constant Ship Speed Lines (1/2)

- ☑ For a given ship with the same number of propeller blades, but different propeller diameter, the following relation between necessary power and propeller speed can be assumed.

$$P_2 = P_1 \cdot \left(\frac{n_2}{n_1} \right)^\alpha$$

where,

P: Propulsion power (DHP)

n: Propeller speed

α : Constant ship speed coefficient

(0.25~0.30 for bulk carriers and tankers, 0.15~0.25 for reefers and container vessels)

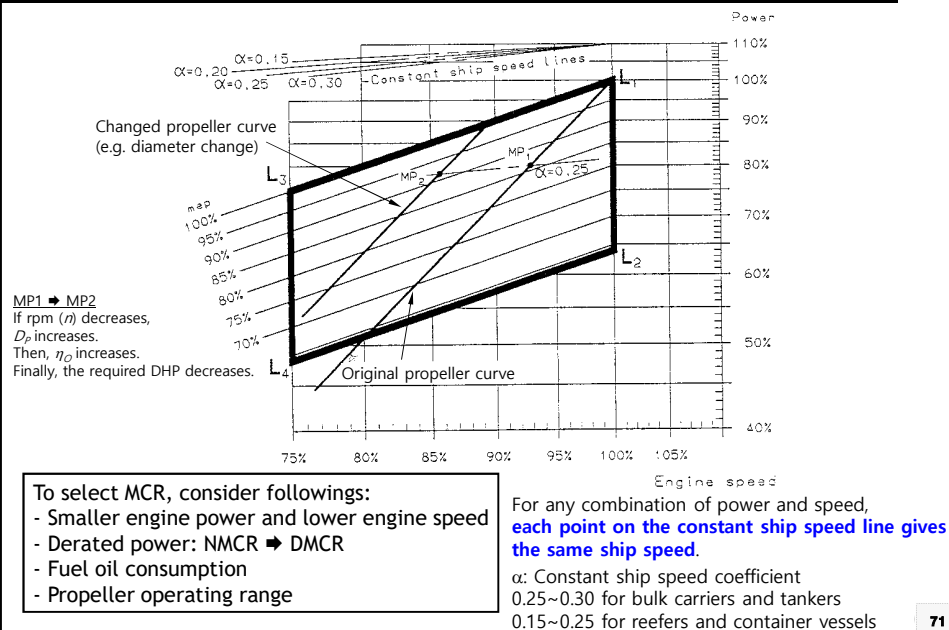
Cf. for the given propeller (the same number of propeller blades and the same propeller diameter)

$$P_{prop.} \propto n^3$$

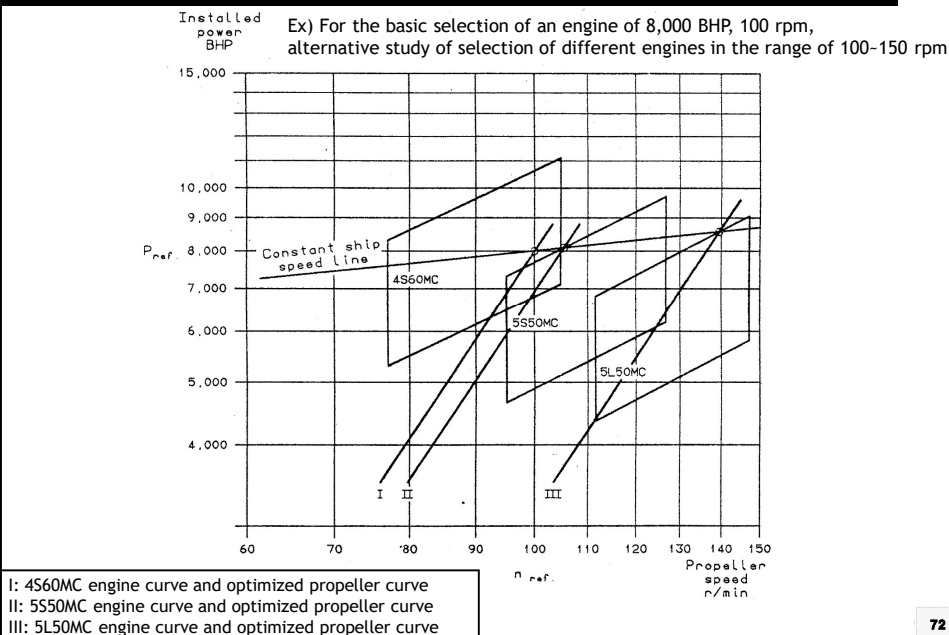
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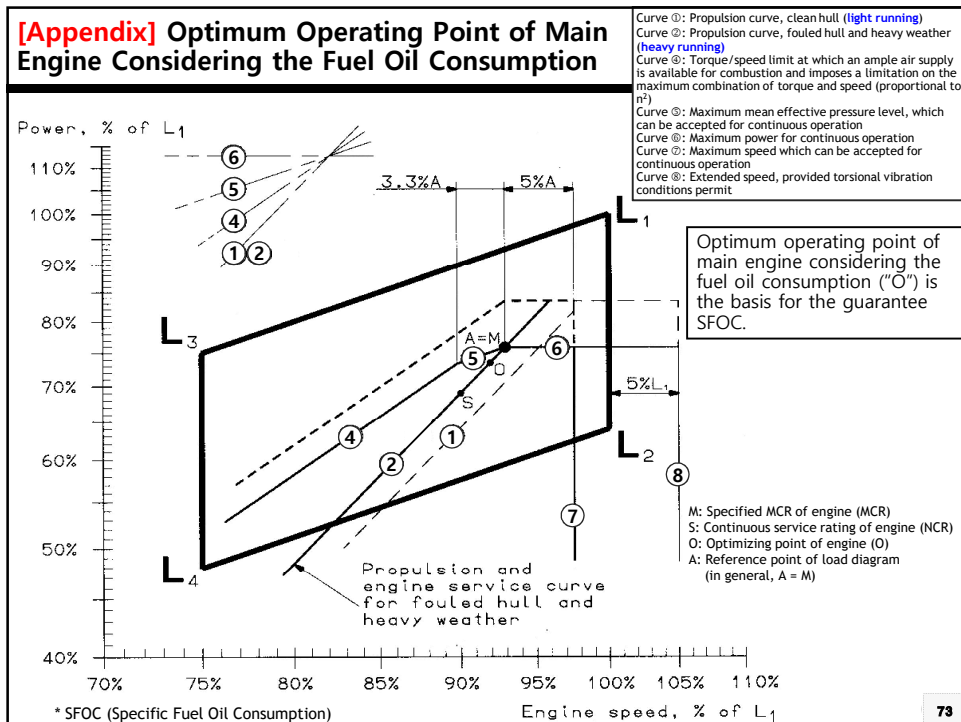
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[Appendix] Selection of Alternative MCR by Using Constant Ship Speed Lines (2/2)



[Appendix] Selection of Alternative Engine Type by Using Constant Ship Speed Lines





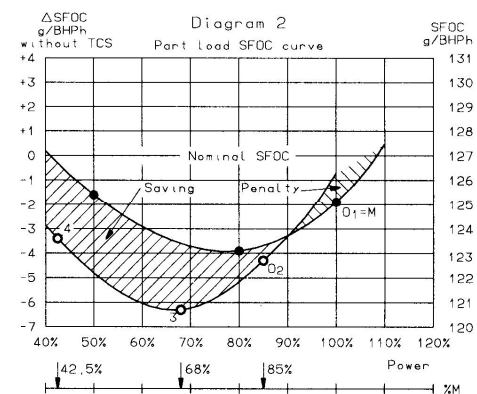
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[Appendix] Example of Selection of Optimum Point "O" Considering SFOC (1/2)

Data at nominal MCR (L_1):		Data of optimising point (O):	
Power: 100% (L_1)	21,360 BHP	O_1	O_2
Speed: 100% (L_1)	106 r/min	Power: 100% of (O)	17,730 BHP 15,100 BHP
Nominal SFOC	127 g/BHP	Speed: 100% of (O)	95.4 r/min 90.1 r/min
		SFOC found:	125 g/BHP 122.6 g/BHP

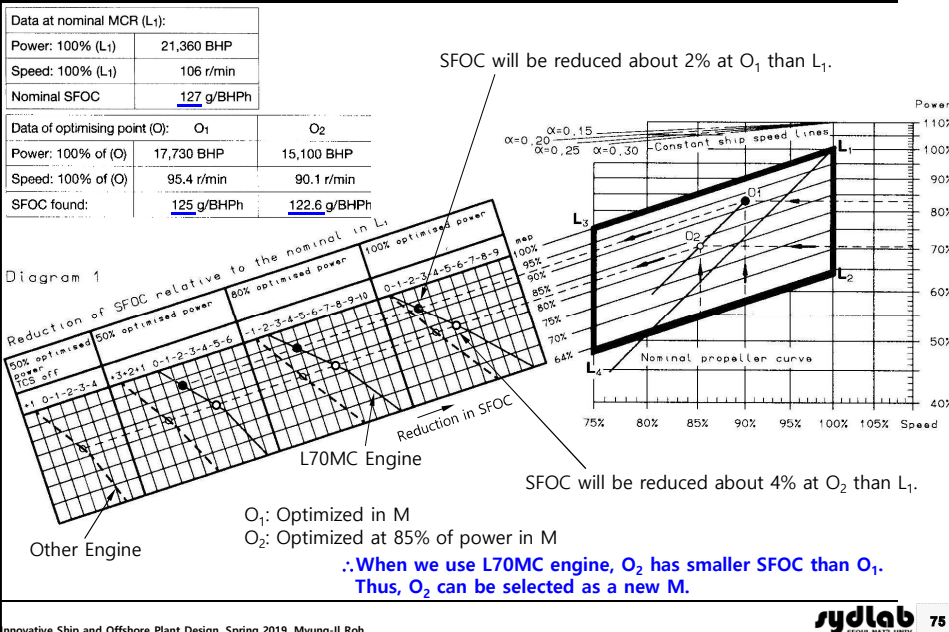
L70MC	Nominal SFOC in g/BHP at nominal MCR (L_1)
Conventional turbochargers	127
High efficiency turbochargers	125
High efficiency turbochargers and TCS	min. 122

O_1 : Optimised in M
 O_2 : Optimised at 85% of power in M
 Point 3: is 80% of $O_2 = 0.80 \times 0.85$ of M = 68% M
 Point 4: is 50% of $O_2 = 0.50 \times 0.85$ of M = 42.5% M



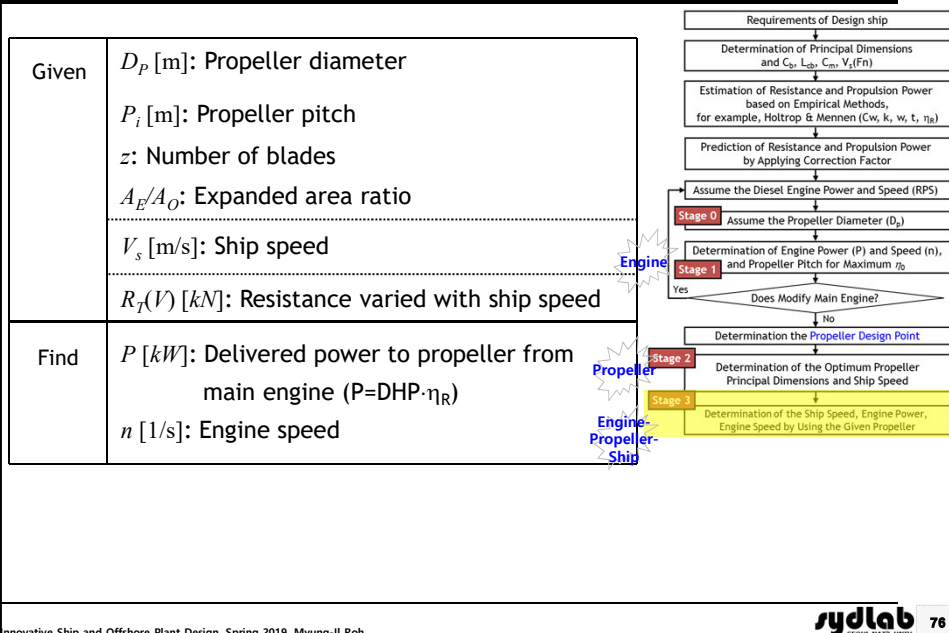
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[Appendix] Example of Selection of Optimum Point "O" Considering SFOC (2/2)



[Stage 3] Determination of Ship Speed, Engine Power, Engine Speed by Using the Determined Propeller (1/5)

- The propeller principal dimensions have been determined.



[Stage 3] Determination of Ship Speed, Engine Power, Engine Speed by Using the Determined Propeller (2/5)

Given	$D_p, P_i, z, A_E/A_O; V_s [\text{m/s}]; R_T(V) [\text{kN}]$
Find	$P [\text{kW}], n [1/\text{s}]$

- Condition 1: The propeller absorbs the torque delivered by main engine.

$$\frac{P}{2\pi n} = \rho \cdot n^2 \cdot D_p^5 \cdot K_Q \cdots (1)$$

where, $P = DHP \cdot \eta_R$

- Condition 2: The propeller should produce the required thrust for a given ship speed.

$$\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T \cdots (2)$$

2 Unknowns

2 Equations



Nonlinear determinate problem

➔ Not an optimization problem

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[Stage 3] Determination of Ship Speed, Engine Power, Engine Speed by Using the Determined Propeller (3/5)

Calculation By Hand

- 1 Express the Condition 2 as $K_T = c_2 J^2$.

Condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_p^4 \cdot K_T$, Advance Ratio: $J = \frac{V_A}{n \cdot D_p} \Rightarrow n = \frac{V_A}{J \cdot D_p}$

$$K_T = \frac{R_T}{(1-t)\rho D_p^4} \cdot \frac{1}{n^2} \Rightarrow \frac{R_T}{(1-t)\rho D_p^4} \cdot \left(\frac{J \cdot D_p}{V_A} \right)^2$$

$$K_T = \frac{R_T}{(1-t)\rho D_p^2 V_A^2} J^2$$



$$c_2 = \frac{R_T}{(1-t)\rho D_p^2 V_A^2}$$

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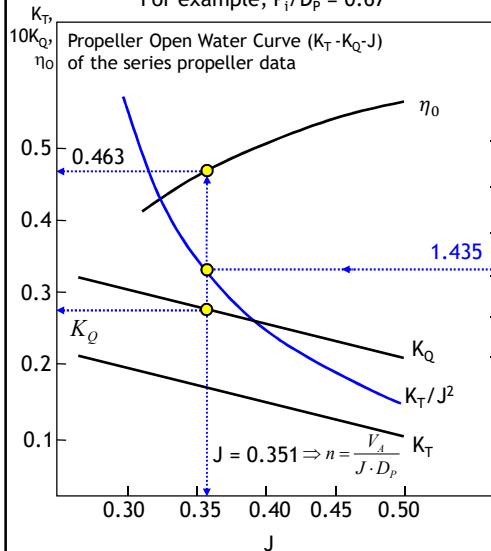
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[Stage 3] Determination of Ship Speed, Engine Power, Engine Speed by Using the Determined Propeller (4/5)

Calculation By Hand

2 Calculate P (DHP· η_R) and n.

For example, $P_i/D_p = 0.67$



Propeller Open Water Curve (K_T - K_Q -J) of the series propeller data, for example, B-series propeller data

Condition 2 $\frac{K_T}{J^2} = c_2$, $c_2 = \frac{R_T}{(1-t)\rho D_p^2 V_A^2}$

$P = DHP \cdot \eta_R$ Condition 1

$DHP = 2\pi \cdot \rho \cdot n^3 \cdot D_p^5 \cdot K_Q / \eta_R$

$= \frac{EHP}{\eta_D} = \frac{R_T \cdot V_s}{\eta_{O,max} \cdot \eta_H \cdot \eta_R}$

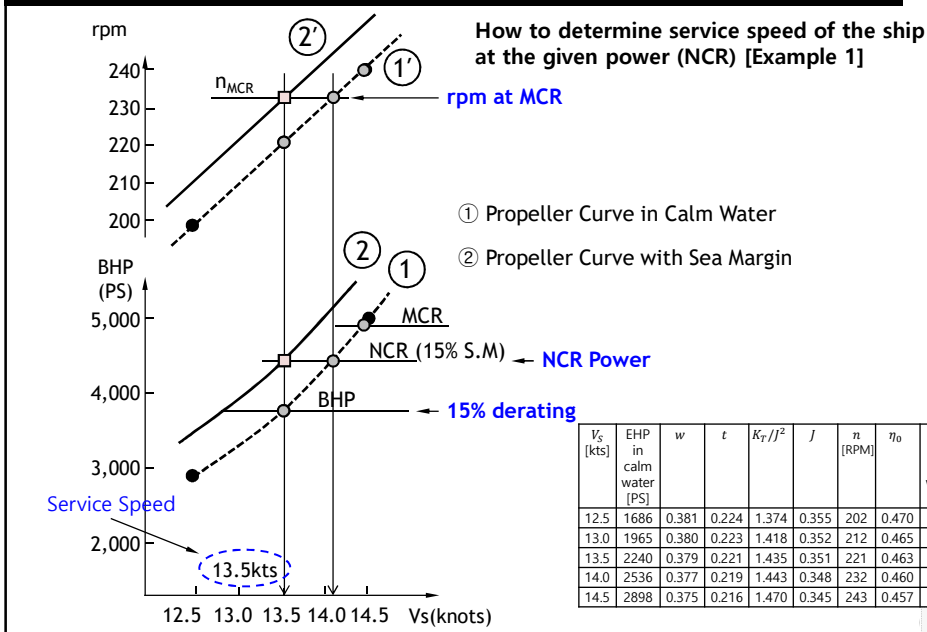
$BHP = \frac{DHP}{\eta_T}$ η_T : Transmission efficiency

V_s [kts]	EHP in calm water [PS]	w	t	K_T/J^2	J	n [RPM]	η_0	BHP in calm water
12.5	1686	0.381	0.224	1.374	0.355	202	0.470	2867
13.0	1965	0.380	0.223	1.418	0.352	212	0.465	3367
13.5	2240	0.379	0.221	1.435	0.351	221	0.463	3844
14.0	2536	0.377	0.219	1.443	0.348	232	0.460	4376
14.5	2898	0.375	0.216	1.470	0.345	243	0.457	5020

Repeat this procedure by varying ship speed. 79

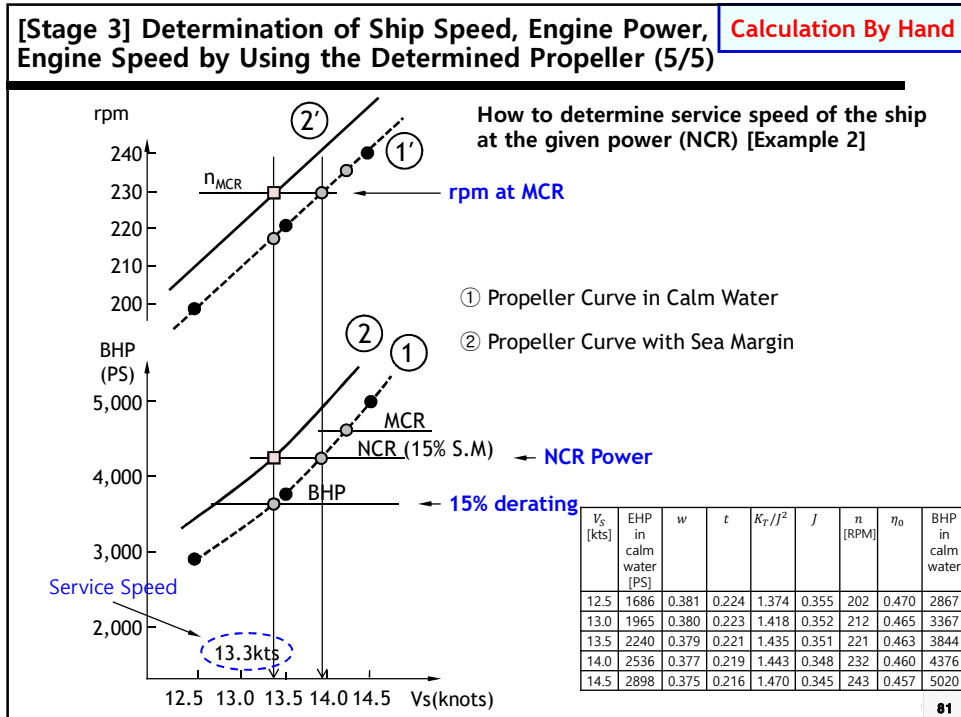
[Stage 3] Determination of Ship Speed, Engine Power, Engine Speed by Using the Determined Propeller (5/5)

Calculation By Hand



V_s [kts]	EHP in calm water [PS]	w	t	K_T/J^2	J	n [RPM]	η_0	BHP in calm water
12.5	1686	0.381	0.224	1.374	0.355	202	0.470	2867
13.0	1965	0.380	0.223	1.418	0.352	212	0.465	3367
13.5	2240	0.379	0.221	1.435	0.351	221	0.463	3844
14.0	2536	0.377	0.219	1.443	0.348	232	0.460	4376
14.5	2898	0.375	0.216	1.470	0.345	243	0.457	5020

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7.4 Example of Determination of Propeller Principal Dimensions and Main Engine Selection (for Step 2)

Example of Determination of Propeller Principal Dimensions (1/9)

Example) Determination of Propeller Principal Dimensions of
DWT 7,400 ton/400TEU Container Ship

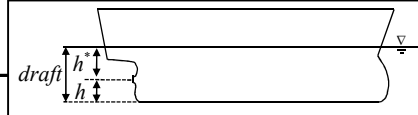
Given Data

Power and Speed of Diesel Engine

- MCR = 4,500 PS, at 220 rpm
- NCR = 85% MCR, at 208 rpm
- Propeller RPM : 220 rpm
- Blade Number (z): 4

Miscellaneous Data

- h (Shaft Center Height): 2.35 [m]
- h^* (Shaft Immersion Depth): 4.15 [m]
- Draft: 6.5 [m]
- Sea Margin = 15%



Model Test Data

Ship Speed V [knots]	EHP in calm water [PS]	T [kN]	R [kN]	w	t	η_R	$\eta_H = \frac{1-t}{1-w}$
12.5	1686	248	192.5	0.381	0.224	1.018	1.254
13.0	1965	278	216.0	0.380	0.223	1.022	1.253
13.5	2240	304	236.8	0.379	0.221	1.024	1.254
14.0	2536	331	258.5	0.377	0.219	1.026	1.253

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Example of Determination of Propeller Principal Dimensions (2/9)

☒ Propeller Design Point

NCR = 3,825 [PS]

$N_{MCR} = 220/60$ [1/s]

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Example of Determination of Propeller Principal Dimensions (3/9)

1 Assume the Expanded Area Ratio (A_E / A_o).

Assume $A_E / A_o = 0.55$.

2 Assume the ship speed V .

Assume $V = 13.5 [kts]$.

$V = 13.5 [kts] = 13.5 \times 0.5144 = 6.945 [m/s]$ ※ If the ship speed changes, coefficients are determined by using linear interpolation.

Ship Speed V [knots]	EHP in calm water [PS]	T [kN]	R [kN]	w	t	η_R	$\eta_H = \frac{1-t}{1-w}$
13.5	2,240	304	236.8	0.379	0.221	1.024	1.254

$$P = DHP \cdot \eta_R = \frac{NCR}{1 + \text{Sea Margin} / 100} \times 0.736 \times \eta_T \times \eta_R$$

$$= \frac{3,825}{1 + 0.15} \times 0.736 \times 0.98 \times 1.024 = 2,457 [kW]$$

* 1 [PS] = 0.73575 \approx 0.736 [kW]
* $\eta_T = 0.98$ (engine at stern)

※ η_R should be considered to change the delivered power from after body into the delivered power without hull because the POW Curve was generated from propeller in open water.

* 1 [PS] = 75 [kgf·m/s] = 75×10^{-3} [Mg]·9.81 [m/s²]·[m/s] = 0.73575 \approx 0.736 [kW]

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Example of Determination of Propeller Principal Dimensions (4/9)

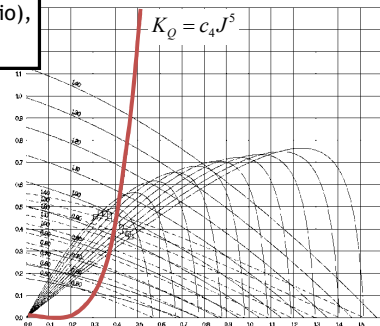
3 Express the Condition 1 as $K_Q = c_4 J^5$.

$$V_A = V(1 - w) = 6.945 \times (1 - 0.379) = 4.313$$

$$c_4 = \frac{P \cdot n^2}{2\pi \rho V_A^5} = \frac{2,457 \times (220 / 60)^2}{2\pi \times 1.025 \times 4.313^5} = 3.4367$$

$$\therefore K_Q = c_4 J^5 = 3.4367 J^5$$

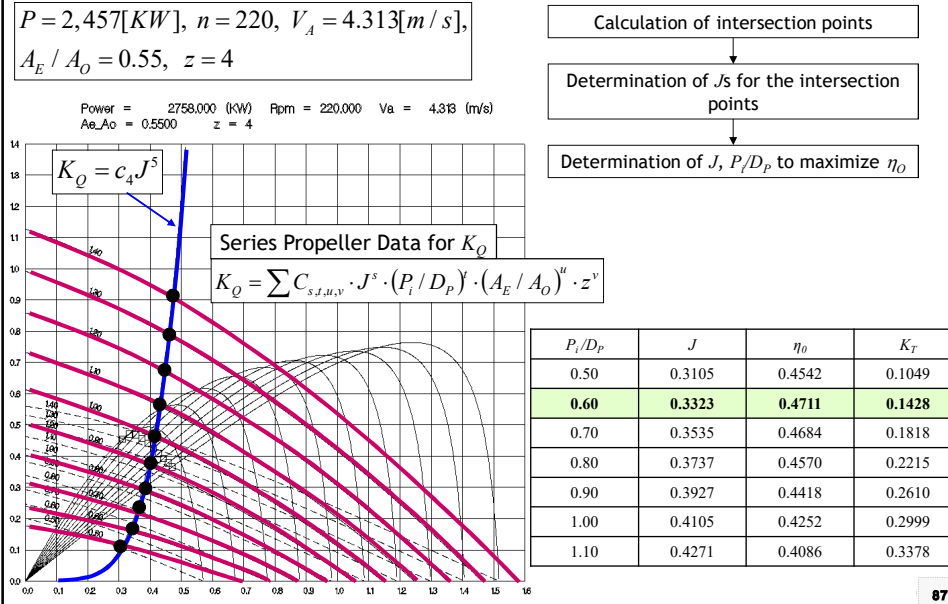
4 By using the set of K_T , K_Q , η_0 (varied with pitch ratio), determine J_x to maximize η_0 and K_T at J_x .



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Example of Determination of Propeller Principal Dimensions (5/9)



Example of Determination of Propeller Principal Dimensions (6/9)

5 By using J_x from Step 4, calculate n_x .

$$J = \frac{V_A}{n \cdot D_p} \Rightarrow D_p = \frac{V_A}{n \cdot J} = \frac{4.313}{(220/60) \times 0.3323} = 3.5396[\text{m}]$$

6 Do the values of D_{px} and K_{Tx} satisfy the Condition 2?

The thrust which is required to propel the ship for the given speed (T_S) = $\frac{R_T}{1-t} = \frac{236.8}{1-0.221} = 304[\text{kN}]$

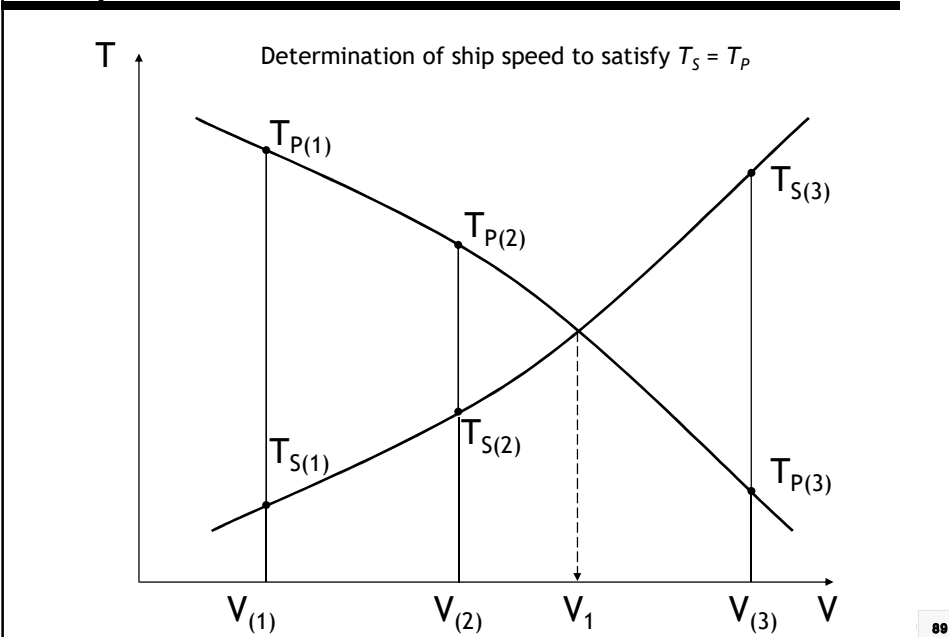
The thrust which is produced by the propeller (T_P)

$$= \rho \cdot n^2 \cdot D_p^4 \cdot K_T = 1.025 \times (220/60)^2 \times 3.5396^4 \times 0.1428 = 308.8956[\text{kN}]$$

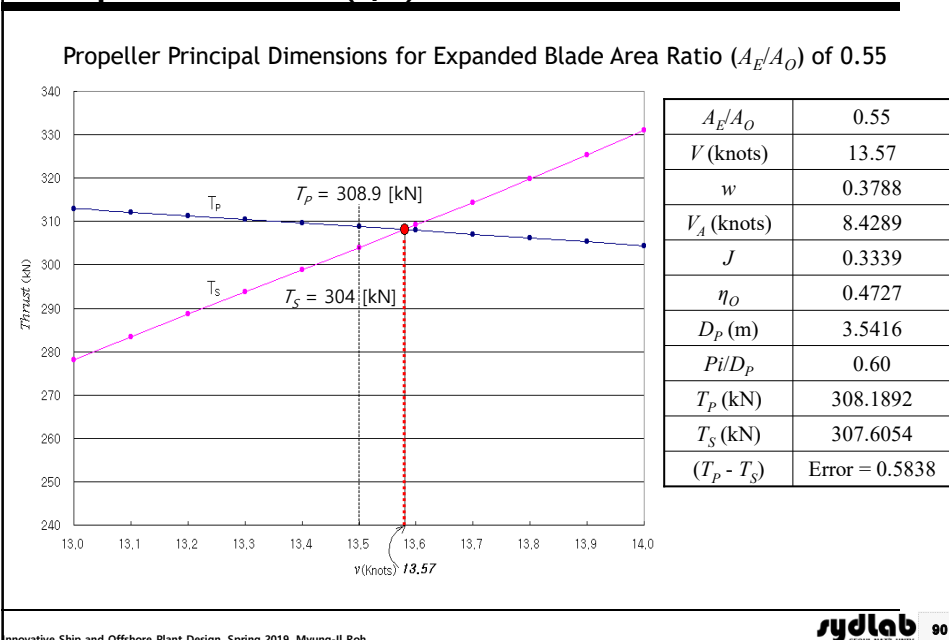
If $T_S < T_P$,

the ship can go faster. ➔ Assume higher ship speed and repeat steps 3 to 6.

Example of Determination of Propeller Principal Dimensions (7/9)



Example of Determination of Propeller Principal Dimensions (8/9)



Example of Determination of Propeller Principal Dimensions (9/9)

7 Does the expanded area ratio (A_E / A_O) satisfy the [Condition 3](#)?

$$A_E / A_O \geq K + \frac{(1.3 + 0.3z) \cdot T}{D_P^2 \cdot (p_0 + \rho g h^* - p_v)}$$

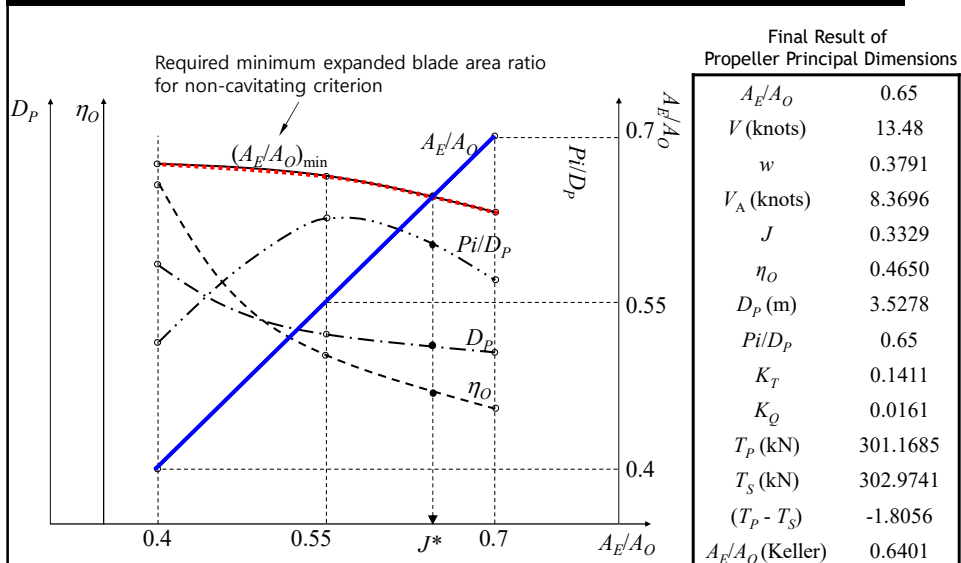
$$= 0.2 + \frac{(1.3 + 0.3 \times 4) \cdot 308.1892}{3.5416^2 \times (99.047 + 1.025 \times 9.81 \times 4.15)} = 0.6363$$

➔ Assume another expanded ratio and repeat steps 2 to 7.

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Check for the Required Minimum Expanded Blade Area Ratio



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Reference Slides

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Interaction between a Hull and a Propeller

- ☑ Propeller has to work behind the ship and in consequence one has an interaction upon the other.
- ☑ How does the hull affect the water in which the propeller is working? How does the propeller affect the hull?
- ☑ A ship affects the water near its stern in 3 aspects:
 - Pressure increase at the stern
 - Boundary layer (a propeller is in the boundary layer or way of the ship.)
 - Water particle velocity induced by ship generated waves

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The Influence of the Hull on the Propeller (1/2)

☑ Wake factor (fraction)

- Water particle velocity near the propeller is not the same as the ship velocity.

$$w = V_s - V_A \quad (V_s : \text{Ship velocity, } V_A : \text{Flow velocity at its stern})$$

$$\text{Froude wake factor: } w_F = \frac{V_s - V_A}{V_A} \Rightarrow V_A = \frac{V_s}{(1 + w_F)}$$

$$\text{Taylor wake factor: } w_T = \frac{V_s - V_A}{V_s} \Rightarrow V_A = V_s(1 - w_T)$$

The relationship between Froude and Taylor wake factors:

$$w_T = \frac{w_F}{1 + w_F} \quad \text{or} \quad w_F = \frac{w_T}{1 - w_T}$$

When $V_A < V_s$, **positive** wake (most cases, a single screw)

When $V_A > V_s$, **negative** wake (only for high speed ship)

The Influence of the Hull on the Propeller (2/2)

☑ Wake factor (fraction) (continued)

- w_T and w_F are determined by the measurements made in a model test (near a hull's stern) or in a real ship test.
- Nominal wake: Wake measured near the stern of a hull in the absence of the propeller (using pilot tubes)
- Effective wake: Wake measured in **the presence of propeller**. The measurements show that a propeller at a rotating speed n behind a hull advancing at velocity (V_s), delivers thrust (T). By comparing it to the results of the same propeller in the open water tests, we will find that at the same revolutions n , the propeller will develop the thrust T but at a different speed (usually lower), known as effective speed of advance (V_A). The difference between V_s and V_A is considered as the effective wake.
- Relation between nominal wake and effective wake: Since propellers induce an inflow velocity which reduces the positive wake to some extent, **the effective wake factor usually is 0.03~0.04 lower than the corresponding nominal wake**.

The Influence of the Propeller on the Hull (1/2)

☑ Thrust-deduction factor (fraction)

- When a hull is towed, there is an area of high pressure over the stern, which has a resultant forward component to reduce the total resistance.
- With a self-propelled hull (in the presence of the propeller), the pressure at the stern is decreased due to the propeller action.
- Therefore, there is a **resistance augment due to the presence of the propeller**.
- If T is the thrust of the propeller and R_T is the towing resistance of a hull at a given speed V_s , then in order that the propeller propel the hull at this speed, T must be greater than R_T because of the resistant augment.
- The normalized difference between T and R_T is called the thrust-deduction factor, and denoted by t .

$$t = \frac{T - R_T}{T} = 1 - \frac{R_T}{T} \Rightarrow R_T = T(1 - t)$$

The Influence of the Propeller on the Hull (2/2)

☑ Thrust-deduction factor (fraction) (continued)

$$t = \frac{T - R_T}{T} = 1 - \frac{R_T}{T} \Rightarrow R_T = T(1 - t)$$

where,

R_T : Total resistance of bare hull

T : Thrust after subtracting the resistance of the rudder
and other stern appendages

t : Measured in experiments depends, not only on the shape of the hull
and the characteristics of the propeller, but also the type of the rudder

Propeller Efficiency

- ☑ The efficiency of a propeller in open water is called open water efficiency or propeller efficiency.

$$\eta_0 = \frac{T \cdot V_A}{2\pi n Q_0}$$

where, V_A is the advance speed, T is the thrust, n is the rotation speed (number of rotations per unit time), and Q_0 is the torque measured in the open water test when the propeller is delivering thrust T at the rotation speed n .

- ☑ In the case the same propeller behind a hull, at the same advance speed it delivers the same thrust T at the same revolution n but needs torque Q . In general, Q is different from Q_0 . Then, the efficiency of the propeller behind the hull,

$$\eta_B = \frac{T \cdot V_A}{2\pi n Q}$$

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Relative Rotation Efficiency

- ☑ The ratio of behind-hull efficiency to open-water efficiency is called the relative rotative efficiency.

$$\eta_R = \frac{\eta_B}{\eta_0} = \frac{Q_0}{Q}, \quad \text{thus} \quad \eta_B = \eta_R \eta_0$$

- ☑ The difference between Q_0 and Q is due to
- wake is not uniform over the disc area while in open water, the advance speed is uniform
 - model and prototype propellers have different turbulent flow. (Remember then Reynolds number are not the same)

$$\begin{aligned} \eta_R &= 1.0 \sim 1.1 \text{ for single-screw ship} \\ &= 0.95 \sim 1.0 \text{ for twin-screw ship} \end{aligned}$$

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Hull Efficiency

- ☑ The hull efficiency is defined as the ratio of the effective power for a hull with appendages to the thrust power developed by propellers.

$$\eta_H = \frac{EHP}{THP} = \frac{R_T \cdot V_s}{T \cdot V_A} = \frac{1-t}{1-w}$$

where,

EHP : Effective horse power, $EHP = R_T \cdot V_s$

R_T : Total resistance of bare hull

V_s : Speed of the ship

THP : Work done by the propeller in delivering a thrust T

V_A : Advanced speed

(= Speed of the propeller with respect to the ambient water)

Propulsive Efficiency

- ☑ The propulsive efficiency (Quasi-propulsion coefficient) is defined as the ratio of the effective horse power to the delivery horse power.

$$\eta_D = \frac{EHP}{DHP} = \frac{R_T V_s}{2\pi n Q} = \frac{TV_A}{2\pi n Q} \cdot \frac{R_T V_s}{TV_A} = \eta_B \cdot \eta_H = \eta_O \cdot \eta_R \cdot \eta_H$$

where,

EHP : Effective horse power, $EHP = R_T \cdot V_s$

DHP : Delivered horse power, $DHP = 2\pi n Q$

η_O : Propeller efficiency in open water

η_R : Relative rotative efficiency

η_H : Hull efficiency

Cavitation on a Propeller (1/3)

☑ Problems

- Decrease of the thrust of the propeller ➔ Decrease of its efficiency
- Cause of vibration of hull and the propeller
- Generation of uncomfortable noise
- Cause of erosion of the propeller blade

☑ Criteria for prevention of cavitation

- Mean thrust loading coefficient

$$\tau_c = \frac{T}{\frac{1}{2} \rho V_R^2 A_p}$$

where,

ρ : Density of water, T : Thrust

A_p : Project blade area, $\frac{A_p}{A_D} = 1.067 - 0.229 \frac{P}{D}$

V_R : Relative velocity at 0.7 R of a propeller

$$V_R^2 = V_A^2 + (2\pi \cdot 0.7R \cdot n)^2$$

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Cavitation on a Propeller (2/3)

☑ Cavitation Number

- The cavitation is most likely to occur at the tips of blades where the relative velocity is the largest and the hydro-static pressure is the lowest when blades rotate to the highest position.
- It can also occur near the roots where blades join the boss of a propeller because the attack angle is the largest.

$$\sigma = \frac{p_0 - p_v}{\frac{1}{2} \rho V_R^2}$$

where,

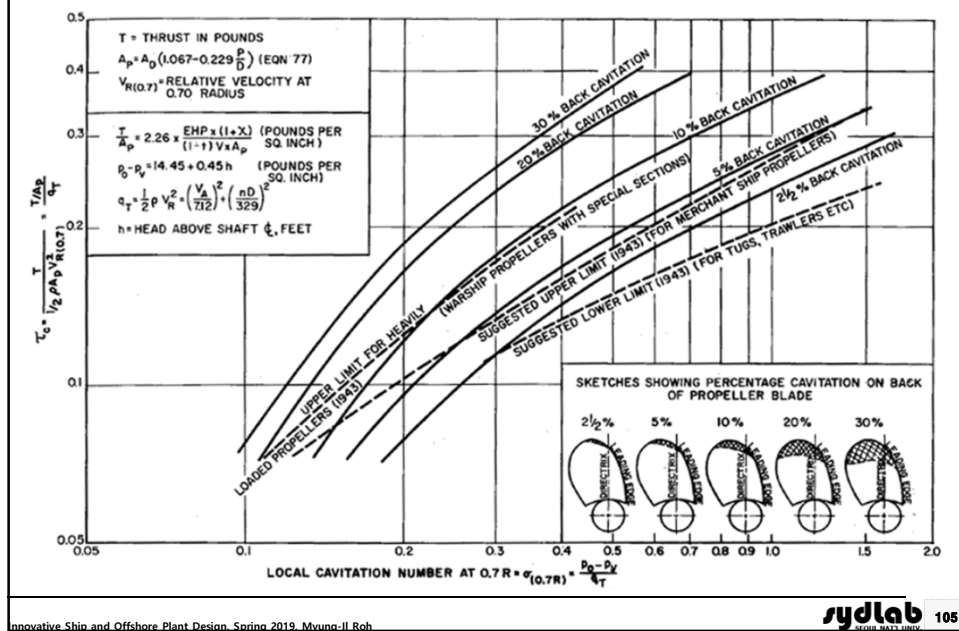
p_0 : Pressure at some point of a blade

p_v : Vapor pressure of water

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Cavitation on a Propeller (3/3)



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