Lecture Note of Innovative Ship and Offshore Plant Design

Innovative Ship and Offshore Plant Design

Part I. Ship Design

Ch. 7 Propeller and Main Engine Selection

Spring 2018

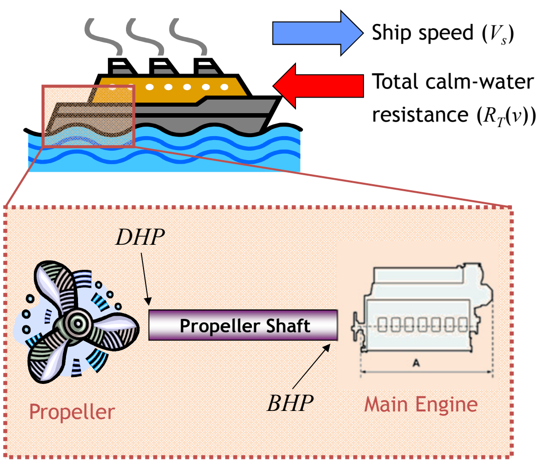
Myung-Il Roh

Department of Naval Architecture and Ocean Engineering
Seoul National University

Contents

Ch. 7 Propeller and Main Engine Selection

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



① EHP (Effective Horse Power)

$$EHP = R_T(v) \cdot v$$ (In Calm Water)

② DHP (Delivered Horse Power)

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

(η_D : Propulsive efficiency)

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

③ BHP (Brake Horse Power)

$$BHP = \frac{DHP}{\eta_T}$$

(η_T : Transmission efficiency)

④ NCR (Normal Continuous Rating)

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

⑤ DMCR (Derated Maximum Continuous Rating)

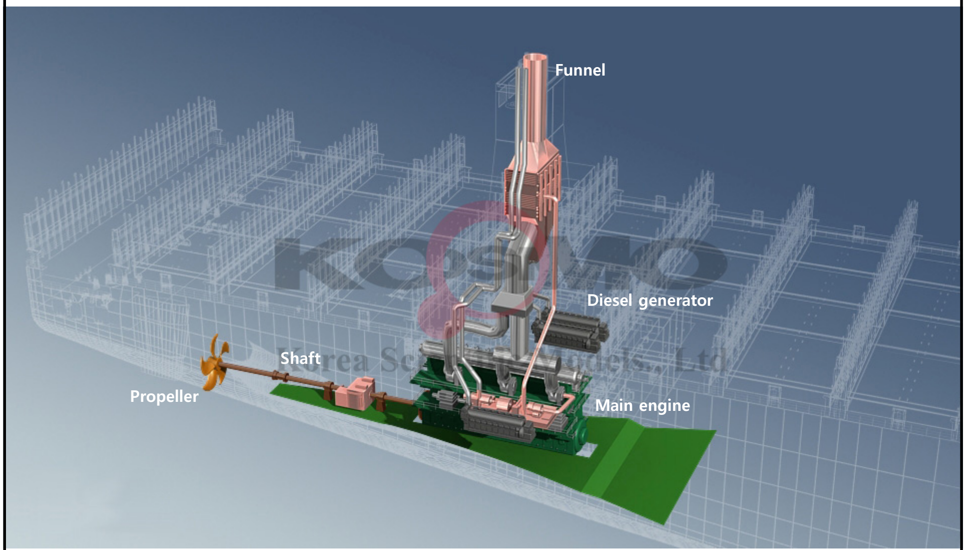
$$DMCR = \frac{NCR}{\text{Engine Margin}}$$

⑥ NMCR (Nominal Maximum Continuous Rating)

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

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

Example of a Diesel Engine and Propeller



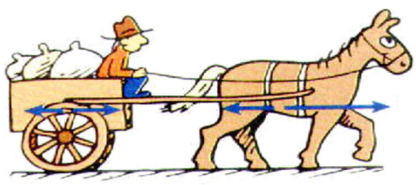
* Reference: Korea Scientific Models

1. Characteristics of Propeller

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**

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

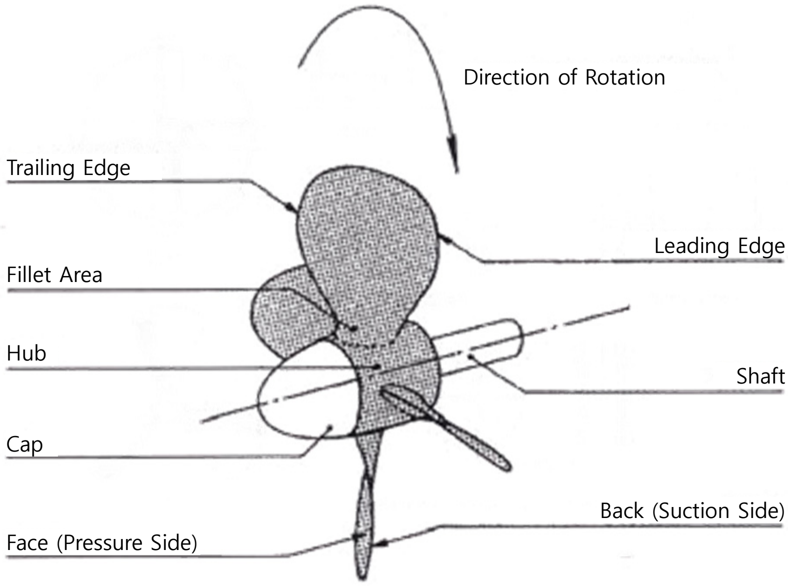
Find

Wheel Design = Propeller Design

Maximum Speed = Maximum Speed of a Ship

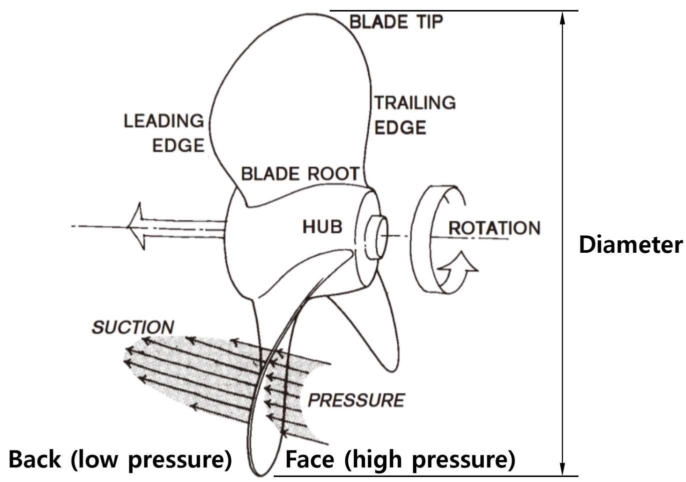
Wheel Diameter = Principal Dimensions of a Propeller

Propeller Components



Principal Dimensions of a Propeller (1/4)

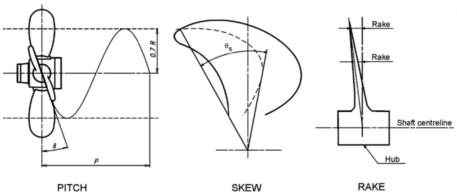
☑ **Diameter**

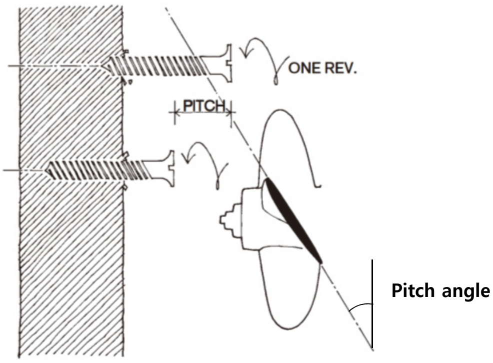


Principal Dimensions of a Propeller (2/4)

☑ 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.

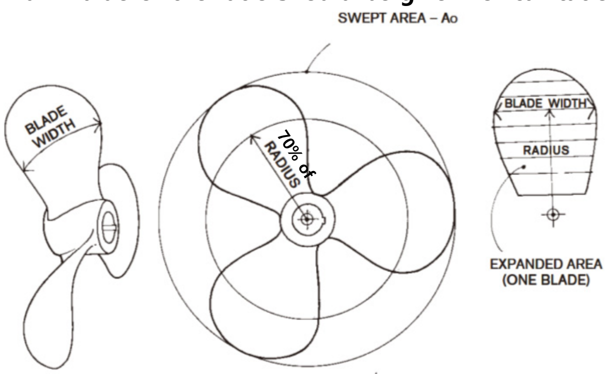




Principal Dimensions of a Propeller (3/4)

☑ 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.



- RELATIVE EXPANDED BLADE AREA $A_E / A_O = \dfrac{\text{TOTAL BLADE AREA } A_E}{\text{SWEPT AREA } A_O}$

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

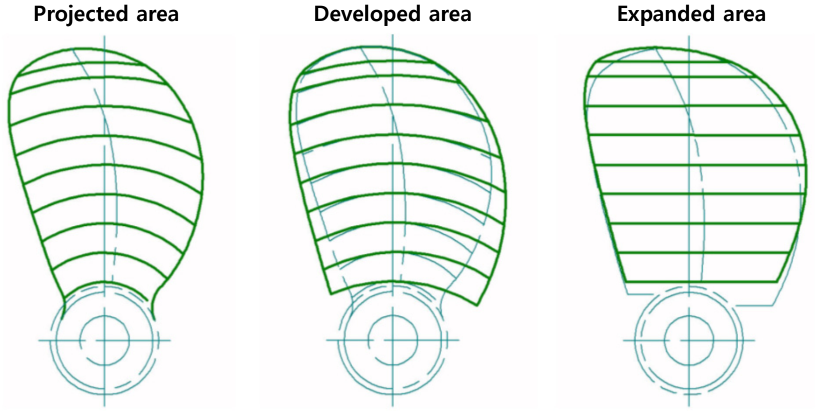
[Reference] Blade Area Ratio (BAR) (1/2)

☑ 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.

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



<u>Conversion between each other</u>

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

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

PAR becomes small if P_i/D_P becomes large.
PAR ∝ DAR ∝ EAR (PAR < DAR < EAR)
Thus, high Pi/Dp and small PAR result in high possibility of cavitation.

Principal Dimensions of a Propeller (4/4)

☑ Ship Speed (Vs)

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

[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

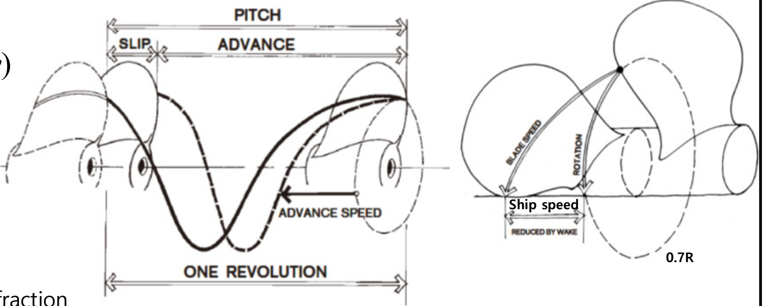
Advance Speed

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

Advance Ratio

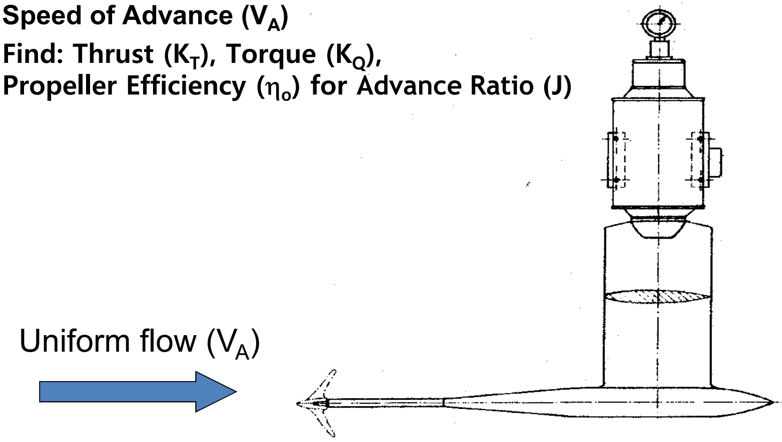
$$J = \frac{V_A \cdot (1/n)}{D_P} = \frac{V_A}{n \cdot D_P}$$

where, w: wake fraction



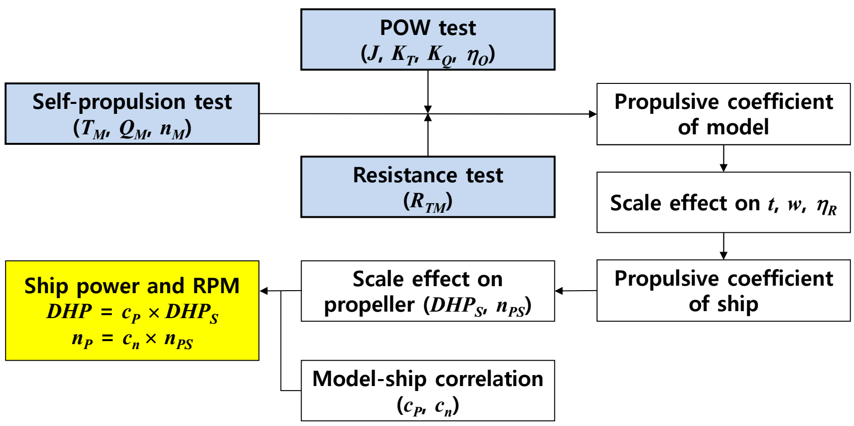
Propeller Open Water (POW) Test

- ☑ 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)



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

Towing Tank Test



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

Main Non-dimensional Coefficients of Propeller

From dimensional analysis:

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

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

③ Advance ratio: $J = \dfrac{V_A}{n \cdot D_P}$

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

④ Propeller efficiency: $\eta_o = \dfrac{J}{2\pi} \cdot \dfrac{K_T}{K_Q}$
(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/m^3]

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

Propeller Efficiency (η_O)

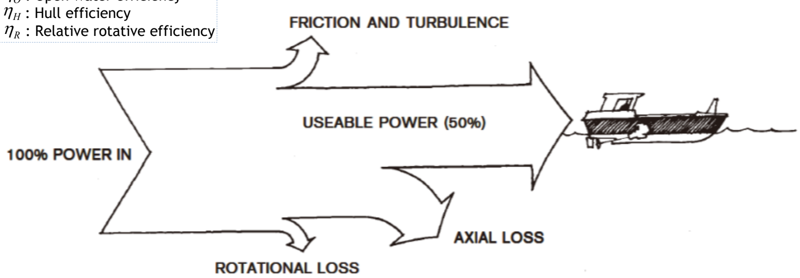
☑ **Efficiency of a propeller itself.**
☑ **One of components of propulsive efficiency (η_D)**

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

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

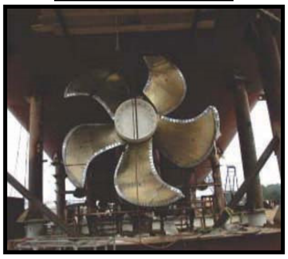
$\eta_D = \eta_O \cdot \eta_H \cdot \eta_R$
η_O : Open water efficiency
η_H : Hull efficiency
η_R : Relative rotative efficiency

Output loses for propeller



POW Propeller Model

Actual Propeller



Geometric Similarity

Model Propeller

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

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

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

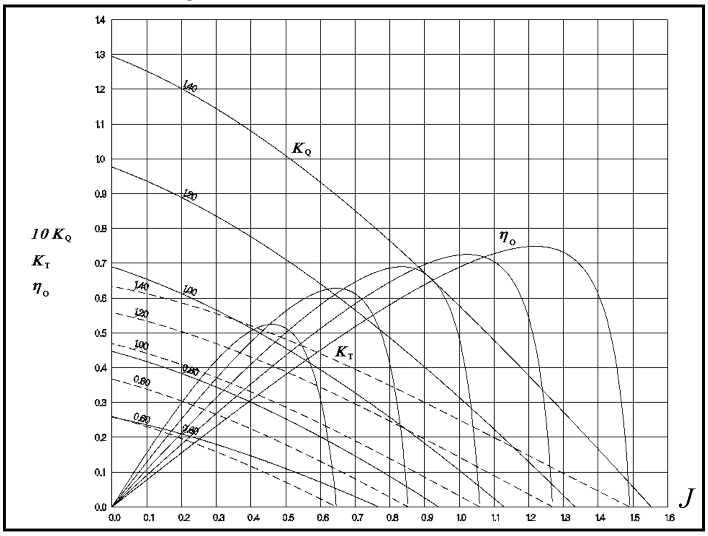
$$V_A = V_s \cdot (1 - w)$$

Same non-dimensional coefficients

$$\left(K_T, K_Q, J\right)$$

Propeller Open Water (POW) Curve

- Values of K_T, K_Q, and η_O at different pitch ratio (P_i/D_P)



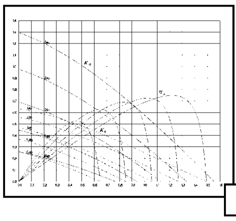
$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_P^{\ 4}}$$

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

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

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

Propeller Regression Polynomials for POW Curve



- Regression Polynomial

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

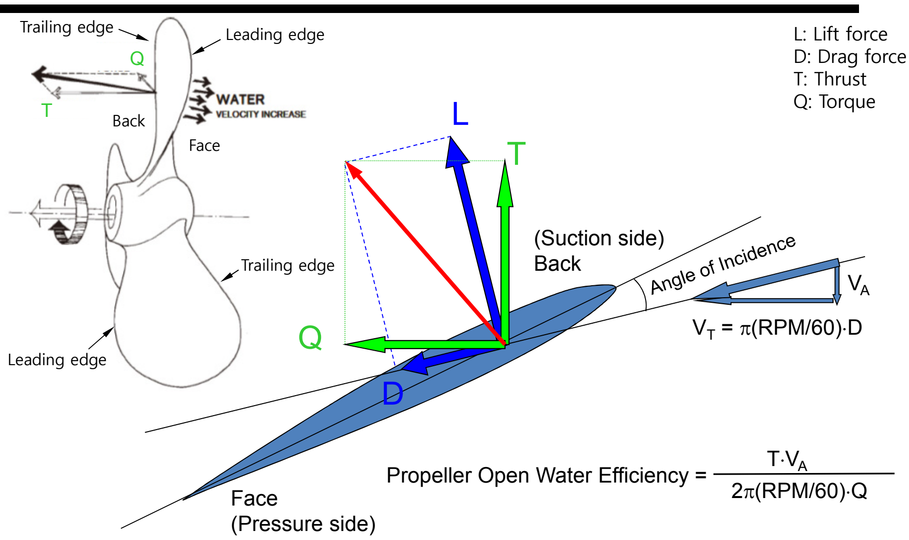
$$K_T \ and \ K_Q = \sum C_{s,t,u,v} (J)^s (P_i / D_P)^t (A_E / A_O)^u z^v$$

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
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Innovative Ship and Offshore Plant Design, Spring 2018, Myung-Il Roh

sydlab SEOUL NAT'L UNIV. 23

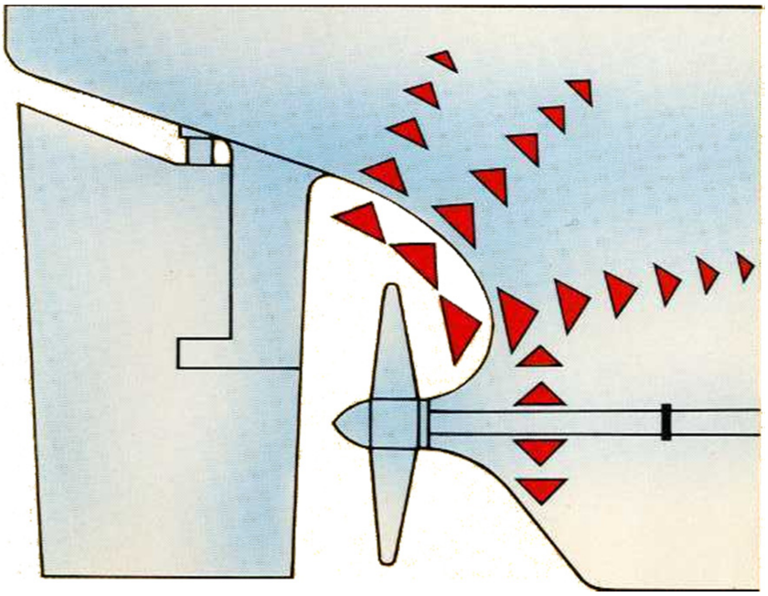
Forces Acting on Propeller



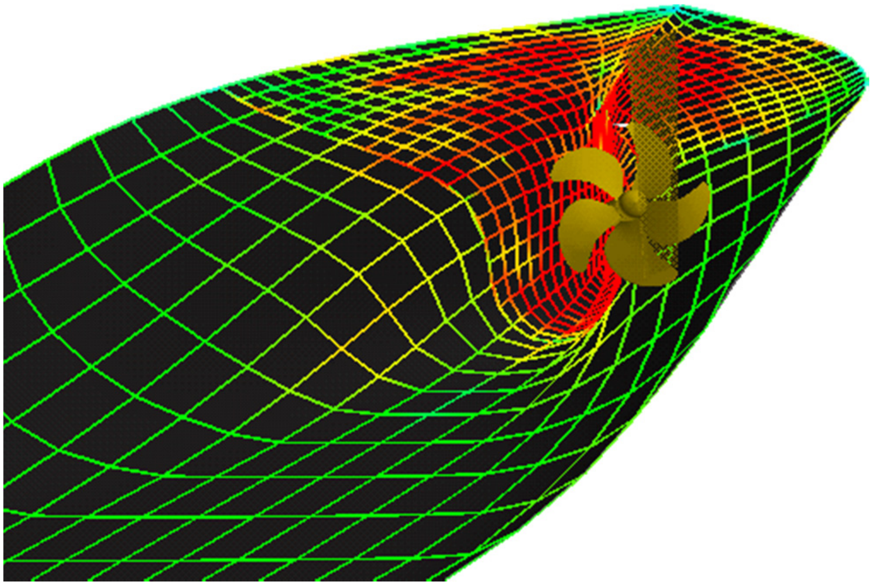
Innovative Ship and Offshore Plant Design, Spring 2018, Myung-Il Roh

sydlab SEOUL NAT'L UNIV. 24

Hull Vibration Due to Propeller Rotation



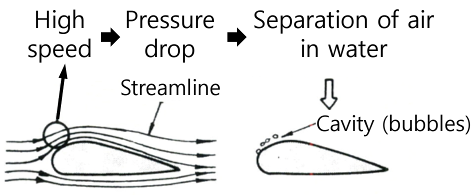
Pressure on Hull Due to Propeller Rotation

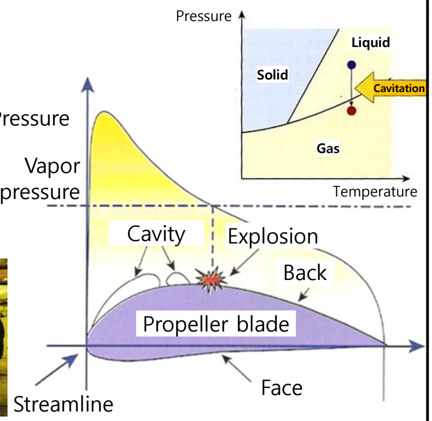


Cavitation

- ☑ **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**





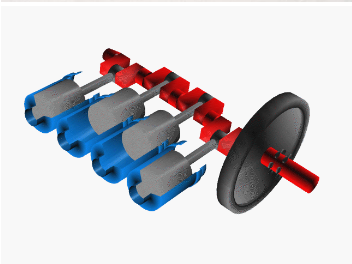
2. Characteristics of Diesel Engine

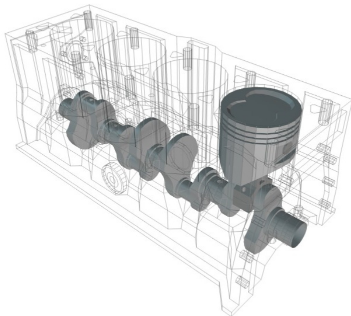
Example of a Main Diesel Engine of Ship

Crank Shaft in the Maine Engine

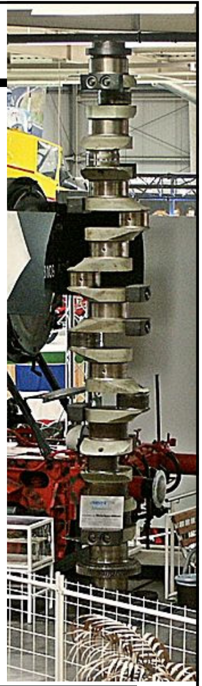
☑ **Device to translate linear piston motion into rotation**

☑ **BHP (Brake Horse Power): Power which is delivered to crank shaft from the main engine**





Crank shaft for 6-cylinder marine diesel engine



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 Presure (kN/m^2)

L : Piston Stroke (m)

A : Piston Cross-Sectional Area (m^2)

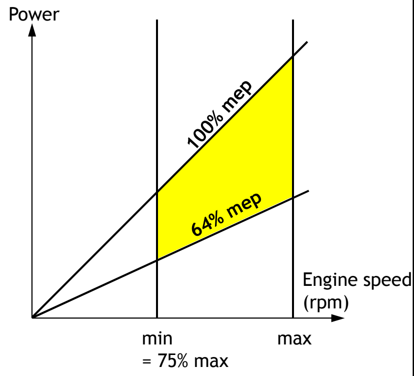
n : Number of Revolutions ($1/s$)

Z : Number of Cylinder

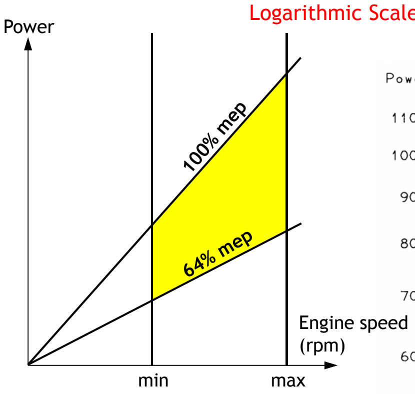
If A and Z are constant,

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

Therefore,

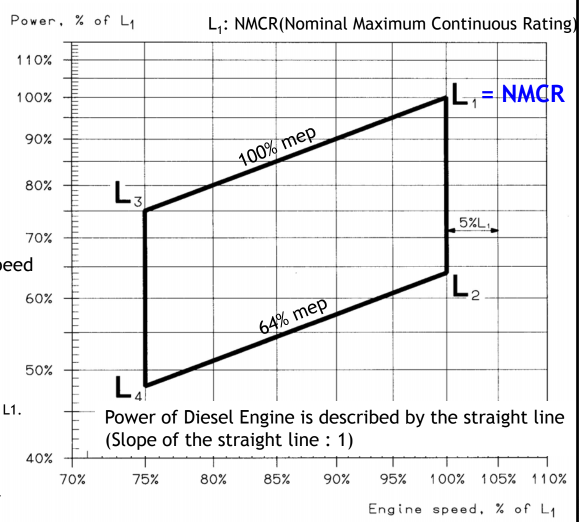


Diesel Engine Layout Diagram



Logarithmic Scale

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.

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

6 L 70 MC Mk V

- Mk V — Mark: Engine version
- MC — Engine programme
- 70 — Diameter of piston in cm : bore
- L — Stroke/bore ratio

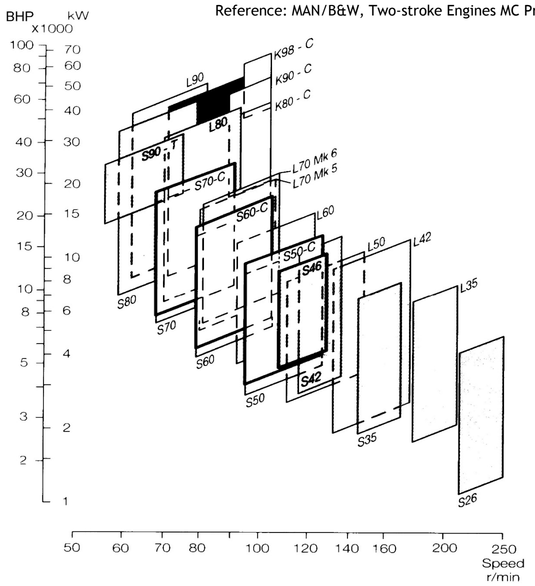
S	Super long stroke	approximately 3.8
L	Long stroke	approximately 3.2
K	Short stroke	approximately 2.8

- 6 — Number of cylinders

* Currently, MAN Diesel & Turbo

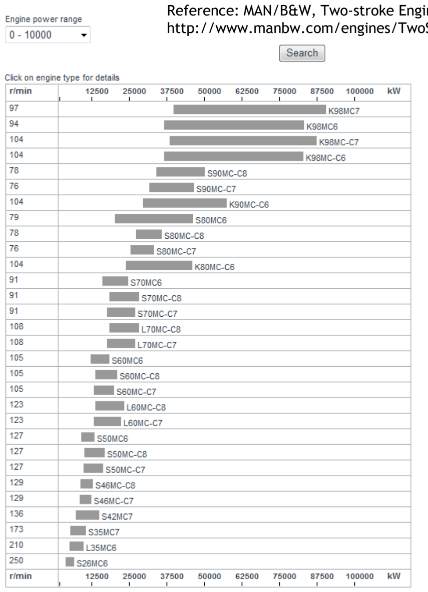
MAN/B&W Diesel Engine (1/2)

Reference: MAN/B&W, Two-stroke Engines MC Program, 1996



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

Reference: MAN/B&W, Two-stroke Engines MC Program, 2007
http://www.manbw.com/engines/TwoStrokeLowSpeedPropEnginesProgram.asp



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

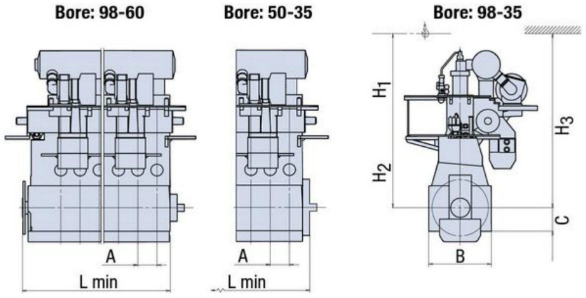
Main Data

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

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



L_{min}: Minimum length of engine
A: Cylinder distance
B: Bedplate width
C: Crankshaft ℄ to underside of foot flange
H_1: Normal lifting procedure
H_2: Reduced height lifting procedure
H_3: With electric double-jib crane

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.

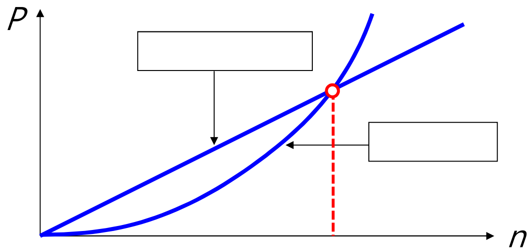
Matching the Powers and RPMs of Propeller and Diesel Engine

Output Power of a Diesel Engine

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

Power Absorbed by a Propeller

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



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%

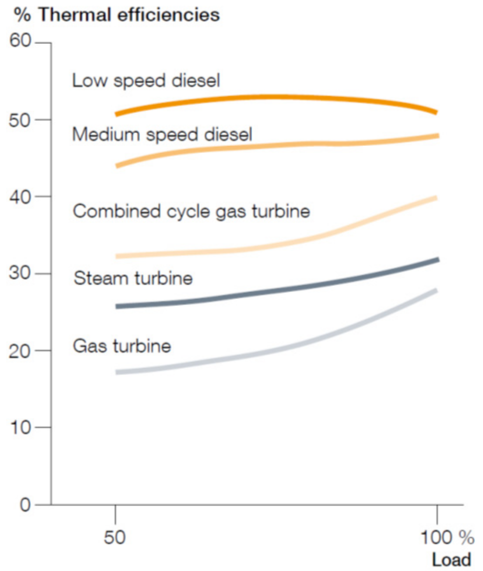
NCR, Engine Margin, DMCR

☑ 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

3. Procedure of the Determination of Propeller Principal Dimensions and Main Engine Selection

Procedure of the Determination of Propeller Principal Dimensions and Main Engine Selection

Requirements of Design ship

Determination of Principal Dimensions and C_b, L_{cb}, C_m, V_s(Fn)

Estimation of Resistance and Propulsion Power based on Empirical Methods, for example, Holtrop & Mennen (Cw, k, w, t, η_R)

Prediction of Resistance and Propulsion Power by Applying Correction Factor

Assume the Diesel Engine Power and Speed (RPS)

Stage 0 — Assume the Propeller Diameter (D_p)

Engine — Stage 1 — Determination of Engine Power (P) and Speed (n), and Propeller Pitch for Maximum η_0

Does Modify Main Engine? (Yes / No)

Propeller — Determination the Propeller Design Point

Stage 2 — Determination of the Optimum Propeller Principal Dimensions and Ship Speed

Stage 3 — Engine-Propeller-Ship — Determination of the Ship Speed, Engine Power, Engine Speed by Using the Given Propeller

Basis Ship

Principal Dimensions and Cb, Lcb, Cm, Vs of the Basis Ship

Prediction of Resistance and Propulsion Power in Calm Water Based on the Model Test (Cw, k, w, t, η_R)

Estimation of Resistance and Propulsion Power Based on Empirical Methods, for example, Holtrop & Mennen

Correction Factor Calculation from Model Test Result and Empirical Method

	Determination of the Main Engine Power (P) and Speed (n), and Propeller Pitch (P_i)
Given	$D_p[m]$, A_E/A_o, z; $v[m/s]$; $R_T(v)[kN]$
Find	$P[kW]$, $n[1/s]$, $P_i[m]$

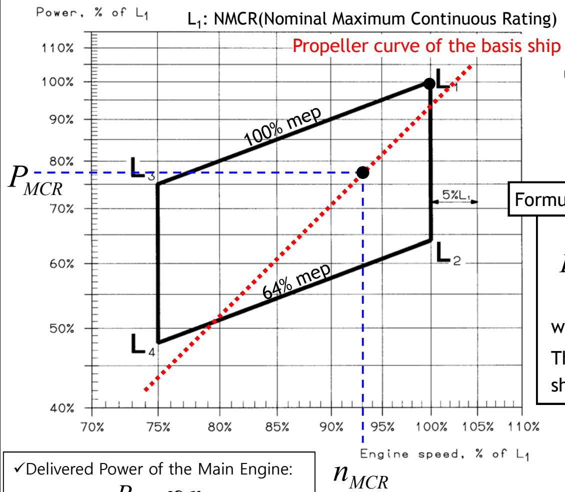
	Determination of the Propeller Principal Dimensions and Ship Speed for Maximum η_0 (Optimization Problem)
Given	z; $P[kW]$, $n[1/s]$; $R_T(v)[kN]$
Find	$D_p[m]$, $P_i[m]$, A_E/A_o; $v[m/s]$

	Determination of the Ship Speed, Engine Power, Engine Speed (Nonlinear Equation)
Given	$D_p[m]$, $P_i[m]$, A_E/A_o, z; $v[m/s]$; $R_T(v)[kN]$
Find	$P[kW]$, $n[1/s]$

43

[Stage 0] Assumption of the Propeller Diameter

Propeller curve of the basis ship is drawn by connecting point (P_{MCR}, n_{MCR}) and origin (P=0, n=0).



✓Delivered Power of the Main Engine:
$$P_{D.E.} \propto n$$

✓ Power Absorbed by the Propeller:
$$P_{prop.} \propto n^3$$

- 1st Method: Use the diameter of the basis ship.
- 2nd Method: When the diameter of the basis ship is not given, estimate the diameter as follows.

Formula for estimation of propeller diameter (D_P)

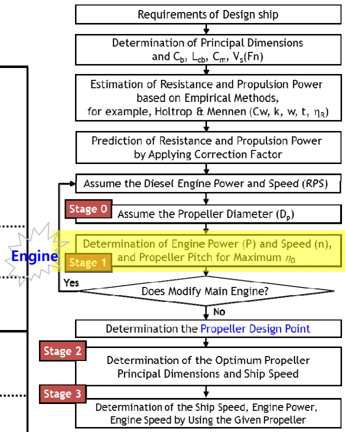
$$D_p = 15.4 \times \left(\frac{P_{MCR}}{n_{MCR}^3} \right)_{basis\ ship}^{0.2} \times c_1$$

where, $c_1 = 1$ for 5 blades, 1.05 for 4 blades. The MCR (P_{MCR}) and rpm (n_{MCR}) of the basis ship are used.

44

[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.

[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.

$$\underbrace{\frac{P}{2\pi n}}_{\text{Torque delivered by the main engine}} = \underbrace{\rho \cdot n^2 \cdot D_P^{\ 5} \cdot K_Q}_{\text{Torque absorbed by the propeller}} \cdots (1)$$

Torque delivered by the main engine = Torque absorbed by the propeller

where, $P = DHP \cdot \eta_R$

* Relative Rotation Efficiency (η_R): The ratio of behind-hull efficiency to open-water efficiency is called the relative rotative efficiency. $\eta_R = \frac{Q_0}{Q}$

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

- Condition 2:

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

The thrust which is required to propel the ship for the given speed = The thrust which is produced by the propeller

[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, 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

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

where, $P = DHP \cdot \eta_R$

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

Nonlinear optimization problem

Objective Function: Maximum η_0

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

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

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

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

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

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

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

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

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

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

- **Lagrange function:**

$$H(P_i, n, P) = F(P_i, n) + \lambda_1 \cdot G_1(P_i, n, P) + \lambda_2 \cdot G_2(P_i, n) \quad \cdots\cdots \quad \text{(d)}$$

- **Stationary point of H:** $\nabla H\left(P_i, n, P, \lambda_1, \lambda_2\right) = 0$

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

$$\frac{\partial H}{\partial n} = \frac{1}{2\pi} \cdot \frac{\partial J}{\partial n} \cdot \frac{K_T}{K_Q} + \frac{J}{2\pi} \cdot \frac{\{(\frac{\partial K_T}{\partial n}) \cdot K_Q - (\frac{\partial K_Q}{\partial n}) \cdot K_T\}}{K_Q{}^2} + \lambda_1 \cdot (-\frac{P}{2 \cdot \pi \cdot n^2} - \rho \cdot 2 \cdot n \cdot D_P^5 \cdot K_Q - \rho \cdot n^2 \cdot D_P^5 \cdot \frac{\partial K_Q}{\partial n})$$

$$+ \lambda_2 \cdot (-\rho \cdot 2 \cdot n \cdot D_P^4 \cdot K_T - \rho \cdot n^2 \cdot D_P^5 \cdot \frac{\partial K_T}{\partial n}) = 0 \cdots\cdots \quad \text{(f)}$$

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

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

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

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)

Calculation By Hand

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]

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.

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

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).

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

Calculation By Hand

1

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]

2

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

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

Advance Ratio: $J = \dfrac{V_A}{n \cdot D_P} \Rightarrow n = \dfrac{V_A}{J \cdot D_P}$

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

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

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

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

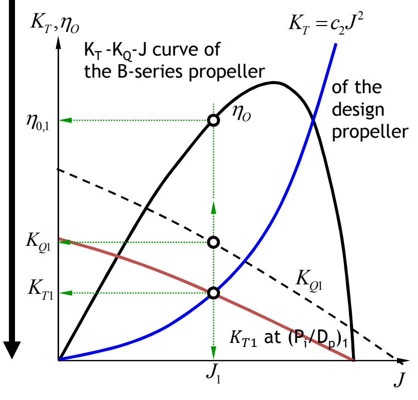
Calculation By Hand

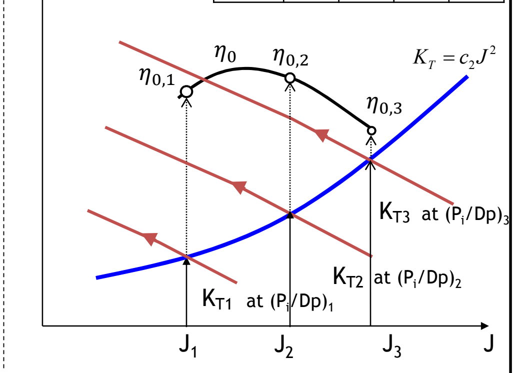
3

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}





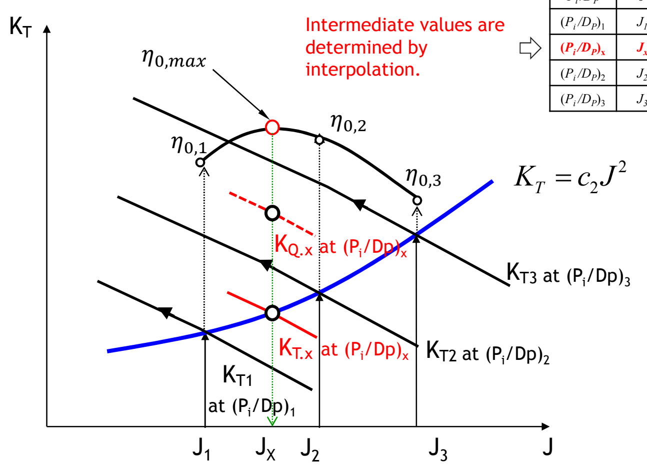
[Stage 1] Determination of the Main Engine Power (P) and Engine Speed (n), and Propeller Pitch (P_i) for Maximum η_0 (8/10)

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}



[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.

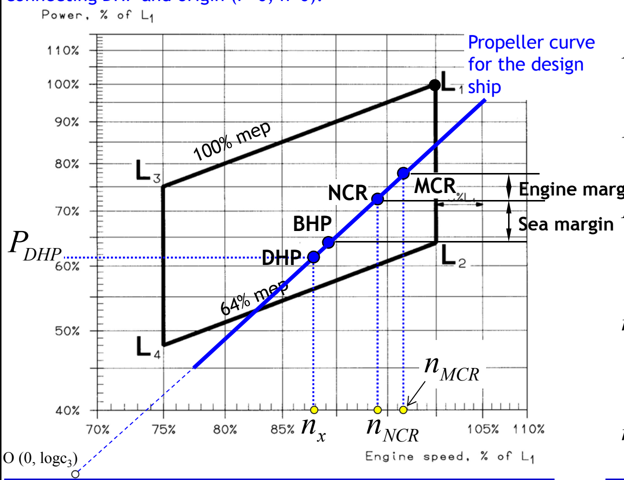
$$J_x = \frac{V_A}{n_x \cdot D_P} \Rightarrow n_x = \frac{V_A}{D_P \cdot J_x}$$

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

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

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

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



P_x (= DHP·η_R) is determined from optimization.

$$BHP = \frac{DHP}{\eta_T}$$

η_T: Transmission efficiency

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

$$MCR = NCR / E.M$$

E.M: Engine Margin

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

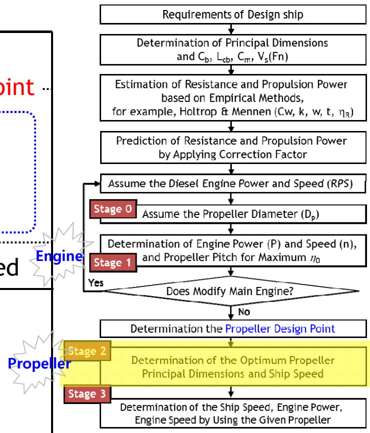
$$n_{MCR} = \sqrt[3]{\frac{MCR}{c_3}}$$

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.

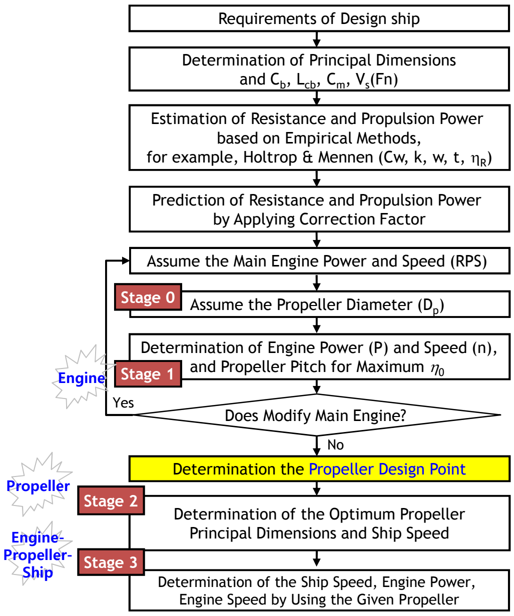
If the NCR and MCR are not in the layout diagram of main engine, select another engine.

[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (1/8)

Given	z: Number of blades
	Propeller Design Point
	P [kW]: Delivered power to propeller from main engine (NCR)
	n [1/s]: RPS at MCR
	$R_T(V)$ [kN]: Resistance varied with ship speed
Find	D_P [m]: Propeller diameter
	P_i [m]: Propeller pitch
	A_E/A_O: Expanded area ratio
	V [m/s]: Ship speed

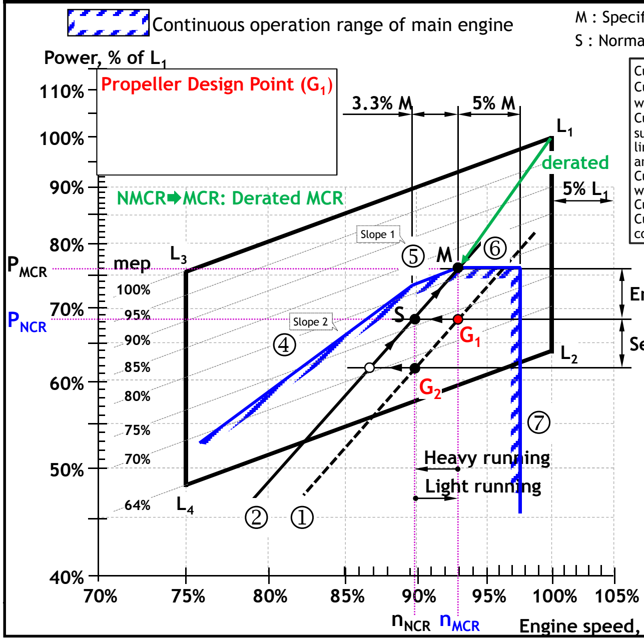


Propeller Design Point - Matching the Propeller and Main Engine



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

M : Specified MCR for propulsion (DMCR or MCR)
S : Normal continuous rating for propulsion (NCR)



Curve ①: Propulsion curve, clean hull (light running)
Curve ②: Propulsion curve, fouled hull and heavy weather (heavy running)
Curve ④: Torque/speed limit at which an ample air supply is available for combustion and imposes a limitation on the maximum combination of torque and speed (proportional to n^2)
Curve ⑤: Maximum mean effective pressure level, which can be accepted for continuous operation
Curve ⑥: Maximum power for continuous operation
Curve ⑦: Maximum speed which can be accepted for continuous operation

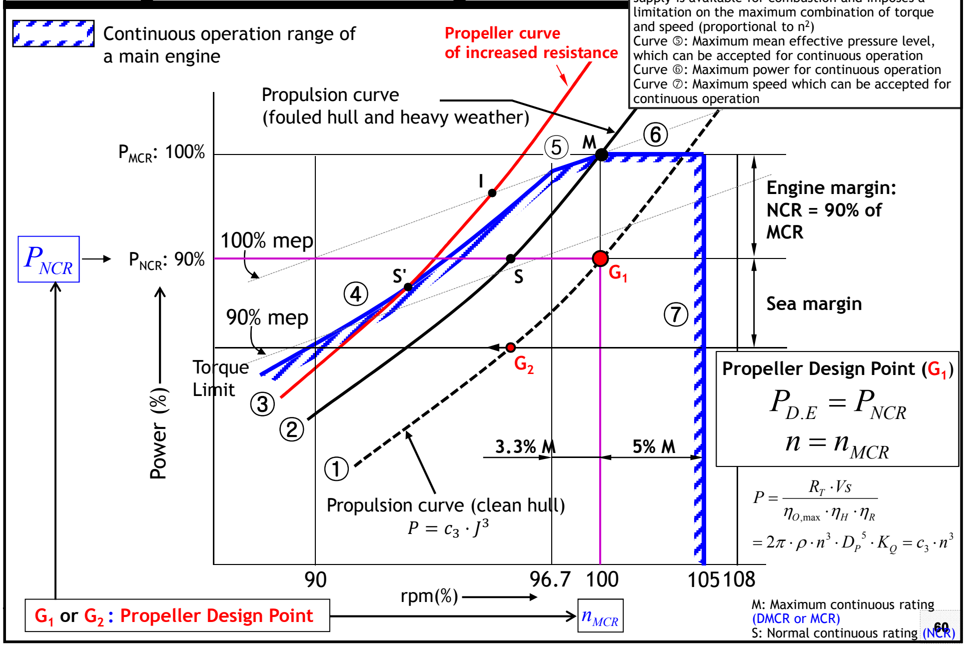
G_2 is the intersection point of the curve ① with the reduced power considering the sea margin and also propeller design point.

MCR point can be any point within the layout diagram. When choosing the MCR, we have to consider the revolution of propeller, fuel consumption, and propeller operation layout and others all together.
Once the MCR point has been chosen, and provided that the shaft line and auxiliary equipment are dimensioned accordingly, the specified MCR point is now the maximum rating.
That is, the standard of all power and number of revolutions becomes MCR.

59

Matching the Propeller and Main Engine in the Load Diagram

Curve ①: Propulsion curve, clean hull (light running)
Curve ②: Propulsion curve, fouled hull and heavy weather (heavy running)
Curve ④: Torque/speed limit at which an ample air supply is available for combustion and imposes a limitation on the maximum combination of torque and speed (proportional to n^2)
Curve ⑤: Maximum mean effective pressure level, which can be accepted for continuous operation
Curve ⑥: Maximum power for continuous operation
Curve ⑦: Maximum speed which can be accepted for continuous operation



Propeller Design Point (G_1)

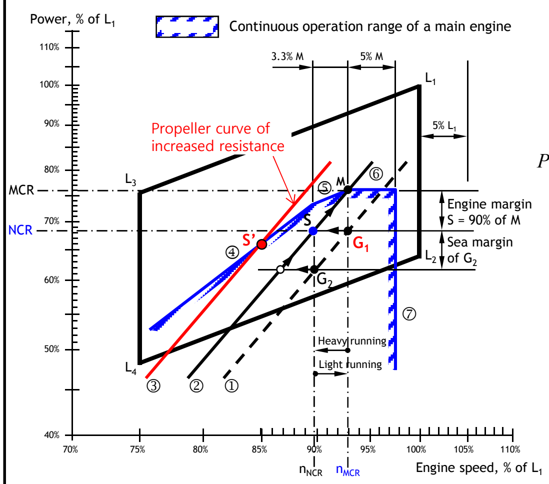
$$P_{D.E} = P_{NCR}$$
$$n = n_{MCR}$$

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

M: Maximum continuous rating (DMCR or MCR)
S: Normal continuous rating (NCR)

60

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)

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

$$n = n_{MCR}$$

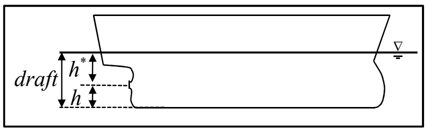
$$P = \frac{R_T \cdot Vs}{\eta_{O,\max} \cdot \eta_H \cdot \eta_R} = 2\pi \cdot \rho \cdot n^3 \cdot D_P^{\ 5} \cdot K_Q = c_3 \cdot n^3$$

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: can be calculated by using one of the two formulas.

① Formula given by Keller

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

K: Single Screw = 0.2, Double Screw = 0.1

P_0-P_v = 99.047 [kN/m²] at 15℃ Sea water

h*: Shaft Immersion Depth [m]

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

T: Propeller Thrust [kN]

or ② Formula given by Burrill

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

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

$$\boxed{B_P = n \cdot P^{0.5} / V_A^{2.5}} \leftarrow \boxed{v_A = v \cdot (1 - w)[knots]}$$

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

$n[rpm]$

62

[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]

4 Unknowns

2 Equality constraints

1 Inequality constraint

- **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.**

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

Nonlinear indeterminate problem

Objective Function: Maximum η_0

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

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.

[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 $K_Q = c_4 J^5$.

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

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

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

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

$$\boxed{K_Q = c_4 J^5}$$

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

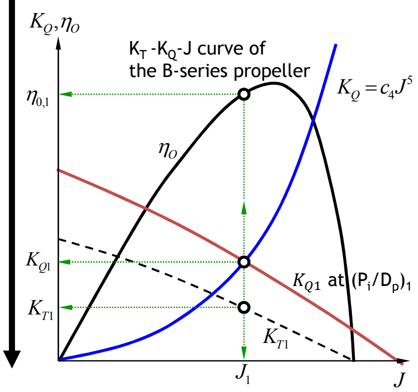
Calculation By Hand

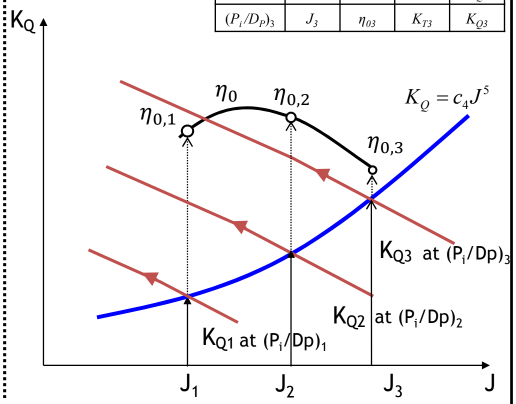
4

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 $K_Q = c_4 J^5$ 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}





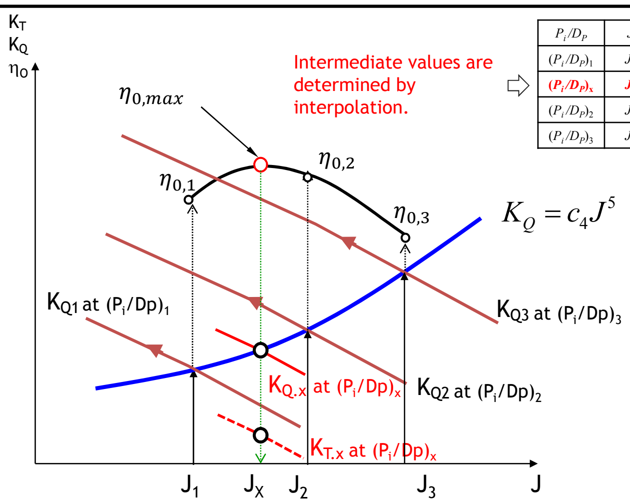
[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (6/8)

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}



[Stage 2] Determination of the Propeller Principal Dimensions for Maximum η_0 (7/8)

Calculation By Hand

5 Calculate $D_{P.x}$ by using J_x at Step 5.

$$J = \frac{V_A}{n \cdot D_P} \Rightarrow D_{P.x} = \frac{V_A}{n \cdot J_x}$$

6 Do the values of D_{Px} and $K_{T.x}$ satisfy the Condition 2?

No!! Go to 2: Assume another speed V.

Check the Condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_{P.x}{}^4 \cdot K_{T.x}$

Yes!!

7 Does the expanded area ratio (A_E / A_o) satisfy the Condition 3?

No!! Go to 1: Assume another expanded area ratio (A_E / A_o).

Check the Condition 3: $A_E / A_O \geq K + \frac{(1.3 + 0.3z) \cdot T}{D_P{}^2 \cdot (p_0 + \rho g h^* - p_v)}$

Yes!!

STOP

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

Calculation By Hand

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

2 Assume the speed V.

3 Express the Condition 1 as $K_Q = C_1 J^5$.

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

1st Loop

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 ratio $(P_i/D_p)_x$ at J_x.

2nd Loop

3rd Loop

5 Calculate $D_{P.x}$ by using J_x at step 4: $J_x = \frac{V_A}{n \cdot D_{P.x}}$.

6 Do D_{Px} and K_{Tx} satisfy the Condition 2?

Condition 2: $\frac{R_T}{1-t} = \rho \cdot n^2 \cdot D_{P.x}{}^4 \cdot K_{T.x}$

7 Does the expanded area ratio (A_E / A_o) satisfy the Condition 3?

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.

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

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

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

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

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

☑ 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

[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.

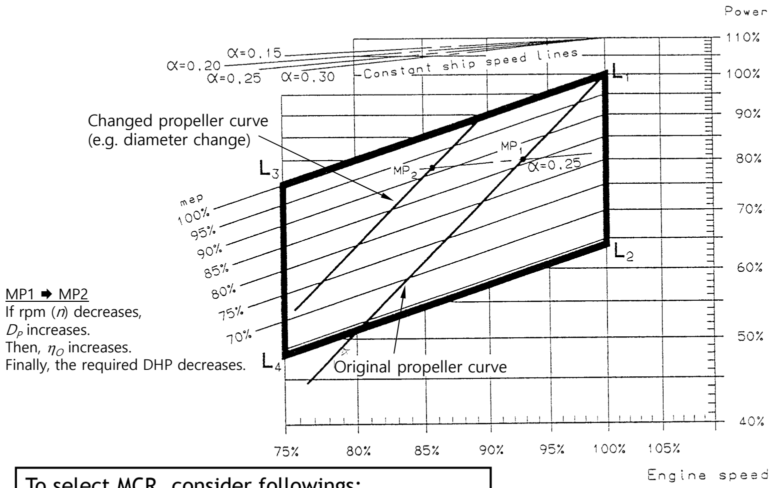
$$P_2 = P_1 \cdot \left(\frac{n_2}{n_1}\right)^{\alpha}$$

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)

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

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



To select MCR, consider followings:
- Smaller engine power and lower engine speed
- Derated power: NMCR ➡ DMCR
- Fuel oil consumption
- Propeller operating range

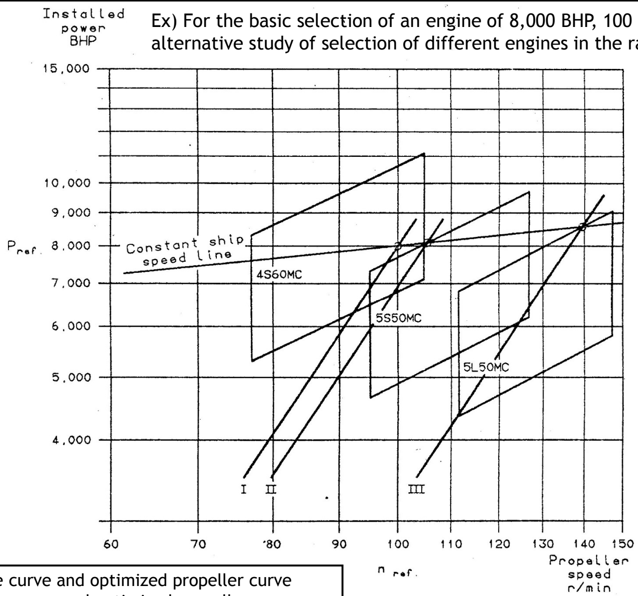
For any combination of power and speed, **each point on the constant ship speed line gives the same ship speed**.

α: Constant ship speed coefficient
0.25~0.30 for bulk carriers and tankers
0.15~0.25 for reefers and container vessels

71

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

Ex) For the basic selection of an engine of 8,000 BHP, 100 rpm, alternative study of selection of different engines in the range of 100~150 rpm

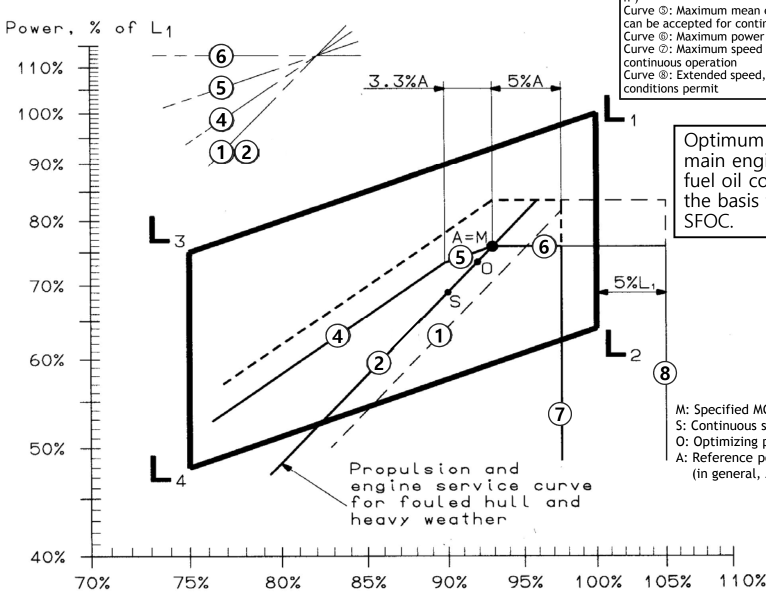


I: 4S60MC engine curve and optimized propeller curve
II: 5S50MC engine curve and optimized propeller curve
III: 5L50MC engine curve and optimized propeller curve

72

[Appendix] Optimum Operating Point of Main Engine Considering the Fuel Oil Consumption

Curve ①: Propulsion curve, clean hull (**light running**)
Curve ②: Propulsion curve, fouled hull and heavy weather (**heavy running**)
Curve ④: Torque/speed limit at which an ample air supply is available for combustion and imposes a limitation on the maximum combination of torque and speed (proportional to n^2)
Curve ⑤: Maximum mean effective pressure level, which can be accepted for continuous operation
Curve ⑥: Maximum power for continuous operation
Curve ⑦: Maximum speed which can be accepted for continuous operation
Curve ⑧: Extended speed, provided torsional vibration conditions permit



Optimum operating point of main engine considering the fuel oil consumption ("O") is the basis for the guarantee SFOC.

M: Specified MCR of engine (MCR)
S: Continuous service rating of engine (NCR)
O: Optimizing point of engine (O)
A: Reference point of load diagram
(in general, A = M)

* SFOC (Specific Fuel Oil Consumption)

73

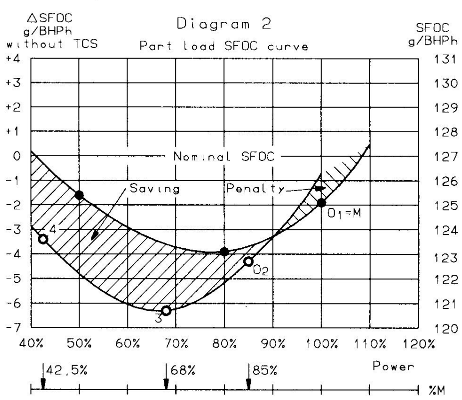
[Appendix] Example of Selection of Optimum Point "O" Considering SFOC (1/2)

Data at nominal MCR (L_1):	
Power: 100% (L_1)	21,360 BHP
Speed: 100% (L_1)	106 r/min
Nominal SFOC	127 g/BHPh

Data of optimising point (O):	O_1	O_2
Power: 100% of (O)	17,730 BHP	15,100 BHP
Speed: 100% of (O)	95.4 r/min	90.1 r/min
SFOC found:	125 g/BHPh	122.6 g/BHPh

L70MC	Nominal SFOC in g/BHPh 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 x 0.85 of M = 68% M
Point 4: is 50% of O_2 = 0.50 x 0.85 of M = 42.5% M



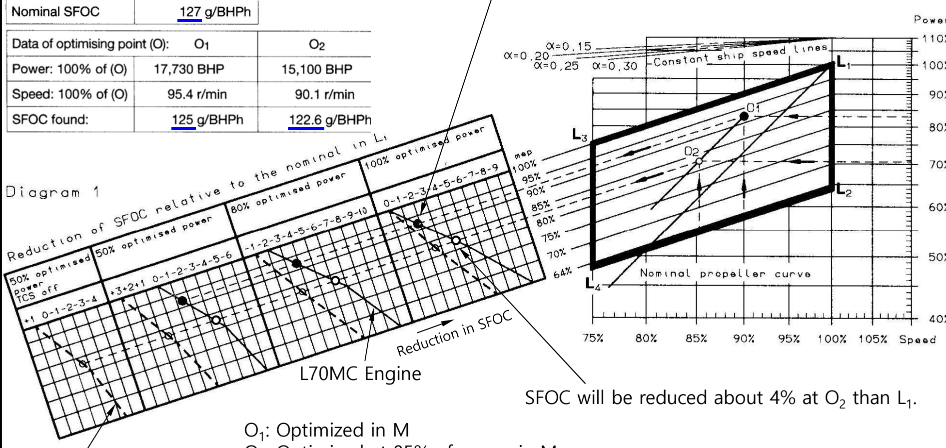
74

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

Data at nominal MCR (L_1):	
Power: 100% (L_1)	21,360 BHP
Speed: 100% (L_1)	106 r/min
Nominal SFOC	127 g/BHPh

Data of optimising point (O):	O_1	O_2
Power: 100% of (O)	17,730 BHP	15,100 BHP
Speed: 100% of (O)	95.4 r/min	90.1 r/min
SFOC found:	125 g/BHPh	122.6 g/BHPh

SFOC will be reduced about 2% at O_1 than L_1.



SFOC will be reduced about 4% at O_2 than L_1.

O_1: Optimized in M

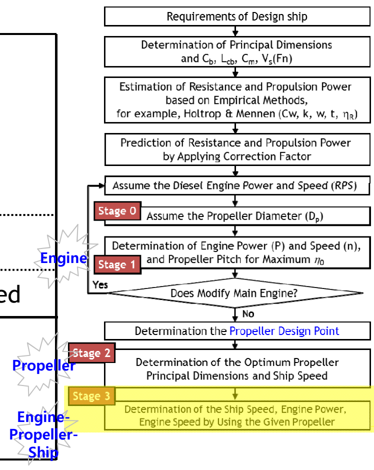
O_2: Optimized at 85% of power in M

∴When we use L70MC engine, O_2 has smaller SFOC than O_1. Thus, O_2 can be selected as a new M.

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

- The propeller principal dimensions have been determined.

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



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

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

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

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

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

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

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

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

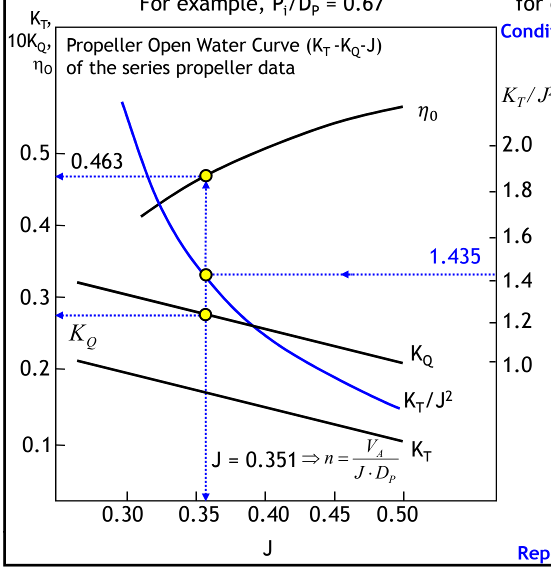
$$c_2 = \frac{R_T}{(1-t)\rho D_P^{\ 2} V_A^{\ 2}}$$

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

Calculation By Hand

2 Calculate P ($DHP\cdot\eta_R$) 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 $\frac{K_T}{J^2} = c_2, \quad c_2 = \frac{R_T}{(1-t)\rho D_P^2 V_A^2}$

$P = DHP\cdot\eta_R$ **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

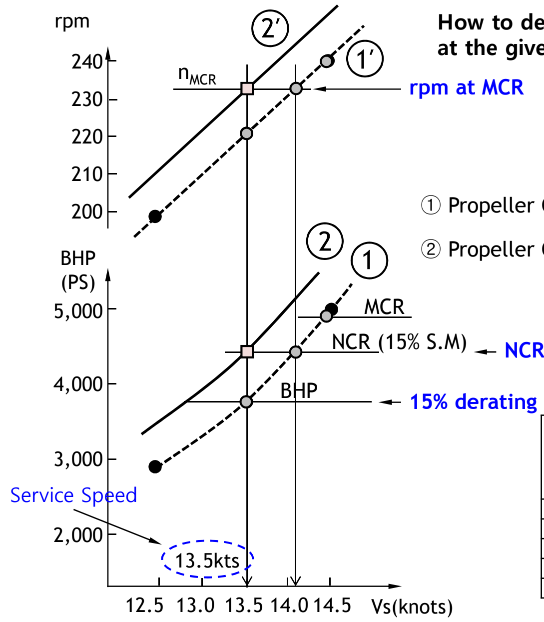
V_s [kts]	③ EHP in calm water [PS]	w	t	① K_T/J^2	② J	n [RPM]	④ η_O	③ BHP in calm water
12.5	1686	0.381	0.224	1.374	0.355	202	0.470	2867
13.0	1965	0.380	0.223	1.418	0.352	212	0.465	3367
13.5	2240	0.379	0.221	1.435	0.351	221	0.463	3844
14.0	2536	0.377	0.219	1.443	0.348	232	0.460	4376
14.5	2898	0.375	0.216	1.470	0.345	243	0.457	5020

Repeat this procedure by varying ship speed.

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

Calculation By Hand

How to determine service speed of the ship at the given power (NCR) [Example 1]



① Propeller Curve in Calm Water

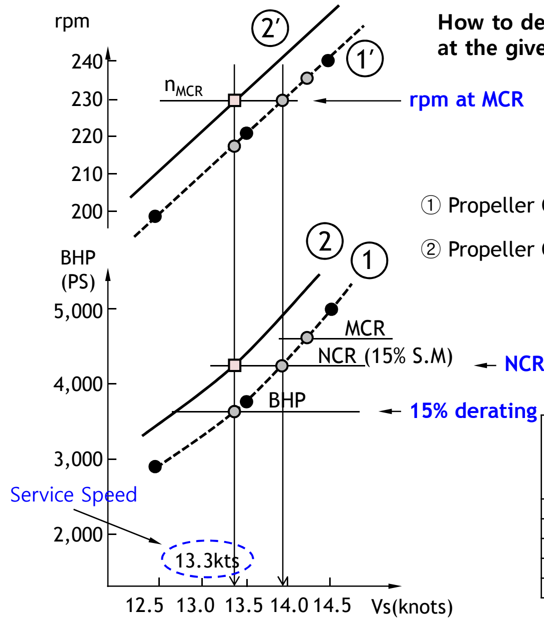
② Propeller Curve with Sea Margin

V_s [kts]	EHP in calm water [PS]	w	t	K_T/J^2	J	n [RPM]	η_O	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

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

Calculation By Hand

How to determine service speed of the ship at the given power (NCR) [Example 2]



① Propeller Curve in Calm Water

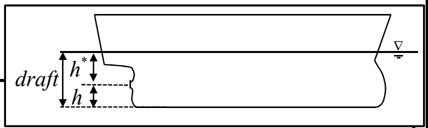
② Propeller Curve with Sea Margin

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

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

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

☑ Propeller Design Point

NCR = 3,825 [PS]

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

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

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

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

* 1 [PS] = 0.73575 ≅ 0.736 [kW]
* η_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 ≈ 0.736 [kW]

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

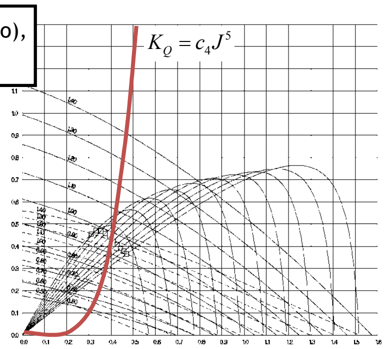
3 Express the Condition 1 as $K_Q = c_4 J^5$.

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

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

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

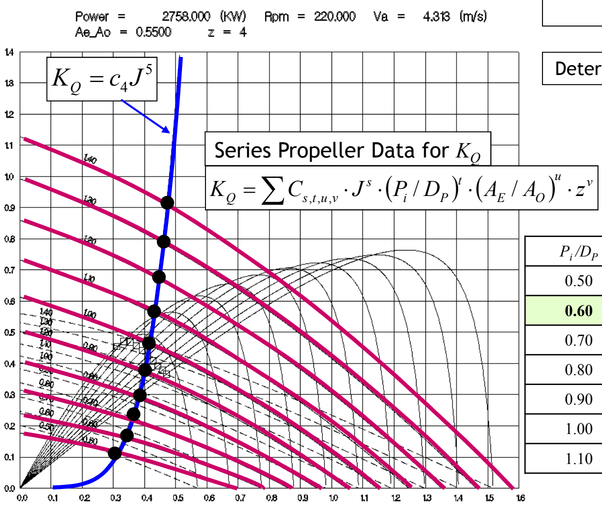
4 By using the set of K_T, K_Q, η_0 (varied with pitch ratio), determine J_x to maximize η_0 and K_T at J_x.



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

$P = 2,457[KW],\ n = 220,\ V_A = 4.313[m/s],$
$A_E / A_O = 0.55,\ \ z = 4$

Calculation of intersection points
↓
Determination of Js for the intersection points
↓
Determination of J, P_i/D_P to maximize η_O



P_i/D_P	J	η_0	K_T
0.50	0.3105	0.4542	0.1049
0.60	**0.3323**	**0.4711**	**0.1428**
0.70	0.3535	0.4684	0.1818
0.80	0.3737	0.4570	0.2215
0.90	0.3927	0.4418	0.2610
1.00	0.4105	0.4252	0.2999
1.10	0.4271	0.4086	0.3378

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

5 | By using J_x from Step 4, calculate n_x.

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

6 | Do the values of D_{Px} and $K_{T,x}$ satisfy the Condition 2?

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

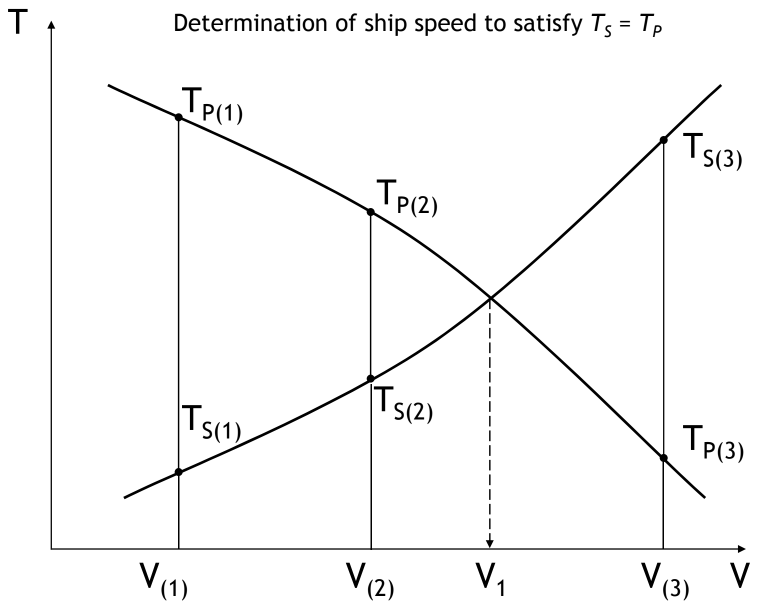
The thrust which is produced by the propeller (T_P)

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

If $T_S < T_P$,

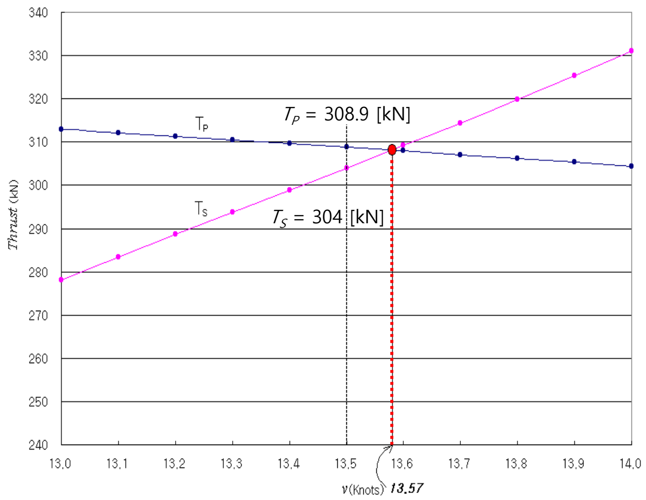
the ship can go faster. ➡ Assume higher ship speed and repeat steps 3 to 6.

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



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

Propeller Principal Dimensions for Expanded Blade Area Ratio (A_E/A_O) of 0.55



A_E/A_O	0.55
V (knots)	13.57
w	0.3788
V_A (knots)	8.4289
J	0.3339
η_O	0.4727
D_P (m)	3.5416
Pi/D_P	0.60
T_P (kN)	308.1892
T_S (kN)	307.6054
$(T_P - T_S)$	Error = 0.5838

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

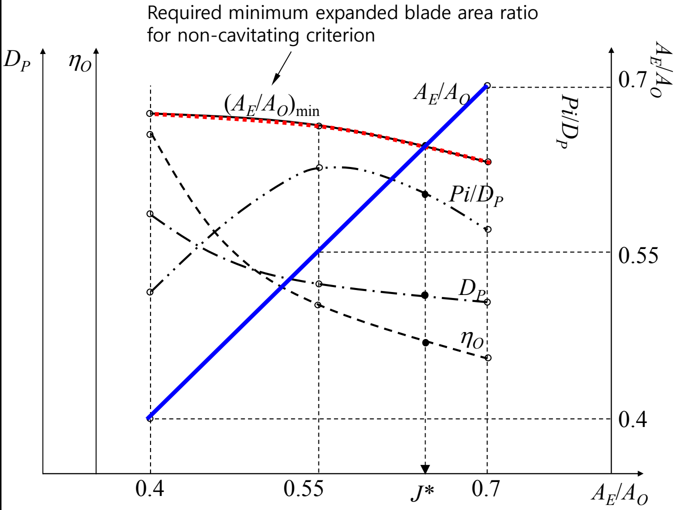
7	Does the expanded area ratio (A_E / A_o) satisfy the Condition 3?

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

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

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

Check for the Required Minimum Expanded Blade Area Ratio



Final Result of Propeller Principal Dimensions

A_E/A_O	0.65
V (knots)	13.48
w	0.3791
V_A (knots)	8.3696
J	0.3329
η_O	0.4650
D_P (m)	3.5278
Pi/D_P	0.65
K_T	0.1411
K_Q	0.0161
T_P (kN)	301.1685
T_S (kN)	302.9741
$(T_P - T_S)$	-1.8056
A_E/A_O (Keller)	0.6401

Reference Slides

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

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.**

$w = V_s - V_A$ (V_s: Ship velocity, V_A: Flow velocity at its stern)

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

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

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 $V_A > V_s$, **nagative** 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 trust 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,**

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

Relative Rotation Efficiency

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

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

☑ **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)**

η_R **= 1.0~1.1 for single-screw ship**
= 0.95~1.0 for twin-screw ship

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.**

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

where,

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

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

η_O: Propeller effiency 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

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

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: Presuure at some point of a blade

p_v: Vapor presuure of water

Cavitation on a Propeller (3/3)