CONFIDENTIAL

UNIVERSITI KUALA LUMPUR
Malaysian Institute of Marine Engineering Technology

FINAL EXAMINATION
JANUARY 2016 SESSION

SUBJECT CODE : LNB 30203
SUBJECT TITLE : SHIP RESISTANCE AND PROPULSION
LEVEL : DEGREE
TIME / DURATION : 9.00 am – 12.00 pm / (3 HOURS)

DATE : 26 MAY 2016

INSTRUCTIONS TO CANDIDATES

1. **Please read the instructions given in the question paper CAREFULLY.**
2. **This question paper is printed on both sides of the paper.**
3. **Please write your answers on the answer booklet provided.**
4. **Answer should be written in blue or black ink except for sketching, graphic and illustration.**
5. **This question paper consists of TWO (2) sections; Section A and B. Answer all questions in Section A; For Section B, answer THREE (3) questions only.**
6. **Answer all questions in English only.**

THERE ARE10 PAGES OF QUESTIONS, INCLUDING THIS PAGE.

SECTION A (Total: 40 marks)

INSTRUCTION: Answer ALL questions

Question 1

a) If the total resistance coefficient of a ship is given by the ITTC 1978 procedure as $C_{TS} = (1+k)C_{FS} + C_R + \Delta C_F + C_A + C_{AAS}$, show that this expression can also be written as;

$$C_{TS} = C_{TM} + (1+k)(C_{FS} - C_{FM}) + \Delta C_F + C_A + C_{AAS}.$$

(2.5 marks)

b) The Froude's law of comparison states that "The residuary resistance of geometrically similar ships are in the ratio of the cubes of their linear dimensions when their speeds are in the ratio of the squares of their lengths" Is this statement correct or incorrect? Derive the scale ratio of the residuary resistance.

(2.5 marks)

c) The general expression for a wave can be written in the form of $V_W^2 = \frac{gL_W}{2\pi}\tanh\frac{2\pi h}{L_W}$. Determine the expressions for deep and shallow water conditions.

(2.5 marks)

d) The resistance of a vessel is greater in shallow water than in deep water conditions. Is this statement correct or incorrect? Explain why?

(2.5 marks)

e) The fluid flow characteristics for geometrically similar model and full scale are not the same. Explain why? What will be the physical correction used in model testing in a towing tank to correct the flow to be identical to the full scale flow?

(2.5 marks)

f) Describe two ways of minimizing a wave resistance of a ship? Explain how bulbous bow plays a role in this.

(2.5 marks)

g) The dimensional analysis of the resistance of a ship can be expressed in its final form of

$$\frac{R}{1/2\rho SV^2} = f\left[-,-,\frac{p}{\rho V^2}\right]$$

Filled in the two missing dimensionless number and describe what are these two numbers called.

(2.5 marks)

h) Why a residuary resistance curve in some cases do exhibits a series of 'hump' and 'hollows'? Explain why?

(2.5 marks)

(Total 20 marks)

Question 2

a) The dimensional analysis of the thrust of a ship propeller can be expressed in its final form of

$$\frac{T}{\frac{1}{2}\rho D^2 V_A{}^2} = f\left[\frac{gD}{V_A{}^2}, -, -, \frac{\upsilon}{V_A D}\right]$$

Filled in the two missing dimensionless number and describe what are these two numbers called.

(2.5 marks)

b) Why does the angle of the propeller blade change with increasing distance from the hub?

(2.5 marks)

c) If the open water efficiency is defined as $\eta_O = \frac{T.V_A}{2\pi nQ}$, show that the open water efficiency can also be defined as $\eta_O = \frac{J}{2\pi}.\frac{K_T}{K_Q}$.

(2.5 marks)

d) If the scaling ratio for the propeller diameter is $\frac{D_S}{D_M} = \lambda$ and the advance velocity is $\frac{V_{AS}}{V_{AM}} = \sqrt{\lambda}$, prove that the scaling ratio for the propeller thrust can be defined as $\frac{T_S}{T_M} = \frac{\rho_S}{\rho_M}.\lambda^3$.

(2 .5 marks)

e) When advance ratio is maintained model propeller revolutions are smaller than a geometrically similar full scale propeller. Is this statement correct or incorrect? Explain why.

(2.5 marks)

f) From a design point of view, what can be done to increase the propeller efficiency? Refer to two (2) design parameters that do not alter the hull design significantly.

(2.5 marks)

g) Explain clearly, using clear sketches for the following forms of cavitation:

I. Tip vortex cavitation

II. Sheet cavitation on the leading edge of a propeller blade

Name the testing facility to observe the forms of cavitation as mentioned above.

(2.5 marks)

h) How can cavitation on a propeller be reduced? Name two (2) measures and explain.

(2.5 marks)

(Total 20 marks)

SECTION B (Total: 60 marks)

INSTRUCTION: Answer three (3) questions only

Question 3

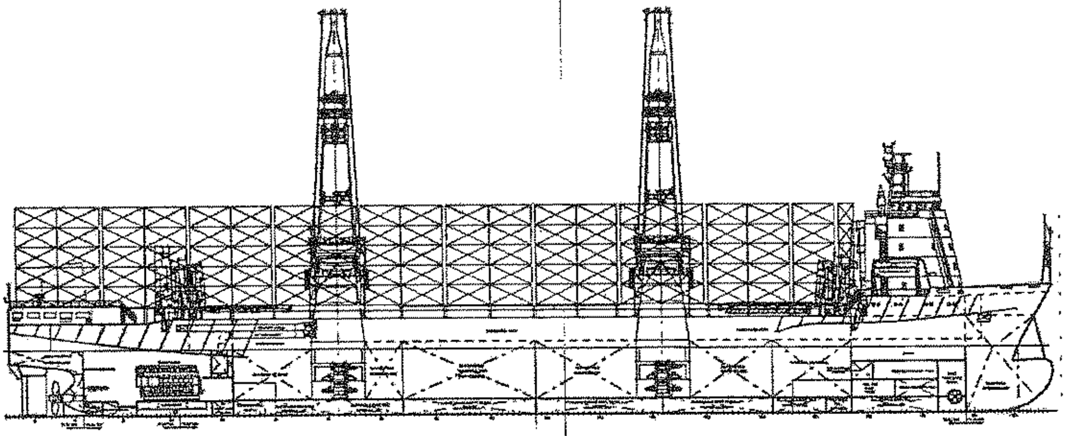


Figure 3.1 The longitudinal view of a proposed 18,680 dwt multi-purpose carrier with L = 142 m. Source: Grubisic et al (2008) – A 18680 dwt Multipurpose / Heavy Lift Cargo Vessel, Part 1, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.

You are an engineer working in a commercial towing tank facility. For a client Global Jaya Shipping, you have tested two different designs, design A and design B (see Table 3.1) for a 142 m multi-purpose carrier (shown in Figure 3.1). Both designs have the same length, same displacement and same speed and were tested at 1/71 model scale. Surprisingly, both have the same drag of 0.9 N regarding to your towing tank results.

a) Which design would you suggest to your client, Global Jaya Shipping? Use ITTC 1978 approach including form factor *(1 + k)* of 1.12 to support your suggestion. Assume the correlation allowance, C_A to be 0.0004. The air resistance coefficient C_{AAS}, was calculated to be 0.0000386.

(15 marks)

b) Based on your experience as a ship designer, which design would you expect to be more beneficial from a resistance point of view at higher speed when wave-making dominates the total resistance? Explain.

(5 marks)

Table 3.1 Main particulars of two proposed designs of a multi-purpose carrier.

Parameter	units	design A	design B
Speed	[kn]	12.0	12.0
Displacement	[m^3]	13,500	13,500
Length	[m]	142	142
Breadth	[m]	23.4	17.8
Draft	[m]	5.00	7.10
wet. surface area	[m^2]	2540	2360
model scale ratio	-	1/71.0	1/71.0
drag at model scale	[N]	0.900	0.900

(Total 20 marks)

Question 4

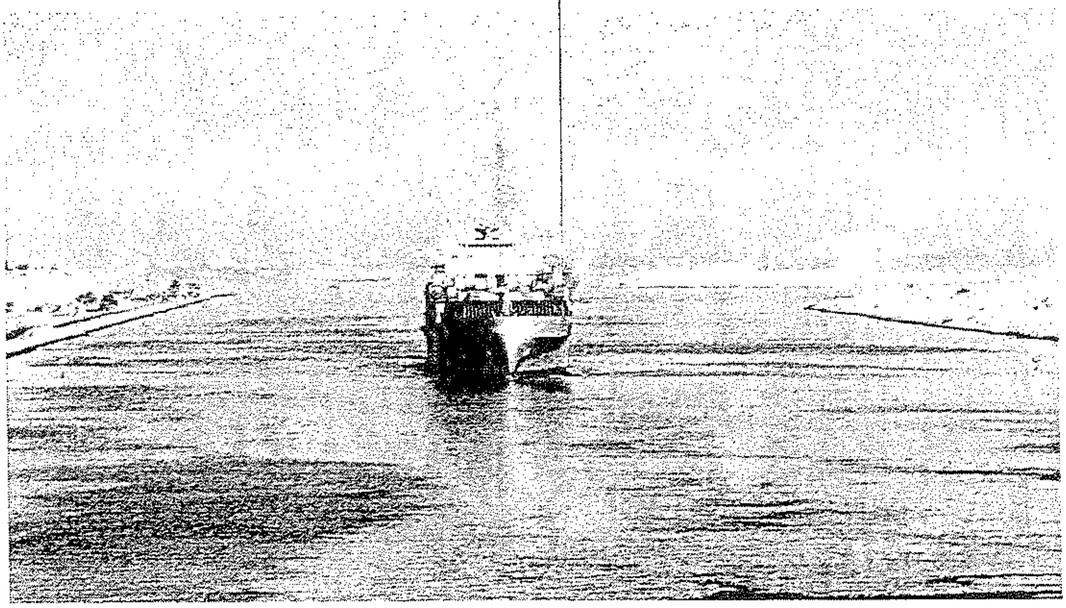


Figure 4.1 'Coastal Isle' cruising in the Suez Canal, Egypt. The dimensions of the canal are shown in Figure 3.2

A container ship 'Coastal Isle' cruising at speed 21 knots in deep water moves into the Suez Canal as shown in Figure 3.1. The channel dimensions are shown in Figure 3.2. The ship has the following parameters:

$L = 147$ m $B = 15.4$ m $T = 4.5$ m $C_B = 0.7$

Using the enclosed diagram in **Annex 1**, estimate the reduction in velocity as a percentage of deep-water velocity,

a) Using Landweber curve (curve $\frac{V_h}{V_I}$ to base of $\frac{\sqrt{A_X}}{R_H}$)

(10 marks)

b) Using Schlictings curve (curve $\frac{V_I}{V_\infty}$ to base of $\frac{V_\infty}{\sqrt{gh}}$)

(4 marks)

c) Using Schlictings curve (curve $\frac{V_h}{V_I}$ to base of $\frac{\sqrt{A_X}}{h}$)

(4 marks)

d) State on which method that are recommended and why?

(2 marks)

State all assumptions. The midship coefficient of the ship is given by $C_M = 0.984 + 0.067 (C_B - 0.6)$. Plot the intersections in the enclosed diagram given and attached it to the answer script.

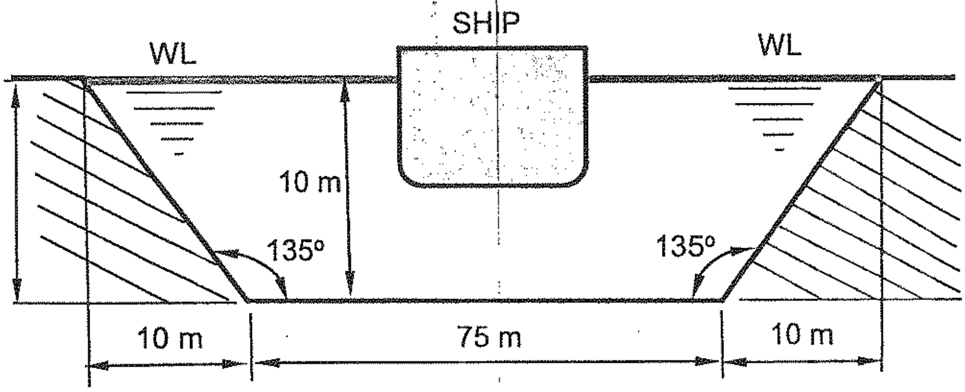


Figure 4.2 The dimensions of the Manchester Ship Canal

(Total 20 marks)

Question 5

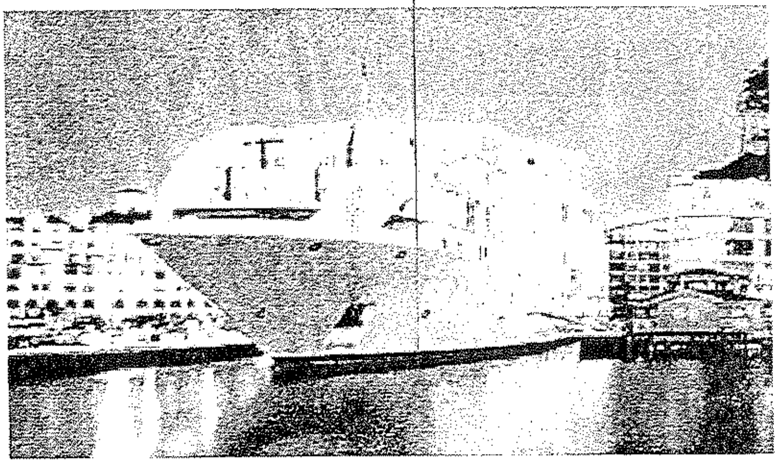


Figure 5.1 The 142m long seven-deck floating hotel ship, *Sunborn Gibraltar* (image taken from Shiprepair & Conversion Technology, RINA, 1st Quarter 2014)

The propellers for a floating ship, *Sunborn Gibraltar* (shown in Figure 5.1) are to be designed for a speed of 25 knots. From the point of view of minimizing vibration and cavitation, the propellers are to have 3 blades and a blade area ratio of 0.65. The ship has a twin screw installation. An early resistance prediction reveals that the total resistance for the ship at full scale is 625kN. The propeller rotational shaft speed is required to be 230 RPM to suit the main power plant. The wake fraction is 0.14 and the thrust deduction factor is 0.16. Your task as the ship designer are as the followings:

a) Using the Wageningen B-series K_T-K_Q-J chart (see Annex 2) for this blade area ratio, estimate the required pitch to diameter ratio of these screws, the propeller diameter and the efficiency at which they will operate. To calculate this you must tabulate J and K_T values using the K_T-J^4 relationship.

(15 marks)

b) If the maximum propeller diameter that can be fitted after taking into account all required clearances is 3.2 m, calculate the new open water efficiency and the new pitch ratio required, as a result of limiting the propeller diameter.

(5 marks)

(Total 20 marks)

Question 6

For Parts a) and b) assume the following values: $w = 0.25$, $t = 0.18$, $\eta_R = 0.97$.

a) A new futuristic luxury cruise liner, *le France* (shown in Figure 6.1), designed for a North Atlantic route is to have a vessel speed of 25 knots. Early resistance prediction reveals that the vessel will be installed with a 19,600 kW internal combustion engine with a shaft speed of 180 RPM. Using the B_P-δ for propeller Wageningen B4.70 (see Annex 3) and assuming the shafting efficiency to be 0.98, calculate the open water efficiency, pitch-diameter ratio and the propeller diameter.

(10 marks)

b) Using Burrill's cavitation diagram (see Annex 4), determine the amount of cavitation if the propeller shaft axis immersion is 3.5 m.

(10 marks)

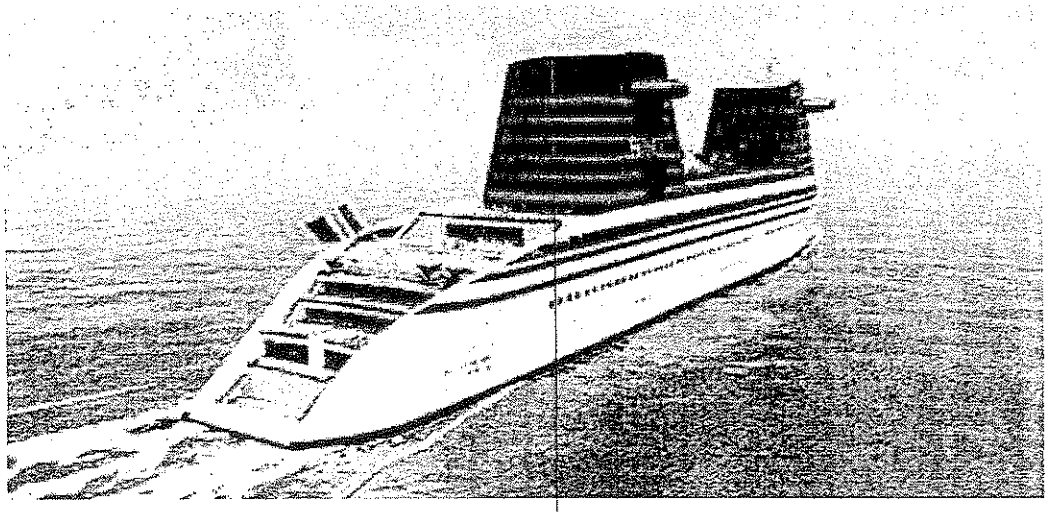


Figure 6.1 The new 260m long luxury cruise liner, *le France*, capable of accommodating 550 passengers with two funnel-shaped super structures, each will house spacious living areas, restaurants and salons. (Image taken from Oceanshaker.com)

(Total 20 marks)

Question 7

You are a towing tank engineer and are required to make a scale effect correction to the propeller thrust and torque using the method proposed by Lindgren et al (1978) which is currently used in the ITTC 1978 Extrapolation procedure no 7.5-02-03-01.4 (see Annex 6) to an open water propeller test results tabulated in Table 7.1 below.

Table 7.1 The open water test results for a 1/29 scaled propeller running at 21 rev/secs.

V_A (metre /sec)	Q (Newton.metre)	T (Newton)
0.29	0.46	24.46
0.8	0.40	21.16
1.31	0.32	17.64
1.81	0.26	12.48

The open water test was done in a towing tank, with the advance velocity, V_A varied at each run as listed in the first column in Table 7.1. The propeller was set at a constant shaft speed of 21 rev/sec. The model propeller is 1:29 of the full scale propeller.

a) Calculate the corrected full scale propeller thrust and torque coefficient for ***J = 0.52***. The propeller drawing is shown in Annex 2 (all units in meter). You may find all the necessary data in the drawing. (Some interpolations are required).

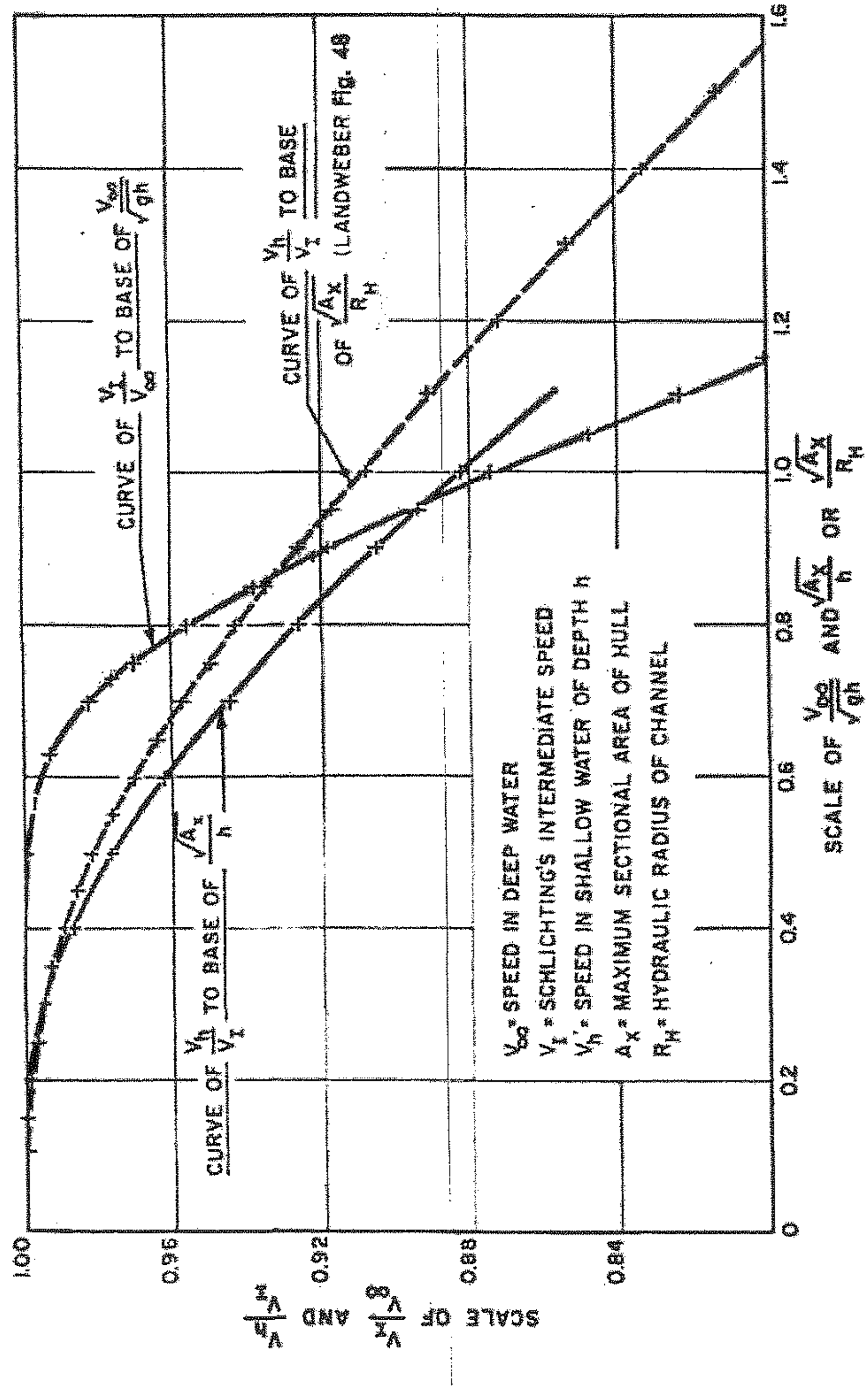
(15 marks)

b) If this open water test was conducted in a cavitation tunnel with a circulation speed of 5.0 m/s, maintaining ***J* at 0.52**, determine the new rate of rotation for the same model propeller and the new local Reynolds number at 0.75 radius fraction of the propeller blade.

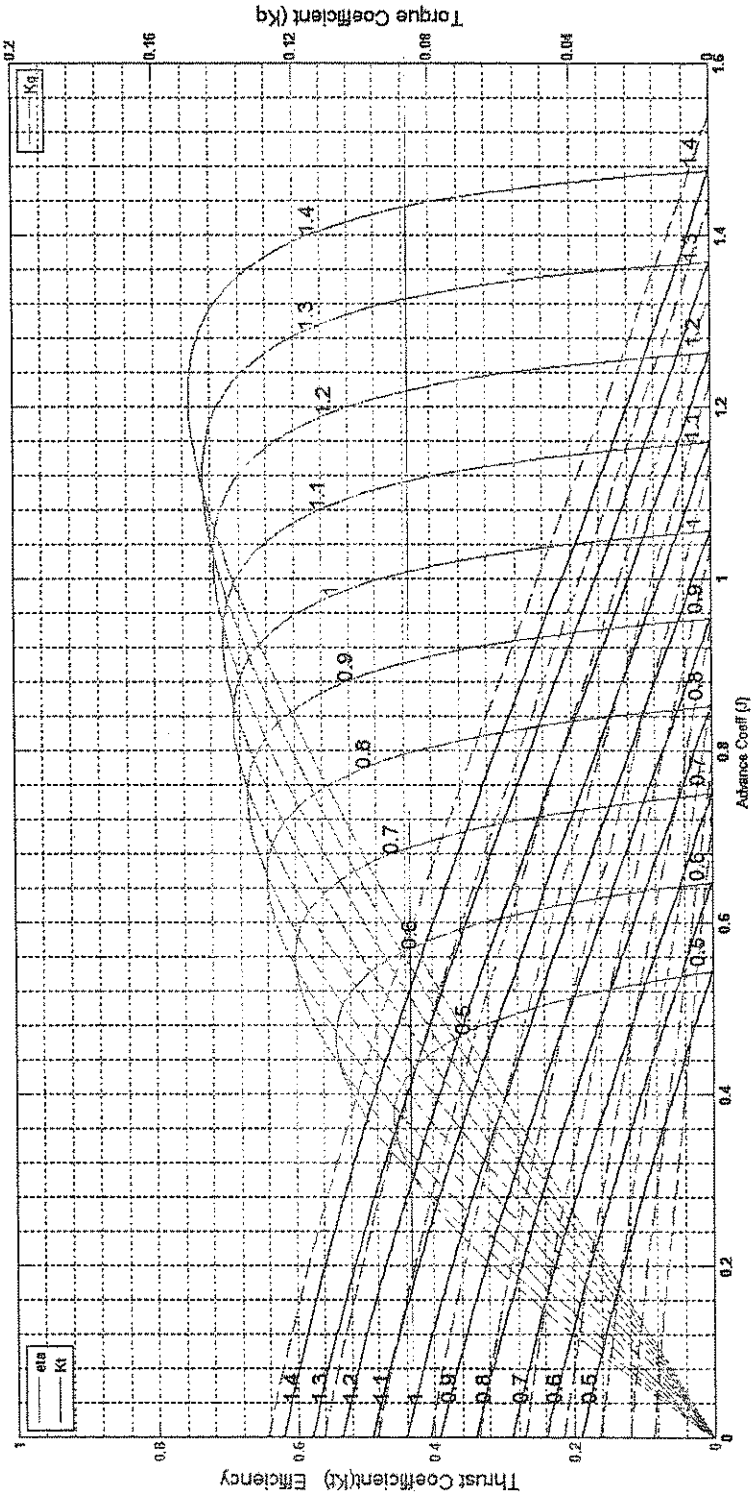
(5 marks)

(Total 20 marks)

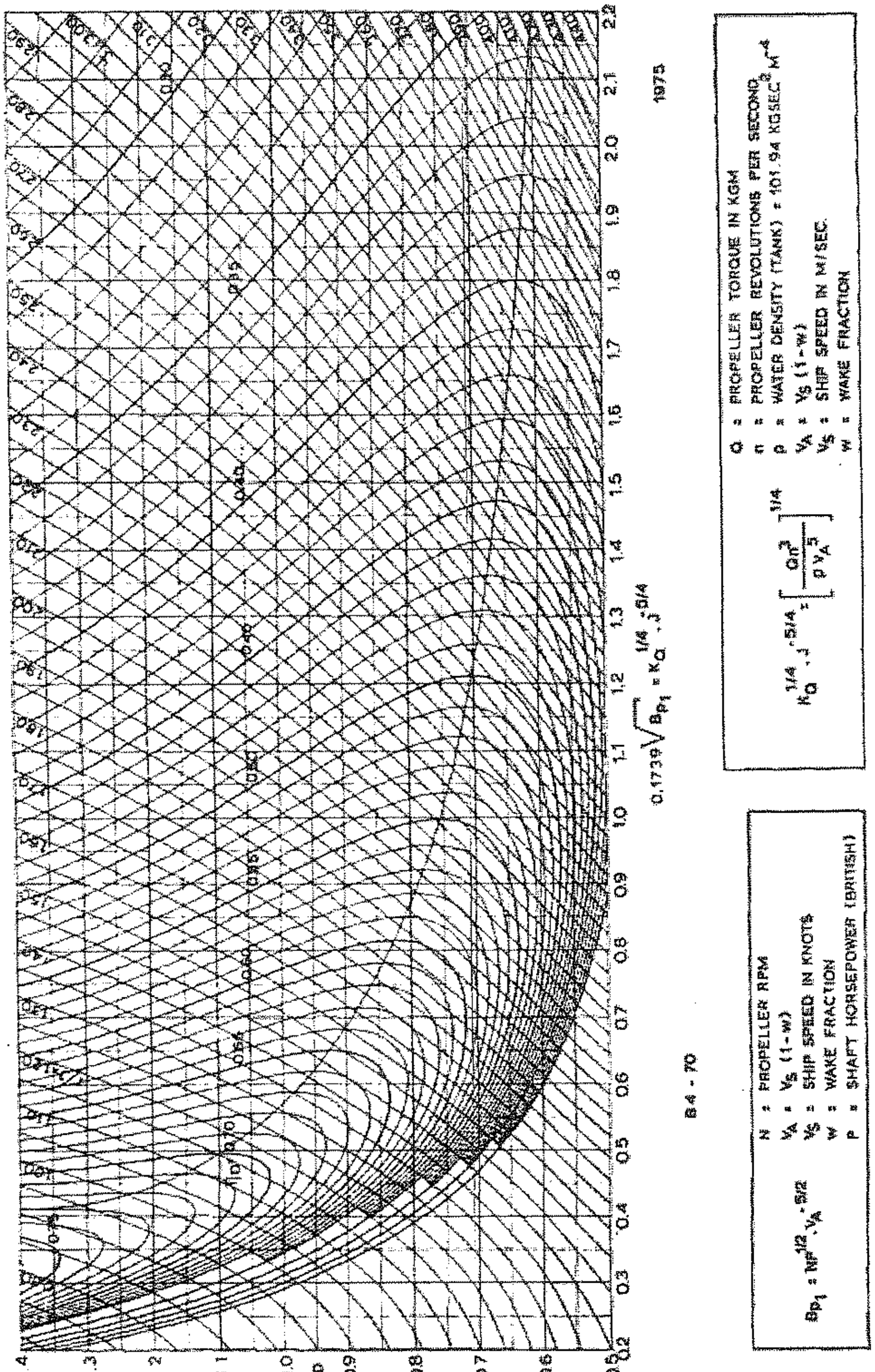
END OF QUESTION



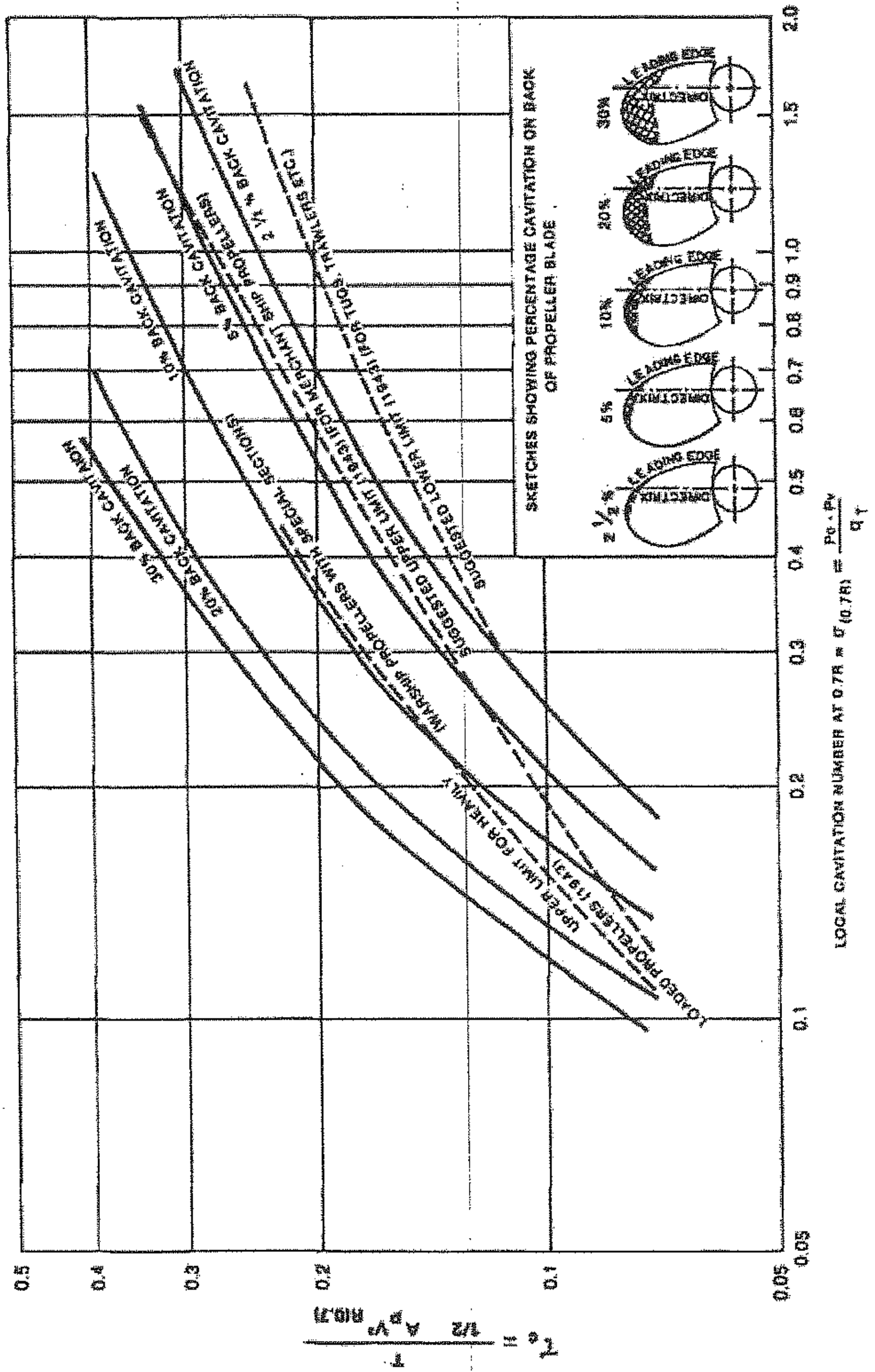
Annex 1 Curves of velocity ratios for calculating resistance in shallow water (Schlichting)



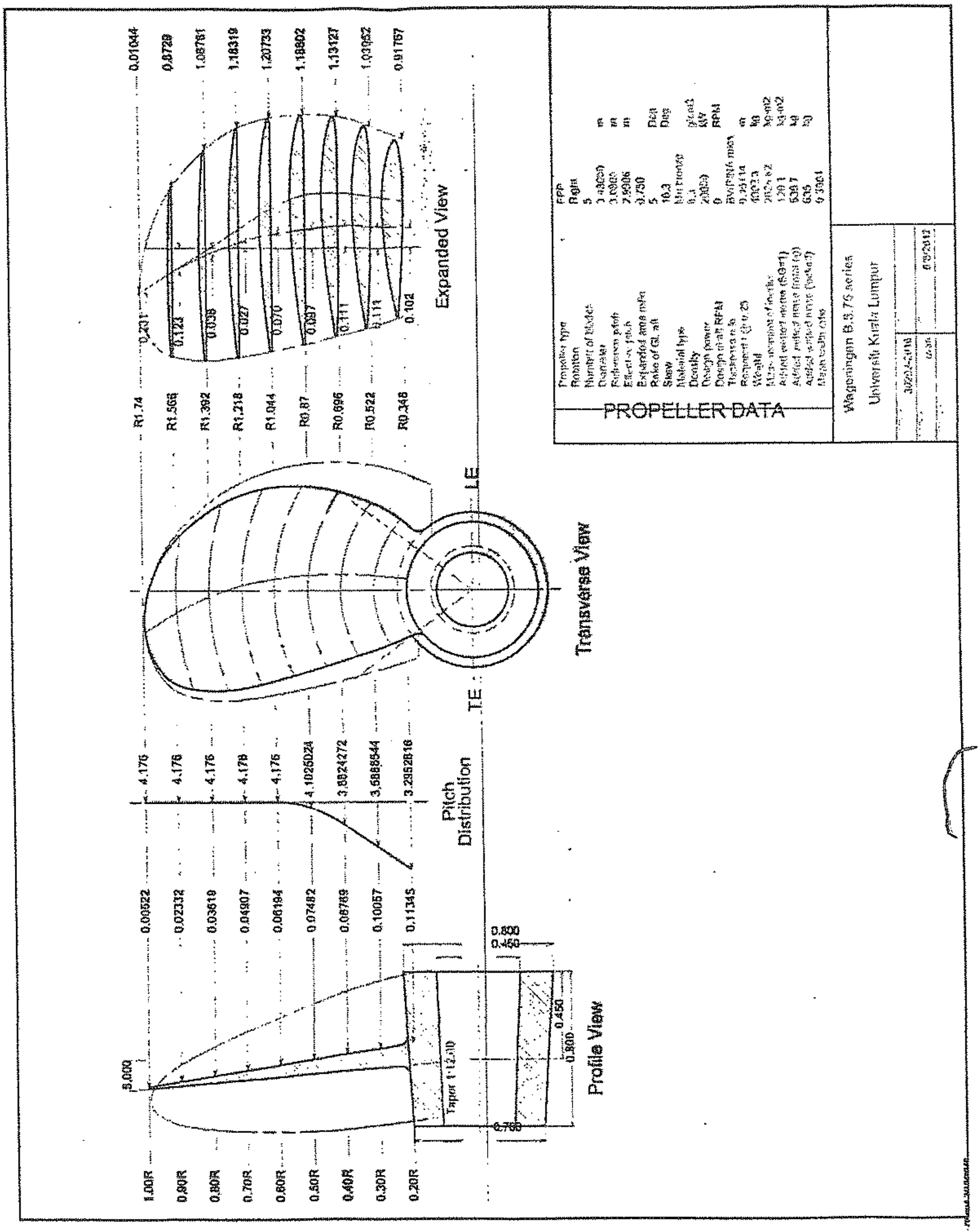
Annex 2 Wageningen B series K_T-K_Q-J chart for 3 blades propeller with BAR 0.65



Annex 3 *B_P-δ* chart for 4 blades propeller with BAR 0.70



Annex 4 Burrill chart for cavitation check



Annex 5 Propeller drawing for a 5 bladed propeller.

USEFUL FORMULA & DATA

Density

Fresh water	= 1000 kg/m^3
Sea water	= 1025 kg/m^3
Air at 15°C	= 1.225 kg/m^3

Kinematic viscosity

Fresh water at 15°C = 1.139 x 10^{-6} m^3/s
Sea water at 15°C = 1.183 x 10^{-6} m^3/s
Fresh water at 27°C = 0.854 x 10^{-6} m^3/s

Granville Line Formulation

$$C_{FO} = \frac{0.0776}{(\log_{10} \mathrm{Re} - 1.88)^2} + \frac{60}{\mathrm{Re}}$$

Hughes Line Formulation

$$C_{FO} = \frac{0.066}{(\log_{10} \mathrm{Re} - 2.03)^2}$$

ATTC Line Formulation

$$\frac{0.242}{\sqrt{C_F}} = \log_{10}(\mathrm{Re}.C_F)$$

ITTC 1957 Model Ship Correlation Formulation

$$C_F = \frac{0.075}{(\log_{10} \mathrm{Re} - 2)^2}$$

Non-dimensional coefficient for total resistance

$$C_T = \frac{R_T}{\frac{1}{2}\rho S V^2}$$

ITTC 1978 Resistance Prediction – Updated 2014

The total ship resistance coefficient without bilge keels is given by;

$$C_{TS} = C_{FS}(1+k) + C_R + \Delta C_F + C_A + C_{AAS}$$

where;

C_{FS} = frictional coefficient of ship according to the ITTC 1957 ship model correlation line

C_R = residual resistance calculated from the total and viscous resistance of the model

$$= C_{TM} - (1+k)C_{FM}$$

Bilge keels can be allowed for by multiplying the C_{FS} and C_A terms by the ratio

$\frac{S + S_{BK}}{S}$, S_{BK} = surface area of the bilge keels

The correlation allowance is calculated from

$$C_A = (5.68 - 0.6\log \mathrm{Re}) \times 10^{-03}$$

The roughness allowance is calculated from

$$\Delta C_F = 0.044\left[\left(\frac{k_s}{L_{WL}}\right)^{\frac{1}{3}} - 10.\mathrm{Re}^{-\frac{1}{3}}\right] + 0.000125$$

k_S can be taken as 150 x 10^{-6} m.

Air resistance is calculated from

$$C_{AAS} = C_{DA}\frac{\rho_A . A_{VS}}{\rho_S . S_S}$$

A_{VS} = transverse projected area of ship above the waterline

Propeller scale effect correction

$$K_{TOS} = K_{TO} - \Delta K_T$$
$$K_{QOS} = K_{QO} - \Delta K_Q$$

$$\Delta K_T = -\Delta C_D \times 0.3 \frac{P}{D} . \frac{cZ}{D}$$

$$\Delta K_Q = \Delta C_D \times 0.25 \frac{cZ}{D}$$

$$\Delta C_D = C_{DM} - C_{DS}$$

$$C_{DM} = 2\left(1 + 2\frac{t}{c}\right)\left[\frac{0.044}{R_{nco}{}^{1/6}} - \frac{5}{R_{nco}{}^{2/3}}\right]$$

$$C_{DS} = 2\left(1 + 2\frac{t}{c}\right)\left[1.89 + 1.62 \log_{10} \frac{c}{k_p}\right]^{-2.5}$$

$$k_p = 30 \times 10^{-6} m$$

$$R_{nco} = \frac{c\sqrt{V_A{}^2 + (2\pi nr)^2}}{\upsilon}$$

Emerson Blockage correction

$$\frac{\Delta V}{V} = 1.65 \frac{m_3}{1 - m_3 - F_{nh}{}^2}$$

$$m_1 = \frac{A_M}{A}$$

$$m_2 = \frac{\nabla}{A \times L}$$

$$m_3 = \frac{m_1 + m_2}{2}$$

$$F_{nh} = \frac{V}{\sqrt{gh}}$$

A_M : midship sectional area f model

A : tank cross sectional area

∇ :model volume displacement

L : model length

V : model speed before correction

Schuster Blockage correction

$$\frac{\Delta V}{V} = \frac{m_1}{1 - m_1 - F_{nh}{}^2} + \left(1 - \frac{R_V}{R_T}\right) . \frac{2}{3} . F_{nh}{}^{10}$$

Ship Flow of Transmission of Power

$$P_E = R_T V_S$$

$$P_T = T . V_A$$

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

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

$$J = \frac{V_A}{nD}$$

$$\eta_O = \frac{K_T}{K_Q} . \frac{J}{2\pi}$$

$$\eta_H = \frac{P_E}{P_T} = \frac{R_T . V_S}{T . V_A}$$

$$\eta_B = \frac{P_T}{P_D}$$

$$\eta_D = QPC = \frac{P_E}{P_D} = \eta_R \eta_O \eta_H = \frac{(1-t)}{(1-w)} \eta_B$$

Propeller Torque $Q = \dfrac{P_D}{2\pi n}$

Propeller Thrust $T = \dfrac{P_T}{V_A}$

$$\eta_R = \frac{\eta_B}{\eta_O} = \frac{P_T}{P_D} . \frac{P_{DO}}{P_{TO}}$$

Thrust identity; $P_T = P_{TO}$; $\therefore \eta_R = \dfrac{P_{DO}}{P_D}$

Torque identity; $P_D = P_{DO}$; $\therefore \eta_R = \dfrac{P_T}{P_{TO}}$

$$\frac{P_E}{P_B} = \eta_S \eta_R \eta_O \eta_H$$

$t = \dfrac{T - R_T}{T}$ or $\dfrac{R_T}{T} = 1 - t$

$\omega = \dfrac{V_S - V_A}{V_S}$ or $\dfrac{V_A}{V_S} = 1 - \omega$

Apparent Slip $= \left(1 - \dfrac{V}{Pn}\right)$

True Propeller Slip $= \left(1 - \dfrac{V_A}{Pn}\right)$

Propeller Design using Charts and Polynomials

Known power, RPM and advance velocity

$$\frac{K_Q}{J^5} = \frac{Q}{\rho n^2 D^5}\left(\frac{nD}{V_A}\right)^5 = \frac{Qn^3}{\rho V_A^5}$$

Known power, diameter and advance velocity

$$\frac{K_Q}{J^3} = \frac{Q}{\rho n^2 D^5}\left(\frac{nD}{V_A}\right)^3 = \frac{Qn}{\rho D^2 V_A^3} = \frac{P_D}{2\pi\rho D^2 V_A^3}$$

Known thrust, diameter and advance velocity

$$\frac{K_T}{J^2} = \frac{T}{\rho n^2 D^4}\left(\frac{nD}{V_A}\right)^2 = \frac{T}{\rho V_A^2 D^2}$$

Known thrust, RPM and advance velocity

$$\frac{K_T}{J^4} = \frac{T}{\rho n^2 D^4}\left(\frac{nD}{V_A}\right)^4 = \frac{Tn^2}{\rho V_A^4}$$

Cavitation Considerations

Burrill's Method

$$V_R = \left[(0.7\pi nD)^2 + V_A{}^2\right]^{\frac{1}{2}}$$

$$P_O = P_{atm} + \rho g h$$

Atmospheric pressure

$$P_{atm} = 101300\ N/m^2$$

Vapour pressure of water

$P_V = 1700\ N/m^2$ at 15°C

$$\sigma = \frac{P_O - P_V}{q_T}$$

$$q_T = 0.5\rho V_R{}^2$$

$$\frac{A_P}{A_D} = \left[1.067 - 0.229\frac{P}{D}\right]$$

$$\tau_c = \frac{T}{\frac{1}{2}\rho A_P V_{R(0.7)}^2}$$

Keller's method

$$\frac{A_E}{A_O} = \frac{(1.3 + 0.3Z)T}{(P_O - P_V)D^2} + K$$

Propeller Lifting Line Theory

$$\tan\beta = \frac{V_A}{2\pi n r} = \frac{J}{\pi x}$$

$$\eta_i = \frac{\tan\beta}{\tan\beta_i}$$

$$\therefore \tan\beta_i = \frac{\tan\beta}{\eta_i}$$

$$a' = \frac{\tan^2\beta_i(1-\eta_i)}{1+\tan^2\beta_i}$$

$$k'T_i = \pi^3 k x^3 a'(1-a')$$

$$k'Q_i = k'T_i\frac{\lambda_i}{2}$$

$$K'T = k'T_i(1-\varepsilon\tan\beta_i)$$

Table of Contents

Edited by	Approved
26th ITTC Propulsion Committee	26th ITTC
Date 02/ 2011	Date 09/2011

1978 ITTC Performance Prediction Method

1. PURPOSE OF PROCEDURE

The procedure gives a general description of an analytical method to predict delivered power and rate of revolutions for single and twin screw ships from model test results.

2. DESCRIPTION OF PROCEDURE

2.1 Introduction

The method requires respective results of a resistance test, a self propulsion test and the characteristics of the model propeller used during the self propulsion test,

The method generally is based on thrust identity which is recommended to be used to predict the performance of a ship. It is supposed that the thrust deduction factor and the relative rotative efficiency calculated for the model remain the same for the full scale ship whereas on all other coefficients corrections for scale effects are applied.

In some special cases torque identity (power identity) may be used, see section 2.4.4.

2.2 Definition of the Variables

C_A	Correlation allowance
C_{AA}	Air resistance coefficient
C_{App}	Appendage resistance coefficient
C_D	Drag coefficient
C_F	Frictional resistance coefficient
C_{FC}	Frictional resistance coefficient at the temperature of the self propulsion test
C_{NP}	Trial correction for propeller rate of revolution at power identity
C_P	Trial correction for delivered power
C_N	Trial correction for propeller rate of revolution at speed identity
C_R	Residual resistance coefficient
C_T	Total resistance coefficient
D	Propeller diameter
F_D	Skin friction correction in self propulsion test
J	Propeller advance coefficient
J_T	Propeller advance coefficient achieved by thrust identity
J_Q	Propeller advance coefficient achieved by torque identity
K_T	Thrust coefficient
K_{TQ}	Thrust coefficient achieved by torque identity
K_Q	Torque coefficient
K_{QT}	Torque coefficient achieved by thrust identity
k	Form factor
k_P	Propeller blade roughness
N_P	Number of propellers
n	Propeller rate of revolution
n_T	Propeller rate of revolution, corrected using correlation factor
P	Propeller pitch
P_D, P_P	Delivered Power, propeller power

P_{DT}	Delivered Power, corrected using correlation factor
P_E, P_R	Effective power, resistance power
Q	Torque
R_C	Resistance corrected for temperature differences between resistance- and self propulsion test
Re	Reynolds number
R_T	*Total* resistance
S	Wetted surface
S_{BK}	Wetted surface of bilge keels
T	Propeller thrust
t	Thrust deduction factor
V	Ship speed
V_A	Propeller advance speed
w	Taylor wake fraction in general
w_Q	Taylor wake fraction, torque identity
w_R	Effect of the rudder(s) on the wake fraction
w_T	Taylor wake fraction, thrust identity
Z	Number of propeller blades
β	Appendage scale effect factor
ΔC_F	roughness allowance
ΔC_{FC}	Individual correction term for roughness allowance
Δw_C	Individual correction term for wake
η_D	Propulsive efficiency or quasi-propulsive coefficient
η_H	Hull efficiency
η_0	Propeller open water efficiency
η_R	Relative rotative efficiency
ρ	Water density in general

Subscript "$_M$" signifies the model
Subscript "$_S$" signifies the full scale ship

2.3 Analysis of the Model Test Results

The calculation of the residual resistance coefficient C_R from the model resistance test results is found in the procedure for resistance test (7.5-02-02-01).

Thrust T_M, and torque Q_M, measured in the self-propulsion tests are expressed in the non-dimensional forms as in the procedure for propulsion test (7.5-02-03-01.1).

$$K_{TM} = \frac{T_M}{\rho_M D_M^4 n_M^2} \quad \text{and} \quad K_{QM} = \frac{Q_M}{\rho_M D_M^5 n_M^2}$$

Using thrust identity with K_{TM} as input data, J_{TM} and K_{QTM} are read off from the model propeller open water diagram, and the wake fraction

$$w_{TM} = 1 - \frac{J_{TM} D_M n_M}{V_M}$$

and the relative rotative efficiency

$$\eta_R = \frac{K_{QTM}}{K_{QM}}$$

are calculated. V_M is model speed.

Using torque identity with K_{QM} as input data, J_{QM} and K_{TQM} is read off from the model propeller open water diagram, and the wake fraction

$$w_{QM} = 1 - \frac{J_{QM} D_M n_M}{V_M}$$

and the relative rotative efficiency

$$\eta_R = \frac{K_{TQM}}{K_{TM}}$$

are calculated. V_M is model speed.

The thrust deduction is obtained from

$$t = \frac{T_\mathrm{M} + F_\mathrm{D} - R_\mathrm{C}}{T_\mathrm{M}}$$

where F_D is the towing force actually applied in the propulsion test. R_C is the resistance corrected for differences in temperature between resistance and self-propulsion tests:

$$R_\mathrm{C} = \frac{(1+k).C_\mathrm{FMC} + C_\mathrm{R}}{(1+k).C_\mathrm{FM} + C_\mathrm{R}} R_\mathrm{TM}$$

where C_FMC is the frictional resistance coefficient at the temperature of the self-propulsion test.

2.4 Full Scale Predictions

2.4.1 Total Resistance of Ship

The total resistance coefficient of a ship without bilge keels is

$$C_\mathrm{TS} = (1+k)C_\mathrm{FS} + \Delta C_\mathrm{F} + C_\mathrm{A} + C_\mathrm{R} + C_\mathrm{AAS}$$

where

- k is the form factor determined from the resistance test, see ITTC standard procedure 7.5-02-02-01.

- C_FS is the frictional resistance coefficient of the ship according to the ITTC-1957 model-ship correlation line

- C_R is the residual resistance coefficient calculated from the total and frictional resistance coefficients of the model in the resistance tests:

$$C_\mathrm{R} = C_\mathrm{TM} - (1+k)C_\mathrm{FM}$$

The form factor k and the total resistance coefficient for the model C_TM are determined as described in the ITTC standard procedure 7.5-02-02-01.

The correlation factor for the calculation of the resistance has been separated from the roughness allowance. The roughness allowance ΔC_F per definition describes the effect of the roughness of the hull on the resistance. The correlation factor C_A is supposed to allow for all effects not covered by the prediction method, mainly uncertainties of the tests and the prediction method itself and the assumptions made for the prediction method. The separation of ΔC_F from C_A was proposed by the Performance Prediction Committee of the 19th ITTC. This is essential to allow for the effects of newly developed hull coating systems.

The 19th ITTC also proposed a modified formula for C_A that excludes roughness allowance, which is now given in this procedure.

- ΔC_F is the roughness allowance

$$\Delta C_\mathrm{F} = 0.044\left[\left(\frac{k_\mathrm{S}}{L_\mathrm{WL}}\right)^{\frac{1}{3}} - 10 \cdot Re^{-\frac{1}{3}}\right] + 0.000125$$

where k_s indicates the roughness of hull surface. When there is no measured data, the standard value of k_s=150×10^{-6} m can be used.

- C_A is the correlation allowance.
  C_A is determined from comparison of model and full scale trial results. When using the roughness allowance as above, the 19th ITTC recommended using

$$C_\mathrm{A} = (5.68 - 0.6\log Re) \times 10^{-3}$$

to give values of $\Delta C_F + C_A$ that approximates the values of ΔC_F of the original 1978 ITTC method. It is recommended that each institution maintains their own model-full scale correlation. See section 2.4.4 for a further discussion on correlation.

- C_{AAS} is the air resistance coefficient in full scale

$$C_{AAS} = C_{DA}\frac{\rho_A \cdot A_{VS}}{\rho_S \cdot S_S}$$

where, A_{VS} is the projected area of the ship above the water line to the transverse plane, S_S is the wetted surface area of the ship, ρ_A is the air density, and C_{DA} is the air drag coefficient of the ship above the water line. C_{DA} can be determined by wind tunnel model tests or calculations. Values of C_{DA} are typically in the range 0.5-1.0, where 0.8 can be used as a default value.

If the ship is fitted with bilge keels of modest size, the total resistance is estimated as follows:

$$C_{TS} = \frac{S_S + S_{BK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + C_R + C_{AAS}$$

where S_{BK} is the wetted surface area of the bilge keels.

When the model appendage resistance is separated from the total model resistance, as described as an option in the ITTC Standard Procedure 7.5-02-02-01, the full scale appendage resistance needs to be added, and the formula for total resistance (with bilge keels) becomes:

$$C_{TS} = \frac{S_S + S_{BK}}{S_S}\left[(1+k)C_{FS} + \Delta C_F + C_A\right] + C_R + C_{AAS} + C_{AppS}$$

There is not only one recommended method of scaling appendage resistance to full scale. The following alternative methods are well established:

1) Scaling using a fixed fraction:

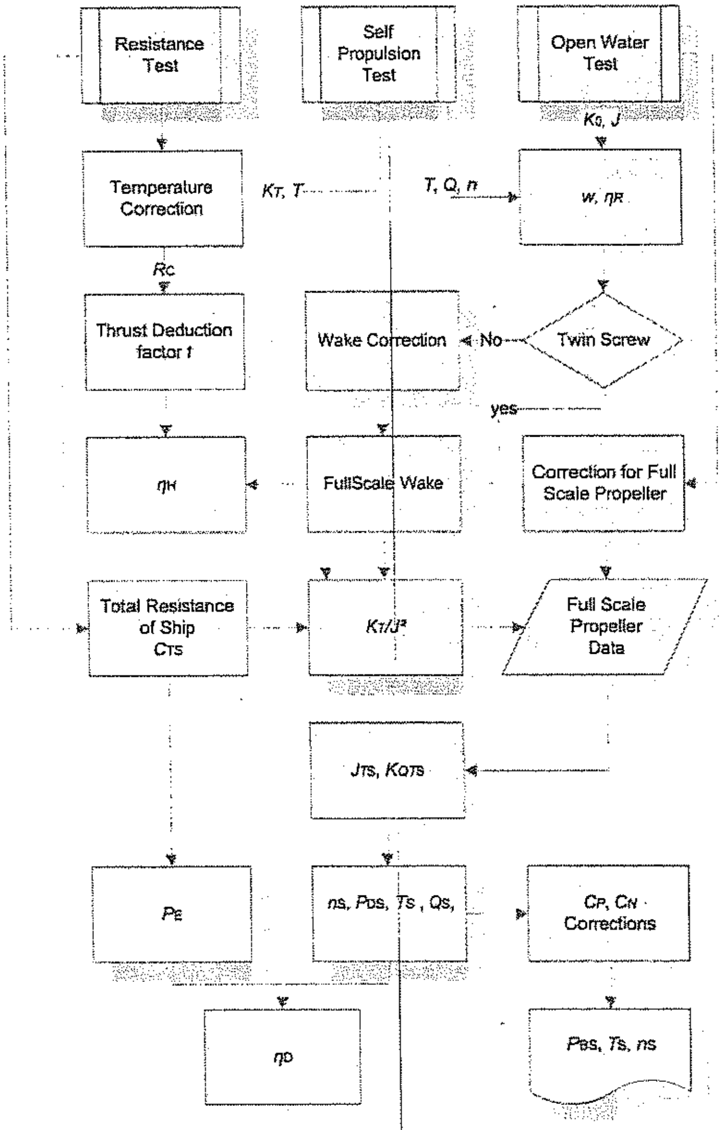
$$C_{AppS} = (1-\beta)\cdot C_{AppM}$$

where $(1-\beta)$ is a constant in the range 0.6-1.0.

2) Calculating the drag of each appendage separately, using local Reynolds number and form factor.

$$C_{AppS} = \sum_{i=1}^{n}(1-w_i)^2 \cdot (1+k_i)\cdot C_{FSi}\cdot\frac{S_i}{S_S}$$

where index i refers to the number of the individual appendices. w_i is the wake fraction at the position of appendage i. k_i is the form factor of appendage i. C_{FSi} is the frictional resistance coefficient of appendage i, and S_i is the wetted surface area of appendage i. Note that the method is not scaling the model appendage drag, but calculating the full scale appendage drag. The model appendage drag, if known from model tests, can be used for the determination of e.g. the wake fractions w_i. Values of the form factor k_i can be found from published data for generic shapes, see for instance Hoerner (1965) or Kirkman and Klöetsli (1980).



2.4.2 Scale Effect Corrections for Propeller Characteristics.

The characteristics of the full-scale propeller are calculated from the model characteristics as follows:

$$K_{TS} = K_{TM} - \Delta K_T$$

$$K_{QS} = K_{QM} - \Delta K_Q$$

where

$$\Delta K_T = -\Delta C_D \cdot 0.3 \cdot \frac{P}{D} \cdot \frac{c \cdot Z}{D}$$

$$\Delta K_Q = \Delta C_D \cdot 0.25 \cdot \frac{c \cdot Z}{D}$$

The difference in drag coefficient ΔC_D is

$$\Delta C_D = C_{DM} - C_{DS}$$

where

$$C_{DM} = 2\left(1+2\frac{t}{c}\right)\left[\frac{0.044}{(Re_{c0})^{\frac{1}{6}}} - \frac{5}{(Re_{c0})^{\frac{2}{3}}}\right]$$

and

$$C_{DS} = 2\left(1+2\frac{t}{c}\right)\left(1.89+1.62\cdot\log\frac{c}{k_P}\right)^{-2.5}$$

In the formulae listed above c is the chord length, t is the maximum thickness, P/D is the pitch ratio and Re_{c0} is the local Reynolds number with Kempf's definition at the open-water test. They are defined for the representative blade section, such as at r/R=0.75. k_P denotes the blade roughness, the standard value of which is set $k_P=30\times10^{-6}$ m. Re_{c0} must not be lower than 2×10^5.

2.4.3 Full Scale Wake and Operating Condition of Propeller

The full-scale wake is calculated by the following formula using the model wake fraction w_{TM}, and the thrust deduction fraction t obtained as the analysed results of self-propulsion test:

$$w_{TS} = (t + w_R) + (w_{TM} - t - w_R)\frac{(1+k)C_{FS} + \Delta C_F}{(1+k)C_{FM}}$$

where w_R stands for the effect of rudder on the wake fraction. If there is no estimate for w_R, the standard value of 0.04 can be used.

If the estimated w_{TS} is greater than w_{TM}, w_{TS} should be set as w_{TM}.

The wake scale effect of twin screw ships with open sterns is usually small, and for such ships it is common to assume $w_{TS} = w_{TM}$.

For twin skeg-like stern shapes a wake correction is recommended. A correction like the one used for single screw ships may be used.

The load of the full-scale propeller is obtained from

$$\frac{K_T}{J^2} = \frac{S_S}{2D_S^2}\cdot\frac{C_{TS}}{(1-t)\cdot(1-w_{TS})^2}$$

where N_P is the number of propellers.

With this K_T / J^2 as input value the full scale advance coefficient J_{TS} and the torque coefficient K_{QTS} are read off from the full scale propeller characteristics and the following quantities are calculated.

- the rate of revolutions:
$$n_S = \frac{(1-w_{TS})\cdot V_S}{J_{TS}\cdot D_S} \qquad \text{(r/s)}$$
- the delivered power of each propeller:
$$P_{DS} = 2\pi\rho_S D_S^5 n_S^3 \frac{K_{QTS}}{\eta_R}\cdot 10^{-3} \qquad \text{(kW)}$$
- the thrust of each propeller:
$$T_S = \left(\frac{K_T}{J^2}\right)\cdot J_{TS}^2 \rho_S D_S^4 n_S^2 \qquad \text{(N)}$$
- the torque of each propeller:
$$Q_S = \frac{K_{QTS}}{\eta_R}\cdot \rho_S D_S^5 n_S^2 \qquad \text{(Nm)}$$
- the effective power:
$$P_E = C_{TS}\cdot\frac{1}{2}\rho_S V_S^3 S_S \cdot 10^{-3} \quad \text{(kW)}$$

- the total efficiency:

$$\eta_D = \frac{N_P \cdot P_{DS}}{P_E}$$

- the hull efficiency:

$$\eta_H = \frac{1-t}{1-w_{TS}}$$

2.4.4 Model-Ship Correlation Factor

The model-ship correlation factor should be based on systematic comparison between full scale trial results and predictions from model scale tests. Thus, it is a correction for any systematic errors in model test and powering prediction procedures, including any facility bias.

In the following, several different alternative concepts of correlation factors are presented as suggestions. It is left to each member organisations to derive their own values of the correlation factor(s), taking into account also the actual value used for C_A.

(1) Prediction of full scale rates of revolutions and delivered power by use of the C_P - C_N correction factors

Using C_P and C_N the finally predicted trial data will be calculated from

$$n_T = C_N \cdot n_S \qquad \text{(r/s)}$$

for the rates of revolutions and

$$P_{DT} = C_P \cdot P_{DS} \qquad \text{(kW)}$$

for the delivered power.

(2) Prediction of full scale rates of revolutions and delivered power by use of ΔC_{FC} - Δw_C corrections

In such a case the finally trial predicted trial data are calculated as follows:

$$\frac{K_T}{J^2} = \frac{S_S}{2D_S^2} \cdot \frac{C_{TS} + \Delta C_{FC}}{(1-t)\cdot(1-w_{TS}+\Delta w_C)^2}$$

With this K_T/J^2 as input value, J_{TS} and K_{QTS} are read off from the full scale propeller characteristics and the following is calculated:

$$n_T = \frac{(1-w_{TS}+\Delta w_C)\cdot V_S}{J_{TS}\cdot D_S} \qquad \text{(r/s)}$$

$$P_{DT} = 2\pi\rho_S D_S^5 n_T^3 \frac{K_{QTS}}{\eta_R} \cdot 10^{-3} \qquad \text{(kW)}$$

(3) Prediction of full scale rates of revolutions and delivered power by use of a C_{NP} correction

For prediction with emphasis on stator fins and rudder effects, it is sometimes recommended to use power identity for the prediction of full scale rates of revolution.

At the point of K_T-(J)-Identity the condition is reached where the ratio between the propeller induced velocity and the entrance velocity is the same for the model and the full scale ship. Ignoring the small scale effect ΔK_T on the thrust coefficient K_T it follows that J-identity correspond to K_T- and C_T-identity. As a consequence it follows that for this condition the axial flow field in the vicinity of the propeller is on average correctly simulated in the model experiment. Also the axial flow of the propeller slip stream is on average correctly simulated. Due to the scale effects on the propeller blade friction, which affect primarily the torque, the point of K_Q-identity (power identity) represents a slightly less heavily loaded propeller than at J-, K_T- and C_T-identity. At the power identity the average rotation in the slipstream corresponds to that of the actual ship and this condition is regarded as important if tests on stator fins and/or rudders are to be done correctly.

In this case, the shaft rate of revolutions is predicted on the basis of power identity as follows:

$$\left(\frac{K_Q}{J^3}\right)_{\mathrm{T}} = \frac{1000 \cdot C_P \cdot P_{\mathrm{DS}}}{2\pi\rho_{\mathrm{S}} D_{\mathrm{S}}^2 V_{\mathrm{S}}^3 (1-w_{TS})^3}$$

$$\frac{K_{Q0}}{J^3} = \left(\frac{K_Q}{J^3}\right)_{\mathrm{T}} \cdot \eta_{\mathrm{RM}}$$

$$n_{\mathrm{S}} = \frac{(1-w_{TS}) \cdot V_{\mathrm{S}}}{J_{TS} \cdot D_{\mathrm{S}}}$$

$$n_{\mathrm{T}} = C_{NP} \cdot n_{\mathrm{S}}$$

3. VALIDATION

3.1 Uncertainty Analysis

Not yet available

3.2 Comparison with Full Scale Results

The data that led to 1978 ITTC performance prediction method can be found in the following ITTC proceedings:

(1) Proposed Performance Prediction Factors for Single Screw Ocean Going Ships (13th 1972 pp.155-180) Empirical Power Prediction Factor (1+X)

(2) Propeller Dynamics Comparative Tests (13th 1972 pp.445-446)

(3) Comparative Calculations with the ITTC Trial Prediction Test Programme (14th 1975 Vol.3 pp.548-553)

(4) Factors Affecting Model Ship Correlation (17th 1984 Vol.1 pp274-291)

4. REFERENCES

(1) Hoerner, S.F. (1965) "Fluid-Dynamic Drag". Published by the author.

(2) Kirkman, K.L., Klöetsli, J.W. (1980) "Scaling Problems of model appendages", 19th American Towing Tank Conference, Ann Arbor, Michigan