ZEIT4005

NAVAL ARCHITECTURE AND MARINE ENGINEERING

RESISTANCE

- Importance
  - SPEED - achieve a specified speed on trials
    - (contractual requirement)
  - The first step in establishing the powering needs of a ship is the determination of its resistance at the required speed through both water and air.

Chapter 9

RESISTANCE

- Components of Total Resistance, [$\mathbf{R_T}$]
  - Each component can be equated to a component of a towline pulling the ship horizontally through the water and air.
  - The components of ship resistance can be determined:
    - singularly by empirical methods
    - by specific model experimentation
    - from regression equations of the results of model tests or full scale ship trials results of like ships
    - or by a combination of these methods

COMPONENTS OF RESISTANCE

- SEVEN COMPONENTS OF TOTAL RESISTANCE
  - Frictional Resistance, R_f
    - of underwater hull form assuming a smooth surface
  - Frictional Resistance for Roughness, R_a
  - Frictional Resistance for Underwater Fouling, R_{foul}
  - Residuary Resistance, R_R
    - includes *Wave* and *Form Resistance* of underwater hull
  - Resistance of Underwater Appendages, R_A
  - Resistance in Waves, R_W
  - Resistance in Wind, R_{wind}
    - *Air Resistance*

RESISTANCE

- The following expressions are commonly used :
  - *Barehull Resistance*

    $\mathbf{R_{BH} = R_f + R_R}$ for a model

    $\mathbf{= R_f + R_a + R_R}$ for full scale ship
  - *Total Resistance*

    $\mathbf{R_T = R_{BH} + R_A + R_{wind}}$ for full scale ship

Frictional Resistance

- From experience with the correlation of ship model test results with the full scale ship performance on acceptance trials, expressions for frictional resistance have been developed and accepted internationally.
- 1957 ITTC Friction Formulation gives a frictional resistance coefficient, $\mathbf{C_f}$, of a smooth flat plate:

$$\mathbf{C_f = 0.075 / (Log_{10}\, R_N - 2)^2}$$

Where $\mathbf{R_N}$ is the Reynolds Number, $\mathbf{R_N = V L / \nu}$
V is velocity of the ship through the water,
L is length of ship or model on the waterline, and
$\boldsymbol{\nu}$ is kinematic viscosity of the water ($\nu = \mu/\varrho$ =viscosity/density)

Frictional Resistance

- Using the well established resistance expression, the frictional resistance of a ship or model can be equated to the resistance of a smooth flat plate of the same underwater surface area of the ship or model such that :

$$\mathbf{R_f = 0.5\, \varrho\, A\, V^2\, C_f}$$

where: ϱ is the density of water
A is the area of underwater form of ship or model
V is the velocity of the ship through the water
$\mathbf{C_f}$ is the friction coefficient (different for laminar and turbulent flow)

Blasius published laminar results in 1908.

Prandtl and von Karman separately published turbulent results in 1921

Frictional Resistance for Roughness

- The expression for frictional resistance is only applicable for a smooth surface or a surface that is representative of a ship model produced for model testing purposes in a ship model towing tank
- The surface of the underwater hull of a full size ship is much rougher because of the presence of welds, out of fairness of the form and because of the anti-fouling paint applied to the hull
- For a full size ship such as a frigate or a destroyer, an additional allowance of $\mathbf{C_a}$ equal to 0.0008 is added to the $\mathbf{C_f}$ determined from the above expression. Note that this correction does not apply to model correlation.

Frictional Resistance for Underwater Fouling

- This is another frictional resistance allowance that is added to $\mathbf{C_f}$ to allow for underwater fouling resistance on the full scale ship.
- The actual value of $\mathbf{C_{fouling}}$ is dependent on the number of days the ship has been out of dock, the effectiveness of the anti-fouling paint, the number of ship running days and the extent of marine organisms that are present in the water.
- A realistic value of $\mathbf{C_{fouling}}$ is difficult to determine. For this reason, contractual ship speed is normally specified for the ship having a clean bottom.

Residuary Resistance

- $\mathbf{R_R}$, of a ship is composed of two components (always extrapolated as one)
  - wavemaking resistance
    - the generation of gravity waves along the length of the ship
  - form resistance
    - generation of eddies etc over and above that of a flat plate
- Residuary resistance determined from
  - ship model experiments
  - interpolation of systematic series of ship model tests such as the Taylor Series, Series 60, and the HSDHF Series

Residuary Resistance

- $\mathbf{R_R}$, in these series is presented as a function of $\mathbf{F_N}$, in terms of parameters such as $\mathbf{C_P}$, $\mathbf{C_B}$, $\mathbf{L_{WL}/ B_{WL}}$, and $\mathbf{B_{WL}/ d}$ where:

$$\mathbf{F_N = V / (g\ L_{WL})^{0.5}}$$

and: **V** is the velocity of the ship through the water,
g is the acceleration due to gravity, and
$\mathbf{L_{WL}}$ is the length on the waterline.

- $\mathbf{R_R}$ can also be determined directly from the model test results of a ship that directly resembles the design with appropriate corrections being made for differences in design parameters.
- $\mathbf{R_R}$ can be expressed as resistance per unit of ship displacement or more correctly it can be calculated from $\mathbf{C_R}$ when using the following expression :

$$\mathbf{R_R = 0.5\, \varrho\, A\, V^2\, C_R}$$

Ship Model Extrapolation

- A ship model is towed along a towing tank at various speeds under a moving carriage. The drag of the model as it is towed is measured by a force balance fixed to the carriage. With a knowledge of dimensional analysis it can be shown that dynamic similarity exists between a ship model and the full size ship for the generation of gravity waves and that the residuary resistance coefficient, $\mathbf{C_R}$, for the ship equals the residuary resistance coefficient for the model if the Froude Number for the model ($\mathbf{F_N}$ **model**) equals the Froude Number for the ship ($\mathbf{F_{N\ ship}}$). By measuring the bare hull resistance of the model at various speeds through the water the resistance of the full scale ship can be extrapolated.

RESISTANCE

SHIP MODEL EXTRAPOLATION

Law of Dynamic Similarity

Froude Number for the model ($\mathbf{F_{N\ model}}$) equals the Froude Number for the ship ($\mathbf{F_{N\ ship}}$).

$$\mathbf{F_N = V / (g\ L_{WL})^{0.5}}$$

Geometrically similar model

Model size dependent on speed and tank

Testing methods

$$\mathbf{R_{BH\ model} = 0.5\ r\ A_{model}\ V^2{}_{model}\ C_{BH\ model}}$$
$$\mathbf{C_{BH\ model} = CR_{\ model} + Cf_{\ model}}$$
$$\mathbf{C_{R\ model} = CR_{\ ship}} \quad \text{for corresponding } F_N$$

Therefore,

$$\mathbf{C_{BH\ ship} = C_{f\ ship} + C_{R\ model}} \quad \text{for corresponding } F_N$$

and $\mathbf{R_{BH\ ship} = 0.5\ r\ A_{ship}\ V^2{}_{ship}\ C_{BH\ ship}}$

Resistance of Underwater Appendages

- Underwater appendages include
  - rudders, bilge keels, stabiliser fins, propeller shafts, shaft bracket arms, shaft bracket bossings, hull bossings for propeller shafts, and where fitted, sonar domes
  - Because of scale effects it is not possible to accurately determine the resistance of these appendages by ship model experiments in a ship model towing tank
  - From full scale ship trials it has been determined that the appendage resistance of a ship can range from 5 to 10 percent of the bare hull resistance, $\mathbf{R_{BH}}$.

Resistance of Underwater Appendages

- For appendages that are aligned with the general flow of water and have almost no cross section shape or a very high length to thickness ratio such as bilge keels and rudders, the following expressions can be assumed

$$\mathbf{R_{\ Bilge\ Keels} = 0.75\ \varrho\ A_{app}\ V^2\ C_{\ f\ ship}}$$
$$\mathbf{R_{\ Rudders} = 0.85\ \varrho\ A_{app}\ V^2\ C_{\ f\ ship}}$$

In both expressions $\mathbf{A_{app}}$ is the total surface area of the respective appendage

Resistance in Waves

- $\mathbf{R_W}$, is very difficult to determine. Most reliable method is with ship model data from a towing tank
  - model towed through a range of regular waves with various heights and frequencies, or
  - determined from standard series experiments either by direct interpolation or with regression equations
- Depending on the wave height, frequency and direction in relation to the ship, $\mathbf{R_W}$ can be as much as 30% of $\mathbf{R_R}$
  - Speed in waves rarely written into acquisition contract
  - $\mathbf{R_W}$ is usually neglected and speed in calm water is accepted

Air Resistance

- $\mathbf{R_{wind}}$, can be determined with a model of the abovewater form in a wind tunnel or by empirical methods. For example, the air resistance of a ship heading directly into the wind is given by:

$$\mathbf{R_{wind} = 0.5\,\varrho\,A\,V^2\,C_{wind}}$$

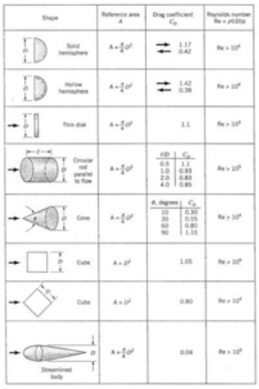
where: ϱ is the density of air
A is the frontal cross section area of the ship above the waterline
V is the relative wind velocity
$\mathbf{C_{wind}}$ is the drag coefficient

$\mathbf{C_{wind}}$ can vary from 0.97 to 1.50 and can be taken as 1.20 for a frigate

Total resistance, $\mathbf{R_T}$, of the ship can be expressed as :

$$\mathbf{R_T = R_{BH} + R_{APP} + R_{wind} + R_W}$$

Drag Coefficients for Geometric Shapes
Munson, Young & Okiishi 2002, p 594



Shape	Reference area A	Drag coefficient C_D	Reynolds number $Re = \rho UD/\mu$
Solid hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.17 ← 0.42	$Re > 10^4$
Hollow hemisphere	$A = \frac{\pi}{4}D^2$	→ 1.42 ← 0.38	$Re > 10^4$
Thin disk	$A = \frac{\pi}{4}D^2$	1.1	$Re > 10^3$
Circular rod parallel to flow	$A = \frac{\pi}{4}D^2$	ℓ/D / C_D: 0.5 / 1.1 1.0 / 0.93 2.0 / 0.83 4.0 / 0.85	$Re > 10^5$
Cone	$A = \frac{\pi}{4}D^2$	θ, degrees / C_D: 10 / 0.30 30 / 0.55 60 / 0.80 90 / 1.15	$Re > 10^4$
Cube	$A = D^2$	1.05	$Re > 10^4$
Cube	$A = D^2$	0.80	$Re > 10^4$
Streamlined body	$A = \frac{\pi}{4}D^2$	0.04	$Re > 10^5$

Example

The total resistance of a ship model when towed in fresh water in a ship model tank at a speed of 5m/s is 350N. The LWL of the model is 5.0m and its underwater wetted surface area is 4.0m^2. Determine the total resistance in salt water of a geometrically similar ship at the corresponding speed assuming the LWL of the ship is 25.0m.

Assume the following for the freshwater in the ship model towing tank:

Temp	**16.30 Deg C**
ρ	**999.65 kg/m^3**
ν	**1.1012 x10^{-6} m^2/s**

Assume the following for the ship water (saltwater).

Temp	**15.00 Deg C**
ρ	**1025 kg/m^3**
ν	**1.1907 x10^{-6} m^2/s**
g	**9.806 m/s^2**

Determining residuary resistance coefficient, C_R, for ship model from information provided.

since $\mathbf{R_T}_{\text{model}} = 0.5\,\rho_{\text{tank water}}\,\mathbf{A}_{\text{model}}\,\mathbf{V}_{\text{model}}^2\,\mathbf{C_T}_{\text{model}}$

$\mathbf{C_T}_{\text{model}} = 350 / (0.5 \times 999.65 \times 4 \times 5^2) = 0.007002$

$\mathbf{R_N}_{\text{model}} = (\mathbf{V}_{\text{model}}\ \mathbf{LWL}_{\text{model}}) / \nu_{\text{tank water}}$
$= (5) \times (5) / (1.1012 \times 10^{-6})$
$= 2.2703 \times 10^7$

and $\text{Log}_{10}\,\mathbf{R_N}_{\text{model}} = 7.356$

$\mathbf{C_f}_{\text{model}} = 0.075 / (\text{Log}_{10}\,\mathbf{R_N} - 2)^2$
$= 0.075 / (5.356)^2$
$= 0.002614$

$\mathbf{C_T}_{\text{model}} = \mathbf{C_f}_{\text{model}} + \mathbf{C_R}_{\text{model}}$

$\mathbf{C_R}_{\text{model}} = 0.007002 - 0.002614$
$= 0.004388$

Determining corresponding speed for ship by equating Froude Numbers:

$\mathbf{F_N}_{\text{model}} = \mathbf{F_N}_{\text{ship}}$

$\mathbf{V}_{\text{model}} / (\mathbf{g}\ \mathbf{LWL}_{\text{model}})^{0.5} = \mathbf{V}_{\text{ship}} / (\mathbf{g}\ \mathbf{LWL}_{\text{ship}})^{0.5}$

$\mathbf{V}_{\text{ship}} = 5 \times (9.806 \times 25)^{0.5} / (9.806 \times 5)^{0.5}$
$= 11.180$ m/s

$\mathbf{R_N}_{\text{ship}} = (\mathbf{V}_{\text{ship}}\ \mathbf{LWL}_{\text{ship}}) / \nu_{\text{seawater}}$
$= 11.180 \times 25 / (1.1907 \times 10^{-6})$
$= 2.3474 \times 10^8$

and $\text{Log}_{10}\,\mathbf{R_N}_{\text{ship}} = 8.3706$

$\mathbf{C_f}_{\text{ship}} = 0.075 / (\text{Log}_{10}\,\mathbf{R_N} - 2)^2$
$= 0.075 / (6.3706)^2$
$= 0.001848$

$\mathbf{C_T}_{\text{ship}} = \mathbf{C_f}_{\text{ship}} + \mathbf{C_R}_{\text{model}}$
$= 0.001848 + 0.004388$
$= 0.006236$

Since $\mathbf{R_T}_{\text{ship}} = 0.5\,\rho_{\text{seawater}}\,\mathbf{A}_{\text{ship}}\,\mathbf{V}_{\text{ship}}^2\,\mathbf{C_T}_{\text{ship}}$

and since the linear scale of ship to model is 5, the wetted surface area ratio of ship to model is 25. Therefore the wetted surface area of the ship is 100 m^2.

Therefore,
$\mathbf{R_T}_{\text{ship}} = 0.5 \times 1025 \times 100 \times 11.180^2 \times 0.006236$

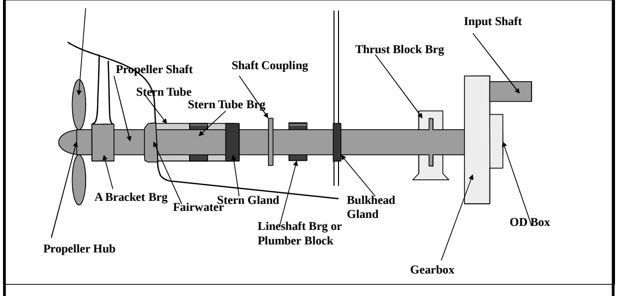
$= 39.946$ kN

POWERING

- Convert the resistance into delivered power, shaft power and ultimately into brake power for sizing the main engines

$$\mathbf{Power = R\ V}$$

- Logical steps of conversion considering total resistance, shafting, thrust block, gearbox, prime engine output coupling.



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Effective Power

- Effective power naked, $\mathbf{EP_{naked}}$, represents the power required to pull the bare hull through the water such that :

$$\mathbf{EP_{naked} = R_{BH}\ V}$$

- Effective power appended, $\mathbf{EP_{appended}}$, represents the power to pull the appended hull of the full scale ship through the water such that :

$$\mathbf{EP_{appended} = (R_{BH} + R_{APP})\ V}$$

- *E*ffective power total, $\mathbf{EP_{total}}$, is the same as $\mathbf{EP_{appended}}$ for the full scale ship and $\mathbf{EP_{naked}}$ for a ship model. The term $\mathbf{EP_{total}}$ is the more commonly used term for both model and full scale ship.

Delivered Power

- Delivered power, $\mathbf{P_D}$, is the power needed to be available at the propulsor to propel the ship at the specified speed

$$\mathbf{P_D = EP_{total} / (\eta_H \cdot \eta_R \cdot \eta_O)}$$

where η_H is the hull efficiency,
η_R is the relative rotative efficiency of the propeller
η_O is the open water efficiency of the propeller

- The hull efficiency of a ship model or a ship

$$\mathbf{\eta_H = (1 - t) / (1 - w)}$$

where **t** is the thrust deduction fraction
w is the wake fraction

Thrust deduction fraction and the wake fraction

- obtained from self propulsion model tests or by empirical methods
  - t and w account for the interaction between the propeller and the hull
  - The wake fraction accounts for the velocity of the water entering the propeller not necessarily being equal to the velocity of the ship over the ocean floor

$$\mathbf{Wake = V_S - V_A}$$

and wake fraction, **w,** is given by

$$\mathbf{w = (V_S - V_A) / V_S}$$

where $\mathbf{V_S}$ is the speed of the ship over the ocean floor
$\mathbf{V_A}$ is the advance speed of the water entering the propeller disc

Thrust deduction fraction and the wake fraction

- Empirical methods
  - eg a twin screw destroyer or frigate with a C_B of 0.5, the wake fraction can be taken as +0.09. Where C_B is in the order of 0.65, the wake fraction can be taken as +0.15.
- The thrust deduction fraction accounts for the influence of pressure variations induced by the propeller around the ship. The thrust deduction fraction is expressed as follows :

$$\mathbf{t = (T - R_{appended}) / T}$$

where **T** is the thrust required to be produced by the propeller

- For destroyers and frigates with twin shafts the following expression can be assumed for a first estimate :

$$\mathbf{t = 0.7w + 0.06}$$

Thrust Power

- Thrust Power, $\mathbf{P_T}$, is the power that must be produced by a propeller to achieve the required ship speed in the specified conditions where :

$$\mathbf{P_T = T\ V_A = EP_{total} / \eta_H}$$

- Normally, **T** is determined for the appended ship only but where contractual conditions or service requirements dictate, $\mathbf{R_{wind}}$, $\mathbf{R_{fouling}}$ or $\mathbf{R_{waves}}$ can be added to **T** afterwards to determine the applicable delivered power.

Propeller Efficiencies

- A first estimate of the open water efficiency, η_O, can be taken as **0.65** for a destroyer or frigate.

- The relative rotative efficiency, η_R, is a correction made to the open water performance of the propeller when it is placed behind the ship. For single propeller ships the value of η_R can range from 0.95 to 0.98 while for a twin propeller ship it can range from 0.98 to 1.00.

Shaft Power

- Shaft power, $\mathbf{P_S}$, is the power required in the propeller shaft and can be expressed as :

$$\mathbf{P_S = P_D / \eta_T}$$

Where

η_T is the transmission efficiency up to the gearbox

(A 1% loss in efficiency can be taken for each bearing supporting the propeller shaft up to the thrust block)

Brake Power

- The brake power, $\mathbf{P_B}$, is the output power from the prime mover forward of the thrust block and gearbox and can be expressed as follows :

$$\mathbf{P_B = P_S / \eta_G}$$

where

η_G is the combined efficiency of the thrust block and the gearbox

(Can be assumed as 0.97)

Quasi Propulsion Coefficient

- The Quasi Propulsion Coefficient, **QPC**, is an expression commonly used to identify the product of the following efficiencies :

$$\mathbf{QPC = \eta_O \, \eta_R \, \eta_H}$$

Propulsive Coefficient

- The Propulsive Coefficient, PC, is an expression commonly used to identify the product of the following efficiencies :

$$\mathbf{PC = \eta_O \, \eta_R \, \eta_H \, \eta_T}$$

Both the QPC and the PC can be used to compare efficiencies of similar ships or classes of ships

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Power Margins

- An appropriate power margin must be added to $\mathbf{P_B}$ at each stage of the powering estimation to allow for uncertainties in calculations and experimentation
  - For example, at the Feasibility Design phase the margin can be as much as 10% of $\mathbf{P_B}$. This margin can be progressively reduced to 4% of $\mathbf{P_B}$ during the final stages of the Contract Design and after the propeller design has been fairly well defined.

PROPULSION

- How is driving force to be produced?

Chapter 10

Propulsors

- Numerous devices can produce thrust in water
  - conventional screw propeller – MOST COMMON
  - propeller in an accelerating nozzle
  - propeller in a decelerating nozzle
  - vertical axis propeller
  - water jet
- All of these devices are able to convert shaft torque into thrust on the propeller blades ultimately pushing or pulling the ship through the water

Propulsors

- The propeller in an accelerating nozzle (*Kort Nozzle*) is a conventional propeller in a shrouded aerofoil section ring which induces a more uniform flow into the propeller disc and accelerates the water flow to the disc. The prime advantage of this propulsor is that it can provide additional thrust from the duct at slow advance speeds. It is fitted to vessels such as tugs.

- The propeller in a decelerating nozzle (*Pump Jet*) is also a propeller in a shroud which provides a uniform flow of water to the disc. The configuration of this nozzle is such that flow of water to the disc is slowed down. Its application is in destroyers, frigates and submarines where underwater propulsor radiated noise must be minimised. The nozzle delays the onset of cavitation on the propeller.

Propulsors

- The vertical axis propeller is used on vessels that require a high degree of manoeuvrability without the use of other ship control surfaces such as rudders. This device is used on tugs and minehunters that require manoeuvrability at slow advance speeds.

- The water jet is primarily used on very high speed vessels because of its increased efficiency over the conventional screw propeller, its reduced vulnerability to underwater damage and its manoeuvrability properties.

Propeller Design

- Momentum theory can explain the generation of thrust by a liquid passing through a rotating propeller disc.
  - does not adequately lend itself to the actual design of the screw
- “Blade Element Theory” in conjunction with “Circulation Theory” using the “lifting line” or “lifting surface” methodologies can be used.
- A practical method of designing the simple moderately loaded screw propeller is from a standard propeller series.

Warship Propeller Design

- Warship propellers not only have to provide the necessary propulsion performance but have to do so with a minimum of noise to the highest possible advance speeds. This makes the warship propeller design more complex than one for commercial applications.

Geometrical Particulars of Screw

- propeller diameter, **D**
- pitch, **P**
- blade area ratio, **AE/AO**
- blade thickness, **t**
- blade camber
- blade section shape
- blade outline
- rake
- skew
- leading edge
- trailing edge
- convention for rotation

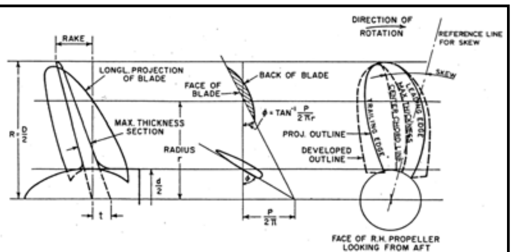


Fig. 8 Typical propeller drawing

Diameter D Pitch ratio $= \frac{P}{D}$

Pitch P Blade thickness ratio $= \frac{t}{D}$

No. of blades 4 Pitch angle $= \phi$

Disk area = area of tip circle $= \frac{\pi}{4}D^2 = A_0$

Developed area of blades, outside hub $= A_D$

Developed area ratio $= DAR = \frac{A_D}{A_0}$

Projected area of blades (on transverse plane) outside hub $= A_P$

Projected area ratio $= PAR = \frac{A_P}{A_0}$

Blade width ratio $= BWR = \frac{\text{Max. blade width}}{D}$

Mean width ratio $= MWR = \frac{A_D/\text{length of blades (outside hub)}}{D}$

Propeller Design

- The design of a propeller must evolve with the design of the ship
  - For example, during the conceptual design phase of the ship it is only necessary to initially determine a propeller whose diameter and rotational speed provides an acceptable open water efficiency. The propeller diameter is usually restricted by the draft and beam of the ship as well as its minimum tip clearance from the hull. Its rotational speed may be governed by available gear box reduction ratios.

Initial Design

- Propeller diameter and propeller rotational speed
  - where practical, the propeller tips should be kept within the bounds of the ships keel line and its half beam to reduce vulnerability to physical damage
  - propeller tip clearance from the hull of the ship should be at least 20% of the propeller diameter to minimise propeller induced vibration in the hull structure
  - propeller blade tip speed should be kept below 45 m/s to avoid early onset of blade tip vortices which can create noise
  - for initial powering estimates an acceptable open water propeller efficiency η_O can be assumed as 65%
  - shaft angle should be less than 8 degrees to the horizontal

Design - Sizing

- Determine the values of propeller diameter, **D**; propeller shaft speed, **N**; pitch/diameter ratio, **P/D**; and a blade area ratio, **AE/AO**; necessary to avoid the onset of back bubble cavitation for an acceptable open water efficiency, η_O.
- Standard series propeller charts and propeller cavitation charts can be used
  - process is iterative whereby the propeller is selected to provide the required thrust at the specified ship speed with the maximum possible open water efficiency η_O.

Design - Sizing

- During the later stages of the preliminary design or the early stages of the contract design phase of the ship, it can be assumed that ship model tests will be conducted to refine the hull form to more accurately determine $\mathbf{EP}_{\mathbf{appended}}$ and the hull efficiency elements **w** and **t**. The standard series propeller charts can then be used once again with the new information to further refine the principal propeller characteristics.

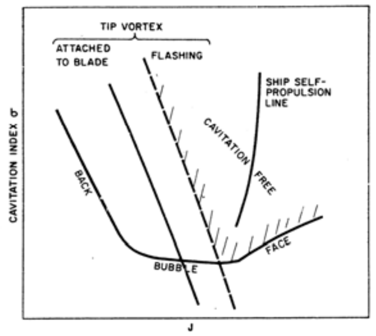
Design of Blades

- Determine the blade pitch distribution to minimise bubble and sheet blade cavitation.
  - apply circulation theory (methodology developed by Morgan and Eckhardt) or lifting surface principles
- Decide if a uniform or non uniform wake to be assumed
  - for warships, normal practice is to assume a non uniform wake.
    - This requires that a wake survey is undertaken in the vicinity of the propeller disc on a ship model in the ship model towing tank. The wake survey results can be simulated in the propeller cavitation tunnel to further refine the blade shape and pitch distribution.

Design of Blades

- Having completed the design of the blades using circulation theory, conduct blade strength calculations.
- Then manufacture a model of the propeller for cavitation testing.
  - The cavitation tunnel, being a fully enclosed water channel with a working section can be set up to simulate the wake of the ship in the vicinity of the propeller disc and simulate the appropriate cavitation number.
  - The propeller is tested at various advance speeds, $\mathbf{V_A}$, and the onset of the various types of cavitation is observed. At this stage the pitch distribution across the blade, the leading edge shape and the camber can be refined to delay the onset of cavitation.
  - A cavitation onset chart, similar to that depicted in the next slide, can be prepared for the propeller.

Cavitation



Standard Series Charts / Equations

- For commercial lightly loaded propellers these charts are sometimes considered to be adequate for the final design of the propeller.
- The standard propeller series is a simple representation of the results of propeller model tests carried out with a series of 30 to 40cm diameter model propellers with varying pitch/diameter ratios and blade area ratios.
  - The model propellers are fitted to a probe leg dynamometer (like an outboard motor leg) and run down the tank under the towing carriage over a range of advance speeds. The propeller revolutions are kept as high as possible to simulate the full scale Reynolds Number, $\mathbf{R_N}$.

Standard Series Charts / Equations

- For the purpose of kinematic similarity, it can be shown that the advance coefficient, **J**, can be taken as being the same for the model and the full scale propeller. That is, in non-dimensional terms :

$$\mathbf{J_{ship} = J_{model} = V_A / N\,D}$$

where $\mathbf{V_A}$ is the advance speed of the propeller through the water,
N is the revolution of the propeller in revs/s, and
D is the diameter of the propeller.

Standard Series Charts / Equations

- The propeller thrust, **T**, and the propeller torque, **Q**, are measured by the dynamometer on the probe and plotted as additional two non-dimensional coefficients on a base of **J.** These coefficients are as follows :

Thrust Co-efficient $\mathbf{K_T = T / \varrho\, N^2 D^4}$

Torque Co-efficient $\mathbf{K_Q = Q / \varrho\, N^2 D^5}$

where ϱ is the density of the water in which the propeller is operating

- The open water efficiency of the propeller is such that :

$$\eta_O = \mathbf{T\,V_A / (2\,\pi\,Q\,N) = J\,K_T / (2\,\pi\,K_Q)}$$

PROPULSORS

- There has been a number of propeller standard series developed. These include:
  a. the Gawn Series
  b. the Wageningen B-Series
  c. the NPL Series
  d. the KCN Series
  e. the Taylor Series

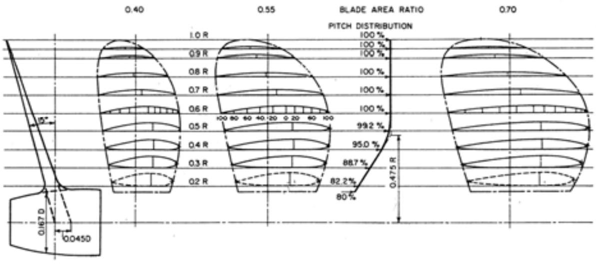
- The Wageningen B-Series is based on 120 model propellers tested at MARIN

PROPULSORS

Wageningen B-Screw Series
Source: Lewis 1988, p 186.

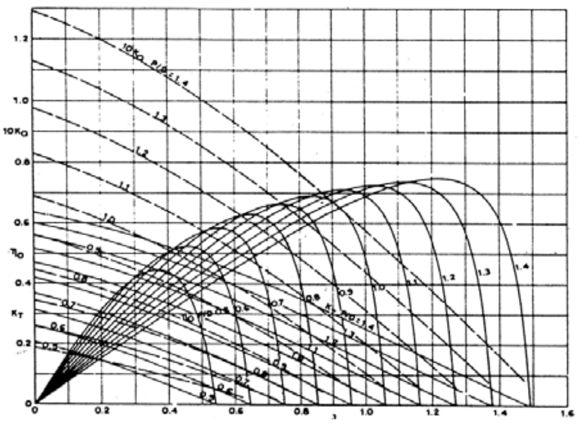
Blade Number,Z	Blade Area Ratio, A_E/A_O
2	.30
3	.35 .50 .65 .80
4	.40 .55 .70 .85 1.0
5	.45 .60 .75 1.05
6	.50 .65 .80
7	.55 .70 .85

PROPULSORS



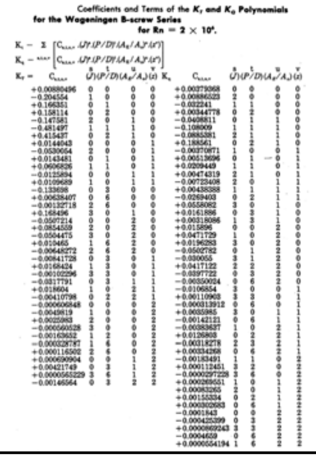
K_T K_Q Curves

- For many purposes, it is useful to have diagrams giving the characteristic of open-water tests. Shown in the next slide are the test results for the Wageningen B5-75 propeller in $\mathbf{K_T}$, $\mathbf{K_Q}$ and **J** format.



Regression Equation

- The regression equations and coefficients to estimate $\mathbf{K_T}$ and $\mathbf{K_Q}$ for the Wageningen B-Series propellers are shown in the next slide.
  - These equations are intended for computer based use in preliminary ship design studies. The corrections for Reynolds effects and other aspects of implementing the equations are discussed in the source document.


Coefficients and Terms of the K_T and K_Q Polynomials for the Wageningen B-screw Series for $Rn = 2 \times 10^6$.

$$K_T = \sum_{s,t,u,v} \left[C_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_O)^u \cdot (z)^v \right]$$
$$K_Q = \sum_{s,t,u,v} \left[C_{s,t,u,v} \cdot (J)^s \cdot (P/D)^t \cdot (A_E/A_O)^u \cdot (z)^v \right]$$

K_T = $C_{s,t,u,v}$	s (J)	t (P/D)	u (A_E/A_O)	v (z)	K_Q $C_{s,t,u,v}$	s (J)	t (P/D)	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	1	1	1	0	−0.108009	1	1	1	0
+0.415437	0	2	1	0	−0.0885381	2	1	1	0
+0.0144043	0	0	0	1	+0.188561	0	2	1	0
−0.0530054	2	0	0	1	−0.00370871	1	0	0	1
+0.0143481	0	1	0	1	+0.00513696	0	1	0	1
+0.0606826	1	1	0	1	+0.0209449	1	1	0	1
−0.0125894	0	0	1	1	+0.00474319	2	1	0	1
+0.0109689	1	0	1	1	−0.00723408	2	0	1	1
−0.133698	0	3	0	0	+0.00438388	1	1	1	1
+0.00638407	0	6	0	0	−0.0269403	0	2	1	1
−0.00132718	2	6	0	0	+0.0558082	3	0	1	0
+0.168496	3	0	1	0	+0.0161886	0	3	1	0
−0.0507214	0	0	2	0	+0.00318086	1	3	1	0
+0.0854559	2	0	2	0	+0.015896	0	0	2	0
−0.0504475	3	0	2	0	+0.0471729	1	0	2	0
+0.010465	1	6	2	0	+0.0196283	3	0	2	0
−0.00648272	2	6	2	0	−0.0502782	0	1	2	0
−0.00841728	0	3	0	1	−0.030055	3	1	2	0
+0.0168424	1	3	0	1	+0.0417122	2	2	2	0
−0.00102296	3	3	0	1	−0.0397722	0	3	2	0
−0.0317791	0	3	1	1	−0.00350024	0	6	2	0
+0.018604	1	0	2	1	−0.0106854	3	0	0	1
−0.00410798	0	2	2	1	+0.00110903	3	3	0	1
−0.000606848	0	0	0	2	−0.000313912	0	6	0	1
−0.0049819	1	0	0	2	+0.0035985	3	0	1	1
+0.0025983	2	0	0	2	−0.00142121	0	6	1	1
−0.000560528	3	0	0	2	−0.00383637	1	0	2	1
−0.00163652	1	2	0	2	+0.0126803	0	2	2	1
−0.000328787	1	6	0	2	−0.00318278	2	3	2	1
+0.000116502	2	6	0	2	+0.00334268	0	6	2	1
+0.000690904	0	0	1	2	−0.00183491	1	1	0	2
+0.00421749	0	3	1	2	+0.000112451	3	2	0	2
+0.0000565229	3	6	1	2	−0.0000297228	3	6	0	2
−0.00146564	0	3	2	2	+0.000269551	1	0	1	2
					+0.00083265	2	0	1	2
					+0.00155334	0	2	1	2
					+0.000302683	0	6	1	2
					−0.0001843	0	0	2	2
					−0.000425399	0	3	2	2
					+0.0000869243	3	3	2	2
					−0.0004659	0	6	2	2
					+0.0000554194	1	6	2	2

Using K_T K_Q Curves

- First necessary to determine the appropriate value of **J** knowing the required advance speed, $\mathbf{V_A}$, the assumed propeller diameter, **D** and the propeller rotational speed, **N**.
- Then a matter of determining the value of $\mathbf{K_T}$ while assuming the required thrust **T**.
  - Entering the chart will provide the appropriate pitch/diameter ratio, **P/D**. The corresponding values of $\mathbf{K_Q}$ and η_O can then be found for the equivalent pitch/diameter ratio on the same vertical **J** line.

Using K_T K_Q Curves

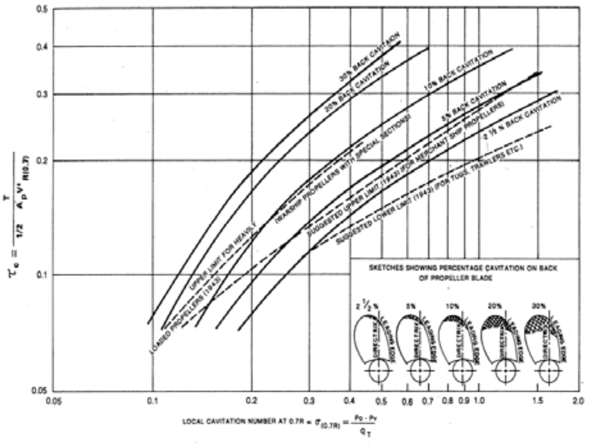
- At this stage, depending on the value of η_O, it may be necessary to further adjust **D** and **N** to achieve a better value of η_O near the top of the efficiency curve. It may even be necessary to further adjust **P/D** as part of the iterative process to achieve an acceptable efficiency.
- The curves can also be used with known values of **J** and $\mathbf{K_Q}$ to determine an appropriate value of $\mathbf{K_T}$, and thus, the thrust **T**. With this approach it may be necessary to adjust $\mathbf{V_A}$.

AE/AO Determination

- While this process is aimed at achieving the required thrust for minimum torque or by utilising available torque to obtain maximum thrust, it should be noted that each chart is for a discrete blade area ratio. For this reason, a further iteration with varying values of **AE/AO** may be necessary to determine the minimum **AE/AO** such that the thrust **T** produced by the propeller blades does not create bubble cavitation leading to reduced thrust and the inducement of material erosion.
  - For warship propellers, a good starting point is for a propeller with four blades and a **AE/AO** of at least 0.85.

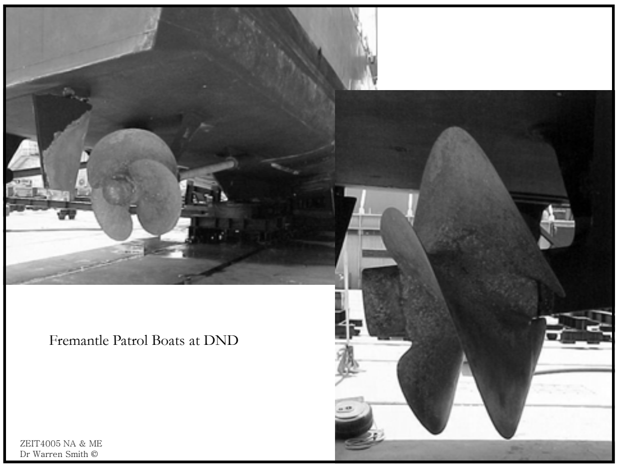
Cavitation

- To check for the possibility of back bubble cavitation, the Burrill cavitation chart, shown in the next slide, can be used. Burrill defined a coefficient τ_C expressing the mean thrust loading on the blades and plotted this against the cavitation number, $\sigma_{0.7R}$. To allow for an appropriate margin for cavitation on warship propellers, it is assumed that the local cavitation number is 87% of that calculated.



Strength

- The next step in the design process is to check the propeller blade thickness, **t**, for strength by scaling up from the model propeller offsets to the full size propeller
  - Various methods
  - Minimum blade thicknesses are specified by ship classification societies.



Fremantle Patrol Boats at DND