National Exams May 2003
98-NAV-A2, Hydrodynamics of Ships I: Resistance and Propulsion

3 hours duration

Notes:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. This is a closed book exam. Casio or Sharp calculator models are allowed.
3. Attempt all questions. The value of each question is noted in square brackets. The total value of the questions is 100.
4. A data sheet, a propeller chart, and a cavitation chart are provided. Please write neatly.
5. Pass in the entire exam paper, including any answers you give on the papers provided.

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1. [10] Use a diagram to show the relationship between the following components of ship resistance. Do *not* define the terms.

steering resistance
frictional resistance due to form
viscous resistance
wave resistance
viscous pressure resistance
pressure resistance
frictional resistance due to flat plate
appendage resistance
frictional resistance
total resistance

2. You have to use a model resistance experiment to evaluate the resistance of a 160m long ship whose design speed is 20.0 knots and whose wetted surface is 6,650 m^2. You want to avoid laminar flow problems, so have decided to have a minimum Reynolds number of 1×10^6 at the lowest model speed that will be tested, which corresponds to a Froude number of 0.10.

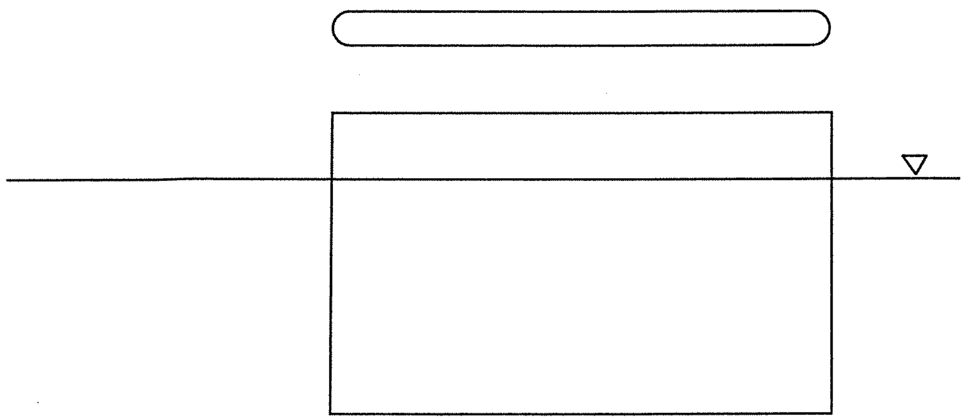
2.a) [10] (i) What is the minimum model size that you can use? (ii) For this size model, what is the model test speed and Reynolds number that corresponds to 20.0 knots full scale? Assume the tests are done in fresh water at 15°C.

2.b) [10] Assume the model that you use is 6 m long, rather than the minimum size you calculated above. You then determine from your experiments at the model speed corresponding to the design speed (20.0 knots) that the total model resistance is 77.00N. Make an estimate of ship total resistance and the effective power at this speed using the ITTC 78 method with the following simplifications and assumptions: air resistance is negligible and the roughness resistance coefficient C_A is 0.0004, the form factor is 0.230, the temperature of the tow tank water is 15°C, and the water temperature for which full scale predictions are to be made is 15°C. Show all work.

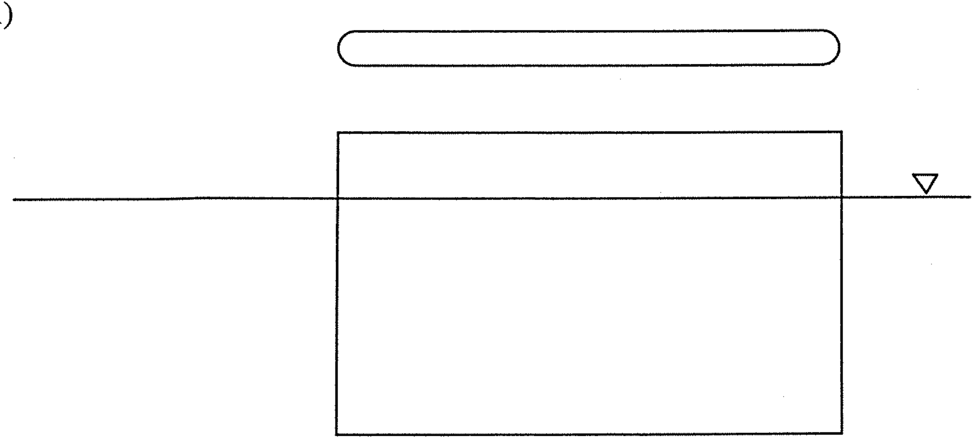
3. [10] Estimate the resistance of a smooth, hydrodynamically streamlined body that is towed at a steady speed underwater (deep) behind a service ship. The body is 5m long, has a surface area of 30m^2, and its design tow speed is 8 knots. It is geometrically similar to another towed body for which you have model test data that show its form factor to be 0.22. State any important assumptions that you make.

4. [10] The transverse waves generated by a vessel moving at constant speed at the free surface will move at the same speed as the vessel. As the speed changes, so too will the wave heights and wave lengths. As vessel speed increases, the total resistance will increase, but the variation in wave pattern with speed will result in local "humps" and "hollows" in the resistance curve.
Using the simply shaped body below (plan view shown on top and profile under it), show how wave patterns at two different speeds can give rise to destructive and constructive wave interference. For both cases, *neatly* draw the wave patterns on the paper and pass it in with your exam. Also give the corresponding Froude numbers, showing all work.

(i)



(ii)



5.a) [10] In simple momentum theory, the details of the propeller geometry are not considered. Rather, we are concerned with the overall changes in water velocity and pressure due to the action of the propeller, and how those changes give rise to thrust.

- On the top grid provided below, sketch the spatial distribution of the propeller race. Show the upstream and downstream portions of the propeller race and indicate clearly where the propeller disk is. Label the velocity and pressure far upstream of the disk V_A and p_o, respectively, where p_o is the free stream pressure. Label the velocity and pressure far downstream of the disk V_2 and p_o, where p_o is again the free stream pressure.
- On the middle plot, draw a sketch of the velocity distribution along the propeller race that corresponds to the spatial distribution sketch. Label the velocity at the disk V_1.
- On the bottom plot, draw a sketch of the pressure distribution that corresponds to the spatial and velocity distribution sketches. Label the pressures immediately up- and downstream of the propeller disk p_1 and p'_1, respectively. *Pass in these sketches with your exam.*

5.b) [3] Use Bernoulli's equation to show that the change in pressure Δp across the propeller disk can be found to be

$$\Delta p = \frac{1}{2}\rho\left(V_2^2 - V_A^2\right).$$

5.c) [2] We can further show that the ideal efficiency of the propeller can be written as

$$\eta = \frac{V_A}{V_A + u_I}$$

where u_I is the induced velocity at the propeller disk. Based specifically on this finding, what can you conclude about propeller efficiency and propeller design? Explain your answer with reference to the equation for ideal efficiency above.

6. [10] Define each of the following terms *and* illustrate your definition with a sketch.

- camber
- pitch
- suction and pressure sides
- fixed pitch and controllable pitch
- rake and skew

7. [10] Consider a propeller blade section at radius r with a pitch angle ϕ and rotational speed n advancing in a flow with velocity V_A. Draw and label a sketch showing the fluid velocity components and resultant, the incidence and advance angles, the lift and drag vectors, and the thrust and torque load vectors.

8.a) [8] Using the B4-55 chart, make a preliminary design for the propeller of a small re-supply vessel. The ship has an operating speed of 12 knots and a brake power of 600kW. The shaft efficiency and transmission efficiency are estimated to be 0.98 and 0.96, respectively. The shaft speed is 360 rpm. The hull form can accommodate a maximum propeller diameter of 1.68 meters with a shaft centerline 2.35 meters below the free water surface. The original model test data results for this vessel are available: predicted resistance at 12 knots for the full-scale hull with appendages is 50kN; wake fraction is 0.265.

(i) Select a *P/D* ratio using the attached chart.
(ii) Determine the thrust delivered at 12 knots.
(iii) Calculate the open water efficiency η_o of the chosen propeller.
(iv) Estimate the thrust deduction fraction.
(v) Calculate the propulsive efficiency η_D.

The density of water can be taken to be 1025 kg/m^3. Assume the water temperature is 15°C.

8.b) [7] Check the propeller selected in 8.a) above for cavitation using Burrill's method (use the attached sheet). Show all work and pass in the chart with the exam. The vapor pressure of water can be taken to be 14 kPa, and the atmospheric pressure is 101 kPa. (i) Approximately how much back cavitation can be expected to occur? (ii) If you decide that 5% back cavitation is acceptable, estimate the appropriate expanded blade ratio. For this problem, you can assume A_E is equal to A_D.

Data sheet for 98-NAV-A2

$$C_T = \frac{R_T}{\frac{1}{2}\rho V^2 S} \qquad F_n = \frac{V}{\sqrt{gL}} \qquad R_n = \frac{VL}{\upsilon} \qquad R_n = \frac{c_{0.75R}\sqrt{V_A^2 + (0.75\pi nD)^2}}{\upsilon}$$

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \qquad C_F = 0.072\left(\frac{VL}{\upsilon}\right)^{-0.2} \qquad C_F = 1.327\left(\frac{VL}{\upsilon}\right)^{-0.5}$$

$$P_E = RV \qquad P_T = TV_A \qquad P_D = 2\pi nQ$$

$$C_{TS} = (1+k)C_{FS} + C_{TM} - (1+k)C_{FM} + C_A + C_{AA} \qquad L_{WT} = 2\pi\frac{V^2}{g}$$

$$J = \frac{V_A}{nD} \qquad V_A = V_S(1-w) \qquad R = T(1-t)$$

$$\eta_o = \frac{K_T J}{2\pi K_Q} \qquad \eta_D = \eta_H \eta_B = \frac{P_E}{P_D} \qquad \eta_T = \eta_H \eta_B \eta_S \eta_M \frac{1}{1+x} d_r$$

$$\frac{P_E}{P_{Bc}} = \frac{P_E}{P_T}\frac{P_T}{P_D}\frac{P_D}{P_S}\frac{P_S}{P_B}\frac{P_B}{P_{Bs}}\frac{P_{Bs}}{P_{Bc}}$$

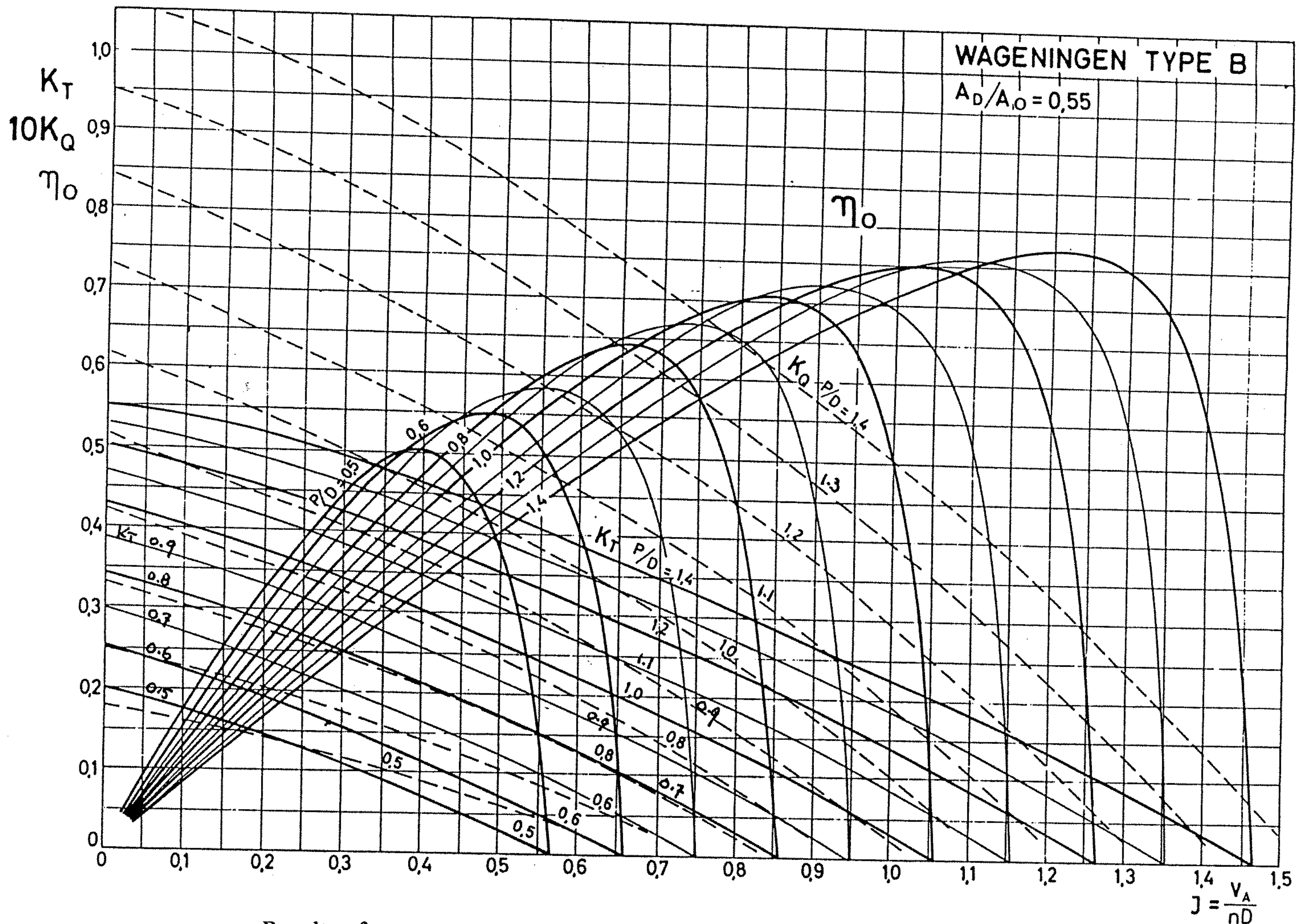
$$K_T = \frac{T}{\rho n^2 D^4} \qquad K_Q = \frac{Q}{\rho n^2 D^5} \qquad \delta = 0.37x\left(\frac{\upsilon}{Vx}\right)^{1/5}$$

Equations for Burrill's chart

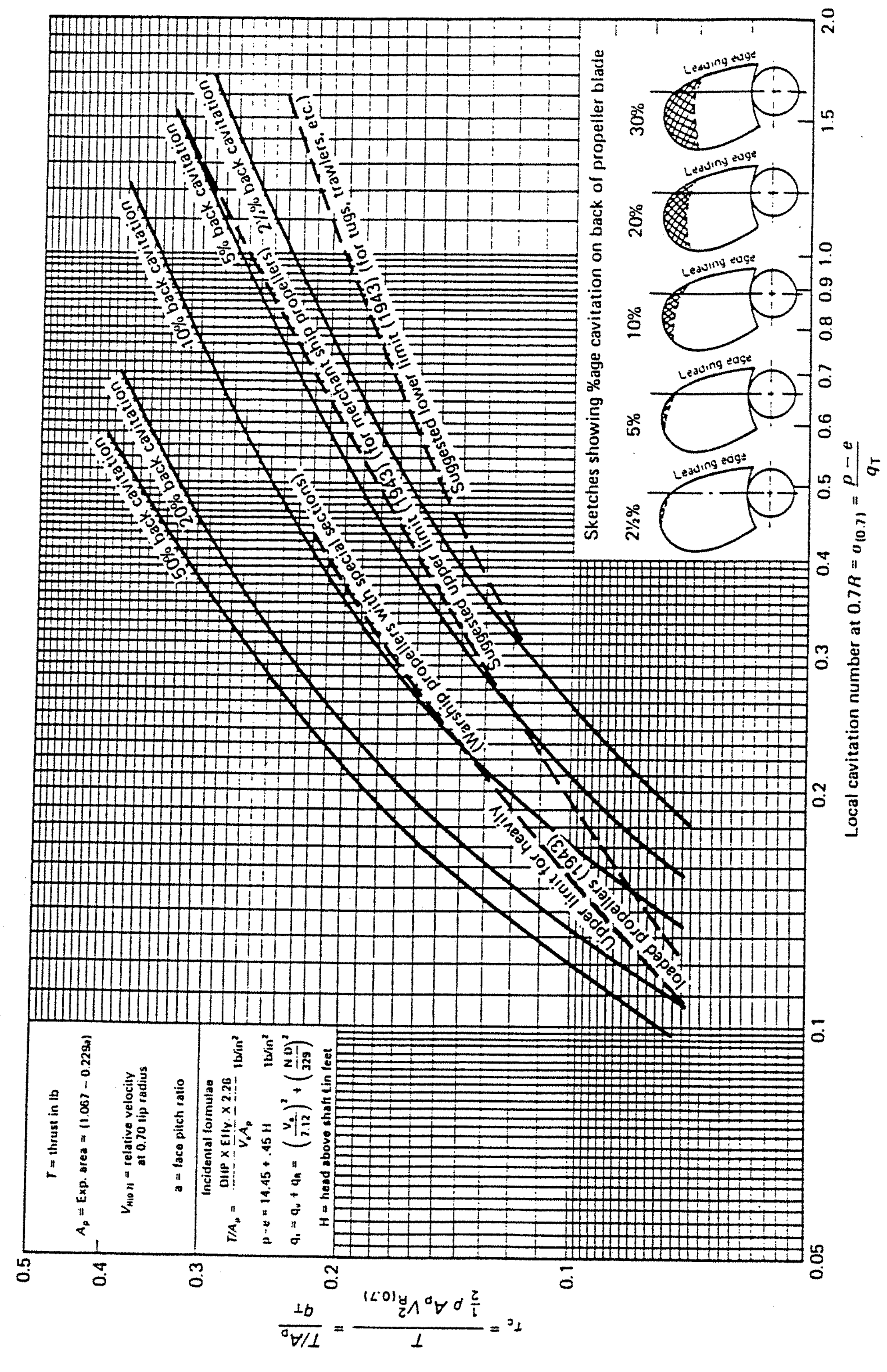
$$\sigma_{0.7R} = \frac{p_o - p_v}{\frac{1}{2}\rho\left(V_A^2 + (0.7\pi nD)^2\right)} \qquad \tau_c = \frac{T}{A_p q_{0.7R}} \qquad A_E \cong \frac{A_p}{1.067 - 0.229\, P/D}$$

Constants and data

1 knot = 0.5144 m/s
$g = 9.806$ m/s^2
$\upsilon = 1.139\times10^{-6}$ m^2/s $\quad \rho = 999$ kg/m^3 (freshwater @ 15°C)
$\upsilon = 1.188\times10^{-6}$ m^2/s $\quad \rho = 1026$ kg/m^3 (saltwater @ 15°C)



Results of open-water tests on four-bladed model propellers of the Wageningen B 4-55 type.



T = thrust in lb
A_p = Exp. area = (1.067 − 0.229a)
$V_{R(0.7)}$ = relative velocity at 0.70 tip radius
a = face pitch ratio
Incidental formulae
$T/A_p = \frac{\text{DHP} \times \text{Effy.} \times 2.26}{V_a A_p}$ lb/in²
$p - e = 14.45 + .45\ H$ lb/in²
$q_T = q_v + q_R = \left(\frac{V_a}{7.12}\right)^2 + \left(\frac{N\ D}{329}\right)^2$
H = head above shaft ℄ in feet
50% back cavitation
20% back cavitation
10% back cavitation
5% back cavitation
2½% back cavitation
Upper limit for heavily loaded propellers (1943)
Warship propellers with special sections
Suggested upper limit (1943) (for merchant ship propellers)
Suggested lower limit (1943) (for tugs, trawlers, etc.)
Sketches showing %age cavitation on back of propeller blade
2½% 5% 10% 20% 30%
Leading edge
Local cavitation number at $0.7R = \sigma_{(0.7)} = \frac{p - e}{q_T}$
$\tau_c = \frac{T}{\frac{1}{2}\rho A_p V^2_{R(0.7)}} = \frac{T/A_p}{q_T}$
0.05 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.5 2.0
0.05 0.1 0.2 0.3 0.4 0.5