HOMEWORK SOLUTIONS - CHAPTER 7

Section 7.2

Ship Drive Train

1. a. Draw a simplified picture of a ship's drive train with a prime mover, reduction gears, bearings, seals, struts, and propeller.

   b. Show where the brake horsepower, shaft horsepower, delivered horsepower, and thrust horsepower would be measured.

   c. Rank the horsepowers in part "1.b" from highest in magnitude to lowest.
7-2 A ship with a drive train illustrated in Figure 7.1 has the following mechanical efficiencies:

Reduction Gear \( \eta_{\text{gear}} = 95\% \)

Bearings/Seal/Strut \( \eta_{\text{shaft}} = 98\% \)

Calculate the power delivered to the propeller if the prime mover is producing 10,000 brake horsepower (HP).

Solving for \( DHP \):

\[
\eta_{\text{gear}} = \frac{\text{SHP}}{BHP}
\]

and

\[
\eta_{\text{shaft}} = \frac{DHP}{\text{SHP}}
\]

rearranging for \( DHP \):

\[
DHP = \text{SHP} \cdot \eta_{\text{shaft}} = BHP \cdot \eta_{\text{gear}} \cdot \eta_{\text{shaft}} = 10,000 \cdot 0.95 \cdot 0.98 = 9,310 \text{ HP}
\]

delivered to the propeller.
Section 7.3

Effective Horse Power

3. a. What is effective horsepower? In your description give its symbol and units.
   - Effective horsepower is the power required to move the ship at a given speed without the action of its propeller.
   - EHP (HP)

b. How is EHP determined in the design of a ship?
   - EHP is determined by performing a Froude Expansion on towing tank data obtained for a scale model of the ship.
4. EHP = 33,000 Hp (predicted in tow tank) @ 25 kts.

SHP required is PC = 60%?

\[
PC = \frac{EHP}{SHP} \quad SHP = \frac{33000 \text{Hp}}{0.6} = 55,000 \text{Hp}
\]

5. EHP = 50,000 Hp @ 30 kts.

What is SHP required if PC (M_{propulsion}) is:

a) 55%

\[
SHP = \frac{EHP}{PC} = \frac{50,000 \text{Hp}}{0.55} = 90,909 \text{ Hp}
\]

b) 60%

\[
SHP = \frac{EHP}{PC} = \frac{50,000 \text{Hp}}{0.60} = 83,333 \text{ Hp}
\]

c) 65%

\[
SHP = \frac{EHP}{PC} = \frac{50,000 \text{Hp}}{0.65} = 76,923 \text{ Hp}
\]
A ship has hull resistance data shown in the table below.

<table>
<thead>
<tr>
<th>Ship Speed [knots]</th>
<th>Total Hull Resistance [lbs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>70,000</td>
</tr>
<tr>
<td>10</td>
<td>100,000</td>
</tr>
<tr>
<td>13</td>
<td>135,000</td>
</tr>
<tr>
<td>15</td>
<td>170,000</td>
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<tr>
<td>17</td>
<td>220,000</td>
</tr>
<tr>
<td>20</td>
<td>265,000</td>
</tr>
<tr>
<td>23</td>
<td>375,000</td>
</tr>
<tr>
<td>25</td>
<td>500,000</td>
</tr>
</tbody>
</table>

(a) Plot the resistance data and determine the effective horsepower required for a speed of 22 kts.

Interpolating (linearly) to estimate the resistance at 22 kts,

\[ R_T(22 \text{ kts}) \approx R_T(20 \text{ kts}) + \left( \frac{22 \text{ kts} - 20 \text{ kts}}{23 \text{ kts} - 20 \text{ kts}} \right) \cdot (R_T(23 \text{ kts}) - R_T(20 \text{ kts})) \]

\[ R_T(22 \text{ kts}) = 265,000 \text{ lb} + \left( \frac{2 \text{ kts}}{3 \text{ kts}} \right) (375,000 \text{ lb} - 265,000 \text{ lb}) = 338,333.3 \text{ lb} \]

\[ EHP(22 \text{ kts}) = \frac{V \cdot R_T(22 \text{ kts})}{550 \frac{ft}{s \cdot HP}} = \frac{22 \text{ kts} \cdot 1.688 \frac{ft}{s \cdot lb} \cdot 338,333.3 \text{ lb}}{550 \frac{ft}{s \cdot HP}} = 22,844.26 \text{ HP} \]
(b) If the ship has a propulsive efficiency of 60%, what shaft horsepower is required to achieve a speed of 22 kts?

\[ P.C. = \frac{EHP}{SHP} \Rightarrow SHP = \frac{EHP}{P.C.} = \frac{22,844.26 \text{ HP}}{60\%} = 38,073.8 \text{ HP} \]

(c) The ship is to have a maximum speed of 25 kts. How many shaft horsepower must be installed to achieve this speed?

\[ SHP = \frac{EHP}{P.C.} = \frac{V \cdot R_T}{550 \frac{ft}{s} \cdot \frac{lb}{s} \cdot \frac{HP}{s} \cdot 60\%} = \frac{25 \text{ kts} \cdot 1.688 \frac{lb}{ft} \cdot 500,000 \text{ lb}}{550 \frac{ft}{s} \cdot \frac{lb}{s} \cdot 60\%} = 63,939.4 \text{ HP} \]
What would happen to total hull resistance if the ship's draft (i.e. displacement) were to increase?

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

If \( \Delta \uparrow \Rightarrow S \uparrow \Rightarrow \) wetted surface area \( S \uparrow \)

Since \( S \uparrow \) as \( \Delta \uparrow \) then \( R_T \uparrow \)
(a) Define laminar and turbulent flow.

- Laminar flow: smooth, steady flow where streamlines move around bodies in a well ordered and predictable manner. Characterized by lower skin friction.
- Turbulent flow: chaotic, choppy, unsteady flow where high levels of disorder (vorticity) is present. Characterized by higher skin friction.

(b) A ship with $L_{pp} = 500 \text{ ft}$ is traveling at a speed of $25 \text{ kts}$. Calculate the Reynolds number for this ship and speed. Also determine the nominal length of laminar flow along the hull at this speed.

Assuming a kinematic viscosity of seawater of $\nu = 1.24 \times 10^{-05} \frac{\text{ft}^2}{\text{s}}$,

$$R_n = \frac{V \cdot L}{\nu} = \frac{25 \text{ kts} \cdot 1.688 \frac{\text{ft}}{\text{kts}} \cdot 500 \text{ ft}}{1.24 \times 10^{-05} \frac{\text{ft}^2}{\text{s}}} = 1.7016 \times 10^9$$

Find the $L$ along the hull at $25 \text{ kts}$ where the $R_n = 5 \times 10^5$

$$R_n = \frac{V \cdot L_{laminar to turbulent transition}}{\nu} = 5 \times 10^5$$

Rearranging:

$$L_{laminar to turbulent transition} = 5 \times 10^5 \frac{\nu}{V} = 5 \times 10^5 \frac{1.24 \times 10^{-05}}{25 \text{ kts} \cdot 1.688 \frac{\text{ft}}{\text{kts}}} = 0.147 \text{ ft}$$

(c) The same ship has slowed to a speed of $5 \text{ kts}$. Determine the new Reynolds number for the ship.

Determine the nominal length of laminar flow along the hull associated with this speed.

$$R_n = \frac{V \cdot L}{\nu} = \frac{5 \text{ kts} \cdot 1.688 \frac{\text{ft}}{\text{kts}} \cdot 500 \text{ ft}}{1.24 \times 10^{-05} \frac{\text{ft}^2}{\text{s}}} = 3.40 \times 10^8$$

Find the $L$ along the hull at $5 \text{ kts}$ where the $R_n = 5 \times 10^5$

$$R_n = \frac{V \cdot L_{laminar to turbulent transition}}{\nu} = 5 \times 10^5$$

Rearranging:

$$L_{laminar to turbulent transition} = 5 \times 10^5 \frac{\nu}{V} = 5 \times 10^5 \frac{1.24 \times 10^{-05}}{5 \text{ kts} \cdot 1.688 \frac{\text{ft}}{\text{kts}}} = 0.735 \text{ ft}$$
(11) Waterplane view of a ship showing laminar flow at the bow, the transition point, boundary layer, flow separation, and wake.

(12) How does an increase in the ship's speed affect viscous resistance?

\[ C_V = C_F + kC_F \]
\[ = (1 + k)C_F \]

\[ C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \]
\[ R_n = \frac{VL}{U} \]

Therefore as \( V_s \uparrow \Rightarrow R_n = \frac{VL}{U} \uparrow \Rightarrow C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \Rightarrow C_F \downarrow \)

and as \( C_f \downarrow \Rightarrow C_V = (1 + k)C_F \downarrow \Rightarrow C_V \downarrow \)

As ship speed increases, the viscous resistance decreases.

\[ R_{\text{Viscous}} = \frac{1}{2} C_V \rho V^2 S \]

Since \( V \) and is squared \( R_{\text{Viscous}} \uparrow \) as speed \( \uparrow \).
13) A DDG ($L_{pp} = 465\text{ ft}$) and AOE ($L_{pp} = 740\text{ ft}$) are steaming together at 23 knots. Which ship has greater $C_F$?

$$C_F = \frac{0.075}{(\log_{10} R_n - 2)^2} \quad \Rightarrow \quad R_{n_{\text{DDG}}} < R_{n_{\text{AOE}}} \quad \text{and} \quad C_{F_{\text{DDG}}} > C_{F_{\text{AOE}}}

As \quad R_n \uparrow \Rightarrow C_F \downarrow$$

14) An FFG ($\Delta = 4000\text{ LT}, L_{pp} = 408\text{ ft}, T = 16\text{ ft}$) and CVN ($\Delta = 88,000\text{ LT}, L_{pp} = 1080\text{ ft}, T = 37\text{ ft}$) are steaming at the same Reaylon's $H$. Which ship has the greater $C_V$? Explain

$$C_V = (1 + k)C_F \quad \Rightarrow \quad K = 19\left[\frac{V}{LBT} \cdot \frac{B}{L} \right]^2$$

$$\begin{align*}
\text{FFG} & : \quad V = \frac{4000\text{ LT} \cdot 2240\text{ lb/ft} \cdot 64\text{ lb/ft}^3}{140,000\text{ ft}^3} = 140,000\text{ ft}^3 \\
K_{FFG} & = 19\left[\frac{V}{LBT} \cdot \frac{B}{L} \right]^2 = 19\left[\frac{V}{L^2T} \right]^2 = 19\left[\frac{140,000\text{ ft}^3}{(408\text{ ft})^2(16\text{ ft})} \right]^2 = 1.0
\end{align*}$$

$$\begin{align*}
\text{CVN} & : \quad V = \frac{88,000\text{ LT} \cdot 2240\text{ lb/ft} \cdot 64\text{ lb/ft}^3}{3,08 \times 10^6\text{ ft}^3} = 3.08 \times 10^6\text{ ft}^3 \\
K_{CVN} & = 19\left[\frac{V}{L^2T} \right]^2 = 19\left[\frac{3.08 \times 10^6\text{ ft}^3}{(1080\text{ ft})^2(37\text{ ft})} \right] = 13.56
\end{align*}$$

If $C_{F_{\text{CVN}}} = C_{F_{\text{FFG}}}$ then $C_{V_{\text{CVN}}} > C_{V_{\text{FFG}}}$ since $K_{CVN} > K_{FFG}$
How can the ship operator reduce the effects of wave making resistance?
Operate at slower speeds. At slower speeds viscous resistance dominates.
Additionally, ships should operate in the "hollows" of its resistance curve, if known, where the destructive interference effect will lower ship resistance.

Other types of resistance (name and describe)
- Air resistance: air resistance on the ship's superstructure
- Appendage: resistance due to rudder, struts, propellers, shafting, bilge keels, etc.
- Steering: resistance due to rudder motions for coursekeeping
- Wind/Current: resistance due to wind and current resisting the ship's motion
- Added resistance due to waves: energy or resistance encountered due to ship's motions in a seaway (heaving, pitching, rolling, etc.)
- Shallow Water Effects: increased resistance due to restricted flow around ship's bottom, more pronounced at higher speeds

Why does it take more power to achieve the same speed in shallow water than in deep water?
What dangers are associated with operating at high speeds in shallow water?

The flow of water around the bottom of the hull is restricted in shallow water, therefore the water flowing around the hull speeds up. The faster moving water increases the viscous resistance on the hull.

The faster moving water also decreases the pressure under the hull. This allows the ship to sink and trim and may lead to grounding in charted safe water.
20. How can the operator take advantage of environmental factors to reduce resistance?

Wind and current are two of the biggest environmental factors affecting a ship. Wind resistance on a ship is a function of the ship’s sail area, wind velocity and direction relative to the ship’s direction of travel. For a ship steaming into a 20-knot wind, ship’s resistance may be increased by up to 25-30%.

Ocean currents can also have a significant impact on a ship’s resistance and the power required to maintain a desired speed. Steaming into a current will increase the power required to maintain speed.

Therefore, the prudent mariner will plan his or her voyage to avoid steaming against ocean currents and prevailing winds whenever possible, and to steam with currents and winds whenever possible.

21. Briefly explain the terms geometric similarity and dynamic similarity.

*Geometric similarity* is obtained when all characteristic dimensions of the model are directly proportional to the ship’s dimensions.

\[
\text{Scale Factor} = \lambda = \frac{L_S (\text{ft})}{L_M (\text{ft})}
\]

*Dynamic similarity* means that the velocities, accelerations, and forces associated with fluid flow around both the model and full-scale ship have scaled magnitudes and identical directions at corresponding locations along the hull.

22. Explain how geometric similarity and partial dynamic similarity are achieved in resistance testing.

The wave pattern produced by a geometrically similar model and ship looks the same when the model and ship are traveling at the same speed to square root of length ratio. This is the Law of Corresponding Speeds, and is written as:

\[
\frac{V_S}{\sqrt{L_S}} = \frac{V_M}{\sqrt{L_M}}
\]

where: \(V_S = \text{ship velocity (ft/s)}\)
\(V_M = \text{model velocity (ft/s)}\)
\(L_S = \text{ship length (ft)}\)
\(L_M = \text{model length (ft)}\)
A new class of supply ship is being tested in the towing tank. The ship has a length of 680 ft and the model is built to a scale factor of 29.57.

(a) What length is the model?

\[ \lambda = \frac{L_S}{L_M} \rightarrow L_M = \frac{L_S}{\lambda} = \frac{680}{29.57} = 23.0 \text{ ft} \]

(b) The ship has a maximum speed of 20 kts. What speed must the model be towed at in order to achieve partial dynamic similarity?

\[ \frac{V_M}{\sqrt{L_M}} = \frac{V_S}{\sqrt{L_S}} \rightarrow V_M = V_S \cdot \lambda^{-\frac{1}{2}} = 10 \text{ kt} \cdot 1.688 \text{ ft/s} \cdot (29.57)^{-\frac{1}{2}} = 6.21 \frac{ft}{s} \]

(c) What is the purpose of towing tank testing?

Tow tank testing permits evaluation of powering and resistance estimates for the ship at lower relative cost than full scale testing. This often is used to validate design tool results which predict the EHF for the hull.
Propellers

24. On a sketch of a screw propeller, show the hub, blade tip, blade root, propeller diameter, pressure face, and suction back.

25. Describe two methods for quantifying the pitch of a propeller.

Propeller pitch \((P)\) is the ideal linear distance parallel to the direction of motion that would be traveled in one revolution of the propeller shaft; similar to what happens when you turn a wood screw one revolution into a block of wood.

The pitch angle \((\phi)\) of a propeller is the angle that any portion of the blade makes from perpendicular to the water flow. Since any point on a propeller blade describes a helix, the pitch of a propeller \((P)\) and pitch angle are related through the following equation:

\[
\tan \phi = \frac{P}{2\pi r}
\]
26. Briefly describe the differences between fixed pitch, variable pitch, and controllable pitch propellers.

**Fixed Pitch Propeller:** A fixed pitch propeller is a propeller whose pitch is fixed and cannot be changed while the propeller shaft is rotating. A fixed pitch propeller may have either constant or variable pitch.

**Variable Pitch Propeller:** The pitch \( P \) varies at each radial distance from the blade root to tip. Additionally, the pitch may vary across the face of the blade from leading edge to trailing edge at any radial distance from the hub.

**Controllable Pitch Propeller:** This type of propeller allows the pitch of a propeller to be changed while the propeller shaft is rotating. This is accomplished by using an electro-hydraulic system to change the pitch angle of the blades. While the entire propeller is classified as a controllable pitch propeller, the blades can also be variable pitch, producing a controllable variable pitch propeller.

27. A propeller is described as having a pitch of 15 feet. What does this mean for the ship’s operator?

**Propeller pitch** \( P \) is the ideal linear distance parallel to the direction of motion that would be traveled in one revolution of the propeller shaft; similar to what happens when you turn a wood screw one revolution into a block of wood.

A propeller pitch of 15 feet indicates that the propeller would ideally advance 15 feet forward for every revolution. In reality, the propeller will not advance a full 15 feet due to inefficiencies inherent in propellers.
10. 7-28 (G) Using the equations for the thrust loading coefficient and ideal propeller efficiency, answer the following:

\[ C_t = \frac{T}{\frac{1}{2} \rho \cdot A_O \cdot V_A^2} \]
\[ \eta_{prop, ideal} = \frac{2}{1 + \sqrt{1 + C_t}} \]

(a) Will a larger propeller be more or less efficient than a smaller propeller?

A larger propeller means that \( A_O \uparrow \Rightarrow C_t \downarrow \Rightarrow \eta_{prop, ideal} \uparrow \) and so a larger propeller to have a higher efficiency than a smaller propeller.

(b) Will high thrust and low ship speed give high or low efficiency?

\( T \uparrow \text{ and } V_A \downarrow \Rightarrow C_t \downarrow \Rightarrow \eta_{prop, ideal} \downarrow \)

and therefore a low efficiency will be achieved at low ship speed and high thrust.
29. Briefly describe why propeller cavitation occurs.

Cavitation is the formation and subsequent collapse of vapor bubbles in regions on propeller blades where pressure has fallen below the vapor pressure of water. Cavitation occurs on propellers that are heavily loaded, or are experiencing a high thrust loading coefficient.

30. What is the relationship between thrust loading and propeller cavitation?

An analysis of the equation for the thrust coefficient \((C_T)\) reveals that high propeller thrust \((T)\) and low speed through the propeller \((V_A)\) increases the thrust loading coefficient which may result in cavitation.

\[
C_T = \frac{T}{\frac{1}{2} \rho A_v V_A^2}
\]

31. Explain the following terms:

a. Tip cavitation

Blade tip cavitation is the most common form of cavitation. Tip cavitation forms because the blade tips are moving the fastest and therefore experience the greatest dynamic pressure drop.

b. Sheet cavitation

Sheet cavitation refers to a large and stable region of cavitation on a propeller, not necessarily covering the entire face of a blade. The suction face of the propeller is susceptible to sheet cavitation because of the low pressures there.

c. Spot cavitation

Spot cavitation occurs at sites on the blade where there is a scratch or some other surface imperfection.
32. What measures can the operator take to minimize propeller cavitation?

- **Speed**
  Every ship has a cavitation inception speed, a speed where tip cavitation begins to form. Unless operationally necessary, ships should be operated at speeds below cavitation inception.

- **Thrust**
  For ships with manual throttles (steam turbine), the Throttleman must not increase shaft speed and thrust too quickly when accelerating the ship. The Throttleman should open the throttle slowly, allowing flow velocity to increase or decrease proportionally with propeller thrust. Ships may use an acceleration table to guide the Throttleman in opening throttles or hydrophones calibrated to detect cavitation from the propeller.

- **Pitch**
  Operators of ships with controllable pitch propellers must take care that propeller pitch is increased or decreased in a smooth manner. This is usually done as part of the ship’s propulsion control system. Incorrect operation of the pitch control system may cause high thrust loading on the propeller blades and increase the likelihood of cavitation.

- **Depth**
  Since cavitation is a function of hydrostatic pressure, increasing hydrostatic pressure (i.e. depth) will reduce the likelihood of cavitation. As a submarine’s depth increases, hydrostatic pressure increases and cavitation inception is delayed. Therefore, a submarine can operate at higher speeds at deeper depths with little worry about cavitation noise.

- **Fouling**
  The propeller must be kept unfouled by marine organisms and free of nicks and scratches. Even a small scratch can cause significant spot cavitation and result in an increase in radiated noise as well as erosion of the blades. The Navy conducts regular underwater inspections and cleaning of its propellers to prevent the effects of fouling.