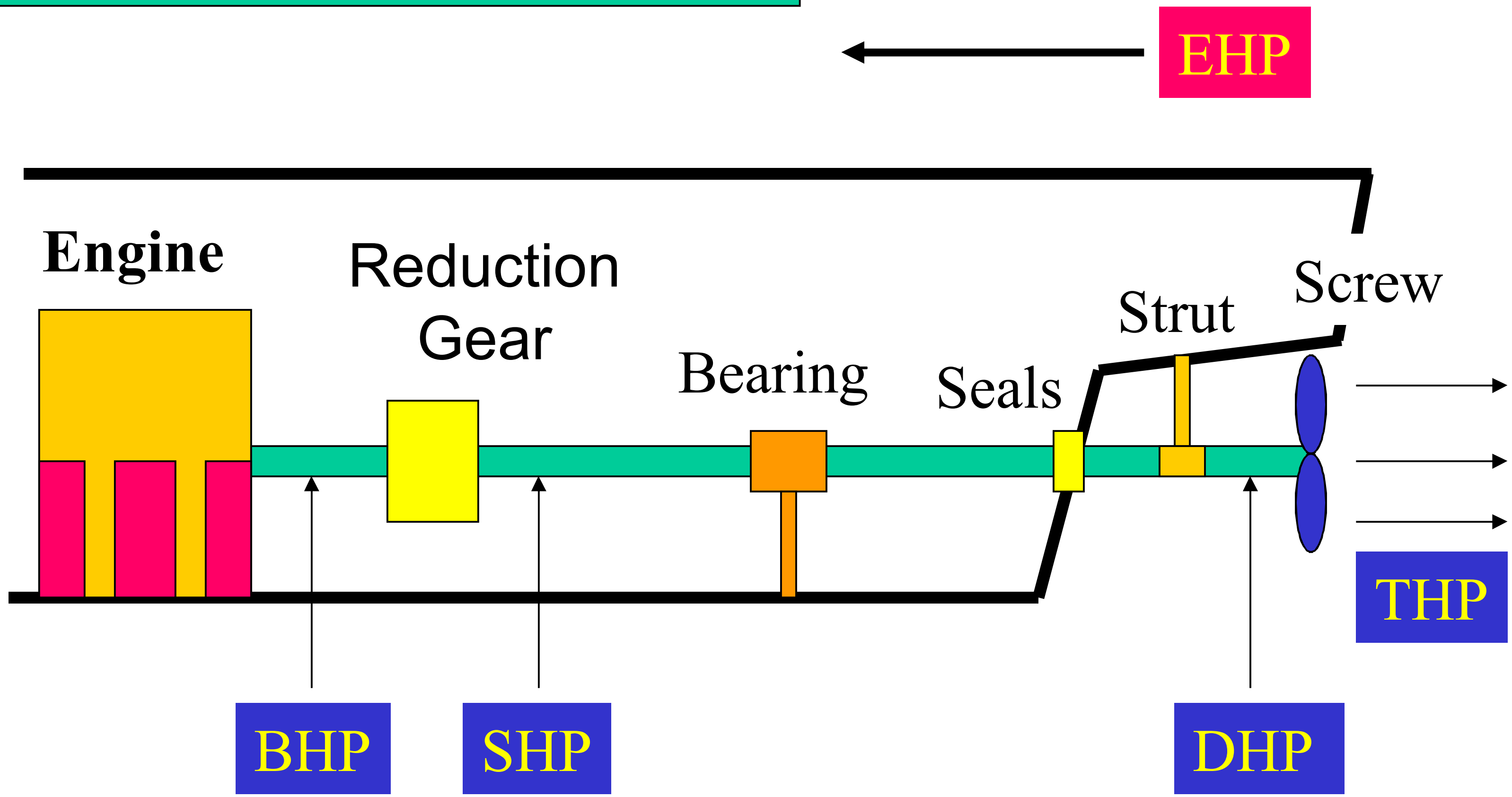
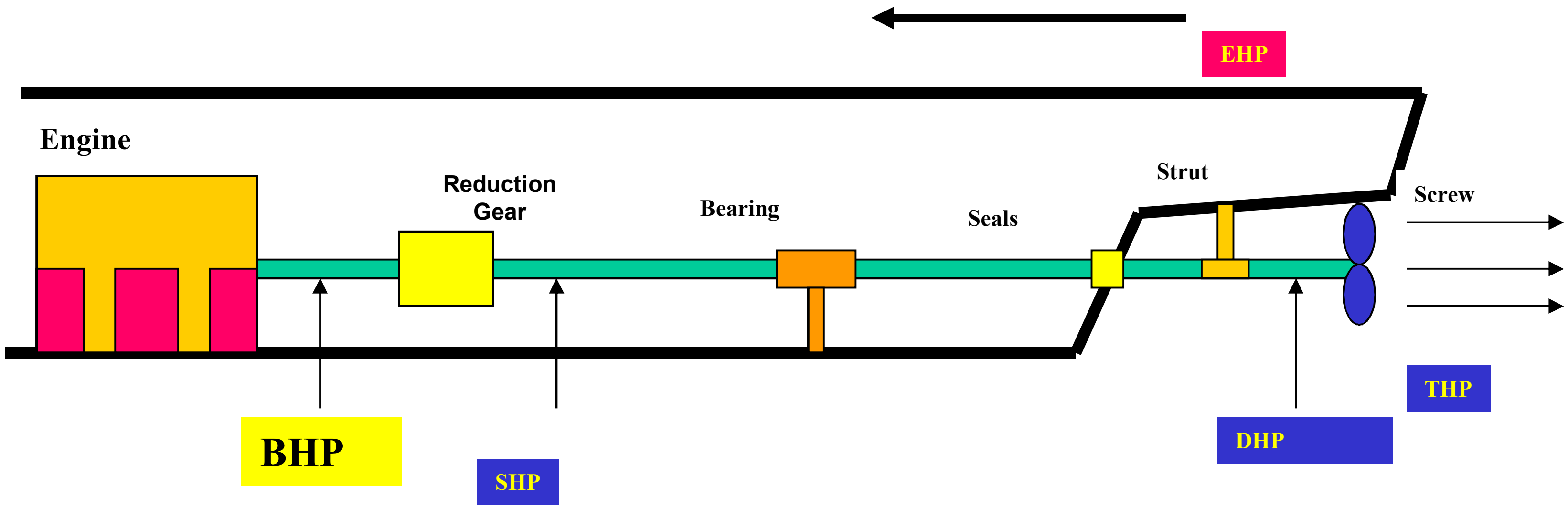
7.2 Ship Drive Train and Power

Ship Drive Train System



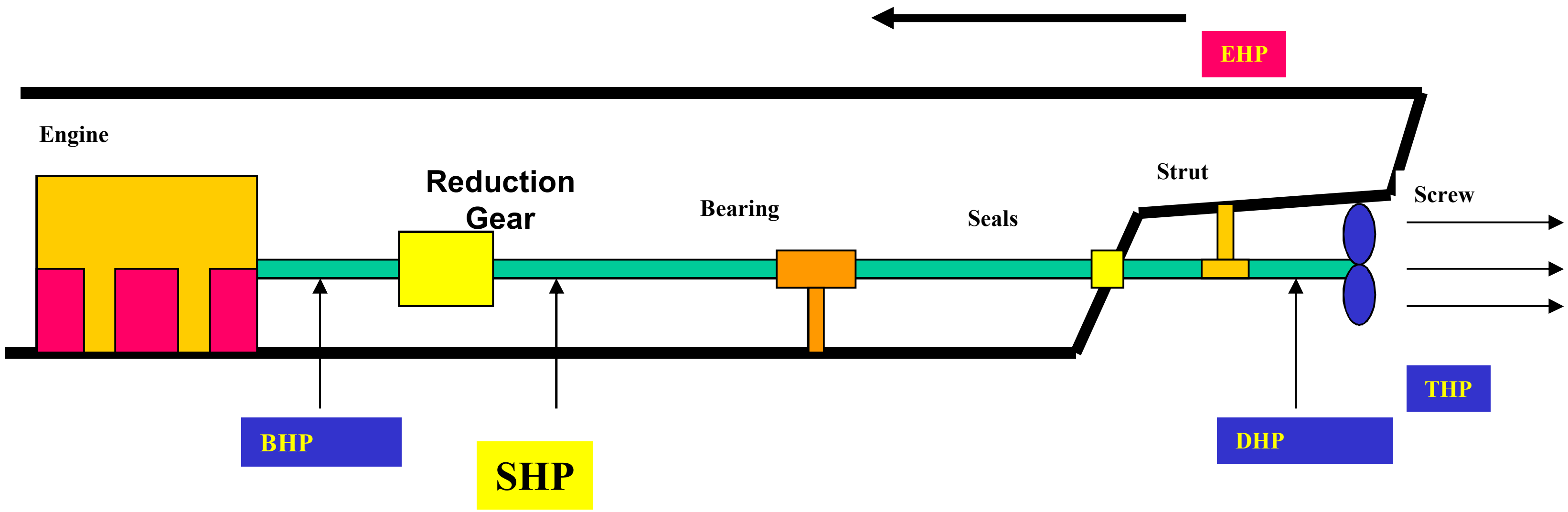
Ship Drive Train and Power



Brake Horsepower (BHP)

- Power output at the shaft coming out of the engine before the reduction gears

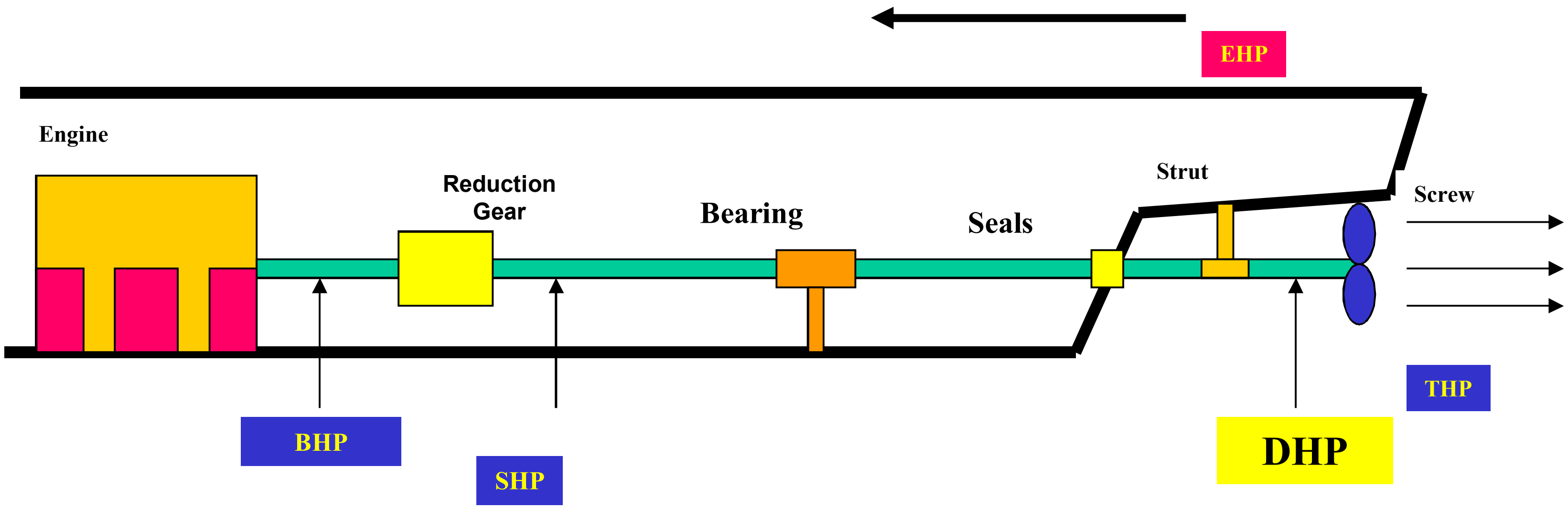
Ship Drive Train and Power



Shaft Horsepower (SHP)

- Power output at the shaft coming out of the reduction gears

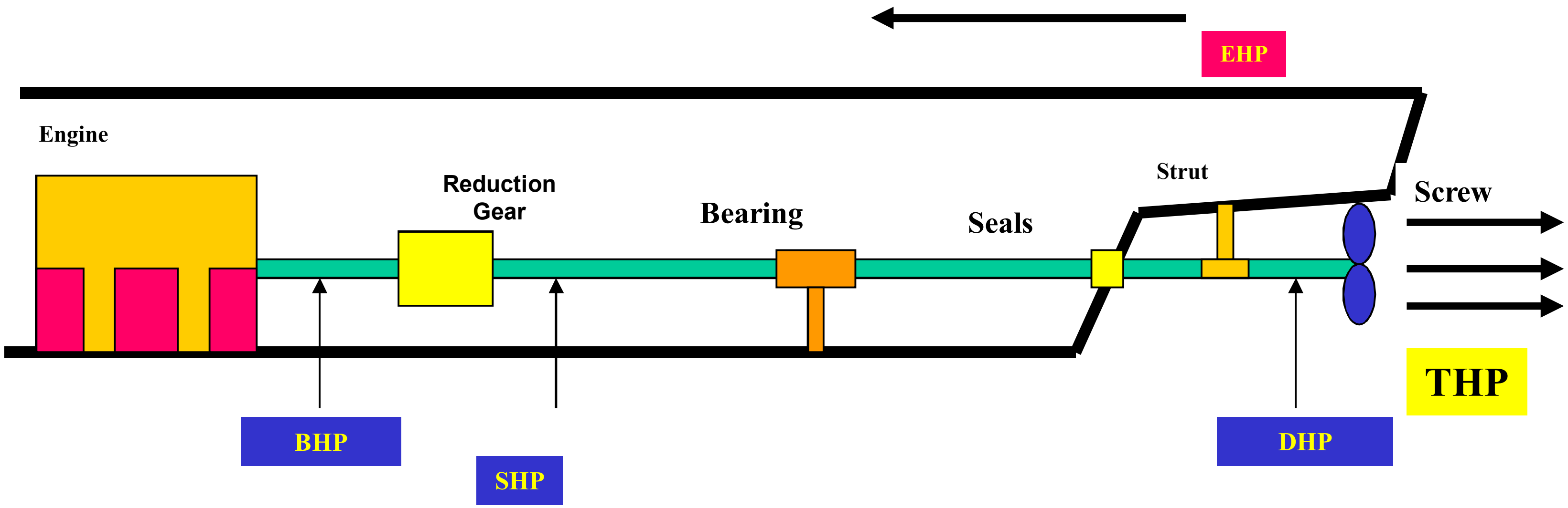
Ship Drive Train and Power



Delivered Horsepower (DHP)

- Power delivered to the propeller
- DHP=SHP – losses in shafting, shaft bearings and seals

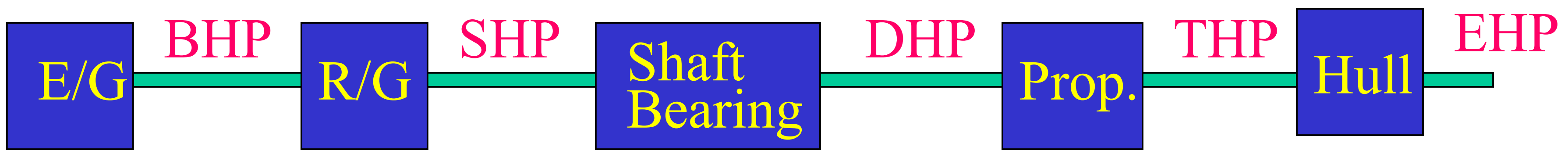
Ship Drive Train and Power



Thrust Horsepower (THP)

- Power created by the screw/propeller
- THP=DHP – Propeller losses
- THP is the end result of all HP losses along the drive train

Ship Drive Train and Power



Relative Magnitudes

BHP > **SHP** > DHP > THP > EHP

The reverse relationship can NEVER be true because there is ALWAYS some loss of power due to heat, friction, and sound

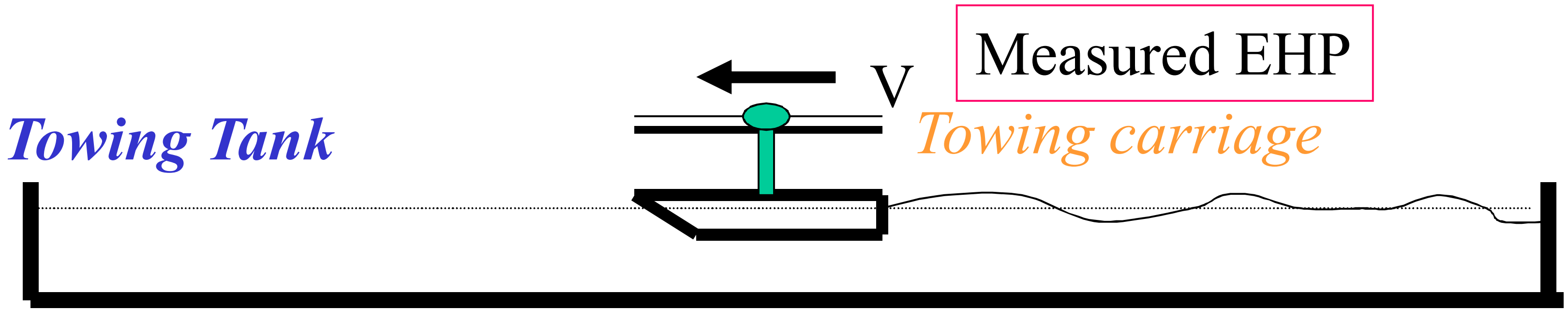
7.3 Effective Horsepower (EHP)

The power required to move the ship hull at a given speed in the absence of propeller action

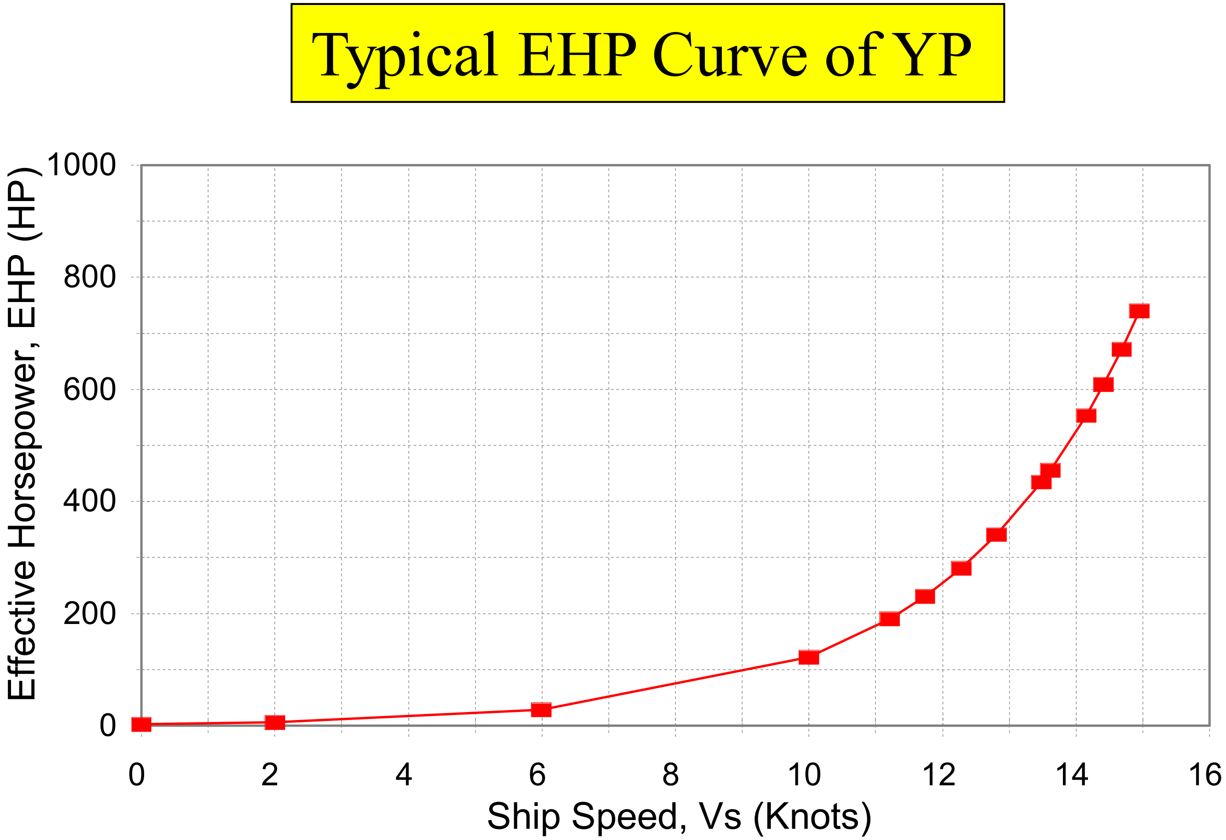
EHP is not related to Power Train System

- EHP can be determined from the towing tank experiments at the various speeds of the model ship

- EHP of the model ship is converted into EHP of the full scale ship by Froude's Law.



Effective Horsepower (EHP)



The required EHP varies depending on the vessel's speed.

Effective Horsepower (EHP)

EHP Calculation

$$EHP(H_P) = \frac{R_T(lb) \cdot V_S\left(\frac{ft}{s}\right)}{550\left(\frac{ft\ lb}{s\ H_P}\right)}$$

R_T = total hull resistance

V_S = speed of ship

$$R_T \cdot V_S \Rightarrow (lb)\cdot\left(\frac{ft}{s}\right) = \frac{lb \cdot ft}{s} = \frac{J}{s} = Watts$$ **: Power**

$$1\ Watts = 1/550\ H_P$$

7.4 Propulsion Efficiency

The loss in HP along the drive train can be related in terms of

EFFICIENCY, or "η"

Gear Efficiency

$$\eta_{gear} = \frac{SHP}{BHP}$$

$$\frac{\text{Shaft Horsepower}}{\text{Brake Horsepower}}$$

-Highlights the loss of horsepower from the engine to the shaft as a result of the reduction gears

- SHP is always less than BHP

Propulsion Efficiency

Shaft Transmission Efficiency

$$\eta_{shaft} = \frac{DHP}{SHP}$$

$$\frac{\text{Delivered Horsepower}}{\text{Shaft Horsepower}}$$

- The loss of horsepower from the reduction gears to the propeller due to the bearings and seals that support and seal the drive shaft

- The loss of power is converted to heat and sound due to friction

Propulsion Efficiency

Hull Efficiency (The loss of power will be a function of the hull design)

$$\eta_H = \frac{EHP}{THP}$$ $\frac{\text{Effective Horsepower}}{\text{Thrust Horsepower}}$

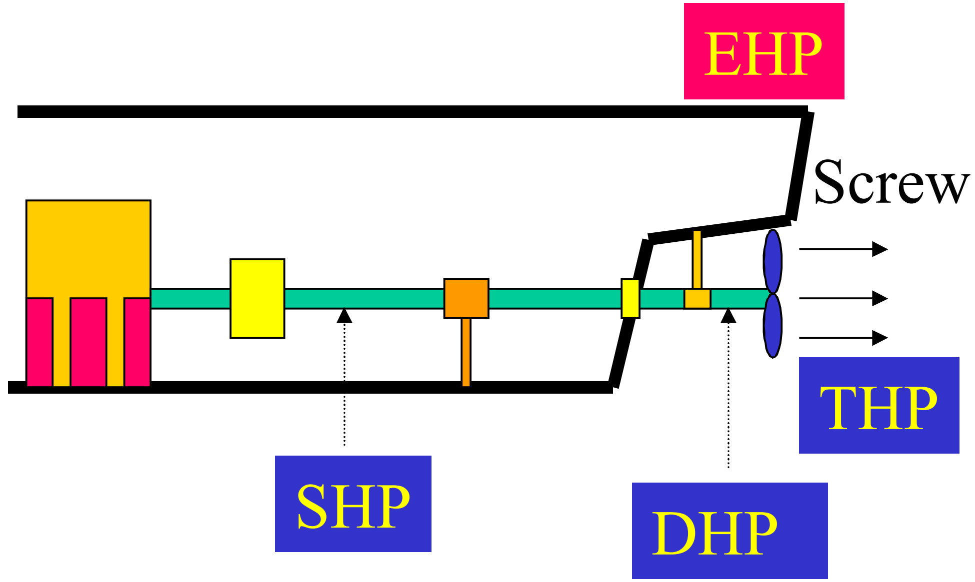
- **Hull efficiency changes due to hull-propeller interactions.**
- **Well-designed ship :** $\eta_H \succ 1$
- **Poorly-designed ship :** $\eta_H \prec 1$

- Flow is not smooth.
- THP is reduced.
- High THP is needed to get designed speed.

Propulsion Efficiency

Propeller Efficiency

$$\eta_{propeller} = \frac{THP}{DHP}$$



Propulsion Efficiency

Propulsive Efficiency (Coefficient (PC))

$$\eta_P = \frac{EHP}{SHP}$$

$$\frac{\text{Effective Horsepower}}{\text{Shaft Horsepower}}$$

- Combines the losses due to the bearings, guides, and the propeller efficiency

-Compares the output from the reduction gears to the required towing HP

-Commonly ranges from 55 - 75%

-Once η_p is found, can try different power plants, gearing, and fuel efficiencies

Example:

Through modeling of a ship's design, it is found that the towing horsepower required to maintain a speed of 20 knots is 23,500 HP. Assuming a propulsive efficiency of 68%, what is the expected required power output from the reduction gears (shaft horsepower)?

Solution:

$$\eta_P = \frac{EHP}{SHP}$$

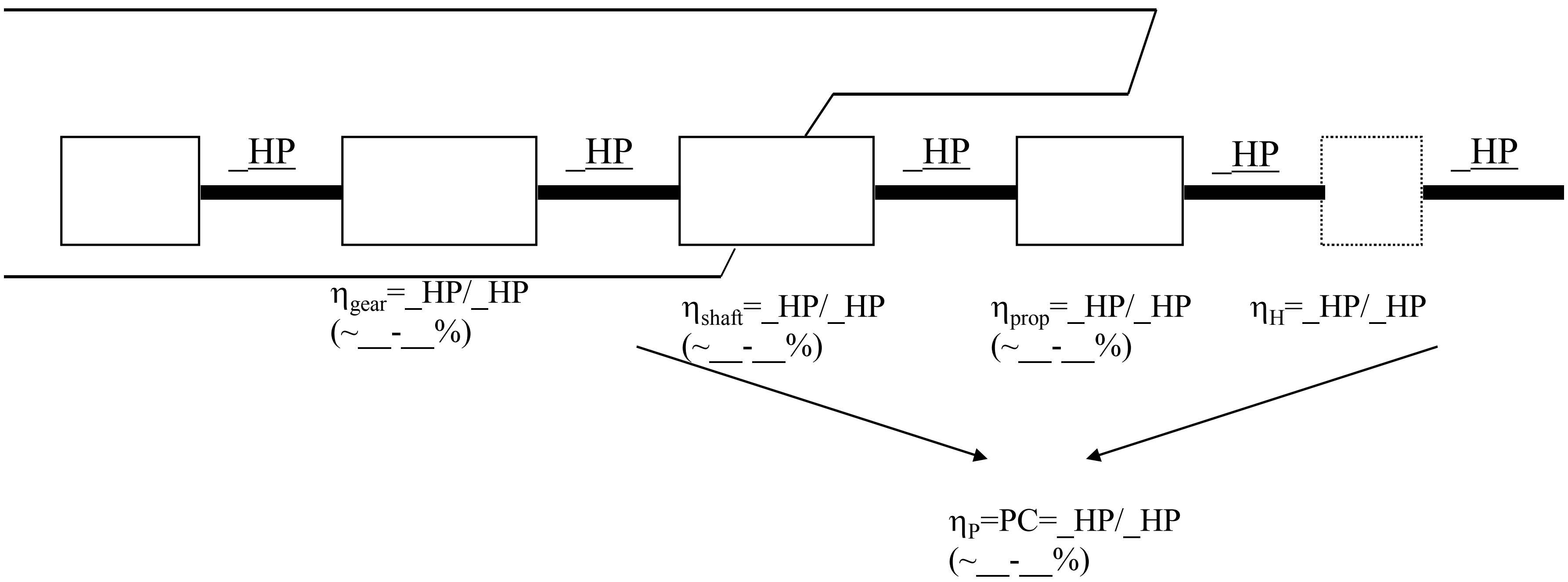
$$.68 = \frac{23{,}500\ HP}{SHP}$$

$$SHP = 23{,}500\ HP\ /\ .68$$

$$SHP = 34{,}559\ HP$$

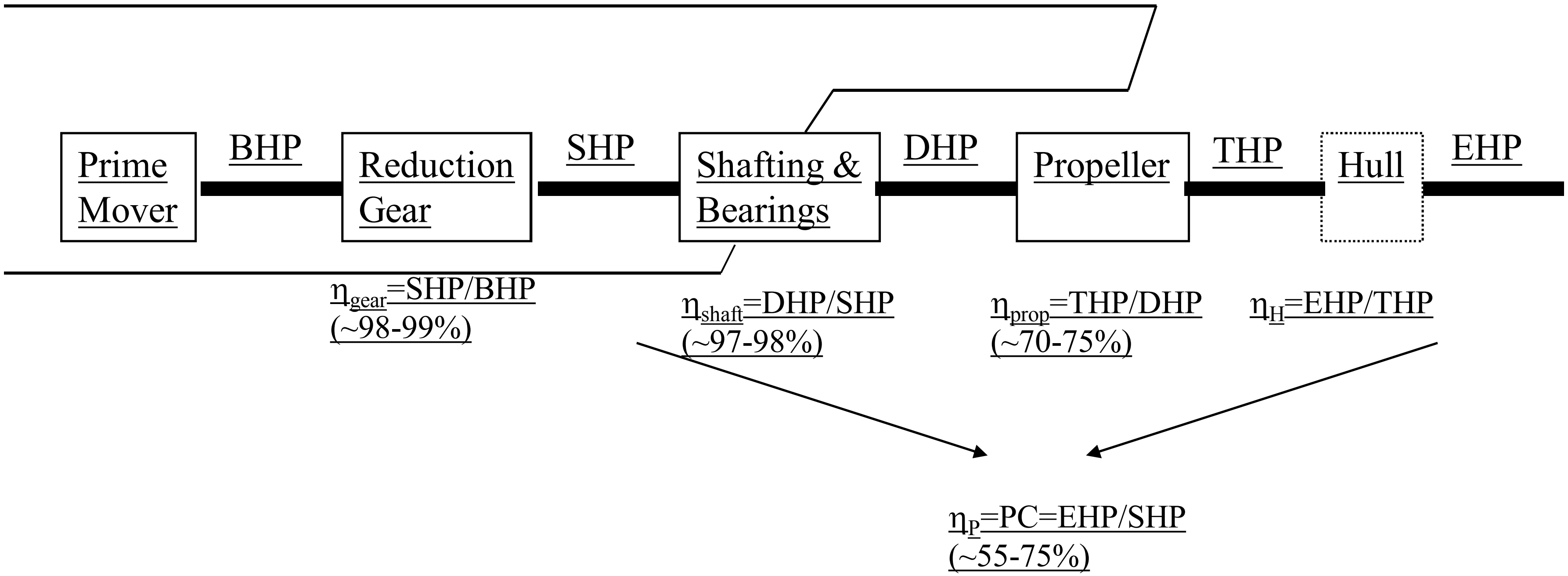
Example Problem

What are the various components, HPs, ηs and common values for ηs for the drawing below?



Example Answer

What are the various components, HPs, ηs and common values for ηs for the drawing below?



7.5 Total Hull Resistance

Total Hull Resistance (R_T)

The force that the ship experiences opposite to the motion of the ship as it moves.

EHP Calculation

$$EHP(H_P) = \frac{R_T(lb) \cdot V_S\left(\frac{ft}{s}\right)}{550\left(\frac{ft\ lb}{s\ H_P}\right)}$$

R_T = total hull resistance

V_S = speed of ship

Total Hull Resistance

Coefficient of Total Hull Resistance

- Non-dimensional value of total resistance

$$C_T = \frac{R_T}{0.5\rho V_s^2 S} \Rightarrow \frac{\text{lb}}{\left(\frac{lb \cdot s^2}{ft^4}\right)\left(\frac{ft}{s}\right)^2 ft^2} \Leftarrow \text{non - dimension}$$

C_T = Coefficient of total hull resistance in calm water

R_T = Total hull resistance

ρ = Fluid density

V_S = Speed of ship

S = wetted surface area on the submerged hull

Total Hull Resistance

Coefficient of Total Hull Resistance

-Total Resistance of full scale ship can be determined using C_T, ρ, S and V_S

$$R_T(lb) = 0.5\rho S {V_S}^2 \cdot C_T$$

C_T : determined by the model test

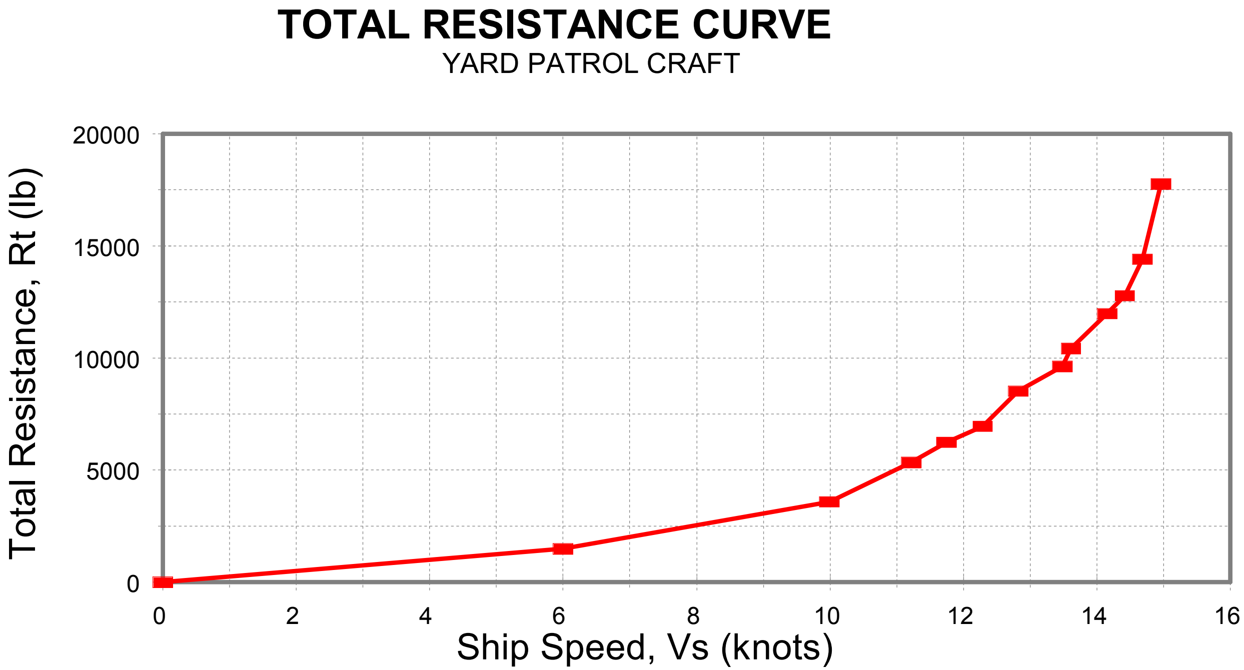
ρ : available from water property table

S : obtained from Curves of form

V_S : Full scale ship speed

Total Hull Resistance

Relation of Total Resistance Coefficient and Speed



$$R_T \approx C_T \cdot V_S{}^2$$
$$\propto V_S{}^n$$
$$n = \text{from 2 at low speed}$$
$$\text{to 5 at high speed}$$

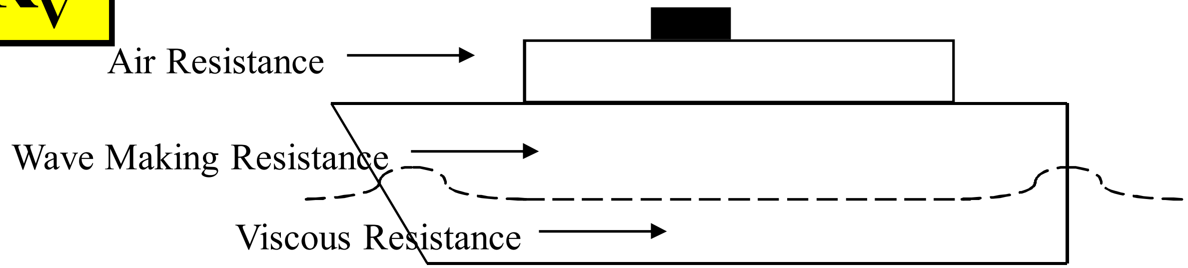
$$EHP \approx R_T V_S \approx C_T \cdot V_S{}^2 \cdot V_S$$
$$\propto V_S{}^n$$
$$n = \text{from 3 at low speed}$$
$$\text{to 6 at high speed}$$

7.6 Total Hull Resistance

Resistance values, denoted by **R**, are *dimensional* values

$\mathbf{R_T}$ = Total hull resistance is the sum of all resistance

$$\mathbf{R_T = R_{AA} + R_W + R_V}$$



$\mathbf{R_{AA}}$ = Resistance caused by calm air on the superstructure

$\mathbf{R_W}$ = Resistance due to waves caused by the ship

- A function of beam to length ratio, displacement, hull shape & Froude number (ship length & speed)

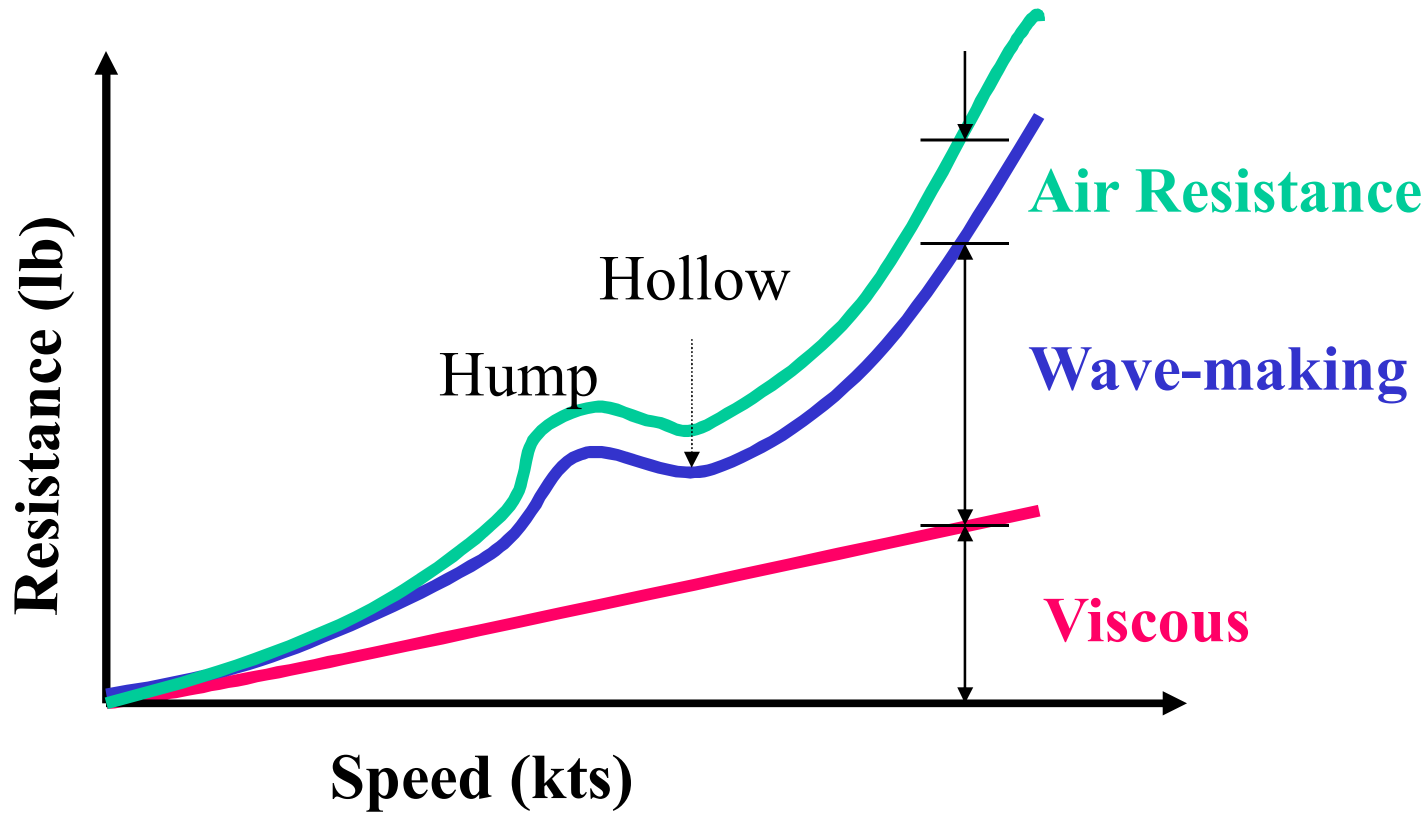
$\mathbf{R_V}$ = Viscous resistance (frictional resistance of water)

- A function of viscosity of water, speed, and wetted surface area of ship

For pilots, this is subsonic, incompressible drag

Total Hull Resistance

Total Resistance and Relative Magnitude of Components



- Low speed : *Viscous R*
- Higher speed : *Wave-making R*
- Hump (Hollow) : location is ***function of ship length and speed***.

Components of Total Resistance

Viscous Resistance

- **Resistance due to the *viscous stresses* that the fluid exerts on the hull.**
  (due to friction of the water against the surface of the ship)
- ***Viscosity, ship's velocity, wetted surface area*** **of ship generally affect the viscous resistance.**

Wave-Making Resistance

- **Resistance *caused by waves generated by the motion of the ship***
- **Wave-making resistance is affected by *beam to length ratio, displacement, shape of hull, Froude number (ship length & speed)***

Air Resistance

- **Resistance *caused by the flow of air over the ship with no wind present***
- **Air resistance is affected by projected area, shape of the ship above the water line, wind velocity and direction**
- **Typically 4 ~ 8 % of the total resistance**

Components of Total Resistance

Dimensionless Coefficients

C_T = Coefficient of **total hull resistance**

$$\mathbf{C_T = C_V + C_W}$$

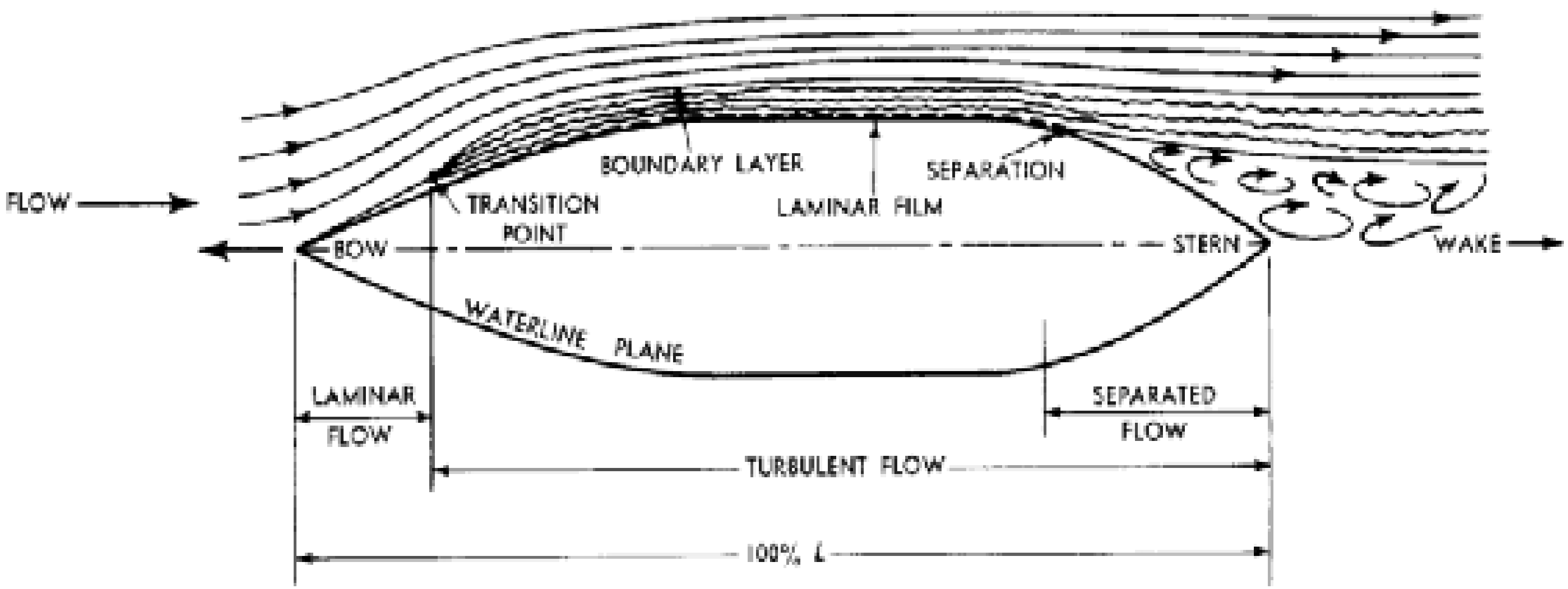
$\mathbf{C_V}$ = Coefficient of **viscous resistance** over the wetted area of the ship as it moves through the water

- C_F = Tangential component (skin resistance)
- KC_F = Normal component (viscous pressure drag)

$\mathbf{C_W}$ = Coefficient of **wave-making** resistance

Coefficient of Viscous Resistance (C_V)

Viscous Flow around a ship



Real ship : Turbulent flow exists near the bow.

Model ship : *Studs or sand strips* are attached at the bow to create the turbulent flow.

Coefficient of Viscous Resistance (C_V)

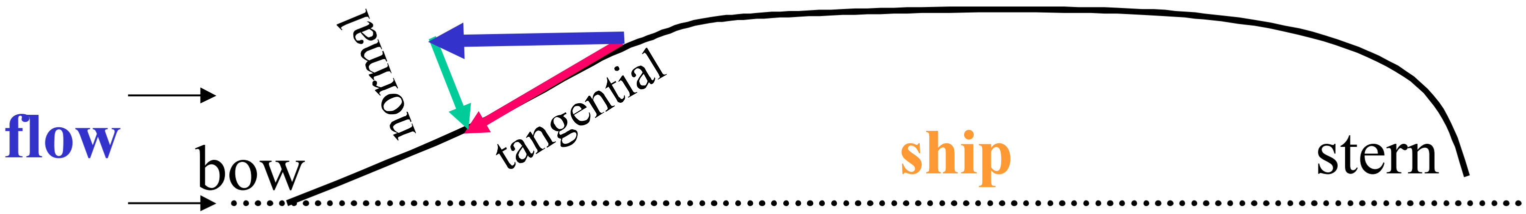
Coefficients of Viscous Resistance

- **Non-dimensional quantity of viscous resistance**
- **It consists of tangential and normal components.**

  CF=tangential (skin friction) component of viscous resistance

  KCF=normal (viscous pressure/form drag) component of viscous friction

$$C_V = C_{tangential} + C_{normal} = C_F + KC_F$$



Tangential Component : C_F

- **Tangential stress is parallel to ship's hull and causes a net force opposing the motion ;** ***Skin Friction***
- **It is assumed** C_F **can be obtained from the experimental data of flat plate.**

Coefficient of Viscous Resistance (C_V)

Tangential Component of $C_V = C_F$

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

$$R_n = \frac{L V_S}{\nu}$$

Semi-empirical equation

R_n = **Reynolds Number**

L = **L_{pp}(ft)**

V_S = **Ship Speed(ft/s)**

ν = **Kinematic Viscosity (ft^2/s)**

$= 1.2260 \times 10^{-5}\ ft^2/s$ **for fresh water**

$= 1.2791 \times 10^{-5}\ ft^2/s$ **for salt water**

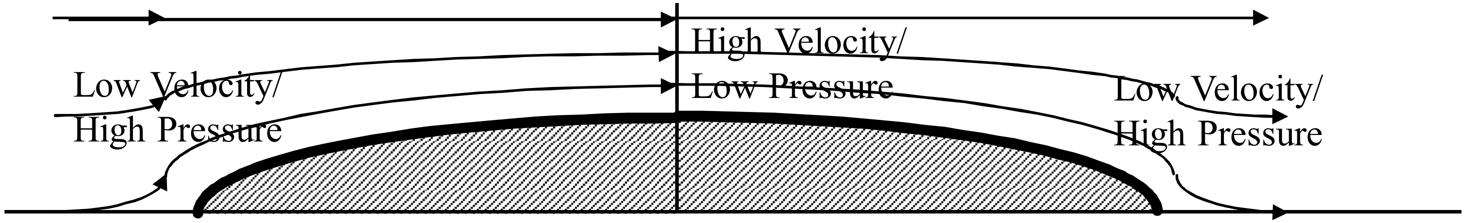
Coefficient of Viscous Resistance (C_V)

Boundary Layer Separation Resistance

Bernoulli's Equation:
$p/\rho + V^2/2 + gz = \text{constant}$

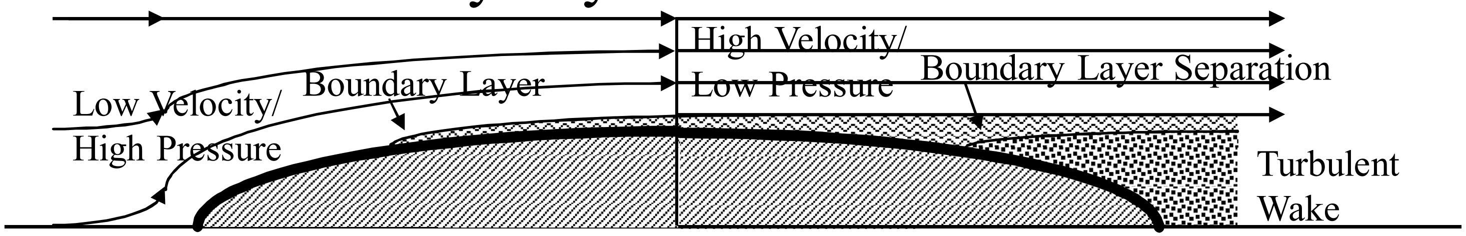
Viscous Pressure/Form Drag

– Laminar Flow



– Turbulent Flow

- Boundary Layer



Coefficient of Viscous Resistance (C_V)

Tangential Component: C_F

- **Relation between viscous flow and Reynolds number**

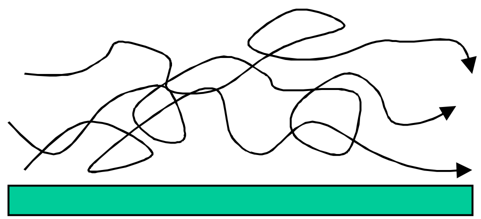
  · **Laminar flow** : ***In laminar flow, the fluid flows in layers in an orderly fashion. The layers do not mix transversely but slide over one another.***

  · **Turbulent flow** : ***In turbulent flow, the flow is chaotic and mixed transversely.***

Flow over flat plate

Laminar Flow

$R_n <$ **about** 5×10^5



Turbulent Flow

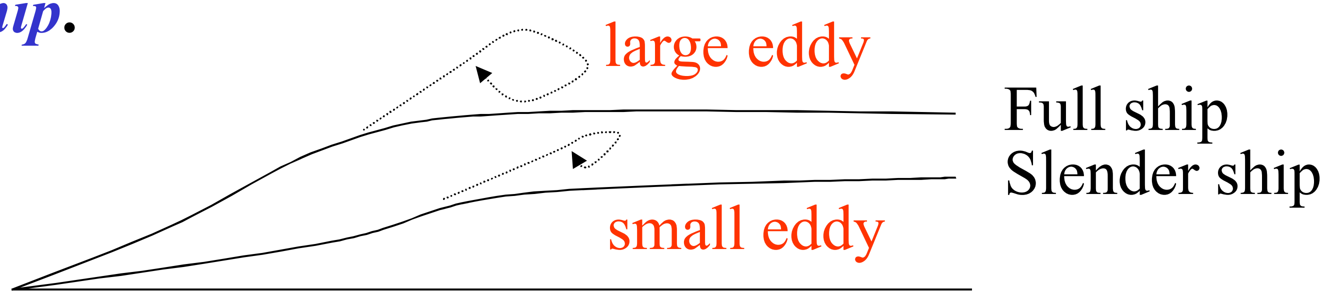
$R_n >$ **about** 5×10^5

Coefficient of Viscous Resistance (C_V)

Normal Component: KC_F

- Normal component causes a pressure distribution along the underwater hull form of ship
- A high pressure is formed in the forward direction opposing the motion and a lower pressure is formed aft.
- *Normal component generates the eddy behind the hull*.
- It is affected by hull shape.

  ***Fuller shape ship has larger normal component than slender ship*.**



Coefficient of Viscous Resistance (C_V)

Normal Component: KC_F

- It is calculated by the product of Skin Friction with Form Factor.

$$\textbf{Normal Component of } C_v = K\, C_F$$

$$C_F = \textbf{Skin Friction Coeff.}$$

$$\mathrm{K} = \textbf{Form Factor}$$

$$\mathrm{K} = 19\left(\frac{\nabla(\mathrm{ft}^3)}{L(ft)B(ft)T(ft)}\frac{B(ft)}{L(ft)}\right)^2$$

Coefficient of Viscous Resistance (C_V)

$$C_V = C_{tangential} + C_{normal} = \mathbf{C_F} + \mathbf{K\,C_F}$$

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

$$K = 19\left(\frac{\nabla(\mathrm{ft}^3)}{L(ft)B(ft)T(ft)}\frac{B(ft)}{L(ft)}\right)^2$$

$$R_n = \frac{LV_S}{\nu}$$

K= Form Factor

R_n = **Reynolds Number**

L = **$\mathbf{L_{pp}}$(ft)**

V_S = **Ship Speed(ft/s)**

ν = **Kinematic Viscosity (ft^2/s)**

$= \mathbf{1.2260 \times 10^{-5}\, ft^2/s}$ **for fresh water**

$= \mathbf{1.2791 \times 10^{-5}\, ft^2/s}$ **for salt water**

Coefficient of Viscous Resistance (C_V)

Reducing the Viscous Resistance Coeff.

- Method :

Increase L while keeping the submerged volume constant

1) Form Factor K $\downarrow$ $\Rightarrow$ Normal component $KC_F \downarrow$

$\therefore$ Slender hull is favorable. (Slender hull form will create a smaller pressure difference between bow and stern.)

2) Reynolds No. Rn $\uparrow$ $\Rightarrow$ CF $\downarrow$ $\Rightarrow$ $KC_F \downarrow$

Froude Number F_n

The Froude Number (inertia force/gravity force) is another dimensionless value derived from model testing:

$$Fn = \frac{V}{\sqrt{gL}}$$

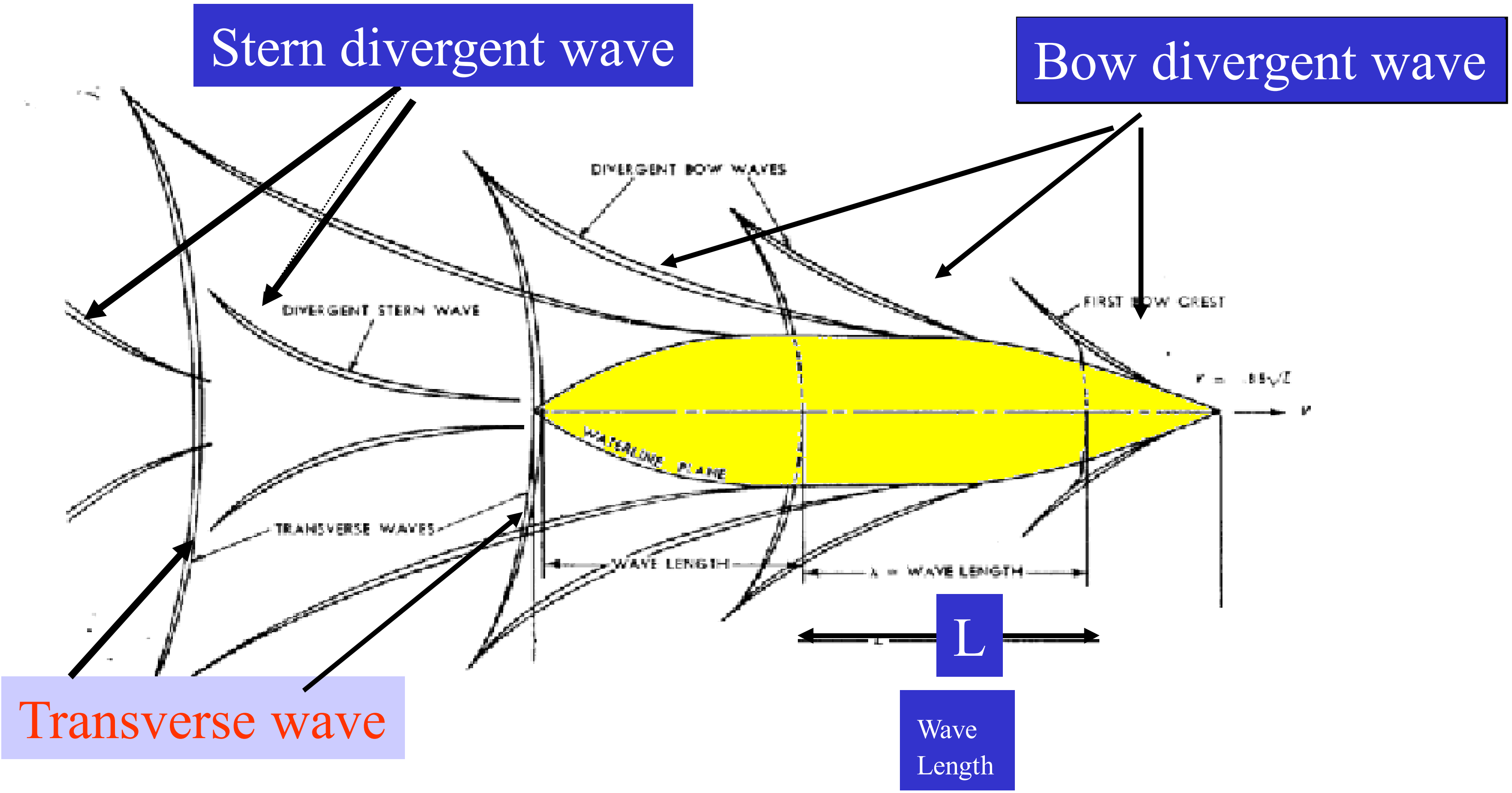
Also used, but not dimensionless, is the Speed-to-Length Ratio:

$$\text{Speed-to-Length Ratio} = \frac{V}{\sqrt{L}}$$

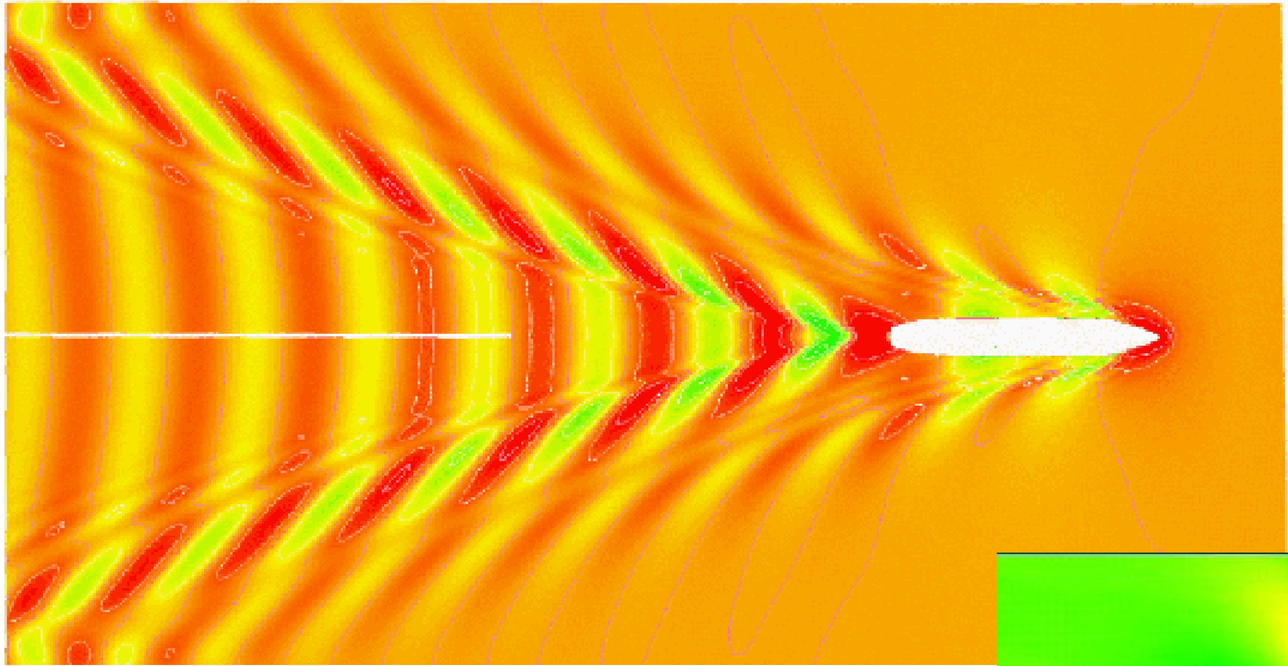
...Velocity is typically expressed in Knots (1 knot = 1.688ft/s)

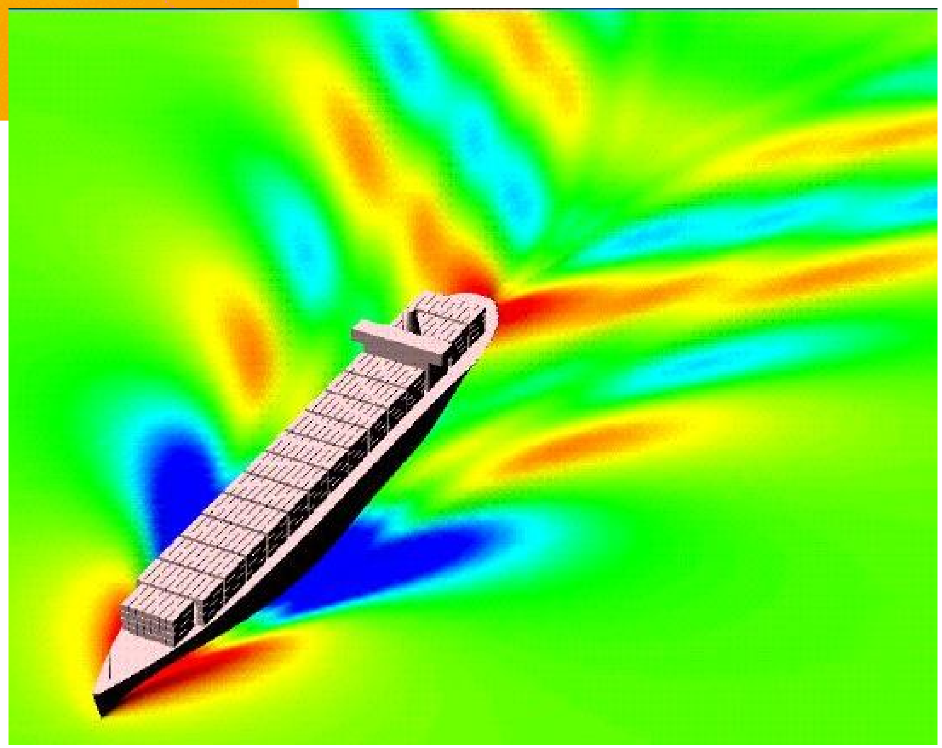
Coefficient of Wave Resistance C_W

Typical Wave Patterns are made up of TRANSVERSE and DIVERGENT waves



Coefficient of Wave Resistance C_W





Coefficient of Wave Resistance C_W

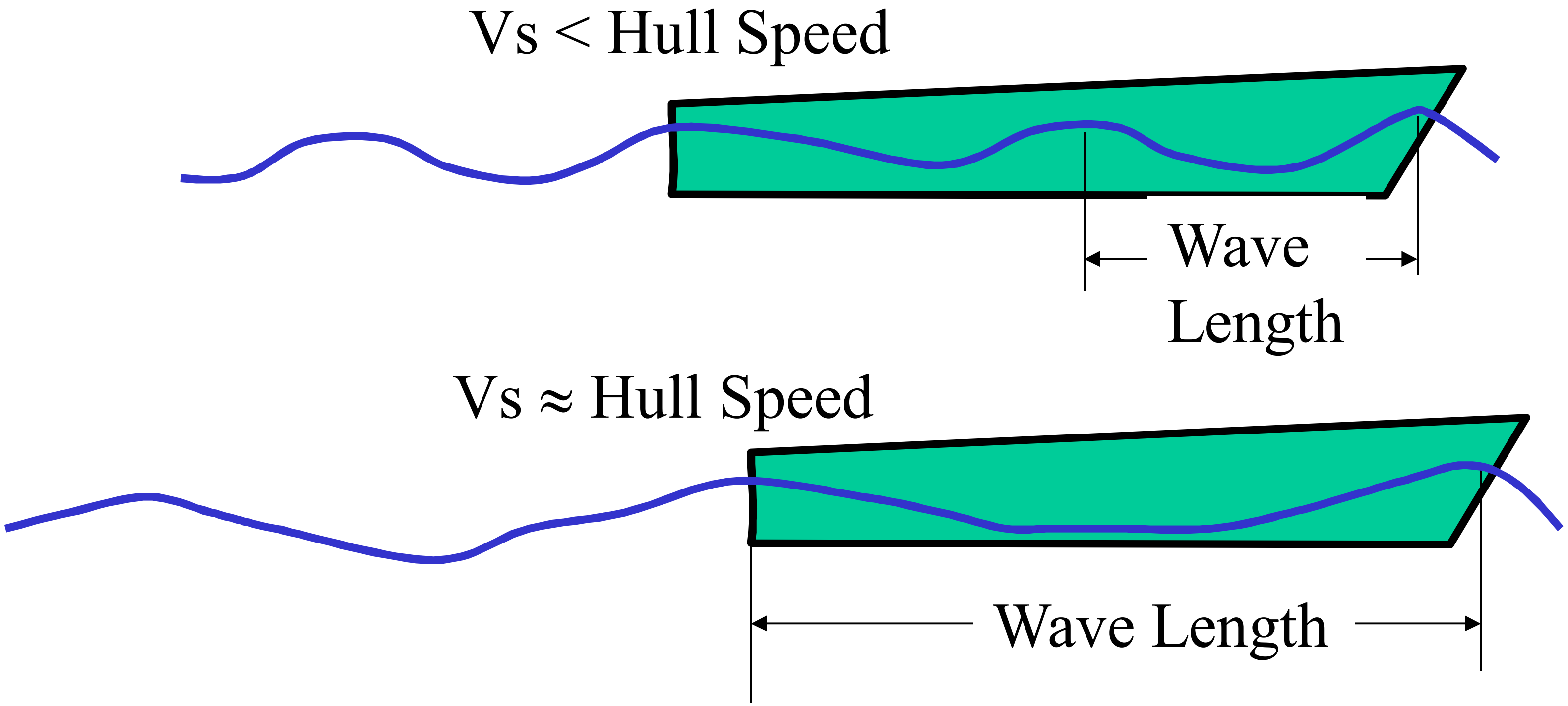
Transverse wave System

- It travels at approximately ***the same speed as the ship***.
- At slow speed, several crests exist along the ship length because the wave lengths are smaller than the ship length.
- ***As the ship speeds up, the length of the transverse wave increases.***
- ***When the transverse wave length approaches the ship length, the wave making resistance increases very rapidly.***

  This is the ***main reason for the dramatic increase in Total Resistance as speed increases.***

Coefficient of Wave Resistance C_W

Transverse wave System



Slow Speed

High Speed

Hull Speed* : *speed at which the transverse wave length equals the ship length.

(Wavemaking resistance drastically increases above hull speed)

Coefficient of Wave Resistance C_W

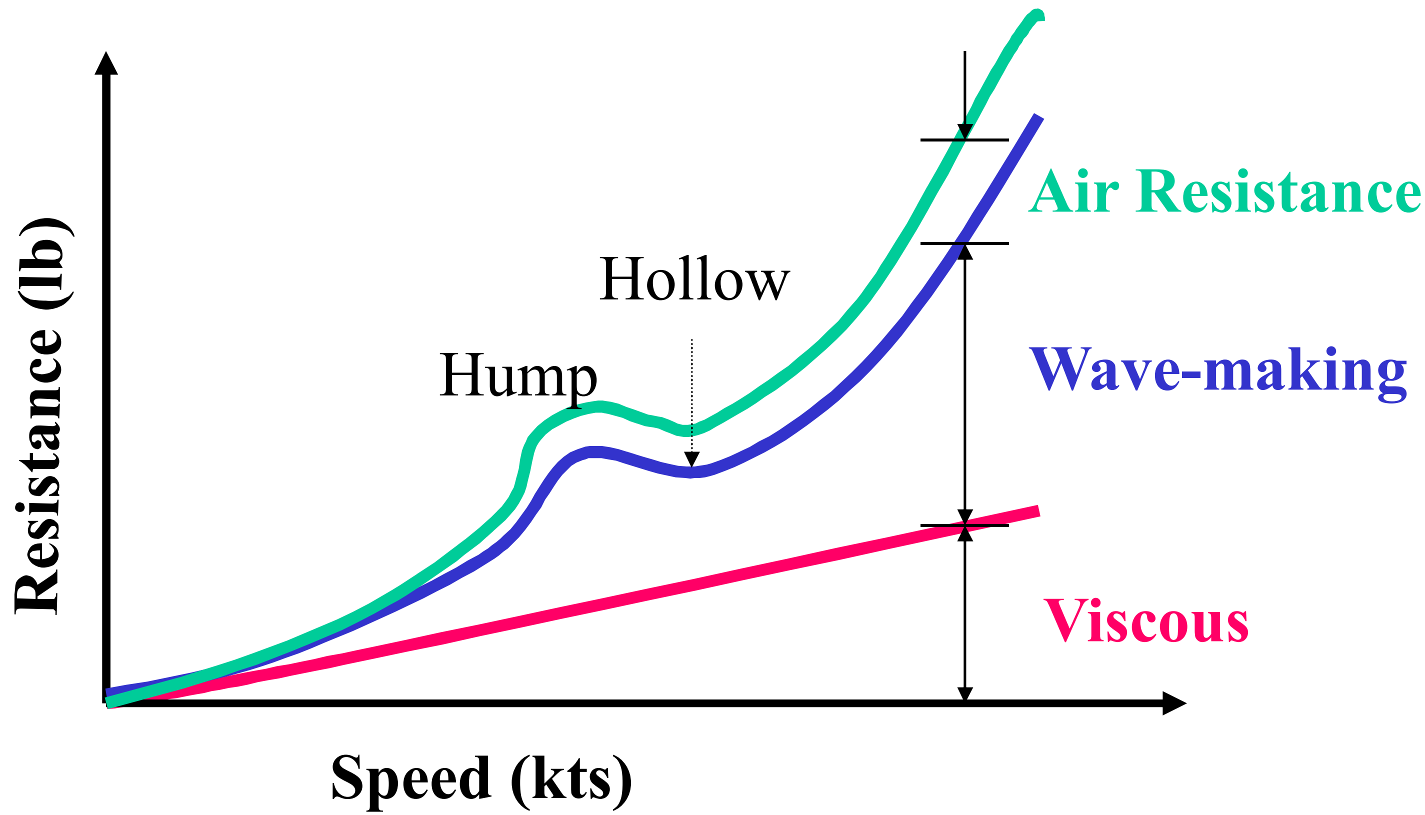
Divergent Wave System

- It consists of ***Bow and Stern Waves***.
- Interaction of the bow and stern waves create the ***Hollow or Hump*** on the resistance curve.

Hump : When the bow and stern waves are *in phase*, the crests are added up so that larger divergent wave systems are generated.

Hollow : When the bow and stern waves are *out of phase*, the crests matches the trough so that smaller divergent wave systems are generated.

Coefficient of Wave Resistance C_W



- Low speed : *Viscous R*
- Higher speed : *Wave-making R*
- Hump (Hollow) : location is ***function of ship length and speed***.

Coefficient of Wave Resistance C_W

Calculation of Wave-Making Resistance Coeff.

- **Wave-making resistance is affected by**
  - **beam to length ratio**
  - **displacement**
  - **hull shape**
  - **Froude number**
- **The calculation of the coefficient is *far difficult and inaccurate from any theoretical or empirical equation.***
  (Because mathematical modeling of the flow around ship is very complex since there exists fluid-air boundary, wave-body interaction)
- **Therefore *model test in the towing tank and Froude expansion* are needed to calculate the Cw of the real ship.**

Coefficient of Wave Resistance C_W

It takes energy to produce waves, and as speed increases, the energy required is a square function of velocity!

$$L_{wave} = \frac{2\pi V^2}{g}$$

The limiting speed, or hull speed, can be found as:

$$V = 1.34\sqrt{L_s}$$

Note: Remember at the hull speed, L_{wave} and L_s are approximately equal!

Coefficient of Wave Resistance C_W

Reducing Wave Making Resistance

1) *Increasing ship length to reduce the transverse wave*

- Hull speed will increase.
- Therefore increment of wave-making resistance of longer ship will be small until the ship reaches to the hull speed.
- *EX* :

FFG7 : ship length 408 ft
hull speed 27 KTS

CVN65 : ship length 1040 ft
hull speed 43 KTS

Coefficient of Wave Resistance C_W

Reducing Wave Making Resistance

2) ***Attaching Bulbous Bow to reduce the bow divergent wave***

- Bulbous bow generates the second bow waves .

- Then the waves interact with the bow wave resulting in ideally no waves, practically smaller bow divergent waves.

- *EX* :

DDG 51 : 7 % reduction in fuel consumption at cruise speed

3% reduction at max speed.

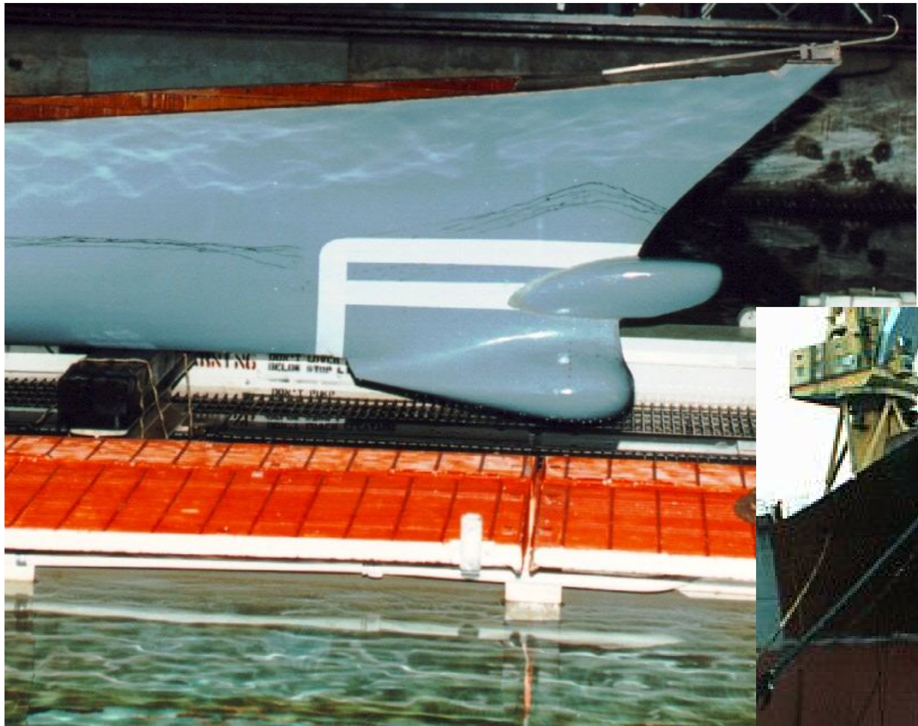
design &retrofit cost : less than $30 million

***life cycle fuel cost saving for all the ship : $250 mil*.**

Tankers & Containers : adopting the Bulbous bow

Coefficient of Wave Resistance C_W

Bulbous Bow



Coefficient of Total Resistance

Coefficient of total hull resistance

$$C_T = C_V + C_W + C_A$$
$$= C_F(1+K) + C_W + C_A$$

C_A: Correlation Allowance

Correlation Allowance

- **It accounts for hull resistance due to surface roughness, paint roughness, corrosion, and fouling of the hull surface.**
- **It is only used when a full-scale ship prediction of EHP is made from model test results.**
- **For model,** $C_A = 0$ **Since model surface is smooth.**
- **For ship, empirical formulas can be used.**

Other Type of Resistances

Appendage Resistance

- **Frictional resistance caused by the underwater appendages such as** ***rudder, propeller shaft, bilge keels and struts***
- **2~24% of the total resistance in naval ship.**

Steering Resistance

- ***Resistance caused by the rudder motion*****.**
- **Small in warships but troublesome in sail boats**

Added Resistance

- ***Resistance due to sea waves which will cause the ship motions*** **(pitching, rolling, heaving, yawing).**

Other Type of Resistances

Increased Resistance in Shallow Water

- *Resistance caused by shallow water effect*
- **Flow velocities under the hull increases in shallow water.**
    - **Increase of frictional resistance due to the velocities**
    - **Pressure drop, suction, increase of wetted surface area**

      → Increases frictional resistance
- **The waves created in shallow water take more energy from the ship than they do in deep water for the same speed.**

  → Increases wave making resistance

Operating to Minimize Resistance

- ✓ Keep the hull clean
- ✓ Operate at a prudent speed
  - Keep speed below “hump speed” to optimize economy

7.7 Tow Tank Modeling

So far we've discussed what resistance is and how it can quantified using:

- R_T by measuring the actual resistance force
- C_T dimensionless coefficients that can be used to compare resistance between dissimilar hull shapes and sizes

We can now measure the resistance in a hull and use the data to designing a ship's power plant

- Using the resistance data, an effective power plant can be designed
- Taking into account the relationship between
  - Effective Horsepower, EHP
  - Shaft Horsepower, SHP

Tow Tank Modeling

Resistance and power are related!

$$EHP = \frac{R_t \; V_s}{550 \; \frac{\text{ft - lb}}{\text{sec-HP}}}$$

Resistance can be measured in two ways:

- Computer modeling
  - Can be very difficult to mathematically model viscous flow in 3 dimensions
- Tow Tank testing
  - Producing a geometrically and dynamically similar model to test
  - Relate model performance to expected actual ship performance

Tow Tank Modeling

Tow Tank testing is the obvious way to go! But to do so, your "model" ship must meet some criteria:

1. Geometric Similarity

- The dimensions of the model and ship must be scaled exactly
- The "Scale Factor" is called λ (lambda)

$$\lambda = \frac{L_S \text{ (ft)}}{L_M \text{ (ft)}}$$

Length

$$\lambda^2 = \frac{S_S \text{ (ft}^2)}{S_M \text{ (ft}^2)}$$

Area

$$\lambda^3 = \frac{V_S \text{ (ft}^3)}{V_M \text{ (ft}^3)}$$

Volume

where: M = Model S = Ship

…Note that a "minor" error in any length measurement will be cubed (n^3)in volume scaling!

Tow Tank Modeling

2. Dynamic Similarity

- Motion of the vessel must also be scaled, including:
  - Ship's velocity
  - Acceleration
  - Viscosity of the water

- Dynamic similarity can only be approximated as water's viscosity and the forces of gravity can not be manipulated

$$C_{W_M} = C_{W_S}$$

$$C_{V_M} \neq C_{V_S}$$

- The trade-off is a "partial similarity"
- Froude's Law of Comparison or **"Law of Corresponding Speeds"**

Tow Tank Modeling

The Law of Corresponding Speeds says:

$$\frac{V_S}{\sqrt{L_S}} = \frac{V_M}{\sqrt{L_M}}$$

Tow Tank Modeling

We've already defined λ as:

$$\lambda = \frac{L_S\ (ft)}{L_M\ (ft)}$$

If we wanted to solve for the scale speed for the model,

$$\mathbf{V_M = V_S \frac{\sqrt{L_M}}{\sqrt{L_S}}}$$

or

$$\mathbf{V_M = V_S\ \lambda^{-1/2}}$$

...NOTE! 1 kt is equal to 1.688 ft/sec! ALL velocities are done in feet/sec!

Example 1:

The USS Monitor was 197 ft long and 40 ft across the beam and was able to maintain a maximum speed of 6 kts. You would like to create a model for testing that is 5 ft long.

How wide should the model be? How fast should the model be towed to represent the actual ship's max speed?

$$\lambda = L_S/L_M$$

$$\lambda = 197 \text{ ft} / 5 \text{ ft}$$

$$\boxed{\lambda = 39.4}$$

Solving for the width,

$$\lambda = W_S/W_M$$

$$W_M = 40 \text{ ft}/39.4$$

$$\boxed{W_M = 1.015 \text{ ft}}$$

Solving for the maximum speed,

$$\frac{\mathbf{V_S}}{\sqrt{\mathbf{L_S}}} = \frac{\mathbf{V_M}}{\sqrt{\mathbf{L_M}}}$$

$$V_M = V_S \, \lambda^{-1/2}$$

$$V_M = 6 \text{ kts } (1.688 \text{ ft/sec-kts}) \times 39.4^{-1/2}$$

$$V_M = 10.128 \text{ ft/s} \times .1593$$

$$\mathbf{V_M = 1.6134 \text{ ft/s}}$$

Example 2:

The Yard Patrol (YP) is 110 ft long. It has a top speed of 13 kts on a good day. It displaces 150 LT.

How long must a 1:25 scale model be? How fast must it be towed to simulate the top speed?

$\lambda = 25$ (the scale is given!)

$25 = L_S/L_M$

$L_M = 110ft/25$

$L_M = 4.4$ ft (52.8 in)

Solving for the maximum speed,

$$\frac{\mathbf{V_S}}{\sqrt{\mathbf{L_S}}} = \frac{\mathbf{V_M}}{\sqrt{\mathbf{L_M}}}$$

$$V_M = V_S\, \lambda^{-1/2}$$

$$V_M = 13 \text{ kts } (1.688 \text{ ft/sec-kts}) \times 25^{-1/2}$$

$$V_M = 21.944 \text{ ft/s} \times .0.20$$

$$\mathbf{V_M = 4.39 \text{ ft/s}}$$

Example Problem

You are the chief Naval Architect assigned to design a new YP for the Naval Academy. You have already decided on a displacement, hull size and shape. You now need to use tow tank testing of a model to determine the engine size and fuel capacity required.

Ship Data:

- Δ=300LT Length=100ft Beam=25ft Draft=6ft Wetted Surface Area=3225ft^2 Desired Max Speed=15kts

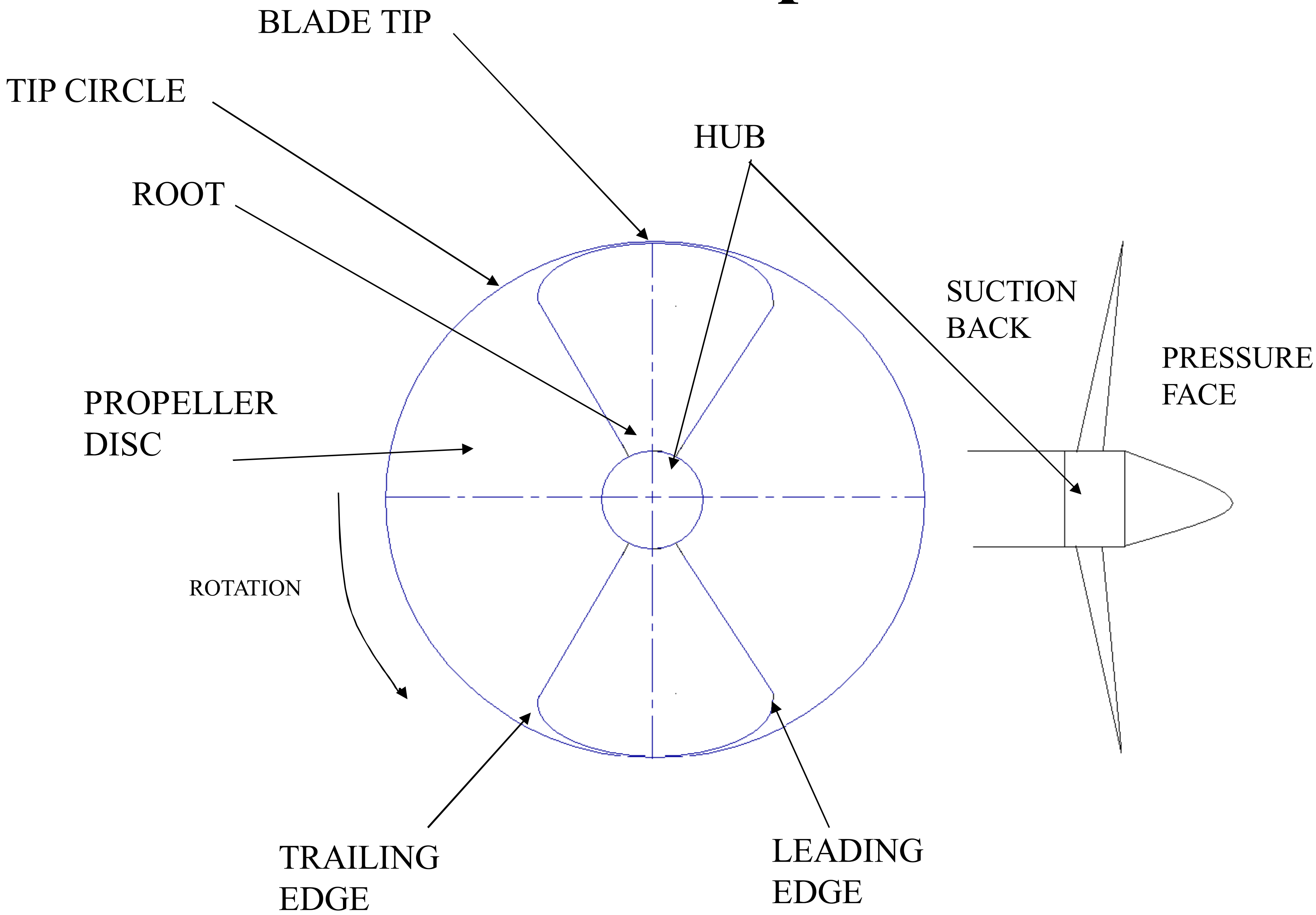
Example Problem

- The maximum length of model which the tow tank can handle is 5ft. If the model is constructed of this length, to maintain geometric similarity, what would be its beam?
- Maintaining geometric similarity, what is the wetted surface area of the model?
- Maintaining geometric similarity, what is the displacement of the model in pounds? (Assume tow tank is seawater.)
- Maintaining dynamic similarity, at what speed in ft/s do we need to tow the model?
- At this speed, the model resistance is 6.58lb. Coefficient of Viscous Resistance (model)(C_v)=0.0064 What is the wave making coefficient (C_w)?
- At 15kts, C_v for the ship is 0.0030. What is the resistance for the full size ship at this speed?
- What is the EHP at this speed and, if we expect η_p=55%, how many SHP are required?

Example Answer

- Scale Factor $=\lambda=L_s/L_m=100ft/5ft=20$; $B_m=B_s/\lambda=25ft/20=1.25ft$
- $A_m=A_s/\lambda^2=3225ft^2/20^2=8.06ft^2$
- $\Delta=F_B=\rho gV$ Thus, it is proportional to submerged volume which is proportional to λ^3; $\Delta_m=\Delta_s/\lambda^3=300LT\times(2240lb/LT)/20^3=84lbs$
- Law of Corresponding Speeds: $v_m=v_s/\lambda^{1/2}=15kts\times(1.688ft/s\text{-}kt)/20^{1/2}=5.7ft/s$
- $C_T=R_T/(\frac{1}{2}\rho SV^2)=6.58lb/[\frac{1}{2}\times1.99lb\text{-}s^2/ft^4\times8.06ft^2\times(5.7ft/s)^2]=0.0253$; $C_w=C_T-C_v=0.0253-0.0064=0.0189$
- $C_{ws}=C_{wm}$; $C_T=C_v+C_w=0.0189+0.0030=0.0219$
- $R_T=C_T\times\frac{1}{2}\rho SV^2=0.0219\times\frac{1}{2}\times(1.99lb\text{-}s^2/ft^4)\times3225ft^2\times(15kt\times1.688ft/s\text{-}kt)^2=45{,}100lb$
- $EHP=R_TV/(550ft\text{-}lb/s\text{-}HP)=45{,}100lb\times15kt\times1.688ft/s\text{-}kt/(550ft\text{-}lb/s\text{-}HP)=2076HP$; $SHP=EHP/\eta_p=2076/0.55=3775HP$

7.8 Screw Propellers



Screw Propellers

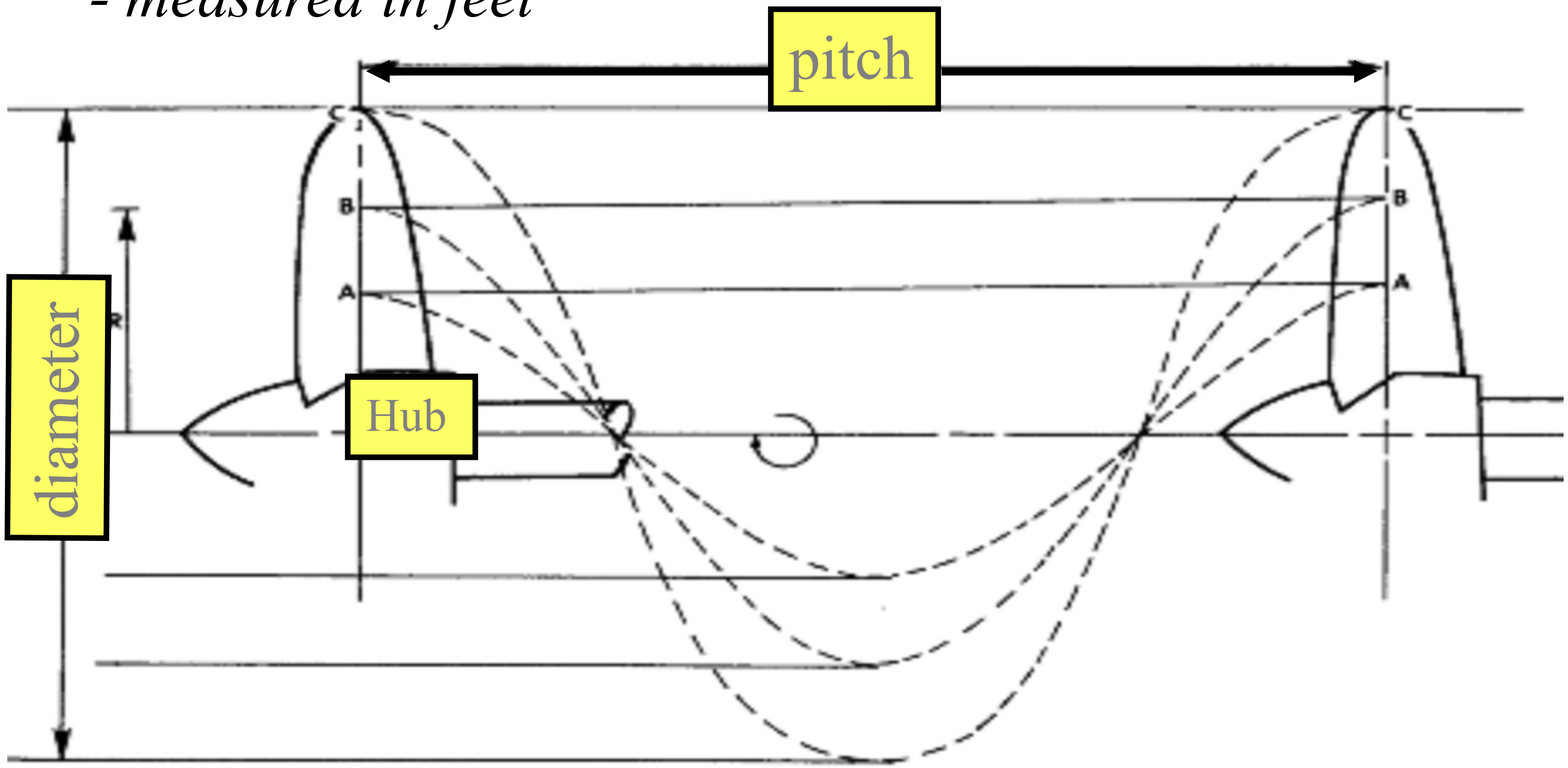
Definitions

- **Diameter(D)** : distance from tip to tip
- **Hub** : the connection between propeller and shaft
- **Blade Tip** : the furthest point on the blade
- **Blade Root** : the point where the blade meets the hub
- **Pitch(P)** : *Theoretical* distance a propeller would move in one revolution
- **Pitch Angle** : Angle of the blade with respect to incoming flow. It usually varies from root to tip.
- **Fixed Pitch** :
  - The pitch is constant all the way from the blade root to the blade tip.
  - Blade is fixed to the hub and cannot be altered.
- **Tip Circle** : Circle described by the blade tip rotation
- **Propeller Disc** : The area circumscribed by the propeller's tip circle

Screw Propellers

Propeller Pitch

The distance that the blade travels in one revolution, P
- measured in feet



Screw Propellers

Propeller Pitch Angle

The **pitch angle** relates the ***pitch length*** to the ***circumference*** of the propeller blade:

$$\tan \phi = \frac{P}{2\pi r}$$

… Pitch angle ϕ is the angle that any part of the blade makes perpendicular with the water flow

Screw Propellers

Types of Propeller Pitch

1. Constant Pitch- The pitch angle does not change, it is the same at the root as at the tip of the blade, but the pitch will vary or the pitch does not change, but the pitch angle does change.

2. Variable Pitch- The pitch angle changes as the distance from the root changes (ϕ is defined at a blade radius of .7r)

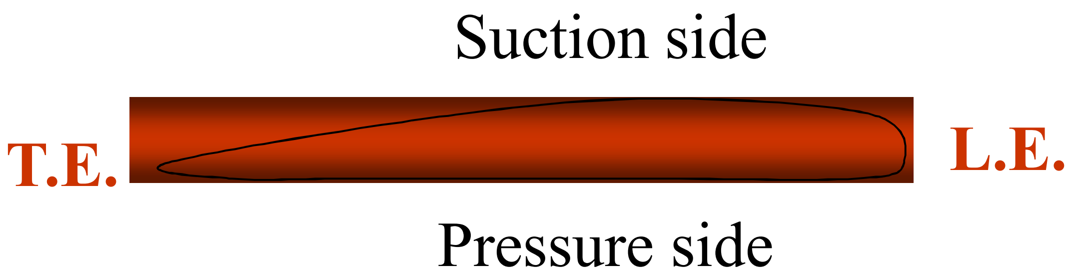
3. Fixed Pitch- The blade is permanently attached to the hub and cannot change.

4. Controllable Pitch- The position of the blade can be altered while the blade rotates, thereby changing the pitch angle.

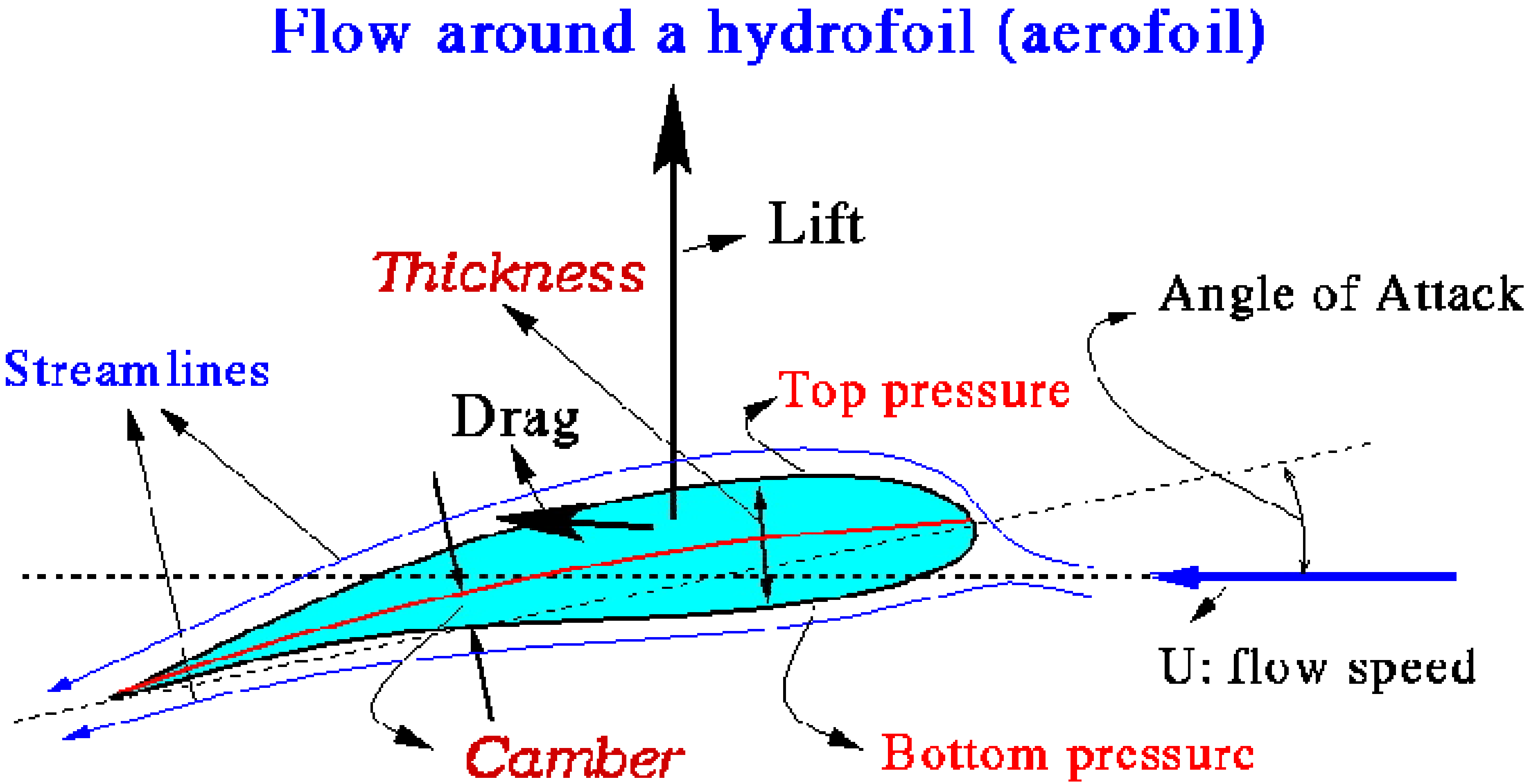
Screw Propellers

Definitions

- **Pressure face :**
  - **- High pressure side of blade. The astern side when going ahead**
- **Suction Back : Low pressure side. Surface opposite the face**
- **Leading edge :** Forward edge of the blade, first to encounter the water stream
- **Trailing edge :** Last part of the blade to encounter the water stream

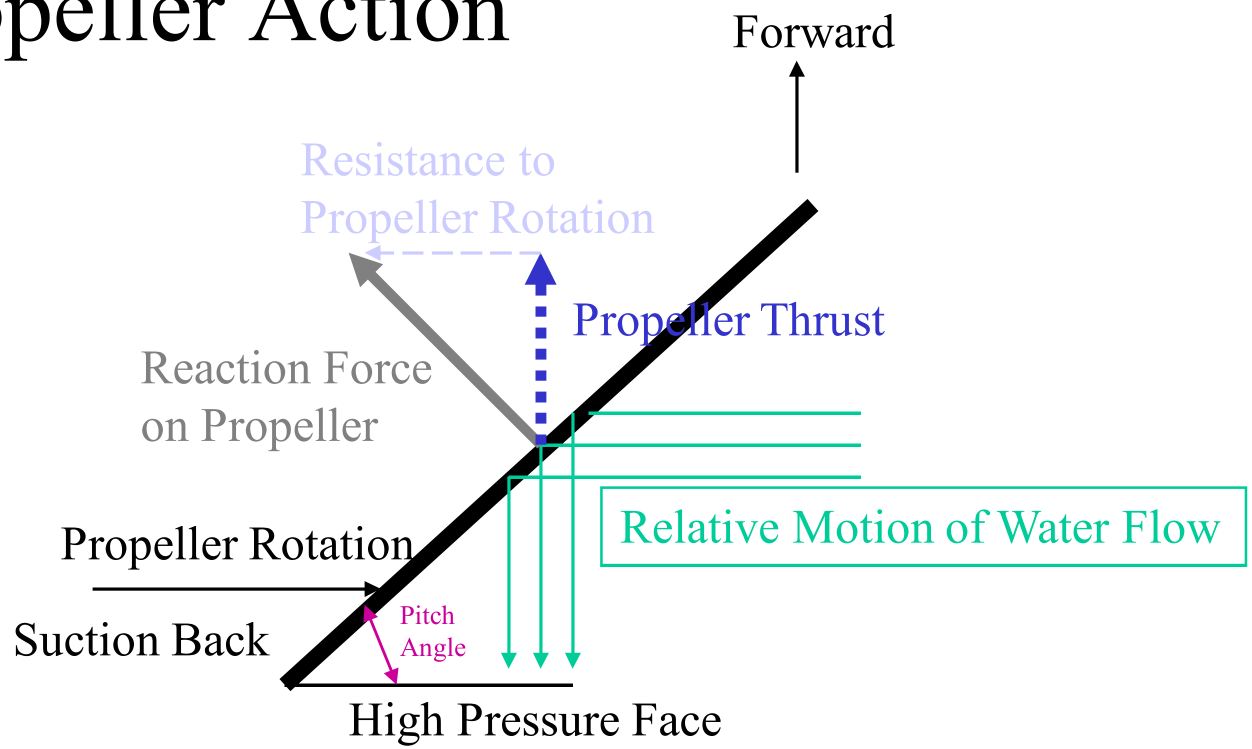


Screw Propellers



Screw Propellers

Propeller Action

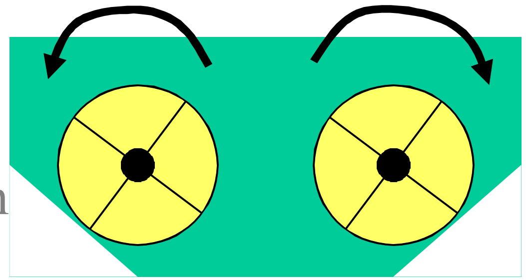


Screw Propellers

Propeller Rotation

Left hand screw

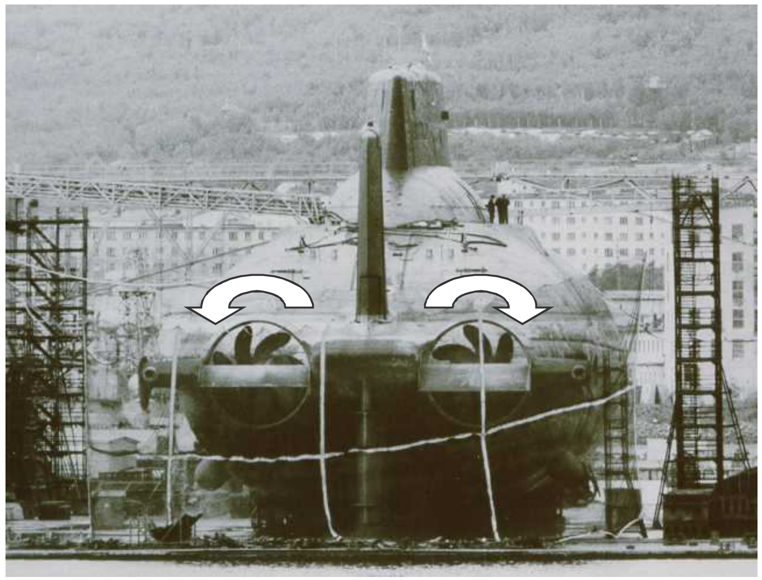
- Rotates Counter Clock-wise when viewed from astern
- Single screw ships use this type



Naval Ship

Right hand screw

- Rotates Clock-wise when viewed from astern



Submarines & torpedoes

Counter Rotating Propellers

- Have both a right and left hand screw
- Eliminates torque created by the rotation
- Torque will cause the stern to make a turn in the direction of rotation

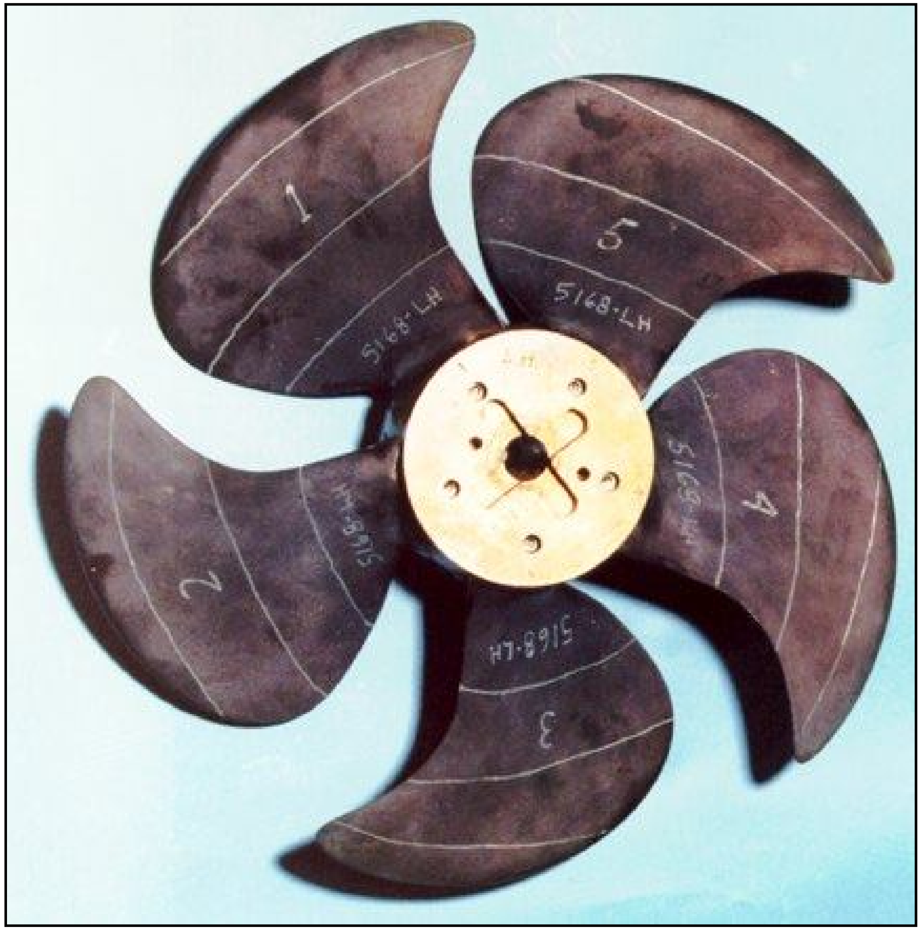
Screw Propellers

The Skewed Propeller

Advantages:
- Reduced interaction between propeller and rudder wake
- Reduced vibration and noise

Disadvantages:
- Expensive
- Less efficient operating in reverse

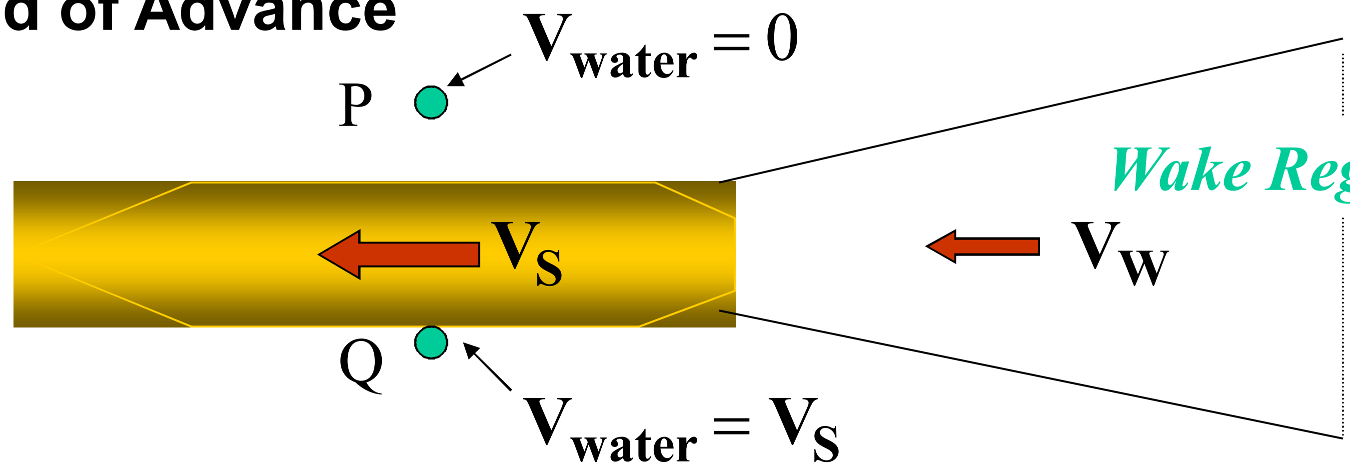
Highly Skewed Propeller for a DDG 51



Screw Propellers

Propeller Theory

- **Speed of Advance**



- **The ship drags the surrounding water . This *wake* follows the ship with a *wake speed* (Vw).**
- **The flow speed at the propeller is,**

$$V_A = V_S - V_W$$

Speed of Advance

Screw Propellers

Propeller Theory

Propeller Efficiency

$$\eta_{propeller} = \frac{2}{1+\sqrt{1+C_t}} \quad \Leftrightarrow \quad \eta_{propeller} = \frac{THP}{DHP}$$

$$C_T = \frac{T}{0.5\rho V_A^2 A_o}$$

(~70 % for well-designed PP.)

C_T : Thrust loading coefficient

T : Propeller thrust

A_o : Area of the projected propeller disc

- **For a given T (Thrust),**

Ao ↑ (i.e., ***Diameter*** ↑) ; ***C_T*** ↓ ; **Prop Eff.** ↑ → Maximum

The larger the diameter of propeller, the better the propeller efficiency

Screw Propellers

Propellers generate thrust as soon as they rotate, even before the ship starts moving

$K_T = T/(\rho n^2 D^4)$

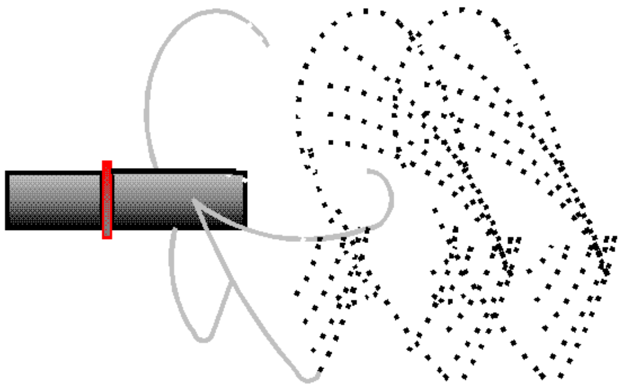
- K_T=thrust coefficent
- ρ=water density
- n=shaft RPM
- D=propeller diameter

Screw Propellers

Propeller Cavitation

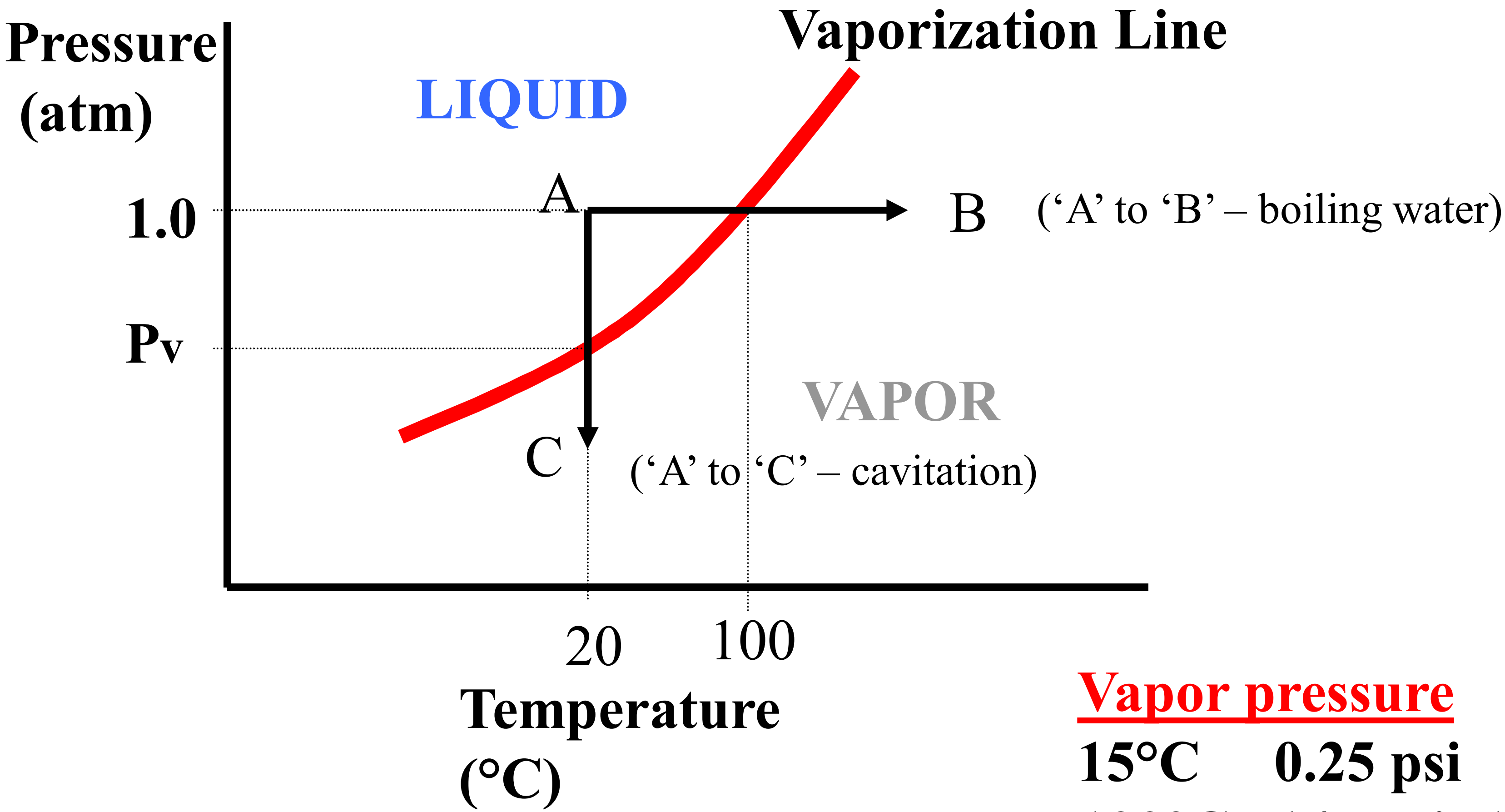
- ***The formation and collapse of vapor bubbles on propeller blades where the pressure has fallen below the vapor pressure of water***

Cavitation occurs on propellers that are heavily loaded, or are experiencing a high thrust loading coefficient



Screw Propellers

Cavitation Process

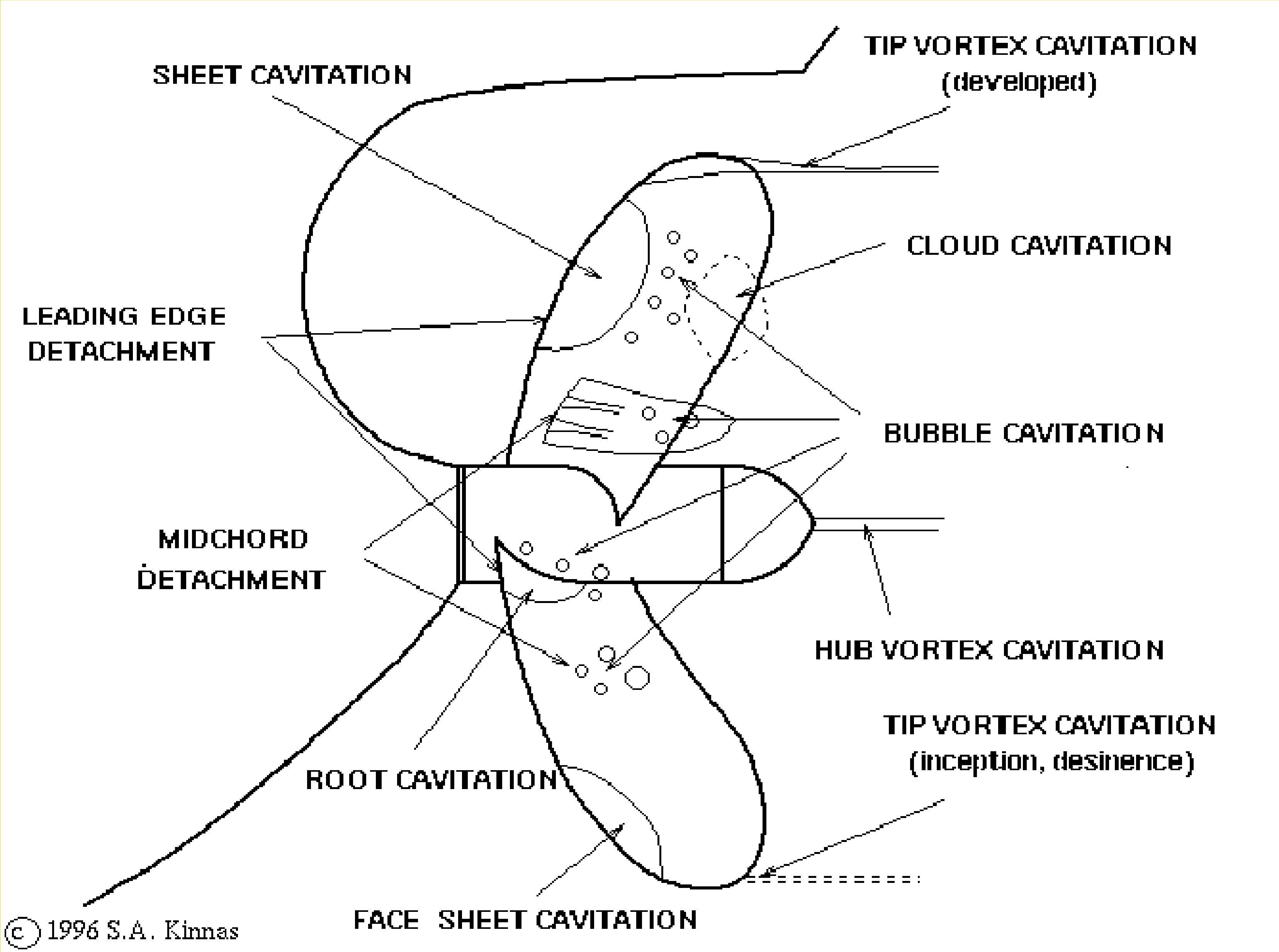


Vapor pressure

15°C 0.25 psi

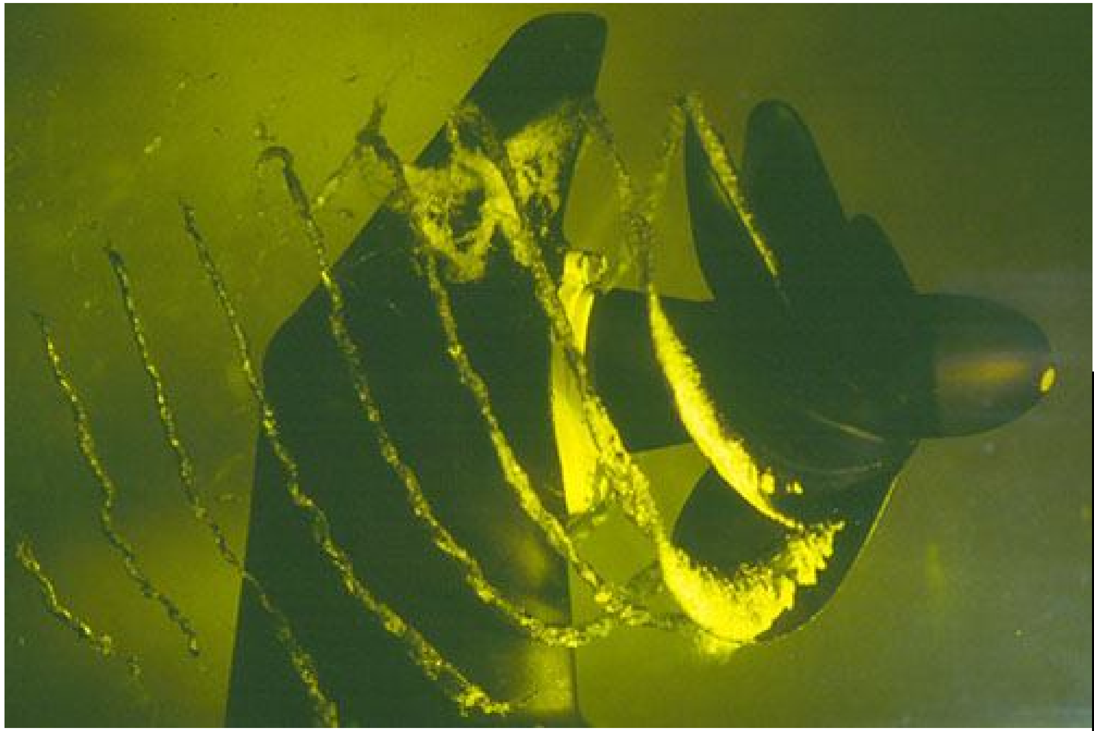
100°C 14.7psi=1atm
=101 kPa

Screw Propellers



Screw Propellers

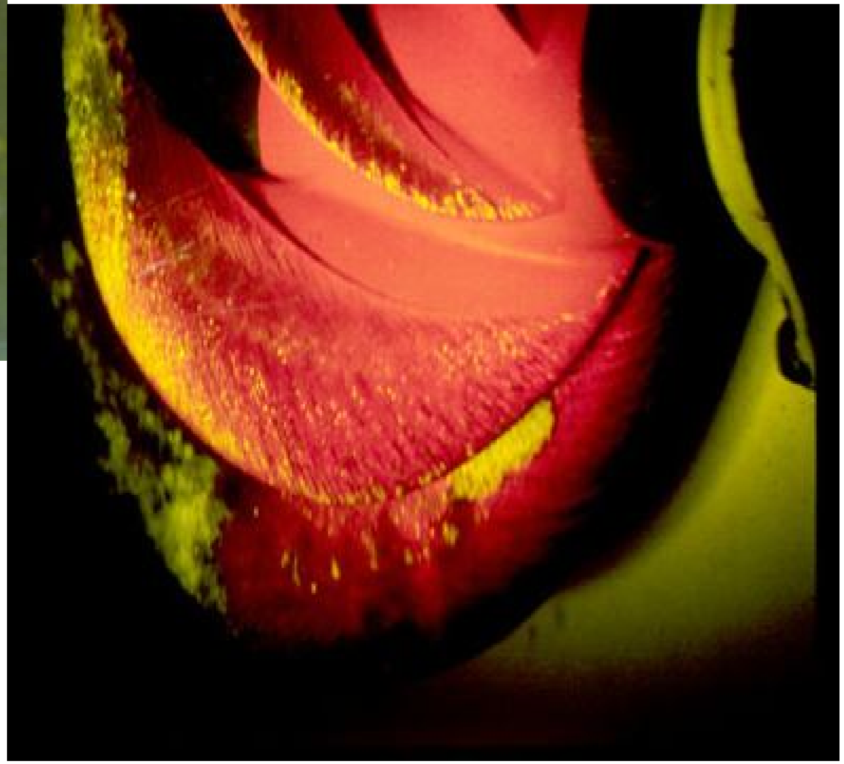
Blade Tip Cavitation



Navy Model Propeller 5236

Flow velocities at the tip are fastest so that pressure drop occurs at the tip first.

Sheet Cavitation



Large and stable region of cavitation covering the suction face of propeller.

Screw Propellers

Consequences of Cavitation

1) Low propeller efficiency (Thrust reduction)
2) Propeller erosion (Mechanical erosion)
   (Severe damage to propeller : up to 180 ton/in^2)
3) Vibration due to uneven loading
4) Cavitation noise due to impulsion by the bubble collapse

Screw Propellers

Preventing Cavitation

- Remove fouling, nicks and scratch.
- Increase or decrease the engine RPM smoothly to avoid an abrupt change in thrust.

  rapid change of rpm $\Rightarrow$ high propeller thrust but small change in V_A $\Rightarrow$ larger C_T $\Rightarrow$ cavitation & low propeller efficiency
- Keep appropriate pitch setting for controllable pitch propeller
- For submarines, diving to deeper depths will delay or prevent cavitation as hydrostatic pressure increases.

Screw Propellers

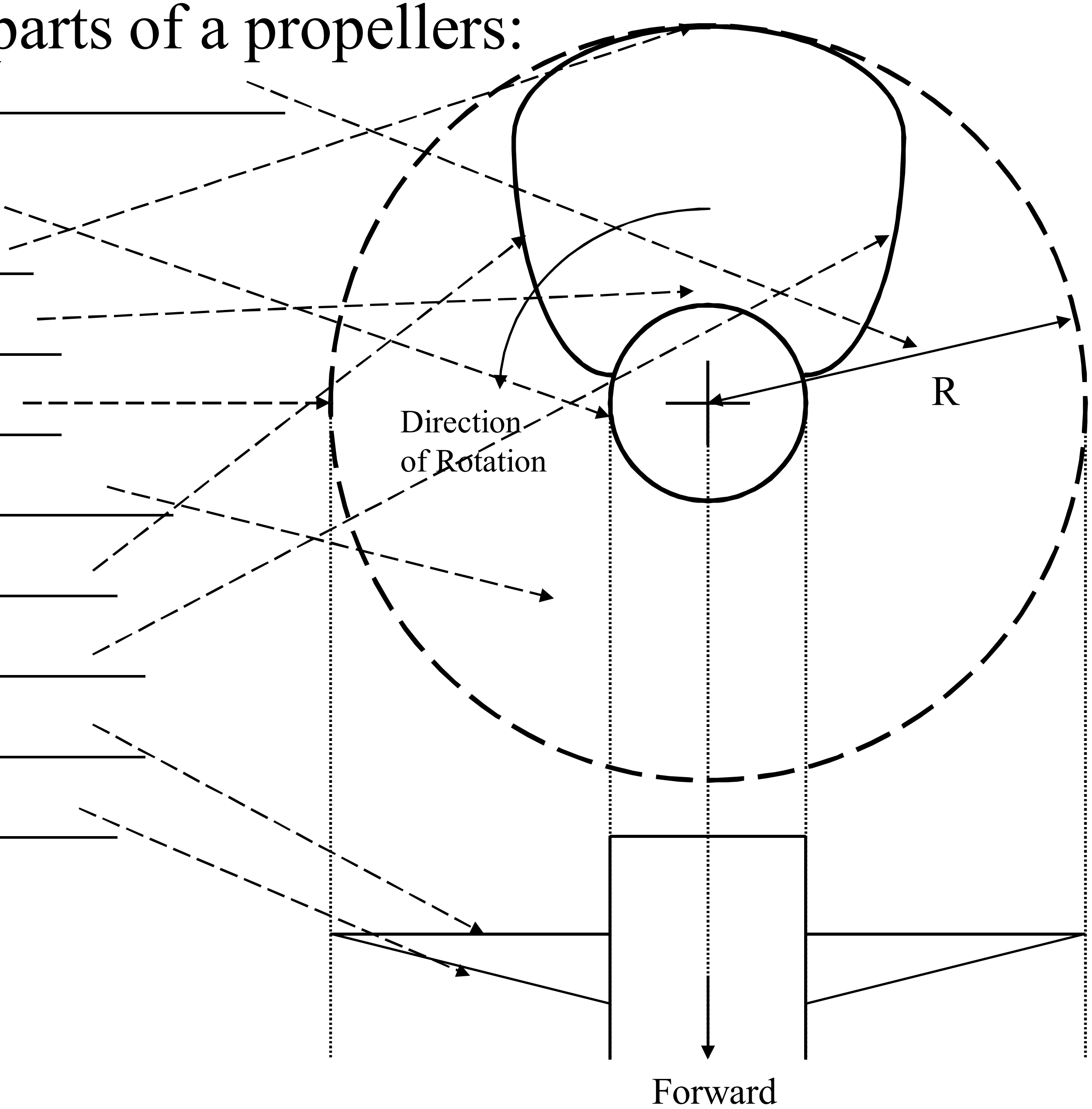
Ventilation

- If a propeller operates too close to the water surface, surface air or exhaust gases are drawn into the propeller blade due to the localized low pressure around propeller.
- The load on the propeller is reduced by the mixing of air or exhaust gases into the water causing effects similar to those for cavitation.
- Ventilation often occurs in ships in a very light condition(small draft) and in rough seas.

Example Problem:

Name the parts of a propellers:

- ______________________________
- _____
- ______________
- ________________
- ________________
- ________________________
- ____________________
- _____________________
- _____________________
- ____________________



Example Answer:

Name the parts of a propellers:

- Propeller Radius (R)
- Hub
- Blade Tip
- Blade Root
- Tip Circle
- Propeller Disc
- Leading Edge
- Trailing Edge
- Pressure Face
- Suction Back