# SHIP THEORY - PROPULSION

## PROPELLER DESIGN AND CAVITATION

Prof. Dr. S. Beji

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# Introduction

- Propuslion: Propulsion is the act or an instance of driving or pushing forward of a body, i.e. ship, by a propeller (in our case a screw propeller).

- Propusion systems: There are many types of ship propulsion devices. Unusual and inefficient devices were invented, tried and discarded. The screw type of ship propeller with its many variations is the prime propulsive device of modern ships.
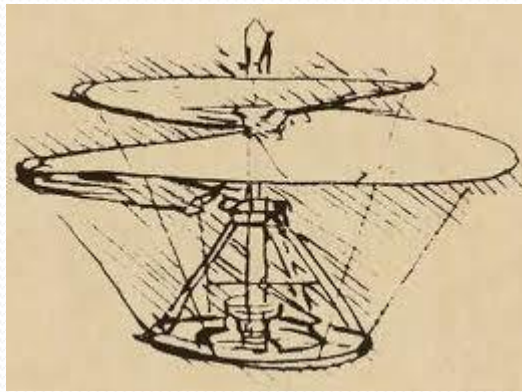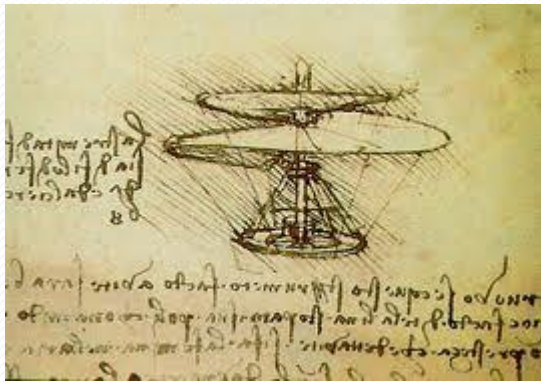
# Introduction

- A brief history and development of screw propeller:

Archimedes (287-212 BC) invented his 'Archimedian screwpump' to irrigate the field of Syracuse in Sicily. Archimedes's scew is a machine historically used for transferring water from a low-lying body of water into irrigation ditches
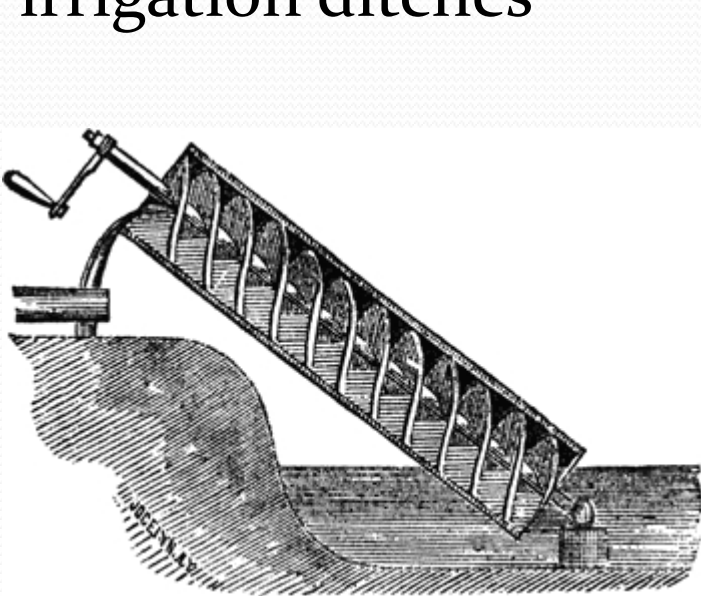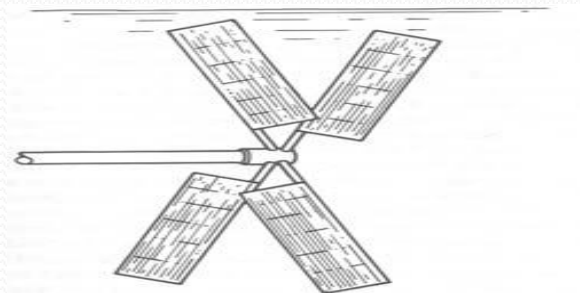
# Introduction

- Leonardo da Vinci (1452-1519) had sketches of aerial screw helicopter.



- In 1681 Hooke suggested to use of a horizontal watermill for ship propulsion. In 1683 he modified it to measure water currents and saw the potential of using it for ship propulsion.

# Introduction

- 1802/04 C. Steves used a kind of screw propeller similar to today's screws to propel a 7.5 m twin screw steamer.

- In 1828 R. Wilson the Scottish farmer successfully demonstrated the first principles.

- In 1836 P. Smith, the English farmer achieved the first practical application using an Archimedes type screw.

- In 1836 J. Ericsson, the Swedish engineer developed a contra-rotating propeller.
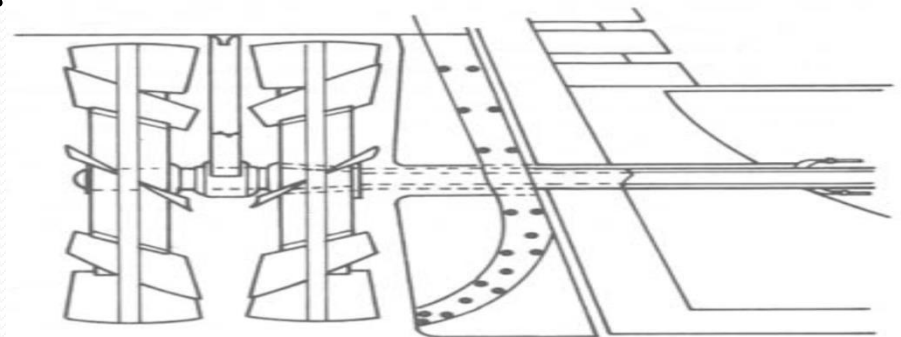


Figure 1.6    Ericsson's contra-rotating screw propeller (1836)

# Introduction

- In 1839 Smith equipped 237 ton of ship Archimedes with screw propellers having a great success and this led to change to screw type propellers in place of paddle propulsion systems.

- In 1840's and 1850's development of steam engines contributed to effective use of screw propellers.

- Great Britain was the first to cross the Atlantic by a screw propelled ship in 1845.

- In 1880's Thornycroft designed propellers similar to today's propellers.
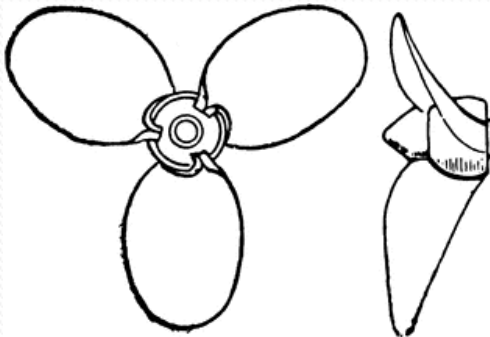
# Modern Propulsion Systems

- Fixed Pitch Propellers (FPP)

These propellers have traditionally formed the basis of propeller production. They make up the greater percentage of propellers, being fitted in a wide range of vessels from small powerboats to large tankers and bulk carriers. They are easy to manufacture.
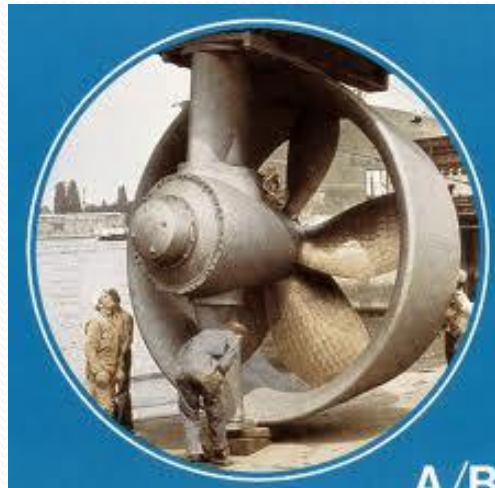
# Modern Propulsion Systems

- Ducted Propellers

Consist of two components: 1) An annular duct having an aerofoil cross section 2) A propeller inside the duct.

The presence of duct would reduce the pressure forces induced on the hull. This kind of propellers sometimes is referred to as Kort nozzles. Usually used on heavily loaded propellers or propellers with limited diameter. Vessels that normally operate above a certain speed are therefore normally not fitted with ducts. When towing, tugboats sail with low speed and heavily loaded propellers, hence they are often fitted with ducts.
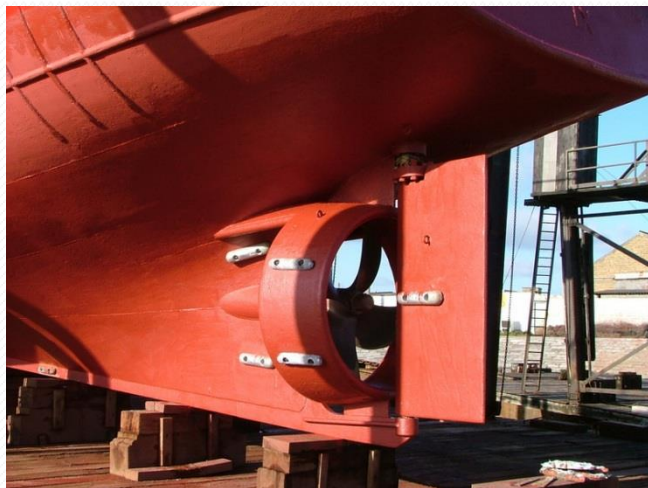
# Modern Propulsion Systems

- Contra-rotating Propellers

These propellers have two coaxial propellers sited one behind the other and rotating in opposite directions. They have the hydrodynamic advantage of recovering part of the slipstream rotational energy which would otherwise be lost to a conventional single screw system. This leads to an energy saving about 15% in power. Improved efficiency but higher drag and cost. It is usually applied to small outboard units operating at around 1500 to 2000 RPM due to the mechanical problems associated with longer line shafting systems of larger vessels.

# Modern Propulsion Systems

- Overlapping Propellers

Two propellers are not mounted coaxially but are each located on separate shaft systems. The system has rarely been used in practice. Although the propulsion efficiency of this system is higher than a single propeller, this system causes vibration and cavitation.
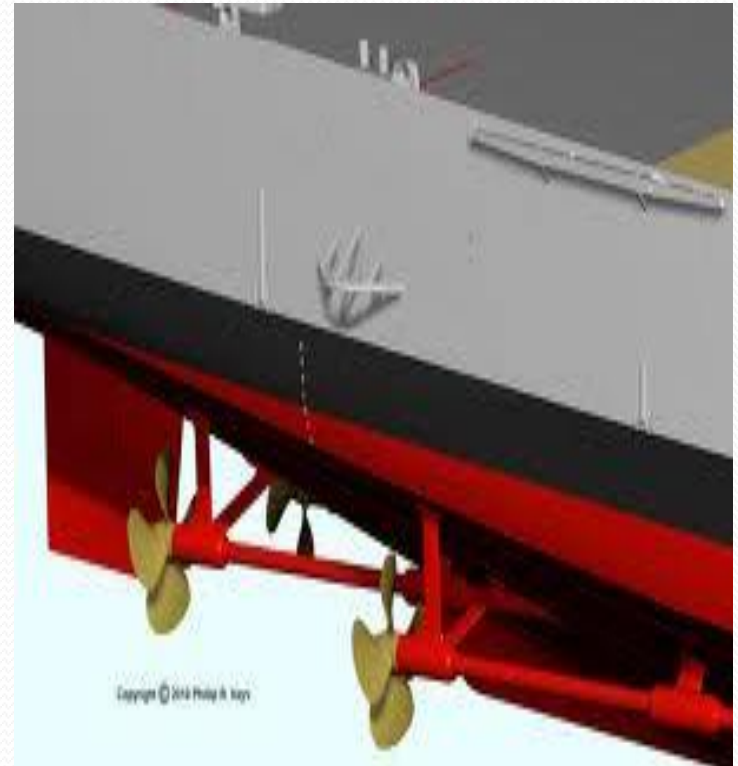
# Modern Propulsion Systems

- Controllable (Variable) Pitch Propellers (CPP)

The choice of a CPP to a FPP is due to flexibility of its control rather than propulsion efficiency at service condition. CPP provides an extra degree of freedom in its ability to change blade pitch. It is especially used for ferries, tugs, trawlers, and fisheries due to better maneuverability than FPPs. Manufacturing cost is very high and it requires more maintenance and repair.

# Modern Propulsion Systems

- Waterjet Propulsion Systems

This system has found considerable application on a wide variety of small high speed craft, although it is also used for larger ships. The operation principle of waterjet is that water is drawn through a ducting system by an internal pump adding energy and the water is expelled aft at high velocity. The unit's thrust is primarily generated as a result of momentum increase given to the water. For high speeds the system is preferred to a conventional propeller. While a conventional propeller experiences cavitation at high speeds (45 knots), the pump of the waterjet unit would normally not cavitate. Furthermore it has a good maneuverability.



Kamewa FF-series waterjet

# Modern Propulsion Systems

- Cycloidal Propellers (Voith Schneider Propeller)

The Voith Schneider propeller (VSP), also known as a cycloidal drive (CD) is a specialized marine propulsion system. It is highly maneuverable, being able to change the direction of its thrust almost instantaneously. It is widely used on tugs and ferries.
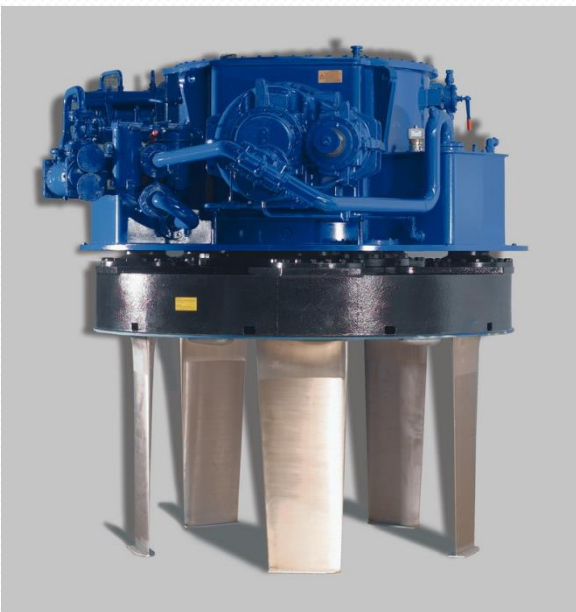
# Modern Propulsion Systems

- Azimuth Podded Propulsion

It provides propellers with high maneuverability, low fuel consumption, high efficiency, low noise and less cavitation. Today, the major users of pod units have been cruise liner operators. The introduction of pod propulsion, which will allow the propulsion unit to be placed without considering any shaft arrangements or space for machinery will, of course, give the naval architect many new opportunities to design the 'ultimate hull form'.
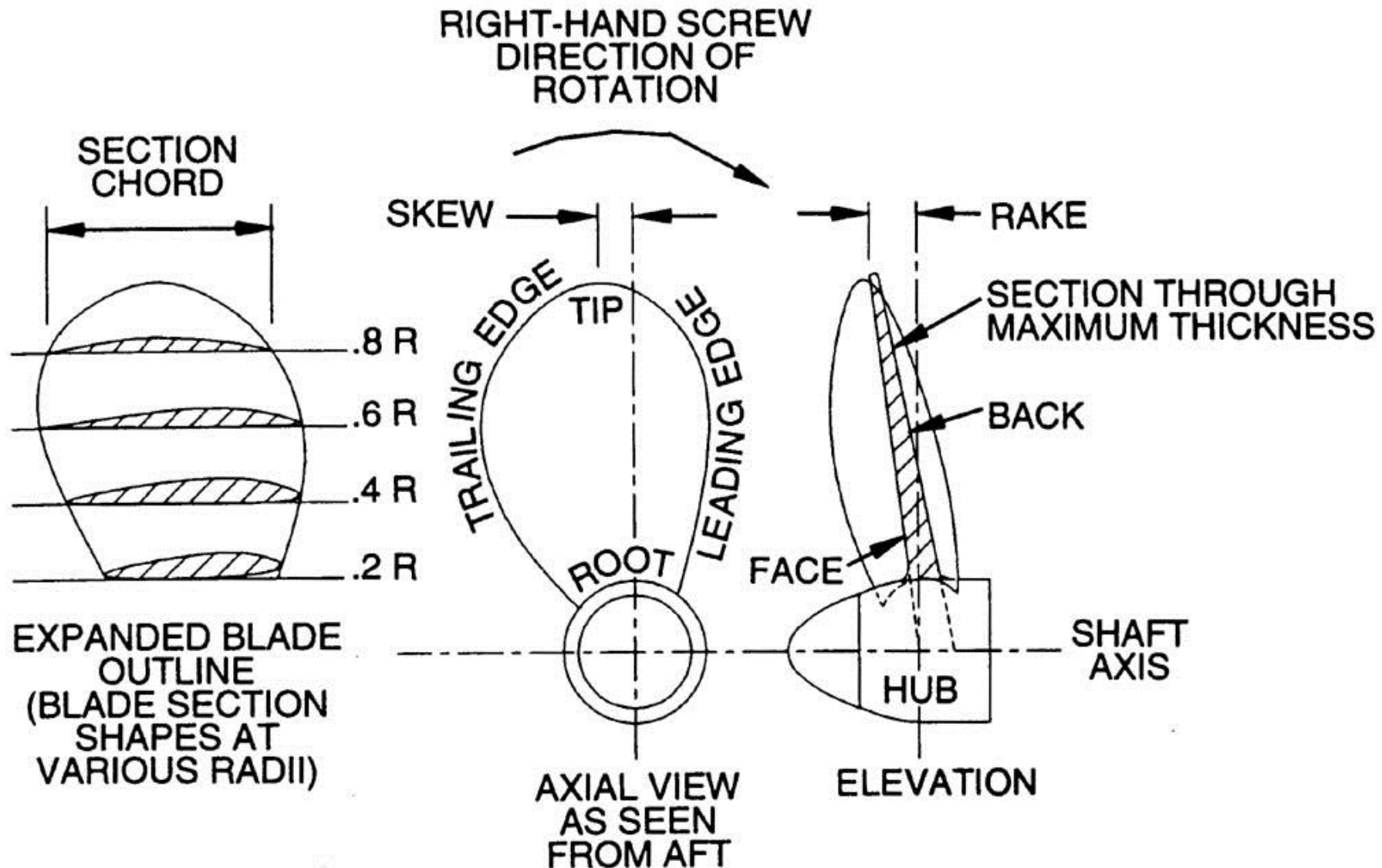
# Propeller Basics

- Certain definitions are essential for propellers:

The simplest of all is the 'blade' as the most important part of a propeller. Then comes the number of blades. The part of a propeller that sits on the shaft is called 'boss'.  When we look at a propeller from behind a ship, if it rotates clockwise it is called a 'right-handed' propeller; otherwise it is a 'left-handed' propeller. Most propellers are right-handed. The edge of a blade that is on the rotating side is the 'leading edge'. The edge that is not on the rotating side is 'trailing edge'. The outermost point of the blade is called 'tip' or 'tip of the blade'. The part of the blade connected to the boss is the 'root'. Finally the outside of the blade as seen from behind the ship is 'face' while the inside of the blade is 'back'.
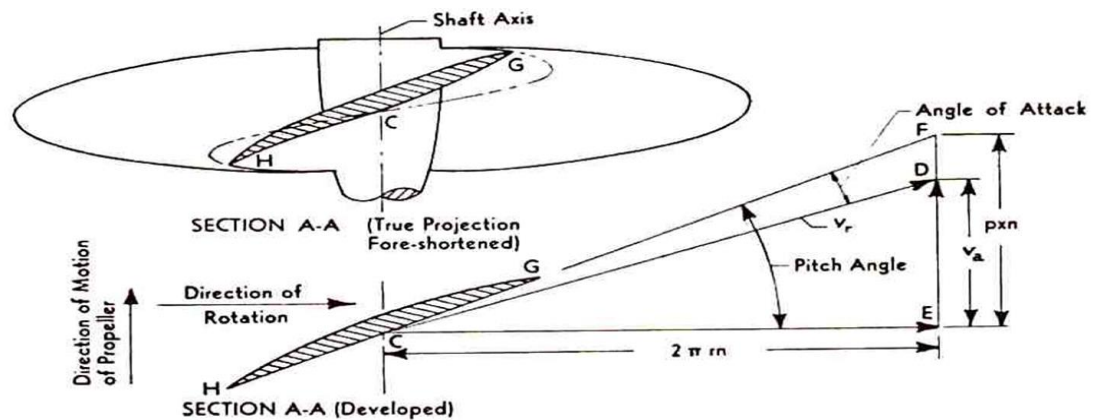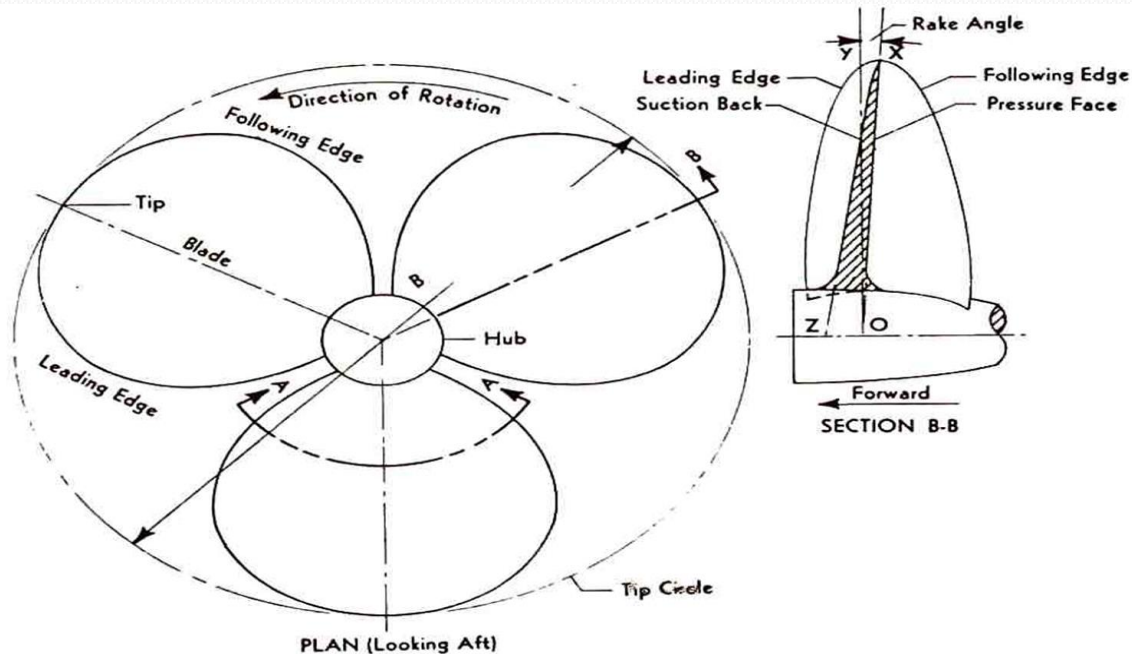
# Propeller Basics

# Propeller Basics

- Definitions and quantities describing propellers may be enumerated as follows.

- Blade

- Diameter, Area

- Right-handed, Left-handed

- Root, Boss

- Tip, Leading edge, Trailing edge

- Pitch, Skewness, Rake

- Angle of attack, slip

- Torque, Thrust, n (rps), N (rpm)

- Velocity of advance ($V_A$), Ship speed ($V_S$).

# Propeller Basics

# Propeller Basics

- Face: The side of a propeller blade which faces downstream during ahead motion is called face or pressure side (when viewed from aft of a ship to the bow the observed side of a propeller blade is called face or pressure side).

- Back: The side of a propeller blade which faces generally direction of ahead motion is called back or suction side (when viewed from aft of a ship to the bow the unseen side of a propeller blade is called back or suction side).

- Leading Edge: When the propeller rotating the edge piercing the water is called leading edge.

- Trailing Edge: When the propeller is rotating the edge following the leading edge is called trailing edge.

# Propeller Basics

- Pitch: Consider a point P lying on the surface of a cylinder of radius r which is at some initial point Po and moves as to form a helix over the surface of a cylinder. The propeller moves forward as to rotate and this movement creates a helix. When the point P has completed one revolution of helix that means the angle of rotation $\theta = 360^o$ or $2\pi$, the cylinder intersects the X-Z plane and moves forward at a distance of P.

- If the cylinder is opened out the locus of the point P lies on a straight line.

- In the projection one revolution of the helix around the cylinder measured normal to the OX axis is equal to $2\pi r$.

- The distance moved forward by the helical line during this revolution is p.

- The angle θ is termed the pitch angle and the distance p is the pitch.

# Propeller Basics

DIRECTION OF ROTATION

REFERENCE LINE FOR SKEW

RAKE

LONGL. PROJECTION OF BLADE

BACK OF BLADE

FACE OF BLADE

SKEW

LEADING EDGE

MAX. THICKNESS

CENTER CHORD LINE

TRAILING EDGE

$\phi = \tan^{-1}\dfrac{P}{2\pi r}$

MAX. THICKNESS SECTION

$R = \dfrac{D}{2}$

RADIUS r

PROJ. OUTLINE

DEVELOPED OUTLINE

$\dfrac{d}{2}$

t

$\dfrac{P}{2\pi}$

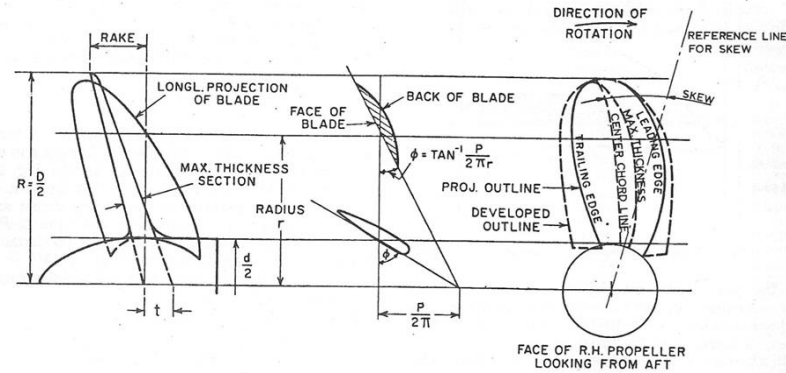FACE OF R.H. PROPELLER LOOKING FROM AFT

Fig. 8 Typical propeller drawing

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

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

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

Disk area $=$ area of tip circle $= \dfrac{\pi}{4}D^2 = A_o$

Developed area of blades, outside hub $= A_D$

Developed area ratio $= DAR = \dfrac{A_D}{A_o}$

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

Projected area ratio $= PAR = \dfrac{A_P}{A_o}$

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

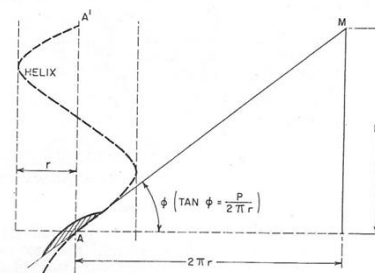Mean width ratio $= MWR = \dfrac{A_D / \text{length of blades (outside hub)}}{D}$

HELIX

$r$

$P$

$\phi \left( \tan \phi = \dfrac{P}{2\pi r} \right)$

$2\pi r$

Fig. 9 Definition of pitch angle

$\phi =$ Pitch angle of screw propeller

M

SLIP

S

VELOCITY OF WATER RELATIVE TO BLADE

SPEED OF ADVANCE $V_A$

$Pn$

BLADE SECTION AT RADIUS $r$
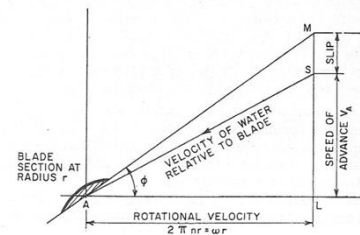
$\phi$

ROTATIONAL VELOCITY

$2\pi nr = \omega r$

Fig. 10 Definition of slip

$\tan \phi = \dfrac{Pn}{2\pi nr} = \dfrac{P}{2\pi r}$

Real slip ratio $s_R = \dfrac{MS}{ML} = \dfrac{Pn - V_A}{Pn} = 1 - \dfrac{V_A}{Pn}$

# Propeller Basics

- Example: A propeller of 4.0 m diameter has 3.0 m constant pitch. The distance of the blade tip face from a plane normal to the axis is 263.3 mm, while the distance of a point on the face at the root section (radius 400 mm) from the same plane is 52.7 mm, both distances being measured in a plane through the propeller axis. The midpoint of the root section is 69.5 mm towards the leading edge from a plane through the propeller axis, while the blade tip is 1285.6 mm towards the trailing edge from the same plane. Determine the pitch, rake and skew angles of the propeller. (Basic Ship Propulsion, Gokarn & Ghoose)

- Solution: The pitch angle: $\varphi = \tan^{-1}(P/2\pi r) = \tan^{-1}(3/2\pi \cdot 2) = 13.4^o$

  The rake angle: $\tan \varepsilon = \frac{Difference\ in\ rakes}{Difference\ in\ radii} = \frac{263.3 - 52.7}{2000 - 400} = \frac{210.6}{1600} = 0.131625, \ \varepsilon = 7.5^o$

The angles which the midpoints of the root section and the tip make with the reference plane are given by

$$\sin \theta_0 = \frac{69.5}{400} = 0.17375, \qquad\qquad \theta_0 = 10^o$$
$$\sin \theta_1 = \frac{-1285.6}{2000} = -0.6428, \qquad\qquad \theta_1 = -40^o$$

The skew angle is therefore $\quad \theta_s = (\theta_0 - \theta_1) = 10^o - (-40^o) = 50^o$

# Propeller Drawing

- The design drawing of a propeller consists of four parts:
  1. A side elevation (profile view) of the propeller
  2. An expanded blade outline with details of the section shapes
  3. The pitch distribution if it is not uniform
  4. Transverse view (Projection outline and Developed outline of the blade)
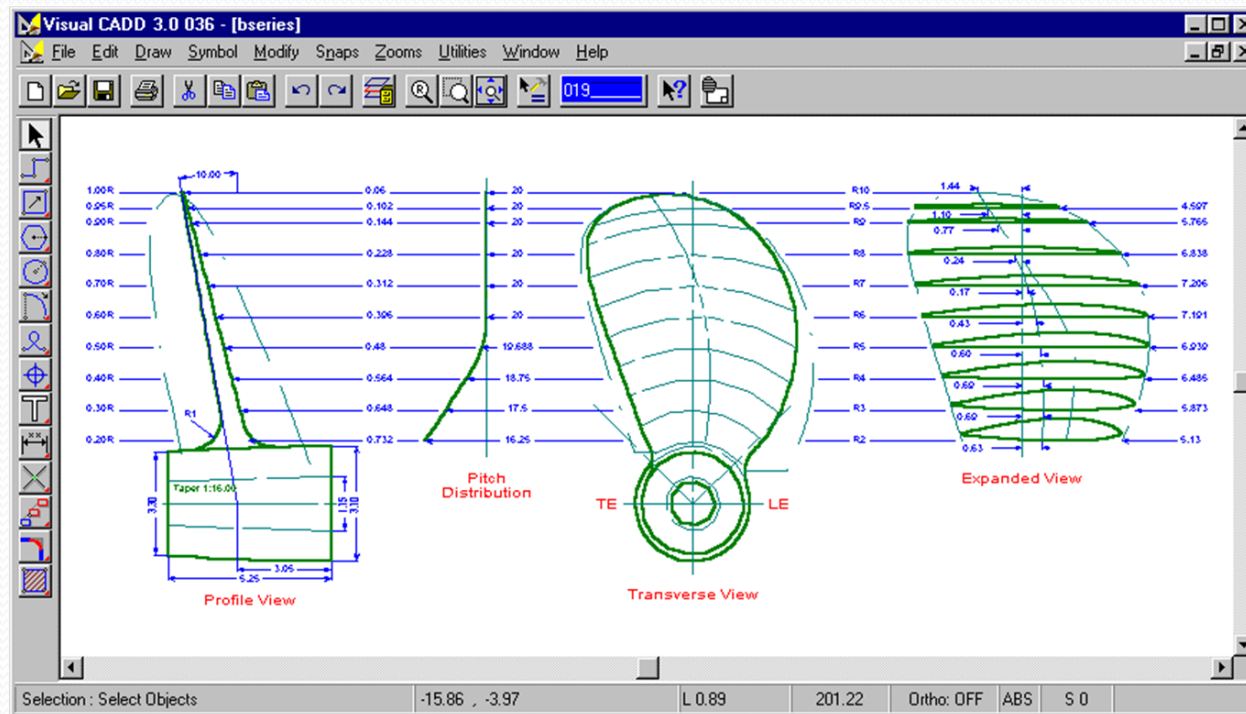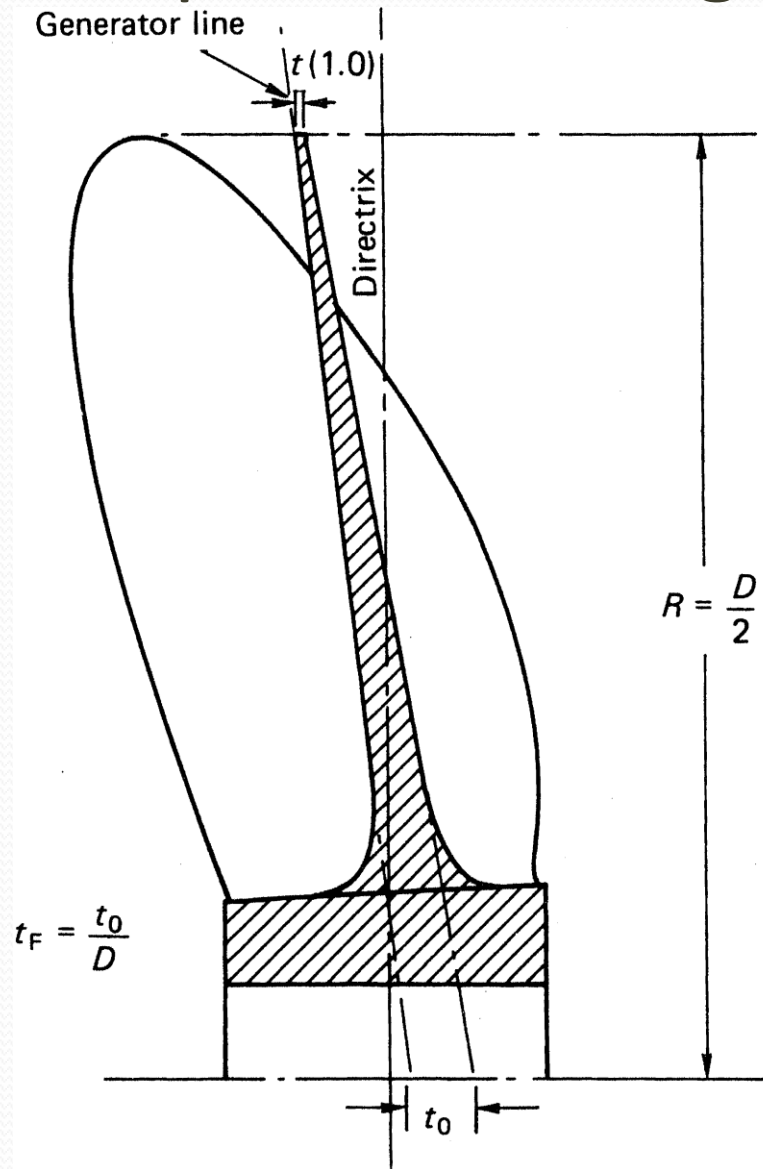
# Propeller Drawing

- Blade shapes are defined by specifying the shapes of cross sections obtained by the intersection of a blade by co-axial circular cylinders of different radii. These sections are called radial sections or cylindrical sections. Since all the Z (number of blades) propeller blades are identical, only one blade needs to be defined.

- Typically face and back coordinates of blade sections are calculated using tables given as a part of methodical series charts. The well-known propeller series are Schaffran, Taylor, Gawn, and the B-screw (or Wageningen-B). Today Wageningen-B series is probably the most commonly used series. To calculate the blade section coordinates using the B-series the following quantities are need. The blade number Z, the propeller diameter D, the expanded area ratio $A_E/A_0$, and the maximum blade thickness $t_{max}$ of the blade section. To determine the blade thicknesses, the rules laid by the societies for the minimum thickness of a certain section are used. Starting with this particular section and the blade tip thickness which is determined as a fraction of the specified section thickness the rest of the section thicknesses are calculated by linear or nonlinear interpolation formulas.

- If the propeller blade sections are designed according to the method prescribed by the B-series, $t_{max}$ of the blade section are calculated from the given tables as $S_r$. For calculating the blade section ordinates the formulas given may be used.

# Propeller Drawing

- For computing the blade section ordinates the Wageningen formulas require the edge thicknesses. The edge thicknesses may usually be estimated as a certain percentage of the maximum blade section thickness $t_{max}$. Typical section edge thicknesses are shown in the table below as a proportion of the maximum section thickness for conventional free-running, non-highly skewed propellers. In the case of a highly skewed propeller, defined by the Rules of Lloyd's Register as one having a propeller skew angle in excess of 25°, the trailing edge thicknesses would be expected to be increased from those of the table by amounts depending on the type and extent of the skew. The implication of the table is that the leading and trailing edges have 'square' ends. This clearly is not the case: these are the thicknesses that would exist at the edges if the section thicknesses were extrapolated to the edges without rounding (Marine Propellers and Propulsion, J. S. Carlton, 2006).

| r/R | Leading edge $t_{l.e.}/t_{max}$ | Trailing edge $t_{t.e.}/t_{max}$ |
|-----|-------------------------------|--------------------------------|
| 0.9 | 0.245 | 0.245 |
| 0.8 | 0.170 | 0.152 |
| 0.7 | 0.143 | 0.120 |
| 0.6 | 0.134 | 0.100 |
| 0.5 | 0.130 | 0.085 |
| 0.4 | 0.127 | 0.075 |
| 0.3 | 0.124 | 0.068 |
| 0.2 | 0.120 | 0.057 |

# Propeller Drawing

# Propeller Drawing

- Thus, using the necessary parameters and the given tables the blade section profiles are drawn for each radius (0.2R-1.0R). Connecting the tips of the leading edges on one side and the tips of the trailing edges on the other side gives the 'expanded outline' of the propeller. The area of this outline multiplied by the blade number Z gives the 'expanded area' $A_E$ of the propeller. The expanded area divided by the 'disc area' $A_0 = \pi D^2/4$ is termed as the expanded area ratio: $A_E/A_0$.

- In propeller calculations the expanded area is the most frequently used quantity. Besides the expanded outline, for manufacturing purposes, the projected outline and the developed outline are used in propeller drawing. Drawing of these outlines requires more details. First of all a horizontal axis and the propeller reference or a generator line are drawn. The blade cross sections are drawn for each radius (0.2R-1.0R). For any given radius $r$, a circular arc with radius $r$ and another circular arc with radius $r \cdot (\sec\varphi)^2$ are drawn as shown in the figure following. Here $\varphi$ is the pitch angle of the section under consideration.

**Propeller Drawing**
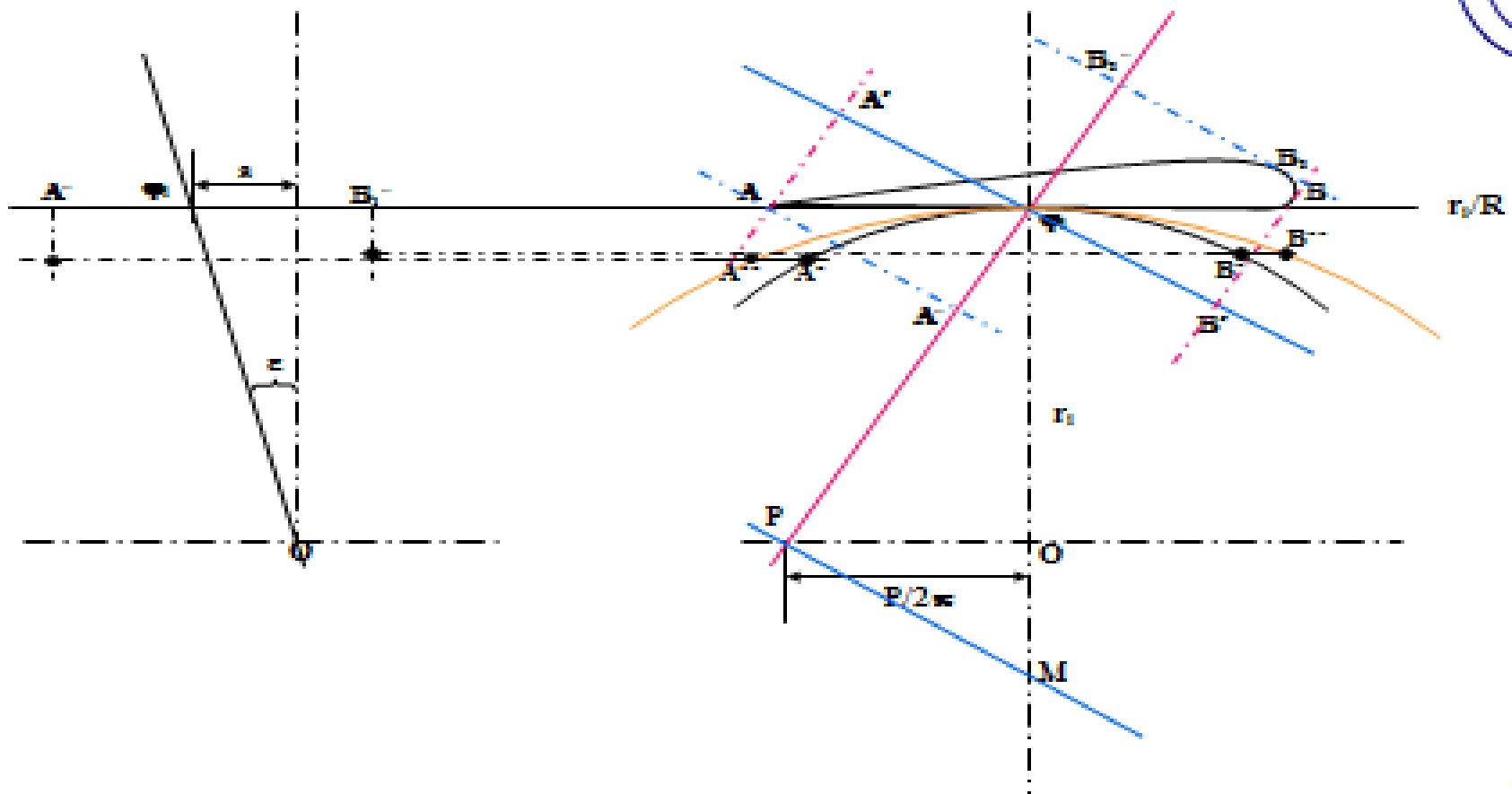
# Propeller Drawing

- For the leading edge part the projected length of the blade section is $r \cdot \theta_L$, for the trailing edge part the projected length of the blade section is $r \cdot \theta_T$. These lengths are ticked on the circular arc of radius $r$ for each side. In the figure this operation is equivalent to carrying the length $\varphi A'$ onto the circular arc of radius $r$ as $\varphi A^*$ and carrying the length $\varphi B'$ onto the circular arc of radius $r$ as $\varphi B^*$. Joining of all these points for the entire blade sections gives the projected outline.

- For obtaining the developed outline the procedure for the blade sections with offsets in both or either ends are different than those without offsets as shown in the figure. If there are no offsets then simply horizontal lines from the points $A^*$ and $B^*$ are drawn to intersect with the arc of radius $r \cdot (\sec \varphi)^2$. The points $A^{**}$ and $B^{**}$ are the points for drawing the developed outline. Connecting these points for all the blade sections gives the developed outline. When the blade sections have offsets then the vertical lines from the leading edge tip and from the trailing edge tip are drawn to intersect the base line. The intersection points are now treated as $A$ and $B$ in the figure and the process is repeated to obtain $A^{**}$ and $B^{**}$.