Chapter 1

General Introduction

1.1 Ships

The Earth may be regarded as a "water planet", since 71 percent of its surface is covered by water having an average depth of 3.7 km. Transportation across the oceans must therefore have engaged the attention of humankind since the dawn of history. Ships started thousands of years ago as simple logs or bundles of reeds and have developed into the huge complicated vessels of today. Wooden sailing ships are known to have appeared by about 1500 BC and had developed into vessels sailing around the world by about 1500 AD. Mechanical propulsion began to be used in ships by the beginning of the 19^{th} Century, and iron followed by steel gradually took the place of wood for building large oceangoing ships, with the first iron-hulled ship, the "Great Britain", being launched in 1840.

Ships today can be characterised in several ways. From the point of view of propulsion, ships may be either self-propelled or non-propelled requiring external assistance to move from one point to another. Ships may be ocean-going or operating in coastal waters or inland waterways. Merchant ships which engage in trade are of many different kinds such as tankers, bulk carriers, dry cargo ships, container vessels and passenger ships. Warships may be divided into ships that operate on the surface of water such as frigates and aircraft carriers, and ships that are capable of operating under water, viz. submarines. There are also vessels that provide auxiliary services such as tugs and dredgers. Fishing vessels constitute another important ship type.

Most of these types of ships have very similar propulsion arrangements. However, there are some types of very high speed vessels such as hovercraft and hydrofoil craft that make use of unconventional propulsion systems.

1.2 Propulsion Machinery

For centuries, ships were propelled either by human power (e.g. by oars) or by wind power (sails). The development of the steam engine in the 18th Century led to attempts at using this new source of power for ship propulsion, and the first steam driven ship began operation in Scotland in 1801. The early steam engines were of the reciprocating type. Steam was produced in a boiler from raw sea water using wood or coal as fuel. Gradual advances in steam propulsion plants took place during the 19th Century, including the use of fresh water instead of sea water and oil instead of coal, improvements in boilers, the use of condensers and the development of compound steam engines. Reciprocating steam engines were widely used for ship propulsion till the early years of the 20th Century, but have since then been gradually superseded by steam turbines and diesel engines.

The first marine steam turbine was fitted in the vessel "Turbinia" in 1894 by Sir Charles Parsons. Since then, steam turbines have completely replaced reciprocating steam engines in steam ships. Steam turbines produce less vibration than reciprocating engines, make more efficient use of the high steam inlet pressures and very low exhaust pressures available with modern steam generating and condensing equipment, and can be designed to produce very high powers. On the other hand, turbines run at very high speeds and cannot be directly connected to ship propellers; nor can turbines be reversed. This makes it necessary to adopt special arrangements for speed reduction and reversing, the usual arrangements being mechanical speed reduction gearing and a special astern turbine stage, or a turbo-electric drive. These arrangements add to the cost and complexity of the propulsion plant and also reduce its efficiency.

Since its invention in 1892, the diesel engine has continued to grow in popularity for use in ship propulsion and is today the most common type of engine used in ships. Diesel engines come in a wide range of powers and speeds, are capable of using low grade fuels, and are comparatively efficient.

Low speed diesel engines can be directly connected to ship propellers and can be reversed to allow the ship to move astern.

Another type of engine used for ship propulsion is the gas turbine. Like the steam turbine, the gas turbine runs at a very high speed and cannot be reversed. Gas turbines are mostly used in high speed ships where their low weight and volume for a given power give them a great advantage over other types of engines.

Nuclear energy has been tried for ship propulsion. The heat generated by a nuclear reaction is used to produce steam to drive propulsion turbines. However, the dangers of nuclear radiation in case of an accident have prevented nuclear ship propulsion from being used in non-combatant vessels except for a few experimental ships such as the American ship "Savannah", the German freighter "Otto Hahn" and the Russian icebreaker "V.I. Lenin". Nuclear propulsion has been used in large submarines with great success because nuclear fuel contains a large amount of energy in a very small mass, and because no oxygen is required for generating heat. This enables a nuclear submarine to travel long distances under water, unlike a conventional submarine which has to come to the surface frequently to replenish fuel and air for combustion.

In addition to the conventional types of ship propulsion plant discussed in the foregoing, attempts are being made to harness renewable and non-polluting energy sources such as solar energy, wind energy and wave energy for ship propulsion and to develop advanced technologies such as superconductivity and magneto-hydrodynamics. However, these attempts are still in a preliminary experimental stage.

1.3 Propulsion Devices

Until the advent of the steam engine, ships were largely propelled by oars imparting momentum to the surrounding water or by sails capturing the energy of the wind. The first mechanical propulsion device to be widely used in ships was the paddle wheel, consisting of a wheel rotating about a transverse axis with radial plates or paddles to impart an astern momentum to the water around the ship giving it a forward thrust. The early steamers of the 19^{th} Century were all propelled by paddle wheels. Paddle wheels are quite efficient when compared with other propulsion devices but have several drawbacks including difficulties caused by the variable immersion of the paddle wheel in the different loading conditions of the ship, the increase in the overall breadth of the ship fitted with side paddle wheels, the inability of the ship to maintain a steady course when rolling and the need for slow running heavy machinery for driving the paddle wheels. Paddle wheels were therefore gradually superseded by screw propellers for the propulsion of oceangoing ships during the latter half of the 19^{th} Century.

The Archimedean screw had been used to pump water for centuries, and proposals had been made to adapt it for ship propulsion by using it to impart momentum to the water at the stern of a ship. The first actual use of a screw to propel a ship appears to have been made in 1804 by the American, Colonel Stevens. In 1828, Josef Ressel of Trieste successfully used a screw propeller in an 18 m long experimental steamship. The first practical applications of screw propellers were made in 1836 by Ericsson in America and Petit Smith in England. Petit Smith's propeller consisted of a wooden screw of one thread and two complete turns. During trials, an accident caused a part of the propeller to break off and this surprisingly led to an increase in the speed of the ship. Petit Smith then improved the design of his propeller by decreasing the width of the blades and increasing the number of threads, producing a screw very similar to modern marine propellers. The screw propeller has since then become the predominant propulsion device used in ships.

Certain variants of the screw propeller are used for special applications. One such variant is to enclose the propeller in a shroud or nozzle. This improves the performance of heavily loaded propellers, such as those used in tugs. A controllable pitch propeller allows the propeller loading to be varied over a wide range without changing the speed of revolution of the propeller. It is also possible to reverse the direction of propeller thrust without changing the direction of revolution. This allows one to use non-reversing engines such as gas turbines. When propeller diameters are restricted and the propellers are required to produce large thrusts, as is the case in certain very high speed vessels, the propellers are likely to experience a phenomenon called "cavitation", which is discussed in Chapter 6. In circumstances where extensive cavitation is unavoidable, the propellers are specially designed to operate in conditions of full cavitation. Such propellers are popularly known as "supercavitating propellers".

Problems due to conditions of high propeller thrust and restricted diameter, which might lead to harmful cavitation and reduced efficiency, may be avoided by dividing the load between two propellers on the same shaft. Multiple propellers mounted on a single shaft and turning in the same direction are called "tandem propellers". Some improvement in efficiency can be obtained by having the two propellers rotate in opposite directions on coaxial shafts. Such "contra-rotating propellers" are widely used in torpedoes.

Two other ship propulsion devices may be mentioned here. One is the vertical axis cycloidal propeller, which consists of a horizontal disc carrying a number of vertical blades projecting below it. As the disc rotates about a vertical axis, each blade is constrained to turn about its own axis such that all the blades produce thrusts in the same direction. This direction can be controlled by a mechanism for setting the positions of the vertical blades. The vertical axis propeller can thus produce a thrust in any direction, ahead, astern or sideways, thereby greatly improving the manoeuvrability of the vessel. The second propulsion device that may be mentioned is the waterjet. Historically, this is said to be the oldest mechanical ship propulsion device, an English patent for it having been granted to Toogood and Hayes in 1661. In waterjet propulsion, as used today in high speed vessels, an impeller draws water from below the ship and discharges it astern in a high velocity jet just above the surface of water. A device is provided by which the direction of the waterjet can be controlled and even reversed to give good manoeuvrability. Waterjet propulsion gives good efficiencies in high speed craft and is becoming increasingly popular for such craft.

Because of their overwhelming importance in ship propulsion today, this book deals mainly with screw propellers. Other propulsion devices, including variants of the screw propeller, are discussed in Chapter 12.

CHAPTER 2

Screw Propellers

2.1 Description

A screw propeller consists of a number of blades attached to a hub or boss, as shown in Fig. 2.1. The boss is fitted to the propeller shaft through which the power of the propulsion machinery of the ship is transmitted to the propeller. When this power is delivered to the propeller, a turning moment or torque Q is applied making the propeller revolve about its axis with a speed ("revolution rate") n, thereby producing an axial force or thrust T causing the propeller to move forward with respect to the surrounding medium (water) at a speed of advance V_A. The units of these quantities in the SI system are:

Q : Newton-metres
n : revolutions per second
T : Newtons
V_A : metres per second

The revolution rate of the propeller is often given in terms of revolutions per minute (rpm), and the speed of advance in knots (1 knot = 0.5144 metres per second).

The point on the propeller blade farthest from the axis of revolution is called the blade tip. The blade is attached to the propeller boss at the root. The surface of the blade that one would see when standing behind

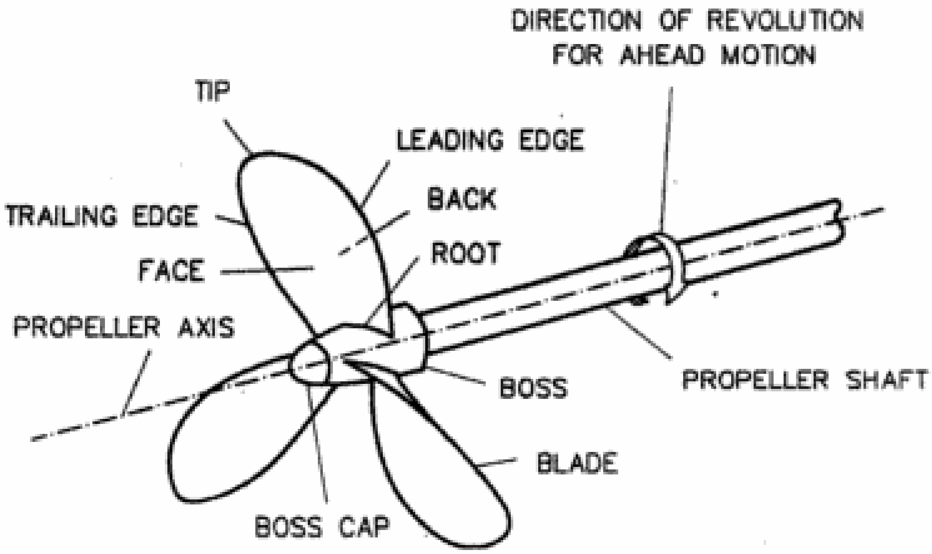

Figure 2.1 : A Three-Bladed Right Hand Propeller.

the ship and looking at the propeller fitted at the stern is called the face of the propeller blade. The opposite surface of the blade is called its back. A propeller that revolves in the clockwise direction (viewed from aft) when propelling the ship forward is called a right hand propeller. If the propeller turns anticlockwise when driving the ship ahead, the propeller is left handed. The edge of the propeller blade which leads the blade in its revolution when the ship is being driven forward is called the leading edge. The other edge is the trailing edge.

When a propeller revolves about its axis, its blade tips trace out a circle. The diameter of this circle is the propeller diameter D. The number of propeller blades is denoted by Z. The face of the propeller blade either forms a part of a helicoidal or screw surface, or is defined with respect to it; hence the name "screw propeller". A helicoidal surface is generated when a line revolves about an axis while simultaneously advancing along it. A point on the line generates a three-dimensional curve called a helix. The distance that the line (or a point on it) advances along the axis in one revolution is called the pitch of the helicoidal surface (or the helix). The pitch of the

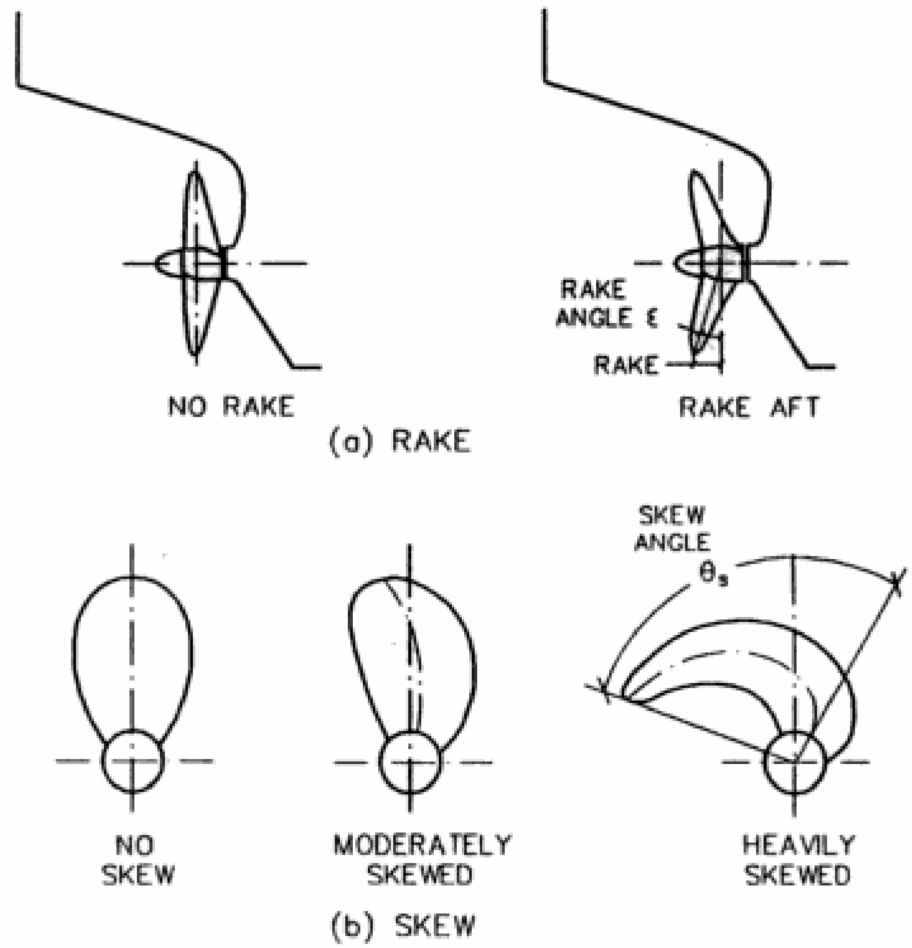

Figure 2.2 : Rake and Skew.

helicoidal surface which defines the face of a propeller blade is called the (face) pitch P of the propeller.

If the line generating the helicoidal surface is perpendicular to the axis about which it rotates when advancing along it, the helicoidal surface and the propeller blade defined by it are said to have no rake. If, however, the generating line is inclined by an angle ε to the normal, then the propeller has a rake angle ε. The axial distance between points on the generating line at the blade tip and at the propeller axis is the rake. Propeller blades are sometimes raked aft at angles up to 15 degrees to increase the clearance (space) between the propeller blades and the hull of the ship, Fig. 2.2(a).

Consider the line obtained by joining the midpoints between the leading and trailing edges of a blade at different radii from the axis. If this line is straight and passes through the axis of the propeller, the propeller blades have no skew. Usually however, the line joining the midpoints curves towards the trailing edge, resulting in a propeller whose blades are skewed back. Skew is adopted to reduce vibration. Some modern propeller designs have heavily skewed blades. The angle θ_S between a straight line joining the centre of the propeller to the midpoint at the root and a line joining the centre and the midpoint at the blade tip is a measure of skew, Fig. 2.2(b).

Example 1

In a propeller of 4.0 m diameter and 3.0 m constant pitch, each blade face coincides with its defining helicoidal surface. 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 rake and skew angles of the propeller.

The tangent of the rake angle is given by:

$$\tan\varepsilon = \frac{\text{difference in rake of the two sections}}{\text{difference in their radii}} = \frac{263.3 - 52.7}{2000 - 400}$$

$$= 0.131625$$

$$\text{Rake angle } \varepsilon = 7.5^\circ$$

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

$$\sin\theta_0 = \frac{69.5}{400} = 0.17375 \qquad \theta_0 = 10.00^\circ$$

$$\sin\theta_1 = \frac{-1285.6}{2000} = -0.64280 \qquad \theta_1 = -40.00^\circ$$

The skew angle is therefore $(\theta_0 - \theta_1) = 50^\circ$

2.2 Propeller Geometry

The shape of the blades of a propeller is usually defined by specifying the shapes of sections obtained by the intersection of a blade by coaxial right circular cylinders of different radii. These sections are called radial sections or cylindrical sections. Since all the Z propeller blades are identical, only one blade needs to be defined. It is convenient to use cylindrical polar coordinates (r, θ, z) to define any point on the propeller, r being the radius measured from the propeller axis, θ an angle measured from a reference plane passing through the axis, and z the distance from another reference plane normal to the axis. The $z = 0$ reference plane is usually taken to pass through the intersection of the propeller axis and the generating line of the helicoidal surface in the $\theta = 0$ plane.

Consider the section of a propeller blade by a coaxial circular cylinder of radius r, as shown in Fig. 2.3(a). The blade is pointing vertically up. The figure also shows the helix over one revolution defining the blade face at radius r, and the reference planes $\theta = 0$ and $z = 0$. The projections of this figure on a plane perpendicular to the propeller axis and on a horizontal plane are shown in Fig. 2.3(b) and (c). If the surface of the cylinder is now cut along the line AA_1, joining the two ends of the helix, and the surface unwrapped into a plane, a rectangle of length $2\pi r$ and breadth P (the pitch of the helix) is obtained, the helix being transformed into the diagonal as shown in Fig. 2.3(d). The radial section takes the shape shown in the figure, and this shape is the expanded section at the radius r. The angle $\varphi = \tan^{-1}(P/2\pi r)$ is the pitch angle, and L and T are the leading and trailing edges at the radius r.

The expanded blade section is fundamental to the hydrodynamics of the propeller because its behaviour when advancing at a speed V_A and revolving at a speed n is analogous to the behaviour of an aerofoil of the same shape moving at a velocity obtained by compounding the axial velocity V_A and the tangential velocity $2\pi nr$. The detailed design of a propeller therefore essentially consists in designing the expanded sections. The geometry of the propeller is thus defined through its expanded sections at a number of radii, usually at $r/R = 0.2, 0.3, \ldots 1.0$, where $R = 0.5D$ is the propeller radius. The expanded sections at these radii are obtained as shown in Fig. 2.3 and drawn as shown in Fig. 2.4(a). A line joining the projections, L′ and T′, of the leading and trailing edges on the base line of each section gives the expanded blade outline. The area within the expanded outlines of all the blades is the expanded blade area, A_E.

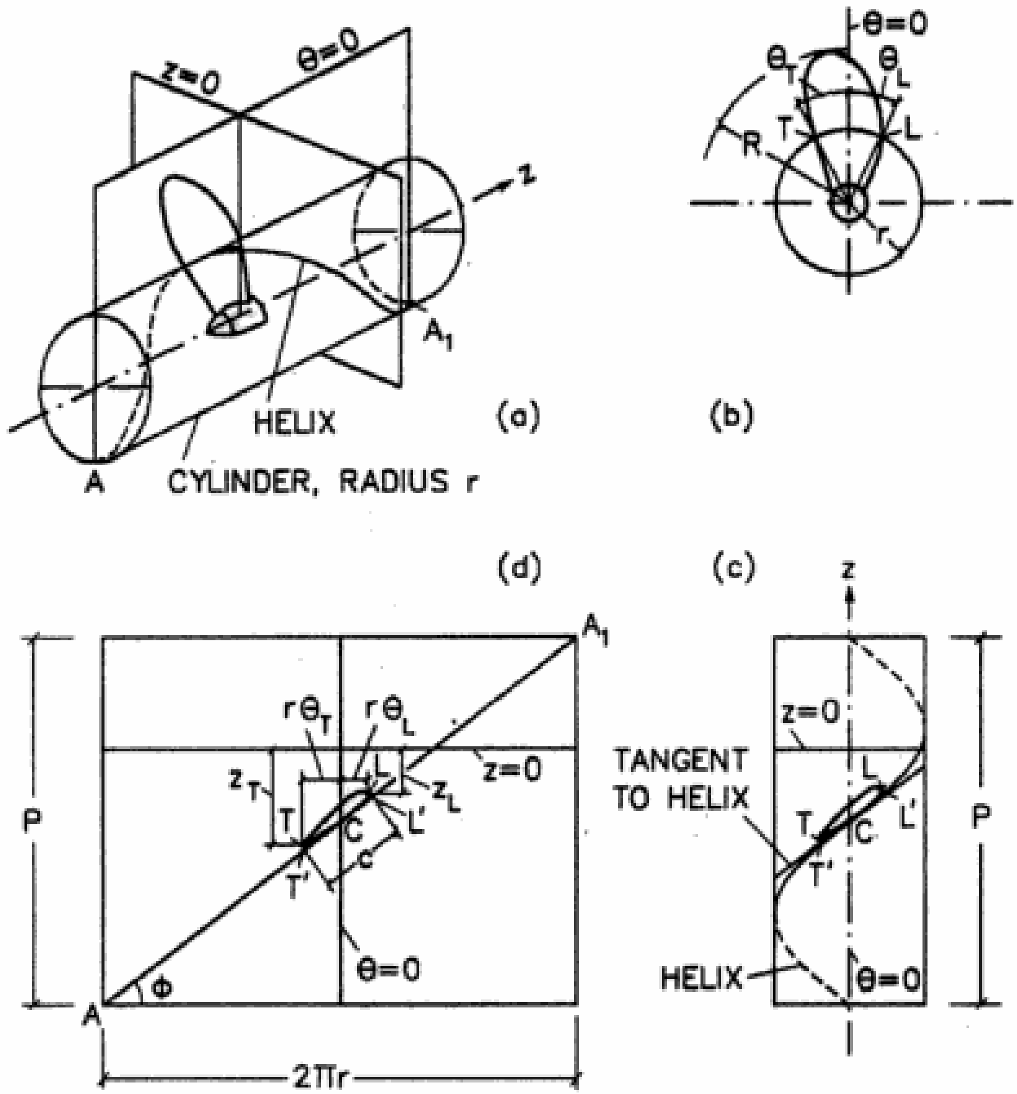

Figure 2.3 : Propeller Blade Cylindrical Section.

Given the expanded blade outline and sections, it is quite simple to obtain the actual shape of the propeller blade as represented by its projections on three orthogonal planes. This is so because from the expanded outline and sections one readily obtains the cylindrical polar coordinates (r, θ, z) of the leading and trailing edges, or indeed of any other point on the propeller blade surface. It is usually convenient to transform these coordinates to Cartesian coordinates using the axes shown in Fig. 2.4: $x = r\cos\theta$, $y = r\sin\theta$, $z = z$. The blade outline projected on a plane normal to the z-axis is called the projected blade outline, and the area contained within the projected outlines of all the blades is called the projected blade area, A_P.

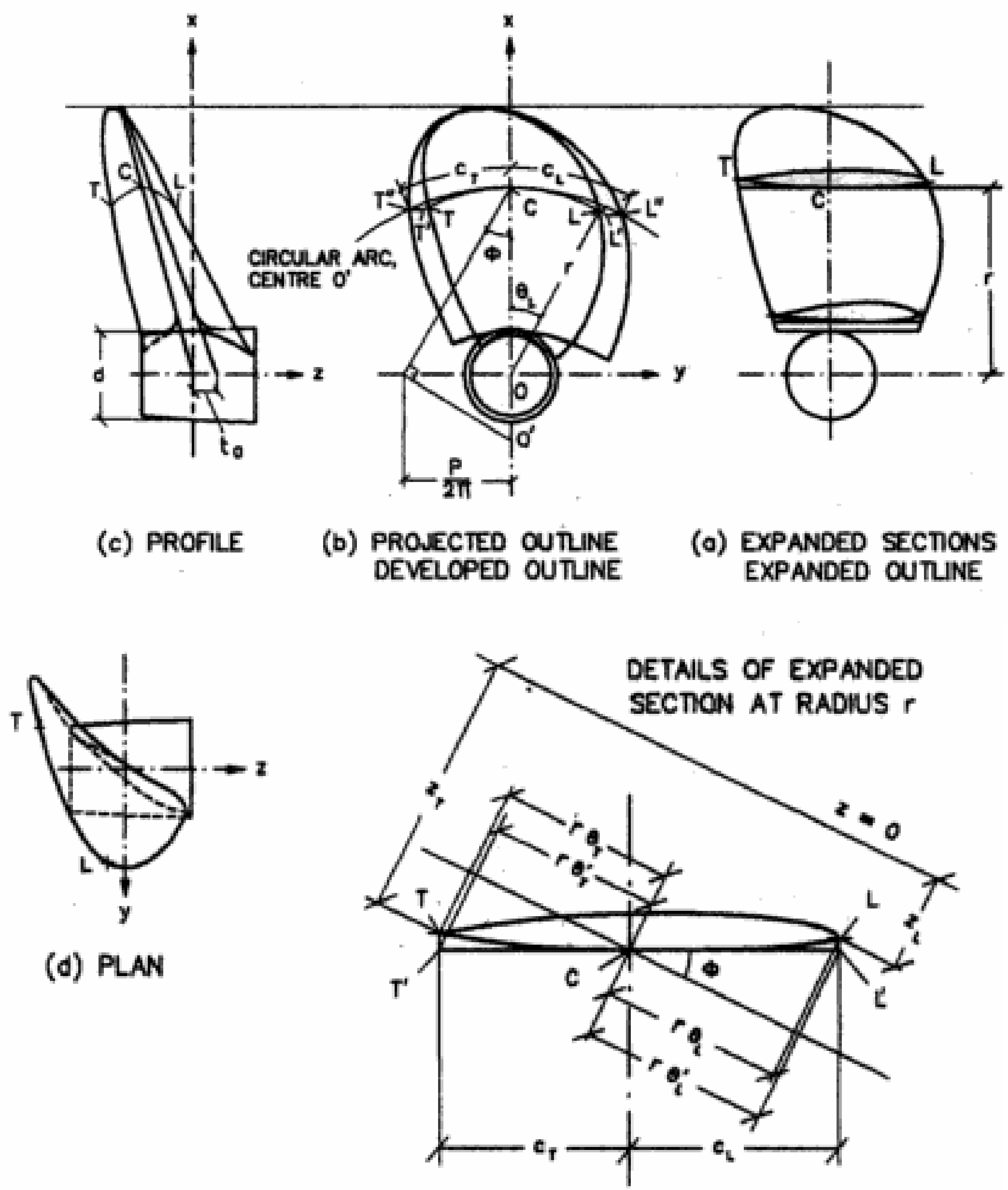

Figure 2.4 : Propeller Drawing.

The projections of the leading and trailing edges of a blade section on a plane tangential to the helix at the point C in Fig. 2.3(d), i.e. L′ and T′, are also associated with what is called the developed blade outline. If these tangent planes for the different radial sections are rotated through the pitch angles φ about the point C, the line joining the projections of the leading and trailing edges at the different radii gives the developed blade outline. The intersection of the tangent plane to the helix with the circular cylinder of radius r is an ellipse of semi-major axis $r \sec \varphi$ and semi-minor axis r. Therefore, in order to obtain the points on the developed outline corresponding to L′ and T′, it is necessary to draw this ellipse and to move the points L′ and T′ horizontally to L″ and T″ on the ellipse, Fig. 2.4(b). Alternatively, L″ and T″ may be obtained by measuring off distances equal to CL′ and CT′ in Fig. 2.4(a) on the circumference of the ellipse as CL″ and CT″ respectively in Fig. 2.4(b). Since drawing an ellipse manually is somewhat tedious, it is usual to approximate the ellipse by a circle having the same radius of curvature as the ellipse at the point C, i.e. $r \sec^2 \varphi$. The centre O″ of this circle may be obtained by the construction shown in Fig. 2.4(b). Paradoxically, the approximation of the ellipse by this circle gives more accurate results because the radius of the circle is exactly equal to the radius of curvature of the helix, which is constant. The developed outline represents what would be obtained if the curved surface of a propeller blade could be developed into a plane. The developed blade outline is sometimes of use during the manufacture of a propeller. The area contained within the developed outlines of all the blades is called the developed blade area, A_D.

A typical propeller drawing consists of the expanded outline and blade sections, the developed outline and the projections of the blade outline on the three orthogonal planes, $x = 0$, $y = 0$ and $z = 0$, as shown in Fig. 2.4. Instead of the projection of the propeller blade on the x - z plane shown in Fig. 2.4(c), the values of z for the leading and trailing edges are sometimes plotted as a function of r to obtain the blade sweep, i.e. the space swept by the blade during its revolution. This is important for determining the clearances of the propeller blade from the hull and the rudder, particularly for heavily skewed blades. The construction lines are naturally not given in the drawing. There are instead a number of additional details. Detailed offsets of the expanded sections are provided. A line showing the variation of the position of maximum thickness with radius is drawn on the expanded outline, and sometimes the loci of the points at which the face of the propeller blade departs from its base line at the different radii. The offset of the face above its base line is variously called wash-back, wash-up, wash-away or setback, a negative offset (below the base line) being called wash-down. The offsets of the leading and trailing edges are called nose tilt and tail tilt. The distribution of pitch over the radius, if not constant, is shown separately. The variation of maximum blade thickness with radius r and the fillet radii where the blade joins the boss are also indicated. The internal details of the boss showing how it is fitted to the propeller shaft may also be given.

Example 2

In a propeller of 5.0 m diameter and 4.0 m pitch, radial lines from the leading and trailing edges of the section at $0.6R$ make angles of 42.2 and 28.1 degrees with the reference plane through the propeller axis. Determine the width of the expanded blade outline at $0.6R$.

The radius of the section at $0.6R$, $r = 0.6 \times \frac{5}{2} = 1.5\,\text{m} = 1500\,\text{mm}$

The pitch angle at this section is given by:

$$\tan\varphi = \frac{P}{2\pi r} = \frac{4}{2\pi \times 1.5} = 0.4244 \qquad \cos\varphi = 0.9205$$

$$\varphi = 22.997^\circ$$

Referring to Fig. 2.3,

$$\theta_L = 42.2^\circ \qquad \theta_T = 28.1^\circ \text{ (given)}$$

The width of the expanded outline at $0.6R$ is:

$$c = \frac{r\,(\theta_L + \theta_T)}{\cos\varphi} \quad \theta_L \text{ and } \theta_T \text{ being in radians}$$

so that,

$$c = \frac{1500\left[\dfrac{42.2^\circ + 28.1^\circ}{57.3}\right]}{0.9205} = 1999.2\,\text{mm}$$

This assumes that the section is flat faced, i.e. L and T in Fig. 2.3(c) coincide with L′ and T′ respectively.

Example 3

The cylindrical polar coordinates (r, θ, z) of the trailing edge of a flat faced propeller blade radial section are (1500 mm, $-30°$, -400 mm). If the pitch of the propeller is 3.0 m, and the expanded blade width is 2000 mm, determine the coordinates of the leading edge.

The leading and trailing edges of a radial section have the same radius, i.e. $r = 1500$ mm.

The pitch angle is given by:

$$\tan\varphi = \frac{P}{2\pi r} = \frac{3000}{2\pi \times 1500} = 0.3183$$

$$\varphi = 17.657° \qquad \cos\varphi = 0.9529 \qquad \sin\varphi = 0.3033$$

If the θ coordinates of the leading and trailing edges are θ_L and θ_T, then the expanded blade width c is given by:

$$c = \frac{r\,(\theta_L - \theta_T)}{\cos\varphi}, \text{ see Fig. 2.3(c)}$$

i.e.

$$2000 = \frac{1500\,[\theta_L^{\circ} - (-30°)]/57.3}{0.9529}$$

or

$$\theta_L = 42.80°$$

Also,

$$z_L = z_T + c\sin\varphi$$

$$= -400 + 2000 \times 0.3033 = 206.6 \text{ mm}$$

i.e. the coordinates of the leading edge are (1500 mm, 42.80°, 206.6 mm).

2.3 Propeller Blade Sections

The expanded blade sections used in propeller blades may generally be divided into two types: segmental sections and aerofoil sections. Segmental sections are characterised by a flat face and a circular or parabolic back, the maximum thickness being at the midpoint between the leading and trailing edges, the edges being quite sharp, Fig. 2.5(a). In aerofoil sections, the face

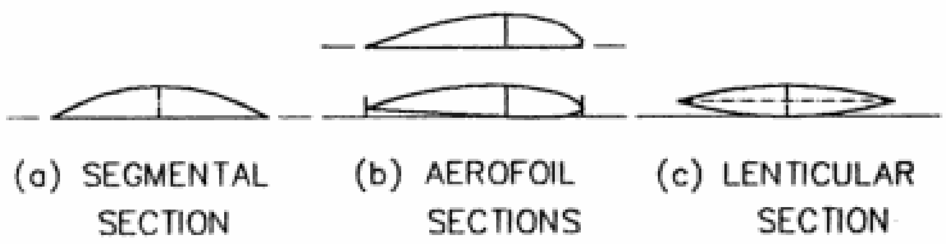

Figure 2.5 : Propeller Blade Sections.

may or may not be flat, the maximum thickness is usually nearer the leading edge, which is often more rounded than the trailing edge, Fig. 2.5(b). More rarely, a propeller may have lens-shaped or lenticular blade sections, Fig. 2.5(c); such sections are used in propellers that are required to work equally efficiently for both directions of revolution.

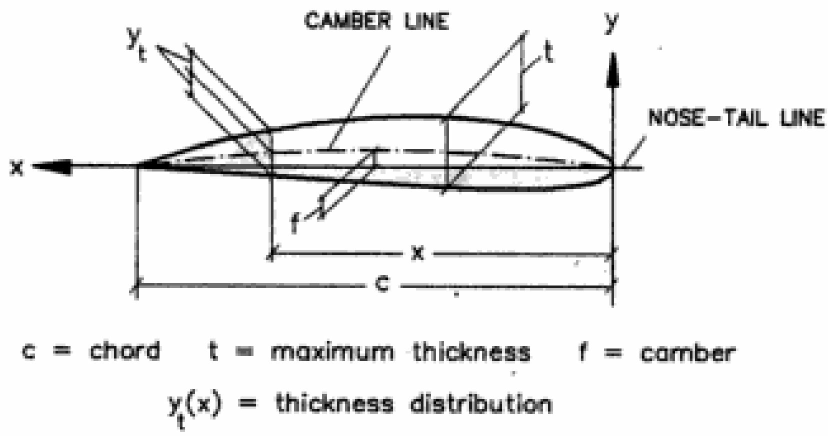

Figure 2.6 : Definition of an Aerofoil Section.

An aerofoil section is usually defined in terms of the mean line or centre line between its lower and upper surfaces, i.e. the face and the back, and a thickness distribution along its length, as shown in Fig. 2.6. The length of the section, or its chord c, is measured between the leading edge or nose and the trailing edge or tail, and the centre line is defined by its offsets $y_c(x)$ from the nose-tail line at different distances x from the leading edge. The offsets of the face and back, $y_t(x)$, are measured from the mean line perpendicular to it. The maximum offset of the mean line is the section camber f and the maximum thickness of the section is its thickness t. Mean lines and thickness distributions of some aerofoil sections used in marine propellers are given in Appendix 2.

Instead of measuring the section chord on the nose-tail line, it is usual in an expanded propeller blade section to define the chord as the projection of the nose-tail line on the base line, which corresponds to the helix at the given radius, i.e. the chord c is taken as L′ T′ rather than LT in Fig. 2.3(c) or Fig. 2.4(a). If the resultant velocity of flow to a blade section is V_R as shown in Fig. 2.7, the angle between the base chord and the resultant velocity is

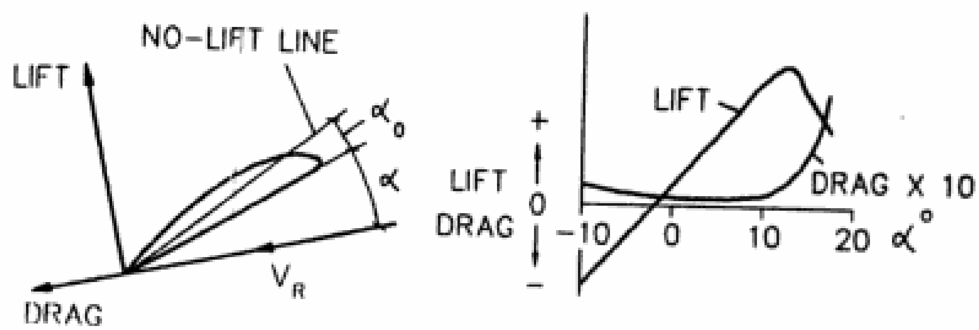

Figure 2.7 : Angle of Attack.

called the angle of attack, α. The blade section then produces a force whose components normal and parallel to V_R are the lift and the drag respectively. For a given section shape, the lift and drag are functions of the angle of attack, and for a certain (negative) angle of attack the lift of the section is zero. This angle of attack is known as the no-lift angle, α_0.

2.4 Alternative Definition of Propeller Geometry

When a propeller is designed in detail beginning with the design of the expanded sections, the geometry of the propeller is sometimes defined in a slightly different way. The relative positions of the expanded sections are indicated in terms of a blade reference line, which is a curved line in space that passes through the midpoints of the nose-tail lines (chords) of the sections at the different radii. A cylindrical polar coordinate system (r, θ, z) is chosen as shown in Fig. 2.8. The $z = 0$ reference plane is normal to the propeller axis, the $\theta = 0$ plane passes through the propeller axis (z-axis),

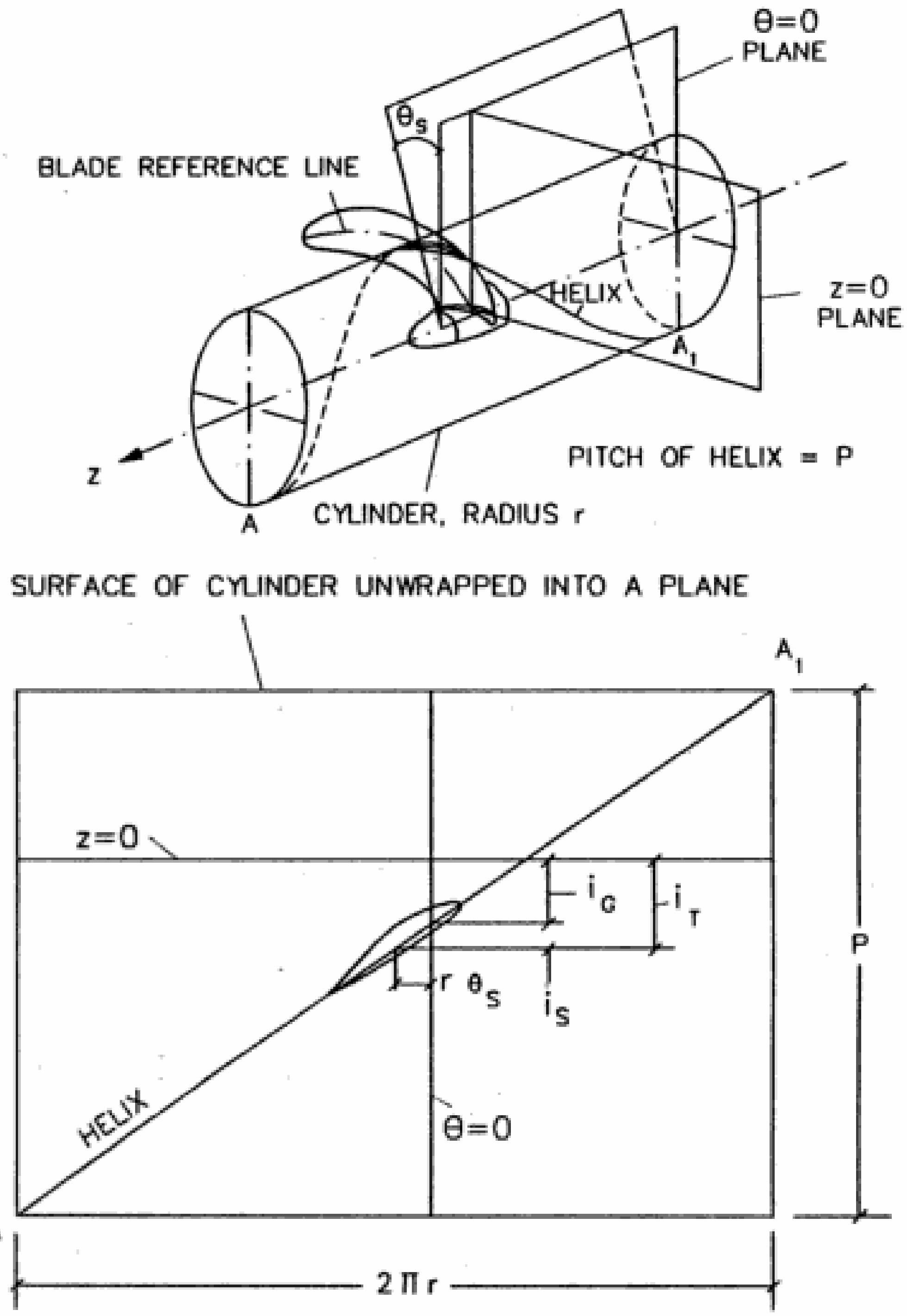

Figure 2.8 : Alternative Definition of Propeller Geometry.

and both pass through the blade reference line at the boss. The pitch helix at any radius r passes through the $\theta = 0$ plane at that radius. The angle between the plane passing through the z-axis and containing the point on blade reference line at any radius and the $\theta = 0$ plane is the skew angle θ_S at that radius. The distance of the blade reference line at any radius from the $z = 0$ reference line is the total rake i_T at that radius, and consists of the generator line rake i_G and skew induced rake i_S as shown in Fig. 2.8. Rake aft and skew back (i.e. towards the trailing edge) are regarded as positive. This requires the positive z-axis to be directed aft.

Rake and skew may be combined in such a way as to produce a blade reference line that lies in a single plane normal to the propeller axis. Warp is that particular combination of rake and skew that produces a zero value for the total axial displacement of the reference point of a propeller blade section.

2.5 Pitch

As mentioned earlier, the face of a propeller blade is defined with respect to a helicoidal surface, the pitch of this surface being the face pitch P of the propeller. The helicoidal surface is composed of helices of different radii r from the root to the tip of the propeller blade. If all the helices have the same pitch, the propeller is said to have a constant pitch. If, however, the pitch of the helicoidal surface varies with the radius the propeller has a radially varying or variable pitch. (In theory, it is also possible to have circumferentially varying pitch when the ratio of the velocity of advance to the tangential velocity of the generating line of the helicoidal surface is not constant.) If $P(r)$ is the pitch at the radius r, the mean pitch $\overline{P}$ of the propeller is usually determined by taking the "moment mean":

$$\overline{P} = \frac{\int_{r_b}^{R} P(r)\, r\, dr}{\int_{r_b}^{R} r\, dr} \tag{2.1}$$

r_b being the radius at the root section where the blade joins the boss and R the propeller radius.

Consider a propeller of diameter D and pitch P operating at a revolution rate n and advancing at a speed V_A. If the propeller were operating in an unyielding medium, like a screw in a nut, it would be forced to move an axial distance nP in unit time. Because the propeller operates in water, the advance per unit time is only V_A, i.e. the propeller slips in the water, the slip being $nP - V_A$. The slip ratio is defined as:

$$s = \frac{nP - V_A}{nP} \tag{2.2}$$

If $V_A = 0$, $s = 1$ and the propeller operates in the 100 percent slip condition. If $V_A = nP$, $s = 0$, and the propeller operates at zero slip. If the value of P used in Eqn. (2.2) is the face (nominal) pitch, s is the nominal slip ratio. However, at zero slip the thrust T of a propeller should be zero, and the effective pitch P_e may be determined in this way, i.e. by putting $P_e = V_A/n$ for $T = 0$. If the effective pitch is used in Eqn. (2.2), one obtains the effective slip ratio, s_e. If in defining slip the speed of the ship V is used instead of the speed of advance V_A, one obtains the apparent slip. (V and V_A are usually not the same).

Example 4

A propeller running at a revolution rate of 120 rpm is found to produce no thrust when its velocity of advance is 11.7 knots and to work most efficiently when its velocity of advance is 10.0 knots. What is the effective pitch of the propeller and the effective slip ratio at which the propeller is most efficient?

$$\text{Effective slip ratio } s_e = \frac{nP_e - V_A}{nP_e}$$

When the propeller produces zero thrust, $s_e = 0$, and:

$$P_e = \frac{V_A}{n} = \frac{11.7 \times 0.5144}{\frac{120}{60}} = 3.0092\,\text{m}$$

When the propeller works most efficiently:

$$s_e = 1 - \frac{V_A}{n\,P_e} = 1 - \frac{10.0 \times 0.5144}{\frac{120}{60} \times 3.0092} = 0.1453$$

2.6 Non-dimensional Geometrical Parameters

As will be seen in subsequent chapters, the study of propellers is greatly dependent upon the use of scale models. It is therefore convenient to define the geometrical and hydrodynamic characteristics of a propeller by non-dimensional parameters that are independent of the size or scale of the propeller. The major non-dimensional geometrical parameters used to describe a propeller are:

- Pitch ratio P/D : the ratio of the pitch to the diameter of the propeller.

- Expanded blade area ratio A_E/A_O : the ratio of the expanded area of all the blades to the disc area A_O of the propeller, $A_O = \pi D^2/4$. (The developed blade area ratio A_D/A_O and the projected blade area ratio A_P/A_O are similarly defined.)

- Blade thickness fraction t_0/D : the ratio of the maximum blade thickness extrapolated to zero radius, t_0, divided by the propeller diameter; see Fig. 2.4(c).

- Boss diameter ratio d/D : the ratio of the boss diameter d to the propeller diameter; the boss diameter is measured as indicated in Fig. 2.4(c).

Aerofoil sections are also described in terms of non-dimensional parameters: the camber ratio f/c and the thickness-chord ratio t/c, where c, f and t are defined in Fig. 2.6. The centre line camber distribution and the thickness distribution are also given in a non-dimensional form: $y_c(x)/t$ and $y_t(x)/t$ as functions of x/c.

Example 5

In a four-bladed propeller of 5.0 m diameter, the expanded blade widths at the different radii are as follows:

r/R	:	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
c mm	:	1454	1647	1794	1883	1914	1876	1724	1384	0

The thickness of the blade at the tip is 15 mm and at $r/R = 0.25$, it is 191.25 mm. The propeller boss is shaped like the frustum of a cone with a length of 900 mm, and has forward and aft diameters of 890 mm and 800 mm. The propeller has a rake of 15 degrees aft and the reference line intersects the axis at the mid-length of the boss. Determine the expanded blade area ratio, the blade thickness fraction and the boss diameter ratio of the propeller.

By drawing the profile (elevation) of the boss, and a line at 15 degrees from its mid-length, the boss diameter is obtained as $d = 834$ mm, giving a boss diameter ratio:

$$\frac{d}{D} = \frac{834}{5000} = 0.1668$$

By drawing the expanded outline (i.e. c as a function of r), the blade width at the root section ($r/R = 0.1668$ or $r = 417$ mm) is obtained as 1390 mm. The area within the blade outline from the root section to $r/R = 0.2$ or $r = 500$ mm is thus:

$$A_1 = \frac{1390 + 1454}{2}\,(500 - 417) = 118026\,\mathrm{mm}^2$$

The area of the rest of the blade may be obtained by Simpson's First Rule, according to which:

$$\int f(x)\,dx = \frac{1}{3} \times s \times \sum_{i=1}^{n} SM_i \times f(x_i)$$

where 1/3 is the common multiplier, s is the spacing between the n equidistant values of x_i, and SM_i are the Simpson Multipliers $1, 4, 2, 4, \ldots, 4, 2, 4, 1$; n must be an odd integer. Here, c is to be integrated over the radius from $0.2R$ to $1.0R$, the spacing between the radii being $0.1R = 250$ mm. The integration is usually carried out in a table as shown in the following:

$\frac{r}{R}$	c mm	SM	$f(A)$
0.2	1454	1	1454
0.3	1647	4	6588
0.4	1794	2	3588
0.5	1883	4	7532
0.6	1914	2	3828
0.7	1876	4	7504
0.8	1724	2	3448
0.9	1384	4	5536
1.0	0	1	0
			39478

$$A_2 = \tfrac{1}{3} \times 250 \times 39478$$
$$= 3289833\,\mathrm{mm}^2$$

The expanded blade area of all the four blades is thus:

$$A_E = 4\,(118026 + 3289833)\,\mathrm{mm}^2 = 13.6314\,\mathrm{m}^2$$

The disc area of the propeller is:

$$A_O = \frac{\pi}{4}D^2 = \frac{\pi}{4} \times 5.000^2 = 19.6350\,\mathrm{m}^2$$

The expanded blade area is therefore:

$$\frac{A_E}{A_O} = \frac{13.6314}{19.6350} = 0.6942$$

The blade thickness extrapolated linearly to the shaft axis is:

$$t_0 = t_1 - \frac{t_1 - t_{0.25}}{1 - 0.25} = 15 - \frac{15 - 191.25}{1 - 0.25} = 250\,\mathrm{mm}$$

where t_0, t_1 and $t_{0.25}$ are the blade thicknesses at $r/R = 0$, 1.0 and 0.25 respectively. The blade thickness fraction is therefore:

$$\frac{t_0}{D} = \frac{250}{5000} = 0.050.$$

2.7 Mass and Inertia

The mass of a propeller needs to be calculated to estimate its cost, and both the mass and the polar moment of inertia are required for determining the vibration characteristics of the propeller shafting system. The mass and polar moment of inertia of the propeller blades can be easily determined by integrating the areas of the blade sections over the radius. The mass and inertia of the boss must be added. Thus, one may write:

$$M = \rho_m\, Z \int_{r_b}^{R} a\, dr + M_{\text{boss}} \tag{2.3}$$

$$I_P = \rho_m\, Z \int_{r_b}^{R} a\, r^2\, dr + I_{\text{boss}} \tag{2.4}$$

where M and I_P are the mass and polar moment of inertia of the propeller, ρ_m is the density of the propeller material, a the area of the blade section at radius r, and M_{boss} and I_{boss} the mass and polar moment of inertia of the propeller boss, the other symbols having been defined earlier.

The area of a blade section depends upon its chord c and thickness t so that for a blade section of a given type, one may write:

$$a = \text{constant} \times c \times t \tag{2.5}$$

The chords or blade widths at the different propeller radii are proportional to the expanded blade area ratio per blade, while the section thicknesses depend upon the blade thickness fraction. One may therefore write:

$$M = k_m\, \rho_m \frac{A_E}{A_O} \frac{t_0}{D} D^3 + M_{\text{boss}} \tag{2.6}$$

$$I_P = k_i\, \rho_m \frac{A_E}{A_O} \frac{t_0}{D} D^5 + I_{\text{boss}} \tag{2.7}$$

where k_m and k_i are constants which depend upon the shape of the propeller blade sections.

Problems

1. A propeller of 6.0 m diameter and constant pitch ratio 0.8 has a flat faced expanded section of chord length 480 mm at a radius of 1200 mm. Calculate the arc lengths at this radius of the projected and developed outlines.

2. The distances of points on the face of a propeller blade from a plane normal to the axis measured at the trailing edge and at 10 degree intervals up to the leading edge at a radius of 1.75 m are found to be as follows:

	TE								LE
Angle, deg :	−37.5	−30	−20	−10	0	10	20	30	32.5
Distance, mm :	750	770	828	939	1050	1161	1272	1430	1550

The propeller has a diameter of 5.0 m. The blade section has a flat face except near the trailing edge (TE) and the leading edge (LE). Determine the pitch at this radius. If the propeller has a constant pitch, what is its pitch ratio?

3. The cylindrical polar coordinates $(r, \theta, z)$of a propeller, r being measured in mm from the propeller axis, θ in degrees from a reference plane through the axis and z in mm from a plane normal to the axis, are found to be (1500, 10, 120) at the leading edge and (1500, −15, −180) at the trailing edge at the blade section at $0.6R$. The blade section at this radius has a flat face. Determine the width of the expanded outline at this radius and the position of the reference line, $\theta = 0$, with respect to the leading edge. What is the pitch ratio of the propeller at $0.6R$? The propeller has no rake.

4. The expanded blade widths of a three-bladed propeller of diameter 4.0 m and pitch ratio 0.9 are as follows:

r/R :	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
c mm :	1477	1658	1808	1917	1976	1959	1834	1497	0

Find the expanded, developed and projected blade area ratios of the propeller. Assume that the root section is at $0.2R$, the blade outline is symmetrical and the blade sections are flat faced.

5. The face and back offsets of a propeller blade section with respect to a straight line joining the leading and trailing edges ("nose-tail line") are as follows:

Distance from leading edge	Face offset	Back offset
mm	mm	mm
0	0	0
50	−24.2	37.8

Distance from leading edge	Face offset	Back offset
mm	mm	mm
100	−32.4	54.8
200	−42.5	77.5
300	−48.0	91.1
400	−50.2	98.3
500	−49.4	99.4
600	−45.3	94.3
700	−38.3	82.8
800	−29.1	64.2
900	−19.2	37.1
1000	−5.0	5.0

Determine the thickness-chord ratio and the camber ratio of the section.

6. A propeller of a single screw ship has a diameter of 6.0 m and a radially varying pitch as follows:

r/R :	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
P/D :	0.872	0.902	0.928	0.950	0.968	0.982	0.992	0.998	1.000

Calculate the mean pitch ratio of the propeller. What is the pitch at 0.7R?

7. A propeller of 5.0 m diameter and 1.1 effective pitch ratio has a speed of advance of 7.2 m per sec when running at 120 rpm. Determine its slip ratio. If the propeller rpm remains unchanged, what should be the speed of advance for the propeller to have (a) zero slip and (b) 100 percent slip?

8. In a four-bladed propeller of 5.0 m diameter, each blade has an expanded area of 2.16 m^2. The thickness of the blade at the tip is 15 mm, while at a radius of 625 mm the thickness is 75 mm with a linear variation from root to tip. The boss diameter is 835 mm. The propeller has a pitch of 4.5 m. Determine the pitch ratio, the blade area ratio, the blade thickness fraction and the boss diameter ratio of the propeller.

9. A crudely made propeller consists of a cylindrical boss of 200 mm diameter to which are welded three flat plates set at an angle of 45 degrees to a plane normal to the propeller axis. Each flat plate is 280 mm wide with its inner edge shaped to fit the cylindrical boss and the outer edge cut square so that the distance of its midpoint from the boss is 700 mm. Determine the diameter, the mean pitch ratio and the expanded and projected blade area ratios of this propeller.

10. A three-bladed propeller of diameter 4.0 m has blades whose expanded blade widths and thicknesses at the different radii are as follows:

r/R :	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Width, mm :	1000	1400	1700	1920	2000	1980	1800	1320	0
Thickness, mm :	163.0	144.5	126.0	107.5	89.0	70.5	52.0	33.5	15.0

The blade sections are all segmental with parabolic backs, and the boss may be regarded as a cylinder of length 900 mm and inner and outer diameters of 400 mm and 650 mm respectively. The propeller is made of Aluminium Nickel Bronze of density 7600 kg per m^3. Determine the mass and polar moment of inertia of the propeller.