Controllable Pitch Propellers

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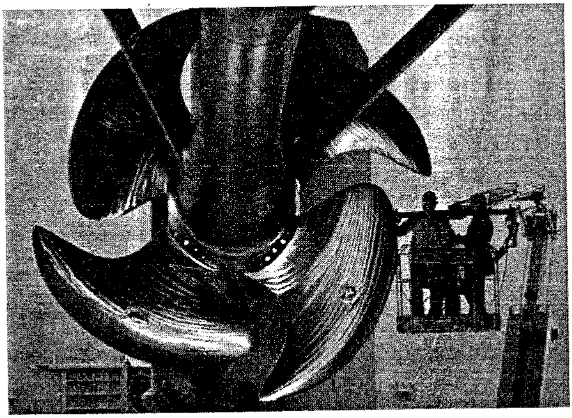

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5 CP Propeller Blades & Geometry

5.1 Definitions

To avoid confusion it is necessary to understand the conventions and terms used by CP propeller designers. This is made more difficult because, over the years, different engineers have used different names for a given feature, and have even used the same name for different features. The following text uses the most generally accepted definitions, while avoiding some of the less common definitions or ambiguous names. If in doubt, ask the originator of the design data for a definition.

In propeller geometry and design a number of different sets of reference frames or coordinates are used. The preferred reference frame, however, is a rectangular Cartesian system of body axes relative to the ship, where the X-axis is the shaft axis and is taken as positive forward, the Y-axis is positive to starboard and the Z-axis is positive downward.

The location of the propeller blade is defined from the 'propeller reference line' or 'directrix', which is perpendicular to the X-axis and usually passes through the origin of the Cartesian coordinates for the propeller.

The propeller blade is defined with constant radius or cylindrical aerofoil sections, that is by sections which lie on cylindrical surfaces at constant radii from the X-axis. The nose-tail line of a blade section (See Figure 5) at each radius intersects the plane defined by the propeller reference line and the X-axis. The locus of these points of intersection is known as the 'generator line' of the blade and is used as the basis for defining the blade geometry. The generator line is sometimes called the 'blade reference line', but this term is also used for the locus of the mid-chord points of the blade sections. So if this term is used, care is needed to ensure that its meaning is understood. For blades with no rake the generator line is a radial line perpendicular to the X-axis and it coincides with the propeller reference line. If rake is present then the generator line will lie in the plane of the propeller reference line and the X-axis, but will be at an angle to the propeller reference line.

A controllable pitch propeller blade swivels about its 'spindle axis', which is generally coincident with the propeller reference line although, very occasionally, the spindle axis may not be at a right angle to the X-axis.

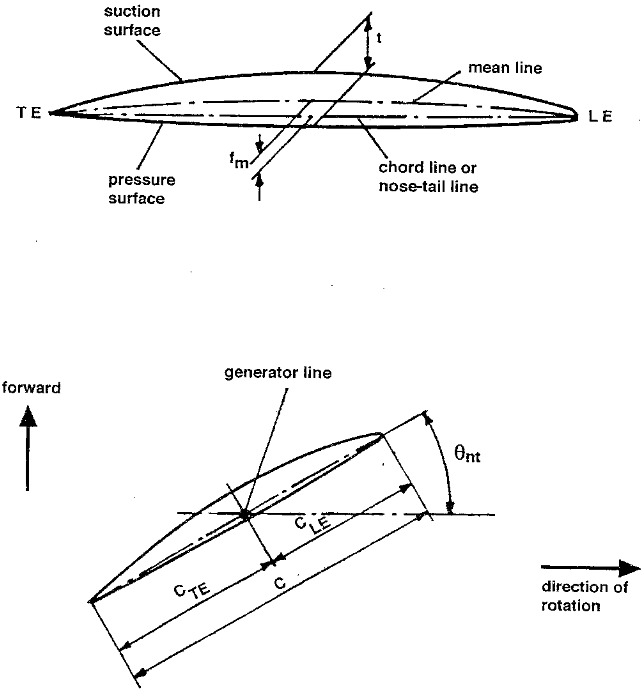

Figure 5. Aerofoil blade section

5.2 Blade Sections

The aerofoil sections used for propellers are those which give a high lift force with low susceptibility to cavitation. It is normal for the leading edge thickness of the outer sections to be increased to provide sufficient strength to the blade edges. As CP propellers do not reverse their direction of rotation there is no need to strengthen the trailing edges as with FP propellers.

Figure 5 shows an aerofoil section. This shows the cylindrical blade section developed, or unrolled, onto a flat plane. The 'chord length' (C) is the width of the blade from the leading edge (LE) to the trailing edge (TE) measured around the surface of the cylinder on which the section lies. The after surface of a blade is at an increased pressure when the propeller is operating in the ahead mode, and this is referred to as the 'pressure surface', 'pressure face', or simply the 'face' of the blade. The convex forward face of a blade is at a reduced pressure when the propeller is operating in the ahead mode, and is referred to as the 'suction surface', 'suction face', or simply as the 'back' of the blade. The 'mean line', or 'camber line', is the curved line which lies midway between the suction and the pressure surfaces, i.e. it is at an equal distance from both surfaces at all points. The 'section thickness' (t) is the maximum thickness of the aerofoil section, and the 'section camber' (f_m) is normally taken as the maximum distance between the mean line and the chord line. Where blades join their blade palms (or hubs in the case of FP propellers) there are generous fillets, but the blade root section thickness is taken to be the thickness of the aerofoil section at the root, without the fillets. The generator line passes through the section chord line and the distances to the section edges are given by the 'leading edge chord length' (C_{LE}) and the 'trailing edge chord length' (C_{TE}).

5.3 Design Pitch

These aerofoil sections are set at an angle to the athwartship YZ plane and, when the blades are set at the design pitch setting, the angle between the YZ plane and the section is the 'pitch angle'. As these are aerofoil sections and not flat plates, there are a number of different possible definitions and the pitch angle must be defined. The most frequently used is the 'nose tail pitch angle', which is the angle between the YZ plane and the nose-tail line, or chord line (see Figure 6, angle θ_{nt}). This is the definition used in this text.

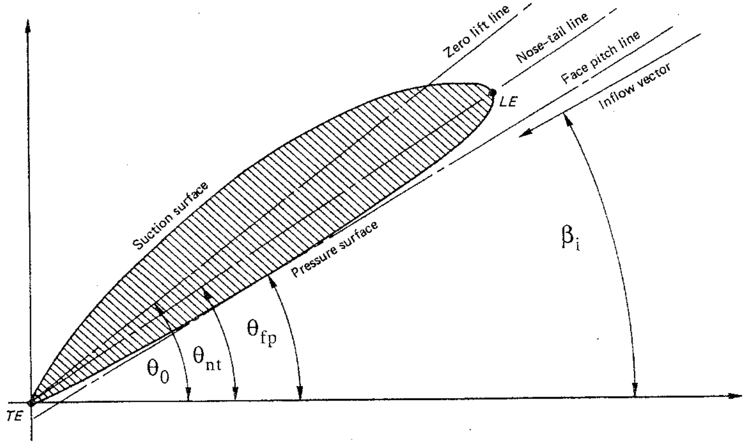

Figure 6. Pitch lines and angles

Another definition used in propeller manufacturing is the 'face pitch angle'. (See Figure 6, angle θ_{fp}). Many blades have been designed using aerofoil sections with flat pressure faces and in these cases the face pitch has a clear definition. Nowadays, the pressure faces of blades are more frequently curved and the face pitch of the section has little meaning, although the 'local face pitch' may be used in checking manufacturing accuracy. In this case, the section chord length is divided into a number of equal lengths, say 10, and the local face pitch is the pitch of a straight line drawn between the points on the blade face, which correspond to the two ends of one of these subdivisions of the section chord.

Use is also made of the 'effective' or 'no-lift pitch angle'. (See Figure 6, angle θ_0.) The effective pitch angle is the angle at which inflow water produces no lift force on the aerofoil section.

The term 'hydrodynamic pitch angle' is the angle of the inflow water relative to a blade section, including the velocity components induced by the propeller itself.

Pitch (p) is often quoted as a linear dimension rather than as an angle. The pitch at a given radius is the distance which that section would advance along the X-axis, when moved in a helix in the direction of the pitch line through one complete revolution. It is equivalent to the pitch of a screw thread. At any radius (r), the pitch is:-

$$p = 2\pi r \tan\theta_{nt}$$

Some blades are designed with a constant design pitch at all radii, but for most blades there will be a variation in the pitch along the radius. The normal convention is to define the 'typical' or 'mean' pitch of the propeller (P) as the pitch at a radius of 70 per cent of the maximum radius (i.e. at 0.7R, where R is the maximum radius of the propeller). An 'effective mean pitch' can also be calculated using a radial moment mean calculation which enables propellers with different radial pitch distributions to be compared for power absorption. It is frequently found that for conventional propellers, as opposed to highly skewed propellers, where the pitch changes continuously and smoothly with radius the effective mean pitch is very near in value to the pitch at 0.7R. In addition, the resultants of the thrust and torque forces distributed over the blades both have their centres of action near 0.7R. For conventional blades, blade strength is calculated using these resultant forces.

The design pitch is often given as a non-dimensional pitch/diameter ratio. The pitch/diameter ratio at any radial section is p/D, where p is the pitch and D is the maximum diameter of the propeller. The mean pitch/diameter ratio of the propeller is P/D where P is the design pitch at 0.7R. If the pitch/diameter ratio of a blade is constant for all radii, then the pitch angle (θ_r) decreases from the root to the tip, tan θ_r being proportional to the inverse of the local radius.

5.4 Pitch Change Effects

Most blades do not have a constant pitch from root to tip when at the design pitch setting. They have lower pitches near the root and tip to reduce the intensity of root and tip vortices. The tangent of the local pitch angle over the blade is therefore not inversely proportional to the radius, although the local pitch angle usually varies from a maximum value at the root to a minimum value at the tip. When the pitch is moved from the design condition, the whole blade turns through the same angle so the percentage change in pitch is much greater at the tip than at the root.

Now at any given radius, pitch(p) $= 2\pi r \tan\theta$

It follows that:- $\tan\theta = \dfrac{p/D}{\pi r/R}$ where $D = 2R$

Consider an example of a non-skewed CP propeller blade at design pitch:

r/R	p/D	θ
0.325	0.971	43.56°
0.4	1.018	39.01°
0.5	1.079	34.48°
0.6	1.130	30.94°
0.7	1.167	27.95°
0.8	1.182	25.19°
0.9	1.172	22.51°
1.0	1.145	20.03°

Now consider the same blade with the pitch angles reduced by 20°, then the equivalent pitch/diameter ratios are as follows:-

r/R	θ	p/D
0.325	23.56°	0.445
0.4	19.01°	0.433
0.5	14.48°	0.406
0.6	10.94°	0.364
0.7	7.95°	0.307
0.8	5.19°	0.228
0.9	2.51°	0.124
1.0	0.03°	0.002

The above p/D values, together with those for some other pitch angle changes, are plotted in Figure 7.

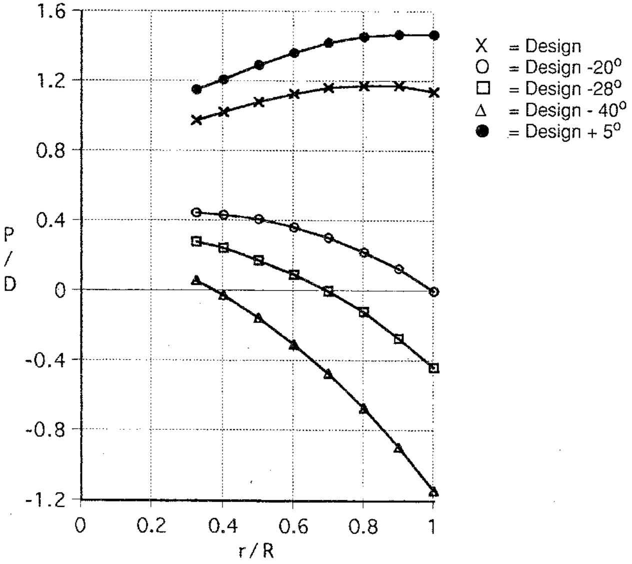

Figure 7. Radial pitch distribution at different pitch settings

It is seen that the changes in pitch/diameter ratio are much greater at the tip than at the root of the blade, and that the radial pitch distribution changes when the blade is turned from the design setting. Note that when the blade has been turned, in the direction of reducing pitch angle, through an angle equal to the design pitch angle at 0.7R, the inner part of the blade (r/R < 0.7) has positive (ahead) pitch and the outer part (r/R > 0.7) has negative pitch. With this blade setting, the inner part of the blade produces ahead thrust while the outer part produces astern thrust. Zero Thrust occurs when these ahead and astern thrusts cancel each other out.

Some applications of CP propellers require equal thrust in both directions. Lateral tunnel thrusters are the most common such application, although there are others such as some double ended ferries. Where equal thrust is required in each direction, plane blades are used. These have no pitch at the mid-stroke position and the blade sections are symmetrical about their nose-tail lines, that is the sections have no camber. When the blade is turned from the zero pitch angle setting, the whole blade has a pitch angle equal to the angle turned, therefore, the pitch at any section is proportional to the section radius. This gives equal performance in either direction, but the thrust developed is concentrated at the outer radii and the total thrust is less than would be obtained with a normal CP blade operating at the ahead design condition.

There is a further effect to be considered when CP propeller blades change pitch angle. The helical blade sections lie on the surfaces of coaxial cylinders. When a large pitch angle change takes place, the radius of any point of the blade which does not lie on the spindle axis changes. Therefore, the outline of the new developed cylindrical section at any given radius (r), is made up of points which were originally at other radial sections. See Figure 8.

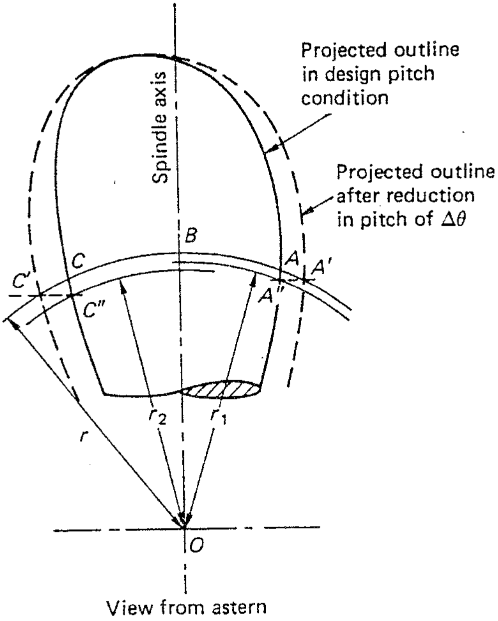

Figure 8. Geometric effects on blade section resulting from changes in pitch angle

The design section at radius r, when viewed from astern, is represented as the arc ABC. When the blade has been reduced in pitch angle the section at radius r is represented by A'BC'. Before the pitch angle reduction, point A' was at point A", that is it was part of the blade section at the smaller radius r_1. Similarly, the point C' was at point C" before the pitch reduction and was at radius r_2. Therefore, the new section at radius r, is made up from points which were originally on a range of sections having radii between r_2 and r. The consequence of this is that the constant radius, helical sections at the reduced pitch are distorted. The greater the change in pitch angle from the design, and the wider the blade section, the larger the distortion. Figure 9 shows an example of the section distortion occurring on a propeller blade used for a North Sea ferry.

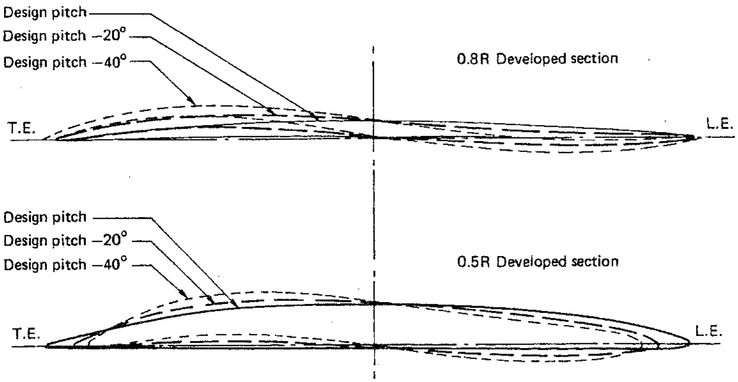

Figure 9. Section distortion due to changes in pitch angle

One consequence of this is that the definition of pitch angle given in Section 5.3 is only satisfactory at the design pitch setting. At other pitch settings the nose-tail pitch line is distorted together with the section shape, and cannot be sensibly used to define the pitch angle. To overcome this difficulty, the pitch angle at any setting other than the design pitch is defined as the design pitch angle at the radius under consideration plus the angle turned (taking the angle turned as negative for reductions in pitch). Therefore, the mean blade pitch angle, at any setting other than the design pitch, is given by:-

Mean blade pitch angle $= \theta_{0.7} + \phi$ where ϕ is the angle turned.

The pitch at 0.7R is then: $p_{0.7} = 0.7\pi D \tan(\theta_{0.7} + \phi)$

The zero pitch angle setting of the blade is defined as the position where:

$$\phi = -\theta_{0.7}$$

This zero pitch angle setting does not necessarily coincide with the setting where the propeller produces Zero Thrust under steady state conditions with the ship stationary. In practice, the term Zero Thrust is used to describe the condition where the net fore-and-aft force on the ship is zero when the ship is stationary in ideal environmental conditions, even though, due to the slight interaction between the propeller and the hull, the net zero fore-and-aft force is not strictly the same as the zero propeller thrust condition. Zero Thrust may occur at a low ahead or a low astern blade pitch angle depending on the design of the blade.

Note that under any other operating condition the propeller can momentarily produce zero thrust by selecting that pitch angle where the propeller is neither driving nor being driven. For example, when running at full ahead, a fairly small reduction in pitch angle will result in zero thrust until the vessel slows. A larger reduction in pitch angle under this condition results in the propeller producing a braking thrust.

Astern operation is a special condition where the big changes of pitch angle away from the design condition result in large changes in the radial pitch distribution, with very large astern (negative) pitches at the outer sections of the blades and where section distortions are significant. During stopping manoeuvres and astern running, further changes occur which affect the performance. The blade faces are reversed, that is the pressure face acts as the suction face and vice versa, and this means that the section camber is in the wrong direction. The angles of incidence, or angles of attack, are large and the consequence of all these factors is that efficiency is reduced and cavitation is well developed. This reduces torque and thrust at higher astern powers.

For FP propellers running astern the position is different. Not only do the pressure and suction faces change place giving reversed camber but, because of the change in direction of rotation, the leading and trailing edges are also reversed. The result is that during stopping manoeuvres heavy pulsating vibration occurs and the propeller may draw air from the surface. This can lead to very severe vibration. During continuous astern running, efficiency is lower than for ahead running, yet higher than a CP propeller running astern. Unlike a CP propeller, full power cannot be absorbed by an FP propeller during astern running.

5.5 Skew

A blade is said to be skewed if the mid-chord points of the different radial sections do not lie on the propeller reference line when viewed in the direction of the X-axis (see Figure 10).

The local skew angle of any section (θ_s) is the angle between the propeller reference line and a line passing through the shaft centre line and the mid-chord point of that section when looking along the shaft centre line (i.e. along the X-axis). The propeller skew angle (θ_{sp}) is the difference between the maximum and minimum section skew angles (θ_s), taking θ_s values on the trailing side of the propeller reference line to be positive, and those on the leading side to be negative (refer to Figure 10). Skewed CP propellers normally use a 'balanced skew' design, where the locus of the section mid-chord points first moves to the leading side of the propeller reference line, and then to the trailing side as the section radius increases. Figure 10 shows a balanced skew design. Many FP propellers have a 'biased skew' design, where the mid-chord points all lie on the trailing side of the propeller reference line.

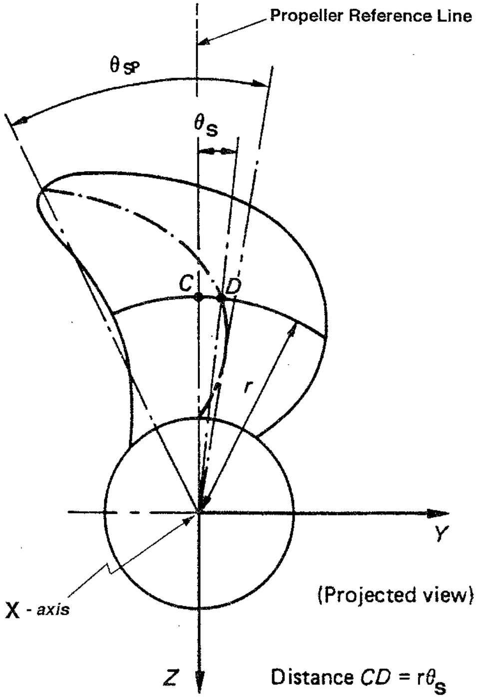

Figure 10. Definition of skew

Blades with a propeller skew angle (θ_{sp}) greater than 25° are generally considered to be high skew blades, although blade skew angles of well over half the angle between two blades (i.e. over 45° for a four-bladed propeller) are frequently used. Section 14.4 discusses the benefits of using high skew blades.

The accepted definition of skew, based on the mid-chord points of the radial sections, followed the practice for defining the skew of aircraft wings. It has no particular hydrodynamic significance for marine propellers, the sweep of the leading edge being of greater importance. (See Section 6.4.)

5.6 Rake

When the blade is inclined backwards or forwards in relation to the propeller reference line, it is said to have 'rake'. Aft rake is used to increase the tip to hull clearance. Forward rake is sometimes used on highly stressed FP propellers, as the resulting centrifugal bending moment partially offsets the bending moment due to the thrust. Aft rake is conventionally taken to be positive.

Although skew is measured as an angle in the YZ plane, it is produced by moving the blade sections helically in the direction of the nose-tail line. Figure 11 shows an unwrapping of two sections of a blade, namely the root section and a section at some larger radius (r).

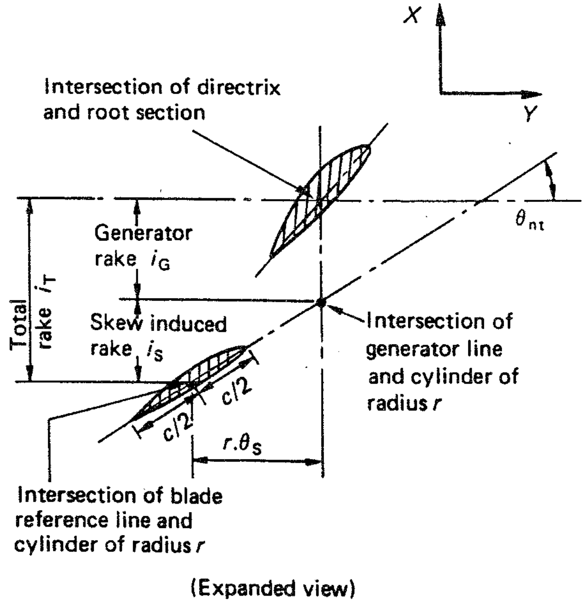

Figure 11. Definition of total rake

It can be seen that the introduction of skew also moves the mid-chord point in the X direction, producing a skew induced rake. The total rake at any radius r, is the arithmetic total of the generator line rake and the skew induced rake. The skew induced rake (i_S) is given by:- $i_s = r\theta_s \tan\theta_{nt}$

5.7 Blade Outlines and Areas

Propeller and CP blade drawings show different outlines of the blades, as shown in Figure 12.

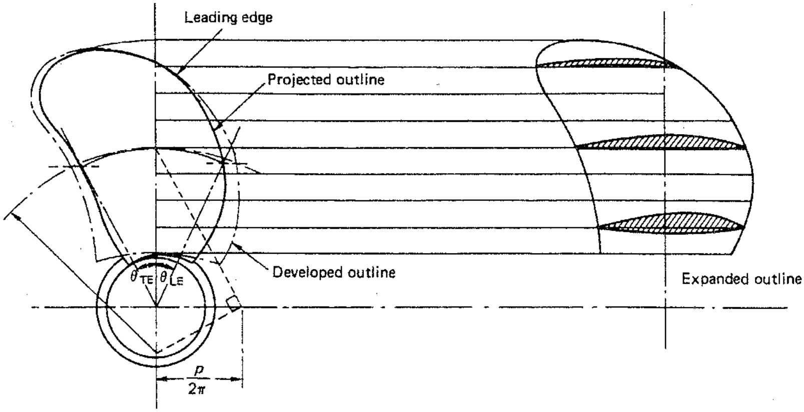

Figure 12. Outlines of blades

The blade 'projected outline' is the outline of the blade looking forward along the X-axis. The 'developed outline' is the outline the blade would have if all blade sections were rotated to have a zero pitch angle. The 'expanded outline' is obtained by plotting the chord lengths of a number of constant radial helical sections, say 10 or more, as straight lines with zero pitch at their correct distances from the shaft centre, and with the correct points of the chord lines lying on the propeller reference line. The 'swept outline' is also sometimes shown on drawings, and this is important as it can be used to show the clearance between the blades and stern aperture.

It is a convention that propeller blades are always shown on the blade drawings as 'right-hand'. A right-hand propeller, when viewed from astern, rotates in a clockwise direction while driving ahead. A note on the blade manufacturing drawing states whether a left or right-hand propeller blade is required.

The blade area of a propeller (A_D) is the total developed area of all the blades, however, it is easier to calculate the expanded area (A_E), which is usually quoted and used. The difference is too small to be significant.

The 'blade area ratio' is the total blade area divided by the area of the propeller disk (A_o). Thus:-

$$\text{Expanded blade area ratio} = \frac{A_E}{A_o} = \frac{4A_E}{\pi D^2}$$

6 Forces and Moments on Blades

While in service the CP propeller blade is subjected to a complex system of loadings. The most important loadings are as follows:-

Thrust	Torque	Centrifugal load	Spindle torque

To get a feel for the magnitude of these loadings, consider two examples of single screw vessels:-

	Tanker	Coastal Ro/Ro
Power bhp	17 000	5200
Ship speed (kN)	16.1	16.5
Rotational speed (rev/min)	90	194
Diameter (D) (m)	7.4	3.6
No. of blades	4	4
Thrust per blade (kN)	320	80
Torque per blade (kN/m)	325	45
C F per blade (kN)	1080	275
Max. spindle torque (kN/m)	195	28.5

The above are mean values at full ahead power except for the spindle torque, which is the projected maximum value during the most adverse manoeuvre.

6.1 *Thrust and Torque*

When the propeller rotates the water flow around the blade produces variations in pressure and friction on the blade surfaces. These pressure and friction forces can be resolved into their axial and peripheral components. The sums of these components are the thrust and torque forces. Because the blades are cantilevered out from their bearings in the hub, these forces produce bending moments. The propeller runs in a non uniform wake, therefore, flow conditions over the blades change as the propeller rotates. This results in changes in the pressure distribution on the blade surfaces causing variations in the thrust and torque loadings. These variations are significant, and in adverse single screw cases can cause cyclic variations in the loadings of 75 per cent, or more, of the mean values.

As stated in Section 5.3, for conventional blades the resultant thrust and torque forces on a blade act at a radius of approximately 0.7R. The resultant thrust and torque forces (T and F_Q respectively) on the propeller blade can be resolved into two forces, F_Y perpendicular to the major longitudinal bending axis of the section line, and F_X acting along this axis. Figure 13 shows the blade section axes.

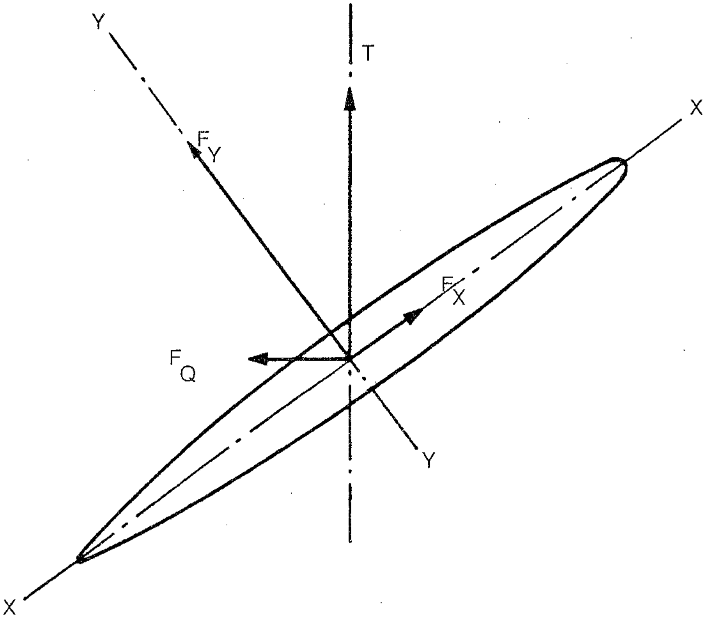

Figure 13. Thrust and torque forces on section

It is acceptable to treat the blade as a cantilever beam and to use the resultant force F_Y to calculate the stresses in conventional CP blades at 0.35R (or 0.4R for a hub/diameter ratio greater than 0.33R). The force F_X has a very small effect on the bending stresses in the blade sections and can usually be neglected. Remember the above is an approximate method. For highly skewed or highly stressed blades it is necessary to undertake a more rigorous treatment using a method such as a lifting surface calculation, to determine the load distribution on the blade in detail. This information can then be used to carry out a finite element stress analysis on the blade. Note that this is not practicable in conditions widely divergent from the design operating point.

6.2 Centrifugal Loading

Centrifugal loading depends on the mass and radius of the centre of gravity of the blade, and on the square of the rotational speed of the propeller. It does not vary as the blade passes through each revolution. As the centroids of the blade sections do not all lie on the blade spindle axis, centrifugal loads also produce a centrifugal bending moment. When designing the blades it is important to arrange the stacking of the blade sections so that the centrifugal bending moments at the blade bearing, and each section of the blade, are not too large.

6.3 Spindle Torque

Spindle torque attempts to twist the blade around its spindle axis. It has three components, namely, hydrodynamic spindle torque, centrifugal spindle torque and frictional torque.

Hydrodynamic spindle torque arises because the pressure distribution on the blade surfaces produces a resultant force which generally does not pass through the blade spindle axis. Its value depends on the blade design (including the skew, rake, blade area and positioning of the blade on its palm), the set pitch and the advance coefficient J (J is the inflow velocity to the propeller in metres/sec divided by the rotational speed in rev/sec and by the propeller diameter in metres). At the design ahead operating condition the hydrodynamic spindle torque is very small. With a reduction in ahead pitch this twisting moment increases in magnitude in the direction which tends to move the blade towards astern pitch. For steady state operating conditions the maximum hydrodynamic twisting moment occurs in the region of zero pitch, but remains high as the blades move towards full astern pitch. The maximum value of the hydrodynamic spindle torque is in the region of zero pitch, with $J = 1.0$. The condition where this occurs in practice will depend on the J value at the design ahead condition. If the J value at the full ahead condition is 1.0 or higher, then the highest hydrodynamic spindle torque will be achieved when, starting from steady full ahead operation, the pitch is rapidly reduced to zero while maintaining full shaft speed. If the J value at full ahead is considerably below 1.0, then the highest hydrodynamic spindle torque will be achieved when, starting from steady full ahead operation, the pitch is rapidly reduced to zero with a reduction in shaft speed. In either case, maximum hydrodynamic spindle torque occurs before the ship speed has appreciably reduced.

The centrifugal twisting moment can be understood by considering a small element of a blade, as shown in Figure 14.

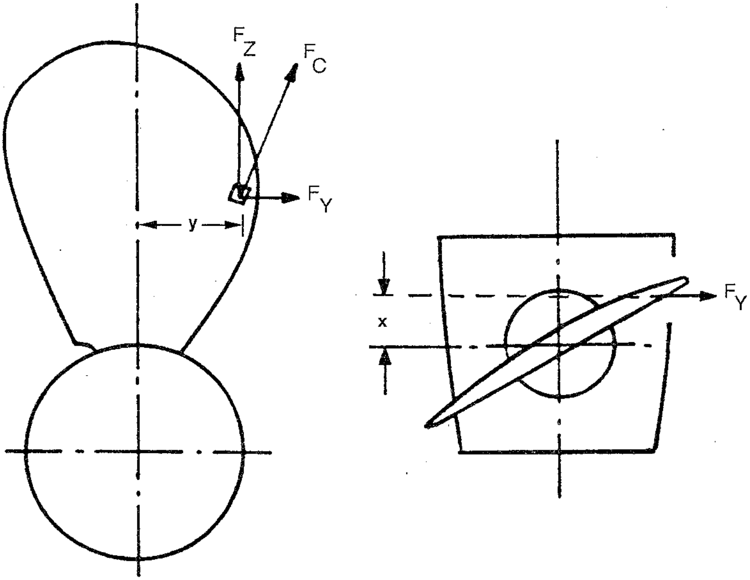

Figure 14. Centrifugal spindle torque

Due to the rotation of the propeller, the blade element is subjected to a centrifugal force (F_c) acting in the radial direction. This force (F_c) can be resolved into two components, F_Z and F_Y.

F_Y produces a twisting moment about the blade spindle axis of $F_Y x$ which is equal to:-

$$F_Y x = m\omega^2 xy$$

Where:

m = mass of the blade element
ω = angular speed (radians/sec)
x and y = the coordinates of the element

The centrifugal twisting moment for the whole blade is determined by integration. The direction of this moment is such that it tends to move the blade into the athwartship YZ plane. Its value is maximum at a pitch angle of 45°, decreasing to zero at 90°. Like the hydrodynamic twisting moment, the centrifugal twisting moment depends on the blade design, including the blade area, skew, rake and positioning of the blade on the palm.

The third element of the blade spindle torque is frictional torque. The blades are supported by bearings in the hub body and relative movement a negative rake. If spindle torques are not controlled the turning moments required to control the blades rise, forces in the hub mechanism increase, and the servomotor operating pressure or size has to increase. This is likely to result in a larger hub diameter and consequently an increase in size of the hydraulic system.

6.4 Skewed Blades

For non-skewed blades, or blades with little skew, the maximum principle stresses are in the radial direction. The highest stresses are near the root of the blade, away from the leading and trailing edges. Highly skewed blades have more complex stress distributions, with high stress areas in their outer sections in the vicinity of the trailing edges. The pattern of blade stresses depends on blade design and whether the skew is balanced or biased. For balanced skew designs, as used in CP propellers, high stresses occur near the trailing edge in the region of the smallest radius of curvature of the trailing edge profile. The stresses here are sensitive to the trailing edge curvature and can be lowered by reducing the concavity of the trailing edge. This can be achieved by increasing the chord lengths of the mid-blade sections, without significantly changing the profile of the leading edge, radial pitch or load distributions. This carries a penalty because it increases the blade area which reduces efficiency. Although increasing the chord lengths of the mid-blade sections reduces the total blade skew, as defined in Section 5.5, it does not effect the favourable qualities of these propellers (see Section 14.4) which are determined by the leading edge sweep together with the radial pitch and load distributions.

Because of the more complex nature of the stress distribution in highly skewed blades it is necessary to carry out a more rigorous blade loading and finite element stress analysis than for blades with only moderate skew.

Highly skewed FP propellers reverse their direction of rotation during manoeuvring and astern running. This, together with deflection of the blade tips which then occurs, results in high loadings in the outer sections of the blades which have to be strengthened to withstand them safely. As CP propellers do not reverse their rotation during astern operation, they can use thinner sections in the outer parts of the blades. This means that they can achieve satisfactory cavitation performance with shorter section chord lengths. The shorter chord lengths mean lower friction losses, which tends to offset the slightly lower efficiency of the CP propeller caused by its larger hub diameter.