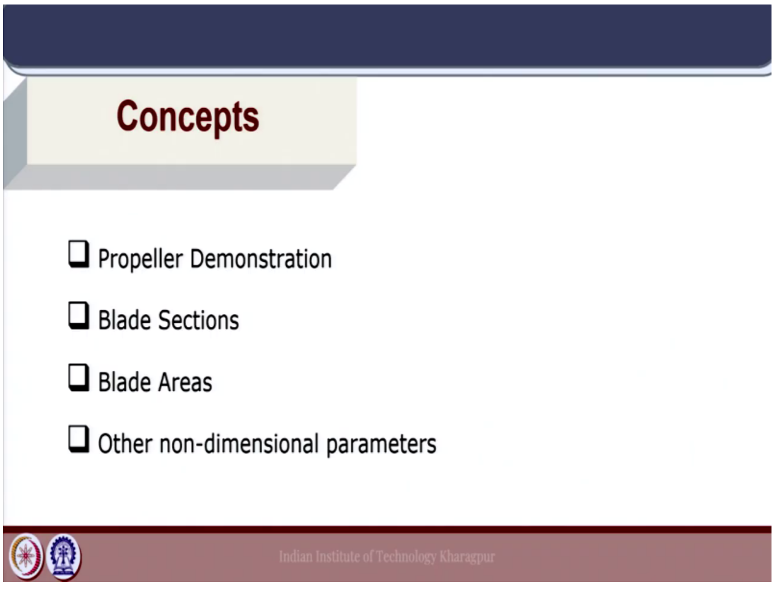
Marine Propulsion

Prof. Anirban Bhattacharyya
Department of Ocean Engineering and Naval Architecture
Indian Institute of Technology, Kharagpur

Lecture - 03
Propeller Geometry (continued)

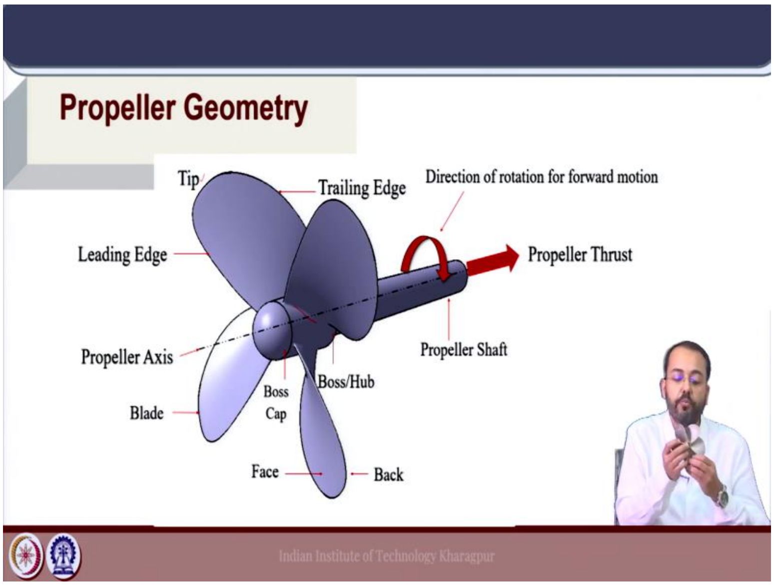
Welcome to the 3rd lecture on the Marine Propulsion course. Today we will continue with Propeller Geometry which was started in lecture 2.

(Refer Slide Time: 00:36)



So, the core concepts that will be covered in this particular lecture will include a demonstration of a model propeller, where we will show the different geometrical aspects of the propeller blade, followed by blade sections, blade areas, the ratios of different blade areas and some other non-dimensional parameters.

(Refer Slide Time: 01:00)



So, this was the propeller geometry that we have covered in the last lecture. The propeller blades are mounted on the boss or the hub and the blade had different parts which consisted of the tip, the root here at the place where it is attached to the hub and the leading and trailing edges.

And, the propeller shaft axis is connected to the hub and the propeller is rotating in a particular direction, in this case which is the clockwise direction and it is producing a thrust in the forward direction where we have the ship. So, now if we see a propeller, let us look into a model propeller.

(Refer Slide Time: 01:57)

This is a model propeller which we use for testing in the towing tank, where we test the propeller; open water characteristics as well as the behind hull performance to estimate ship powering. So, this model is made to a particular scale as per the requirement of the testing. Here we see that you have a central part which is the hub; on this hub the blades are mounted. In this particular case of the propeller, it is a 5 bladed propeller.

Now, if you see from the face of the propeller; so, basically if you stand behind the ship and also behind the propeller from the stern if you look at the propeller blade, the part of the blade which we see is the face of the propeller blade. So, seeing the face of the propeller blade we will be able to know the direction of the propeller rotation for producing forward thrust. In this particular case you see that the leading edge here that the leading edge which is supposed to be ahead of the trailing edge is pitched in this particular direction.

So, there is a angle to the leading edge which is provided that is called the pitch of the propeller blade which we have discussed in length in the last class and this pitch is related to the screw action of the propeller blade. So, this particular propeller blade if the path traced by a point here when it along is called the helical path and this pitch is the pitch of that helix of that particular blade section which defines the geometry of the blade.

So, in this particular case this blade is an anticlockwise rotating propeller blade; that means, it this particular design is a left-handed propeller design, because the propeller blade pitch is in designed in such a way that it produces forward thrust when it is rotated in the anticlockwise direction. Why? Again, why anticlockwise? This is very important to understand because the propeller leading edge, here the propeller leading edge should be leading the trailing edge right.

So, the leading edge should encounter the fluid first. So, that should meet the water first as it rotates that is why this is a left-handed propeller or an anticlockwise rotating propeller when it is producing forward thrust right. And, this is the blade tip; that means, the point on the blade which is farthest from the hub and we have the leading and trailing edges right. And, we have the root of the propeller blade here, the root of the propeller blade which is fitted on the hub.

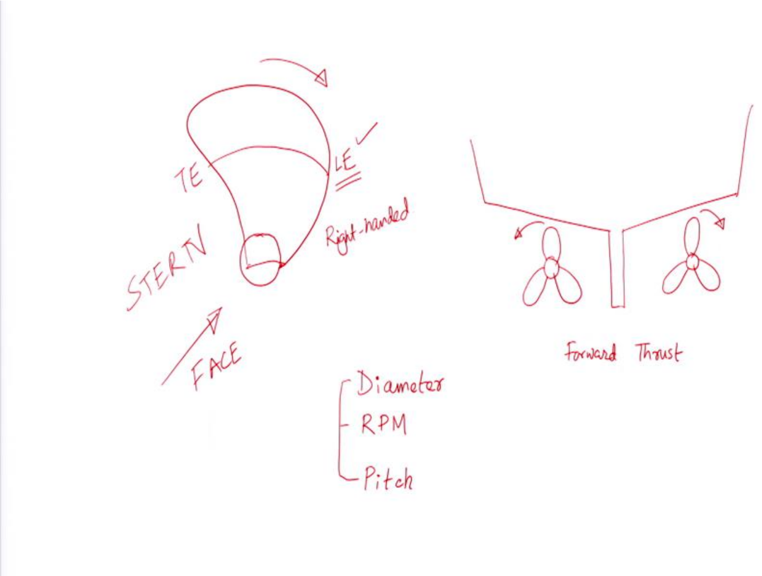
And, on the other side this is connected to the shaft line to the ship. So, on the side which is on the other part of the propeller on the other side. So, this will be the face of the propeller blade and this will be the back of the propeller blade where it is connected to the ship. So, this center of the hub if I look at the extreme center part of the propeller hub that is the shaft axis where the propeller shaft passes; so, the shaft axis will be the center at the center of the propeller boss or the hub.

So, this is a left-handed propeller, and if you see if I try to show you show the propeller from different angles you will see that the blades are very much overlapping with each other ok. So, the blade area is quite high and this is a very standard design which is used for propellers highly three-dimensional design for marine propellers. Now, if we take one more propeller, this is a propeller of very similar design to the first one.

But, this particular propeller if you see what is the main difference between these two propellers? The two propellers are pitched in the opposite directions right so; that means, the leading edge here is basically on the other side in this particular propeller. So, in this propeller the leading edge is on the other side as compared to this propeller.

So, this basically when it rotates in the clockwise direction, it will produce forward thrust as compared to this propeller, which will produce forward thrust in the anti-clockwise direction which is in my right hand. So, let us see that both of them together. So, in this particular case, one of them is rotating in the clockwise direction and one of them is rotating in the anti-clockwise direction and both propellers are producing forward thrust when it moves through water. Why? That is because of the pitch of the propeller blade which is defined in a specific direction ok.

(Refer Slide Time: 07:38)



The handedness of a propeller if we look at the propeller blade from the face so, this means the face of the propeller blade; that means, we are looking from the stern of the ship located at the stern of the ship or aft. So, a right-handed propeller will rotate in the clockwise direction and the blade will be pitched such that it will produce forward thrust while rotating in the clockwise direction.

So, this will be a right-handed propeller right and if I take a cylindrical section on the propeller blade at any particular radius, this part is the leading edge of the propeller blade and here will be the trailing edge of the propeller blade. Because, when it rotates in the clockwise direction then this particular edge will lead the other edge when it rotates in the clockwise direction.

Now, if we have a ship where multiple propellers are fitted, it is possible to have ships, which is very common in certain types of ships. For example, naval vessels where the requirement of thrust is quite high and it is also in many other kinds of vessels where due to thrust requirement we have multiple propellers.

In this particular case let us try to have a simple just very simplistic configuration of shift where we have twin screws; that means, two propellers. So, we have a propeller on the port side and this is a very simplistic drawing I am making of propeller blades and we have a propeller on the starboard side.

So, as we have seen in the two propellers that I have shown just now; so, the two propellers will rotate in the opposite directions. They are pitched in such a way that they will rotate in opposite directions to both of them will produce forward thrust to the ship. So, generally the convention is that they rotate in the outward directions. So, we see that for multiple screw case the general norm is the propellers rotate in the outward directions.

But, each of them will produce forward thrust; so, both of them will produce forward thrust right. The same way as the example of the propeller models that I have shown, they are pitched just in the opposite directions. So, that when they rotate in the outward direction both of them, one of them in the clockwise and another in the anti-clockwise both of them will produce forward thrust to the vessel.

So, the three most important parameters if we see for in case of propellers, one of them is the diameter of the propeller ok, the second is the propeller RPM which is the rate of rotation of the propeller and the third is the pitch of the propeller blade. There are other geometrical aspects, which are also very important, but these are the three most important parameters for the hydrodynamic performance of a marine propeller.

Now, the pitch of a propeller blade is basically coming from the pitch of the screw of which the blade is a part of the helicoidal surface which defines the propeller blade. Now, the pitch gives the capacity of the power absorption by the propeller blade from the engine and also defines the thrust performance of the propeller blade.

Suppose, what would happen if we do not pitch the propeller blade at all? Suppose, if I have the propeller blade, but the blade is not at all pitched; that means, if I have the blades all the blades which are placed just facing the perpendicular to the line of the shaft.

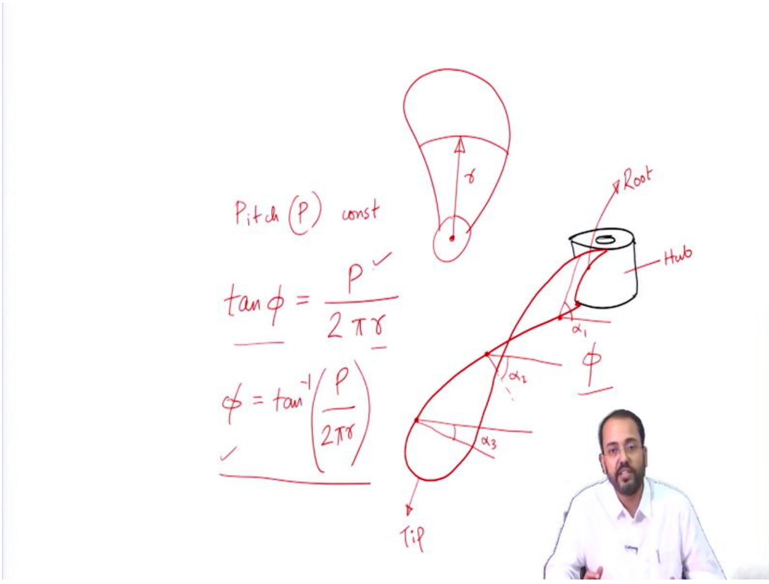
So, there is no pitch angle of the propeller blade. So, in this case what will happen? In this case if there is no pitch angle then the blades will not produce any forward thrust.

They will just produce a disturbance in the flow without producing any forward thrust ok. On the other side then one might think that it is good to have a very high pitch because it is the pitch of the propeller blade which is producing thrust ok.

But, that is also not good in terms of design because pitch if it is kept very high, the pitch of the propeller blade then it will try to absorb much more torque for a particular RPM and that will overload the engine of the ship and also the engine will not operate at its rated speed.

So, the performance of the engine will fall. So, we will try to understand these things in more details when we discuss about propeller design and engine propeller matching. So, as of now it is important to note that the pitch of the propeller blade is extremely important in its hydrodynamic performance ok.

(Refer Slide Time: 13:18)



And, another very important aspect here if we look at the propeller blade, the blade is very much twisted right. So, and the base is fitted here. So, this is the tip of the propeller blade, this is only a single propeller blade which is shown here and this part is the root of the propeller blade and here we have the hub or the boss over which the propeller blade is fixed. Now, if we take an angle at the root section of the propeller blade right and I take another angle here.

So, let us say this is α_1, I am just naming it any particular angle here α_2, and α_3. What do we see here? As the propeller blade is twisted, the angle of the blade varies along the radius. So, we have taken the angles at three different positions, three different radial positions. So, the point alpha the angle α_1 is taken at a radial position which is close to the hub, α_2 is slightly away and α_3 is close to the angle at the close to the tip of the propeller blade.

Now, we have discussed about the variation of pitch with radius we can have propeller blades where pitch is constant, pitch P is constant or we can have another case where the propeller blade pitch is varying with radius.

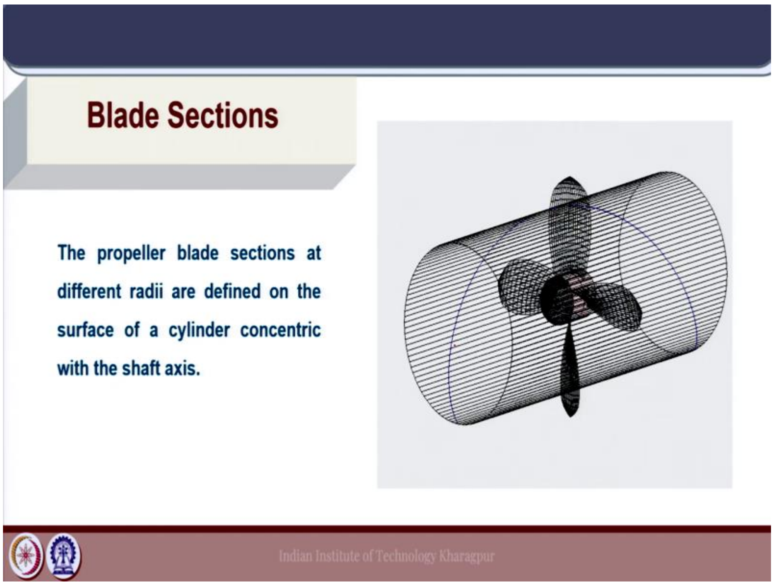
Let us assume for this particular propeller blade where the pitch is constant; that means, all the helix surfaces. So, if I intersect the propeller blade with cylinders of different radii; so, it will intersect at different radial positions and all of them will have the same pitch. So, they can be defined by the same helix ok. In that case, even if the pitch is constant we have seen that the $\tan(\phi)$ the angle of the propeller blade the pitch angle that it forms is $(P/2\pi r)$, where r is the radius of the propeller blade at which we are considering the angle.

So, if I have a propeller blade, r is basically any variable radius right that I am taking for the calculation of the pitch angle. So, even if P is constant, the ϕ the blade angle here will vary depending on the radius and you can see that depending on the radius if I have a lower radius; so, (ϕ) is $\tan^{-1}(P/2\pi r)$. So, what will happen here? At lower values of radius if r is low; that means, closer to the hub the angle phi will be much higher, the blade angle here which is shown.

And, gradually as it increases as I increase the radius from the hub to the tip, the blade angle will increase. So, even if the pitch is constant even if the pitch P is constant, the pitch angle will vary because it is defined with respect to the radius of the propeller. Normally, it is mentioned in terms of the angle ϕ.

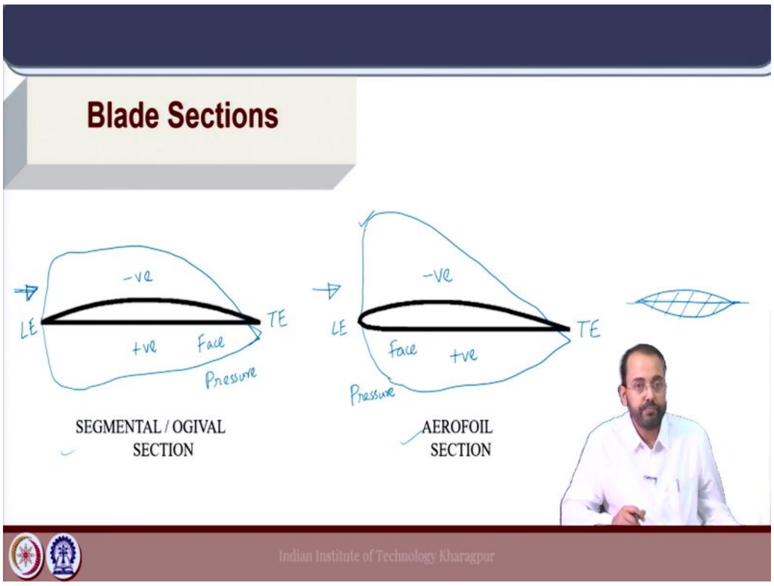
So, here I have just mentioned it as α, but anyway the concept is more important here; that means, the pitch angle of the propeller blade will vary according to radius(r), even if the pitch distribution is constant for the propeller blade. And, also we can have as I said a propeller blade where the pitch distribution is also varying. So, the pitch itself is also varying with radius. So, that can be adopted for specific propeller designs depending on the inflow characteristics which are required for the design.

(Refer Slide Time: 17:33)



So, next it is important to note what are the types of blade sections which are used for propeller blades. So, a blade section is defined by intersecting a propeller blade with a coaxial cylinder. So, if I take a cylinder and intersect the propeller surface at any radius, the section that I get is basically the blade section at that particular radius.

(Refer Slide Time: 18:02)



So, the typical sections which are used for propeller blades are segmental sections and aerofoil sections ok. So, segmental sections are also sometimes were previously called ogival sections. So, these sections are very simplistic designs. They have a flat surface ok and on the other surface the section is basically a round or a parabolic surface ok. So, here the it has a flat face and on the back it is a round or a parabolic surface.

If we look at the segmental section, the inflow velocity which is coming in this direction; what will be the pressure distribution over the two surfaces? So, we have the face which is basically a flat surface which is the pressure side here and on the other side we have the back which is a circular or a parabolic surface. So, on the leading edge we will have a slightly higher value of pressure which will increase and then it can come to a particular value near the trailing edge. And, also here at the back we will have some sort of a pressure distribution like this ok.

Now, if we look at the airfoil section again with a flow from this side because, this is the leading edge here also I should write it here leading edge and trailing edge, basically that defines how the flow will be on a particular section. And, airfoil section because of its design we will have a leading edge pressure peak ok and on the trailing edge it will fall to a lower value of pressure and on the pressure side it will have a consistent pressure, which will come like this.

These may not be the exact contours for pressure of this section, but that gives an idea of the pressure distribution that will appear on this particular sections. So, now, what will happen here we have the positive pressure and the negative pressure if I write negative, positive means we have the pressure side here. This is the pressure side the face or the pressure side, also this is the face pressure side.

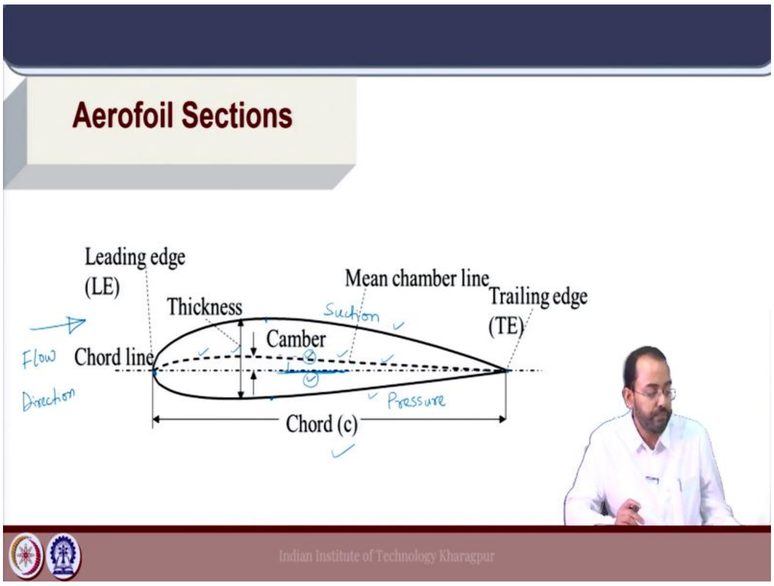
Now, these segmental sections have been very widely used for propeller designs for a long time. But with the development of different airfoil designs, these aerofoil designs have a consistent suction peak. So, this is the suction peak near the leading edge which contributes to the thrust because of the high pressure difference at the leading edge between the two sides and that is why aerofoil sections are used for different sections of a propeller blade now.

So, at the radii values which are close to the tip, there this suction pressure high suction pressure can lead to problems like cavitation and that is why in certain propeller designs a combination of these section types are also used for definition of a propeller blade. So, a propeller blade can have similar type of section and also depending on the propeller design different sections can be defined with respect to different types of sections.

For example, a aerofoil sections at specific values of radius and also at particular radius segmental or ogival sections may also be used. Another type of section is very rarely used for propellers, but it is also sometimes adopted is a lenticular section which is basically having symmetry about the section center line; that means, this particular section is sometimes adopted for propellers which are supposed to produce similar, forward and Aston performance.

So, if a propeller is required to produce similar performance or good performance in both forward and Aston configurations; that means, both when the ship is moving forward as well as backing. So, these sort of symmetrical sections may be considered. And, if we go back to these sections segmental and aerofoil sections so, what will happen if when the ship is operated in the reverse direction; that means, the section will perform in a totally different configuration. So, the edges of the propeller blade will reverse because of the direction of rotation and the performance will be totally different ok.

(Refer Slide Time: 23:24)



Now, just a very brief understanding of the aerofoil section is required because these sections are very widely adopted for a range of propeller designs. So, for the aerofoil section it is typically explained with a set of parameters. So, if the flow is defined from left to right. So, if this is the flow direction, we have the leading edge which meets the flow as we have seen for the propeller blade that is how we define the direction of rotation of the propeller blade with respect to the leading edge right.

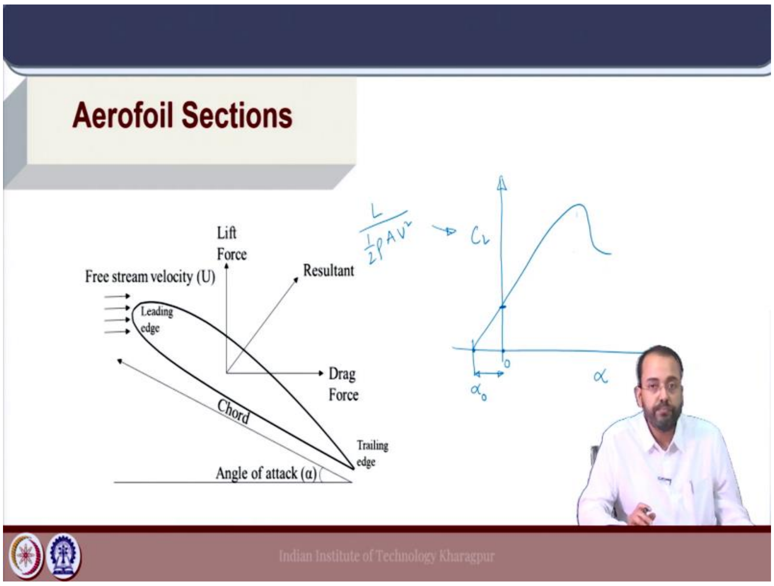
And, on the other side we have the trailing edge of the section. Now, the length of the section is defined by the chord and the line which joins the leading edge and the trailing edge is the chord line of the propeller blade another line here the dotted line, the line on the top which basically joins the center or the midpoint between the top and the bottom surface. So, here we have the pressure side and on top we have the suction side of the airfoil section.

So, between the two sides of the section the center line is shown which joins the basically midpoints between the two surfaces is the above dashed line and the below line is just the nose tail line which is connecting the leading to the trailing edge. And, this thickness is the maximum value of the thickness which is the distance between the two surfaces, the top and the bottom surface the maximum value here is the maximum thickness which is slightly away from the leading edge ok.

So, depending again on the airfoil section, it is may be around 25 percent distance again it depends on the section away from the leading edge. And, the camber if this particular section if the top surface here, if the top surface and the bottom surface if they are symmetric about the chord line, this one, about this line then the section will have no camber, then this dashed line will collapse with this line.

So, both these lines will be the same. So, this line and this line will be the same ok, if the top and the bottom surfaces were symmetrical. But, this particular section is a very typical asymmetric aerofoil section where there is a camber; that means, the top surface and the bottom surface are not symmetrical about the baseline. So, this defines the performance of aerofoil sections, the hydrodynamic performance is defined by these geometrical parameters.

(Refer Slide Time: 26:33)

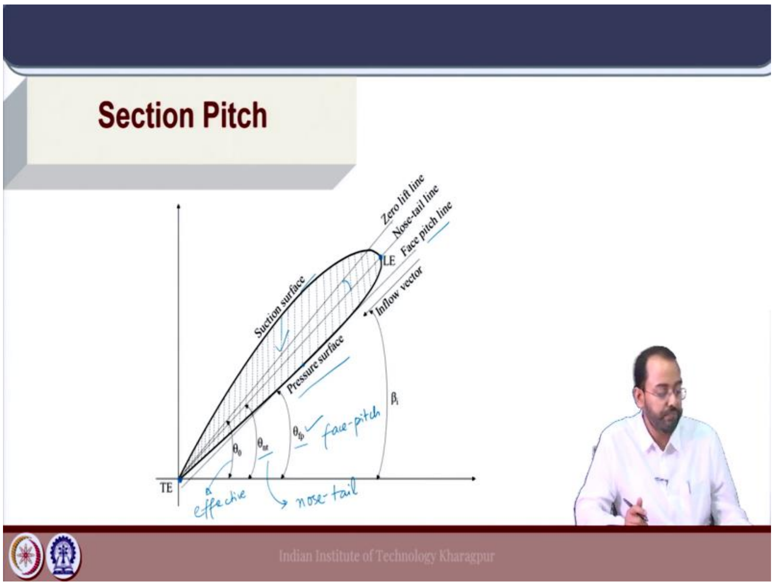


Now, what do we mean by the hydrodynamic performance? A a propeller blade if I now look at this airfoil sections, if there is a flow and that flow is at an angle of attack to this section, the section will generate a lift, which is perpendicular to the direction of the free stream velocity. And, it will also have a drag which is in the direction of the flow.

So, now how is this lift related to the angle of attack? If we look at the lift coefficient C_L, if I divide this lift force (L) by $(0.5\rho AV^2)$, where A is the platform area. So, we get the lift coefficient here and plot it as a function of the angle of attack, we will see that it will be somewhat like this; that means, for a section which has a camber even at 0 angle of attack ok, there will be a small value of lift. And, it will in the lift coefficient will increase and then up to certain value of angle of attack and then it will finally, stall where separation will occur on the surface.

And, these things we will cover later when we discuss about the lifting line theories. So, the idea is the lift is 0 here at a small value of angle of attack ok. So, this is called the 0 lift angle(α_0); that means, at a negative value of angle of attack the lift is 0, because the section has a camber. So, even if there is no angle of attack to the propeller blade section, if I consider this section for a propeller blade it will produce a lift.

(Refer Slide Time: 28:37)



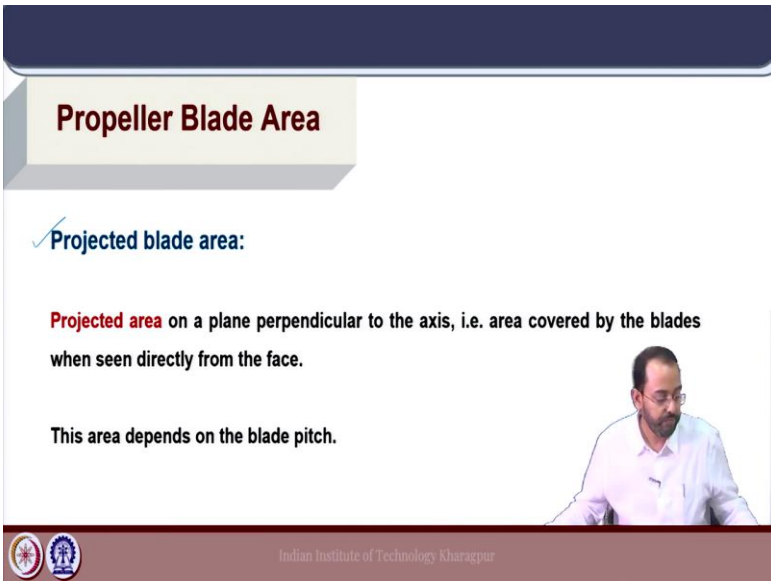
So, now if we look on the section of a propeller blade and the different pitch angles because the pitch of the propeller blade, the angle of the propeller blade can be defined with respect to these concepts; that is why understanding this 0 lift angle is important. Because, now this is the propeller blade section, which is shown here ok, there is a pressure surface and suction surface as we have seen for the aerofoil section. And, if we draw a line and on the pressure surface that will define the face pitch line.

The nose tail line is basically the line joining the leading edge and the trailing edge of the section which is basically the chord line which we have seen for the section. And, on the other side of the nose tail line ok, we will have the zero lift line. Why? Because, the propeller blade section produces 0 lift at a negative value of angle of attack, if it is defined by a cambered a aerofoil section. So that means, we can define the propeller blade pitch angle using all these angles.

For example, θ_{fp} this is the face pitch angle, face pitch. Why? Because, this angle with respect to the horizontal is with the face pitch line, the next one θ_{nt} is the theta nose tail line ok. So, it will define the pitch with respect to the nose tail line and the third angle will be the effective one(θ_0).

So, this is the effective or in different way it can also be called the hydrodynamic pitch of the section which basically, this pitch for this particular section will be defined on with respect to the zero lift line. That means, if I have a flow aligned with the zero lift line of that particular section, that section of the propeller blade will not generate any lift because that is the definition of the no lift angle.

(Refer Slide Time: 30:51)



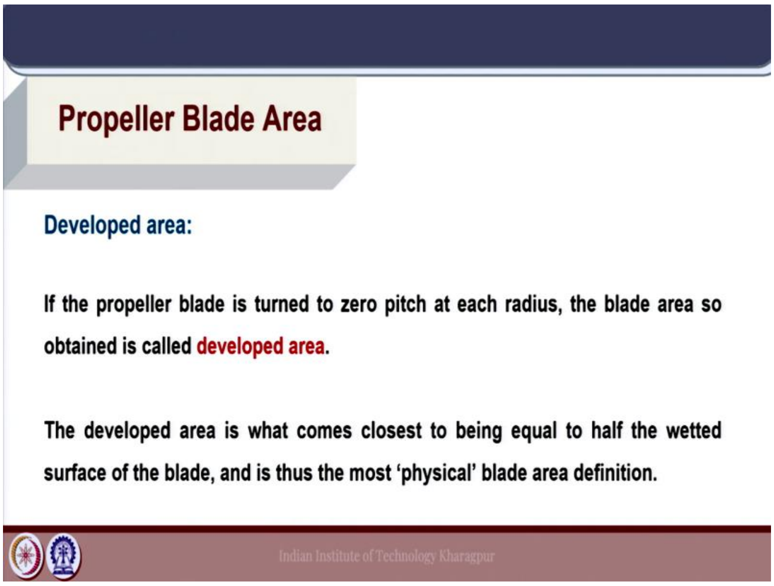
The next important concept to understand is propeller blade area, because propeller blade area defines the area of the propeller blade in different ways and that is an important design parameter which also governs the hydrodynamic performance of the propeller blade.

Now, the first area that we will discuss is the projected blade area; that means, if we look at the propeller blade from the face; if we look at the propeller blade standing behind at the face of the propeller whatever we see here, whatever meets our eye is basically the projected blade area ok.

Now that means, the projected blade area will depend on the pitch of the propeller blade. For example, if this propeller blade, if the blades would have a different pitch angle then the projection on the plane in which we are seeing the propeller blade would have been different.

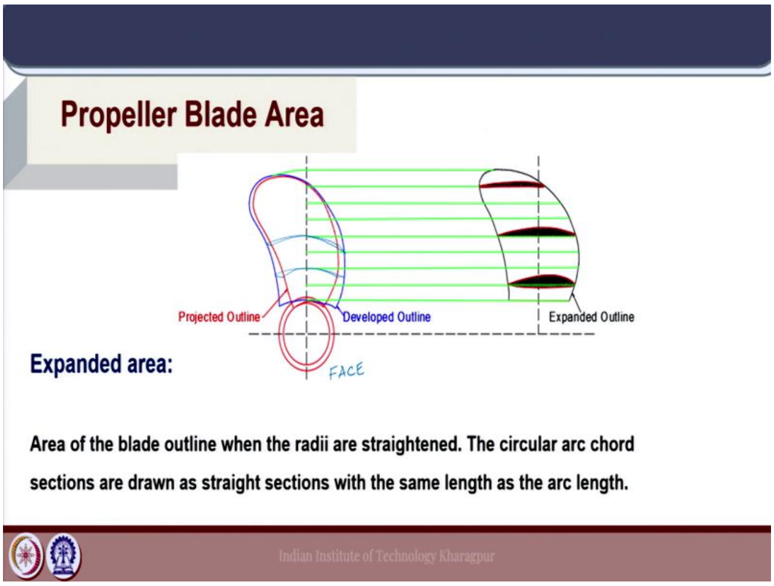
So, if the angles had a higher pitch, if the pitch angle was higher for each of these blades, the projected area would have been lower or if I reduce the pitch I will have a larger projected area. So, that is basically the projected area which depends on the pitch of the propeller blade and as we see from the face of the propeller blade the area which is visible is the projected area.

(Refer Slide Time: 32:17)



Next is the developed area. If at each section the pitch of the propeller blade is turned to zero at each radial section whatever we get is the developed area. So, the developed area is very close to half the wetted surface area and that is a very physical blade area definition, because we have turned the pitch at each section to zero and then we calculate the area of the total propeller depending on the number of blades. So, the total area we have will be the developed area.

(Refer Slide Time: 32:50)



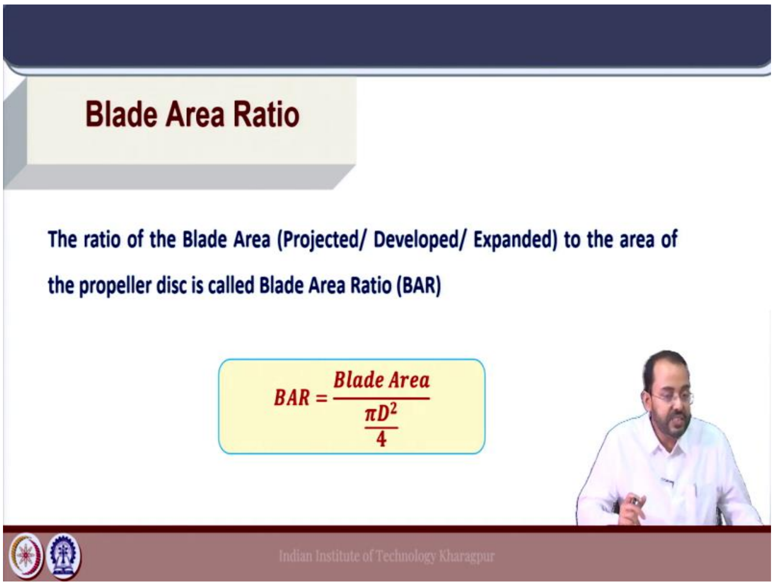
And, the third area is the expanded blade area which we get by straightening the radius. So, let us look at them one by one. If we have the propeller blade and we look at it from the face. So, I am looking at the propeller blade from the face just as I have shown you the propeller. So, the red line that we have here, the red outline is basically the projected outline.

So, whatever we see here on the red line is the projected area of the propeller blade. Now, if we turn the propeller blade at every radius; so, at all these different radii if I turn this to 0 pitch, if I turn all the different propeller blade radii to 0 pitch right, whatever area we get will be the developed outline as per definition.

So, from the developed outline of the propeller blade we can calculate the developed area. Now, what is the expanded area? When all the radii are straightened; that means, these values if I straighten the radius and plot at each radial location, if I plot all the sections. Now, remember these are still cylindrical sections, these propeller blade sections are defined by intersections with a cylinder right. But, in the expanded area concept what we are doing?

We are straightening all these radii which at this radius all these radial sections which were cylindrical sections which are we are expanding it and straightening them. So, the expanded outline which we get after straightening gives us the value of the expanded area. So, this is the expanded outline which gives us the expanded area.

(Refer Slide Time: 34:52)



Now, what is blade area ratio for a propeller? Any of these areas whether it is the projected or developed or expanded area when we divide that with respect to the area of the propeller disc which is ($\pi D^2/4$), which is the area depending on the propeller diameter, which is just the area of the propeller disc, area of the circle taking the diameter of the propeller; we will get a non-dimensional quantity which we call the Blade Area Ratio: BAR. And, this blade area ratio is very important parameter which defines a particular propeller blade with respect to its performance.

(Refer Slide Time: 35:33)

Now, similar to this we have other non-dimensional ratios which by which we divide the parameters of a propeller with standard quantities to get these non-dimensional parameters. Why? Because, in ship model testing we see that both for ships and propellers we have to experiment and get the performance in a different scale. So, to do a scaling study and to assess the hydrodynamic performance, we need to understand its characteristics based on certain non-dimensional ratios ok.

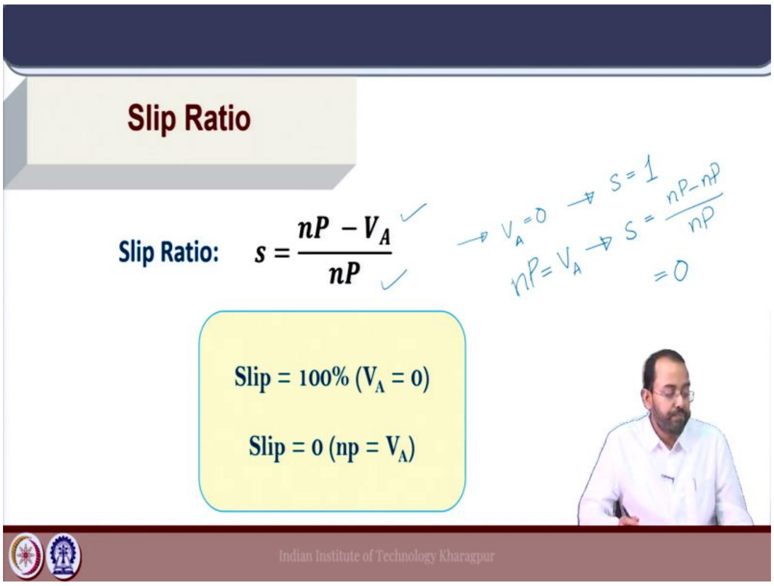
So, that is why we divide these geometrical characteristics using some standard parameters and get the ratios. For example, the simplest one is the pitch ratio which we have already defined the pitch by diameter(P/D). So, next, we have the blade area ratio and when we talk about blade area ratio, the most common way of expression is the expanded blade area ratio; that means, (A_E/A_0) naught, where A_0 is the area of the propeller disc ($\pi D^2/4$).

Next we have another concept of blade thickness fraction. If I take a propeller blade at different radii, the blade will also have a thickness. Now, this thickness value is very less as compared to the other dimensions. Now, this thickness value when it is extrapolated and we take it up to the propeller shaft axis, that value is t_o; the maximum blade thickness and divided by D gives the blade thickness fraction (t_o/D). So, a blade thickness fraction normally the value is close to around 0.04, 0.06 in that range blade thickness fraction.

And, another important parameter is the boss diameter ratio because the propeller has a boss on which the blades are attached and the diameter of the propeller boss defined divided by the diameter of the propeller blade is called the boss diameter ratio. That means, we have the propeller boss this one, this the diameter of the propeller boss divided by the total diameter of the propeller which will give the propeller boss diameter ratio(d/D).

So, these non-dimensional ratios give us a good representation of the propeller geometry and keeping in mind these parameters a blade geometry can be replicated in the model scale like this one which we have already seen, the model propeller blade and we can do hydrodynamic testing of this propeller blades.

(Refer Slide Time: 38:22)



So, next another important parameter for propeller blade is the slip ratio. Now, remember that when we talk about marine propellers, the its basis is a screw action; that is why it is called a screw propeller. And, that is defined by the pitch right because the propeller blades are helicoidal surfaces. Now, if the propeller blade was an actual screw instead of the propeller if it was a screw and it was if it was moving within a nut.

So, nut screw combination and if the medium was unyielding; that means, for one full rotation of the screw, it should have moved by a value distance which is equal to the pitch of the propeller or pitch of the screw. But, the propeller in one full rotation will not move ahead by an amount P. It will move ahead depending on the velocity, it will move ahead by an amount V_A which is the velocity of advance of the propeller blade.

And, as we go along we will understand that this V_A is related to the ship speed also and also depending on the flow characteristics. So that means, the propeller blade is slipping through the fluid because, if it was operating like a screw in an unyielding medium, it would have moved by an amount P in one rotation.

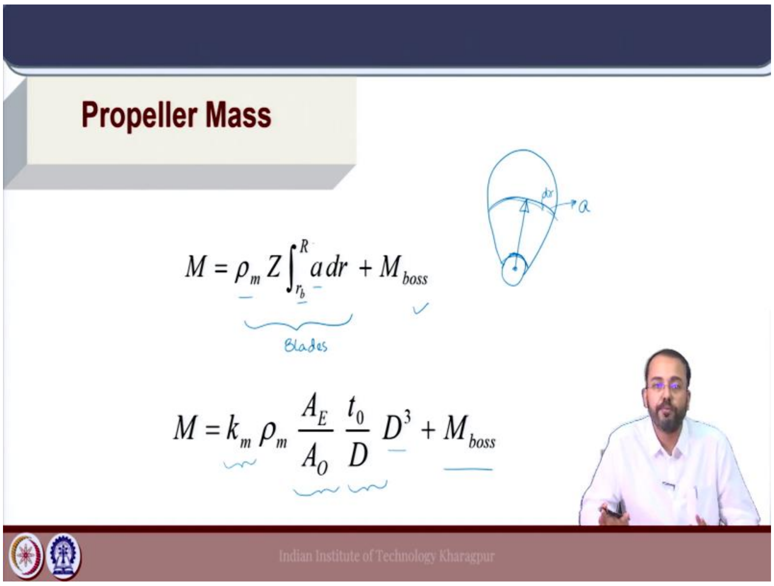
So, for n rotations it would have moved by an amount nP right per second if n is RPM, but if it is moving at V_A meter per second, it is actually moving a distance of V_A in 1 second forward. So, n P minus V A is the slip of the propeller blade and again we divide it by nP to convert it into a ratio which is called the slip ratio of the propeller blade.

So, if V_A is 0; so, suppose if there is no forward velocity, if the propeller is rotating without any forward velocity or the propeller is not moving ahead, it is just rotating at a particular location ok; then it is said to operate at 100 percent slip. That means, if V_A is 0 in this equation we will get V_A equal to 0 will give slip equal to 1; that means, 100 percent slip.

And, if the second case, the two extreme cases basically if nP equal to V_A right, then s will be ((nP - nP)/nP) will be 0; that means, the propeller is not slipping at all, it is purely behaving like a screw and advanced velocity is equal to nP, then the slip is 0. So, at 0 slip what happens?

If the pitch defining the propeller is the effective pitch of the propeller ok, then at 0 slip the propeller will not produce any thrust. If that means, if the propeller's advanced velocity is given by nP, where P is the effective pitch of the propeller blade; it will operate at 0 slip and the propeller blade will not produce any thrust ok.

(Refer Slide Time: 41:40)



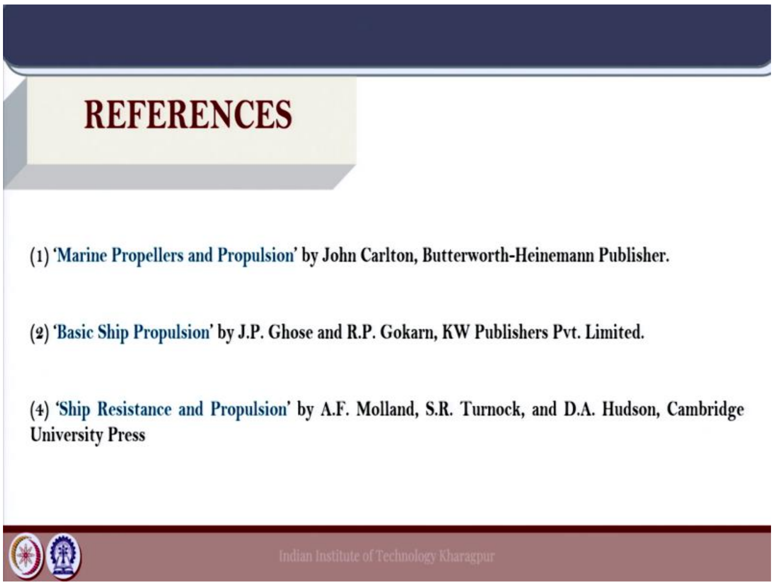
The last part here for the propeller blade the mass. When we want to manufacture a propeller a cost estimate is essential and the mass of a propeller blade is important to have an idea of the cost estimate. And, also mass moment of inertia these values are required for certain strength calculations for propeller blades.

So, the mass of the propeller blade is basically mass of the blades plus mass of the boss. Now, mass of the blades can be defined as an integration of the area of any section, this is a particular radial section of the propeller blade. If I take a propeller blade and take a radial section at a radius r if that section has an area a right and we take a small section over that of thickness dr ok. We integrate it right from the root to the tip that is why between r_b to R right. This we have explained before.

So, that will give the total volume of the propeller blade multiplied by the density of the material will give the mass of the propeller blade ok. Another way just to show the mass as a function of different non-dimensional parameters is that we can express this integration as a function of the blade area ratio and the thickness ratio. Because, the sections of the propeller blade will be functions dependent also on the blade area ratio and the maximum thickness fraction.

The thickness fraction (t_0/D) and (A_E/A_0) and A_0 is $(\pi D^2/4)$, and so, that is why it is multiplied by D^3. And, we have a factor k_m here which is a constant which is required because this A_E/A_0 denotes the entire propeller. So, for a particular propeller design if we relate the mass to these parameters, we will have a constant to define the propeller blade mass. And, on top of that we have the second part which is the mass from the propeller boss ok. So, this will be all for the propeller geometry part.

(Refer Slide Time: 44:06)



You can look into these reference for some more further studies on this topic.

Thank you.