Marine Propulsion

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Lecture - 13
Propeller Open Water Characteristics

Welcome to the 13th lecture of the course Marine Propulsion, today we will be discussing Propeller Open Water Characteristics.

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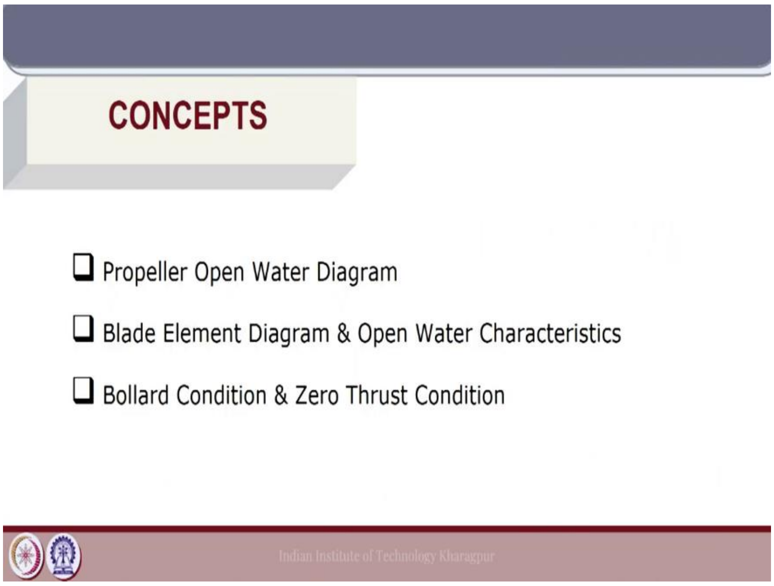

The key concepts covered in today's class, are propeller open water diagram. The relation between the open water characteristics and the blade element diagram that we have studied earlier and the bollard condition and zero thrust condition for a marine propeller.

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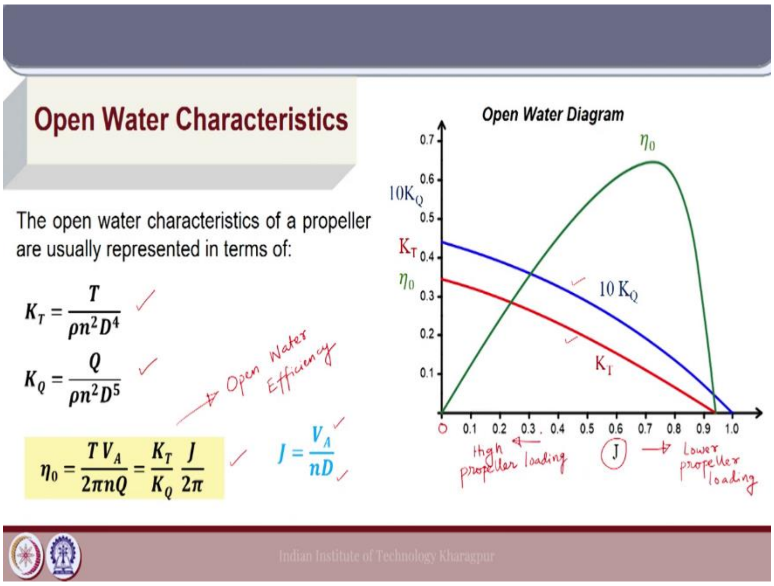

Now, let us look into the typical coefficients that we have discussed for a marine propeller. The open water characteristics are actually the plot of these coefficients for different operation conditions. So, the first one here we have the thrust coefficient K_T which is the thrust non-dimensionalized by ρ n^2 diameter to the power 4 as we have seen in the dimensional analysis and the second one is the torque coefficient K_Q.

So, the open water characteristics of a marine propeller basically consists of the variation of thrust and torque coefficients over an operation range of the propeller which is defined by the advance coefficient J. Which is the velocity of advance V_A/ n D when n is the rotational speed in RPS.

Now, what is the efficiency the open water efficiency of the propeller? Here, in open water we are considering that there is no ship in front of the propeller. So, it is the uniform velocity of advance that the propeller is facing and it is generating a thrust T absorbing a torque Q and we represent using non dimensional coefficients K_T and K_Q.

So, the open water efficiency in this condition will be thrust times the velocity of advance which is the output power divided by the input power (2 π n multiplied by Q). So, if we use these equations for K_T and K_Q, we will be getting this expression K_T/ K_Q × J/2π as the open water efficiency of the propeller; so, this is the open water efficiency.

Now, how will this plot look like? The open water diagram for a propeller, the relation between K_T, K_Q, η_O the open water efficiency with the advance coefficient J, this is what we call the open water diagram. We have K_T and 10 K_Q here plotted as a function of J the advance coefficient and η_O is the open water efficiency. Now, it is observed that the value of K_Q is much lower than K_T that is why to put into perspective in the same diagram $10K_Q$ is plotted instead of K_Q in the open water diagram this is the standard norm for marine propellers.

So, we see that this curve K_T and also $10K_Q$ they decrease with the increase of J. Now, what does increase of J imply? J is V_A/n D; so, as J increases either V_A can increase or n can decrease for a propeller of a specific diameter ok or both can happen. So, as J increases the thrust coefficient and torque coefficient decreases from a highest value at J equal to 0 here both these coefficients have the highest value and they gradually decrease at high J values.

Now, in terms of propeller loading high values of J corresponding to lower propeller loading and low values of J corresponding to high propeller loading. This is what will be explained with the help of blade element diagram ok.

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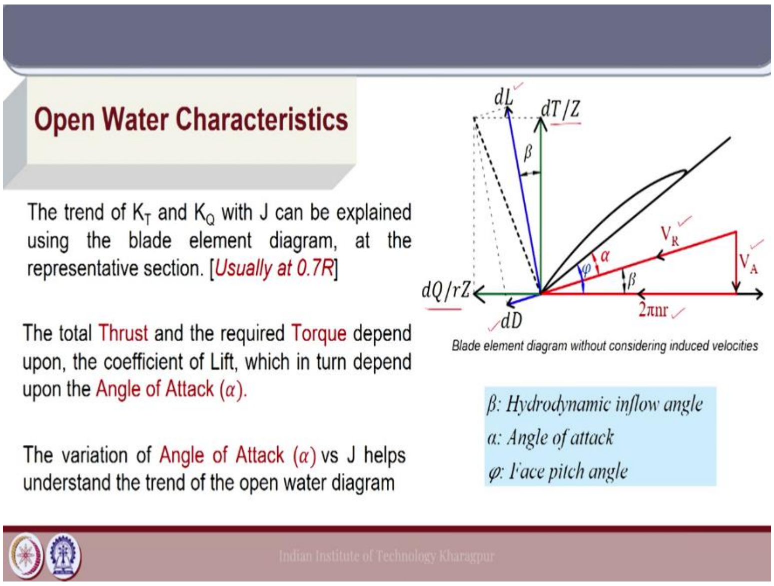

Let us explain this in the context of a representative section; so, the representative section was basically a characteristic section of the propeller blade typically at 0.7R where the characteristics of the section will be similar to that of the propeller. So, we will draw the blade element diagram at that section and try to explain the open water diagram of the propeller. How the thrust and torque behave with J with respect to the angles and forces that we get for the blade element diagram at the characteristic section.

Now, this is the blade element diagram at 0.7R, we have the inflow velocity V_A in the axial direction, the rotational component, the tangential value 2 π n r. The resultant V_R and the three angles that we have the hydrodynamic inflow angle, the phase pitch angle phi, and alpha which is the angle of attack nothing but ϕ - β.

Now, one thing you must understand that here we have not considered any induced velocity. Just to keep it simple the blade element diagram is shown without any induced velocity components that is why we have only V_A and 2 π n r. Now, on the force side we have the lift and drag force, the components of which gives the sectional thrust and torque right.

Now, the total thrust and torque of the propeller blade section depends on the coefficient of lift; and finally, the angle of attack of the particular section that is generated by this particular section. Now, just to explain the open water diagram we assume that we are drawing this blade element diagram for the characteristic or the representative section of the propeller blade ok.

Now, we will see how the angle of attack changes with J which is the advance coefficient of the propeller, because K_T and K_Q we have plotted as a function of J. So, in order to understand the characteristics of the propeller in open water, we need to understand how the angle of attack changes with J which is the advance coefficient of the propeller.

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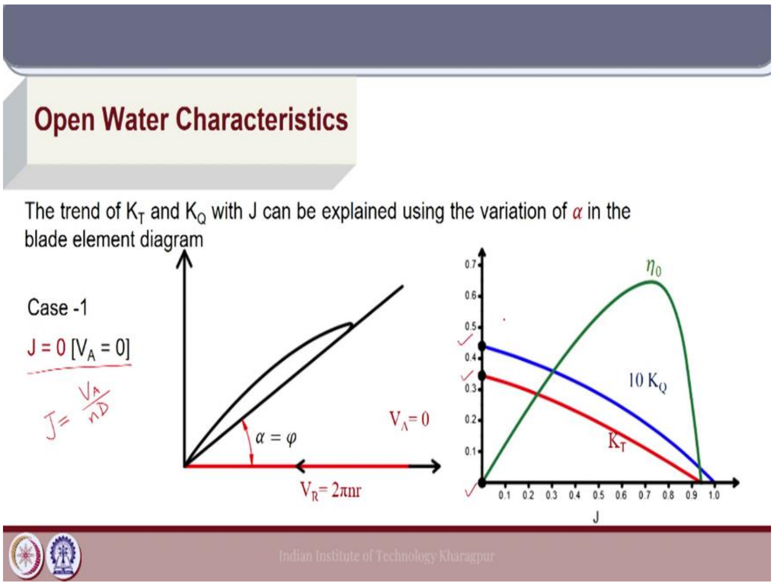

Now, let us take an extreme case of J = 0; now, J = V_A /n D. So, J equal to 0 implies that V_A will be 0; so, at that case what will be your blade element diagram like, there is no component in the axial direction. So, we have the resultant inclined at an angle ϕ which is the phase pitch angle; so, β is 0 here, because V_A is 0. Now, this corresponds to the point on the open water diagram where J is 0.

In this case we have the angle of attack which is maximum because β is 0 in this case. So, the section will produce the highest amount of lift as compared to other cases; hence, K_T and $10K_Q$ here in the open water diagram will have the highest values at J equal to 0 which is the case where the angle of attack is equal to the phase pitch angle of the blade section.

Now, let us try to advance towards the other conditions and gradually increase the value of J and see how the diagram changes both the blade element diagram as well as the point on the open water diagram.

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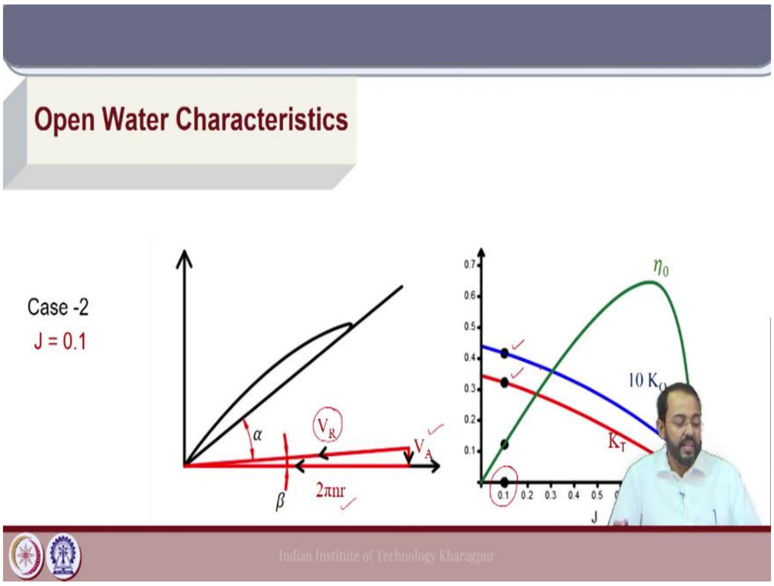

Now, case two if we take a value of J as 0.1 here on the open water diagram what happens. Now, again as I mentioned you can increase J in two ways, we do it here by increasing the velocity keeping the rotational speed n same right. So, we give a small forward velocity V_A; so, that J increases to 0.1. Now, my blade element diagram is shown on the left, we have a small velocity V_A apart from 2 π r n and we have the resultant velocity V_R which is inclined to the horizontal by a small angle β.

So, we have now α is reduced as compared to the previous value because of the value of V_A now which is the axial velocity in the flow. Because of the decrease of α as compared to case 1 what will happen, the sectional lift will decrease and which will result in a small decrease of the thrust as well as torque. Because, we have seen that both thrust and torque of the sections are related to the sectional lifts.

Drags also have a component; so, the lift and drag together will give the final sectional thrust and torque ok.

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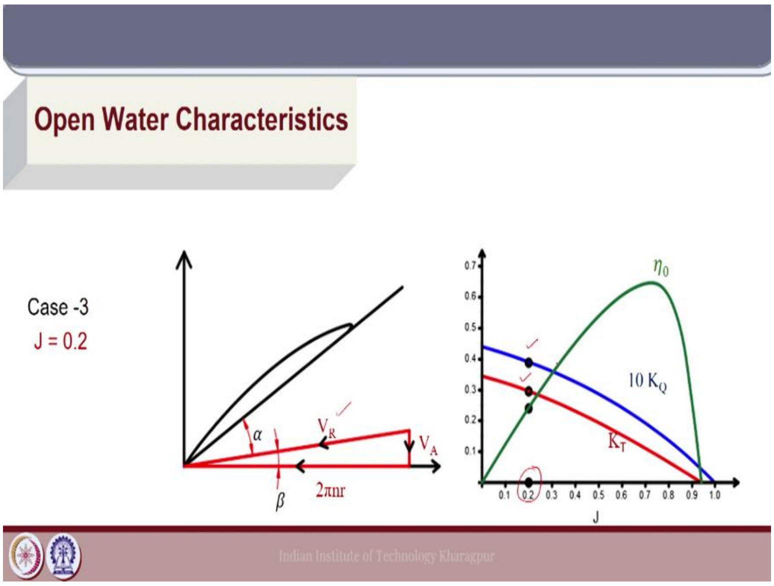

Now, in a similar way let us go to case 3 and increase J further by increasing V_A. So, we go to the next step and again increase the V_A such that J equal to 0.2 now and in the same blade element diagram what happens now V_R is inclined at a slightly higher angle which results in a smaller angle of attack alpha compared to case 2 ok. So, in the same way our K_T and K_Q will gradually reduce as we increase the value of V_A. Now, V_A increases keeping the RPM same means that J is increasing.

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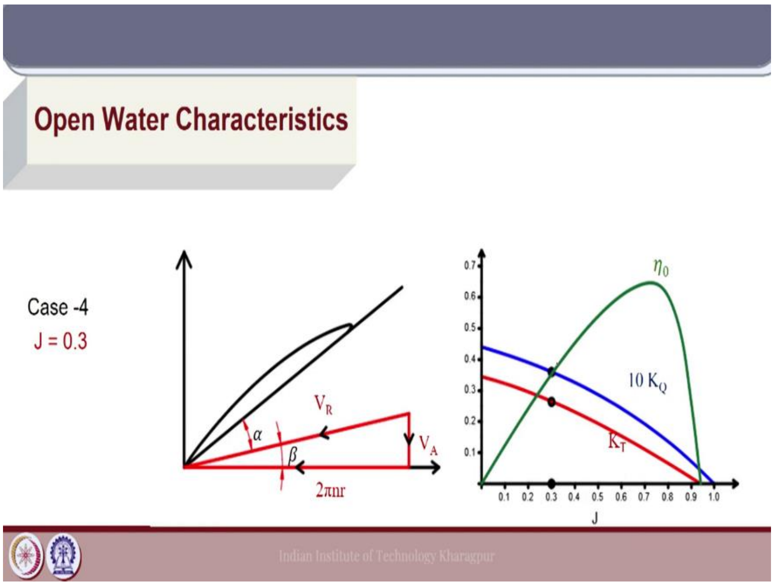

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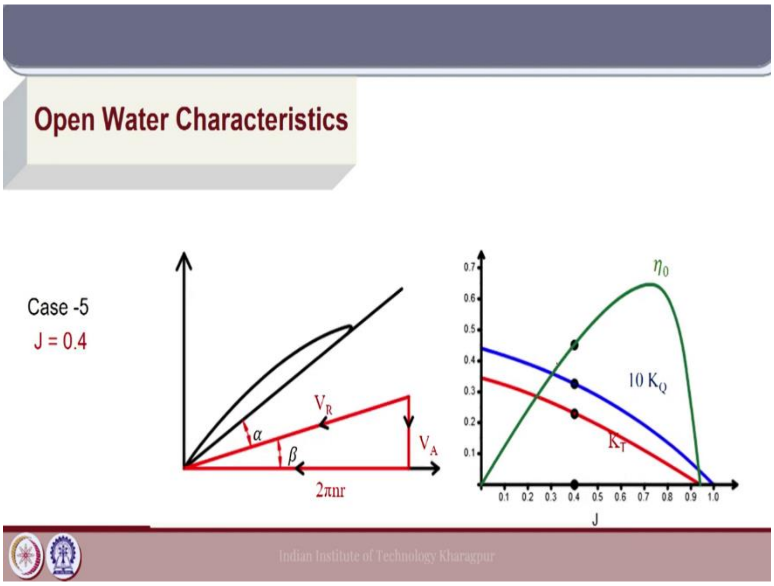

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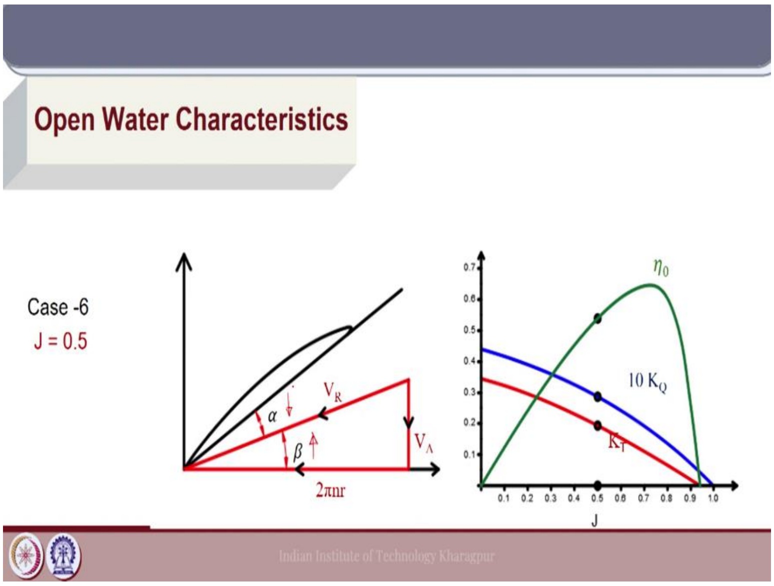

Similarly, if we go on like this from 0.3 to 0.4 we see that the angle β gradually increases. So, this angle β gradually increases which leads to the decrease of α; why? Because the phase pitch angle ϕ of a particular blade section here we assume it at 0.7R which is constant. So, if we gradually increase the J the angle of attack gradually decreases and the sectional thrust and torque will decrease.

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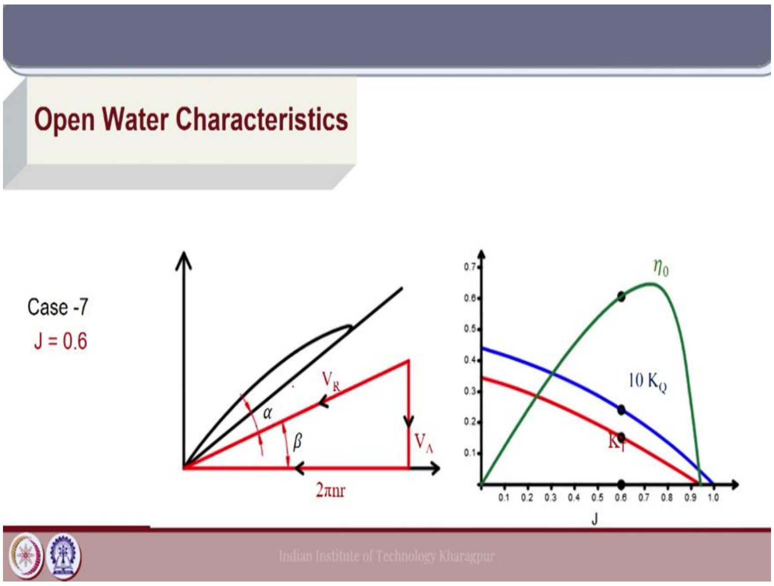

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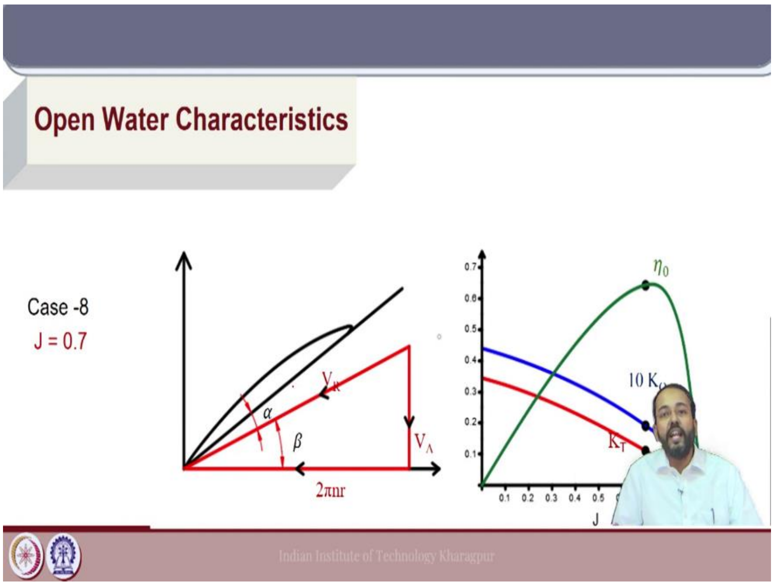

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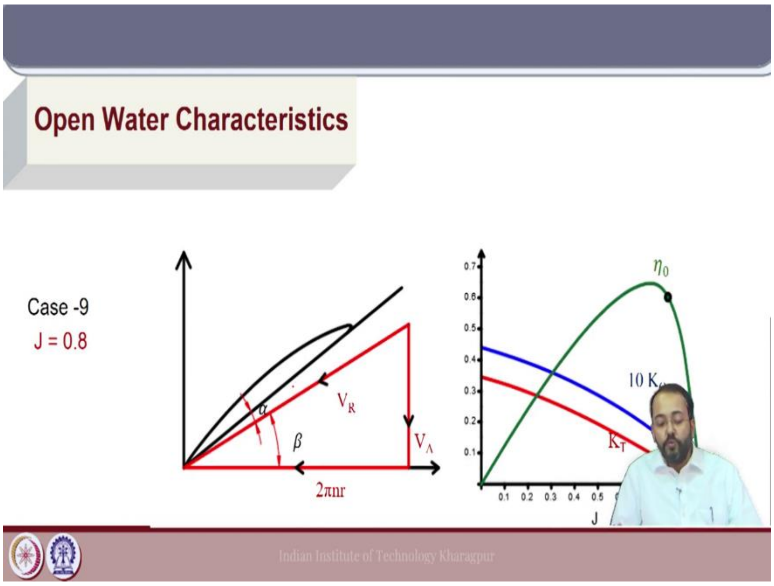

So, in this way if we go ahead to 0.7 and 0.8 the value of α decreases and KT and KQ will gradually decrease. So, this gives an idea of the relation between the open water diagram to the velocities of the blade element and the resultant forces. This is very important for understanding the propeller open water characteristics. Now, we will go to the extreme cases one by one.

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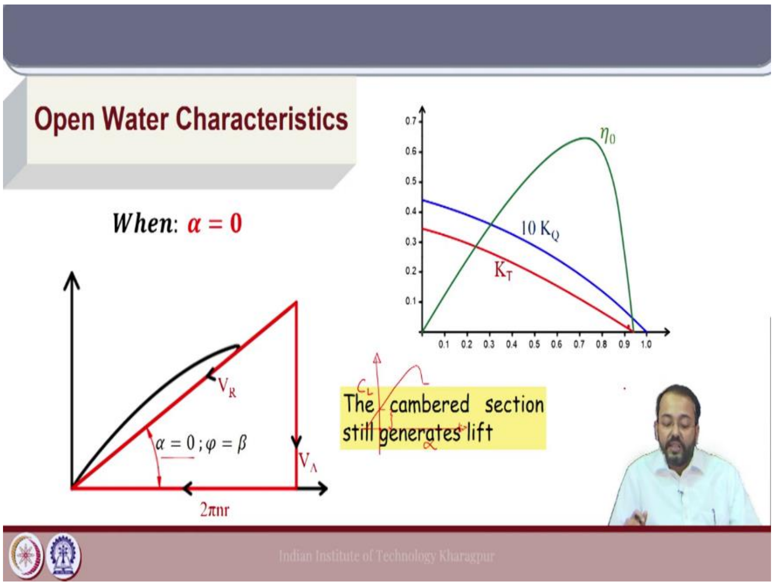

Let us take up the case where α is 0, if we increase V_A further such that the resultant V_R is inclined to the horizontal at an angle which is equal to the phase pitch angle; that means,

$\phi = \beta$. Then we have the angle of attack of that particular blade section the characteristic section that we have taken as 0. Now, what will happen to the open water diagram at this point, because α is 0, the section will produce a very small amount of lift, why? Because, typically these sections are cambered sections.

If this was a symmetric section, for symmetrical aerofoil sections that we have discussed at 0 angle of attack they do not produce any lift. But for cambered sections if you remember this lift coefficient with angle of attack for cambered sections even at 0 angle of attack it has a finite value of lift coefficient right.

So, the section still produces a small amount of lift even at 0 angle of attack. But there will also be drag and the resultant of lift and drag will be reflected in the final K_T, because the sectional thrust is a resultant of both lift and drag. So, let say if we neglect drag for now because of that small lift, K_T will have a very small value somewhere here. But it will still not be 0; so, this is what is mentioned here the cambered section will still generate lift.

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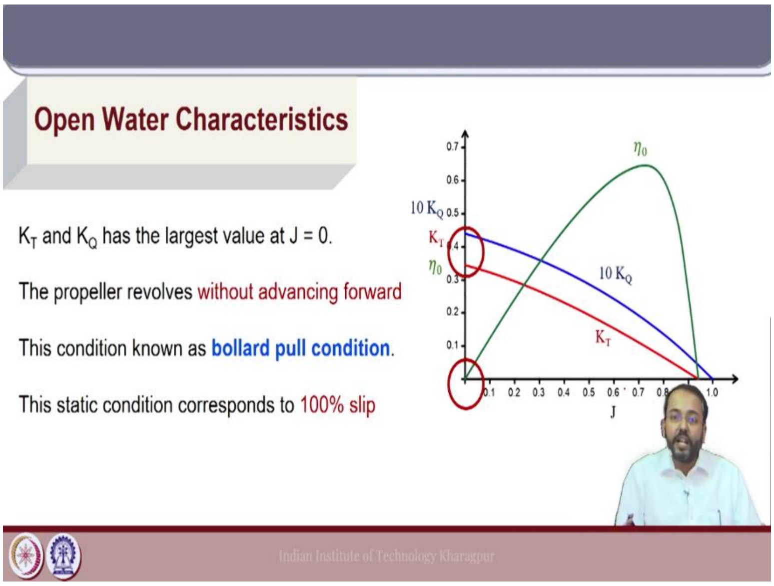

Now, let us go to the other case where J = 0; that means, the case where the propeller is only rotating without any forward velocity. In the open water case, there is no ship; so, we have considered that the propeller is rotating as well as the velocity of advance it is moving forward at V_A. In the open water case, the ship is not considered and the propeller is rotating and moving at a velocity of advance V_A.

What if we say that V $_A$ = 0? Which gives the condition J = 0? In naval architecture terminology we mention this as the bollard pool condition. For tugs which are used for towing duty, the bollard pool is very important where the tug or the boat is attached to a bollard which is on shored and the propeller is rotated at different RPM and the pull exerted on the tow dope is determined.

Now, in this process what is happening the ship is not moving forward, but the propeller is rotating. Because the propeller is rotating as we have seen in the blade element diagram, it has the highest angle of attack at J equal to 0; so, it will give a high value of thrust and also there will be a high value of torque. So, this condition where the propeller revolves without advancing forward is called the bollard pool condition or the static condition.

If we relate it to the slip that we have discussed in propeller geometry, this is the condition of 100 percent slip because the propeller is not moving forward and only rotating. So, this condition is the extreme case here for J equal to 0 where we have the highest value of K_T and KQ and by definition efficiency is 0, because efficiency is given by K_T/ K_Q × J /2 π ok. So, at in the bollard pool condition we have the highest K_T and K_Q.

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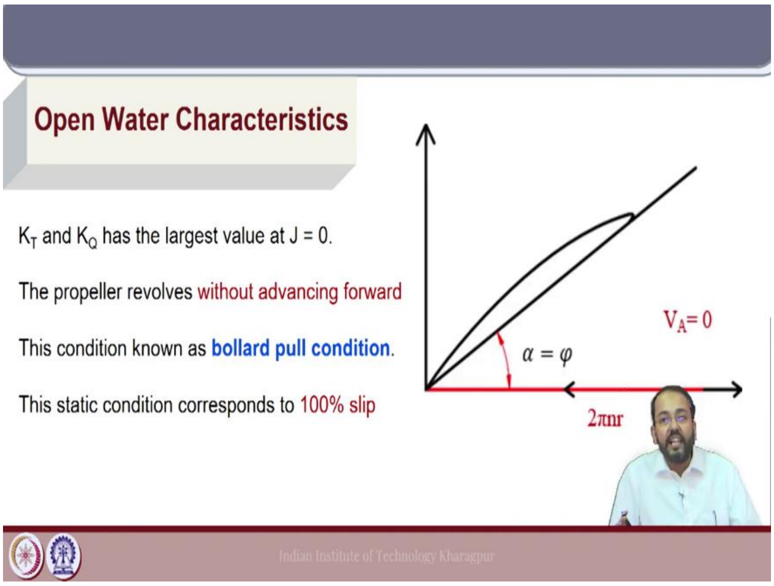

This is the blade element diagram we have already discussed where we have the highest value of angle of attack equal to the phase pitch angle.

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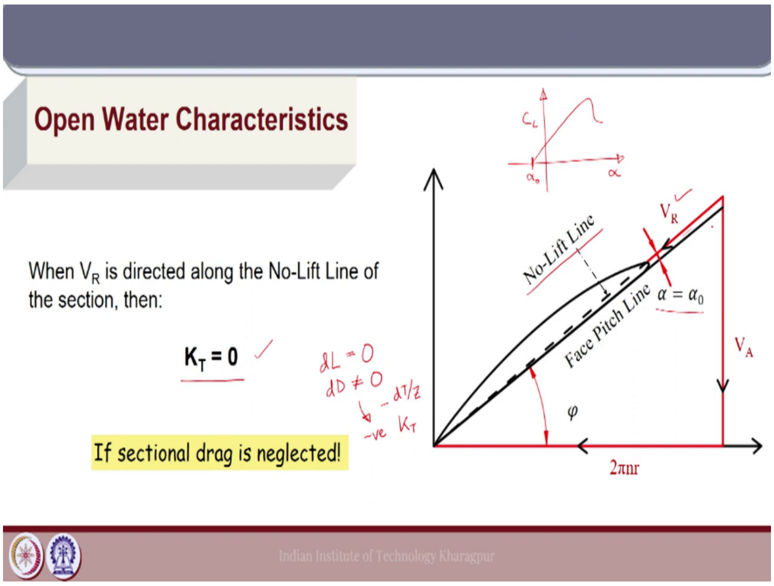

Now, on the other side what happens when K_T is equal to 0, because we have considered the case just now where the angle of attack is 0. So, even at 0 angle of attack the cambered section will provide some lift and so, there will be a small value of thrust. But how do we relate the condition where K_T or the thrust coefficient is 0 in the open water diagram, how do we relate it to the blade element diagram.

So, this is again the blade element diagram for the representative section, K_T is 0, if we neglect drag. Now, this is very important here, sectional drag also plays a role in lowering the value of K_T; let us, for simplicity neglect the drag first; so, to get K_T equal to 0 the lift should be 0. Now, the lift is 0 when the resultant velocity is inclined at an angle which is in lined with the no lift line of the section.

So, again if I draw the lift coefficient versus angle of attack for the blade section here. This is the value of α_0 which is the negative angle of attack or the no lift angle of attack where the lift generated by the section is 0. So, when V_R the resultant velocity is aligned on the other side; that means, on the line where the foil has no lift this angle α_0, at that case we will have the sectional lift is equal to 0.

So, if we neglect drag that will give us the condition where the thrust coefficient of the propeller is 0, I hope this is understood. So, this $\alpha = \alpha_0$, then we have the thrust coefficient is equal to 0 when the V_R is aligned with the no lift line. Now, what happens if we take drag into consideration; if we do that lift will be 0, dL generated by the section because the V_R is aligned with the no lift line.

But in this particular condition dD will not be 0, because the section will have a small value of drag; so, it will lead to a small negative value of K_T. So, negative K_T will arise due to the contribution of the drag, this will cause a –dT/Z of that particular section which will result in the negative K_T. So, ideally for a realistic scenario if we take a representative section the resultant velocity should be at an angle slightly less than the no lift angle shown here.

So, that the small component from the lift generated is neutralized by the drag generated from the section ok. To get the resultant K_T of the propeller blade section as 0 ok. So, if we consider the blade section the resultant value from the lift should cancel out the component from the drag which gives the sectional thrust. So, that the total thrust generated by the section will be 0 in a realistic scenario ok.

So, if we do not consider drag then V_R is aligned with the no lift line for K_T equal to 0, if we consider drag the angle should be slightly lower because of the effect of drag and lift to be cancelling each other ok.

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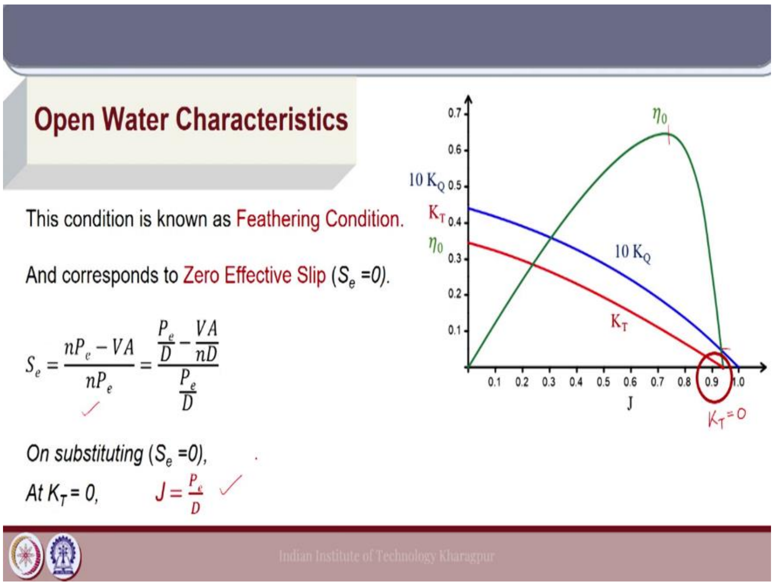

So, now let us go to this condition it is called the feathering condition where K_T equal to 0; so, again K_T equal to 0 implies that the open water efficiency will also be 0. So, in the propeller open water diagram the diagram should be drawn in such a way that η_O should be 0 at the point K_T is 0. And the nature of η_O, the open water efficiency is such that it gradually increases and it reaches a maximum value and after that the value of η_O the drop is very sharp. So, it sharply declines to a value of 0 at K_T equal to 0.

But one must consider that at K_T equal to 0, K_Q is still not 0 K_Q is still positive, why? Because at K_T equal to 0 the component of lift and drag will also give a small K_Q. So, K_Q will become 0 at a J value which will be higher than the J at which K_T is 0 ok. So, the condition where the thrust coefficient is 0 is called the feathering condition and it corresponds to the case where we call the effective slip is 0.

Now, the slip ratio as we have seen is defined by this expression where P_e is the effective pitch of the propeller blade. And we have seen that the action of a marine propeller can be defined with respect to a screw of the pitch which is equivalent to the propeller pitch. So, using that concept of screw pitch we define the slip of the propeller blade and at zero effective slip we will have the thrust coefficient 0 in the open water diagram.

So, if we substitute this, we will get at K_T equal to 0 if we put the effective slip as 0 we can get the advance coefficient J is given by the effective pitch by diameter at which the K_T is 0. Now, the case where K_Q will be 0 will be slightly higher with respect to the J value depending on the relative values of the thrust and torque generated by the blade section. If we again think of the blade section diagram for the propeller blade ok.

So, propeller open water characteristics is very important in the context of marine propulsion. Because, when we try to understand the characteristics of a propeller as a separate entity open water diagram is the basic estimate of the propeller thrust and torque with the change in the propeller loading condition which is J. So, different propellers will have different thrust and torque characteristics which will be given with the help of open water diagram; so, this is the most standard way of expressing propeller characteristics.

In the behind condition the properties of a propeller in terms of characteristic performance its hydrodynamics will change because of the design of the ship the flow into the propeller will change. But the open water characteristics are the intrinsic characteristics of a propeller. So, this hydrodynamic performance is very important to estimate the design of a propeller when it is used in a specific ship.

And we will use these open water characteristics to evaluate propeller design as well as performance for different cases when we do ship powering. This will be all for today's class.