Marine Propulsion

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Lecture - 25
Propeller Cavitation (Part - II)

Welcome to lecture 25 of the course Marine Propulsion. Today we will continue with Propeller Cavitation.

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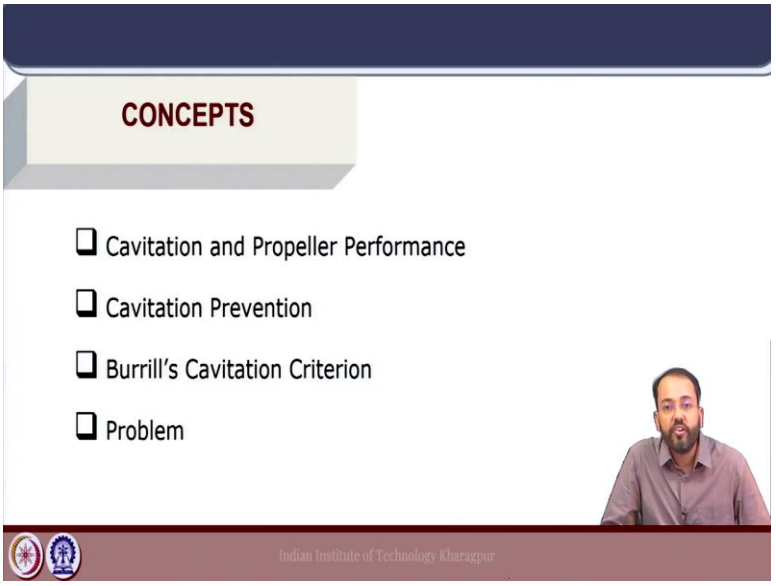

The key concepts covered in today's lecture will be cavitation and propeller performance; prevention of cavitation on propeller blades; then, we will move on to a cavitation criteria which is used in propeller design; Burrill's cavitation criteria and we will discuss a problem based on cavitation criteria.

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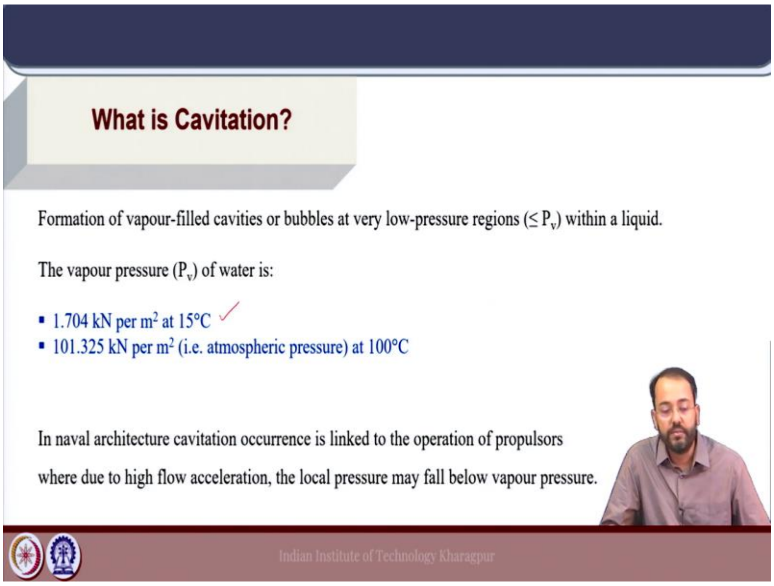

So, just a brief recap of the cavitation phenomena – it is the formation of vapor filled cavities or bubbles at very low pressure within the liquid. And, we have seen for naval architecture application like ship propellers. It is possible that the local velocities may be very high due to flow acceleration around the propeller and that can lead to the local pressure falling below the vapour pressure and, the vapor pressure for water at 15 degree is 1.7 kilonewton per meter square.

So, due to very high velocities on and around the propeller blade it can happen that the dynamic component leads to the fall of the local pressure at any point or a region below the vapor pressure and cavitation may occur.

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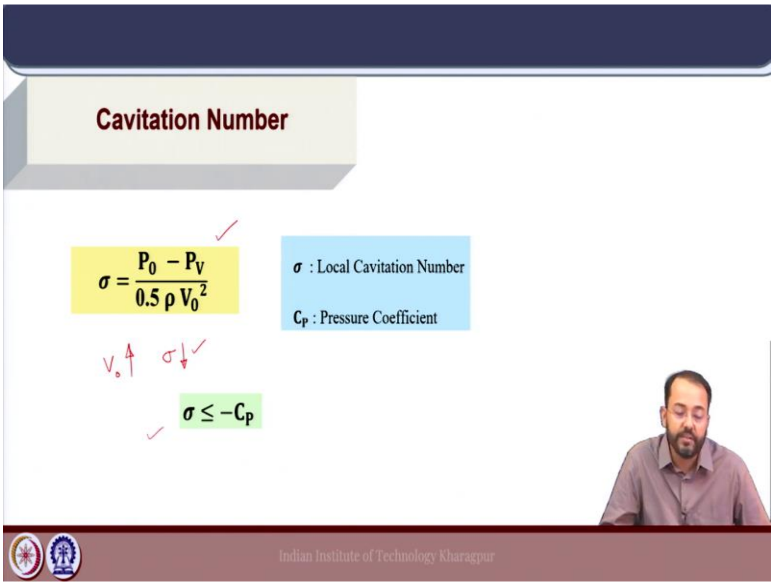

And, we have already defined the cavitation number using this expression where P_0 is the reference pressure and P_V is the vapor pressure at the particular temperature. Now, here if we see the reference velocity is V_0, and we have seen that this reference velocity depends on the way the cavitation number is defined for the propeller. So, typically for a representative section of the propeller blade this will be the resultant velocity at 0.7 R for the propeller blade.

Now, what happens when this velocity increases? So, if this term V_0 increases to high values then the cavitation number value will decrease. For a propeller blade we can say that the probability of cavitation occurrence will be higher and it effects will be more pronounced on the propeller blade if the cavitation number is lower.

So, the higher the velocities on the propeller blade, the lower will be the cavitation number and that will lead to greater probability of cavitation occurrence on the propeller blade. And, this cavitation number for cavitation phenomena to occur just using a simple Bernoulli’s equation derivation we have seen that it should be lower than the pressure coefficient in a negative sense.

So, $\sigma \le -C_P$ is the condition for a particular point on a foil or a propeller blade here to cavitate based on the vapor pressure.

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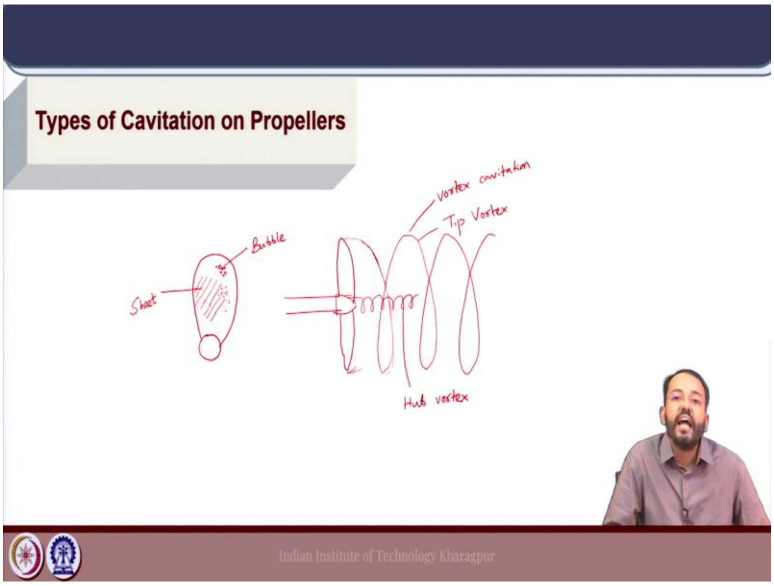

For propeller blades, we have seen different patterns of cavitation depending on both the type as well as its location on the propeller blade. So, if we have a propeller blade here, it can happen that due to high angles of attack combined with higher velocities on the propeller blade a certain portion on the blade can have a sheet of cavitation happening over the suction side typically.

Now, the same can happen on the face of the propeller blade if the angle of attack is negative. Other forms of cavitation are bubble cavitations and at the end of sheet cavitations cloud type cavitation can happen. So, all these different for example, this is sheet we have bubble type and other local spot cavitation, cloud cavitation this can happen depending on the appearance of the cavitation bubbles.

Now, if we look at the propeller from the side, the propeller blade tip, they because of their rotation it sheds helical vortex sheets in the slip stream. So, the vortices pattern will be like this, the number of vortex sheets will depend on the number of propeller blades. So, I have just drawn one helicoidal vortex sheet for reference and the core of these vortices will have low pressure.

Now, as the strength of these vortices increase because of the high propeller loadings it can happen that the pressure at the core falls below the vapor pressure. Then cavitation may occur here at the core of these vortices. So, these are called vortex cavitation if cavitation phenomena is occurring in the vortices and they can be both detached from the propeller blade tip or also attached depending on the extent in which the pressure is below the vapor pressure.

Similarly, the hub also generates vortices the propeller hub. So, this is the tip vortex and this is the hub vortex. Similarly, in the hub vortex if the pressure at the core falls below the vapor pressure, then hub vortex cavitation can also occur ok. So, cavitation may occur on the blade surface on different parts as we have seen, so on the leading edge, trailing edge also near the root or tip and also in the slip stream of the propeller which is mainly the vortex cavitations.

So, cavitation has many effects on the propeller blade. We have seen that it leads to reduction of the thrust and torque and finally, propeller performance. And, also more detrimental effects for bubble cavitation include the formation and implosion of bubbles on the propeller blade which leads to erosion and damage of the blades and finally, it can also lead to vibrations and noise.

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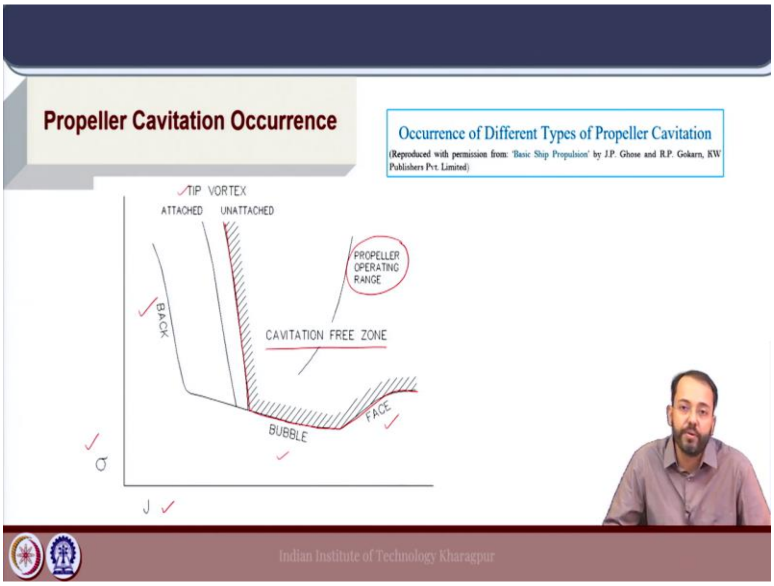

Now, here we will see the different types of cavitation occurrence with respect to a propeller operation. So, initially we have seen very simply the concept of cavitation bucket for a 2D foil section and how the effect of thickness govern the formation of different types of cavitation. Here the same is studied in the context of a standard propeller blade.

So, on the x-axis we have the propeller blade operational point which is defined by the advance coefficient J and on the y-axis we have the cavitation number. So, in this particular diagram the different types of cavitation occurring typically on a propeller blade are shown and over the range of operation how this cavitation change.

For example, if we have the value of J quite low and the cavitation number high, we will have here back cavitation zone. If the cavitation number becomes very low here in this range, bubble cavitation may happen. This is the range for tip vortex cavitation and phase cavitation occurrence is shown here. So, the idea here is this particular zone which is shaded is the cavitation free zone and the propeller operating range should be within this zone ideally.

So, we will see that there are certain ways of designing a propeller with gravitation checks certain criteria can be fulfilled so that a propeller can be operated within the cavitation free zone within some limits that the idea is some levels of sheet cavitation within a limit of tolerance can be allowed. But, the cavitation has many detrimental effects on the propulsion performance and that is why it should be avoided.

So, this diagram gives an idea of the limits in which the propeller operation should be maintained to avoid the different types of cavitation and this is also a cavitation bucket diagram for the propeller.

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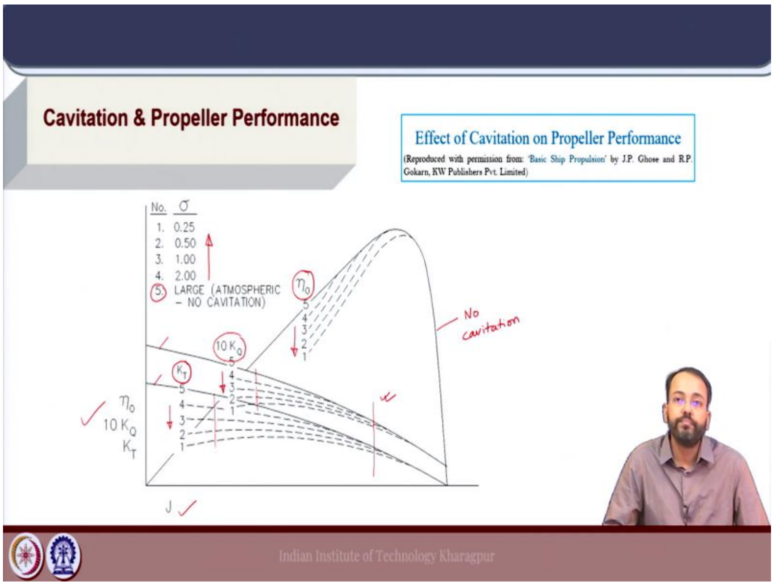

Now, if we try to understand how cavitation affects the propeller performance. By propeller performance its intrinsic performance, we try to point out at the open water diagram where we study only the performance of the propeller.

Now, the flow again we have seen that in the open water and the behind condition will be different because of the wake of the ship and that will also impact the cavitation performance in a way. So, here the cavitation number is shown as a factor which impacts the thrust, torque and efficiency of the propeller blade in the open water condition.

So, we have the standard open water diagram where K_T, 10 K_Q and η_o the open water efficiency are plotted as a function of J the advance coefficient. The firm line corresponds to the case where we have no cavitation, this firm line, these ones right. Case number 5 where the cavitation number is large; that means, it is having no cavitation we have the standard open water diagram.

Now, as we move in this chart towards the vertical direction from 5 to 4, 3, 2, 1 the cavitation number is gradually decreased. Now, as we have seen that as the cavitation number will decrease the probability of cavitation occurrence will increase and higher the cavitation occurrence on the propeller blade it will lead to loss of lift from the propeller blade sections.

If the lift generated by the sections is less, then that will reduce both the thrust and torque and it is observed that the reduction in thrust is higher than the reduction in torque. Here we see that let us say we start with the thrust coefficient K_T as the cavitation number is decreased from 5 to 1 the value of thrust coefficient decreases and another thing is very important here is the effect is much pronounced at high propeller loadings.

High propeller loadings mean lower J values; the lower the advance coefficient the higher the propeller loading because the thrust is high the thrust loading is high in that range, right. So, the effect of reducing the cavitation number or the effect of increasing cavitation occurrence on the blade will have a huge impact on the thrust and similarly, on the torque here both are decreasing.

But, as we go to higher propeller loadings these effects are more pronounced whereas, on the other side the effect on thrust and torque is lower. Similarly, we can calculate the effect of cavitation on the open water efficiency by the resultant of the new thrust and torque that we get after cavitation occurrence and it is observed that similarly, the efficiency is also reduced as the cavitation occurrence increases on the propeller blade.

So, that is one of the main reasons why cavitation phenomena should be avoided if possible in the design stage of the propeller as much as possible so that the propeller blade performance is not affected in critical operation conditions.

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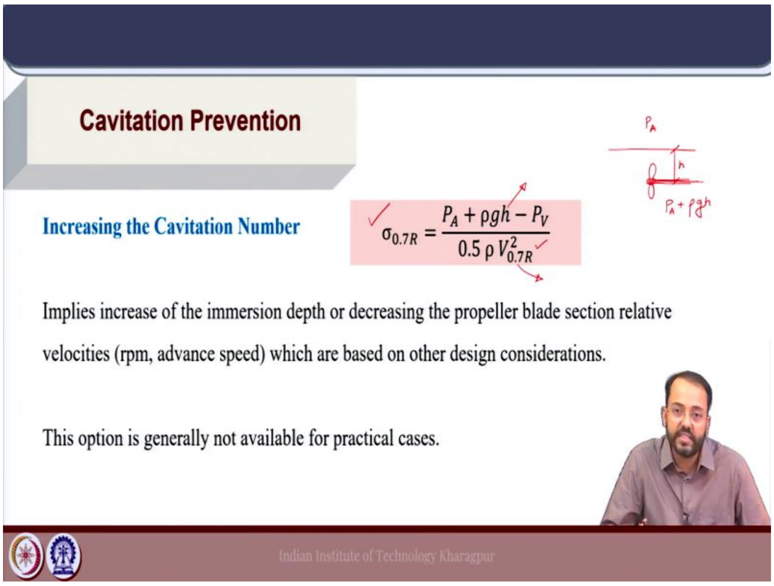

Now, we will look into the aspects of cavitation prevention; that means, how we can use certain techniques to avoid cavitation occurrence on the propeller blade. So, cavitation number is given by this particular equation that we have already seen where P_0 the reference pressure is nothing, but the atmospheric pressure plus the hydrostatic pressure head if we consider the propeller shaft axis as the reference.

So, again if we have the propeller shaft axis immersion is h and P_A is the atmospheric pressure. So, the reference pressure here is $P_A + \rho g h$, and $V = 0.7R$ is the resultant velocity at the blade section at 0.7 radius which is the representative section. So, the velocity at that section will represent the velocity of the propeller blade in terms of cavitation calculations.

Now, the simplest thing that may come to mind is preventing the cavitation by increasing cavitation number because in the last slide we have seen that the lower the cavitation number the higher will be the occurrence of cavitation on the propeller blade. So, if we try to increase the cavitation number what are our options? In the numerator the only thing that can be changed is the h and in the denominator the velocity can be changed, right.

So, increasing cavitation number implies that either the immersion depth has to be increased or the relative velocity of the. Now, $V_{0.7R}$ will depend on both V_A the advance speed and the rpm of the propeller. So, if we want to reduce $V_{0.7R}$, then these velocities have to be reduced either the rpm or the advance speed.

Now, these are already based on other standard design conditions because the advance speed will be based on the design ships speed and the rotation is also dependent on the standard propeller design with respect to the powering requirement and engine propeller matching. So, changing these things are not normally possible for practical cases and also the shaft axis immersion change is also not possible. So, this option is typically not possible for standard practical purposes.

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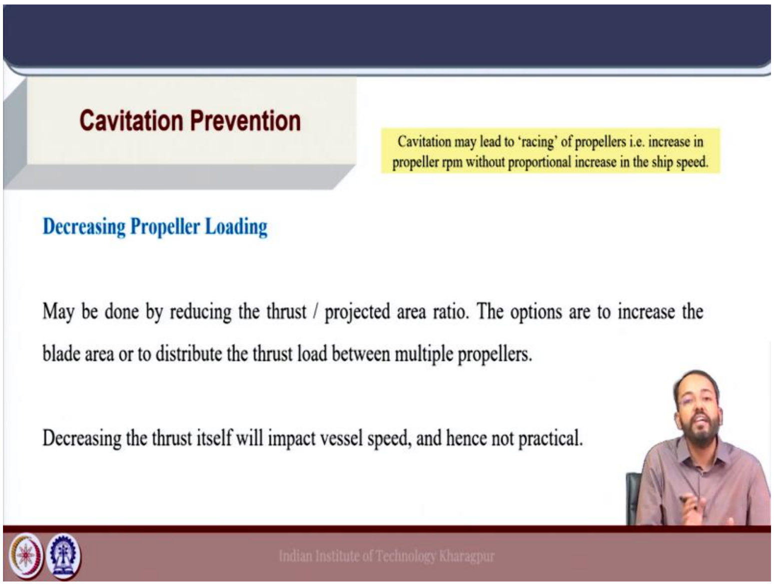

So, what other options do we have? We can decrease the propeller loading. So, if the thrust loading of the propeller is decreased; that means, the thrust per projected area ratio which is standard used for propeller blade cavitation calculations. So, if that is reduced we have seen that the cavitation occurrence is higher at high thrust loading conditions.

So, if the thrust loading can be reduced the occurrence of cavitation in the propeller blade will be less and even if it occurs it will be mild. So, the influence on the propeller efficiency will be much less in terms of reduction of thrust and torque and finally, the efficiency. So, how do we reduce the thrust loading? Either the blade area can be increased or the thrust can be distributed between multiple propellers.

So, for high speed requirement for vessels with very high speed and low propeller diameters it is possible to do this reduction of thrust loading by using twin screw propulsion or multiple propellers where the thrust loading is divided into more than one propeller and that reduces the probability of cavitation occurrence.

Now, on the other hand I can also reduce the thrust instead of reducing the thrust loading, but that is itself again not possible because the thrust is governed by the vessel speed and it is not practical ok. So, for certain vessels historically it has been observed that the phenomena of cavitation is reflected in a racing of propellers which was observed for certain ships and that leads to an increase in propeller rpm without a proportional increase in the ship speed.

So, this is how the cavitation phenomena is reflected in a practical operation condition. So, if cavitation is occurring then it is observed in the racing of propeller where the proportional increase in the ship speed is not observed, but the propeller is having a very high rpm, then it can be suspected that cavitation is occurring on the propeller blades.

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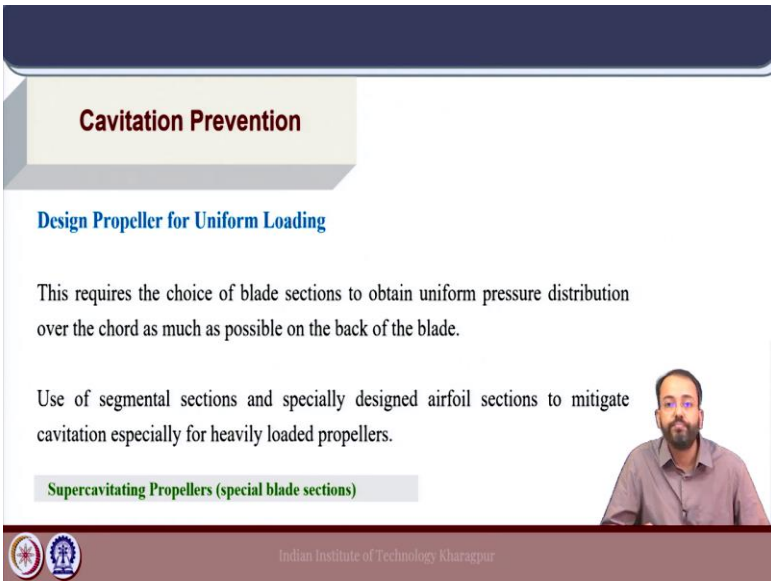

Now, another way to reduce cavitation occurrence is by using proper blade sections which have more uniform distribution of pressure over the cord as much as possible typically on the back of the blade where we have the standard suction side cavitation.

So, there are certain section designs which are available typically segmental sections or specially designed aerofoil sections which help mitigation of cavitation because of their pressure distribution on the particular sections which lead to lowering the suction side peaks and making it more uniform so that they can be used for heavily loaded propellers where cavitation occurrence is critical.

Now, another thing should be mentioned here which is very important for cases where it is impossible to stop cavitation from occurring especially for ships which have very high powering requirement and also restricted propeller diameters. A special design called Supercavitating propellers are used; these Supercavitating propellers have very special blade sections which allow cavitation to happen on the entire suction side of the propeller blade.

This is a very special case where cavitation is allowed to happen by using specialized sections. So, in this class of propellers super cavitation propellers the entire suction side or the back of the blade is covered with cavitation and that can give a good performance in terms of the propeller characteristics in different conditions.

But, these are not standard conventional propellers. They are specially designed and their operation range is determined by the performance characteristics of the ship. So, they are used for vessels where cavitation cannot be otherwise avoided and the thrust loading is very high on the propellers.

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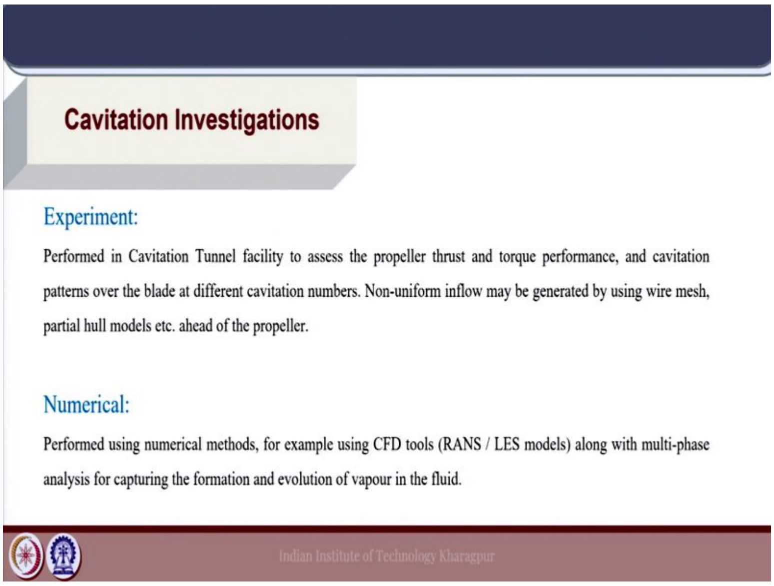

Now, what are the standard ways of cavitation investigation on propeller blades? We have briefly covered the concept of cavitation tunnel under model tests. So, cavitation tests are done in cavitation tunnel facility where the propeller thrust and torque performance as well as cavitation patterns are studied at different cavitation numbers.

So, by cavitation patterns we mean the occurrence of cavitation in different operation conditions or cavitation number on the propeller blade as well as it is slip stream, whether it is sheet, bubble, cloud or vortex cavitation these are observed for a range of cavitation numbers.

And, also the corresponding performance of the propeller the thrust and torque are also measured in the cavitation tunnel facility where it is possible to increase the velocity by a large value so that and also pressure can be controlled to obtain the cavitation phenomena in model propellers.

In cavitation tunnels it is possible to both investigate propellers in uniform inflow and also in non-uniform inflow. The purpose of which is to imitate the conditions of the propeller behind the ship hull where it has to operate in a non uniform inflow field. So, this non-uniform inflow may be generated by using wire mesh or partial hull models in front of the propeller and then the same observations are done.

On the other side, one can also use numerical methods to investigate cavitation performance of propellers. For example, if we use computational fluid dynamics methods RANS and LES models can be used to estimate propeller performance along with that multi phase analysis can be done with proper cavitation models to capture the formation and evolution of vapors in the fluid.

For different cavitation numbers and propeller loadings these models can be used to effectively simulate the occurrence of cavitation in the propeller and also estimate its performance for different operation conditions.

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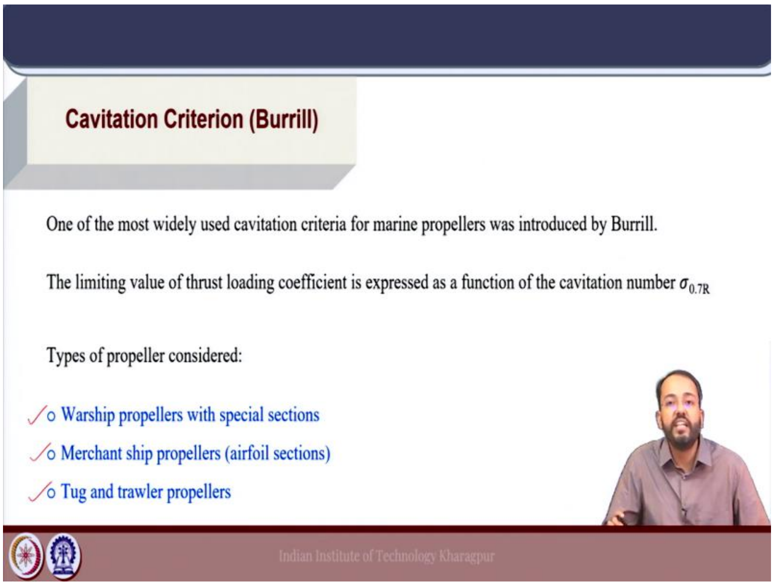

Now, we will look into a cavitation criterion that is used for marine propellers and extensively used for propeller design to get a design within a certain range so that the probability of cavitation occurrence is minimized. One of the most widely used criteria was proposed by Burrill and it is expressed by the thrust loading coefficient of the propeller blade as a function of the cavitation number at 0.7R which is the reference section.

And, different types of propellers are considered which have different ranges of operation for this cavitation criteria. So, the first type are warship propellers with special sections, merchant ship propellers, standard airfoil sections and tug and trawler propellers. Now, the reason of these different types is the design of the sections of these propellers will be different and hence the criteria will be slightly different in terms of the relation between the thrust loading and the cavitation number.

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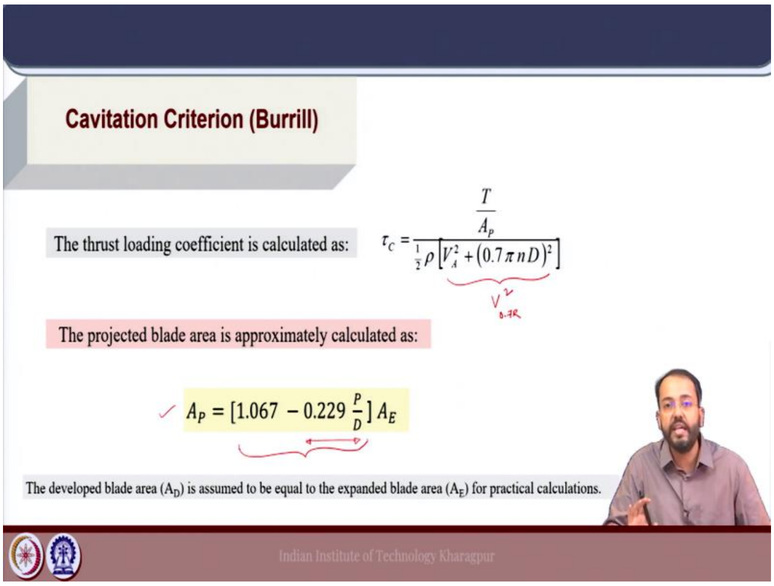

So, the thrust loading for this cavitation criteria is expressed in this form thrust by ½ ρ V^2 which is the resultant velocity. So, this particular expression is actually $V_{0.7R}^2$ the resultant velocity at 0.7R, right and A_P is taken as the projected area of the propeller blade at that particular condition; that means, it will depend on the pitch of the propeller blade because we have seen in propeller geometry that the pitch of the propeller blade will be reflected in the projected area of the propeller blade.

So, it is approximately calculated as this particular expression multiplied by the expanded blade area and this expanded blade area for this calculation is taken to be equal to the developed area for practical purposes. Now, in this equation we see that the projected area is this expression multiplied by A_E. Now, if we increase the pitch ratio P/D of the propeller blade what will happen? This negative part will increase and A_P will decrease.

So, for the same popular blade design in terms of other parameters if we only increase the pitch ratio for the same expanded area the projected area will be low which we have seen in propeller geometry that for the same propeller blade if we increase the pitch it will have a higher angle. So, its projection on a plane which is perpendicular to it will decrease and hence A_P will decrease if P/ D is increased for the same A_E.

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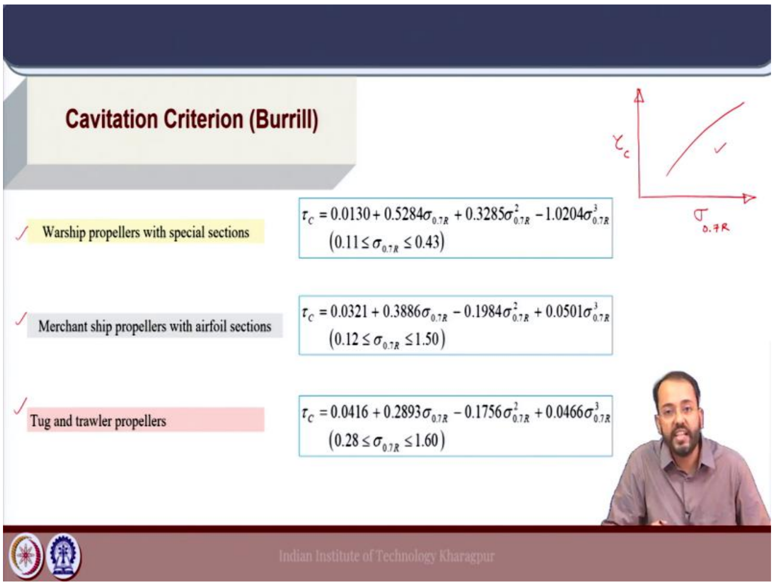

Now, based on the different types of propellers that are used in this cavitation criteria these equations are developed. So, they are obtained by regression over different ranges of operation and typically they are plotted in this form where τ_c or the thrust loading coefficient is shown as a function of the cavitation number with the reference blade element at 0.7 R.

So, we can see that as the cavitation number decreases the value of thrust loading coefficient should also decrease so that the cavitation is kept within certain limits. So, this cavitation criteria gives the limits of the propeller operation in terms of thrust loading for cavitation to be minimized. Now, each of these three cases will be represented by a line like this in the Burrill's diagram which is used for cavitation calculations.

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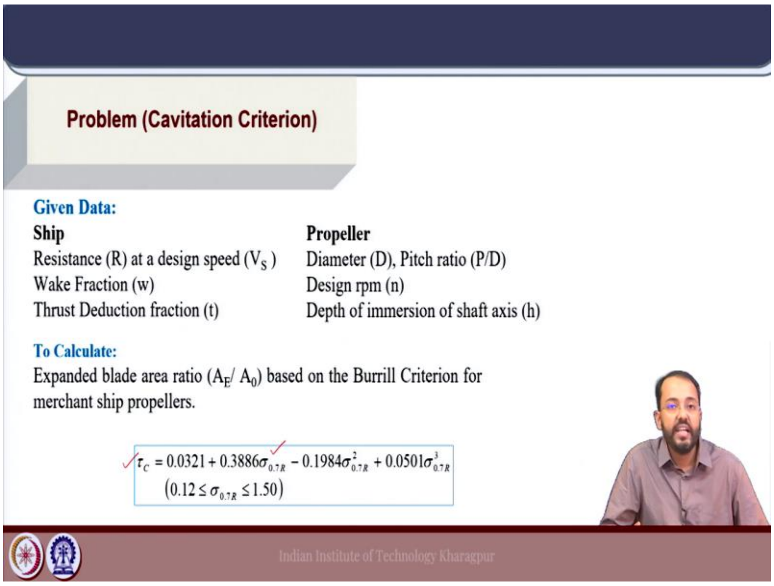

Now, we will do a simple problem of cavitation calculation on a propeller blade using Burrill's cavitation criteria. In this problem we have the ship data given where the resistance of the ship at a particular design speed is given along with wake fraction and thrust deduction fraction.

And, on the propeller side the diameter pitch ratio rpm and shaft immersion of the propeller shaft axis is given. We have to calculate the expanded blade area ratio A_E/A_0 based on Burrill's criteria for merchant ship propellers which is given here. Now, what is this particular criteria giving us it gives us the relation between the thrust loading coefficient and the cavitation number for the propeller blade.

Now, the first step here is to understand how we will calculate the thrust loading coefficient and cavitation numbers and finally, relate them so that we can calculate the expanded blade area. For the thrust loading coefficient it will depend on the thrust of the propeller blade and in this given problem we have the resistance and the thrust deduction given.

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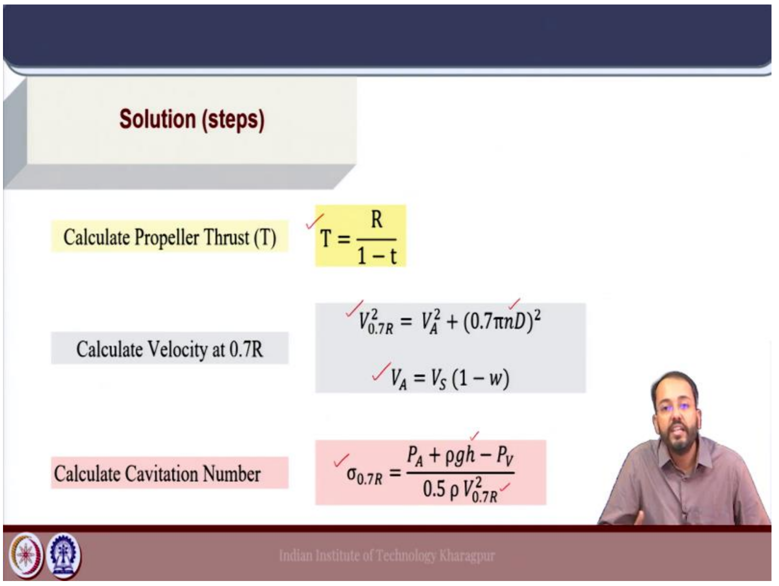

If we look at the solution the first step will be to calculate the propeller thrust. We have the resistance of the ship given and the thrust deduction. So, we can calculate the thrust using this expression. The next step is to calculate the velocity which is the reference velocity at 0.7R. We have the speed of the ship given and the wake fraction. We can use them to calculate the velocity of advance of the propeller blade.

Now, as we have seen from the blade element diagram the resultant velocity at 0.7 R can be computed from this V_A which is the velocity of advance and the component from the propeller rotation which is 0.7 π n D where n is the given propeller rpm, ok. So, this velocity will be the reference velocity used for calculation of cavitation number and also it will be used in relation to the thrust loading coefficient for the propeller blade.

The next step will be to calculate the cavitation number. Now, the cavitation number is based on the pressure at the propeller shaft axis which is P_A + ρ g h where h is the depth of immersion which is given in the problem and we have already computed $V_{0.7R}$. So, this expression gives the value of cavitation number for the particular condition. Now, we have to relate this cavitation number to the thrust loading coefficient based on the Burrill’s criteria.

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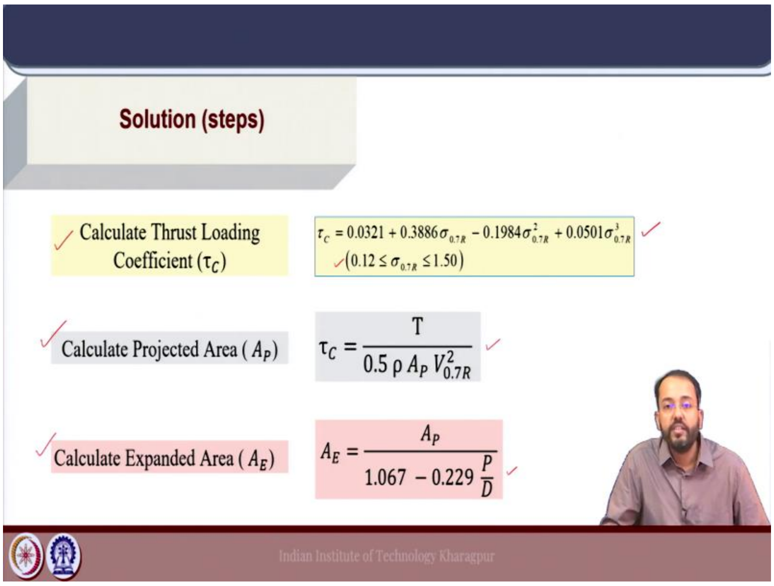

Next, we can calculate the thrust loading coefficient; for merchant ship propellers. The equation is already given for cavitation criteria because we have already computed the cavitation number the thrust loading coefficient can be obtained using this expression and we will see that the calculated cavitation number if it is given for a merchant ship propeller it should lie within this particular range.

So, for all these different types of propellers warship, merchant ship and tug and trawler for these equations a particular range of cavitation number is given based on which these relations between the thrust loading and cavitation number are plotted. Now, once we know the thrust loading coefficient the thrust was calculated previously from the resistance and thrust deduction, we will be able to calculate the projected area A_P of the propeller blade which was unknown in this problem.

All the other terms except A_P are known in this equation, ok. So, if we relate the thrust loading coefficient to the thrust the area and velocity we can get the value of A_P and as we have seen in this cavitation criteria this approximate relation can be used to calculate the expanded blade area from the projected blade area using the value of pitch ratio. In this particular problem pitch ratio was given as an input. So, the expanded blade area can be calculated.

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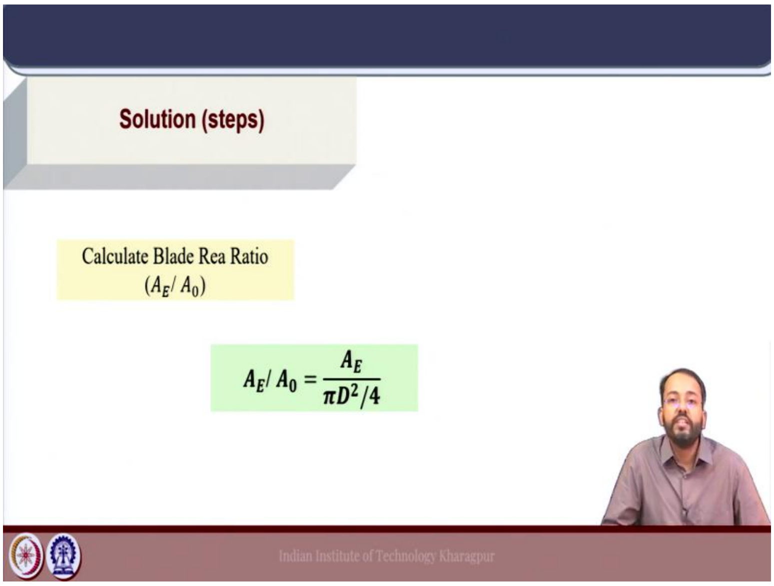

Next the final step from the value of expanded blade area as discussed in propeller geometry we can divide it by the area of the propeller blade, the disc area $\pi D^2/4$ where D is the propeller diameter to get the expanded blade area ratio A_E/A_0. So, the same problem can be framed in different way the idea is to calculate the parameter of a propeller based on cavitation criteria.

So, this Burrill's cavitation criteria is used in propeller design as a cavitation check for certain operation conditions so that the propeller blade cavitation occurrence is minimized and the propeller blade performance is not affected by cavitation. So, this will be all for the cavitation part of this course. We will continue with propeller blade strength in the next lecture.

Thank you.