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

Lecture - 24
Propeller Cavitation (Part - I)

Welcome to lecture 24 of the course Marine Propulsion. Today we will start with Propeller Cavitation.

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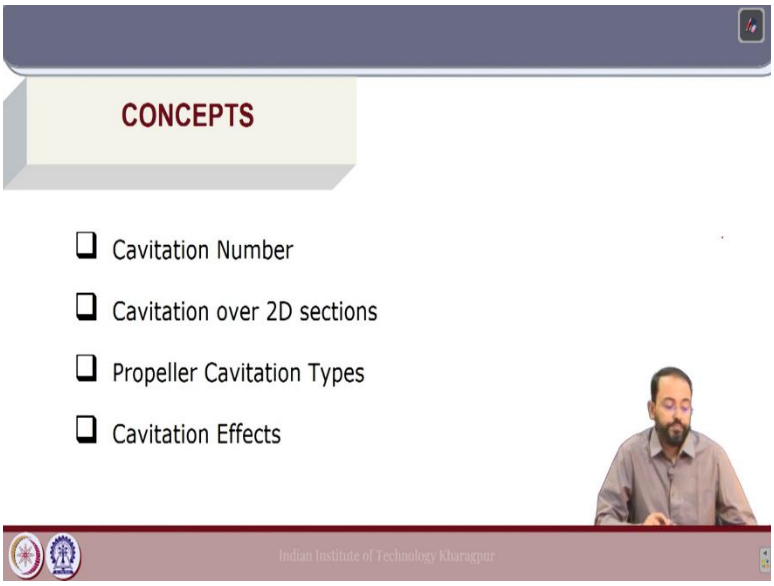

The key topics to be discussed in todays lecture will be the concept of cavitation, cavitation number, the occurrence of cavitation over 2 dimensional sections and then we will move on to the different types of cavitations on a propeller blade and the effects of cavitation in marine propulsion.

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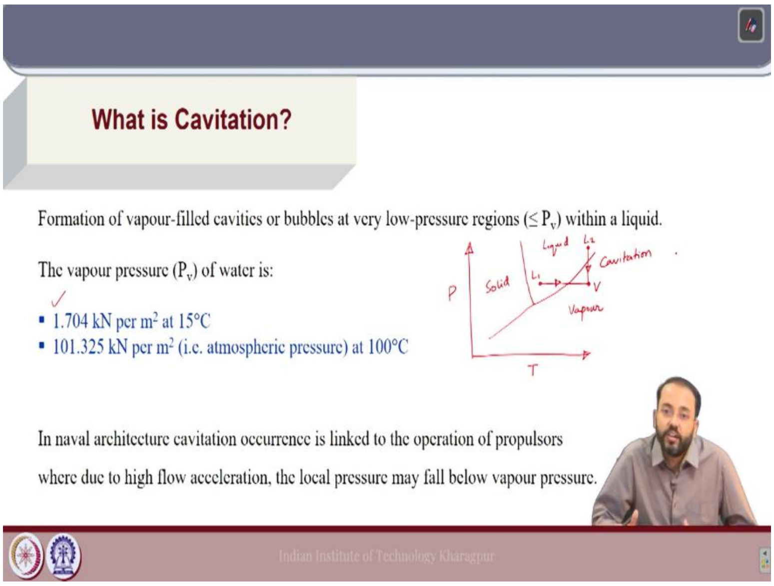

So, what is cavitation? It is the formation of vapour filled cavities or bubbles at very low pressure which is lower than the vapour pressure within a liquid. Now, why are we discussing cavitation as a part of this course?

Because we will see that in the case of marine propellers there are certain regions on the propeller blade or around the propulsion system where the pressures can drop below the vapour pressure under certain operation conditions. And because of that these vapour filled cavities or bubbles are formed and they lead to change in the performance of the propeller and also certain other things like damage to the propeller blade etcetera.

So, cavitation phenomena is important in the context of marine propulsion. The vapour pressure of water is 1.7 kN/m^2 at 15 degree which is the normal temperature of sea water which is taken approximately for calculations and the vapour pressure is equal to the atmospheric pressure at 100 degree centigrade which is the boiling point of water.

So; that means, if due to flow acceleration at certain points, it can happen that the local pressure may fall below the vapour pressure and that can lead to cavitation which is in naval architecture as we are discussing about ship and propellers. So, if we simply look at the phase diagram of water, it looks something like this where we have the solid phase liquid phase and vapour phase.

So, let us take a point here if this is a point L_1 in the liquid phase and another point in the liquid phase L_2 ok and let V be the point in the vapour phase. So, if we move from L_1 to V; that means, the temperature is raised at constant pressure. So, this is typically the phenomena of boiling.

On the other hand if we move from L_2 to V; that means, at the same temperature the pressure is reduced and then water moves from the liquid state to the vapour state. So, this cavitation is a phenomena where due to very low pressure within the liquid in this case water it is being converted from the liquid phase to the vapour phase.

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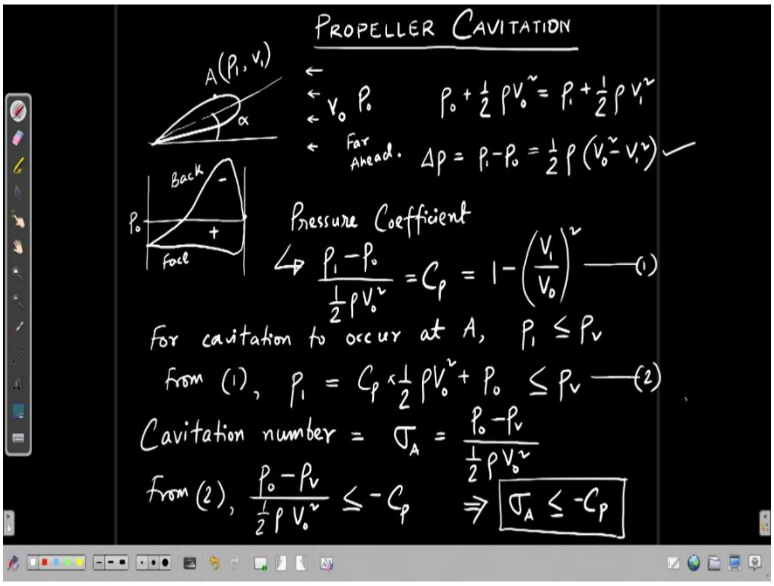

Now, let us try to understand how cavitation may occur on a 2 D section which is a typically the section of a propeller blade at any particular radius. So, if we simply draw a 2 D section at an angle of attack α to an inflow velocity V_0 and let P_0 be the pressure at the same level at a location far ahead. Now let us take a point on this section A where the pressure is P_1 and the velocity is V_1 ok.

Now, we have to use Bernoulli's equation to relate these velocity and pressures and understand the condition for cavitation to occur at the point A. So, if we just simply try to draw the pressure distribution over this section, we will have a suction pressure peak and on the pressure side you have positive pressure on the suction side; that means, on the back we will have negative pressure this is the face and it is drawn as a reference line with P_0.

So, if we apply Bernoulli's equation between a position far ahead and the point A we will get right.

$$P_0 + \frac{1}{2}\rho V_0^2 = P_1 + \frac{1}{2}\rho V_1^2$$

So, the pressure difference ΔP between the point A and the point far ahead at the same level is P_1 - P_0 which is $\frac{1}{2}\rho(V_0^2 - V_1^2)$. Now the pressure coefficient is defined by this difference P_1 - P_0 divided by the dynamic pressure head where P_0 and V_0 are the reference values ok. So, this is C_P the pressure coefficient $\frac{P_1 - P_0}{\frac{1}{2}\rho V_0^2} = C_p$. Now as per this derivation we have $C_P = 1 - (V_1/ V_0)^2$.

$$C_P = 1 - (V_1/ V_0)^2 \tag{1}$$

Now for cavitation to occur at A, what should happen? The local pressure should be lower than the vapour pressure of water at that particular temperature. So, P_1 should be less than or equal to the vapour pressure P_V. Now from 1 what is P_1? Can be written as a function of the pressure coefficient in this way

$$P_1 = C_p \times \frac{1}{2}\rho V_0^2 + P_0 \leq P_V \tag{2}$$

So, this should be less than or equal to the vapour pressure. Now how do we define cavitation number? It is defined as per the definition of cavitation number we have $\sigma_A = (P_0 - P_v) / (\frac{1}{2} \rho V_0^2)$ the local cavitation number is the reference pressure minus the vapour pressure divided by $\frac{1}{2} \rho V_0^2$ ok. Now what do we get from 2? $(P_0 - P_v) / (\frac{1}{2} \rho V_0^2)$ should be less than equal to $-C_P$ we have just arranged the terms on the left and right hand sides of equation 2 ok where C_P is the pressure coefficient.

So, this gives the first term is nothing, but the local cavitation number at the point A. So, we have σ_A less than or equal to $-C_P$. So, this is the condition for cavitation to occur at the point A on the section; that means, the cavitation number should be lower than the minimum value of the pressure coefficient.

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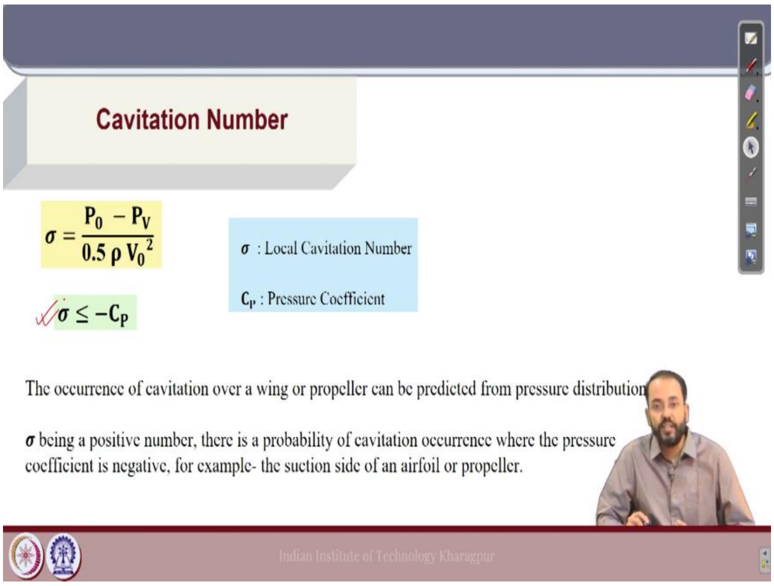

So, this gives the relation between the cavitation number and the pressure coefficient for cavitation to occur. Now for a 2 D section or a wing or propeller the occurrence of cavitation can be predicted from the pressure distribution. σ being a positive number there will be a probability of cavitation occurrence where the pressure coefficient is negative; that means, for cavitation to occur as per this equation the pressure coefficient will be negative typically the suction side on of an airfoil or a propeller ok.

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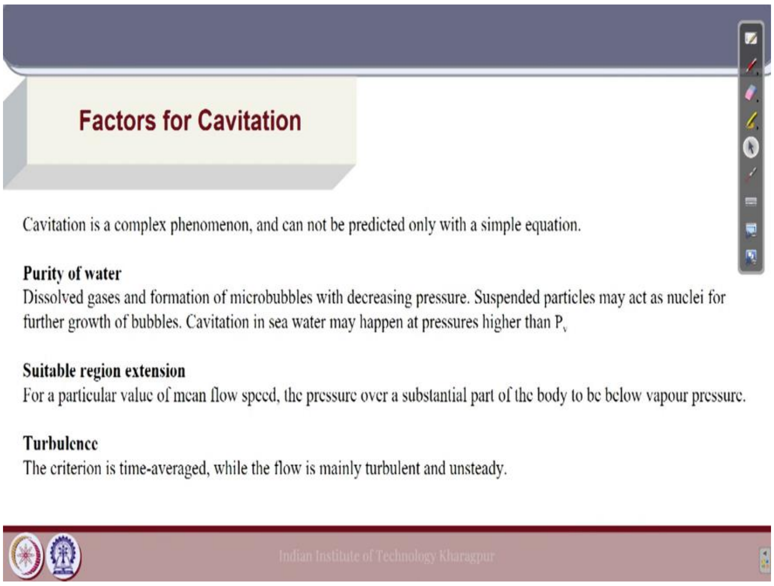

Now, cavitation is a complex phenomena and it cannot be predicted with a single equation. So, cavitation occurrence over any engineering application depends on certain factors and we will look into them one by one.

The purity of water is a very important factor which governs the occurrence of micro bubbles and the pressure decrease and cavitation occurrence depend on these dissolved gases and suspended particles because they form the nuclei on which these bubbles are formed that is one of the reasons why cavitation in sea water can happen at pressures higher than the vapour pressure P_v that we have discussed.

The next factor is a suitable region extension. It means that for a substantial part of the body the pressure should be lower than the vapour pressure for cavitation to occur and sustain.

We see that on the propeller blade the velocity field is varying in both radial and circumferential directions. And also because of the dynamic nature of cavitation the fluctuations of velocity and pressure play a strong role on the development of cavitation bubbles.

And hence over a substantial part of the body the pressure needs to be below the vapour pressure for cavitation to occur and the third part which is very important here is the turbulence in the flow because the criteria that we calculate is typically time averaged, but the actual flow is turbulent and unsteady because of the unsteadiness of the flow that very much impacts the cavitation phenomena specially for propeller blades.

Where we will see that the cavitation occurrence depends on the location of on the propeller blade and the types of cavitation vary from one portion of the blade to another depending on the different flow patterns and the local pressures in those regions on the blade.

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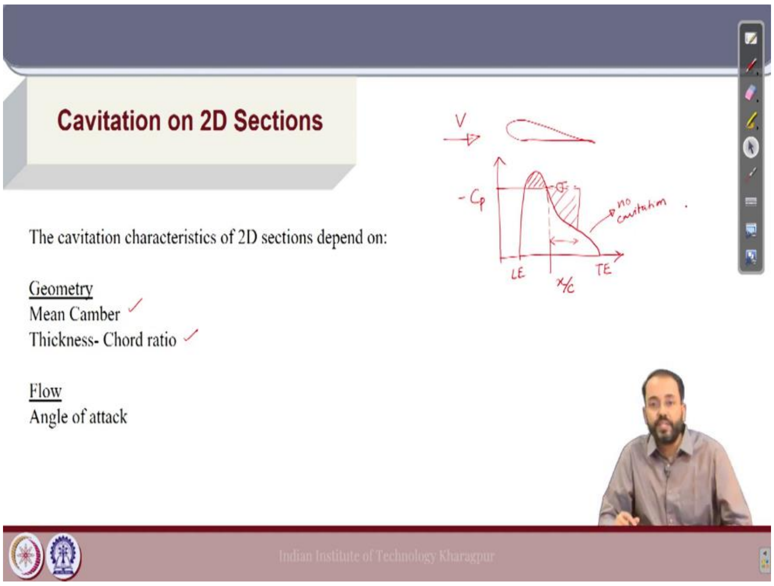

Now, for 2 D section if we look at simple 2 D geometry, the cavitation characteristics will depend on the velocity and pressure of the 2 D section and if we look at the geometrical characteristics, the mean camber and thickness chord ratio are important factors which influence the cavitation of a 2 D section and from the point of view of the flow the angle of attack of the flow is also very important in the cavitation occurrence of a 2 D section.

So, if we simply look at the flow pattern over the 2 D section and look into the development of the pressure distribution. If we plot the C_P over the non-dimensional chord length, we will look into something like this the pressure will be very high on the suction side close to the leading edge and let us say this particular value is σ.

So, we are plotting $-C_P$ here which is the pressure coefficient over the suction side and if this line is the σ line then this will be the zone for cavitation to occur. Now we will see that only the pressure drop does not give the full picture for cavitation to occur and sustain it must occur over a suitable region extension hence it is observed that at certain location.

So, this is the leading edge and here we have the trailing edge. So, over a certain location aft of this point the cavitation will still occur. So, we have a region which is the growth region of cavitation where the bubbles are gradually formed and then we will have a region which is the decayed region where the cavitation phenomena will gradually disappear if the pressure falls below the vapour pressure.

So, this is a very much dynamic phenomena and beyond that section this particular area is basically no cavitation here. Once the pressure is very much higher than the vapour pressure.

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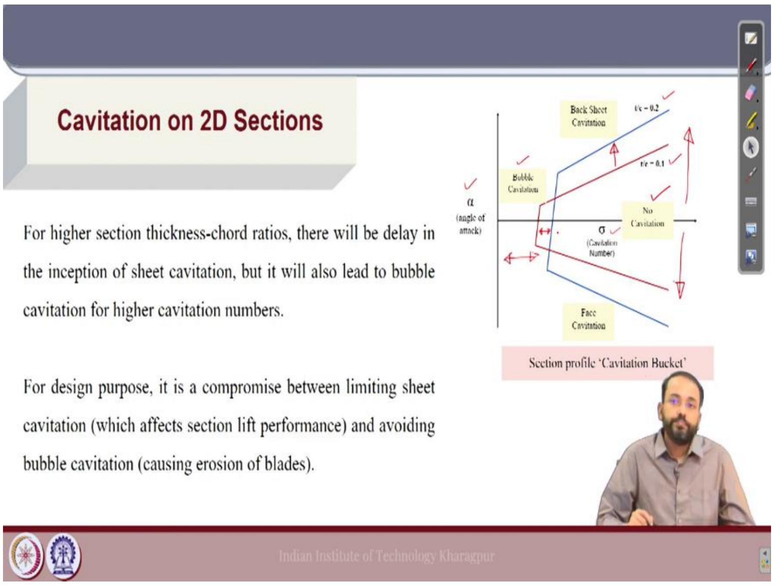

Now, if we look at the influence of the thickness on the cavitation, this is a very important factor in designing the blades of a propeller where the sections have to be chosen based on the cavitation characteristics depending on the operational characteristics of the propeller. Now why we are studying 2 D sections here? Because they form the basis of propeller blade sections which will be used for certain cavitation criteria calculation for propeller design.

Now, if we have higher thickness by chord ratios, the inception of sheet cavitation will be delayed we will study the different types of cavitation sheet cavitation is found because of low pressure over the suction side of propeller blade typically at higher angles of attack and bubble cavitation's are formation of bubbles which are much more harmful from the point of view of bubble collapse and damage to the propellers.

So, if we have higher thickness by chord ratio then inception of sheet cavitation will be delayed, but the section will have bubble cavitation for higher cavitation numbers. Now we will look into it from this diagram there are two sections which are shown with representing values of thickness by chord ratio of 0.1 and 0.2.

So, the red line shows the curve for the cavitation limits for a section with a lower thickness by chord ratio and the blue line shows the limits of cavitation for a section at higher thickness by chord ratio these are called the cavitation buckets because they give the limits of cavitation occurrence for a section. Now the zone at the center is having no cavitation in the y axis we have the angle of attack and in the x axis we have cavitation number. Now the lower is the cavitation number the higher is the probability of cavitation to occur.

So, we see that as we increase the thickness from the red line to the blue line, the envelope now has a wider appearance; that means, we have now a greater zone of no cavitation which is this one right. And beyond that we have back sheet cavitation where angle of attack α is positive and phase cavitation where angle of attack is negative phase; means if we have a negative angle of attack then the pressure side may cavitate then we will have cavitation on the face of the propeller and bubble cavitation is occurring at a point where the cavitation number is very low in this particular region.

Now, if we increase the thickness of the section, it gives us a greater area under no cavitation with the aspect of sheet cavitation, but it also leads to bubble cavitation at higher cavitation numbers; that means, in this domain where the thicker section will not cavitate, but the thinner section will show bubble cavitation ok. So, these factors have to be checked while choosing sections for propeller blades.

Now for design purpose it will be a compromise between limiting sheet cavitation which affects the propeller performance and avoiding bubble cavitation because it causes erosion of the propeller blades.

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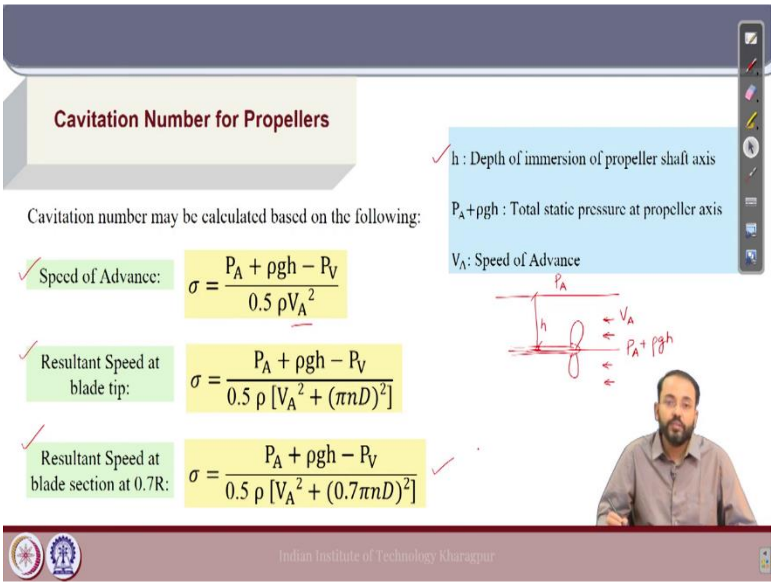

Now, how is cavitation number defined for a propeller? We have different reference speeds based on which cavitation number may be defined for propeller let h be the depth of immersion of the propeller shaft axis.

So, if we have the water line this is h ok and we have atmospheric pressure P_A. So, the reference pressure at the shaft center line is $P_A + \rho g h$. So, the cavitation number for a propeller will be this reference pressure minus vapour pressure divided by $\frac{1}{2} \rho V^2$. Where velocity can be any reference velocity of the propeller system. So, the first one here is the reference velocity based on speed of advance V_A similarly we can have the velocity as the resultant speed at the blade tip.

So, V_A is the velocity of advance and the propeller is also rotating. So, if we take the reference velocity as the resultant velocity at the blade tip, the rotational component will be π n D. So, the cavitation number equation will change in this manner. Similarly, if we look into the cavitation number equation with respect to the resultant velocity at a blade section at 0.7 R which is the representative section we will have this particular equation for the cavitation number.

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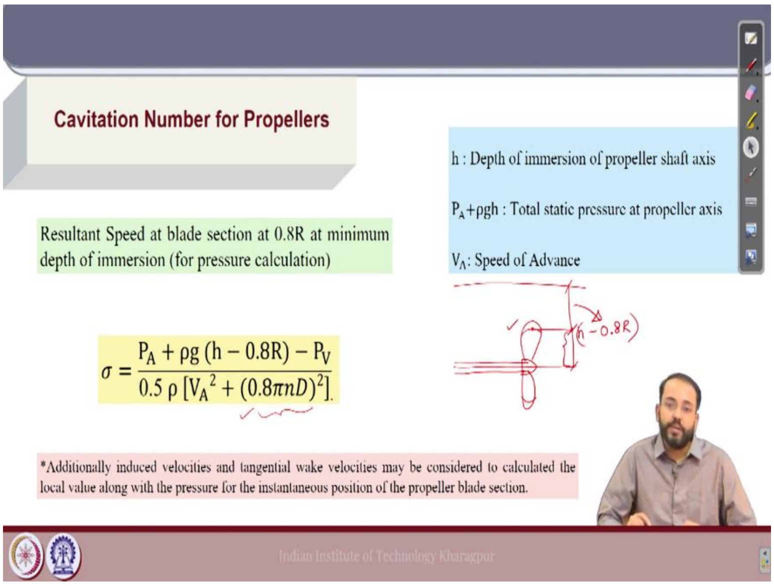

Now, let us look into the cavitation number for a blade section at 0.8 R which is also adopted as a representative section for specific calculations for a minimum depth of immersion; that means, again for the same case if this is h the propeller blade is always rotating; that means, if I take a section at 0.8 R in the vertical location it is here and just 180 degree rotated the location is here.

So, which position will be more susceptible to cavitation? The top position because the pressure is lower in the position here. So, in this position the height of this point below the water surface is h - this value which is 0.8R which is now this one ok.

So, if we use the minimum depth of immersion of that section at 0.8 radius below the surface as the propeller rotates, it will be h - 0.8 R. At other location as it rotates the immersion will be greater than this. So, the cavitation number can be calculated using both the resultant velocity at 0.8 R and the minimum depth of immersion to calculate the pressure using this expression.

Now, we have to note an important point here that the values are simply calculated using velocity of advance and the rotational component due to the propeller rotation at a particular radius. Additionally, induced velocities will also be important in the actual velocity at a particular point and also the tangential wake velocities will be important because as a propeller works behind the ship the wake velocity which is in the tangential direction will also impact this component ok. And that will impact the actual cavitation number if we consider all these velocities at a particular point on the propeller blade.

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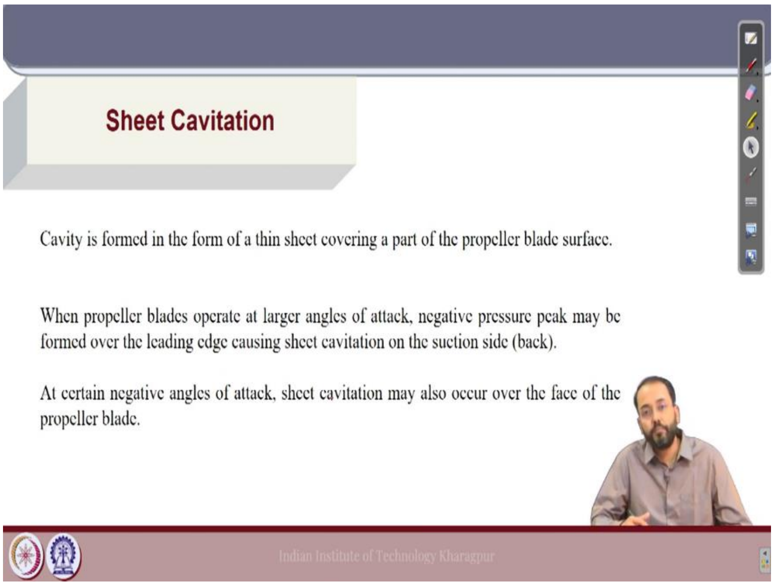

Now, if we look into different types of cavitation on the propeller blade one of the most important is the sheet cavitation where cavity is formed as a thin sheet over a certain part of the propeller blade surface. Now when the blades operate at higher angles of attack typically at high loading conditions a negative pressure peak may be formed over the leading edge which cause sheet cavitation on the back; that means, on the suction side of the blade the diagram that has been drawn previously points out to the location of the cavitation that can occur.

When where the pressure falls below the vapour pressure also at certain negative angles of attack the sheet cavitation can occur on the face of the propeller blade which is typically the pressure side. On the other hand, the bubble cavitation is the formation of bubbles which are spherical cavities.

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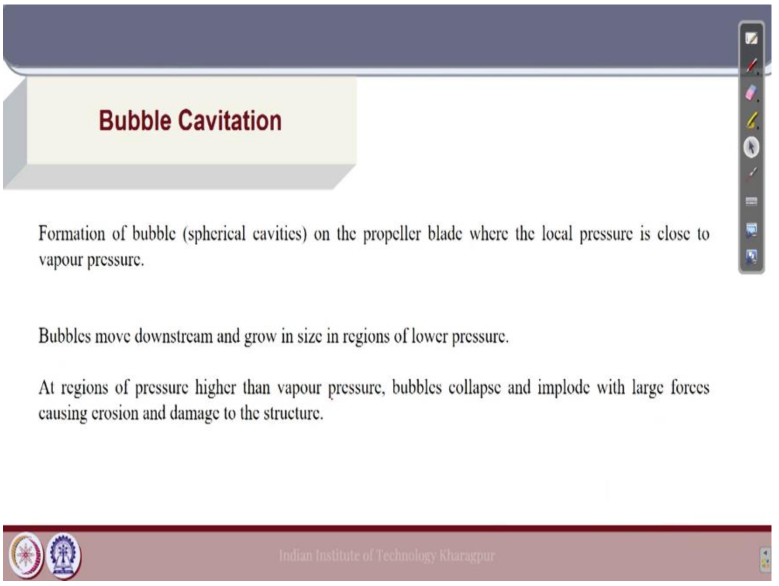

On the propeller blade where the pressure is close to the vapour pressure now these bubble cavitations are very critical because they create very high pressures when they collapse the bubbles gradually migrate to a position downstream after their formation.

Now, if they move into regions of lower pressure these bubbles grow in size finally, when they go to a position where the pressures are slightly higher; that means, higher than the vapour pressure they implode and because of that implosion they create tremendous amount of forces which causes erosion and damage to the propeller blade and these bubbles also lead to hull and propeller vibrations and they have to be avoided in the design criteria when the propeller blade sections are designed.

So, sheet cavitation should be checked and kept within a certain limit. So, that the propeller performance is not affected and on the other hand the bubble cavitation should be totally avoided so, that these bubbles do not form and they do not damage the propeller blade and hull structure.

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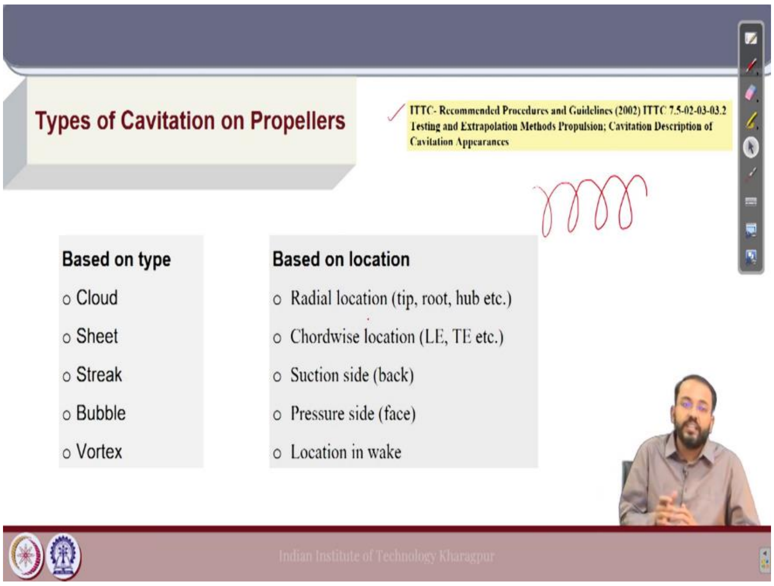

Now, if we look into the different types of cavitation on the propeller blade one may look into this particular ITTC document where different types of cavitation occurring on propeller blade based on both type as well as the location on the propeller blade are discussed.

So, briefly the types are cloud sheet streak bubble and vortex we have already discussed sheet and bubble cavitation these types of cavitation are named after their appearance on the propeller blade. For example, the vortex cavitation is in the vertical structures that are shred from the propeller blade tips as well as the hub. So, these helical vertices are shred from the propeller blade tips that we have studied in propeller theory. Now the core of the vortex has low pressure and when the propeller loading increases it can happen that the pressure at the vortex core falls below the vapour pressure.

And then it leads to vortex cavitation and this vortex cavitation may be both attached as well as not attached to the propeller blade. So, it can happen at the hub where the hub also has a vortex behind it and at the tip of the propeller blade which also has a trailing edge vortex.

So, these vortex cavitations may happen when the pressure and the core of the vortex fall below the vapour pressure. Now based on the location on the propeller blade we can have the radial location which is tip root or hub cavitation on the chordwise location we have the leading edge or trailing edge where the pressure may fall below the vapour pressure and cavitation may occur suction side and pressure side cavitation based on the two sides of the propeller blade or a location in the wake. For example, these vortex cavitation occur in the wake of the propeller where the trailing edge vortices are shred.

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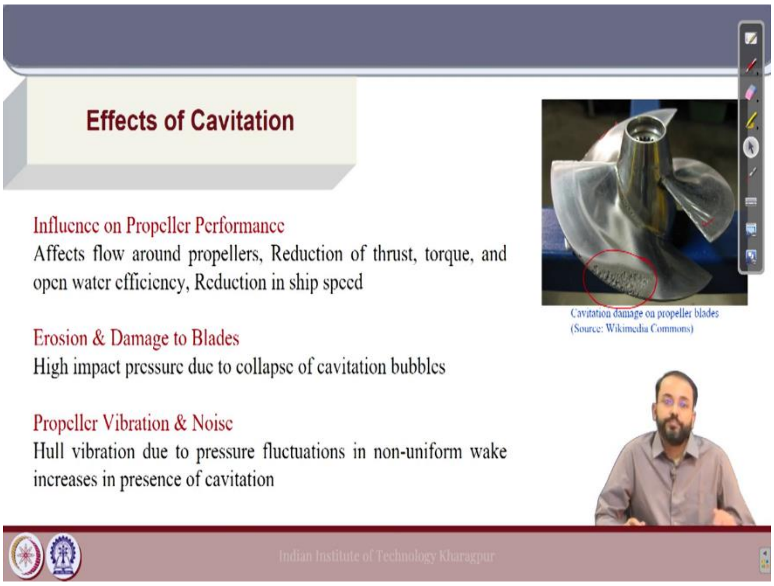

Now, what are the effects of cavitation in marine propulsion? Why are we bothered about cavitation? Because cavitation influences the propeller performance it degrades the performance of a propeller by reducing its thrust and torque and also the efficiency of the propeller blade and finally, it leads to reduction of the ship speed. So, typically if we have cavitation over a certain region of the propeller blade, it will impact the performance in terms of the forces that are generated from the blade sections.

If the blade section lift is lower due to cavitation the thrust will be low and the torque will also be lower finally, the open water efficiency is observed to be lower because the thrust decrease is higher and finally, that leads to reduction of the ship speed. The other effect which is very critical is the effect of bubble cavitation which forms bubbles and these bubbles collapse on certain areas on the propeller or hull which leads to the erosion and damage of propeller blades which is observed in this particular picture.

So, this region of the propeller blade has been damaged due to bubble cavitation where bubbles have imploded at that region and on all the propeller blades it is observed at in certain levels ok. Now these bubbles when they implode they damage the structure because of high energy released by the cavitation bubbles and that causes damage to the propeller the other impact is on the propeller vibration and noise.

Now, because of cavitation it can lead to both propeller and hull vibration and the pressure fluctuations which are already there in a non-uniform wake field increase in the presence of cavitation and that leads to vibration to the hull propeller structure which is damaging for the structure and also the noise that is created is detrimental to animals which are living in the ocean.

So, cavitation leads to both reduction of propeller performance and also erosion and damage to blades and vibration on the hull propeller system. This will be all for today's lecture in the next lecture we will continue with cavitation calculations using standard criteria for ship propellers.

Thank you.