Performance of Marine Vehicles At Sea

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Lecture No. # 20

Cavitation

Good evening. Today we will be talking about cavitation. We will take about an hour's time. The purpose of this lecture is to introduce you to the physics of cavitation and its effects on artifacts that work in water, mostly marine propellers. We will not be looking in details into the physics of cavitation nor mathematical modeling of cavitation nor application of cavitation to design of marine propellers. The intent of this lecture is only to introduce you to the topic of cavitation and its harmful effects and means of preventing cavitation wherever possible.

What is cavitation? Cavitation is a formation of vapor bubbles or cavities in a liquid. This vapor could be due to a change of phase of the liquid itself to gaseous state or it could be due dissolved gases which form a gases cavity inside this fluid, which is not the same material, but some other dissolved gases.

Once cavity is formed inside a liquid, and if it forms on the surface of an artifact, such as a hydrofoil section or a propeller blade, then there are many harmful effects. And therefore, it is not a desirable phenomenon in bodies that work in water where pressure variation is predominant. Cavitation s as a phenomenon was first mentioned by Leonhard Euler. I am sure you have heard the name of Euler or Euler that was in 1754. He had mentioned the phenomenon of cavitation, which is about two and half centuries from now.

And later on, Osborne Reynolds discussed the effect of cavitation in a presentation on raising of propellers, that is a propeller was found to increase its rpm. When run at a particular speed, the propeller was found to raise or the rpm increased without any explanation and Osborn Reynolds had attributed this to cavitation of propellers.

Later on, Sir Charles Parsons, I had mentioned this name to you earlier in the previous lecture. Do you recall? Sir Charles Parsons was involved in building of a ship by name Turbinia. It had a particular power plant, in fact the first major steam power plant installation in a ship, coal based steam power plant, that was sometime in early twentieth century. And this ship developed a speed of 17 knots whereas, its design speed was to be above 30 knots.

So, since the ship did not achieve power, achieve the speed, an investigation was made and Sir Charles Parsons found that the main reason for this was propeller cavitation. So, he changed the propeller arrangements and he put three shafts, that is three engines and on each shaft he put three propellers, that is three propellers working in tandem on each shaft.

So, therefore, he had a total of nine propellers distributed to drive the whole ship. And this, you will be surprised to know that, this increased the speed of the ship with the same power, power did not increase, to 32.75 knots, from 17 knots to 32.75 knots. Just see its almost double for the same power. And subsequently the speed went off further to 34 knots. So, Turbinia is the right example to tell you what cavitation can do to a ship, cavitation of marine propellers can do to a ship. It was so clear that cavitation was the reason for propeller that Sir Charles Parsons decided that this particular aspect of cavitation must be investigated more scientifically in a laboratory.

So, he decided first to test 2 inch diameter small propellers and later on larger propellers of 12 inch propellers in cavitation tunnel. That is the origin of the cavitation tunnel, which I mentioned to you that the small cavitation tunnel of about this size, you can still see in the university of new (( )) at UK, which was designed and built by Sir Charles Parsons first in the world.

And later on bigger cavitation tunnels were made for testing up to 12e inch propellers. In our own country IISC, Bangalore does a lot of work on cavitation in general. They have a cavitation tunnel in which lot of tests are done particularly of turbines and pumps. They have recently embarked upon testing marine propellers in some form or other in the tunnels also.

But the most advanced cavitation tunnel in the country is at naval science and technological laboratory at Visakhapatnam, where big size propellers can be tested, 350 mm in fact, 35 centimeter diameter propellers can be tested for cavitation.

So, this is a broad introduction to cavitation, why it is important. There are number of effects of cavitation, we will see them slowly during the course of our lecture. Now, cavitation you can understand why cavitation occurs in the first place. If you have a water mass somewhere open to atmosphere at normal temperature, always there will be some water evaporating the atmosphere and some water coming back to the condensing onto the surface of water. So, when the water drops get into water they exert a small pressure on the water because it becomes heavier than air and falls into water therefore, there is a small pressure on the water. Depending on the temperature, that pressure that is that is exerted by incoming water drops at the surface water is generally called the vapor pressure. That is at that temperature this is the pressure exerted by water vapor on the surface of water on the water surface.

So, truly the pressure on surface of water is equal to the atmospheric pressure plus this vapor pressure, which is very small at normal temperature. Now, if we heat this water what happens? This vapor pressure increases, that is as we keep on heating the water the pressure on the water surface keeps on increasing. At a 100 degree centigrade the water starts forming vapor inside, instead of the vapor coming to water from outside, water starts boiling from inside. That is the boiling of water occurring at 100 degree centigrade at normal pressure, that is ambient pressure being atmospheric.

Do you understand? That means, the vapor pressure of water at 100 degree centigrade fresh water, that is I am talking about fresh water at 100 degree centigrade, is equal to the atmospheric pressure. That is how the bubbles forms, vapor forms inside and goes out. Am I clear? Do you understand what is vapor pressure?

Now, if for some reason we reduce the pressure of water, we reduce the atmospheric pressure, let us say. Then, what happens? When does the water boil? At a lower temperature. So, you can see the vapor pressure and the temperature are very closely related. And if due to any dynamic action of water, anywhere inside water now, if due to flow of water, anywhere the pressure falls below the vapor pressure, then water cannot sustain itself in liquid state. As we have seen it will try to evaporate and come back. So, it will form vapor. Is that clear? So, when it forms a vapor, it will form a small cavity. That phenomenon is called cavitation.

So, that means if I have absolutely pure water and I allow it to flow in a manner that in its journey the pressure at any point falls, the total pressure, falls below the vapor pressure of water at that temperature, that it will form a cavity. At that place it may be quite below the water surface, it may not be on the surface, isn't it? Then, there a cavity will be formed. This is the phenomenon of cavitation. Have you understood? Now, I will give you some values of vapor pressure of water. This is only to bring to your notice how it changes drastically with temperature.

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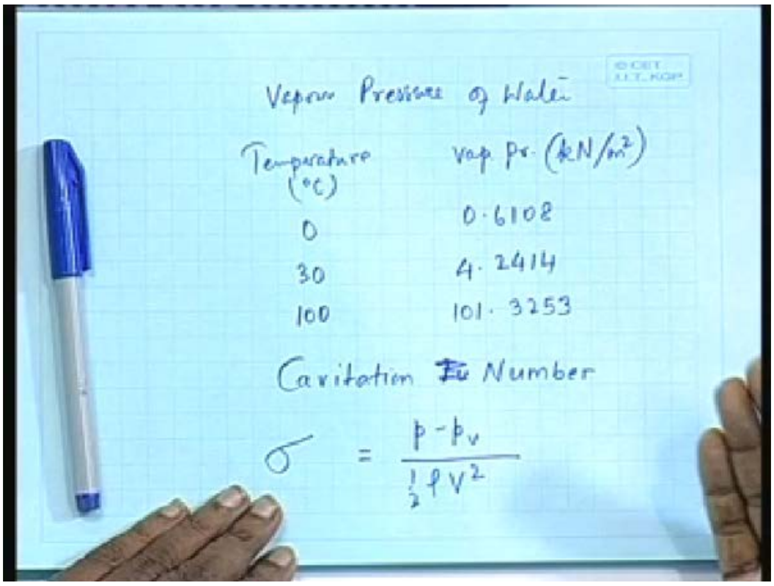

Kilo newtons per meter square. At 0 degrees, it is 0.6108 kilo nektons per meter square, which you can see is very low. At 30 degrees, which would be the ambient temperature here, most of the year it is around 30 degrees, 4 .2414. And at 100 degrees it is equal to atmospheric pressure and the exact value is… 253 kilo nektons per meter square.

Can you see this? Can you see how much the temperature effects it? So, if I am going into a cold climate, same water flow will perhaps cause more cavitation than in a, sorry. In a hotter climate, if suppose the pressure is 3 kilo newtons per meter square, it will form a cavitation at 30 degree temperature, but it will form no cavitation at 0 degree centigrade. You understood?

Now whenever a cavity is formed, there is the phenomenon, there will be interface between gas and the liquid, isn't it? So, we will have surface tension. Now, what is surface tension? Surface tension is a force which is trying to keep the liquid surface. That means there is a force towards the liquid, say in the surface of water the molecules attract each other and the top molecules are attracted only by the bottom molecules because there is no molecule on top. So, there is a force towards the liquid. So, there will be a force towards the liquid. So, to the cavity to remain, the force required will be slightly more than just formation of the cavity itself. That means though we say this is the vapor pressure at which the water will cavitate, there is a possibility that due to surface tension the cavitation number, I have not defined Cavitation number, we will come to it just in a minute, that is the pressure perhaps should fall a little below. So, there is more force for formation of the cavity so that it can be retained. Are you understanding?

So, this surface tension business will change depending on what is the kind of vapor made of, what is the vapor made of. For example, if it is the same liquid, same substance, then it will be one type of surface tension. If it is a dissolved gas, which is because of low pressure it is forming into a bubble, then the surface tension will be different. So, though we can define this vapor pressure, actual formation of vapor may be little less or little more than this pressure because of surface tension.

What is the other thing that will effect formation of cavity? We can see from physics point of view that if we have dissolved particles, then it is possible to form a nucleus of a vapor around the dissolved particle rather than the gas itself, liquid itself becoming a vapor.

If we have a dissolved gas, which normally surface water has a lot of dissolved gas, and if there is a particle, the gas will try to form a bubble around it. And it can form a bubble even much higher than the vapor pressure itself. Do you understand? Can you follow me? But it depends on the solubility of the gas, different gases may form vapor at different this things.

So, this vapor pressure that we are talking of, is an ideal vapor pressure. Do you understand? Actual cavitation may take place quite a lot around it, it may be quite below it or it may be quite above it. Now, I have also mentioned about vapor pressure, now I will define a number that we call cavitation number represented by sigma, which is equal to p by p v divided by half rho v square p minus p v. p is the pressure of the liquid at the point under consideration, p v is the vapor pressure of the liquid. So, p minus p v, if it is 0, then cavitation will occur, isn't it? Theoretically, it may be plus minus this, but theoretically, when this p minus p v is 0 or this cavitation number is 0, cavitation should occur. Half rho v square, rho we know density of water, v is the speed of water. This gives you the dynamic effect, the v. So theoretically, when sigma is 0, we should have cavitation.

But as we have seen, it is not necessary for the p minus p v to be 0, it can occur at a higher pressure or even at a lower pressure. But all we can say at this stage is, as the cavitation number goes down and down the lower the cavitation number, the more is the probability of cacitation. Understood?

So, if a particular liquid in a particular flow condition is causing cavitation, increase in the velocity, thereby reducing the pressure, will cause further cavitation. Is that clear? In other words, if I can reduce the velocity or increase the pressure by some other means, then that cavitation may not occur again. So, this is a very important parameter, this cavitation number and we will remember this, we will try to remember this.

So, from these we can draw certain conclusions, that in a marine propeller how can cavitation occur? Just the pressure and velocity phenomenon. Let us look at a marine propeller. A propeller blade rotates from a height to a lower height then goes up. So, the hydro static pressure acting on the propeller blade, hydro static pressure you understand, the height of water column above the point, will be low when the propeller blade is at the tip and it will be high when it is at the bottom.

On an average, we can say either hydro static pressure acting on the propeller is at the shaft center line, where you have half the blade above half the blade below. But locally the hydrostatic pressure is low at the top and high at the bottom, this is a very broad indication of pressure variation. On top of it we will impose the hydro dynamic pressure. We have seen yesterday that the propeller generates high pressure on the face and low pressure on the back. Have we seen that yesterday, isn't it? So, and that is how you get the lift by pressure variation.

So, when you generate negative pressure on the back side, that negative pressure if it goes below the vapor pressure of water or their about, then it will cavitate. So, the negative pressure on the back of the blade, what does it depend on? It will depend on the blade shape, the kind of aerofoil section you have that is called thickness etcetera, it will depend on the water velocity and it will depend on the angle of attack, isn’t it? Angle of attack is directly related to lift, which in turn is directly related to negative pressure.

So, the more lift you try to generate from the propeller, the more will be the probability of cavitation, that is the negative pressure on the back will increase, isn’t it? We have also talked about the change in velocity in the propeller, the water flow velocity, we have talked about in our previous classes that in the propeller disk the axial and circumferential as well as transverse velocities keep changing over the entire disk.

So, really we do not know about this local cavitation number can sometimes be low even at the bottom of this things because of the flow of water velocity changes or it can be low at the top it can be low at the sides. So, cavitation can occur around a marine propeller anywhere. We look at different types of cavitation that marine propellers experience. Also let us talk about where else in our marine applications cavitation can occur. You have known about hydrofoil boats. Have you heard of hydrofoil boats? That is if you have a boat, which has a section like this and the water line is here say, it has this displacement. We have talked about buoyancy and displacement, we know that. So, in a mode of operations where buoyancy is equal to weight, the whole of this boat is inside water. Buoyancy equal to weight is the normal Archimedes principle.

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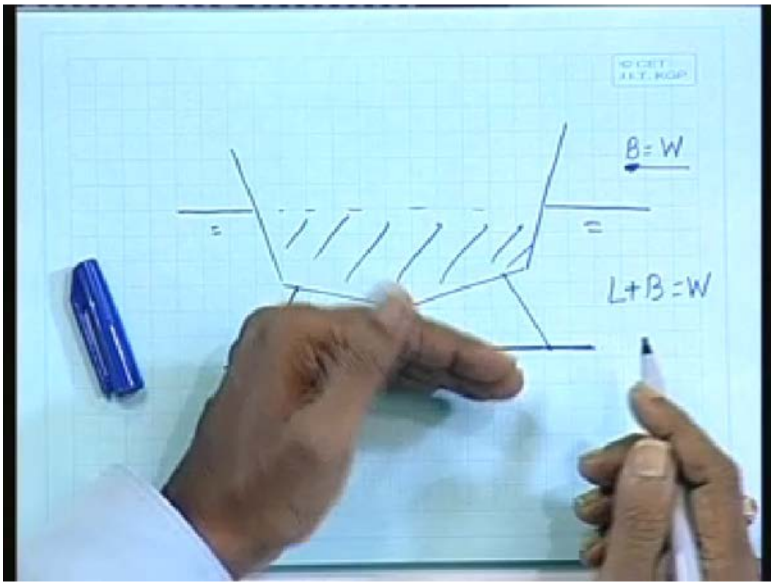

But if we want to move it at a high speed, then this boat has to be lifted out of water, like an aircraft. One of the modes of lifting it out of water is like an aircraft, which is heavier than air machine stays in air. How does it stay? It stays by generation of lift from its wings, isn't it? And that lift is again a function of the speed, that is aircraft speed, the angle of attack that is the angle that the wing makes to the air and the shape. Same in hydrofoil, we can have similarly a wing which can provide a lift and the vessel can, if we have a upward force which is lift, then our buoyancy support that we are writing b equal to w will not be necessary, what will be there is l plus b is equal to w, lift plus buoyancy is equal to w. This will be the equilibrium condition. So, we must get a lift, isn't it? And what better way, I can just say, let us say I have two (( )) coming down and I have a foil here, I am just telling as an example, this is not really telling you about the design of a hydrofoil board. But if I have a foil here that is cross section is that of an aerofoil, then if I move this boat, as the speed increases, this foil will start developing lift and this boat will start coming up and up. Do you understand? But a minimum speed is required and that is after a critical speed only. So, all hydrofoil boats which are supported by hydrofoil, where lift is lift from the hydrofoil lift, can be generated in many ways. I am talking about only lift by hydrofoil, the boat can lift itself. So, this is a normally a high speed boat, where a hydrofoil supported vessel can move at a high speed.

Now, this hydrofoil being an aerofoil section, will work on the same principle of high pressure on the face and low pressure on the back. That is how you get the lift? So, as soon as you reduce the pressure and remember that this foil this vessel will be lifting up. So, this foil will be actually moving up. So, the hydrostatic pressure will be reducing. Do you understand? So, the total pressure on the foil, particularly on the back side will reduce. So, hydrofoils are also prone to cavitation.

What are other hydrofoil sections we use in ships, which work on principle of pressure difference? The rudder also works on the principle of pressure difference. Because aerofoil section, when we turn, it generates lift in one direction that is how the vessel turns. So, again there will be a negative and positive pressure, depending on the velocity of flow onto the rudder, there may be cavitation. Sometimes these cacitation can also occur on the ship body itself. If dynamic pressure, we have seen that wave making is a function of pressure distribution. At some places if there is very low pressure, the body itself can have cavitation occurring on itself.

So, on ships, propellers, rudders, hydrofoils etcetera cavitation can occur. What are the types of cavitation? I will straight away go into explaining to you different types of cavitation from a diagram which I have prepared earlier.

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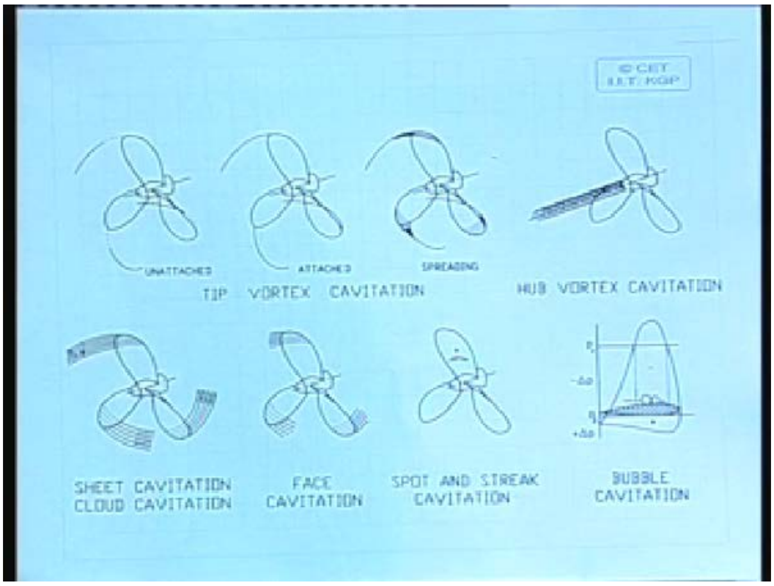

Can you see this diagram? Is it clearly visible? Now, you see we have seen yesterday that propellers at vortices. We have talked about trailing vortex sheets being shed from the propeller. Now, if the strength of the vortex is strong, then you can also see it with the help of a stroboscope. In a tunnel, where the propeller is working we can also see the vortex sheet, if you can have a stroboscopic arrangement of lighting, then you can actually hold the propeller steady and see the vortex being found by the propeller. But you cannot see the vortex as such because it is also water, it is only water moving in a particular direction, it is not changing phase. So, unless there is a bit of air you cannot see it. So, when do we see it? In a vortex you realize that there is a distribution of pressure, pressure being the lowest at the center, as you move towards the center the pressure reduces, the velocity is high. Remember, we said about the velocity being inversely proportional to radius, isn't it? And this vortex strength is high towards the root and tip, that is the end of the propeller blade. If a propeller blade is there, if this is the propeller blade, the vortex strength is high at here and here.

So, what you will see, water strength is high means the center the pressure will reduce. So, there may be a cavitation at the axis of the vortex at the tip and may be at the root. In that case, you will actually see a helicoidally surface being generated as the bubbles keep moving in a helicoidally manner. You can see it in a cavitation tunnel. Do you understand?

We have also noted that velocity increases, velocity keeps increasing from forward of the propeller, across the propeller to some distance aft, isn't it? So, sometimes cavitation inside a vortex will not start at the tip itself, but somewhat after the tip. Do you understand? When you see the vortex formation of the cavities, a little aft of the propeller tip. Can you understand that why it happens? Have you understood? Because the velocity is increasing, the pressure is dropping further. That is called a tip vortex cavitation, but this is unattached. You can see the first diagram, this is the unattached vortex cavitation, the tip is shedding vortices, but it is not attached to the propeller. Can you see it?

Now, if the pressure at the propeller tip itself is low for cavitation, then the vortex will be attached to the tip. So, you will have attached tip vortex cavitation. And tip vortex cavitation, if there is a further reduction of pressure around the blade surface, the tip vortex cavitation will cover tip a little more area of the propeller and you are spreading tip vortex cavitation. So, you will see the cavity moving, see this is from the diameter. So, you will see a big helicoidal surface forming after the propeller tip. It is going, as the propeller is rotating you will see the cavity to the aft of it in a cavitational tunnel, you can actually see the cavity.

Now, if the root forms a cavity, root vortex forms a cavity, the propeller boss, if there pressure there is very low, then the cavity will form with small diameter. So, it will look like a rope. You can see that also. A rope goes in helicoidally surface, strands are wound like that and you will see that like this. This is the hub vortex cavitation or root cavitation also will look like, if at the root of the propeller blade cavitation starts, that will also look like this because the diameter of the cavitation spiral will be small. Is that clear?

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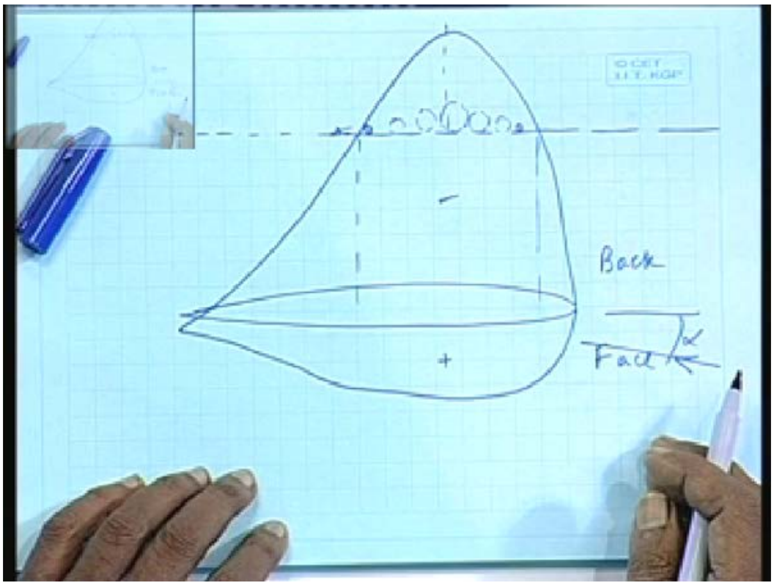

I Now, sometimes let us look at this diagram here, I think I should draw it. If I have a propeller blade like this and I draw the pressure diagram. The pressure diagram will look like this. This is the back, this the face, this will be positive pressure, this will be negative pressure. On the back is the negative pressure, on the face is the positive pressure giving a lift upward. How is the water flow here? Water flow will be something like this at an angle, isn't it? Is that clear?

Now, let us say the vapor pressure of water is somewhere here, a very small amount of vapor pressure, I mean, I have put negative, negative means negative compared to this, this portion is less than vapor pressure of water. Now, if we assume that the cavitational start if pressure falls below this pressure, then this portion of the blade is subject to cavitation, isn’t it? The back of the blade, am I clear?

So, how will it form? First a cavity will form here which may look like a small bubble. Now, this bubble will go on increasing in size till about here, where the pressure is high. So, may be something like this, exerted perhaps. This same bubble may not increase, but water here will start cavitating into bigger bubble.

Now, as the pressure starts falling now, this will start reducing in size. What happens here? This bubble is travelling this side because the flow of water is like that, this bubble is travelling, this small bubble will now cross over to this side, to a side where pressure is higher than the vapor pressure of water. So, it will implode, implode means it will burst, there is water pressure all around trying to press it and it will change its physical property and the bubble will burst. When this bubble bursts on this surface, remember this is touching the surface this is not free, there will be a shock wave transmitted to the blade surface.

So, this type of cavitation is called bubble cavitation, which I have shown here. This cavitation is called a bubble cavitation. You can now see from whatever I have said that, cavitation cannot be predicted only on the basis of vapor pressure of water because of dissolve gases, because of temperature, because of water speed and because of impurities present in water. Therefore, you cannot really predict when the cavitation will occur just by knowing the vapor pressure.

When we try to model it in a cavitational tunnel, it is necessary that the water must be mixed with some amount of gas, that is air, before it is circulated so that at least somewhat resemblance to the real situation can take place. Therefore, in the cavitational tunnel there is a whole mechanism to provide dissolved air in water, when the water flows in the cavitational tunnel to try and simulate actual condition.

Now, suppose there is a spot on the propeller due to some reason, a little dent in the propeller. That place will act as a particle to form a cavity. If the pressure is coming down and I have provided a little protrusion on the propeller surface, then like a dust particle it will form a nucleus for a cavity to form. So, it is possible that as bubble will form there repeatedly even though the rest of the blade is not having cavitation. Do you understand? That type of cavitation s sometimes occurs you will find in a rotating turbine blade or rotating propeller blade or whatever. A spot cavitates continuously. This is shown here in this diagram, you can see it is written spot cavitation.

Now, it so happens that spot may travel over a small distance and then it is called a streak cavitation. Just one line, just a small number of bubbles in a line. These are all types of bubble cavitation of course, bubble cavitation can occur over a wider area, bubbles forming over a wider area, traveling and then bursting, that of course. Then you have what is called a sheet cavitation, that means if the pressure is low, if this pressure, this negative pressure occurs to over a wider area, then this cavity formed over the entire surface and it will form like a sheet. The entire surface will be covered with a cavity. In that case, that is called a sheet cavity, it is not a bubble but it is a sheet. As the sheet moves towards a trailing edge, the sheet will disintegrate not as a bubble but as a sheet. But how does it disintegrate, what will happen? It will burst into small bubbles, very tiny bubbles but a lot of bubbles. So, that will look like a cloud. So, very tiny bubbles formed over a large area are called cloud cavitation. And that is typically when a sheet cavity, sheet formed on back of a blade moves towards the trailing edge.

So, you can see that cavity formation is nearly always towards the aft of leading edge on the back and as it moves forward towards the trailing edge the cavity starts disappearing in some form. Maybe it will be a sheet cavitation, cloud cavitation and cloud burst on the trailing edge or bubbles slowly coming towards the trailing edge and bursting there and disappearing, provided the angle of attack is positive. Am I clear? The same thing applies in hydrofoils, that if angle of attack is positive, you have a cavitation phenomena which is occurring somewhere here and moving towards the trailing edge and disappearing at the trailing edge.

Now, in a propeller, since we know that velocities are varying continuously, you cannot guarantee that the angle of attack will always be positive. There may be cases when angle of attack will be negative. They may be like this. When angle of attack is negative, negative pressure will develop on this side and positive pressure will develop on this side. It may be for a small time or it may be for a larger period, depending on a particular area of the blade moving in a particular velocity field. It can also occur in hydrofoils, depending on the inclinations of foil, the vessels (( )) and all this things. So, in that case you will have face cavitation. Back cavitation will not be there, but you will have face cavitation.

So, you have different types of cavitation based on how the cavities are formed such as spot cavitation, streak cavitation, bubble cavitation or a sheet cavitation or cloud cavitation. You can have different cavitations based on the location of the cavity, such as tip vortex cavitation, root vortex cavitation or hub cavitation. You can have the face cavitation, back cavitation etcetera. So, propeller blade as you can see cavitate in many ways.

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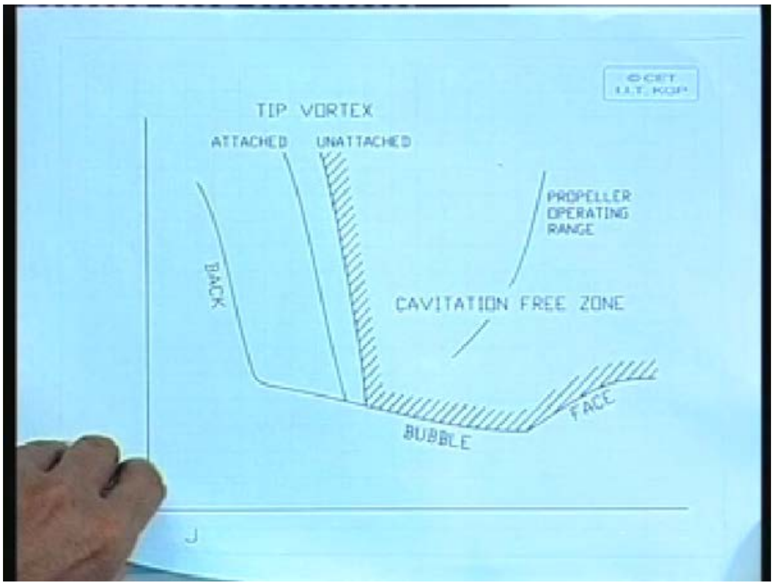

You have done propulsion in your other courses? Something about propulsion? You know what is advance coefficient j, you know the thrust coefficient t and torque coefficient k t and k q advance coefficient j you know. Now, I have introduced you to cavitation number, sigma.

Now, this is the general nature of cavitation of a propeller. This is sigma versus j curve, that is this is the advance coefficient and this is the cavitation number. And depending on the location of the propeller, this portion is the cavitating portion, outside this envelop is the cavitating portion of the propeller. This is unattached tip vortex, as the j reduces further, the tip vortex attaches itself. And further reduction of j, you have back cavitation. But as j increases, but cavitation number is low, slowly the back cavitation then there is the entire thing is bubble and sheet cavitation. And slowly plus towards high j values, high j will occur when the angle of attack may change and you will have face cavitation.

So, this is the area where there is no cavitation, this inside area. So, we like to have the propeller operating in this area. And typical propeller operating range is this, j versus sigma values, you can see. But if your sigma falls below this. Then there will be cavitation. As we have seen, the sigma will depend on local pressure and local velocity, these two things are very important. Understood? We have also seen different types of cavitation. Now, we will see what are the effects of cavitation. What are the effects of cavitation?

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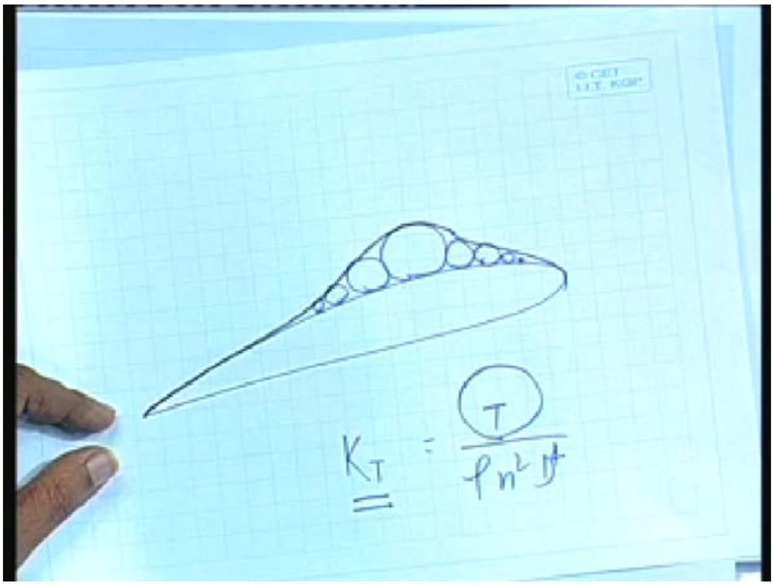

You imagine a propeller blade on which you have a lot of bubbles coming up here. Now, this propeller blade geometry with regard to water is no more this geometry. The geometry has changed to something like this. So, the pressure generated on the back, negative pressure will change. It is now no more the pressure which caused this cavities. The lift that you will get will now change. Do you understand? So therefore, in a cavitating propeller the thrust and torque characteristics will change. If a propeller is cavitating then the thrust and torque characteristics will change. How will it change? This diagram you are aware. Look at the dark lines, full lines j versus k t ten k q and efficiency. This diagram must have been shown to you earlier.

So, you can see the k t curve is this, k q is this and corresponding efficiency is this. This is at non-cavitating condition of the propeller. Now, as you have seen cavitation number reducing, cavitation will occur. And cavitation will occur in small amounts, as the cavitation number goes further down more and more cavitation will occur.

So, the loss of k t and k q will be further more and more. So, here we have given the 1 2 3 4 5 curves with 5 having no cavitation and going towards lower cavitation towards 1. You can see the k t and k q both are falling and so is efficiency. So, you can see that, what is k t? t by rho n square d 4. So, if k t is reducing, what does it mean? t is reducing. And same with k q, that is propeller will be unable to observe the power provided by the engine. q is reducing means, rpm remaining constant. q is reducing means power observed by the propeller will be less. Now, you are forcing the engine with feeding more and more oil to absorb the power. So, as you keep feeding of this thing, propeller and engine must match, one is providing load, the other must be able to take the load.

So, now the propeller at the same rpm is unable to take the load and you are providing more power to the engine, what will happen to the propeller? It will raise, the rpm will increase. Do you understand? If the rpm increases, again as you now know in all marine engines the design for certain amount of rpm axis only, they cannot raise like that. So, engine efficiency will fall, engine will stop. So, we cannot go on increasing rpm. There will be a tendency for the rpm to increase, but it cannot increase. Therefore, the thrust will reduce, the torque absorbed will be less, engine will work inefficiently, thrust will reduce and vessel cannot get the desired speed. This is what will happen if the propeller capitates badly, if there is a drastic drop in efficiency.

Now, you can understand. We talked about turbine at the beginning, we talked about propeller racing, Osborne Reynolds paper on propeller racing, subsequent to turbinia, how the speed increased once the propellers were the load was distributed. We will come to load distribution little later. So, this is one of the main effects of propeller cavitation. A loss of efficiency, loss of speed, loss of thrust and non observance of the full power.

Now, what else occurs? We have seen that the bubble bursts on the propeller blade. If it bursts on the propeller blade, there is a shock transmitted there. Now, imagine the propeller is rotating at constant speed in the same plane, that is whatever velocity variation is there, is the propeller blade each section is experiencing that variation in each rotation. At the top, towards the top, the hydrostatic pressure is less and towards the bottom, hydrostatic pressure is higher.

So, probably propeller will start cavitating more at the top and the cavity will burst as it comes down because the hydrostatic pressure will be more, probably it is possibility. Similarly, in the velocity field, it is possible that one place the local pressure is low and at another place pressure is high. And this will repeat itself in each revolution for that blade. So, what I am trying to say is, if a bubble is bursting, it will keep on bursting at one speed one location continuously in each revolution. Do you get it? It is like hitting a place with a very high force continuously at a specific point. What will happen to that point? There will be a pitting, there will be a hole and propeller will erode. That is called erosion.

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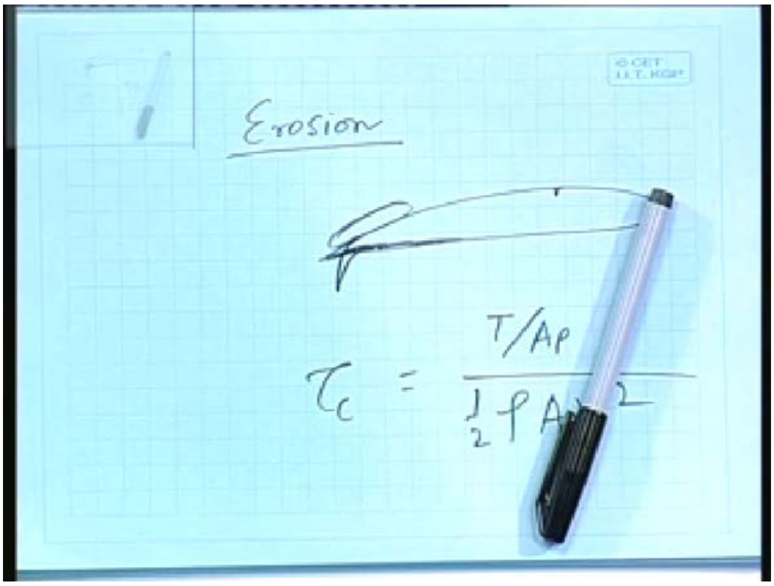

So, what will happen? If you look at a propeller blade, you will have a small pit coming up here. You will find in many marine propellers which are been to sea, when they are (( )), you will find the near the tip there will be a lot of pitting, lot of holes there. This is typically due to cavitation. What is it do? Is this pitting good or bad? It causes further cavitation. As you know, disturbance roughness we have created, efficiency is dropped and speed loss is there, apart from the fouling corrosion of this thing, there is a large amount of speed loss because of the roughness of the propeller surface. Sometimes this pitting can be over a large area and you will have loss of material, that is also possible.

Another thing that takes place, since most of the cavity is going and bursting near the trailing edge, the trailing edge may bend, instead of pitting it may bend. Because there is a large amount of bending edge. See, this is the trailing edge. If a large amount of bubbles is bursting around this place continuously and since there is less material here, which is less strong here compared to here, this may bend. Many times you will find that the propeller trailing edge towards the tip has bent, many damaged propellers have this character, this is another effect that can happen.

And one of the most damaging effects for naval propellers cavitating is the vibration and noise. We have talked about vibration due to variation of (( )) in the propeller disk, we have talked about in earlier class, isn't it? So, if in that variable (( )) we have cavitation, then the variation of pressure field can be as high as ten times, that is the lowest pressure to highest pressure variation, if it is cavitating and cavity is bursting. If cavity is not bursting and is a permanent feature of the blade, it does not matter. But if the cavity is bursting, then the variation of pressure in each revolution into number of blades at that frequency, the variation of pressure would be as high as ten times the normal variation of pressure of a non cavitating propeller. Do you get it?

So, this variation of pressure will send water pressure pluses around the surrounding and the propeller blade itself may vibrate. If it vibrates, it will send noise signals in water due to the propeller vibration as well as due to hull vibration which is being impinged by the water pulses. And for a naval vessel this is extremely damaging because it will send a signature of the ship to the enemy.

Do you understand? This water pulses travel as noise. We can measure it by a noise meter or by eco sounder, a kind of a acoustic signal sensor. So, you can get it and that gives a signature of the ship and its propeller. You are getting two signals, one from the propeller, one from the ship. So, the vessel can be easily detected. The other thing its own sonar detection capability reduces because there is a lot of pulses which disturb any other pulse that may be coming on to it. So, its detection is limited and its possibility of getting detected is high. And this will increase as the speed increases because the vessel will start cavitating more and more. So, cvpitation is a phenomenon which must be avoided. And how do we avoid it? I will go over this quickly. One of the ways is to distribute the negative pressure. Instead of having a peak, can we distribute the negative pressure over a wider area of the blade surface? If we can do that, then typical points of high pressure can be avoided. You can see the section here. It is a segmental section, it is called a segmental section, that is the sections are perhaps part of circular arks rather than aerofoil section.

So, its efficiency will be lower, but its probability of cavitation will be less. So, normally in standard propellers what we do is, where we have aerofoil sections at the starting from the bottom till about middle or little more than the middle of the span, of the radius, towards the tip we convert the propeller blades to slowly to segmental section so that the cavitation of the tip is reduced. This is one way you can do.

And professor (( )) way back in mid nineteen mid 1900s produced a set of diagrams as a function of this thrust coefficient, tau c here is the thrust coefficient, yes I haven't told you about this. Thrust coefficient is this… half rho a v square is known like drag coefficient, lift coefficient, this is thrust coefficient t divided by this, but t per unit area a p is the projected area of the propeller blade, each propeller blade. So, t by a p is thrust per unit area of the propeller blade divided by this gives you thrust coefficient. We have discussed how lift is generated, how lift and torque and thrust are related. Therefore, the thrust as an indication of the negative pressure on the back. So, if the thrust coefficient is high, that means negative pressure is high, there is more probability of cavitation. If thrust coefficient is low, then cavitational probability is low.

So, there is a diagram given by professor (( )). He generated this diagram and suggested limits of cavitation for highly loaded propeller,s for merchant ship propellers and for tugs and trawlers. So, this diagram gives more or less an indication whether the propeller will cavitate or not, provided we know the thrust that you are generating the rpm at which it is moving and the speed of advance of the ship v a.

Now, I will take just two more minutes. You can see this loading, how do we reduce this loading of the propeller? You can see if thrust is high, then propeller is highly loaded. If my A p is also high, projected area is high, then this loading reduces. A p is high means, I must have a larger area of the propeller blade. So, one of the fundamental requirements for reducing cavitation is increase the area or make one or two more propellers, then thrust developed by each propellers is low and the area is also high. So, these are some of the principles of how the cavitation can be reduced.

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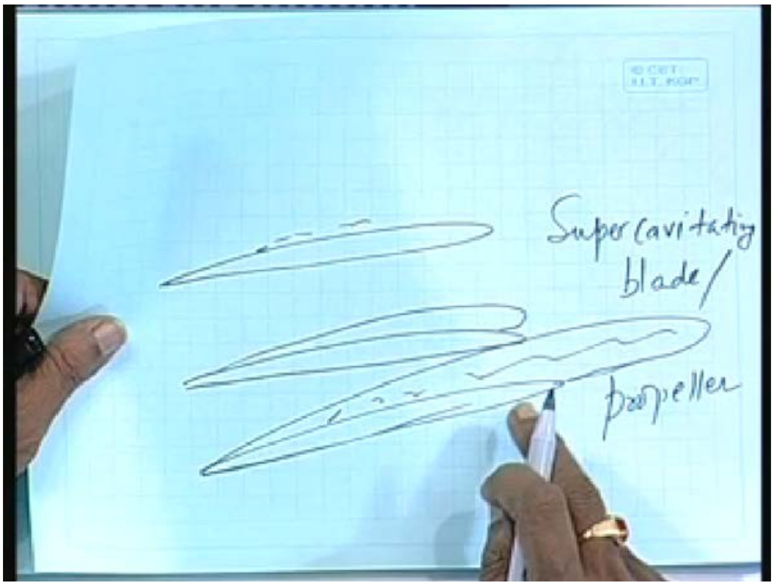

One more this thing I will tell you. See if you have got a propeller blade like this, there will be a cavitation here. As you increase the speed, this propeller blade will slowly generate a cavity which will be a sheet cavitation like this, perhaps spanning over a large portion of the blade. Now, I go on increasing the speed of propeller blade, what will happen? I will have a cavity which will go like this, which will cover the entire blade. And if I can retain this cavity in the entire rotation, then the cavity is not bursting, I will avoid the harmful effect of cavitation.

It is as if I am having a propeller blade of a different geometry. You understood? That means, the complete backside, I cover by means of a cavity and I make sure that this cavity is retained. This phenomenon is called super cavitation or such a blade is called a super cavitating blade and a propeller is called a super cavitating propeller. So, if you have this, then giving a small area you can have the effect of a large area. Now of course, this requires a little bit of modification of design.

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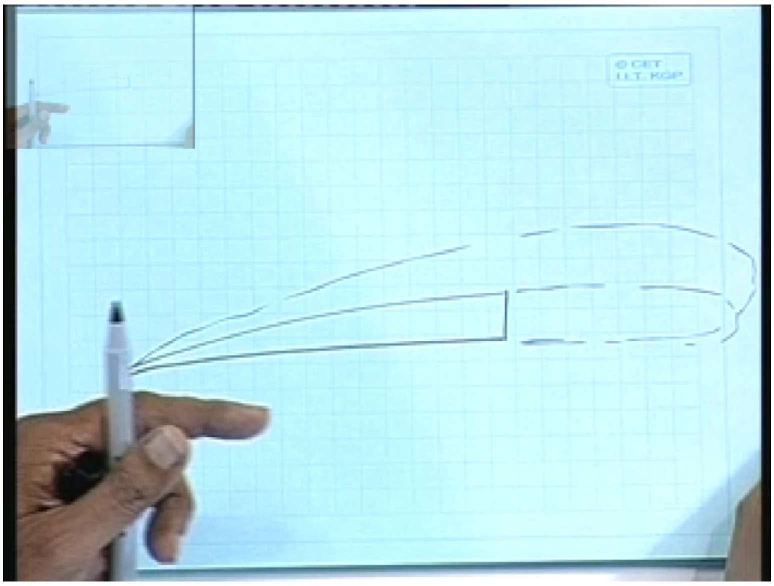

And normally super cavitating propeller blades are of a different nature, it is like this. And you can have a cavity which is like this or which is covering the entire blade like this. So, here you can see the back and the back of the aft of the leading edge are covered by means of a big cavity or a cavity where only the leading edge is covered by means of a cavity, either of these is used. So, thank you then, we will stop here.