**Ship Resistance and Propulsion**
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**Lecture - 5**
**Wave Making Resistance**

Good morning to you. We have already discussed about the various components of resistance of which one is the major component is wave making resistance. The other major component is the frictional resistance.

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There we have seen the physical reasoning for the frictional resistance and how it is related to ships speed or flow velocity. Also, we have seen that it is equal to wave power. It is propulsion to wave power 1.825 that we have already seen. The next major component is the wave making resistance. It is actually coming from the pressure disturbance due to the movement of they come.

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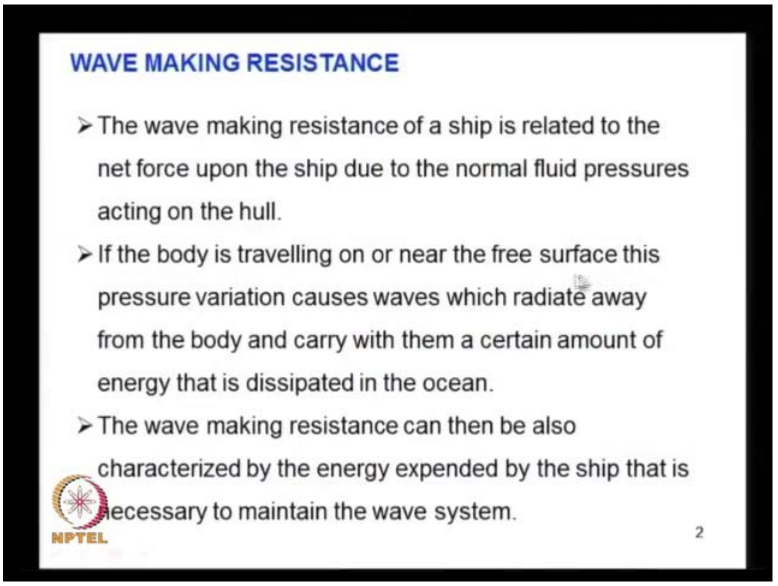


The wave making resistance of a ship is related to the net force upon which acts on the ship due to the normal fluid pressures acting on the hull. So, that is basically due to pressure disturbance. When the ship moves, the ship which is treated as a pressure point when it moves at a steady speed, it generates waves of a characteristic pattern. So, this wave making occurs when the body is at the near surface or at surface, but if it is replaced so much, then you do not get any wave making.

Naturally, there will be no resistance due to the wave making effect. That is a case with submarines and in all that which operate and deep submerged condition, the wave making resistance is not there, but when the submarine comes to the sub surface or near to the surface or at surface, then wave making will be there.

Then, we have to; you have to consider the wave making resistance also for the estimation of total resistance of the submarine when it operates at the surface condition. So, here the body is travelling or near surface. As I said, free surface as a pressure variation cause waves, which is you know it is explained. These waves created by the vessel radiate out. It goes out. These waves possess energy and a continuous loss of energy to ship system, which amounts to the resistance of the ship. That is contributed by the wave making and it is sustained.

So, that is what it means. So, it is associated with the energy. So, we have already discussed before the wave making when we discussed about the wave making component of the resistance when the waves are compared to still water condition. If you consider the still water condition, I will just, I think, I have already explained to you when consider still water and the ship moving there.

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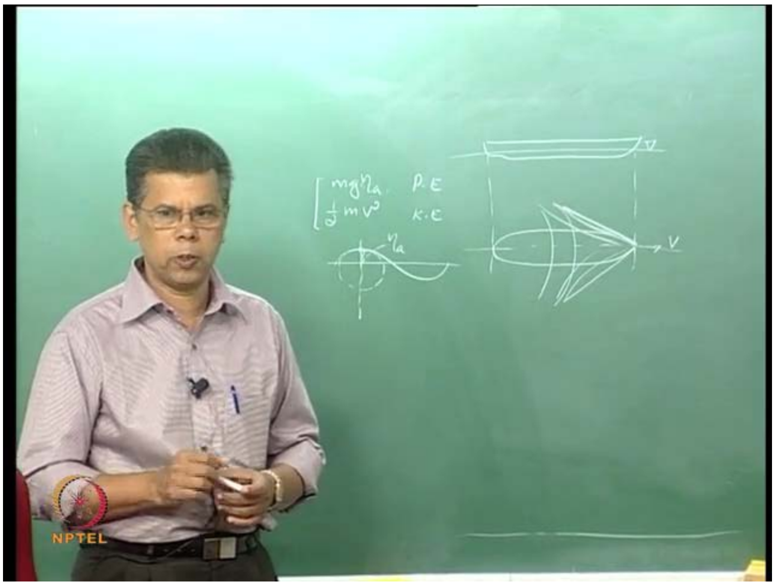


So, if you consider this and if you take the planned view of this, consider this water line where it may be, the ship like this. So, when it is moving with a velocity v, the ship is moving with the velocity v, it generates waves. We will say that it has a characteristic form of the wave. So, you have waves which go in the, there is a divergent wave system and also you have the Trans surfaces system. So, consider this with two waves systems and these waves posses energy. So, you know that if you consider still water and a wave condition, waves in still water, then at still water, there is no disturbance of the water surface. When the ship moves, it generates waves. These waves take this form and due the water particle which was here, it is moved to this place.

So, this is due to the elevation of the water particle. The water particle, now we shall know water particle possess mass. So, due to the change in position of the water particle, there is an energy associated with that, which we call as potential energy. So, this potential energy view is represented by mg in to h or h is given by this or say, if it is a eta a, you put, then you put it is a eta a. So, there is a potential energy associated with that. We have also discussed when we discuss about the component waves.

The water particle is subjected to an orbital motion in a wave, which is usually circular in ship in the proto condition and the water particle oscillates about its mean position. That means the oscillation is among with mean position particular position where it was. This again the water particle which possesses mass, which is subject to a motion, will have kinetic energy associated with that to the motion, so which is given by half m v square. v is the tangential velocity of the particle when it moves of it orbit. Now, the wave possesses two types of energy. This is a potential energy and this is a kinetic energy.

So, the wave possesses energy. The law of conservation of energy applies here. The ship is moving. It generates waves and the waves possess energy in two counts potential energy and kinetic energy. So, this energy has to come from the ship. So, that is how the energy relations are applied to the wave making resistance. So, when the ship moves in still water, no ocean waves are considered. We will be considering just still water. The ship is moving through still water. It generates waves. These waves generate, these waves possess energy and this energy is being lost to the ship, which accounts for the wave making resistance of the ship.

So, that is what is explained here and see that it is related to the energy dissipated in the ocean. That means this is going and thus getting dissipated in to the ocean. So, the wave making resistance can then also be characterized by the energy expended by the ship that is necessary to maintain the wave system. So, that is what it means.

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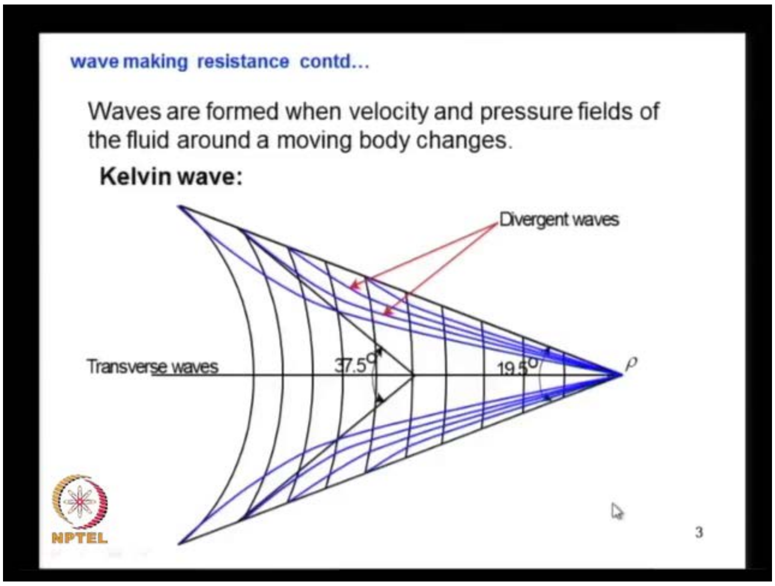

So, if you look to the characteristic pattern of the waves created by the ship in still water which has been studied by Kelvin, he considered a pressure point. You can see this is a pressure point. I take this p is a pressure point, which is moving having a constant speed, so which generates a wave pattern like this. It is as good as saying that you might have noticed in a canal where the fluid is uniform, there is a free stream flow, canals usually irrigation canals and all that, they put a pole to measure that depth of water. You say there is wave form created downstream and this pattern resembles this one. So, this is a typical Kelvin wave pattern.

So, if the speed of the vessel or which you call the fluid number is within acceptable limit that means within moderate or below moderate, as usual is small, then this angle will have this is the half angle. It is not the total half angle is nineteen point five19.5 degrees and this angle again; the half angle is 37.5 degrees. So, this is called, this shows that you know the boundary of the wave pattern created. These blue lines what you see here, they are the divergent waves, which diverges around when the ships moves forward. You will have another system wave in association with these waves which starts from tangentially from the divergent wave.

Then, it comes like that which gets converged towards this side if you draw a tangent to this curve and it will be a normal to the part of the part taken. So, that is how it is done. So, this is a type of this is called the transverse waves. So, the total system of waves are constituted by the divergent waves and transverse waves. So, if you draw a line tangential to this normal from this point and from this point to tangential to this point and over here intersecting with that. This angle, the half angle makes 37.5 degrees. This small angle is 19.5 degrees. This a typical character or a characteristic appearance of a wave generated by a ship in still water and that has been observed and studied by Kelvin and known after his name as Kelvin wave.

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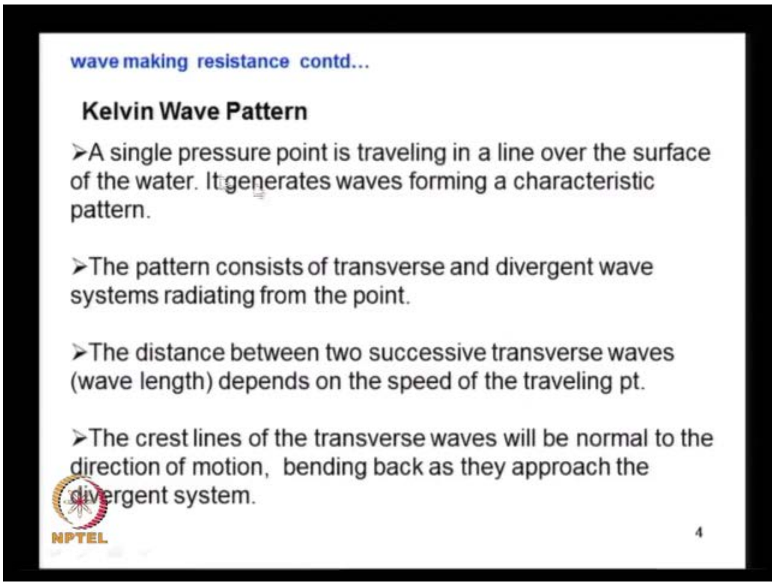


So, Kelvin wave pattern is what you have seen is single pressure point; it is traveling in a line and over the still water surface. We have seen the characteristic pattern of that that is the angle. Then you have seen the pattern of divergent waves and transverse waves. So, that is what is a pattern consists of, transverse and divergent waves. So, system is radiated from the point. The distance between two successive transverse waves or you call as wave length. The crest, the distance between two successive crests and wave length depends on this speed of the moving point or ship.

So, this distance, this is called the wave length. These all are crest lines. What do you see here? The crest of the transverse wave and the distance between successive crests normally, you say it is a wave length. This wave length depends on the speed of the moving point or speed of the ship. So, that is what it means. The crest lines of the transverse waves will be normal to the direction of motion which have I already explained.

The crest line that is if we consider the crest line and if you draw a tangent here, then that tangent is normal to the direction. So, that is what it means. It is normal to the direction of motion bending backward. So, that is what it does. It is bending backward. Now, it diverges. So, from here, it is bending backward. You can see it is bending backward and then it is joining with the divergent wave system. That is the pattern of the Kelvin wave.

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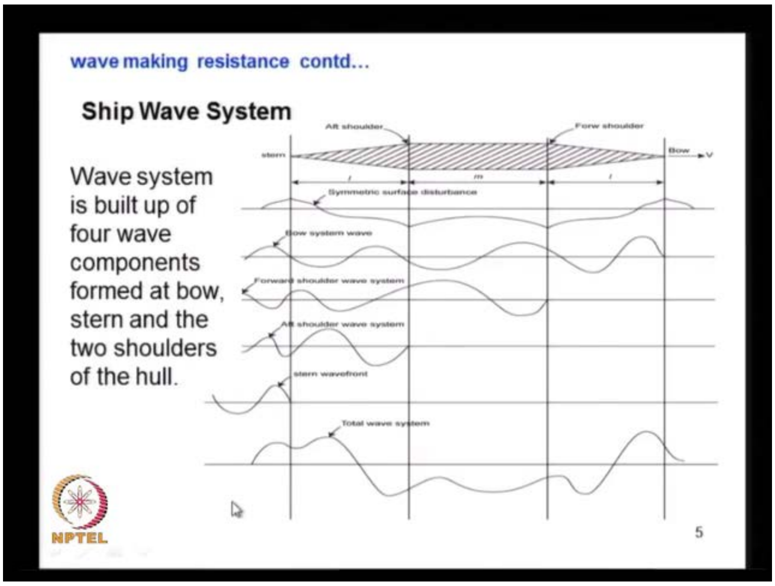


So, we look to the ship waves systems. The ship, if you consider a typical ship, it has got different pressure points. It is not a single point. Depending on the shape of the ship, then be difference regions of pressure disturbances and from each region of pressure disturbance, there will be a system of wave generated. So, what do you show here is see here is the idealist form of a water plane. What do you see think? I have already explained that part still here. So, what you do here?

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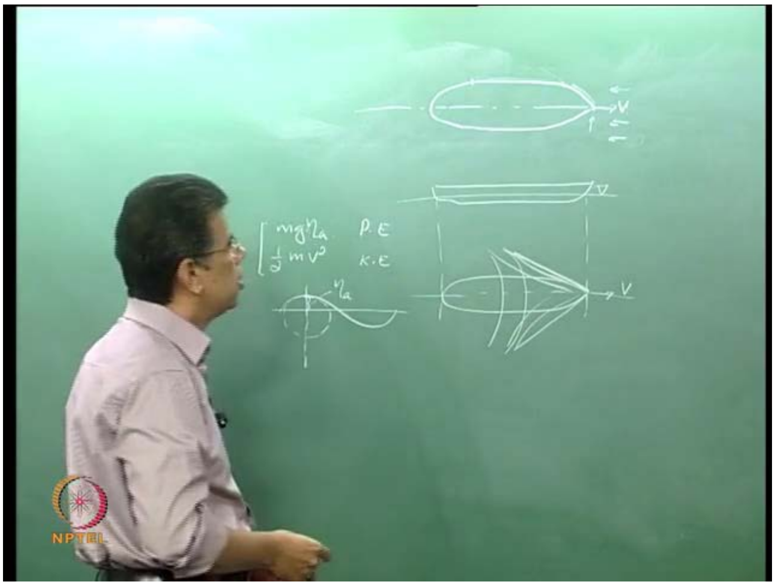

You consider a ship water plane. You consider this is a water plane. Consider that is a water plane at which the ship is floating and this is moving forward. So, you see when it is moving that means the flow is in this direction, the same as with the negative velocity of the ship. So, this point you call it is a forward stagnation point. That means the pressure is maximum here. It is a forward stagnation point. Then you have the flow coming here. When it reaches here, the curvature is changing. It is not continuing like this, but the curvature is changing. When the curvature changes, the flow velocity increases in this case. The flow velocity increases.

When the flow velocity increases, the pressure drops. So, that means there is a point region over which the pressure changes. So, when this pressure changes, then there will be another system of wave generated from there. Now, once it leaves this, it is almost flat here. So, the velocity remains same, but when it comes here, again the curvature is changed. So, what happens? The flow velocity increases that curvature. Whenever there is a curvature, the velocity increases. So, velocity increases there and pressure drops. When the pressure drops again, there will be a wave system created from here.

Finally, if you consider, this point is called the aft stagnation point. So, aft stagnation point that is the place where the stream lines converge and that point again it is zero velocity and maximum pressure. So, you get that another system of wave created from here. So, that is what it is shown here in this diagonal. So, just to show this in a more ideal form, you can see this water plane. This is a bow point. Then you are considering the change curvature this side. That is called the forward shoulder point. Then it is flat here. When it comes here, again the curvature changes, which is called the aft shoulder point.

Then, finally, it comes to the stern. So, instead of putting in the curvature here, just put straight line for you know demonstrating the wave formation. As we said before, this is the forward stagnation point. That is stagnation point. You know that that is a point where velocity is zero. If you look to the Bernoulli's' equation, relation for pressure, then that point will have the maximum pressure. I said you have the velocity head plus the hydrodynamic plus a static everything is equal to constant. So, if one head goes down, the other head will go up. So, here we consider the same static level, water level same. So, only we are just considering the half rho v square term and also the hydrodynamic term pressure.

So, that means if the velocity goes to zero, hydro dynamic pressure will go up because both should be equal to constant. So, that is the principle applied. So, here the velocity is zero which you call the forward stagnation point. The pressure will be high. When the pressure is high, naturally the water surface moves up. So, you see the wave system here. This is a wave system which is generated from the bow. You can say this bow and bow b high pressure region. It starts with the wave crest. You can see that this is a wave crest here and then it propagates backward.

So, when it comes to this point, there is a forward shoulder point. That is a region where I said velocity is higher and pressure is low. When the pressure is low, you can see that it starts with crest, the wave which is originating from here. You can see it just starts with the crest and then propagates backward. Then the wave system at aft shoulder again the same situation because again the velocity increases here and pressure drops. So, the wave system here generates from here this one. So, again I will be starting with a trough. It is not a crest. When it comes to this point, it is a stern that is the aft stagnation point. So, the pressure is high.

So, the waves are coming from there, starting with the wave crest. So, these are the four wave components, which are used to explain the total resultant wave system generated by a ship. So, you consider that you are just actually decomposing the whole phenomena into different components. The resultant effect you get by summing up all the component effects, which you observe near the sea or the wave generated by the ship.

So, this is the thing what you have. So, if you combine all this, you can see here this is the one, you add the whole, you get this, you add the whole thing, and you get this. So, you linearly sum it up and you get this resultant wave. So, the four components added together leads to this wave curve. So, that is the resultant waves of the total wave system of the ship.

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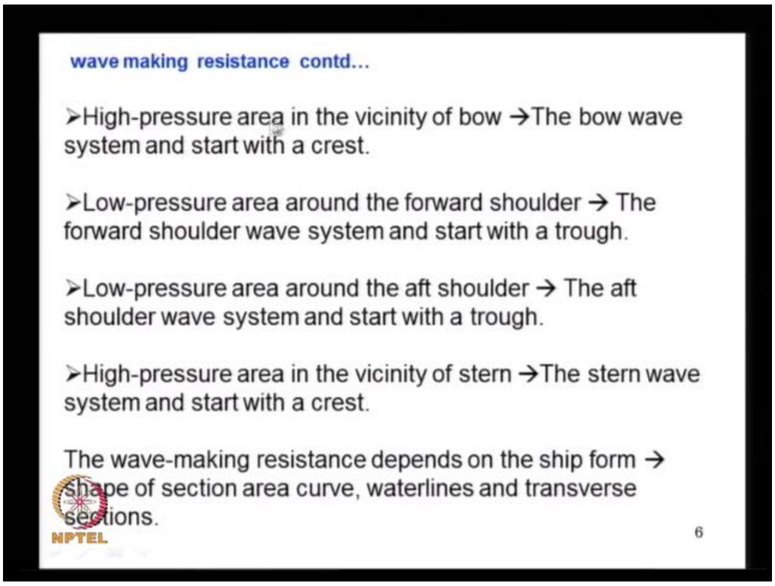


So, that is I have already explained high pressure area in the vicinity of the bow, which we have seen, low pressure area around the forward shoulder, low pressure area around the aft shoulder, I have already explained that. Then high pressure and the vicinity of stern, so and then the wave making resistance depends on the ship from that is the form determines the flow velocity and also the pressure and sub regular wave created by it.

The shape of the section area curve that is if you draw this section area curve which normally you do in one chains, you will see that transverse section area curve and waterlines and transverse section ship, basically the form, ship form, which is indicated by section shape of a section area curve, shape of waterline and shape of the transverse section.

So, these forms matters in the formation of the waves and subsequently the wave making resistance. So, that is why, you can see that the faster ships, you have fine form, so the disturbance created is less. If it is a slow ship like a tanker or a bulk area, the form is fuller because wave making effect is less because the ship operates at a low fluid number and low speed. When it comes to a container ship or may be a passenger high speed passenger furry and all that, then you make it more fine. The wave generation affect becomes less. Then you will see later that the wave making effect is proportional to v to the power six, which we have to consider here.

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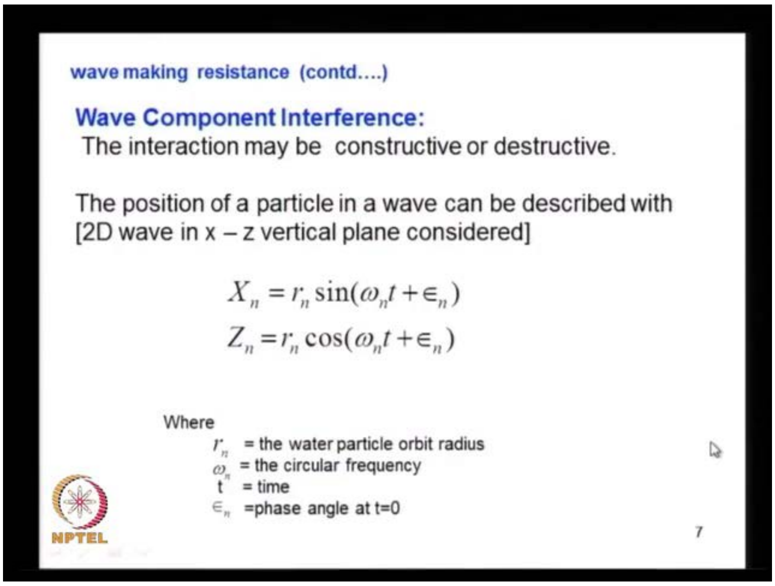


We have seen the four components of waves that is the bow wave, the two shoulder waves and the stern wave. So, these waves, these component waves, there are relative position are the phase between the different components matters in the total wave system of that. Isn't it? You have two wave systems. If they are in phase, they build up. If they are outer face, they may subside. Isn't it? So, these four waves are here, four components waves. We have discussed if these waves, the interaction effect of these waves or the interference of these wave components determines whether it is builds up or subsides.

So, finally, our interest is only to have information about the resultant wave. If the resultant wave is less or the size of the wave is less, then the energy associated wave will be less. Then the wave making resistance also comes down. You know that the energy of a wave is proportional to square of the wave amplitude. So, the wave amplitude is high. Then naturally the energy will be square time suffix. So, it will increase. So, if these four components interact in such way that the resultant wave subsides, then that is an advantage from the design point of the ship or from the wave making resistance point of the ship.

So, it is a responsibility of the ship designer to see that the form of the ship is generated in such a way that these waves generated from the bow and two shoulders and stern, they interact and interact distractively, not constructively. So, that is what the interaction may be constructive or destructive.

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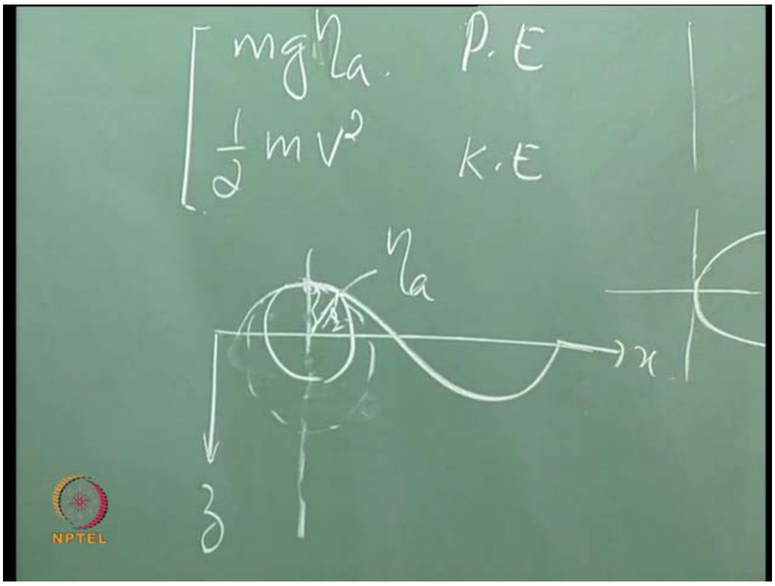


So, the position a particle if you consider wave two dimensional waves, what I have showed here, this is xz plane, this x plane and this is a maybe z, you can put down. xz is is a vertical plane, launched vertical plane. Now, you consider water particle. Then you have orbit usually. This is r, radius, and so radius of the orbit. If that is the case, now you have n. n is equal 1 to 4. So, four wave components we have considered. So, you consider one of it. So, the X component is equal to r n sin omega n t plus epsilon n and the vertical component is given by this relation.

So, what we have is here you can see that r n is a water particle orbital radius, which I have said is the orbital radius water particle. Omega n is the circular frequency of the wave. t is the time and epsilon n is the phase angle. If you consider two angles, what is the phase difference between the two waves? So, these are the quantities which appear in this relation.

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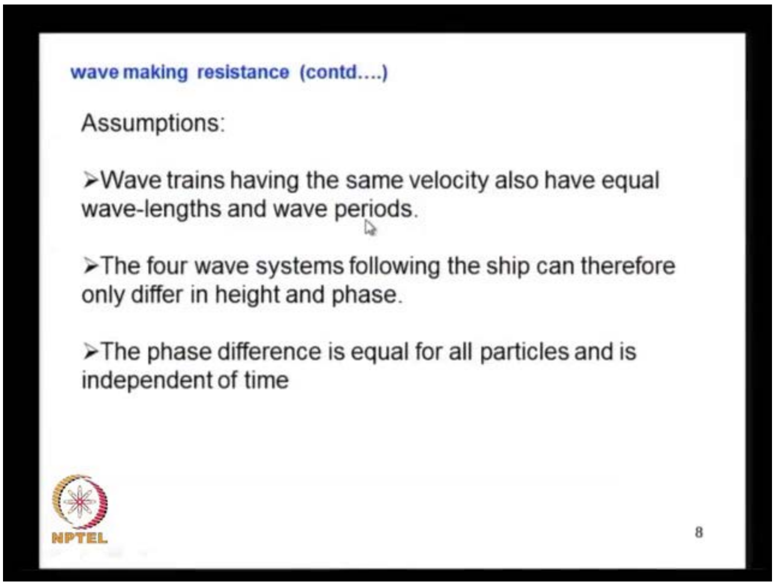


So, the wave trains, some assumptions here, wave trains having the same velocity also have equal wave lengths and wave periods. So, here one of the assumptions made in the Kelvin wave is they move them with the same speed less and the wave length remains same. So, the wave trains, they move with the same velocity, the wave length and wave periods are also equal. The four wave systems following the ship can therefore, only differ in height and phase because their relative position remains same. The only difference is the height and the initial phase difference. The phase difference, we have seen taken at t is equal to 0. So, at is equal to 0, what is the phase difference?

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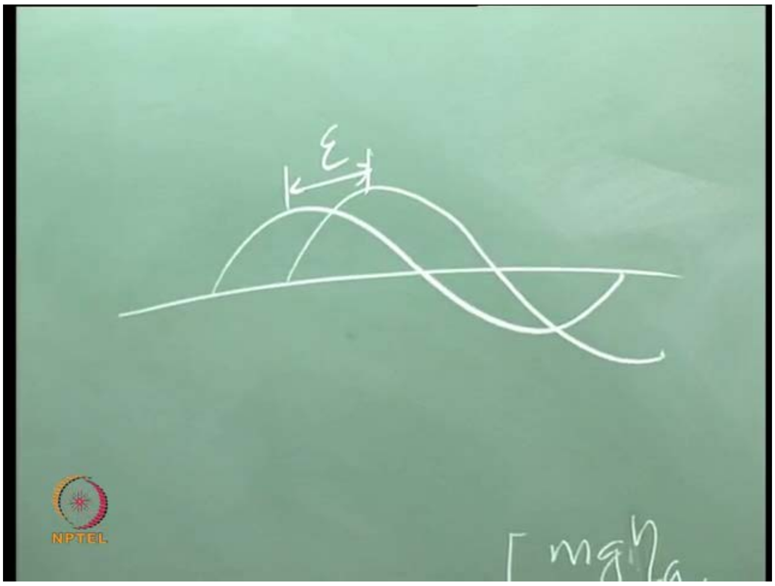

If you consider two waves, one wave here, may be the one generated from the bow, may be that, this is the wave which is generated from the shoulder or some other, may be difference sterns. So, you see the difference. This is the phase difference. So, that is how you define it. The phase difference say get from there. So, the phase difference is equal for all particles and this is independent of time. So, this phase difference for all particles, any particle you take, that phase difference remains same. It is independent of time because we said all the waves move with the same velocity. So, it is independent of time.

Now, you consider we have seen, already mentioned that the four wave components, the resultant waves are obtained by super position and these component waves that is you are adding up all the components. We get the resultant effect. That is what we have done in this here. You have this wave, these four waves. So, if you want to get the resultant, you just here have only one component, you get it. So, when it comes here, you add this. One is positive and the other one is negative. So, it is discrete energy also. I get the resultant here. So, you just add it up. So, the four components are added together to get the resultant wave.

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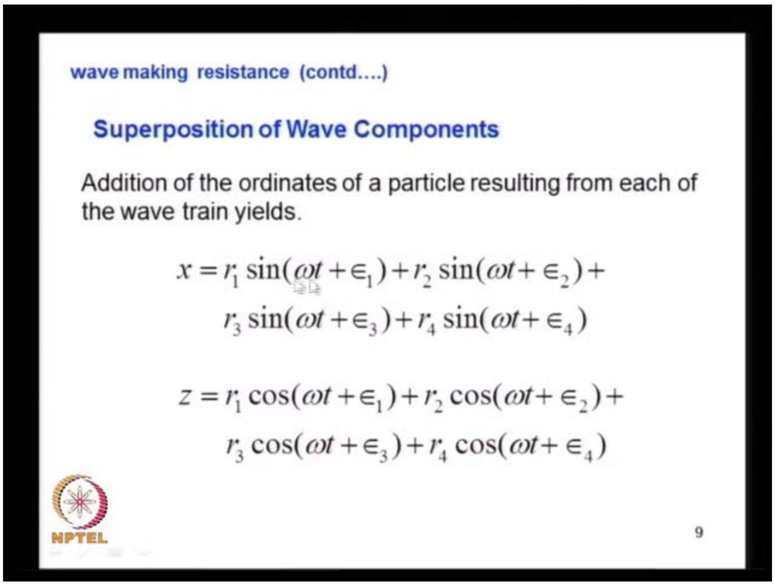


So, that is what is done here. So, the x component will have r1 from the first wave, r2 from the second wave, r3 and r4. So, that is how we get the resultant of the x component. For z also, it is the same components. So, if you add all, you get the co ordinates of each particle. So, I am not going to details. It is clear. This is you are considering four waves.

If the first wave is having the radius of the orbit as r1, the second wave radius of the arbitrary water particle r2, third wave radius r3 and r4, so they are going to have different amplitudes and naturally different radii of orbit. That is how it is. I call it here and you consider it with the independent components values and sum it up to get the total resultant of it.

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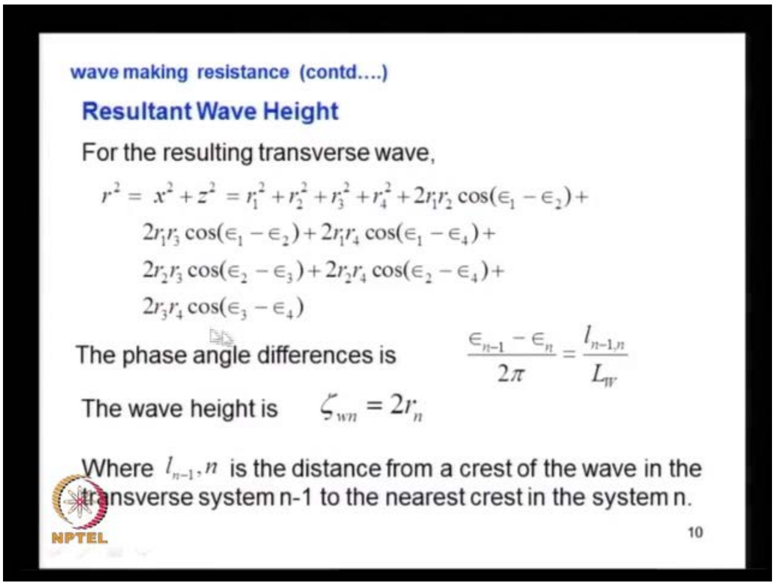


Now, if you can find out r square that is 1 of the resultant wave, if you put r square, you have x is here, z, so x square plus z square is r square. This is in two dimensional, we have considered. So, this is r square x square plus z square. Now, we have relations for x and r z, what you have seen here, x and z, r are here. So, you just substitute that. You come, arrive at this relation. So, this is the relation form, r square, r1 square plus r2 square 1 plus get the coupled terms here, so with the phase differences everything coming. If you work and go through it details of that, you will get this relation. The phase difference, you can see here, the difference epsilon 1 minus epsilon 2 epsilon minus.

So, all these are phase differences. It is the phase difference between one and two wave or this is with one and four wave like that. So, in general, you can put this is epsilon and minus 1 minus epsilon 1 and by 2 pi, which shows, which is same as l n minus l, n 1 by Lw. You can see that what is that l n and n. n should be in subscript here. This is the distance from a crest of the wave in the transverse system n minus 1 to the nearest crest in the system n. So, you are considering two waves, the nth wave and n minus 1 wave.

So, find out what is a difference between the crest, sub consecutive crest of these waves. So, that is the phase difference. That is what is explained here divided by the length of the wave. So, wave height is, actually sub wave amplitude is, wave height, sorry, wave height is two times rn. You can see that in that diagram which I have shown. rn represents the amplitude of the wave. So, rn is amplitude of the wave, and so two times that amplitude is the wave height. So, that is how it is given.

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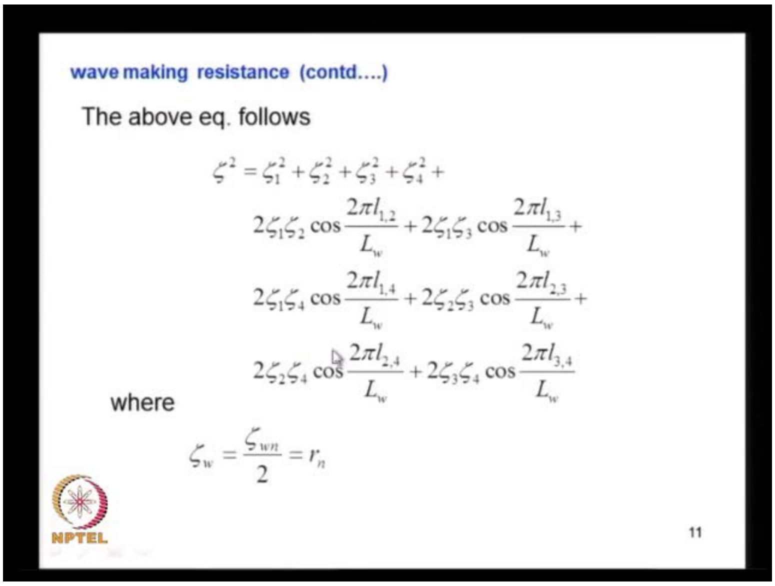


Now, you square the wave amplitude same as the previous relation, the r relation. From this relation, you get this one. You can see this is the representation of rn. This rn represents the wave amplitude. So, you get same substituting in place of r, you get r1, you get psi1 same way as the wave amplitude is used. So, this is a relation now which you got from the previous relation of the r terms. So, from this relation, it reduces to this one.

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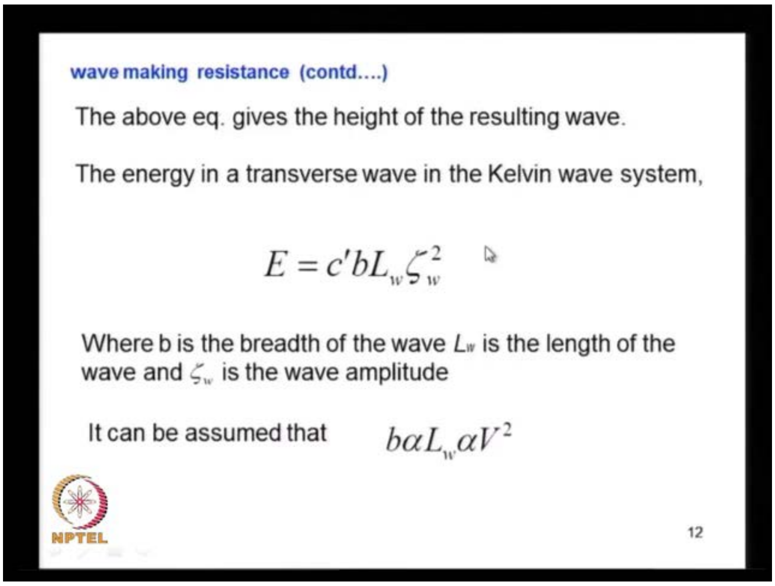


Now, the above relation gives the height of the resulting wave. The energy in a transverse waves in the Kelvin wave, E is equal to energy associated with the wave as I said is proportional to amplitude square. What is the exact relation?

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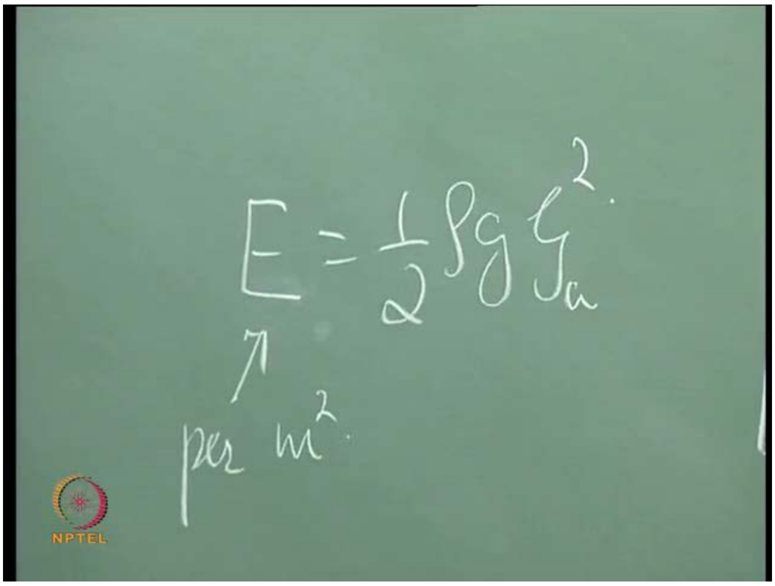


The energy per units or per meter square of the surface is the total energy associated with a wave is equal to half rho g into zeta a square. This is the energy per meter square of the wave surface. So, this is half rho g half of that, half rho g is zeta s square is coming from the potential energy, which you have seen and half of it is coming from the kinetic energy. So, the total is half rho g into zeta a square. That is per unit surface. That is per meter square. Now, you are considering a wave which is having a length Lw and the breath of the waves is b.

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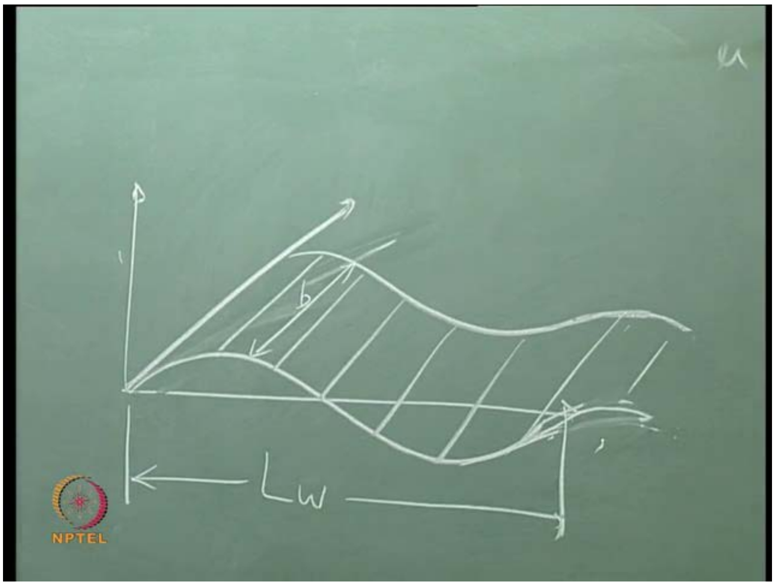


Lw and b, how you define is you consider, yes, you consider this line. You consider a wave. So, just say we just consider of regular wave. So, this is a wave. So, the length means, suppose this is crossing the axis. The length is this is the wave length which is here marked as Lw. It is from here to here. That is a one wave length. This distance, you call it as the breadth of the wave b. So, here we are considering a wave, which is having a length Lw and breadth is equal to b.

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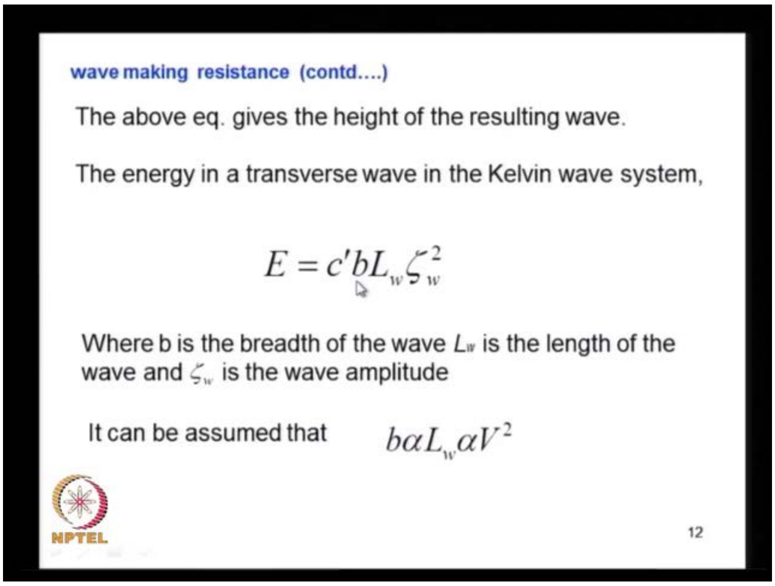


So, here you know that c prime here, the energy is equal to c prime into c prime is half rho g now, half rho g, c prime is a constant into zeta w square into the area. The area is b into Lw. So, it is linear wave with area b into Lw. So, that gives the total area associated with the wave having a length Lw and breadth b. So, that is given by this relation. That is what I have explained. This b is the breadth of the wave and the Lw is the length of the wave, and zeta w is the wave amplitude. So, we can assume that b is proportional to Lw. See here, it takes a breadth, which is of the same order of the length of the wave. We will see how this relation proportional to V square.

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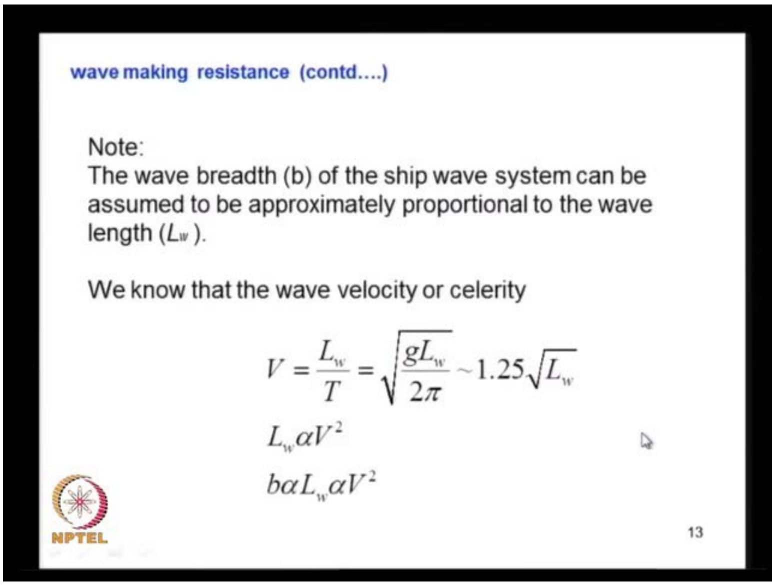

We see that. That is said that the wave breadth is b and the wave length is Lw, we consider. So, here V is equal to Lw that is wave celerity or wave velocity is the wave length by the wave period. Isn’t it, wave length divided by wave period? So, from this relation, you will arrive at this relation g Lw by 2 pi. You know how to arrive at this relation. If you have studied wave theory, you must be able to know. So, Lw by g is equal to, how do you put 2 pi by omega?

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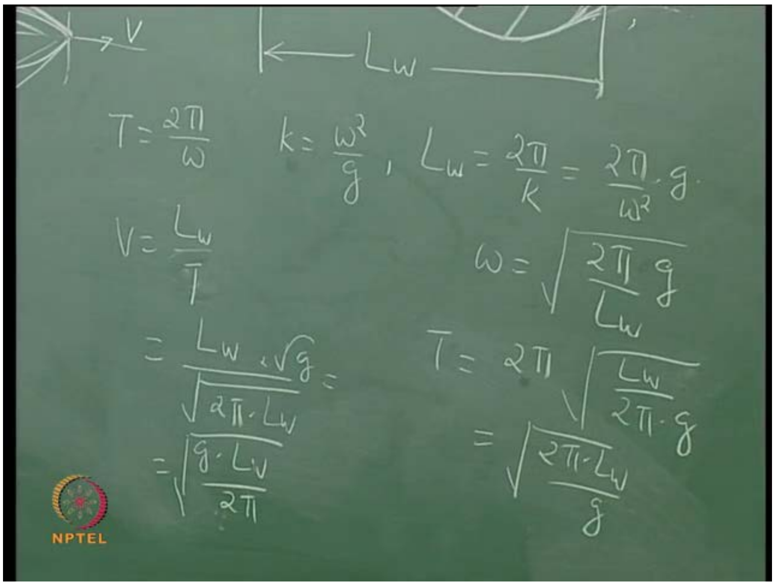


You can say that the period is equal to 2 pi by the circular frequency. How you relate to this that you know. The wave dispersion relation k is equal to omega square by g. Also, you know that relation, the wave length Lw is equal to 2 pi by k or it is same as 2 pi by omega square into g. Is it not? You are substituting. So, that is what you get Lw. You have what you need is V is equal to Lw by b. It is the wave, Lw by T, sorry. Now, if you want to find out from this g is you want to find out omega from this relation, so omega is equal to square root of 2 pi by Lw into g. Is it not? Omega and then g is equal to 2 pi by omega, so 2 pi 2 pi by omega square root 2 pi into square root of Lw by 2 pi into g. Is it not?

That is what we get. I think I am correct. This is omega and t is equal to 2 pi by omega 2 pi into divided by omega that is 2 pi by this. This is correct. So, what we do is V is equal to Lw by, so this we can simplify that is same as to get 2 pi inside so you get square root of 2 pi into Lw by g. Isn't it? So, Lw by square root of 2 pi into Lw into, square of g comes here. So, that is equal to this will go is equal to g into Lw by 2 pi square root. I think that is what the relation here is; I think g into Lw by 2 pi.

That is how you get the relation. So, you are coming to this. This is derived from basic wave theory. From T, you know what is the period of the relation in waves dispersion relation is here and you also know the wave is equal to 2 pi by k by deep water condition. So, then substituting that here, you get omega and from that omega, you get T. Then you are putting T here, then you get V is equal square root of g into Lw by 2 pi. That is the relation what we are getting here, g into Lw by 2 pi, so square of g by 2 pi you get 1.25 into square root of l.

That is how you get this relation, which implies that Lw is proportional to V square. That is what Lw is proportional to V square. We already know breadth is proportional to L square that is also proportional to V square. So, if you look at a previous relation here that is how is arrived. b is proportional to Lw and this is proportional to V square. Why we have written this V square? This has been derived from this to get this V square.

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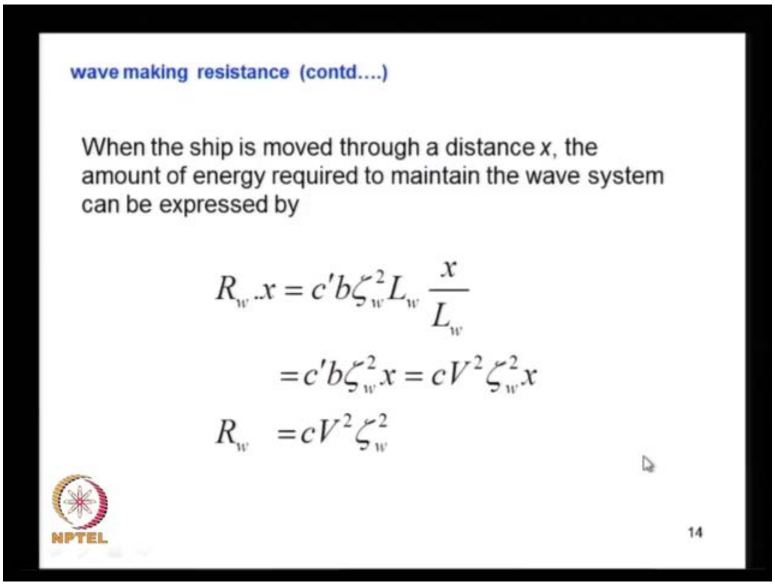


So, now you look at energy relationship generating wave. We are discussing about wave making resistance. Now, you say that the ship has moved through a distance x. The amount of energy required to maintain the wave system now can be expressed as energy that is the force Rw that is resistance into the distance moved x. So, that energy Rw is equal to c w into b into Lw into zeta w square. That we have seen, that into x in relation to Lw, so this is the distance in terms of this. So, then it simplifies into this form, b into zeta w square into x.

Now, you know b is proportional to V square, which we have just seen and substituting there. So, the constant is, the proportionality constant, it is a new proportionality constant here and that into V square into c w square into x. Now, that means Rw is equal to c into V square into c w zeta w square that is c square into wave amplitude square.

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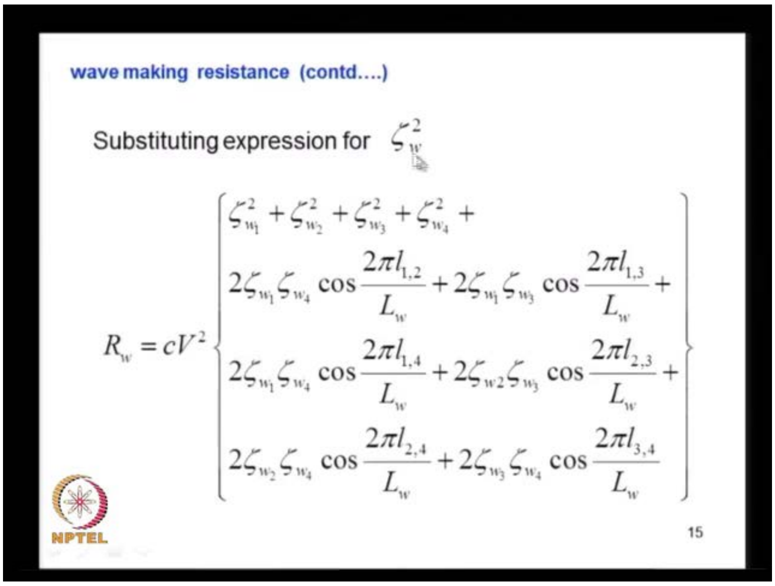


Now, we see zeta w square, we have already seen. We have already seen one or two slides before. This is zeta w, expression for zeta w, zeta w square. So, just see what is happening now. So, zeta w1, zeta w2 is at the same relation here. So, Rw is proportional to c V square into zeta w square. That is what the relation is, Rw is equal c V square into zeta w square. Now, we are substituting the expression for zeta w. So, that is what is done in the bracket. Take the expression here from the previous relation.

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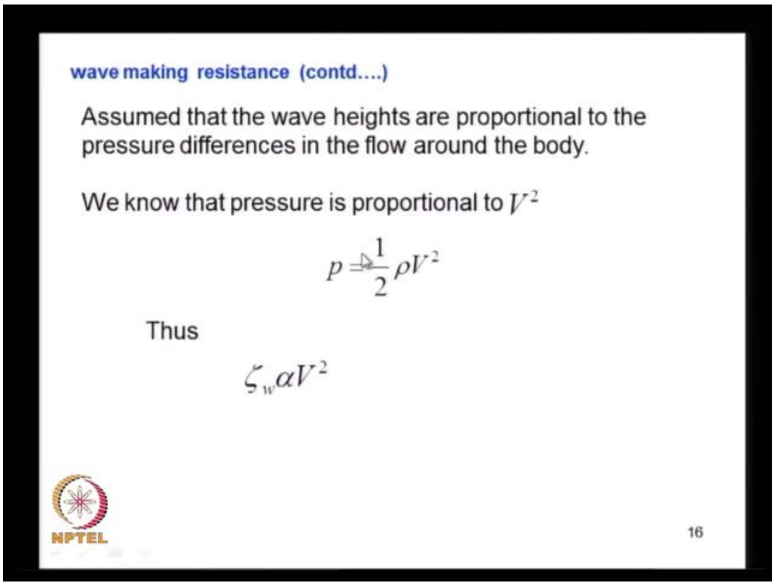


So, if you move further, assume that the wave heights are proportional to the pressure differences. The wave height, the static difference if you consider, it is the height difference around us. Now, we know the pressure, hydrodynamic pressure, the velocity head is p is equal to half p V square. So, pressure is equal to proportional to V square. That means the pressure here, if you consider static is proportional to height or zeta w that is the pressure variation in still water and on the top of the wave, it is that zeta w. The pressure is also given by this relation. That means zeta w is proportional to V square.

That is what it concludes; zeta w, the wave height or the wave amplitude is proportional to velocity square. Now, you take this back. That means here, you can just put zeta w square in terms of that. So, zeta w square will be V to the power 4. Zeta w is V square. Zeta w square is V to the power 4. So, that is what is happening here. You just go through this relation c V square and this is going to be V power 4. So, you take V to the power 4 from all these terms. It will be c into V power 6.

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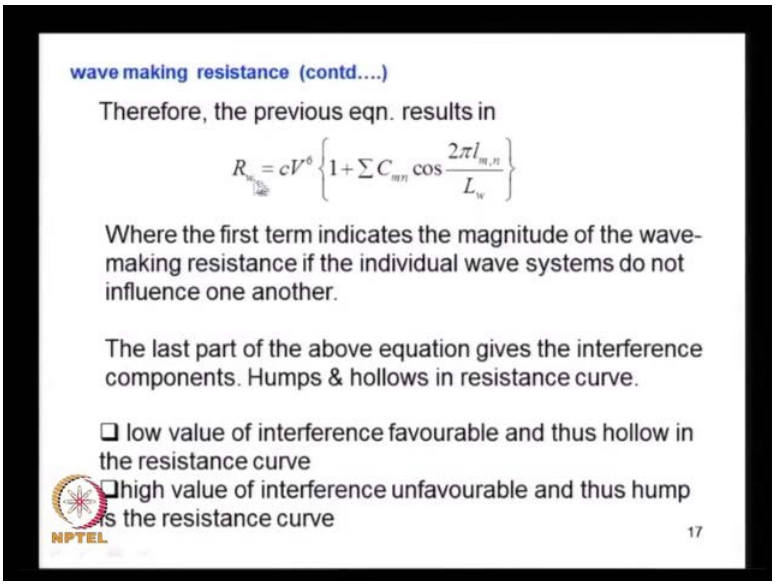


So, you get Rw is equal to c V power 6 into 1 plus the other terms here. So, this is the expression now derived to represent the wave making resistance. This all exercise have been done to understand what is the relation between wave making and ship velocity. Now, you know that the wave making resistance is proportional to V power 6. If you recall that wave, the frictional resistance, we concluded that based on experiment suggested by some research group, Froude, we have seen that frictional resistance is proportional to V power 1.825. Now, that is for the frictional resistance.

Now, for the wave making resistance, it is V power 6. So, that is where the first term indicates the magnitude of the wave making resistance that is 1, the first term, 1 into c V to the power 6. That indicates a wave if the individual wave systems does not interfere. So, if you look at the relation before, see here it is c w zeta w1 zeta w4, this is an interference effect. This is basically couple terms, which are coming from how the wave 1 and wave 4 are interacting here or wave 1 and 3 are interacting here. So, these are the interactive terms or interferences terms, whereas these are stand alone terms, you can see that 1 square, 2 square like that.

So, in the final expression, this one refers to the stand alone terms, whereas this term represents the interference terms. That is how the four wave components, which we considered here, interfere. What is the resultant effect due to the interference which is accounted by this term? So, this term takes care of interference. So, that is the last part of the above equation give the interference components that is this term into c V square represents the interference effect.

So, this term depending on this phase, it can be constructive or it can be destructive. If the phases come close, then it will build up. If the phases are out, then it subsides. So, if it is the phase, in phase, then you will get a positive contribution from this term. If they are defective, then you get a negative effect from here. So, that is why, in the resistance curve, you get humps and hollows in resistance curve.

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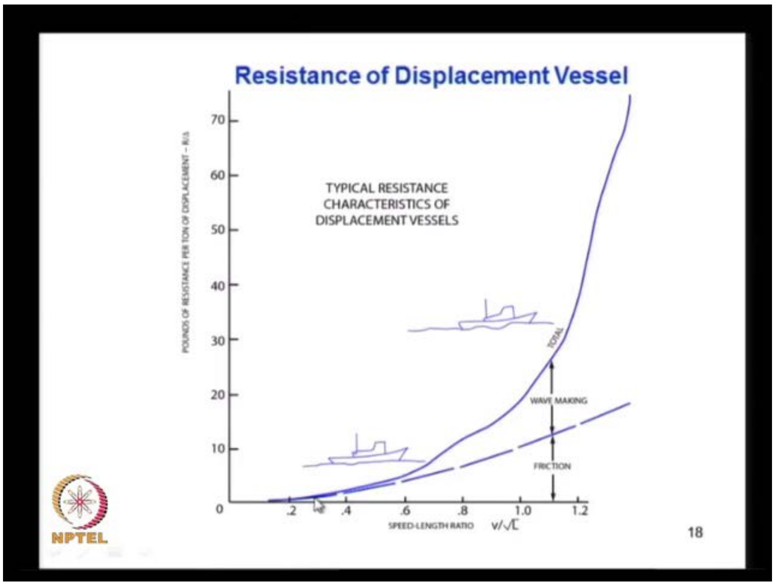


If you look at a next slide, you can see this is the resistance curve, the resistance against V by root L. You can see this is a wave in which the friction goes up. This is V power 1.825. It is going this way, but you see that the difference, this is total resistance. The difference between these two is a wave making component called as residuary, but wave making thing. So, the wave making component, you can just see that what is this? How it develops with the speed of the vessel? It shoots up. You can see that the wave even with the small increment in the speed, the wave making resistance shoots up. So, this occurs because wave making resistance is proportional to V power 6. We have seen that.

So, if these terms, they build up, you get, I missed that point. It is humps and hollows. You can see the humps. Actually, the resistance should have gone like this. Now, this portion, it has moved up, there is a hump in the resistance curve. This is what you called the hump. Why does it happen? The waves interfere constructively. We have seen the four waves, they interfere constructively. So, that is why, the resistance increases. That means this term has added to the resistance, but if this term becomes negative due to outer phase components, then this is going to subtractive component.

So, the total wave making resistance dips. That is the situation where we call a hollow. So, if it dips, then it is a hollow. So, in resistance curves, often you may find the humps and hollows. That depends on the speed and depends on the phase difference between the components. So, low value of interference is favorable and thus hollow is in the resistance curve. So, high value of interference is unfavorable. This is the one we have seen. Now, we look, go into the wave making resistance. That is a next major component of resistance ship.

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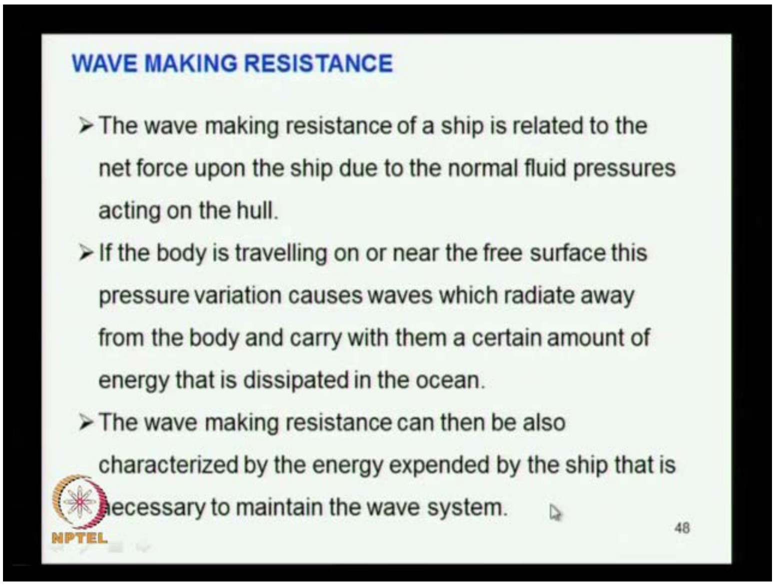


So, wave making, it is related to you know the net force upon the ship due to the normal fluid pressures. We have already seen that. If you look at, remember the diagram which I have shown, the total resistance, the pressure resistance under which comes the wave making resistance and also the frictional resistance. So, the wave making resistance is due to the pressure disturbance. So, if the body is moving, it generates the waves and the waves keep spreading. If the body is travelling on or near the surface, this pressure variation causes waves. It generates waves which radiate away from the body.

These waves, you know, we have already discussed, they posses energy and there is a loss of energy to the ship. So, the ship needs to continuously supply energy for the creation and sustenance of waves. So, there is a continuous loss of energy to the ship, which acts as a resistance offered by or termed as wave making resistance. The wave making resistance can also characterized by the energy expended. That is what I said that it is related to the energy expended by the ship to create and maintain the wave system.

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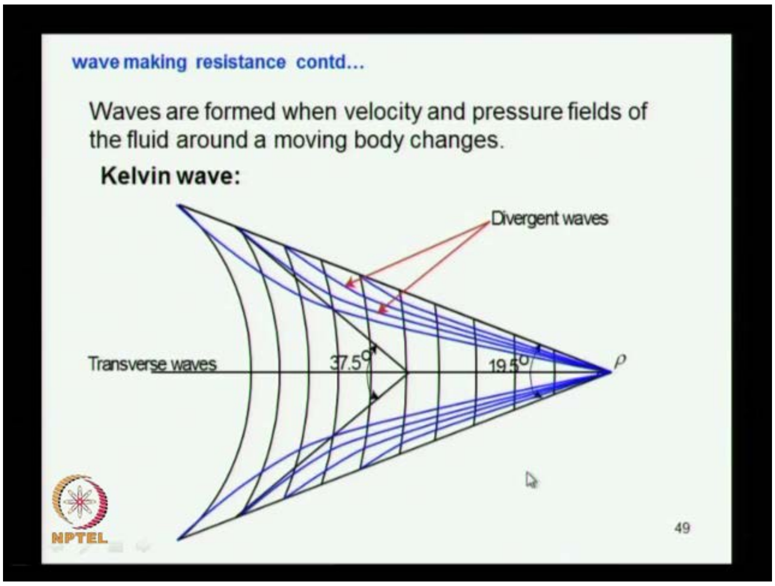


So, here you can say, this has just been studied by Kelvin and he identified that the ship can be treated as pressure point moving, moving pressure point with steady speed. It creates a characteristic wave pattern constituted by divergent waves. You can see this divergent of that is ship the waves which are diverging out and also waves in the transverse direction, the waves in the transverse direction and which are normal here. Its tangents are normal to the center line. Actually, this curve should have taken a tangent here also, this is wrongly drawn. It should go and make a tangent with the divergent wave.

So, it has just come out and merged with the divergent wave. So, this is the wave pattern for the ship and may be later stage, it also depends on Froude number and shallow water effects changes the wave pattern, but this is standard thing. If you consider deep water and vessel going at, you know medium or low speed; you find the pattern is identical. That is why, they are also called the steady wave because the pattern remains the same and is not changing with respect to time. So, this is the wave pattern.

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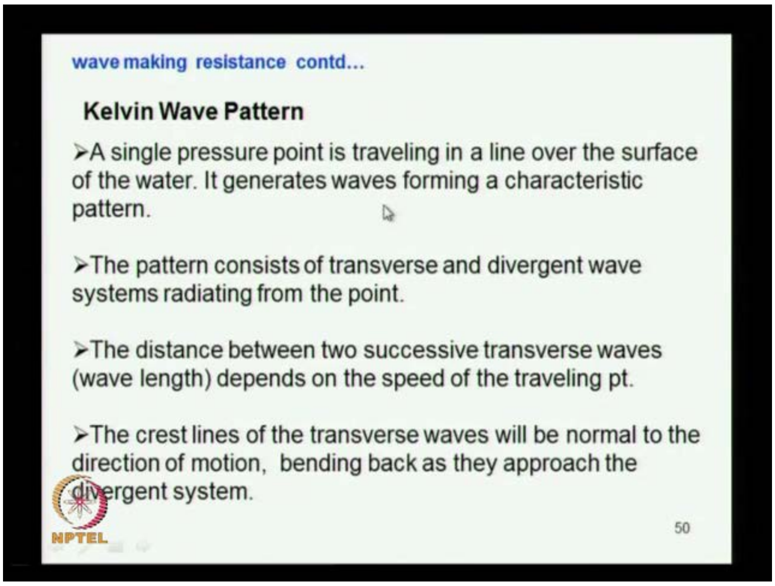


Here, Kelvin what he did is a single point pressure point travelling in a line over the surface of the water can be considered. So, if you look at that, he considered a point pressure and it is moving along in this direction. That is what he considered. The pattern consists of transverse and divergent waves. That is what he said. The pattern is here, divergent waves and transverse waves. The distance between two successive transverse waves, you know it is called wave length, successive transverse waves depends on the speed of the travelling point.

So, this distance is a crest line, this wave. So, distance between two crests is the wave length. So, this length depends on the speed of the vessel. The crest lines of the transverse waves will be normal to the direction of motion which I already said bend back ward as they approach to the divergent system. So, it is curved like this that is the transverse wave, curved backward. It curves like that. So, when you consider a ship wave system, ship is we can say idealized in this form.

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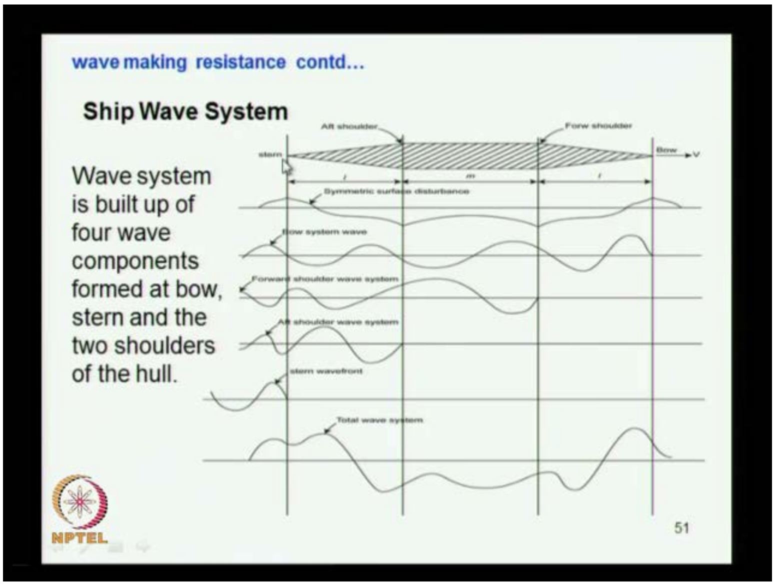


You can see that this is the ideal of form of the ship. May be I will just explain it on the board how it is idealized.

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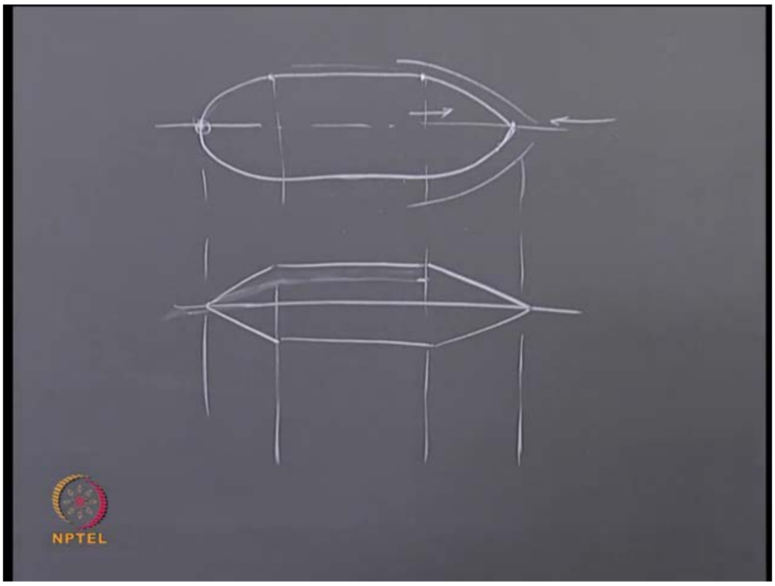

Let us say this is a typical plane of a ship, laminar view of the ship. So, here you have the flow velocity. The ship is moving in this direction. The flow velocity is coming here. So, its flow goes like this. So, here it is gradual, you know, steady shape. So, when it comes here, all of a sudden at this point, the curvature changes. When the curvature changes, what happens? When the curvature changes, there will be a change in velocity. What happens to the velocity? The velocity increases here. So, when velocity increases, what happens to the pressure? The pressure decreases, pressure drops. When there is a pressure change, a wave is generated near the free surface.

So, you have at this point, a pressure change. You have at this point, a pressure. This is stagnation pressure. You have the pressure change. When it comes here, then it comes. After this, the flow is steady and when it comes here, again the curvature changes. So, there will be again a flow variation, there will be a pressure variation and wave generation. When it comes here, this is next stagnation point. There also the pressure is different.

So, this can be treated as good as if you consider, so you just idealize it. May be I will make it bigger. So, this is how we can idealize the ship form. So, that is what is shown here in the, here. That is what is shown here. You see this is the idealized form of the water plane of the vessel. So, this is the velocity. So, this is the bow of the ship. This is the stern of the ship. These two are changes, changing points. One in the bow is called bow over shoulder and one in that is called the aft shoulder. So, here what is this? You can see that this is a bow wave system.

So, you see that a wave is generated from the bow. So, this is a bow point. Just below the bow, a wave is created from the bow. Thus, this is the first point which is pressure point, moving pressure point. So, a wave is created. So, you can see also see that bow of the ship is having a stagnation point. Isn't it? This portion is a stagnation point where the pressure is maximum. So, when the pressure is maximum, the water level increases. We have already seen in one of the previous picture in the bow wave problem. So, that is why, the wave starts with a crest here. You can see that the wave starts with the crest here.

So, the bow wave, then it propagates, and then it propagates backward, goes like this. Then it comes to here, the fore shoulder. You see there is an increase in velocity. So, what happens? The pressure decreases by Bernoulli's' equation that the increase in velocity causes a reduction pressure. When the pressure decreases, there will be dip in the water level. So, the wave starting from here is starting at the trough. So, here you can see it is a trough and then it propagates upward. Here also, there is a velocity increase changing the curvature. Again, it starts at the trough and its aft shoulder also starts the trough.

You can see that where it starts and what is the type of the wave. In the stern, what is this point? This is the aft stagnation point. Again, the pressure is high there. You are not considering viscosity, boundary layer, and flow separation. We have only considered the potential flow. So, here the pressure is high. It starts at the crest. So, that is how the four waves systems are generated from the ship. It is you know general representation, not necessary always. So, here it is a wave system, bow wave system, fore shoulder wave system. Then you have the aft shoulder wave system, then the stern wave system

So, if you club all these things, and sum it linearly, you see, you get a resultant wave system like this. This is the sum of the four wave systems. The ship wave which we see normally can be resolved or decomposed into four components, the components coming from the bow, two components coming from the two shoulders and then from the stern waves. So, these waves or this is the ship wave system. So, the position of these waves, the phase of these waves matters, we will see, which accounts to the total wave system and the size of the resultant wave determines the wave making resistance. I think we will stop now.