Marine Propulsion
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Lecture - 32
Ducted Propeller

Welcome to Lecture 32 of the course Marine Propulsion, the topic today is Ducted Propellers.

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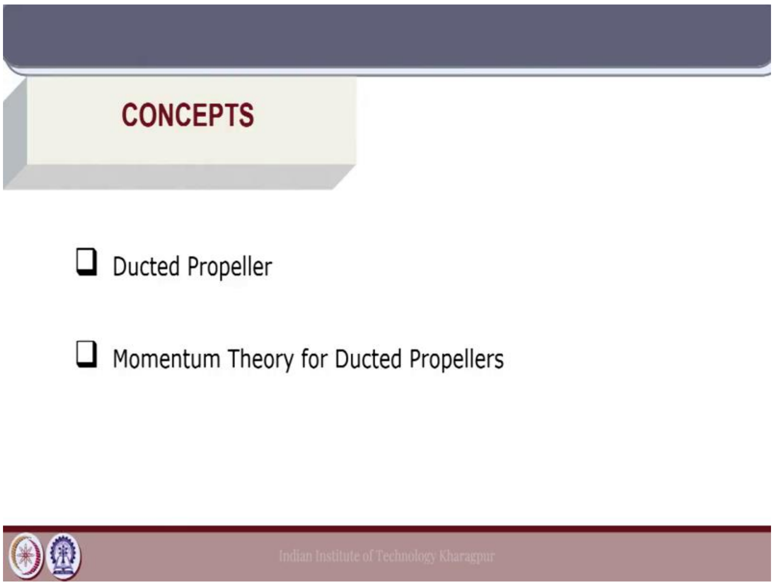

The key concepts covered in today's lecture will be ducted propellers in general and the momentum theory for ducted propellers. So, here we will use the axial momentum theory to define the efficiency of a ducted propeller system.

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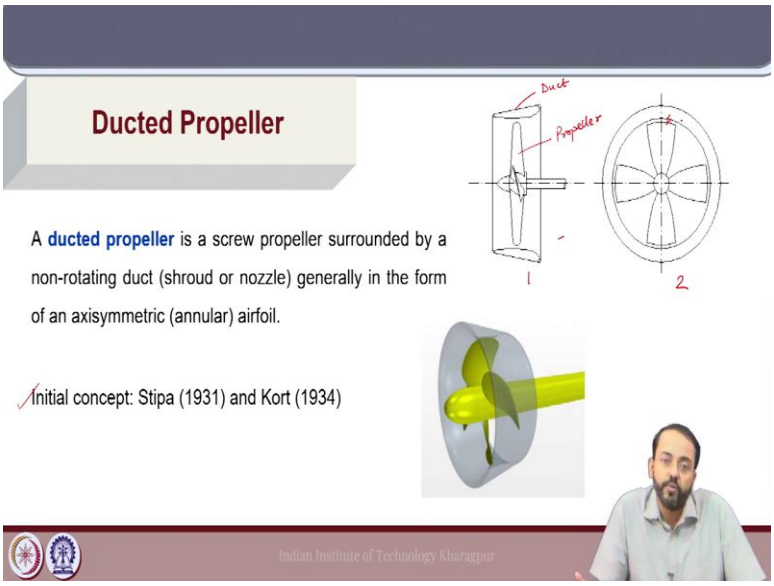

A ducted propeller is a screw propeller surrounded by a non-rotating duct. So, here we have a screw propeller which is surrounded by an axis symmetric duct which is in the shape of a shroud or nozzle and the duct along with the propeller here forms the propulsion system.

So, we have the propeller assembly as the propeller and the duct around it. If we look at the section this part is the duct and this is the propeller and these ducted propellers are typically used for vessels with very high propeller loadings where the duct also provides thrust along with the propeller.

So, the initial concept for ducted propellers were developed as early as 1930s by Stipa and Kort and that is why ducted propellers specially the accelerated ones are also called Kort nozzles. Here we have two views of the ducted propeller one from the side and the second view here from the front and here we can see that there is a small clearance between the propeller blade tip and the duct.

And in ducted propeller, the vortices generated by the propeller blade tip are suppressed by the presence of the duct and both the propeller and duct generates thrust which is important for operation and thrust generation at high propeller loadings; that means, low advance coefficients.

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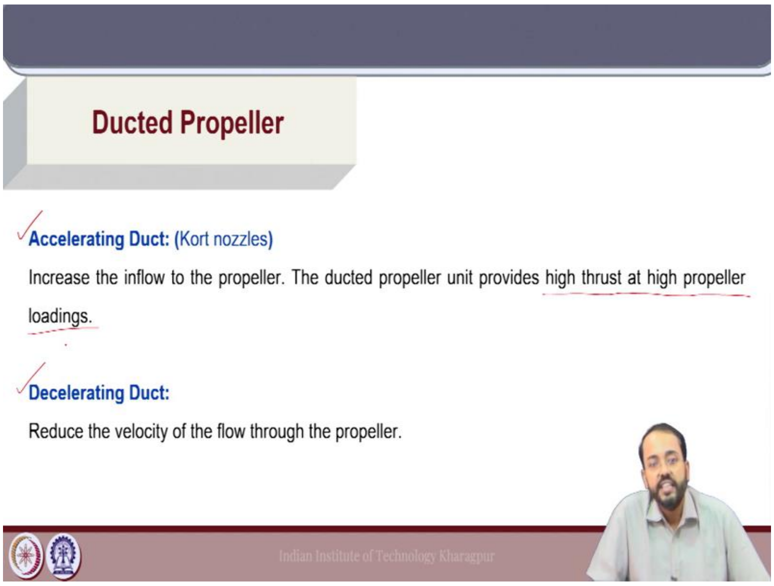

There are two main design concepts for ducted propellers; the first one which is most popularly used is the accelerating duct which are also called Kort nozzles. Now, these ducts increase the inflow into the propeller. So, they accelerate the into the propeller and in doing so, the ducts generate forces a forward component of which is the thrust force and in addition to the propeller force they can provide high thrust at high propeller loading conditions.

Hence, they are used for vessels like tugs, trawlers and other vessels which operate at high propeller loading, so that the high thrust requirement can be met. On the other hand we have another design concept called the decelerating duct which reduces the velocity of flow into the propeller. These are specifically used for vessels where cavitation is a problem and to mitigate the cavitation effects the velocity into the propeller can be reduced using a decelerating duct.

So, when we refer to ducted propellers in general the usual reference is to accelerating ducts which produce high thrust at high propeller loading conditions. Now, we will use simple axial momentum theory to evaluate the thrust and efficiency for a ducted propeller.

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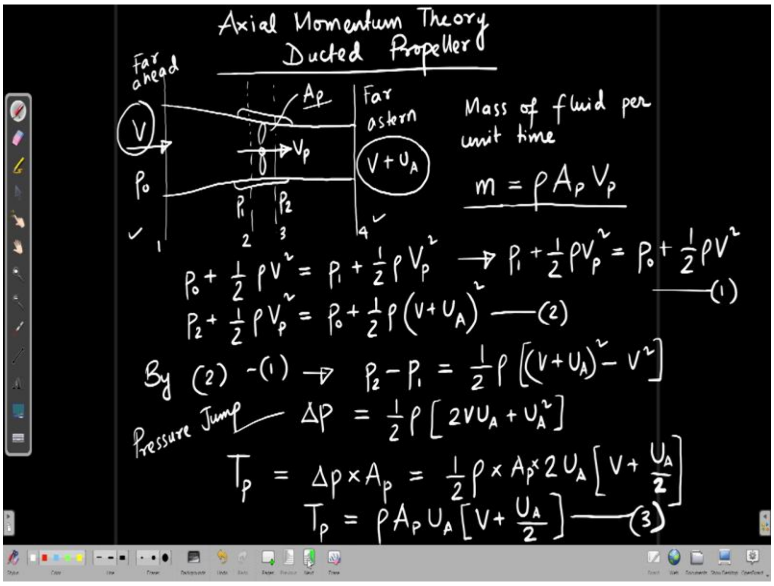

Here we have the ducted propeller instead of the conventional propeller in the same axial momentum theory. So, the duct is shown here which is an accelerating duct because it should accelerate the inflow into the propeller we have the propeller which is taken as a momentum disc and the same assumptions that we have used in the axial momentum theory will hold.

V is the inflow into the domain this is a section taken far ahead and P_0 is the pressure here and we take another section far astern behind the disc, here we have the total velocity $V + U_A$, where U_A is the axial induced velocity and the velocity through the disc is V_P.

And if we take a section just in front and just behind the disc, we have a pressure P_1 here and P_2 and because there is a pressure jump through the system a net thrust is applied by the disc and we have ideal flow assumption with no drag. So, the fluid column is flowing through the ducted propeller of a cross section area let us say A_P and hence the mass of fluid column which is flowing per unit time mass of fluid per unit time is m $\rho A_P \times V_P$. This is the same as we have seen for the conventional problem.

Now, let us apply Bernoulli's equation between the sections 1 and 2 ahead of the disc; that means, in front here we can write $P_0 + ½ \rho V^2 = P_1 + ½ \rho V_P^2$. And similarly, we can apply Bernoulli's equation between the 2 sections at 3 and 4 locations behind the disc, and then we will have $P_2 + ½ \rho V_P^2 = P_0 + ½ \rho \times$ total velocity far astern $(V + U_A)^2$.

So, the first equation can be written as $P_1 + \frac{1}{2} \rho V_P^2 = P_0 + \frac{1}{2} \rho V^2$ just by interchanging the size this is 1 and this is 2. So, by 2 minus 1 we will have $P_2 - P_1 = \frac{1}{2} \rho V_P^2$ and P_0 will cancel out, this is $P_2 - P_1 = \frac{1}{2} \rho (V + U_A)^2 - V^2$ and this difference in pressure between the two sides of the disc is the ΔP which is the pressure jump across the disc.

So, this is pressure jump across the disc this is given by $\frac{1}{2} \rho (2 V U_A + U_A)^2$. Now, what is the thrust that is generated by the propeller? The thrust generated by the propeller only is T_P, here we have to remember that we have two thrust components one from the propeller and one from the duct. So, the thrust generated by the propeller will be given by this pressure jump into the area of the propeller disc A_P which is mentioned here in this simple axial momentum theory.

So, $T_P = \Delta P \times A_P$. So, the right hand side we can write as $\frac{1}{2} \rho \times A_P$ taking 2 U_A common $(V + U_A/ 2)$ and then the thrust T_P becomes $\rho A_P U_A \times (V + U_A/2)$. So, this is the thrust which is generated by the propeller. Here we have to understand that the duct being considered as an accelerating duct should accelerate the flow through the propeller.

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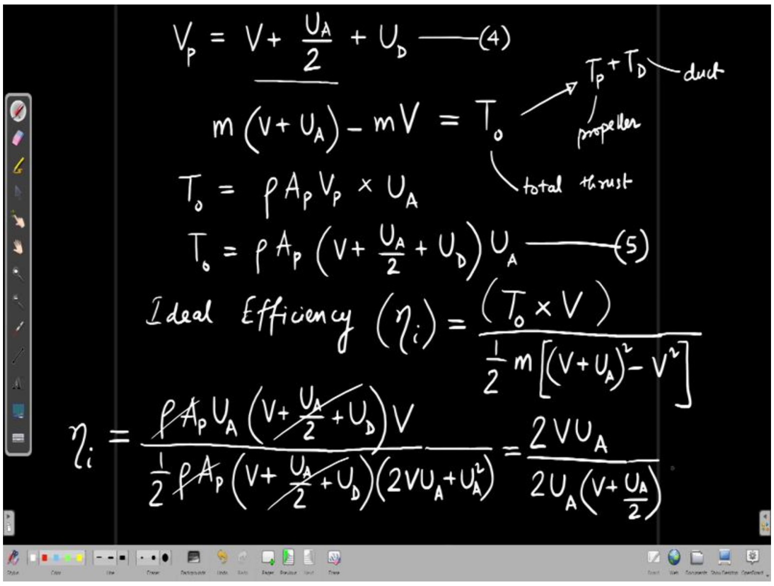

So, the velocity of flow through the propeller disc $V_P = (V + U_A / 2)$ which is half the axial induced velocity. This part is same as the conventional propeller without the duct plus the additional velocity which comes due to the flow acceleration by the duct let us take it as U_D.

Now, if we go back what is the momentum of the fluid? In the inlet the velocity was V and far astern behind the disc, the velocity is $V + U_A$. So, the total thrust applied by the propeller and the duct together is the change of momentum of the fluid that is passing through this ducted propeller system between the section at 4 and 1 in unit time.

So, if m is the mass of fluid per unit time which is shown here the change in momentum which gives the thrust force can be calculated as $m (V + U_A) - mV$. Now, this is the total thrust T_0 which is basically $T_P + T_D$ where T_P is the thrust component of the propeller which is already shown and T_D is the thrust component of the duct. So, this is the total thrust from the change in momentum.

Now, T_0 should be equal to $\rho\ A_P \times V_P$ which is the mass that has been shown in the earlier slide $\times (V + U_A – V) = U_A$ now if we substitute the value of $V_P = V + U_A/2 + U_D$ which is the effect of the duct then, $T_0 = \rho\ A_P \times (V + U_A/2 + U_D) \times U_A$ this is the total thrust of the duct plus the propel. Now, the ducted propeller is considered as a single propulsion unit which includes the performance of the duct as well as the propeller.

So, when we calculate the ideal efficiency of this system η_i it should be the total thrust T_0 multiplied by the velocity head against which the thrust is being provided which is V as before divided by the input power. So, $T \times V$ is the powered output from the system, here we also have the duct along with the propeller that is why instead of T_P we have used T_0 which is the total thrust and the input power is given from the change of kinetic energy between the section far astern and the inlet as before.

Now, if we substitute the values of T and m we can write $\eta_i = (\rho\ A_P\ U_A \times V + U_A/2 + U_D \times V) / (½\ \rho A_P\ (V+U_A/2+U_D)\times((V+ U_A)^2 – V^2)$ or, $(2\ V\ U_A + U_A^2))$. There are certain terms which will be cancelling out in the numerator and denominator $\rho\ A_P$. So, $\eta_i = (2\ V\ U_A) / (2\ U_A\ (V + U_A/ 2))$.

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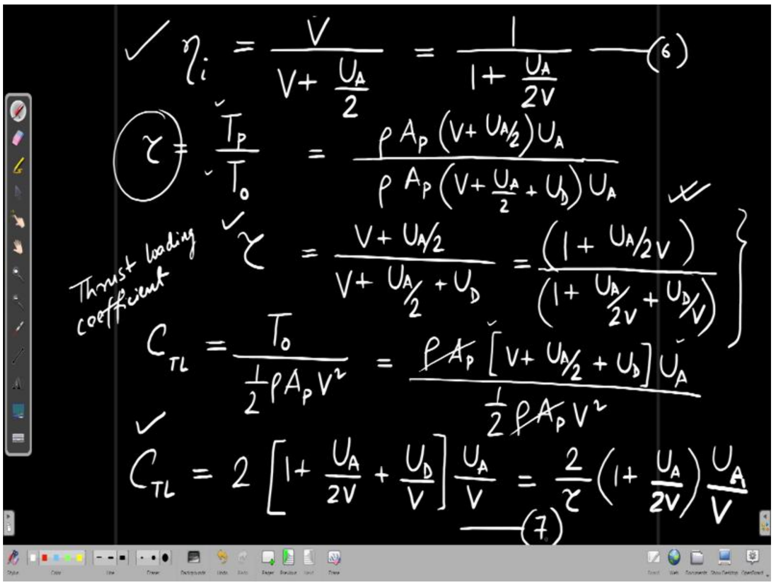

Now, this can be written as $V / (V + U_A/2)$ and in the same way as before we will non-dimensionalize both the numerator and denominator dividing by V. So, this becomes $1 / (1 + U_A/2V)$. So, this is the same equation that we have obtained as before. Now, for a ducted propeller we have the propeller thrust which is $T_{P,}$ and the total thrust T_0 from the duct and propeller combined. And we will define a factor τ which is the ratio of the thrust generated by the propeller to the total thrust from the ducted propeller system.

So, if we use the expressions for T_P and T_0 this is ρ A_P the total velocity through the disc $\times$ U_A. So, this becomes $\tau = (V + U_A/ 2) / (V + U_A/2 + U_D)$ again if we divide by V and make it non dimensional this is $\tau = (1 + U_A/2V) / (1 + U_A/2V + U_D/V)$. This is τ which is the ratio of the propeller thrust to the total thrust from the ducted propeller system.

Now, if we define the thrust loading coefficient which is based on the total thrust. So, this is the thrust loading coefficient based on the total thrust that is $T_0 / (½ \rho A_P V^2)$ the denominator is same as before. So, we can write $(\rho A_P (V + U_A/ 2 + U_D) \times U_A) / (½\rho A_P V^2)$, we will see that it comes to $2 (1 + U_A/2V + U_D/V) \times U_A/V$ because ρ A_P will cancel out and this V^2 we have used to non-dimensionalize both the term within the bracket and also the U_A outside.

Now, if we compare this thrust loading coefficient here with the value of τ obtained this particular expression we can write it as $2 / \tau (1+ U_A/2V) \times U_A/V$ where τ is given by this particular expression. The reason of doing this comparison is to get an expression of C_{TL}

the thrust loading based on the ratio of thrust for the propeller and the total thrust which is given by τ.

Now, as a final expression we will relate the thrust loading coefficient of this ducted propeller unit to the ideal efficiency that is obtained in equation 6. So, this is 7 we will use this relation 7 to get the relation between C_{TL} and η_i.

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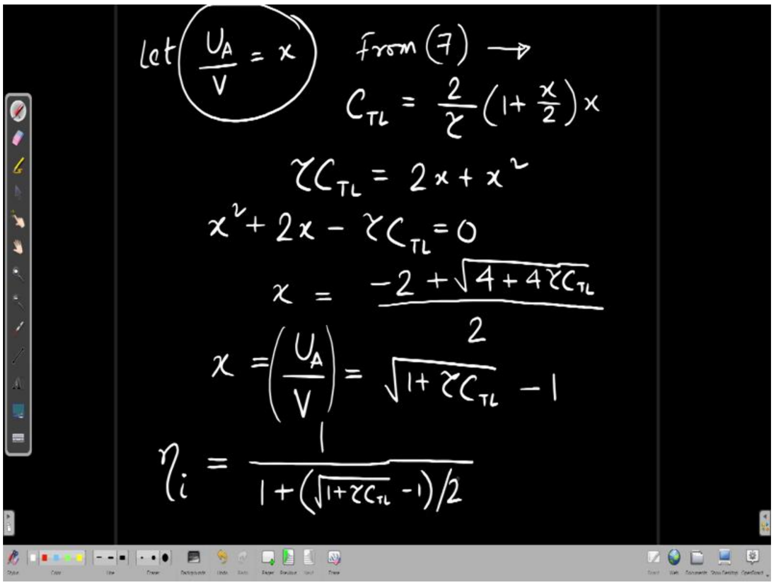

Let us for simplicity assume $U_A/V = x$ then from 7 we can write $C_{TL} = 2/\tau\,(1 + x/2) \times x$ which gives the equation $\tau\, C_{TL}$ equals $2x + x^2$. And finally, we have the quadratic equation $x^2 + 2x - \tau\, C_{TL} = 0$ and from this equation we can simply calculate $x = (-2 + \sqrt{(4 + 4\tau C_{TL})})/2$ only the positive root is taken because U_A/x must be positive the axial induced velocity divided by the inflow velocity this non dimensional fraction should be positive.

So, $x = U_A/V = (\sqrt{1} + \tau\, C_{TL}) - 1$. So, we can replace this particular value of U_A/V in the equation for η_i, η_i will now become $1 / (1 + U_A/2\,V)$; that means, this $U_A/2V = (\sqrt{(1 + \tau\, C_{TL})} - 1)/2$.

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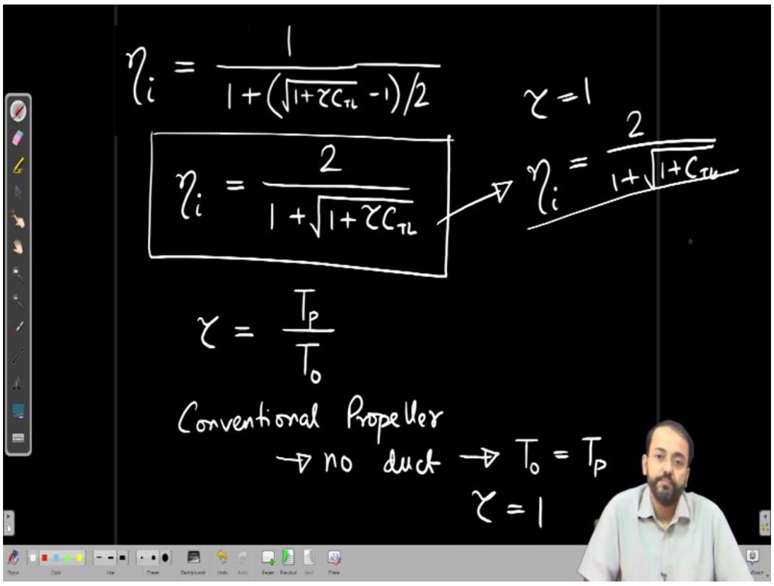

So, finally, we have the ideal efficiency is given by $2 / (1 + \sqrt{(1 + \tau\, C_{TL})}$. This gives the final relation between the ideal efficiency and the thrust loading coefficient for a ducted propeller

Now, if we compare this expression to that of a conventional propeller where there was no duct the tau term was not there, now τ is defined by T_P / T_0 when there is no duct for a conventional propeller. So, conventional propeller, no duct then there is no thrust generated by the duct then T_0 equal to T_P the thrust produced by the propeller is itself equal to the total thrust; that means, τ equal to 1.

So, in this particular expression if we put tau equal to 1 we will get $\eta_i = 2/1\ (1 + \sqrt{(1 + \tau C_{TL})}$ which is the same expression that we have obtained for a conventional open propeller without the duct. So, this expression of ideal efficiency for a ducted propeller gives the relation between the thrust ratio of the propeller to the total thrust τ to the ideal efficiency of the ducted propeller system using momentum theory. This will be all for today’s lecture.

Thank you.