**Marine Propulsion**
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**Lecture - 33**
**Ducted Propeller (continued)**

Welcome, to lecture 33 of the course Marine Propulsion. Today, we will continue with Ducted Propellers.

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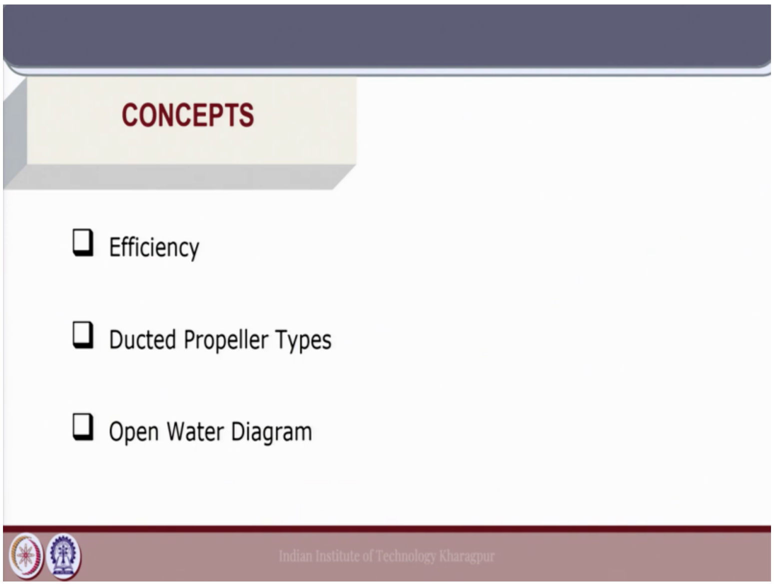


The key concepts to be covered in today's lecture are the efficiency for a ducted propeller, types of ducted propellers, different ducts and propeller designs and their combinations. And, the open water diagram for a ducted propeller where we will have the thrust, torque and efficiency for a ducted propeller in open water conditions.

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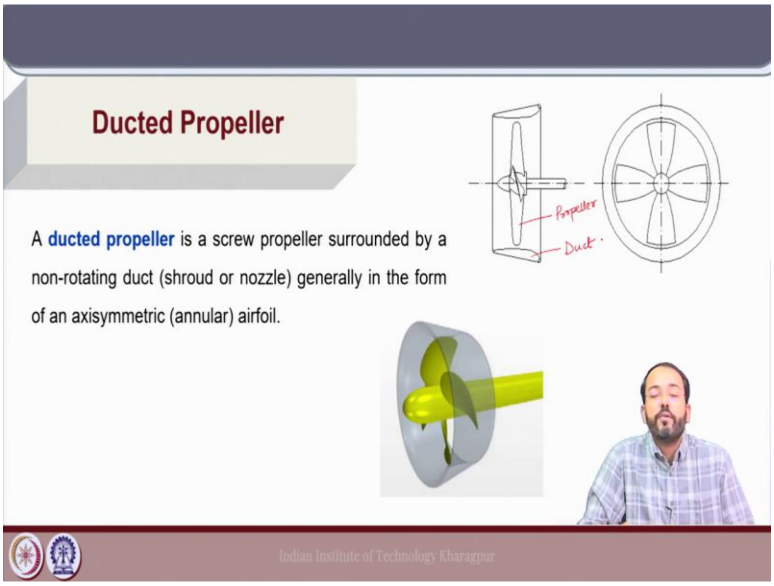


A ducted propeller is a screw propeller surrounded by a non-rotating duct. Now, this duct is in the form of an axisymmetric annular airfoil. So, for a ducted propeller system, we have the propeller here, which is surrounded by a duct. And, the section of a duct is typically that of an airfoil section. And, depending on the performance required, there are different types of duct sections which are used for different operation conditions.

The essence is same that the propeller is surrounded by an annular duct and both the propeller and duct provides force, the forward component of which is mentioned as thrust. And, for the ducted propeller system the propeller and the duct together provides a certain performance characteristics with respect to the operation condition.

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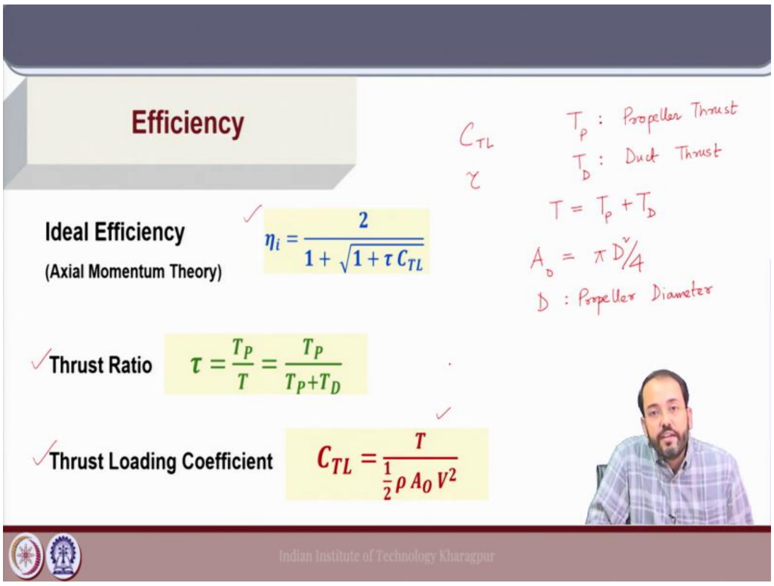


In the previous lecture, we have derived the ideal efficiency for a ducted propeller system using axial momentum theory. Here, the ideal efficiency is expressed as a function of thrust loading coefficient $C_{TL}$ and another factor which is $\tau$, the thrust ratio. So, if we have $T_P$ as the thrust from the propeller and $T_D$ as the thrust generated from the duct.

For a ducted propeller the total thrust is the thrust generated by the propeller added to the thrust generated by the duct. Now, for a standard ducted propeller, the configuration is that of a propeller with an accelerating duct; that we have mentioned before. The accelerating ducted propeller is the standard version which is used in practice, where the duct provides a positive thrust which is in the direction of the motion of ship.

So, the duct thrust adds up to the propeller thrust to give the total thrust $T = T_P + T_D$. Now, the thrust ratio here $\tau$ is defined as the ratio of the propeller thrust to the total thrust. And, this ideal efficiency is a function of the thrust ratio and the thrust loading coefficient given by this expression, which is the total thrust divided by $\frac{1}{2} \rho A_0 V^2$, where V is the forward velocity or the velocity of advance.

And, $A_0$ here in the axial momentum theory is nothing but the disc area because in the axial momentum theory the propeller is replaced by an actuated disc. So, this is $\pi D^2/4$, where D is propeller diameter. It is important to mention here that in the axial momentum theory ideal flow is assumed and that is why the drag is neglected. Now, we can consider the drag force of the duct and that can be used to modify the efficiency from the ideal value to a more appropriate value by considering the drag. And, still we are not considering the blade as such.

So, the number of blades or the actual geometry of the propeller is not considered here as before for axial momentum theory. Now, this ideal efficiency does not include any effect of drag and the flow is also assumed to be ideal. We can use the drag force generated by the duct and calculate the efficiency of this ducted propeller system by including the drag.

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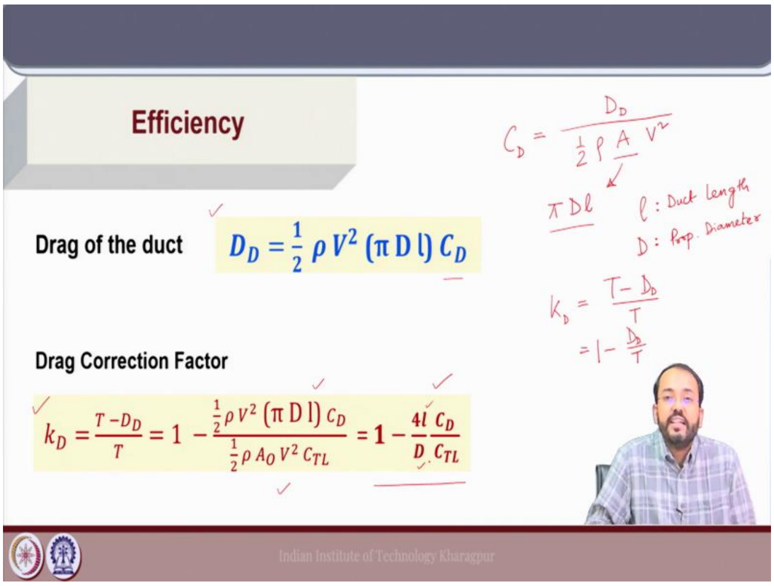


If $D_D$ is the drag force generated by the duct, it will be $C_D$ which is the drag coefficient multiplied by ½ ρ $V^2$A, because drag coefficient is defined by standard drag force by half ρ A $V^2$, that is how we define drag and lift coefficients dividing by ½ ρ $V^2$A. Now, here $D_D$ is the drag force for the duct and A the area over which we compute the drag force is π D l, where l is the length of the duct and D is the propeller diameter.

Now, there is a small tip gap between the propeller blade tip and the duct. Here, in the axial momentum theory because the propeller is assumed as a momentum disc, we are assuming that the propeller diameter is equal to the duct diameter that makes the area here as π D l. And, hence the drag force for the duct can be expressed using this particular equation.

Now, we can include a correction factor $k_D$ which is given as (thrust - drag force) / thrust. And, this correction factor can be used to define the efficiency for the ducted propeller system including the drag. Now, T - $D_D$ / T, $k_D$ = 1- $D_D$/T and $D_D = ½ \rho V^2 (\pi D l) C_D$. And, thrust can be represented with respect to the thrust loading coefficient $C_{TL} \times ½ \rho V^2 A_0$.

$$k_D = 1 - 4l/D \times C_D/C_{TL}$$

And $A_0$ is nothing but $\pi D^2/4$. If we write these expressions finally, the value of drag correction factor can be given in this form. As a function of the drag coefficient and the thrust loading coefficient, where small l here is the length of the duct and D is the diameter of the ducted propeller.

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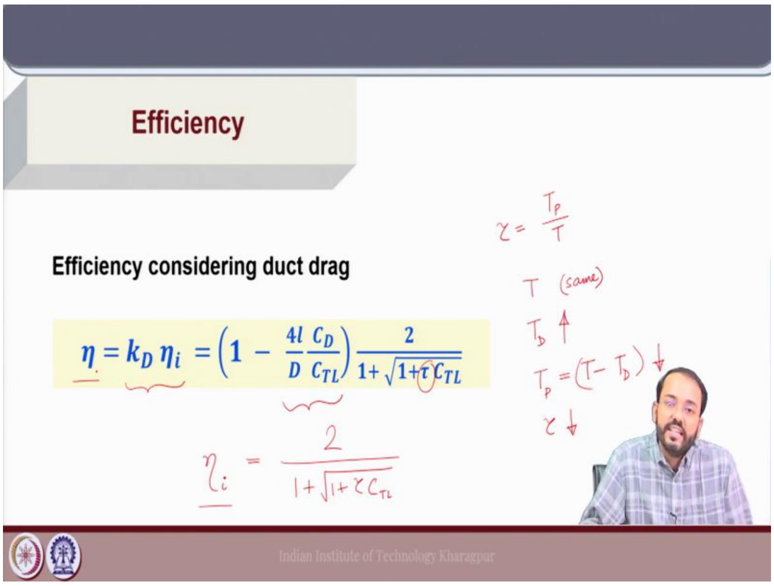


Now, we can write the efficiency considering duct drag as $k_D$ multiplied by the ideal efficiency which was obtained before. So, first we use axial momentum theory to estimate the ideal efficiency for a ducted propeller which is a function of $\tau$ and $C_{TL}$. And, then we use a duct drag correction factor to estimate the efficiency by considering duct drag of the ducted propeller system.

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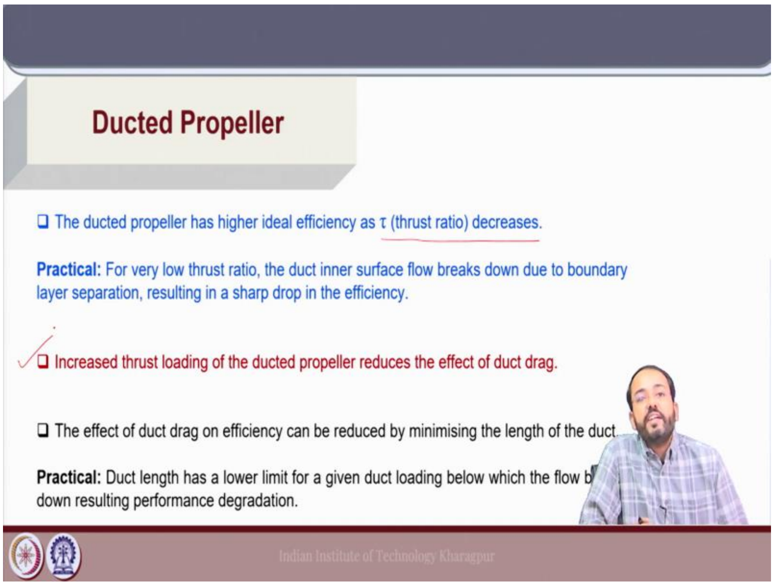


Next, we have to look into each of these factors and what is the influence of these factors on the efficiency of the ducted propeller system. First, it is seen that as $\tau$ decreases in the ideal efficiency equation, if we go back again, $\tau$ is in the denominator and $\tau$ is given by $T_P/T$. The propeller thrust to the total thrust. Now, for the same thrust, which is the total thrust from the ducted propeller system, if $T_D$ increases for same total thrust.

If the component of the thrust that is provided by the duct, if that component increases then $T_P$ is $T - T_D$. So, this $T_P$ must decrease and hence $\tau$ will decrease. So, for the same total thrust, if we have a larger component of thrust from the duct $T_D$ then $\tau$ will decrease, that is mentioned here. As thrust ratio decreases, the ideal efficiency will increase for the ducted propeller that is obtained from the ideal efficiency equation.

Now, for a practical case, if the thrust ratio is very low if $\tau$ is very low, then the duct inner surface flow will break down and boundary layer separation will occur which will result in a sharp drop in efficiency. So, from the ideal flow in the axial momentum theory, we see that the higher the thrust ratio the lower will be the ideal efficiency. And, on the other hand the lower the thrust ratio as $\tau$ decreases the higher will be the ideal efficiency.

But, in a practical scenario if it falls below a certain value for very low value of $\tau$, the flow will separate due to boundary layer separation and also that results in a sharp drop in efficiency. The second point here, the thrust loading of the ducted propeller reduces the effect of the duct drag. Now, again if we go back, the effect of duct drag is considered here because, ideally the efficiency was $2 / 1 + \sqrt{(1 + \tau \times C_{TL})}$. This was the ideal efficiency.

Now, the effect of duct drag is coming from this particular expression and the higher the value of $C_{TL}$, the lower will be this negative factor -4l/ D into drag coefficient divided by the thrust loading coefficient. So, higher the value of the thrust loading coefficient, the lower will be the effect of duct drag in reducing the ideal efficiency to this value. So, the effect of $k_D$ will reduce, if $C_{TL}$ is high, that is mentioned here.

Next, the effect of duct drag on efficiency can be reduced by minimizing the length of the duct. Why? Because, the surface area on which we calculate the drag force is given by $\pi$ × diameter of the propeller × l, where l is the length of the duct. So, if the length of the duct is minimized, that will reduce the duct drag.

Now, again from the practical point of view, if the length is reduced below a certain value then the flow will again break down and because of that the performance of the duct will not be proper. So, the values that we obtain from momentum theory, give us a rough guideline of the efficiency. But, for practical cases there are limits beyond which there are flow separation effects which will guide the final performance and efficiency of the system.

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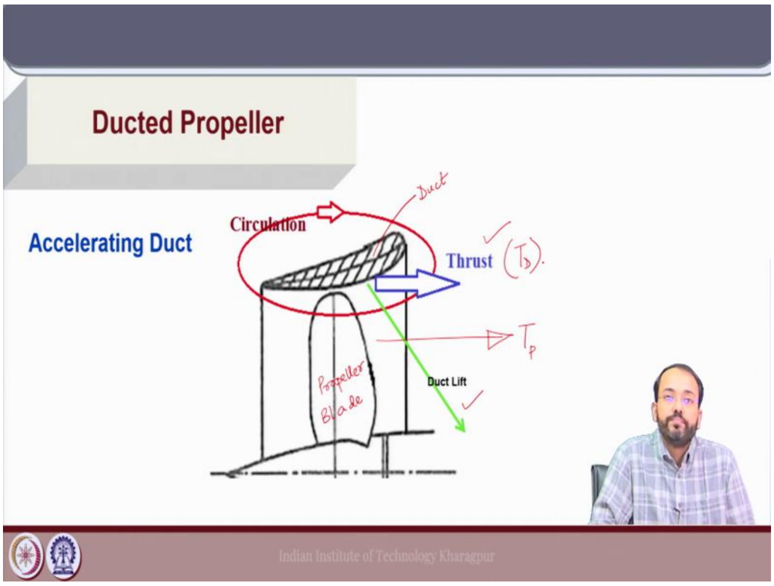

Here, an accelerating duct is shown around a propeller and a section of the duct is shown which generates a force based on the circulation around the duct section. So, we have the propeller blade here and this is the duct. And, based on the duct profile, it guides whether the duct will accelerate the flow into the propeller or whether it will decelerate the flow which is the other case for a decelerating duct.

So, in this particular design, the duct is of accelerating type which increases the inflow into the propeller plane. And, hence the circulation which is generated around the duct is directed such a way that the duct lift is shown in this direction. And, the forward component of that lift is the thrust which is also in the direction of the thrust generated by the propeller $T_P$ and this thrust is the duct thrust $T_D$.

So, for an accelerating duct under high loading conditions, where the duct generates a positive thrust, the total thrust will be higher than the propeller thrust; because the duct thrust is also contributing to the total thrust.

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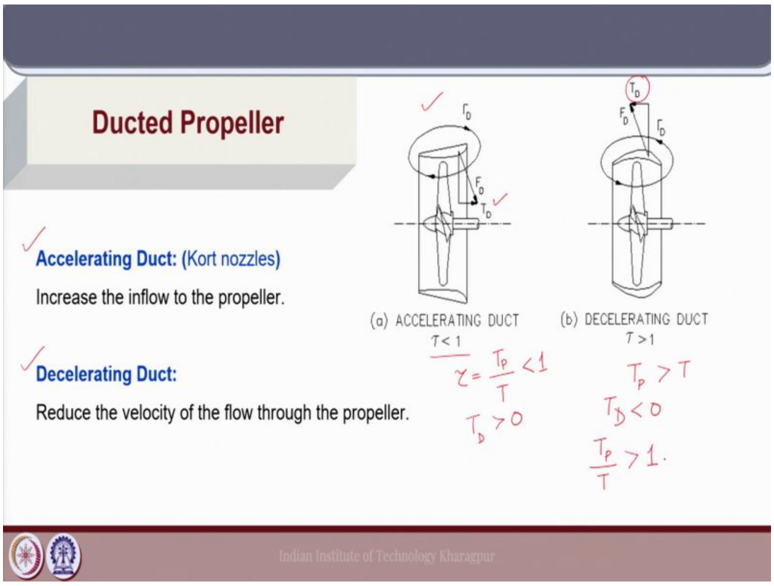


We have two types of ducted propellers as was mentioned briefly in the last lecture. An accelerating duct which increases the inflow to the propeller and a decelerating duct which reduces the velocity of flow through the propeller. Now, here we see the same diagram for an accelerating duct, where the circulation is shown around the duct. And, it generates a lift force, the forward component of which is a duct thrust $T_D$.

So, in this particular duct $\tau$ which is $T_P/T$. The propeller thrust by the total thrust is less than 1, because duct thrust is positive. On the other hand, for a decelerating duct, the circulation is generated in such a way depending on the design of the duct; that it generates a negative thrust. That means, the thrust here $T_D$ is directed opposite to the direction of the propeller thrust under normal operation condition. So, $T_P$ has to be greater than T because, $T_D$ is negative. Since, $T_D$ is negative, $T_P/ T$ is greater than 1 for a decelerating duct.

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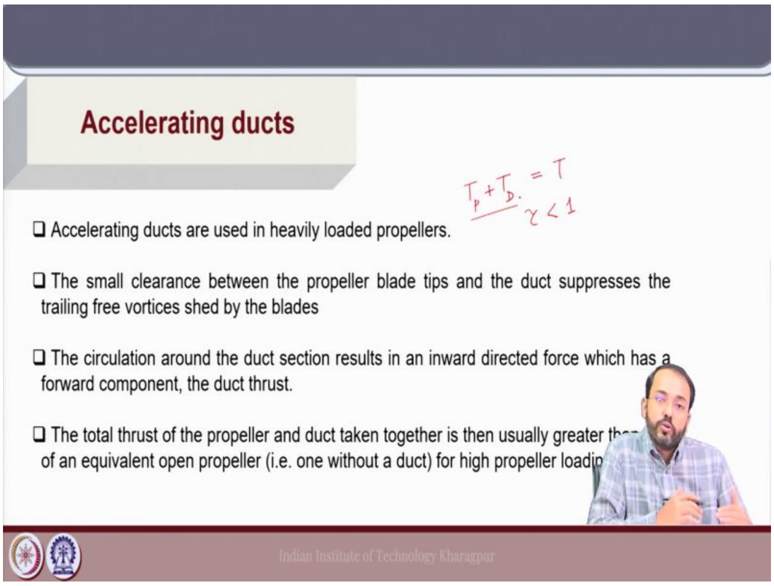


In terms of application, the accelerating ducts are used in heavily loaded propellers where the value of advance coefficient during the operation condition is low. So, in that condition the duct provides a good fraction of the total thrust for the propeller system. And, hence $T_D$ is an important factor in the total thrust of the propeller. We have $T_P + T_D$ equal to the total thrust and the value of $\tau$ is less than 1.

As the duct thrust is also important in providing the forward thrust of the total duct plus propeller system. A small clearance between the propeller blade tips and the duct suppresses the trailing vortex shed by the blades. So, because the propeller blade tip is very close to the inner surface of the duct, the tip vortex which is shed from the propeller tips are suppressed by the presence of the duct. The circulation around the duct results in an inward directed force as we have just seen.

And, this force has a forward component which is the duct thrust which adds up to the propeller thrust to give the total thrust. And finally, the total thrust of the propeller and duct taken together is usually greater than that of an equivalent open propeller. That means, when we say open propeller; that means, a conventional propeller where we do not have the duct. So, the idea here is that if we have a ducted propeller because, the duct is also contributing to the total thrust.

The total thrust produced from the ducted propeller assembly should be higher than the thrust from the open propeller which is without the duct for a similar design. And, this is true for high propeller loading conditions. This we will see from the open water diagrams.

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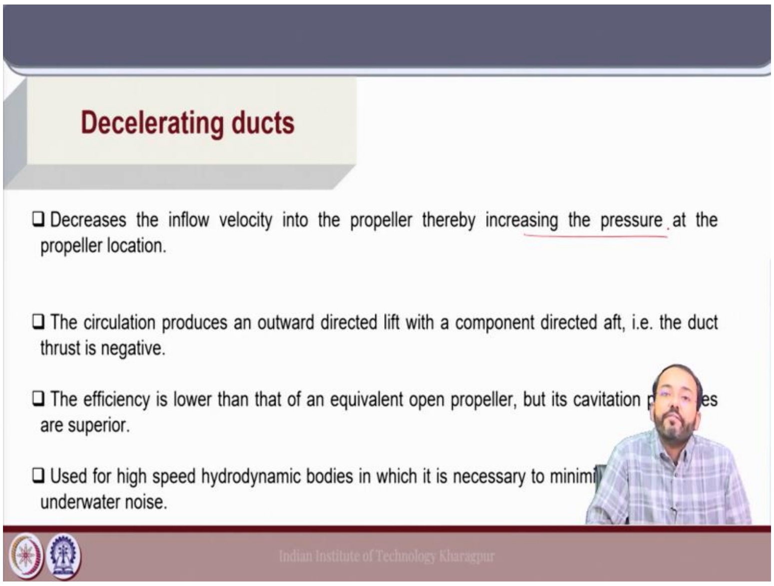


On the other hand, decelerating ducts reduce the inflow velocity into the propeller by increasing the pressure at the propeller location. Now, in this particular case, the circulation around the duct section is such that an outward directed lift is generated. And, the component of that in the x direction is directed aft of the propeller. And, hence the duct thrust is negative for decelerating ducts.

Now, why will we use decelerating ducts? These are utilized for specific ships where cavitation is a problem, because they increase the pressure at the propeller location. So, decelerating ducts are used for cases, where cavitation performance is important. And, the efficiency in this case will be lower than that of an equivalent open propeller, because the thrust is low as the duct thrust is negative. And, in high speed hydrodynamic bodies, where reduction of cavitation is required as well as underwater noise decelerating ducts can be used.

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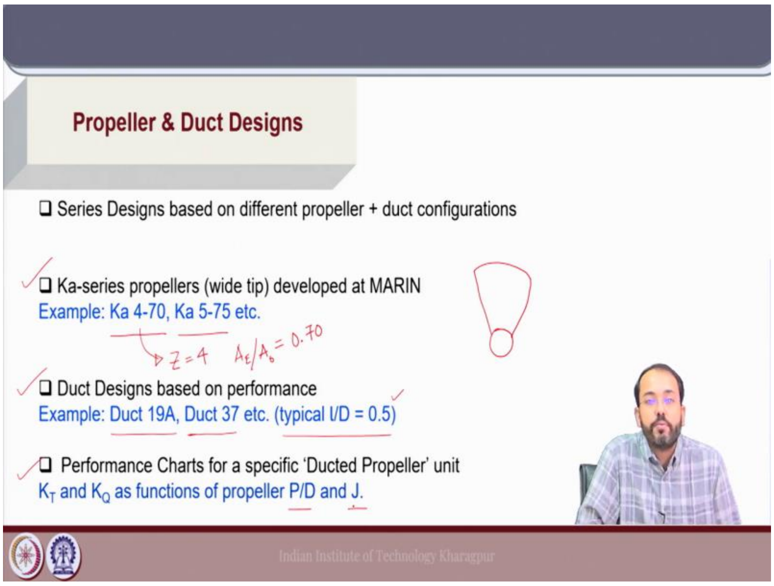


Now, just like open propellers for ducted propellers also there are certain series designs which are developed based on different duct and propeller configurations. So, for a standard conventional propeller, the designs were based on different blade types. Different blade geometric parameters like blade area ratio, pitch ratio, number of blades etcetera.

Similarly, for ducted propellers certain series designs are available for the propeller as well as duct configuration. And, one of the most popular designs is the Ka series propellers which have wide blade tips. So, these propellers they have wide blade tip and with a combination of suitable ducts, a series of these propellers have been developed at MARIN. And, the terminology is very similar to the B series propellers that we have studied earlier.

Here, the Ka series are denoted in this fashion, Ka 4-70 or Ka 5-75. It means for Ka 4-70 propeller z is 4; that means, the propeller is a 4 bladed propeller. And, the blade area ratio $A_E/A_0$ equals 0.70. Similarly, for Ka 5-75 propeller, the number of blades is 5 and the blade area ratio is 0.75.

Now, apart from the propeller, the other important factor is the duct design because for a ducted propeller the propeller and duct both contribute to the total thrust. And, similarly different duct designs are developed like duct 19A, which is one of the most popular duct designs. Duct 37 is another duct design which is used for vessels where good Aston performance is also required. Now, typical l/ D which is used for ducted propellers is in the range of 0.5.

So, the length of the duct divided by the diameter of the propeller is around 0.5 and higher values are also tested. Performance charts for specific ducted propeller units are generated and they include open water thrust and torque coefficients as functions of P/D and J; the pitch ratio and the advance coefficient. So, similar to open propellers, we also have thrust and torque coefficient charts in open water conditions for ducted propellers which are used for the design of ducted propeller units.

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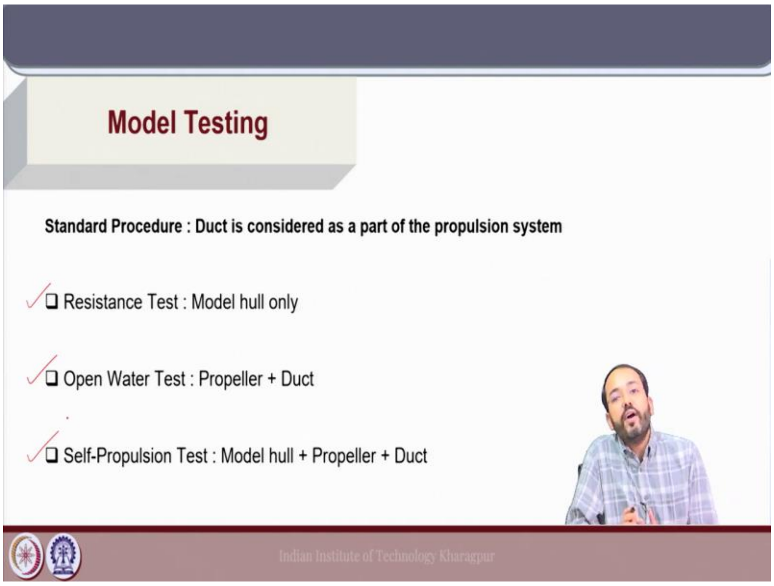


Now, if we look into the model testing perspective for ducted propellers, we have the resistance test where the model hull is only used. And, in this particular design, the duct is considered in general as a part of the propulsion system. So, the duct and propeller together forms the propulsion unit. So, the open water test is performed with the propeller inside the duct.

And finally, the self propulsion test is done for the model hull with the propeller and duct. So, a ducted propeller unit is considered as a single propulsion unit where the duct and propeller together produce the thrust which is required for the vessel to be propelled for a specific operation condition.

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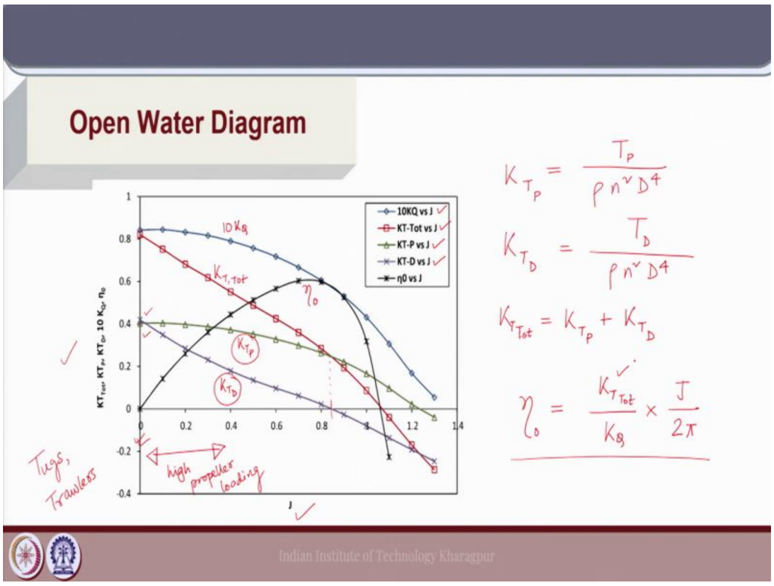


Now, let us look into the open water diagram for a ducted propeller system. Here, we have the different coefficients; the thrust coefficient from the propeller, duct and the total thrust coefficient, the torque coefficient and $\eta_o$. All plotted as a function of the advance coefficient J. So, we have $K_{TP}$ which is the thrust coefficient from the propeller, $K_{TD}$ thrust coefficient for the duct and $K_T$ total or $K_T$ which is the total thrust coefficient. So, $K_T$ as before is defined by this expression.

And, if we write it as $K_{TP}$, then it will be T P. If we write it as $K_{TD}$, it will be thrust from the duct. So, the procedure for non-dimensional is same and we have $K_T$ total equal to $K_{TP}$ + $K_{TD}$ the two components, one from the propeller and duct. Let us look into the plots one by one. The first one $K_{TP}$ is this line; the highest value of $K_{TP}$ is in the bollard pull condition, where J is 0. And, as J increases $K_{TP}$ will decrease.

This is in line with what we have observed for the open propeller, the conventional propeller. Similarly, $10K_Q$ the blue line here has its highest value at the bollard condition, where J equal to 0 and it decreases as J increases. Now, for the duct thrust $K_{TD}$, the highest value is also at the bollard pull condition at J equal to 0. But, it reduces sharply to a value of 0, when the propeller thrust has a positive value here.

And, the total thrust is given by this red line $K_T$ total which is the duct thrust plus the propeller thrust. So, in this case the coefficients. Now, at the bollard pull condition, where J is equal to 0 both the value of the thrust coefficient for the propeller as well as the duct thrust coefficient are highest. So, the value of $K_T$ total is very high and we can see here that $K_{TP}$ and $K_{TD}$ are almost equal. Now, it will depend on the duct and propeller design.

But, the idea here is that the thrust given by the duct as a component of the total thrust is very high in the bollard pull condition. So, ducted propellers are applicable for vessels which operate in the high loading condition in this range, where the J value is low. So, this is high propeller loading. So, typically tugs, trawlers and also other types of vessels which operate in high loading conditions. Now, for tugs and trawlers where the towing duty is critical, the forward speed is very low and a large amount of thrust is required.

So, in these cases ducted propellers can give very high thrusts which are used for effective towing purposes. And, close to the bollard condition we see that the thrust ratio tau is almost equal to 0.5; that means, the portion of thrust produced by the propeller is almost half that of the total thrust because, the thrust coefficient of the propeller as well as the duct are very similar. It will depend on the propeller and duct designs for specific applications.

And, the efficiency for the ducted propeller system $\eta_o$ will be defined based on the total thrust and the torque, in the same formulation as we have obtained for the open propeller. The only difference is that we have the total thrust here in the efficiency term. So, the ducted propeller open water diagram gives a representation of the duct thrust, the propeller thrust and the total thrust and torque and efficiency for the ducted propeller system.

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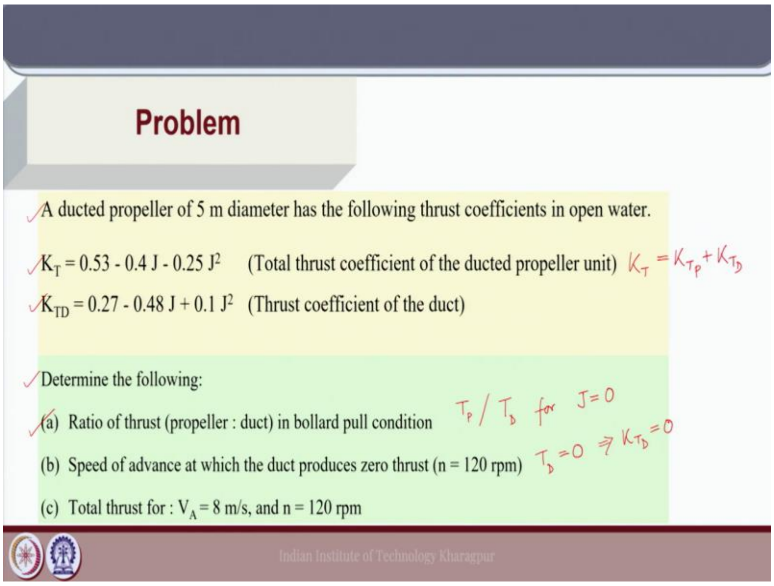


Let us look into a simple problem for ducted propeller in open water. So, here we have a ducted propeller of 5 meter diameter and the thrust coefficients in open water are given. First, we have the total thrust coefficient of the ducted propeller. So, this $K_T$ is equal to $K_{TP}$ + $K_{TD}$, the contributions from both the propeller and the duct. And, next we have the thrust coefficient of the duct; both of them are expressed as a function of the advance coefficient J.

And, in the problem it is required to determine three different things. The first one is the ratio of thrust propeller is to duct in the bollard pull condition. So, $T_P/T_D$ for bollard pull condition; that means, 0 advance speed, J is equal to 0. Next, the speed of advance at which the duct produces zero thrust; that means, thrust of the duct is equal to 0 which implies $K_{TD}$ will be equal to 0.

And, for that condition we have to calculate the speed of advance given the rpm of the propeller. And, the third part is to calculate the total thrust for a given value of $V_A$, the advance speed and the rpm of the propeller.

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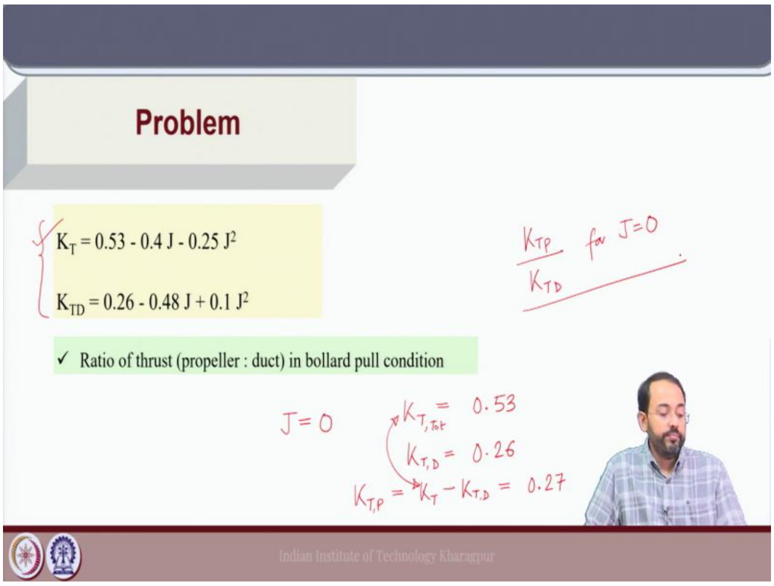


Let us look into these parts step by step. We have the thrust coefficient part of the open water diagram, the total thrust and the duct thrust given in these equations. Now, in the bollard pull condition J will be 0, then $K_T$ the total thrust or $K_T$ total we can write same as $K_T$ here is 0.53.

Because, in the bollard condition the advance coefficient is 0 and $K_{TD}$ is equal to 0.26. So, we can calculate the thrust coefficient from the propeller only as $K_T$ - $K_{TD}$, where $K_T$ is same as the $K_T$ total which is equal to 0.27 here. So, we can get the ratio of the propeller and duct thrust as $K_{TP}$ / $K_{TD}$ for J equal to 0, can be calculated from this part.

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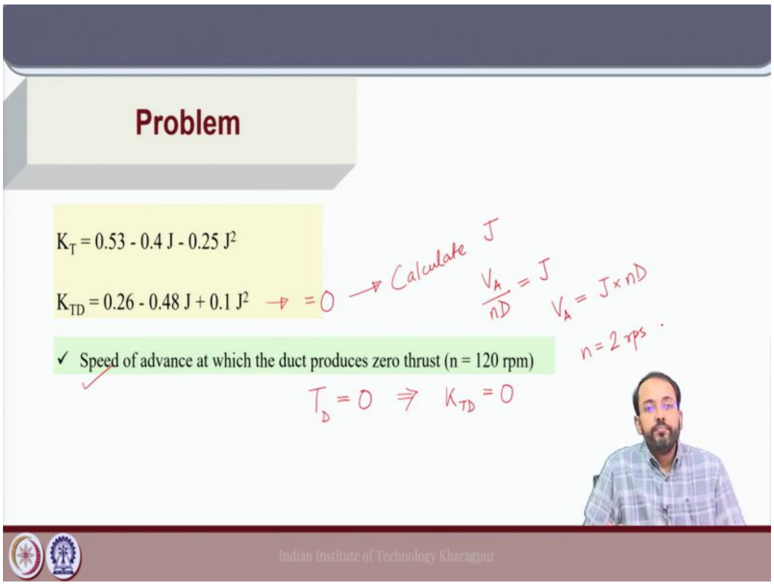


The next part is to calculate the speed of advance at which the duct produces zero thrust. So, for thrust from the duct equals 0; in this condition, $K_{TD}$ should also be equal to 0. So, in this particular equation, if we put this expression as 0, we can calculate the value of J by solving this quadratic equation.

And, from that calculated value of J, $V_A/nD$ is equal to the advance coefficient J and we can calculate $V_A$ which is the speed of advance as required in this problem as $J \times nD$ and n is 2 rps. And, the propeller diameter is also given in the problem. So, we will be able to calculate the speed of advance.

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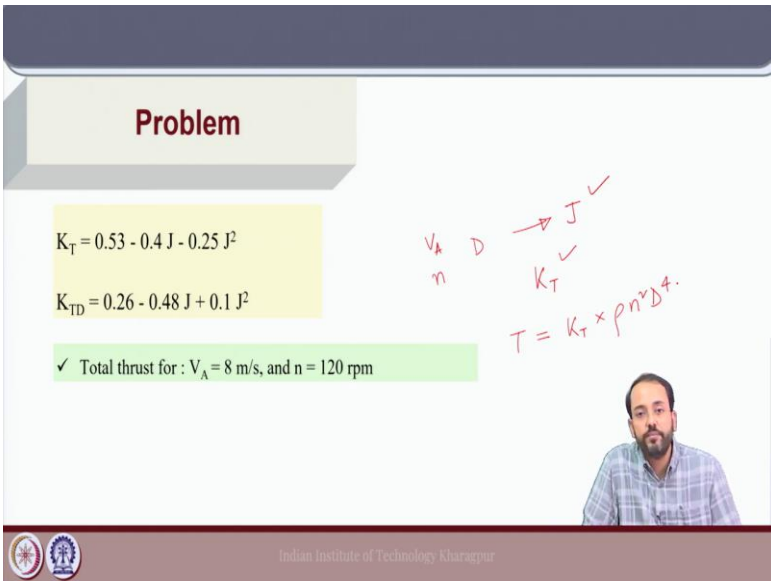


Now, the third part of the problem, here we are required to calculate the total thrust for a given combination of $V_A$ and n. So, for this $V_A$ and n combination, we can use the propeller diameter to get the advance coefficient J. If J is calculated using that value of J, we can calculate the total thrust coefficient $K_T$. And, from the total thrust coefficient $K_T$, we can get the total thrust T is $K_T$ multiplied by this expression.

So, for any advance coefficient value, we can calculate the total thrust as well as the thrust from the duct using this method. So, in this way we can use the open water characteristics for a ducted propeller to calculate the performance of the propeller as well as the duct for different operation conditions. This will be all for the part on ducted propellers.

Thank you.