Marine Propulsion

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Lecture - 30
Propeller Design (Part - I)

Welcome to lecture 30 of the course Marine Propulsion. Today we will continue with Propeller Design.

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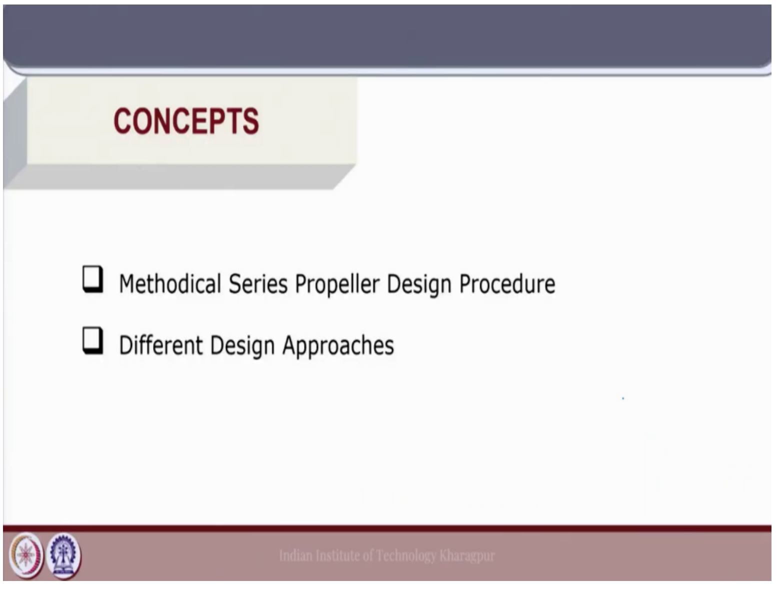

The key concepts to be covered in today's lecture is details on the methodical series propeller design procedure and different approaches that can be used under this methodical series design procedure to arrive at the final propeller design.

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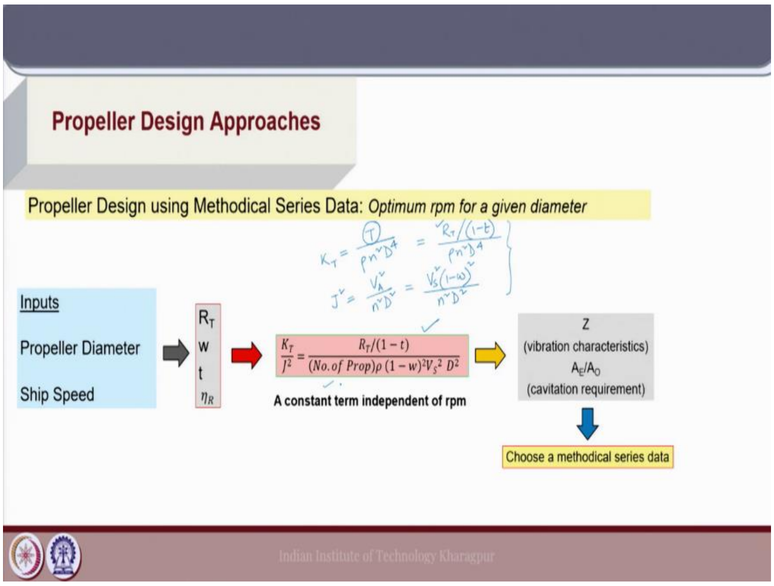

Now, we have seen that there are primarily two design methods that are employed for the design of marine propellers. One is the methodical series propeller design procedure, where the propeller design is based on certain methodical series data, where depending on the input variables we get a set of geometric parameters belonging to that specific series and the other procedure was designing using the circulation theory.

So, here we will discuss the different aspects or the different methodologies in which a propeller can be designed using methodical series. First, we will go through some basic design approaches which are used for preliminary design and then move on to the slightly more detailed design based on the preliminary estimates to get the final design of the propeller for the specific ship characteristics.

The first approach that we will study here is to design the optimum rpm for a given propeller diameter. So, the inputs are the propeller diameter and the design speed of the ship, we have the total resistance of the ship at the design speed and a preliminary estimation of the wake fraction thrust reduction and relative efficiencies used for the design. Now, because we do not know the propeller rpm here, we will start with the non-dimensional parameter K_T / J^2.

So, $K_T = T/(\rho\ n^2\ D^4)$ can be written in this form and $J^2 = V_A{}^2/(n^2\ D^2)$ is this. Now, T = resistance $((R_T) / (1 - t)) / (\rho\ n^2\ D^4)$ and $V_A = V_S \times$ (1 – wake fraction (w)). So now, if we use these two expressions, we can get this particular expression for K_T / J^2.

$$\frac{K_T}{J^2} = \frac{R_T/(1-t)}{(No.\ of\ Prop)\rho\ (1-w)^2 V_S^2 D^2}$$

Why number of propellers here? Because in K_T this thrust that we have is for one propeller, but the resistance here is the total resistance of the ship. So, it has to be divided by the number of propellers to find the K_T / J^2 for a single propeller. The same procedure we have already followed in the ship powering extrapolation from model test results.

Now, this term is independent of rpm, because we want to calculate the optimum rpm from the design process. Next, based on the vibration characteristics and cavitation requirement we select the initial values of the blade number Z and the A_E/A_0 ratio which is the blade area ratio. And then we choose a specific methodical series for designing the propeller.

Now, it depends on the expertise of the propeller designer while choosing the particular series for the design process. Here the basis is that, when we choose the specific series it should be applicable for the propeller design with respect to the operation condition in the specific ship type.

And the choice of Z and A_E/A_0 which is the blade area ratio will lead us to the specific open water diagram for a set of P/ D ratio, where we will be using this input value to get the propeller design parameters.

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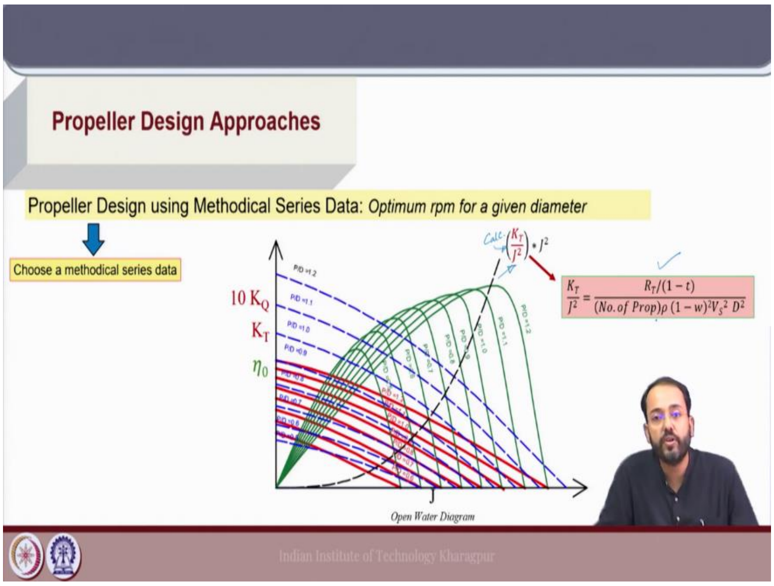

So, once we choose the methodical series data, we have this set of open water diagrams for a varying P/D ratio for the specific value of number of blades Z and the blade area ratio as we have seen. Because every methodical series data is presented as a function of open water characteristics for a specific set of P/D ratio keeping the blade number and the blade area ratio constant and then if they are varied we get new set of data for every geometric parameters.

Now, here the open water diagram shows the thrust coefficient 10 times the torque coefficient and the open water efficiency for a range of P/D ratio as a function of J. Now, we have already calculated K_T/J^2 from the given requirement and that K_T/J^2 is the calculated value here, calculated K_T/J^2.

Now, we need to get the required K_T for different pitch ratios so that we can get the optimum geometry of the propeller based on the efficiency characteristics. So, that calculated K_T/J^2 is multiplied by J^2 to get the required K_T over the entire range and this is given by the dotted black line here. So, it is mentioned here the K_T/J^2 within this bracket is given by the same expression as shown in the previous slide ok.

And here why do we need this? Because we need to intersect this line with the K_T curves for the different pitch ratios to get the design point for our propeller.

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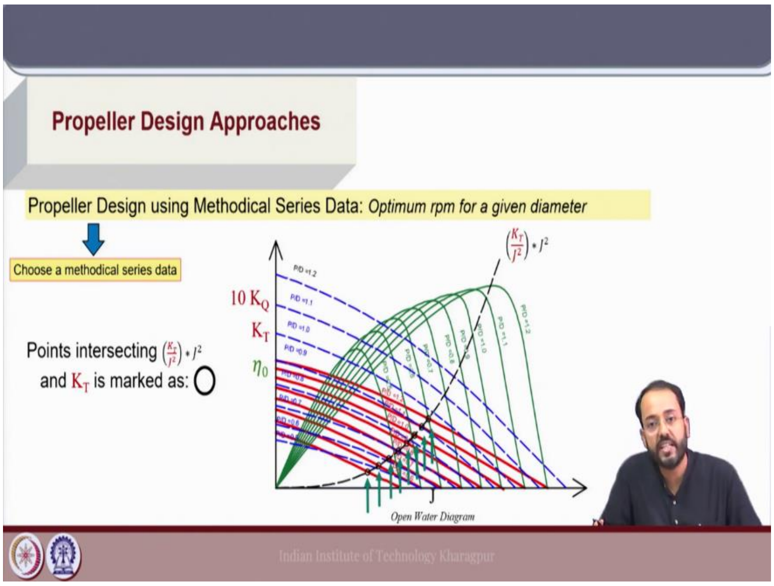

Here the red lines correspond to the K_T curves, the thrust coefficient in the open water and the blue dotted lines are the K_Q curves.

Now, we have to intersect the K_T/J^2 multiplied by J^2 and the K_T curves to get the design points and that is shown by the encircled points where it is intersecting, these are the points specifically shown by arrows. So, we can say that these points form the range of design points with respect to different pitch ratio.

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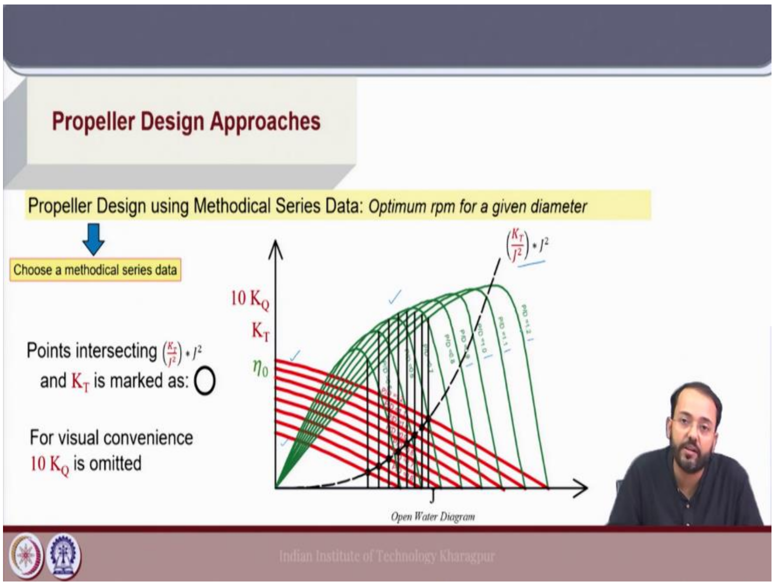

Let us remove the 10 K_Q curves for convenience now. The picture is more clear now each of these intersections of the K_T/J^2 multiplied by J^2 curve and the K_T curves at different pitch ratios is a design point for the required propeller. And we have seen earlier that as we increase the pitch ratio of the propeller blade the thrust and torque coefficient increases, which is shown here in this set of curves. The highest curve here will be for the largest pitch ratio and the curve at the bottom here is for the lowest pitch ratio.

And because of that the intersection points are different for each curve. So, technically we can go to any of these intersection points and that will be a design point for the required propeller, but there is something important that we need to take care of which is the efficiency. These green lines show the efficiency curves for different values of pitch ratio and we have seen that the open water efficiency increases in range when the pitch ratio is increased.

So, for the highest pitch ratio 1.2, the open water efficiency curves has the biggest range in the open water diagram. But locally there will be variations of the maximum efficiency depending on which P/D ratio is used for the efficiency calculation.

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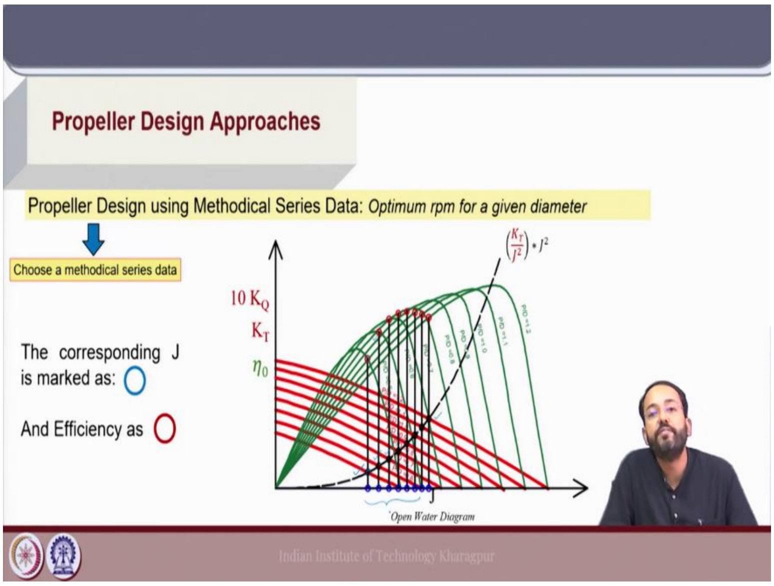

The next step will be to see at what J and what efficiency these intersections correspond to. Let us take the first value here. So, we have the intersection for the lowest value of the P/D ratio and then corresponding to that efficiency curve for that P/D ratio we will get the efficiency for that design point.

Similarly, if we take the 2nd point, 3rd point and so on the line will correspond to the intersections with that P/D ratio for which we are getting the intersections. In this way we can intersect each of these design points with vertical lines corresponding to the P/D ratio for which the K_T was given right and similarly we have a set of J values as the design points, when we intersect at the corresponding K_T curves.

The meaning of these set is that each of these design points where the K_T for a particular pitch ratio is equal to the required K_T for the design, we will have different efficiencies from the open water diagram. And for a propeller design we would go for the maximum efficiency possible to make the design effective and reduce the powering demand for the ship.

So, the corresponding J values are marked with blue circles and the efficiency values are marked with red circles.

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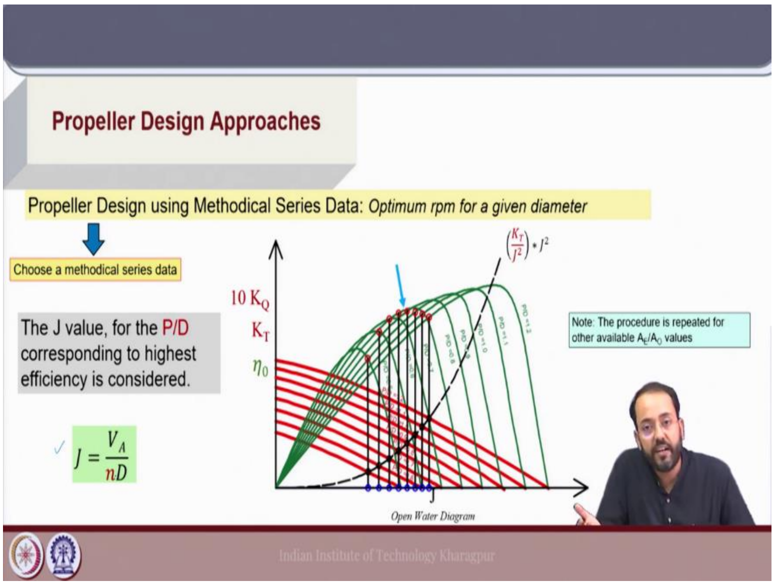

Finally, we will choose the J value for the P/D for which we are getting the highest efficiency and we can see here that the highest efficiency is corresponding to this particular point.

Now, this point is very important. Depending on the specific J value at which the required K_T intersects with the different K_T curves of the propeller, the highest efficiency will correspond to a specific P/D ratio.

And that P/D ratio can be any P/D depending on the range in which the intersections happen. Here that P/D is an intermediate P/D as we see from the design process and for that specific case we get the J and that J is expressed as V_A/nD. Now, we know V_A based on the ship speed and the wake fraction and diameter of the propeller was known from the start of the problem and in this way we can get the propeller rpm. And this particular procedure can be repeated for other available blade area ratio values.

Because for each blade area ratio we will get a set of open water diagrams like this, for varying P/D ratios. So, the same exercise can be done for other A_E/A_0 values and the design can be done.

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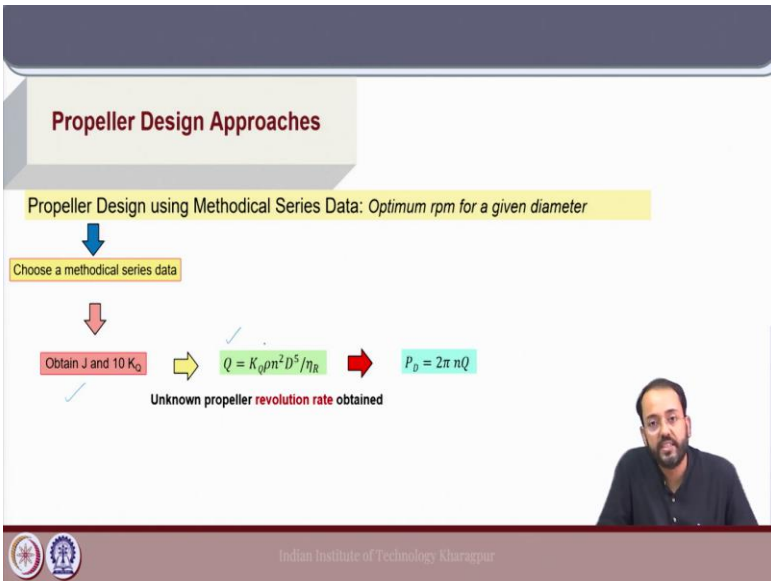

So, here from the methodical series data, we get the J value and for the J value we can get the corresponding $10K_Q$ value, from the $10K_Q$ value we can calculate the propeller torque and also the unknown revolution rate that we have seen and we have the open water torque coefficient and with the η_R we can calculate the torque and finally, the delivered power can be calculated.

So, this is a preliminary design approach to use the open water characteristics of the propeller to get an optimum rpm for a propeller with given diameter and input ship speed characteristics.

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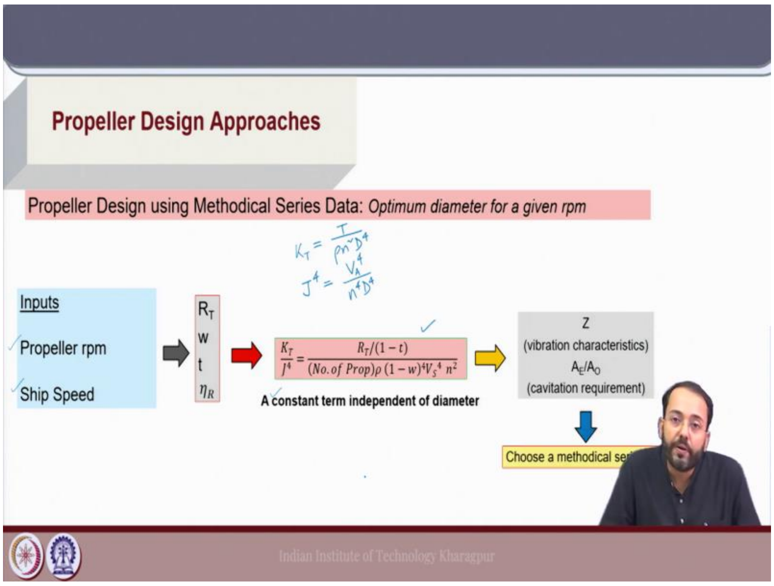

In the second approach we will look into the design problem in just the opposite way; that means, for a given propeller rpm we will use the same design charts to obtain the optimum propeller diameter.

So, we have the propeller rpm and ship speed as inputs. Here again we have the total resistance and the wake fraction, thrust deduction and relative efficiency as an initial estimate. In our discussions of propeller methodical series earlier in this course, a problem was discussed where the propeller diameter was required to be calculated from the given set of open water diagrams for a specific methodical series propeller.

There we have used this concept of K_T/J^4 to calculate the propeller diameter and this particular design approach will help understand that process in a better way. $K_T = T/(\rho\ n^2\ D^4)$ is given in this form and $J^4 = (V_A)^4/(n^4\ D^4)$ is given in this particular expression.

So, if we divide K_T/J^4, then the diameter term is cancelled and because diameter is an output in this particular design problem, instead of K_T/J^2 which was used in the earlier problem where rpm was the output here we will use K_T / J^4. So, that the diameter term is cancelled and we can now calculate this particular expression based on the given input values.

$$\frac{K_T}{J^4} = \frac{R_T/(1-t)}{(No.\ of\ Prop)\rho\ (1-w)^4 V_S^4 n^2}$$

Next again based on the blade vibration characteristics and initial value of the Z which is the number of blades is chosen and the ratio of A_E/A_0 which is the blade area ratio is chosen based on cavitation requirement. And we entered the open waters diagrams for the particular methodical series for which we will do the calculations.

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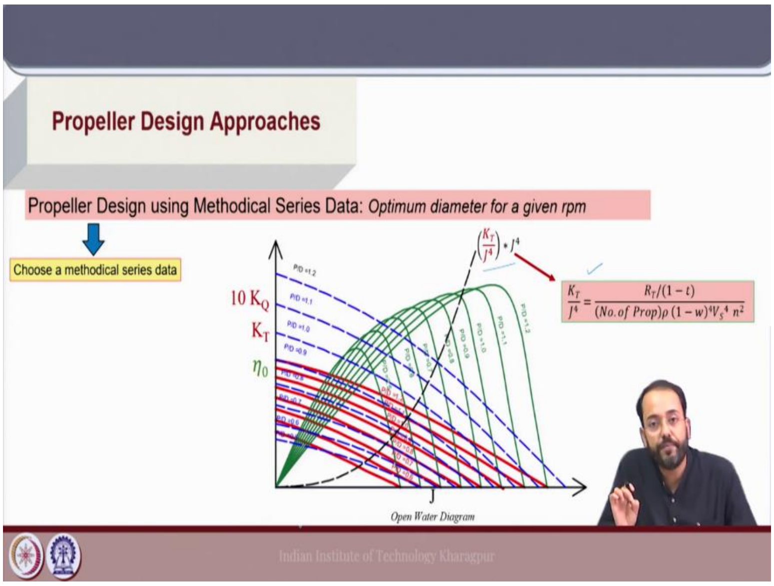

Now, again the similar process will be involved. The only change with respect to the previous process is instead of the line which represented $K_T/ (J^2 \times J^2)$ in the initial process where rpm was not known here, because we have the diameter as unknown we use KT/J^4 which is given by this expression and multiply with J^4 to get the K_T.

The implication is that based on the given parameters, this expression is already calculated and then just like the previous way we compute this curve and we intersect it with the K_T curves for the specific set of open water diagrams. So, again this particular set of open water diagram corresponds to a specific value of Z and blade area ratio and for different P/D ratios this particular diagram is plotted.

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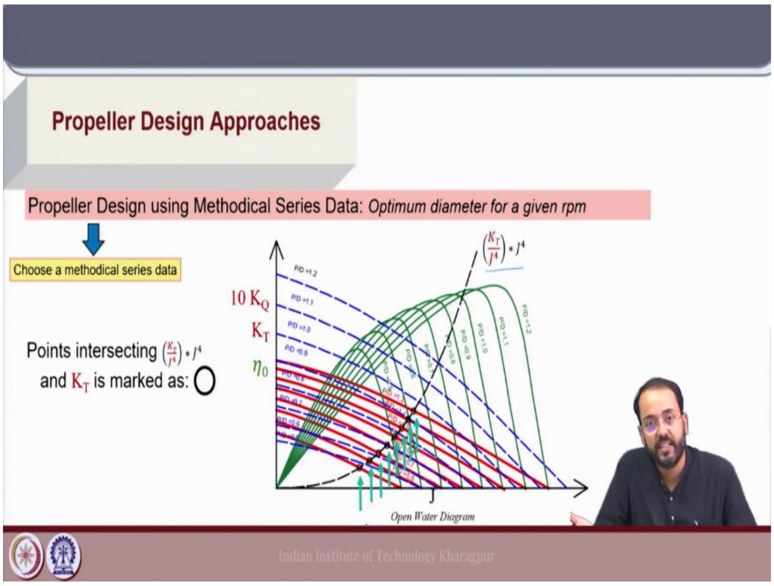

Now, because this expression denotes nothing but K_T, we intersect this curve with the set of open water K_T curves that we have, just like before ok. And we have the different intersection points which are encircled here and also mentioned with arrows ok. Now, again I should emphasize on this point, this dotted black line represents the required K_T and the different red lines are the open water K_T curve for different P/D ratios.

So, the design point will be the intersection of the required K_T with the open water K_T curves and for different P/D ratios we have different intersection points. Each of which is a design point for the propeller and again we will choose the particular design point which gives us the maximum efficiency.

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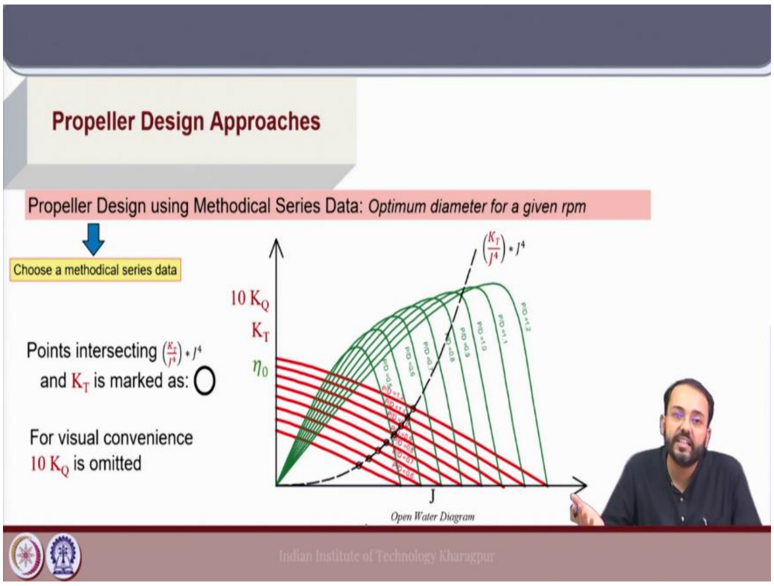

So, we follow the same procedure.

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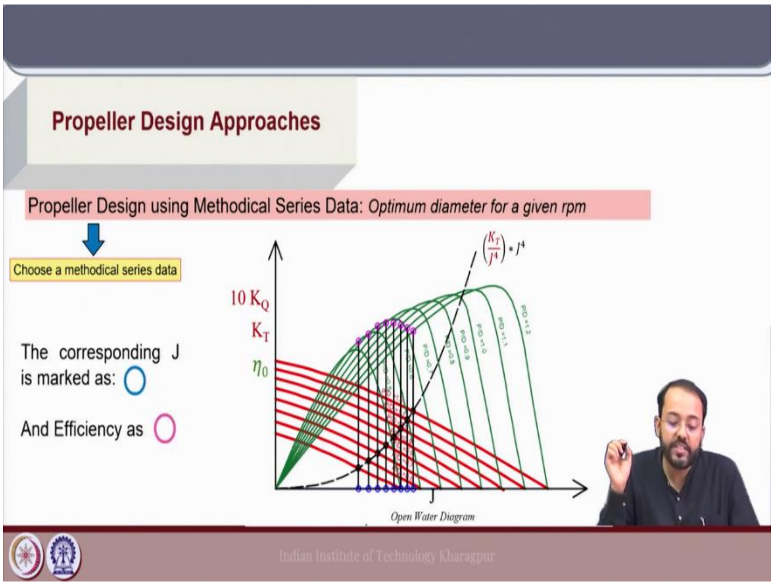

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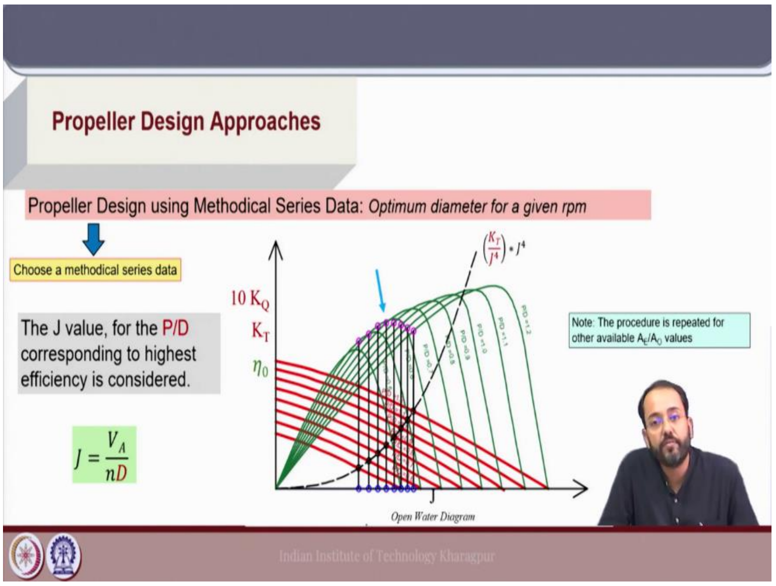

Each of these design points are extended by drawing perpendicular lines and we get different J values corresponding to these design points and we have different efficiency values by extending each design point to the corresponding open water efficiency curve for that P/D ratio to get the open water efficiency. And we choose the point for which we have the highest open water efficiency, just like the case before. So, for this particular value of open water efficiency we can compute the value of J right.

And because V_A is known from the speed of the ship and wake fraction we can calculate the diameter D, because rpm n was known in this particular problem. And again this procedure can be repeated for other values of blade area ratio. In this way we can get the different set of design points and arrive at the propeller design which gives us the optimum diameter corresponding to the maximum efficiency.

Now, these two methods can be used for preliminary design for estimation of the propeller diameter and rpm.

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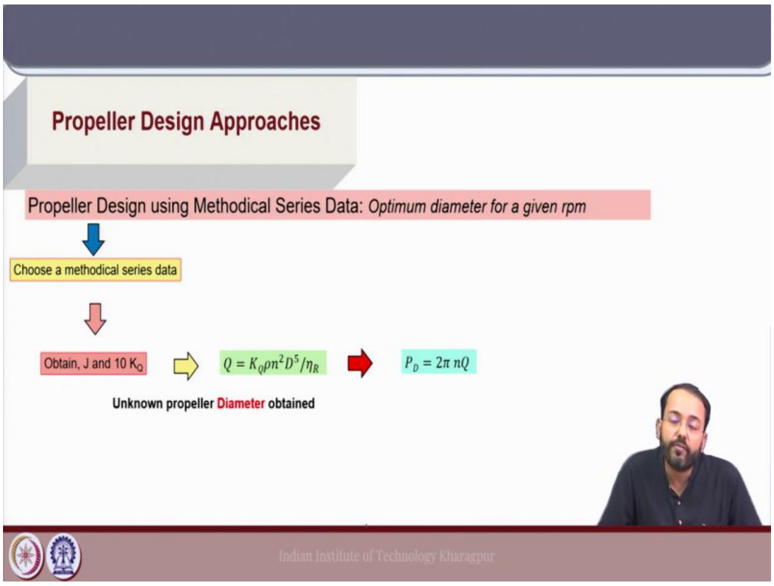

And from that we can get the power of the propeller because corresponding to the maximum efficiency again we can calculate the K_Q and we can calculate the torque and finally, the delivered power of the propeller. So, these methods give an initial estimate for the basic parameters like diameter and rpm of the propeller design and the delivered power required for the particular design.

Now, we will go on to a slightly detailed propeller design procedure where inputs from these methods can be used with the entire speed power curve of the ship to get a more detailed design method where the final propeller design can be obtained with respect to the requirements like cavitation and blade strength requirement.

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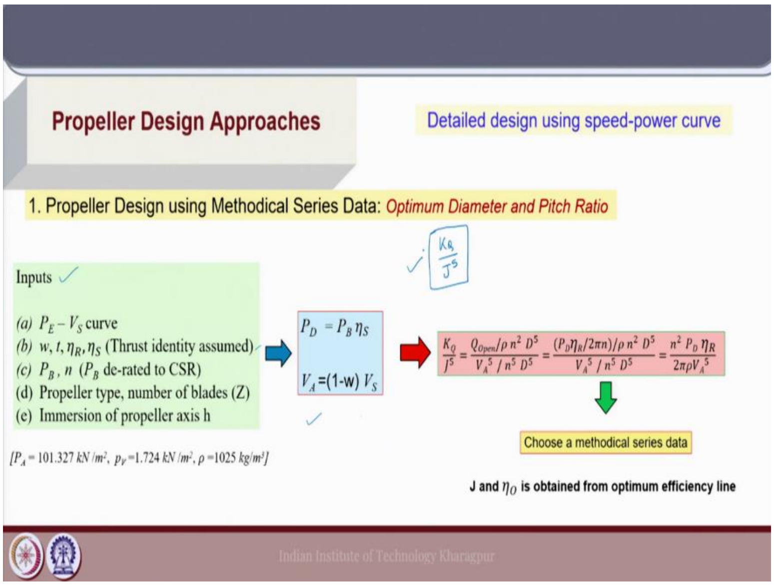

Now, for the detailed propeller design procedure using methodical series data, a series of input parameters are used. The first one being the effective power versus speed curve for the ship for which we are designing the propeller.

Next, we have the hull propeller interaction coefficients. The engine power de-rated to continuous service rating, rpm. Propeller type that we are using because that will correspond to the methodical series that we will be using, the number of blades the immersion of the propeller axis h which is important for calculation of the cavitation criteria.

Now, we will calculate the delivered power and the advance speed using the given expressions and based on that the first step here will be to calculate the expression K_Q/J^5. Why is this particular expression chosen here? Because the delivered power and rpm are known, because K_Q can be related to the delivered power and rpm and propeller diameter will be an output in this design procedure.

So, K_Q/J^5 is used to enter into the propeller design series charts. Now, there are different methods in which propeller design can be done using the methodical series data approach. The exact method followed will depend on the propeller designer and also the input data which is available in the design process and the design can be approached in different ways.

So, in each of these methods there is a non-dimensional parameter like this one which is used to enter the open water charts the charts can be expressed as simple open water diagrams or B P delta charts which we will be using in this particular method. And these charts can be used to get the propeller design parameters typically the geometrical aspects of the propeller and also the operational aspects like rpm, given the specific design constraints to get the final design of the propeller ok.

Now, these parameters that we use to enter into the open water charts will depend on the available input parameters. Now, we will again choose a particular methodical series data and finally, get the J and η_o from the optimum efficiency line.

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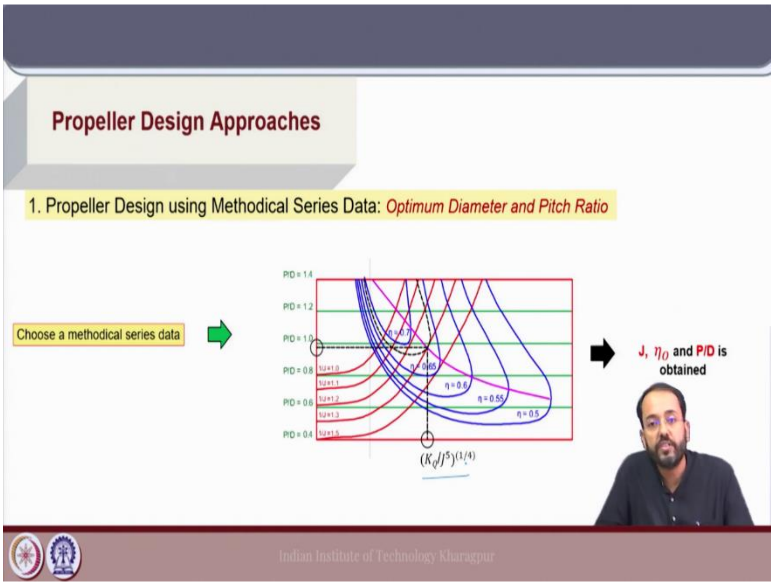

In this method we will use a different version of the open water charts where this expression is related to 1/J for different P/D ratios for the propeller and this pink line shows the optimum efficiency line.

So, this follows the class of charts which represent the type called B P delta charts which were discussed under the methodical series data for propellers. And delta is 1/J in the B P delta diagram as discussed. So, here we have this value as input and for different propeller pitch ratios which are given by these horizontal green lines, we can calculate the location of the optimum efficiency which can correspond to that design point.

The usefulness of this chart is that the optimum efficiency line is already given so that we can interpolate to get our design point. Now, the calculated value of this expression is shown here in this encircled point which is our design point, which we will use to enter into this diagram. We arrive at the optimum efficiency line and for that point we get the P/D ratio and also we can get the open water efficiency by interpolation for that specific design point and that is the output from this design curve.

So, for the given calculated input parameter, we get the J, η_O and P/D as the outputs from these open water charts.

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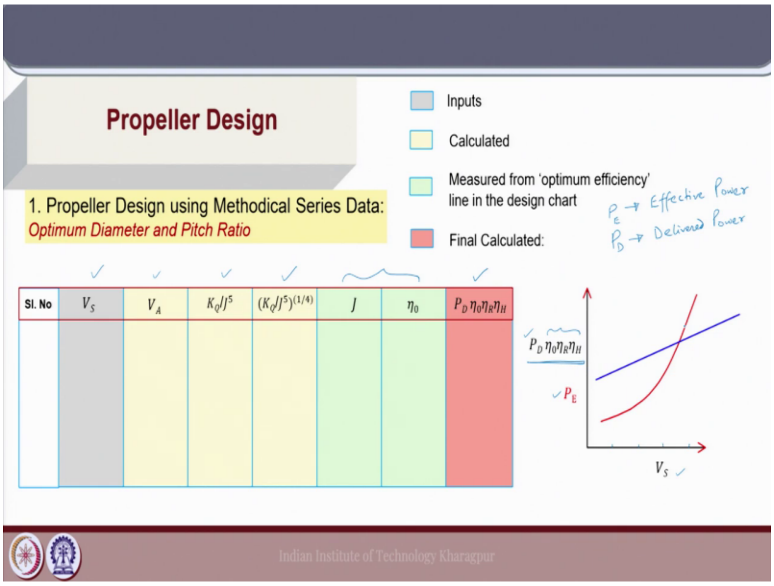

Now, in the next step we calculate the different parameters based on the input and the values that are obtained from the open water charts. Here V_S is the input, the next three terms are calculated as mentioned and from the optimum efficiency line in the design chart we get the value of J and η_O.

And finally, we calculate this expression P_D was known, η_R and η_H was given as an input to this design calculation, but we did not know the value of η_O, which was estimated from the design chart. So, now, we have this expression $P_D \times \eta_O \times \eta_R \times \eta_H$, which is nothing but the design value of the effective power.

Because these three efficiency components relate the effective power P_E to the delivered power P_D. So, here P_E is the effective power, P_D is the delivered power. Now, in this specific design problem the variation of the effective power versus ship speed was given.

So, the red line is an input to the problem. For each particular value of speed we can do this design calculation and obtain the corresponding J and η_O and get the design value of this particular expression $P_D \times \eta_O \times \eta_R \times \eta_H$. And let us say it is represented by the blue line. So, the intersection of these two lines will give us the design point.

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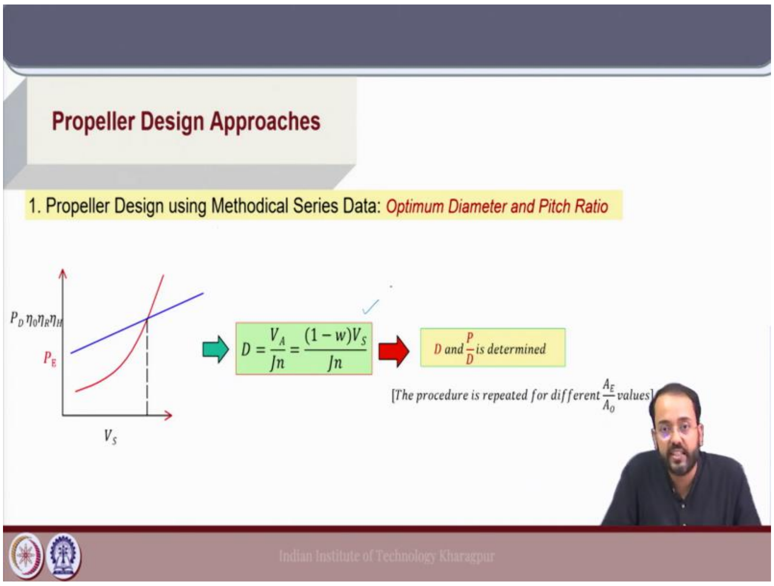

Next, we get the particular design point and for that specific case we calculate the propeller diameter based on this expression. Because in this particular problem the propeller diameter is an output of the design process and in this manner the diameter and pitch ratio of the propeller is determined in the design process.

Now, this procedure will be repeated for different A_E/A_0 values, because the blade area ratio is an important factor for cavitation calculation which we will do next.

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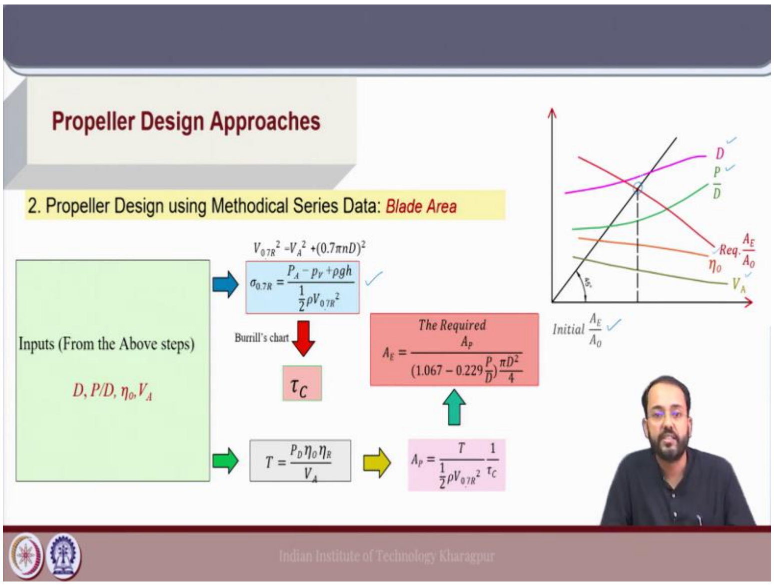

So, the inputs for this calculation will be the propeller diameter, pitch ratio open water efficiency and V_A are known. Next, we calculate the cavitation number for the representative section at 0.7 R on the propeller blade. The details have been discussed in the lecture under propeller cavitation.

And this propeller cavitation number can be related to the thrust loading coefficient using Burrill's chart, which gives the acceptable limits of cavitation for different propeller designs. And we can calculate the thrust from the delivered power and then get the projected area for the propeller blade and finally, the required A_E which is the expanded area can be calculated.

Now, in this way for a given set of input parameters satisfying cavitation criteria we can get the required A_E/A_0 value for the propeller blade.

Now, for each initial A_E/A_0 which we assumed at the beginning of the design process, we can do this set of cavitation calculations to get a required A_E/A_0 values. Now, for certain values of the initial A_E/A_0 we will see that the cavitation criteria will not be satisfied and for certain cases it will be satisfied. The idea is in the design process we have learnt that if very high values of A_E/A_0 is used, then cavitation criteria will be satisfied, but the blade section drag will be very high. So, the efficiency will fall.

On the other side if we have a very low value of blade area ratio for the design propeller, then the chances of cavitation will be high. That is why an optimum value is required to maintain both the efficiency as well as cavitation characteristics. So, here for every initial value of A_E/A_0, we can plot all these different parameters D, P/D, η_O and V_A as in the design charts we entered with an initial value of A_E/A_0.

So, by changing that we will have a range of D, P/D, η_O under the propeller design curve. Now, using the cavitation criteria we can calculate the required A_E/A_0 for each initial value. If we take a 45 degree line here, which is equal to the initial A_E/A_0 value the intersection will be the point where the initial A_E/A_0 is same as the required A_E/A_0.

So, it can be taken as the design point and the parameters at that specific intersection can be chosen in the design process.

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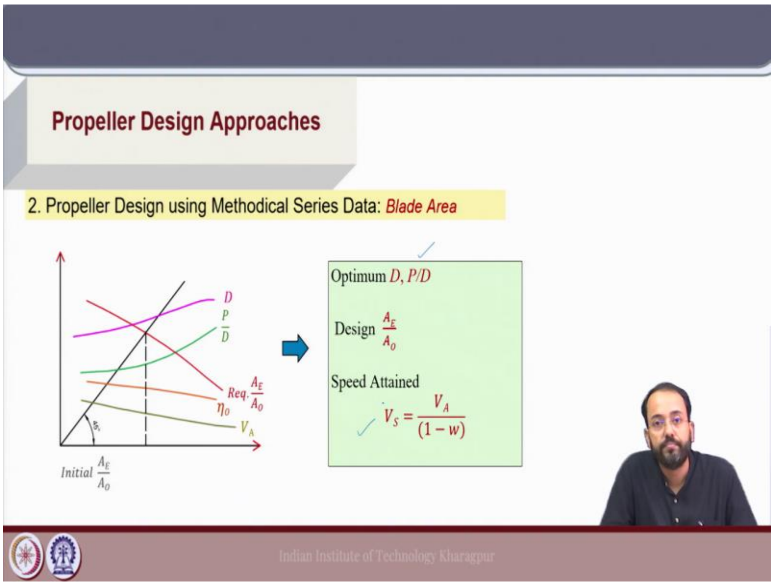

So, we use the same set of curves here to get the optimum diameter P/D ratio and design A_E/A_0. And finally, the attained speed for that specific blade area ratio is given by this expression.

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So, next the blade strength needs to be checked. Here the interesting part of the design process is whatever we have learnt under different parts, the calculation of thrust torque efficiency from the open water diagram, cavitation blade strength everything will be used in the design process to get the final design of the propeller which corresponds to an optimum value of efficiency and satisfying cavitation and strength requirement.

So, in this particular case blade strength can be checked based on classification society rules for the minimum thickness required for different blade sections and the shaft diameter is also determined.

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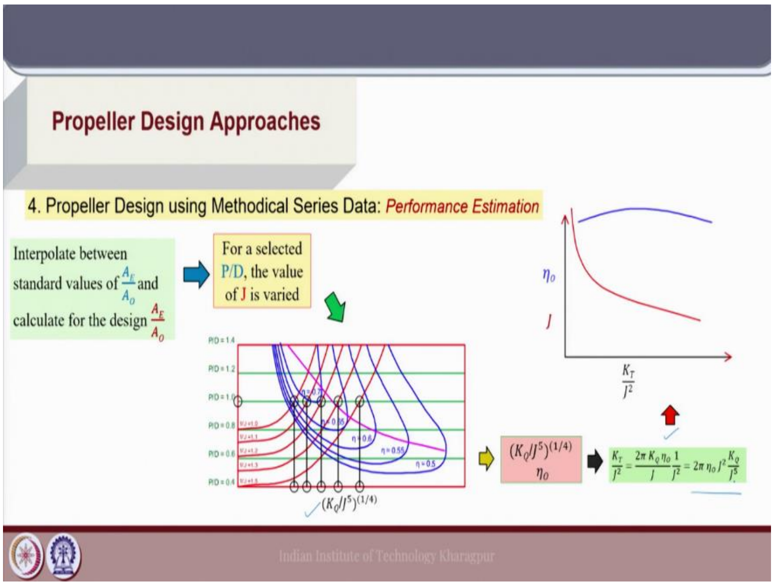

Finally, we will do the performance estimation for the propeller. Now, here we have the standard A_E/A_0 values for the specific series and we calculate these parameters for the design A_E/A_0 values, which is already done. And here for the selected P/D value we will vary the value of J in the propeller curves which are shown here for the different J values, here denoted as one by J for the given P/D which is the design P/D which is obtained now. We get different K_Q/J^5.

So, we go the reverse way now we have obtained the value of P/D pitch ratio which is the design value and for the different values of J for that particular design P/D, we get the respective values of $(K_Q/J^5)^{1/4}$. Which is used in the open water charts and finally, we will use this particular expression and η_O to calculate K_T/J^2. Why? Because K_T/J^2 will be used for the final powering calculations for the design propeller.

So, for the given values of this expression and η_o, K_T/J^2 can be expressed in this form and next we use this to get the value of K_T/J^2 for a range of J and η_o for the design propeller.

Now, the propeller is already designed at this step, we are going to obtain the power for this particular propeller the powering demand and check with the engine power to get the final engine propeller matching.

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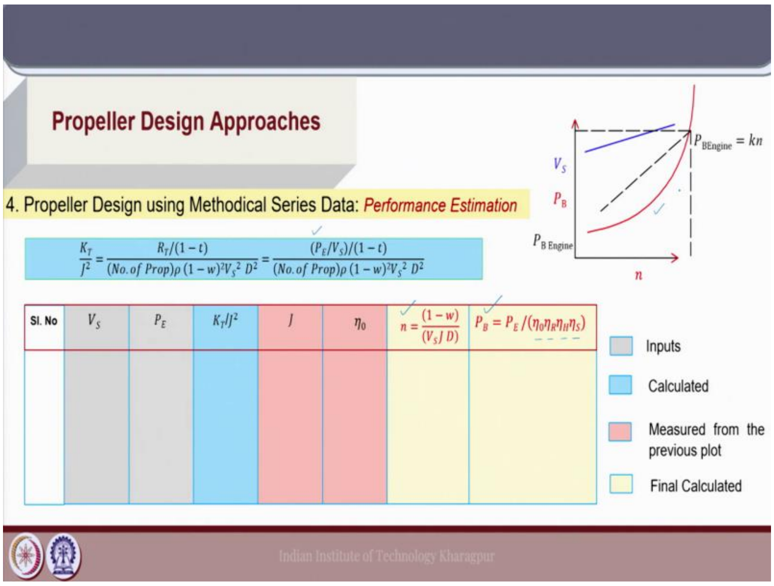

So, here K_T/J^2 can be expressed with respect to the effective power in this form, again we have the number of propellers because this is for only 1 propeller. So, if this is a single screw vessel, then number of propellers is 1. And finally, we have the chart where the inputs are V_S and P_E which are given in this problem the effective power curve at different speeds and finally, for the measured value of J and η_o for the design propeller we get the value of rpm and the engine brake power from the effective power side.

So, we have η_o, η_R, η_H and η_S a shafting efficiency which is assumed and we get the brake power which is required for that design propeller. So, we will use this calculated brake power curve for the propeller which is the red curve and we have seen that the relationship assumed was cubic in nature for a specific propeller within a particular design range.

And this can be intersected with the engine curve for a diesel engine, the brake power versus rpm is typically a straight line. And this propeller curve can be compared with the engine curve and we can get the speed that we are achieving at the design point.

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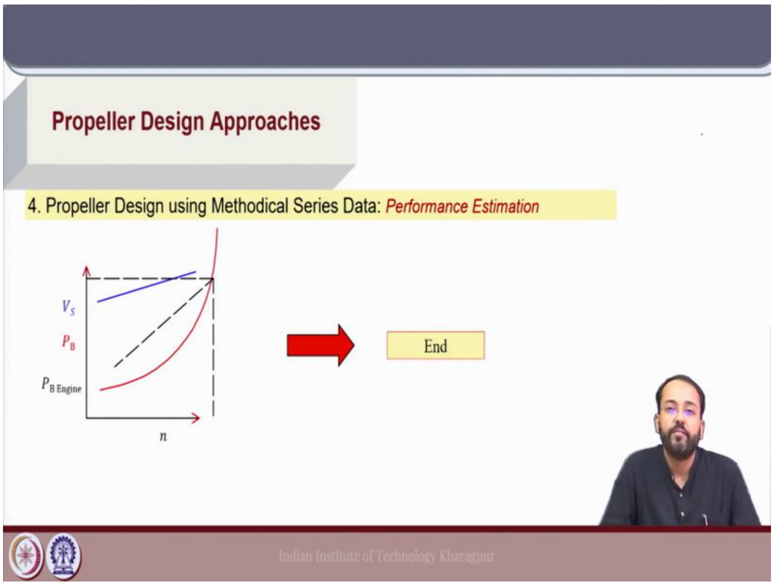

So, the final performance estimation for the propeller which is already designed is to achieve the power with respect to the engine power and the speed that the ship will achieve for the design propeller. So, this brings us to the end of the methodical series propeller design approach. In this way we can use the different open water charts under methodical series propeller design approach to obtain the final propeller design and shift powering characteristics for the specific operation conditions.

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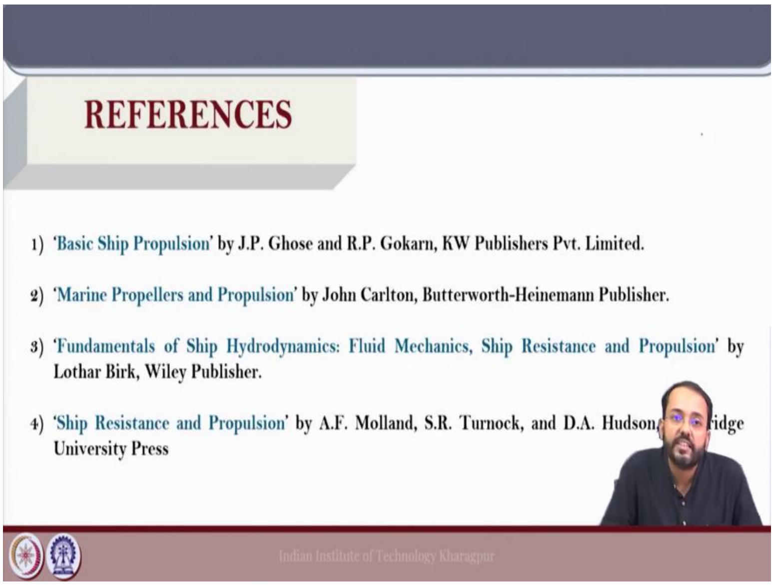

So, this will be all for the propeller design part of this course. Some references are mentioned here which can be used to understand different aspects of marine propeller design.

Thank you.