Marine Propulsion

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Lecture - 14

Propeller Open Water Characteristics (continued)

Welcome to Lecture 14 of the course Marine Propulsion, today we will continue with Propeller Open Water Characteristics.

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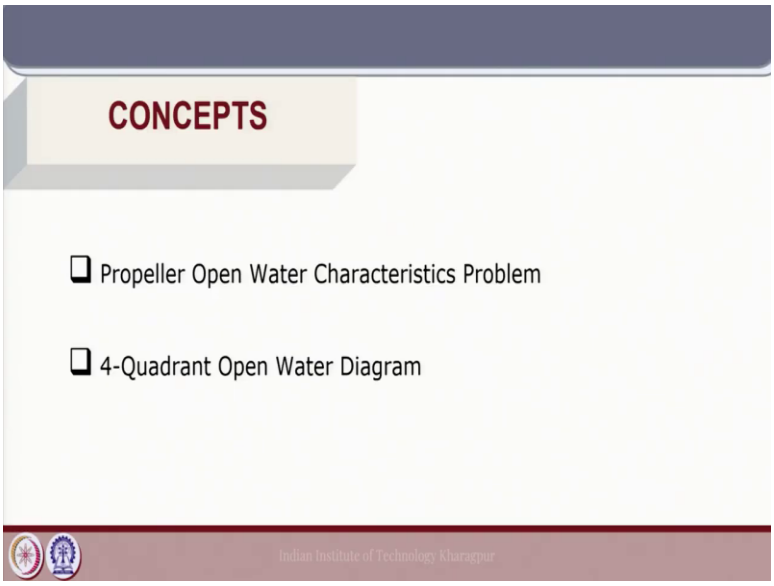

CONCEPTS

❑ Propeller Open Water Characteristics Problem

❑ 4-Quadrant Open Water Diagram

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So, the basic concepts that will be covered are a simple problem using the open water characteristics for a propeller and the concept of 4-quadrant open water diagram for a marine propeller.

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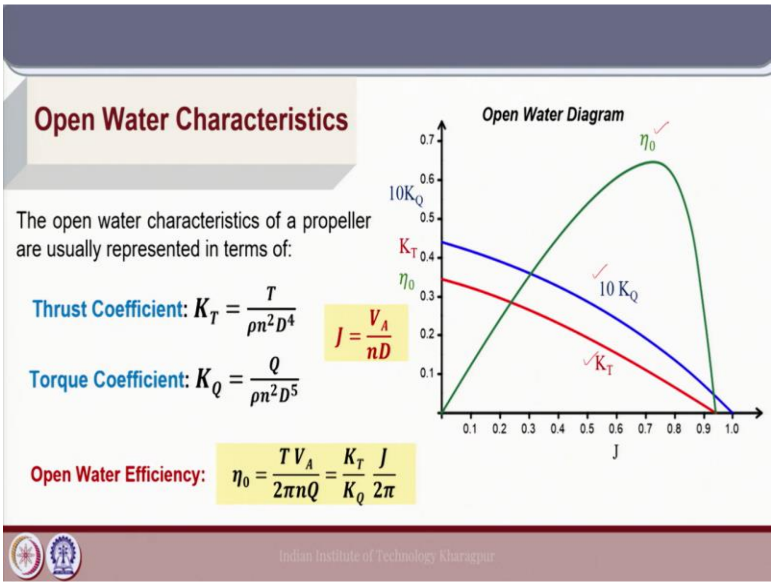

Open Water Characteristics

The open water characteristics of a propeller are usually represented in terms of:

Thrust Coefficient: $K_T = \frac{T}{\rho n^2 D^4}$

$J = \frac{V_A}{nD}$

Torque Coefficient: $K_Q = \frac{Q}{\rho n^2 D^5}$

Open Water Efficiency: $\eta_0 = \frac{T V_A}{2\pi n Q} = \frac{K_T}{K_Q}\frac{J}{2\pi}$

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So, a brief recap of what was discussed in the last class: The open water characteristics of a propeller are the thrust coefficient and torque coefficient expressed as a function of J, where J is the advance coefficient of the propeller.

So, if V_A is the velocity of advance divided by n the rotational speed times diameter is the advance coefficient and the dependence of the propeller thrust and torque coefficient on the advance coefficient is given by the open water characteristics of a propeller. This is how the open water diagram looks like here; we plot K_T, $10K_Q$ and the open water efficiency as functions of the advance coefficient J.

Now, what is open water efficiency? The open water efficiency is the efficiency of the propeller in the open water condition. So, here we do not have a ship in front of the propeller. So, the efficiency is given by thrust multiplied by the velocity of advance divided by $2 \pi n Q$, which finally, is $K_T / K_Q \times J / 2 \pi$.

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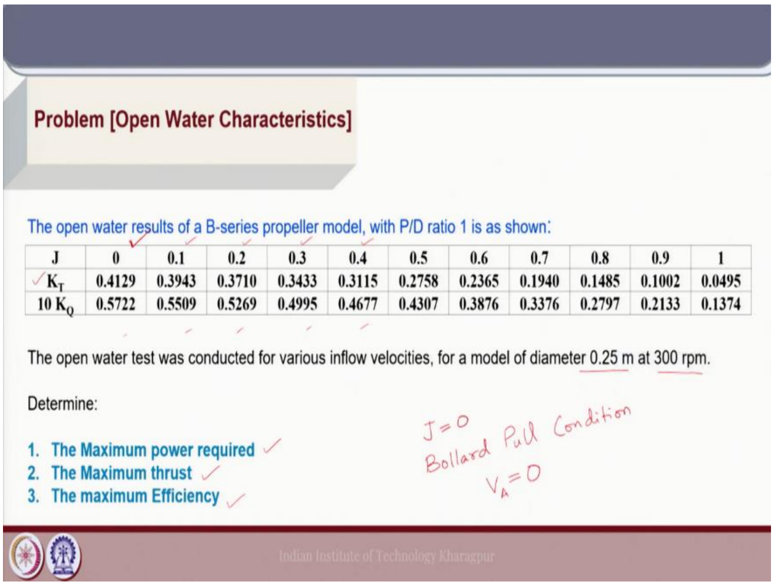

Problem [Open Water Characteristics]

The open water results of a B-series propeller model, with P/D ratio 1 is as shown:

J	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
K_T	0.4129	0.3943	0.3710	0.3433	0.3115	0.2758	0.2365	0.1940	0.1485	0.1002	0.0495
$10\ K_Q$	0.5722	0.5509	0.5269	0.4995	0.4677	0.4307	0.3876	0.3376	0.2797	0.2133	0.1374

The open water test was conducted for various inflow velocities, for a model of diameter 0.25 m at 300 rpm.

Determine:

1. The Maximum power required
2. The Maximum thrust
3. The maximum Efficiency

$J = 0$

Bollard Pull Condition

$V_A = 0$

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So, we will continue with a simple problem on the open water diagram for a propeller. In this particular problem a B-series propeller model is tested and we will discuss in dηils regarding propeller series in the next class. So, it is a specific propeller model with well-defined geometric characteristics for which the open water diagram is plotted and this table given here gives the value of K_T and K_Q at various values of J for the model propeller and the P/ D ratio is 1 for the given case.

So, in the open water test the propeller diameter is 0.25 m and the rpm is 300. So, we have to calculate from the given data the maximum power required, the maximum thrust and the maximum efficiency. So, in the open water diagram where is the location where we have the maximum thrust and torque, it is the bollard pull condition or the condition where J = 0, which is called the Bollard Pull condition given by the point where V_A velocity of advance will be 0 which eventually means that J will be 0.

So, here also from the chart given table we can see that as J increases the values of K_T, K_Q gradually decreases. So, the highest value of thrust and torque are at the point where J = 0 in the bollard pull condition. So, the maximum thrust can be calculated from K_T at the bollard pull condition and the maximum power can be calculated from the given K_Q or the torque coefficient also from the bollard pull condition at J equal to 0 right.

So, we will see how we do it and the maximum efficiency can be computed using any mathematical formulation of getting the curve, once we plot all these points of K_T and K_Q

versus J we will see that the efficiency will gradually increase and then after a particular value of J it will decrease. So, using a suitable analysis the maximum value of efficiency can be obtained using curve plotting techniques.

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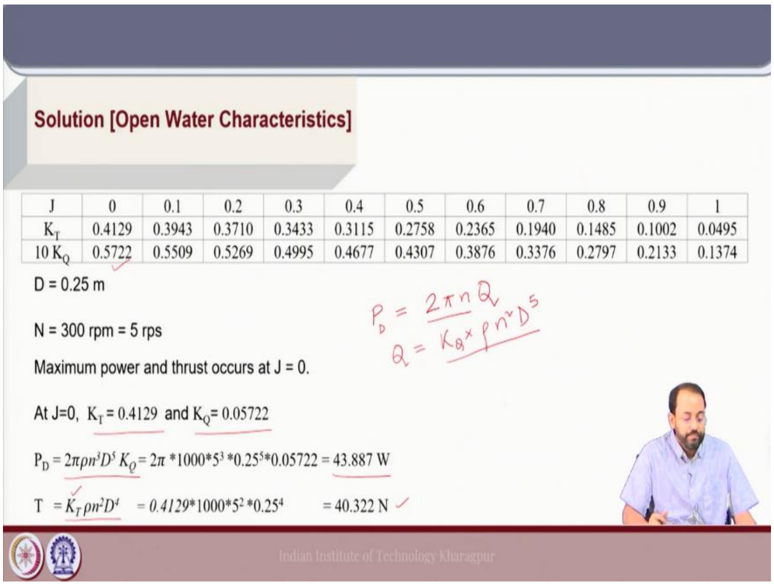

Solution [Open Water Characteristics]

J	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
K_T	0.4129	0.3943	0.3710	0.3433	0.3115	0.2758	0.2365	0.1940	0.1485	0.1002	0.0495
$10\,K_Q$	0.5722	0.5509	0.5269	0.4995	0.4677	0.4307	0.3876	0.3376	0.2797	0.2133	0.1374

$D = 0.25$ m

$N = 300$ rpm $= 5$ rps

Maximum power and thrust occurs at $J = 0$.

At $J=0$, $K_T = 0.4129$ and $K_Q = 0.05722$

$P_D = 2\pi\rho n^3 D^5 K_Q = 2\pi * 1000 * 5^3 * 0.25^5 * 0.05722 = 43.887$ W

$T = K_T \rho n^2 D^4 = 0.4129 * 1000 * 5^2 * 0.25^4 = 40.322$ N ✓

$P_D = 2\pi n Q$

$Q = K_Q \times \rho n^2 D^5$

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So, step by step first maximum power and thrust we can calculate at the bollard pull condition, the thrust coefficient K_T is 0.4129 and K_Q is 0.057 which is this value divided by 10 because in the open water diagram we plot $10K_Q$ instead of K_Q. So, we can use the value of K_Q to find out the value of the delivered power.

Now, how is the power given the power delivered to the propeller will be $2 \pi n Q$ so, where Q is given by $K_Q \times \rho n^2 D^5$. So, multiplying this with $2 \pi n$ will give us this particular expression for the power delivered and with the given values we will be able to calculate the power in this particular case which is the maximum power because K_Q is highest at J equal to 0.

Similarly, we can calculate the thrust value at J equal to 0 using the $K_T \times \rho n^2 D^4$, how T is related to the thrust coefficient. So, if we use this equation we will be able to calculate the maximum thrust.

Now, as discussed the maximum efficiency will be at the point where the value of η_o is maximum. So, now, the maximum efficiency can be computed using the η_o curve and it is variation with J and we can take the maximum value based on any statistical analysis simply that can be used to calculate the maximum efficiency of the open water diagram.

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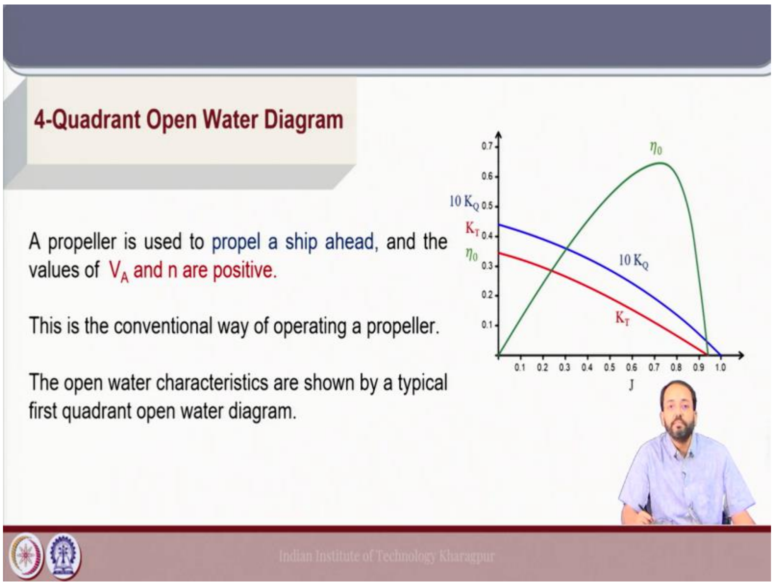

4-Quadrant Open Water Diagram

A propeller is used to propel a ship ahead, and the values of V_A and n are positive.

This is the conventional way of operating a propeller.

The open water characteristics are shown by a typical first quadrant open water diagram.

Now, we will move on to the concept of 4-quadrant open water diagram. Normally, when we plot an open water diagram it is for the case where the ship is moving ahead with the propeller rotating in a direction in which it is producing forward thrust. So, for the simple condition where we plot the open water diagram as we have seen V_A and n are both positive; that means, the propeller is advancing at a particular velocity and the propeller is rotating so, as to produce forward thrust.

So, this is the conventional diagram and so the first quadrant where both V_A and n are positive is the standard open water diagram that we have seen.

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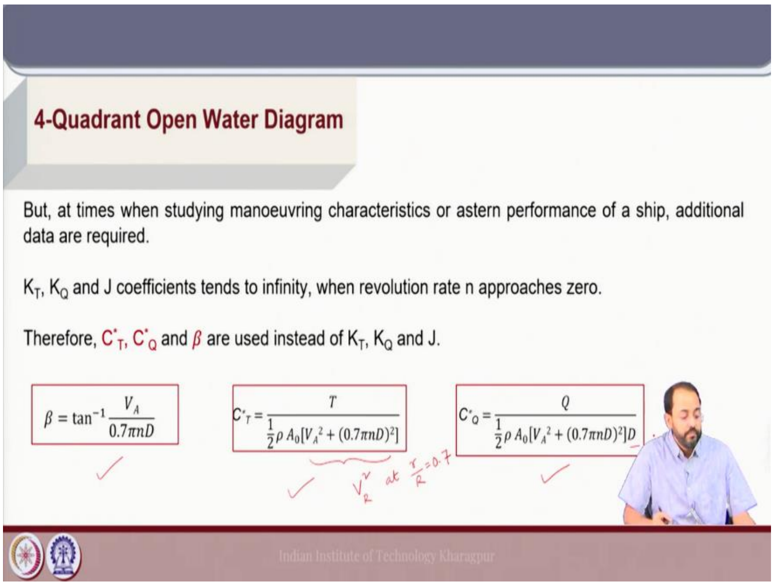

4-Quadrant Open Water Diagram

But, at times when studying manoeuvring characteristics or astern performance of a ship, additional data are required.

K_T, K_Q and J coefficients tends to infinity, when revolution rate n approaches zero.

Therefore, C^*_T, C^*_Q and β are used instead of K_T, K_Q and J.

$$\boxed{\beta = \tan^{-1}\frac{V_A}{0.7\pi n D}}$$ ✓

$$\boxed{C^*_T = \frac{T}{\frac{1}{2}\rho A_0 \underbrace{[V_A^2 + (0.7\pi n D)^2]}_{V_R^2 \text{ at } \frac{r}{R}=0.7}}}$$ ✓

$$\boxed{C^*_Q = \frac{Q}{\frac{1}{2}\rho A_0 [V_A^2 + (0.7\pi n D)^2] D}}$$ ✓

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Due to some specific requirements when we do manoeuvring characteristics or calculate the astern performance of a ship, some additional data for propeller is required.

So, the concept of 4-quadrant open water diagram comes here. So, by definition when the propeller rpm approaches zero, these coefficients K_T, K_Q and J will approach infinity that is why the standard representation of K_T, K_Q versus J cannot be used for the 4 - quadrant open water diagram where we will have reversal of the propeller rpm.

So, in this case the propeller rpm will be gradually reversed and because of that it will pass a point where n is 0. So, we cannot use the standard coefficients we will use a new set of coefficients $C_{T,}$ C_Q and β which is the hydrodynamic inflow angle the β that we have seen before it is expressed using the same concepts which are used instead of K_T, K_Q and J.

So, $\beta = V_A / (0.7\ \pi\ n\ D)$ which is basically from the blade element diagram we know it very well V_A is advanced velocity and 0.7 π n D is the tangential velocity component due to rotation at the representative section because we are taking the characteristic section at 0.7R, so that is how β is computed.

C_T is the thrust coefficient here written in a slightly different way. So, we do not divide it by n^2 instead of that we use the standard notation we have been using for lift and drag coefficients. So, T is divided by $\frac{1}{2} \rho A V^2$, where A is A_0 which is the propeller disc area and V the representative velocity V is the resultant velocity at 0.7R on the propeller blade that we have already discussed. So, it is the resultant of V_A and 0.7 π n D.

So, V_R^2 becomes $V_A^2 + (0.7 \pi n D)^2$ square this term this is the resultant velocity V_R^2 at r/R = 0.7. So, if we take the blade element at 0.7 times the propeller radius, we will have the resultant velocity equal to this value for which the square is taken to get the thrust coefficient and similarly we get the torque coefficient in the same way in addition we multiply by D. So, here we divide with an additional term D here which is the propeller diameter.

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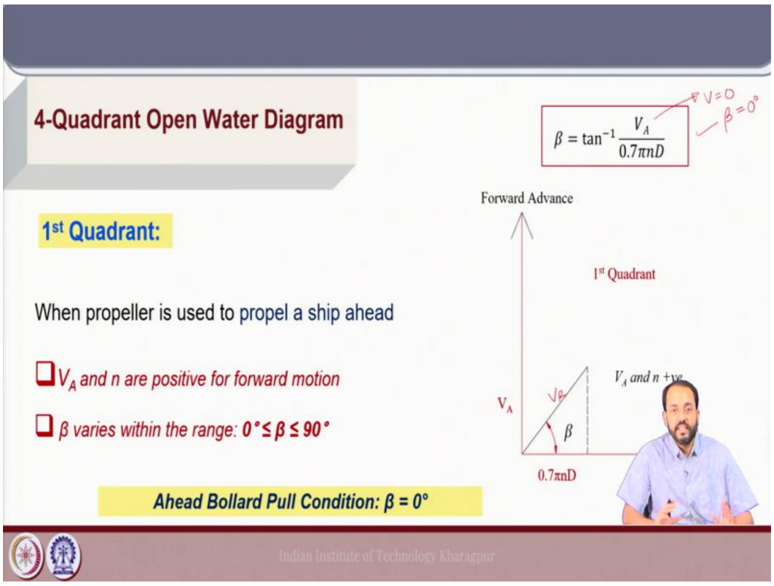

4-Quadrant Open Water Diagram

1st Quadrant:

When propeller is used to propel a ship ahead

- ☐ V_A and n are positive for forward motion
- ☐ β varies within the range: 0° ≤ β ≤ 90°

Ahead Bollard Pull Condition: β = 0°

$$\beta = \tan^{-1}\frac{V_A}{0.7\pi nD}$$

Now, let us look at the 4-quadrants one by one. So, in the first quadrant, which is the standard open water diagram that we have been seeing, where the propeller is used to propel the ship ahead.

V_A and n are both positive for forward motion. So, the ship is advancing forward, here we do not have the ship, but the idea is the propeller is in a condition where it is for standard forward motion of the ship ok. So, in that sense, the velocity of advance for the propeller is positive and the propeller is also rotating in the direction. So, as to give forward motion; that means, n is also positive.

So, β from this equation varies in the range of 0 to 90 degree. So, we have the first quadrant here where both V_A and n are positive and the resultant V_R is inclined at an angle β. So, V_R will be along this line and this is the case for forward advance and ahead motion.

In this particular case, the bollard pull condition is indicated by β is equal to 0, because where V_A will be 0, if V_A equal to 0 then β will also be equal to 0 degree. So, this is the condition for ahead bollard pull; that means, the velocity of advance is 0 which is the original J equal to 0 for the open water diagram that we have seen; here it will correspond to β equal to 0.

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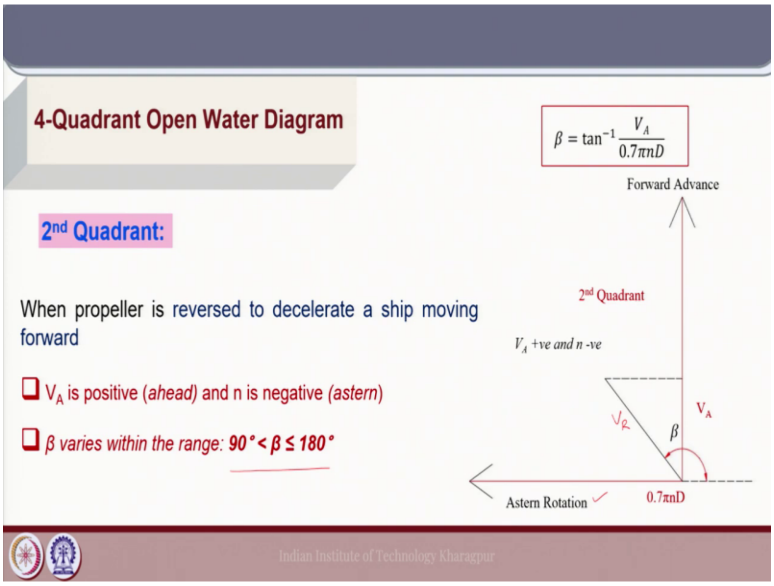

4-Quadrant Open Water Diagram

2nd Quadrant:

When propeller is reversed to decelerate a ship moving forward

- ☐ V_A is positive (*ahead*) and n is negative (*astern*)
- ☐ *β varies within the range: $90° < \beta \leq 180°$*

$$\beta = \tan^{-1}\frac{V_A}{0.7\pi nD}$$

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Next, if we move on to the second quadrant when the propeller is reversed. Now, let us think of the scenario when we want to decelerate the ship by reversing the propeller, but the ship is still moving ahead with a velocity. So, the velocity of advance for the propeller is still positive. So, V_A is positive, but the propeller has already started rotating in the reverse direction, but because of the inertia the ship is moving ahead. So, that such a condition will have V_A the velocity of advance as positive and n as negative.

So, this is the case for the second quadrant where β varies between 90 degree and 180 degree, it is shown using this particular diagram where you have the resultant V_R at an angle greater than 90 degree because in the second quadrant n has now become negative for astern rotation, but V_A is still positive. So, this case corresponds to the second quadrant of the 4-quadrant open water diagram we will go one by one.

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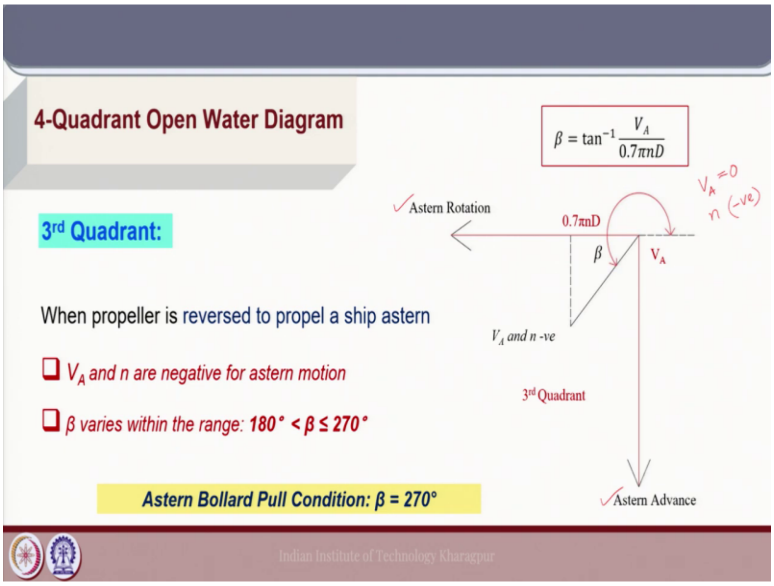

4-Quadrant Open Water Diagram

$\beta = \tan^{-1}\frac{V_A}{0.7\pi nD}$

3rd Quadrant:

When propeller is reversed to propel a ship astern

☐ V_A and n are negative for astern motion

☐ β varies within the range: $180° < \beta \leq 270°$

Astern Bollard Pull Condition: $\beta = 270°$

Next the third quadrant, now let us think of a case where the propeller has already started rotating in the reverse direction and the ship has come to a position where it is forward velocity is 0 and because the propeller is now already giving astern thrust the ship starts moving in the reverse direction.

So, this is the condition where the ship is moving astern. So, V_A is negative because the ship is moving astern the velocity of advance of the propeller in that condition will be negative. And also the propeller is already rotating in the reverse direction to produce astern thrust. So, both V_A as well as n are negative. So, this corresponds to the third quadrant of the propeller open water diagram.

So, V_A and n are both negative and β by definition now will range between 180 degree and 270 degree in this particular diagram. So, this is the third quadrant is a combination of astern advance of the ship; that means, the ship is moving astern and the propeller is rotating in the reverse direction.

And one more thing is important here, if we look at the blade geometry think of the propeller blade geometry when the propeller is rotating in the reverse direction it will produce thrust in the opposite direction, but the characteristics will be different. So, the plot of the K_T or the C_T in this case that any thrust coefficient it will be different from the one that corresponds to the forward case.

So, the astern bollard pull condition will be the case where β is equal to 270 degree; that means, for V_A equal to 0 under the third quadrant and n is negative, this case will correspond to the astern bollard pull condition. The difference from the forward bollard pull condition is that here the propeller is rotating in the reverse direction producing astern thrust.

But the concept of bollard pull is the case where the velocity of advance is 0. So, β equal to 270 degree corresponds to the astern bollard pull where n is negative, but V_A is 0.

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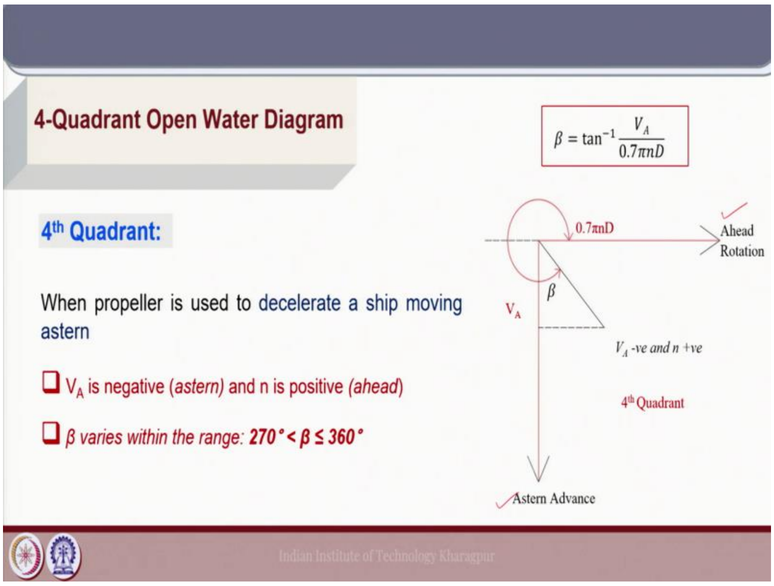

4-Quadrant Open Water Diagram

$$\beta = \tan^{-1}\frac{V_A}{0.7\pi nD}$$

4th Quadrant:

When propeller is used to decelerate a ship moving astern

- ☐ V_A is negative (*astern*) and n is positive (*ahead*)
- ☐ *β varies within the range:* ***270° < β ≤ 360°***

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Now, let us move on to the last quadrant which is the fourth quadrant of the open water diagram. Now the ship was moving astern as well as the propeller was giving astern thrust being rotated in the reverse direction. Now, let us look at the fourth case where the requirement of astern motion is already achieved and we again want to move forward and we reverse the direction of the propeller rotation again to the standard forward direction.

So, the propeller is again rotating in the forward direction, but the ship because of inertia is still moving astern. So, we would again try to go from a position where we have the ship moving astern to the position where the ship will move ahead. So, the propeller is again rotated in the so, the propeller rotation direction is again changed to forward, but the ship is moving astern. So, in this particular condition the ship will decelerate, but it is still moving astern.

So, V_A is negative and n is already positive because we have given the propeller a forward rotation ok. So, this case is a very special case of manoeuvring which corresponds to the 4th quadrant, here combination of V_A negative and n positive where β will range between 270 degree and 360 degree which is the 4th quadrant of the open water diagram.

So, here again we will see that β is aligned at an angle to the horizontal which is more than 270 degrees which corresponds to the 4th quadrant. So, it is a combination of astern advance the ship moving astern and ahead rotation because the propeller rotation direction has already been changed from astern rotation to the rotation case where forward thrust is given so, the positive rotation in that sense.

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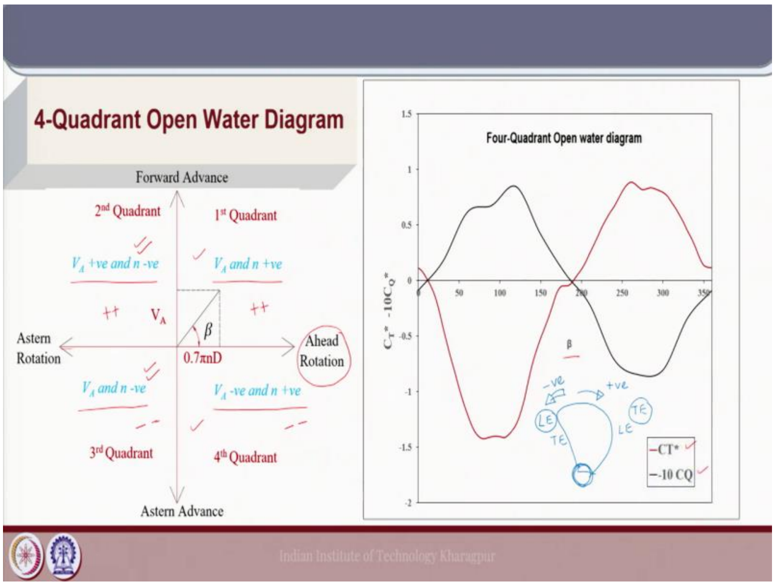

4-Quadrant Open Water Diagram

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So, if we combine all these diagrams together this is what we have the 4 - quadrant of the open water diagram, we have still not shown the C_T and C_Q, but before that let us see all the components together. The 1st case V_A and n both positive, the 2nd quadrant V_A positive n negative, 3rd quadrant VA and n both negative and the 4th quadrant V_A negative and n positive.

So, in this open water diagram if we think of the axis so, we have the ahead rotation case here. So, anything right of the vertical axis in the 1st and 4th quadrant the propeller rotation is in the ahead thrust condition; that means, the propeller is rotating in the positive direction providing forward thrust and anything towards the left of this diagram will be propeller rotating in the astern direction which produces astern thrust.

Now, again we think of a different way, if we think of the horizontal axis anything above the horizontal axis here the 1st and 2nd quadrant will be for forward advance where velocity of advance is positive V_A is positive; that means, it corresponds to a condition where the ship is moving ahead. And anything below the horizontal axis the 3rd and 4th quadrant correspond to the condition where the velocity of advance is negative that is astern advance the ship is moving astern.

So, these are the conditions which combined to give the 4 - quadrant characteristics for a propeller, it typically looks like this, it depends on the propeller design, this is taken for a specific propeller design and the 4- quadrant open water diagram gives the variation of C_T and C_Q over the 4-quadrants of the open water diagram which corresponds to all these cases a combination of all the cases.

So, this is specially used for the normal shift motions as well as maneuvering conditions and astern motion for a ship where the performance of the propeller in the astern motion is also calculated. So, if you see the horizontal axis in this case is β as we have discussed before which varies from 0 to 360 degree and C_T and $10C_Q$ are plotted as functions of β, one very important aspect we need to understand is the performance of a propeller in the forward and astern directions.

Now, if we think of a simple propeller blade, which is mounted on the hub we are just taking one blade and this is a clockwise rotating propeller, if we see from the face and in this case this is the leading edge and this is the trailing edge as per our propeller definition.

Now, this rotation direction will produce forward thrust. So, this is the rotation for producing positive thrust; that means, thrust in the forward direction. Now, when we reverse the direction of rotation of the propeller blade what will happen? It will start to rotate this thick arrow in the reverse direction which will produce negative thrust that is astern thrust.

Now, the propeller geometry is very much different towards the leading and trailing edges. So, when it rotates in the reverse direction basically this will become the leading edge now and this will become the trailing edge because by definition the edge, which will meet the water first will be the leading edge.

Now, the air foil design sections of the air foils which are used to design the propeller are designed in such way that it will perform much better as the propeller rotates in the forward direction. So, in this case the propeller will work at a very sub optimal condition where the astern thrust capacity producing capacity or the coefficients or the performance of a propeller in the astern condition will not be equal to the forward rotating propeller ok.

So, the performance of a propeller when it is rotates in the astern direction or in the reversed condition will be different from the performance of a propeller in the forward rotating condition. So, this will be all for the 4-quadrant open water diagram. We will continue with propeller series where data for different propeller series will be discussed which correspond to the geometry of different types of propellers which are used for designing propellers for specific cases.

Thank you.