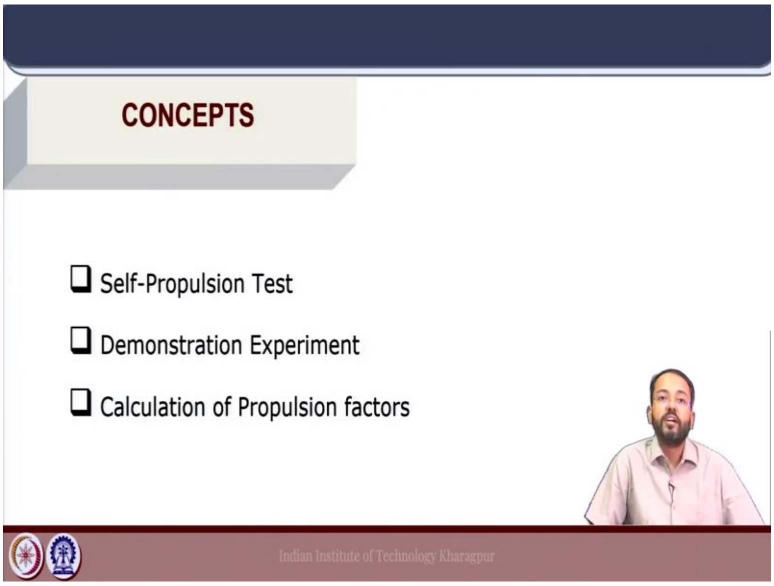
Marine Propulsion
Prof. Anirban Bhattacharyya
Department of Ocean Engineering and Naval Architecture
Indian Institute of Technology, Kharagpur

Lecture - 22
Propeller Model Tests (Part - II)

Welcome to lecture 22 of the course Marine Propulsion, today we will continue with Propeller Model Tests.

(Refer Slide Time: 00:33)



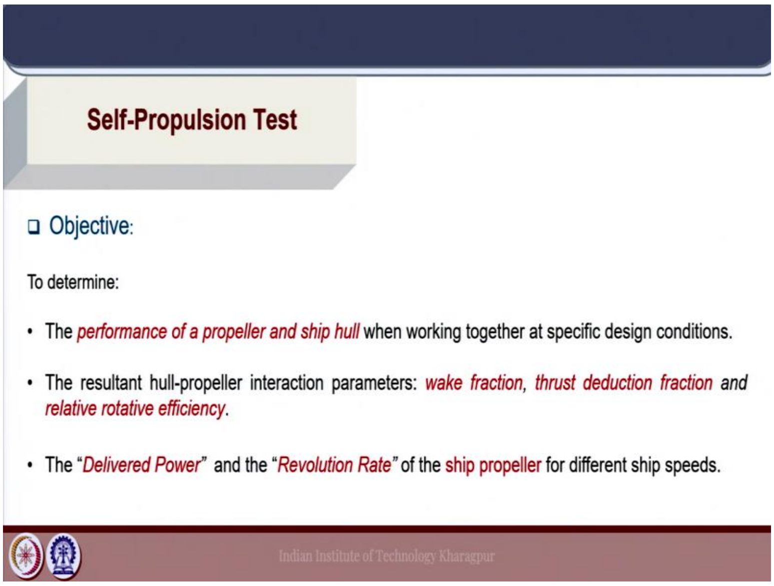
So, the points covered in today’s lecture will be a self-propulsion test of a marine propeller, a demonstration experiment from our facility showing the self-propulsion test in the towing tank, and calculation of propulsion factors from the results of the self-propulsion test, in addition to the results from the resistance and open water tests.

(Refer Slide Time: 00:59)

With regards to model tests for ship powering the 3 tests which are required to do the powering calculations for a ship are the resistance test, the open water test which have been discussed in the last class, and the self-propulsion test which will be discussed today. So, we have the results from these 3 tests which are used together to calculate the propulsion factors and finally do the powering calculations for the ship. In addition to this in general for naval architecture, there are other tests like seakeeping tests in waves and manoeuvring tests.

Which are done for models for assessing the performance of a vessel in waves and also for the manoeuvring performance of a vessel. These tests which are mentioned here are specifically used for ship powering and hence are discussed in this particular course.

(Refer Slide Time: 02:03)

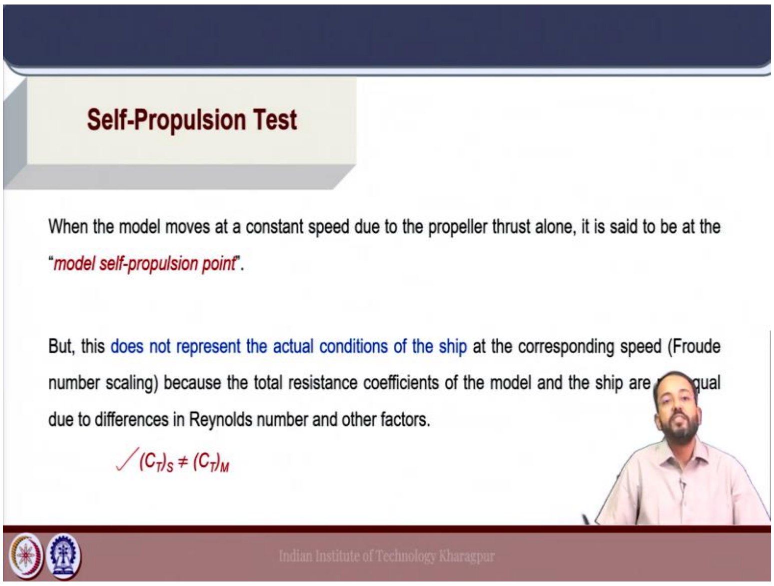


Now, for the self-propulsion test the objective is to determine the performance of the propeller and ship hull, when working together at specific design conditions. That means, how the propeller performs behind the ship and using that we try to estimate the propulsion factors and as we have earlier discussed that the propeller performance is different in open water and behind hull conditions.

Because the ship modifies the flow into the propeller and that changes the propeller thrust and torque characteristics and efficiency. And then the resultant parameters which are the hull propeller interaction parameters we can say or the propulsion factors which includes wake fraction, thrust deduction, relative rotative efficiency can be calculated and from there finally we want to calculate the delivered power and revolution rate of the ship propeller for different speeds.

So, in today's lecture we will look into the first 2 points of this self-propulsion test. So, how to do a self-propulsion test and how to calculate the parameters which relate to the propulsion coefficients? And in the next class we will use this to estimate the delivered power and rpm of the ship propeller in the full scale.

(Refer Slide Time: 03:40)



So, when the model moves at a constant speed due to the propeller thrust alone that condition is called the model self-propulsion point. Till now we have seen that in the open water test the propeller was only moving ahead at a particular speed which was the advance speed and there was no ship hull. So, it was connected to the carriage and it was moved at a particular forward speed.

Here in the self-propulsion test, we have the ship and the propeller together. So, the ship is stored by the carriage and the propeller is also rotating to provide a thrust and if the propeller thrust is good enough to move the ship at that particular constant speed then it is called the model self-propulsion point.

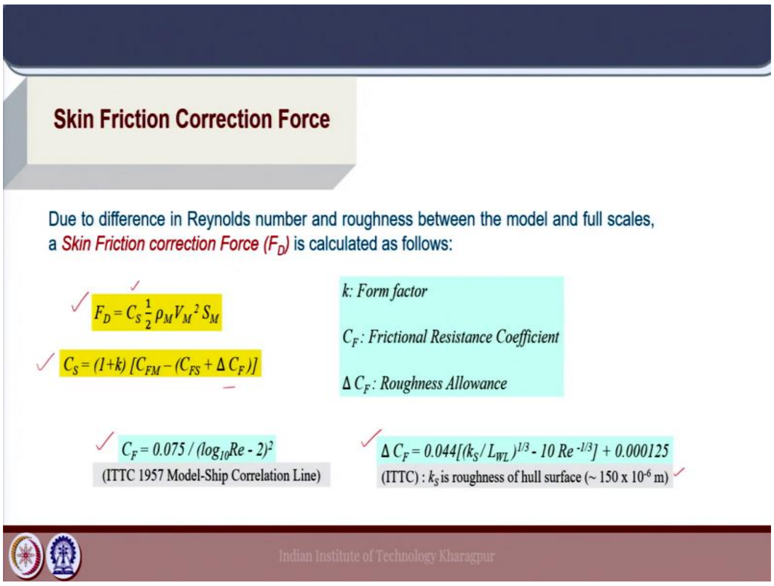
Now, this exactly does not represent the actual conditions for a ship. The understanding of this particular point is very important for a self-propulsion test. The self-propulsion point of the model is not equal to the self-propulsion point in the full scale or in the ship scale. Why? Because we have done Froude scaling we have seen that when we have discussed similarity we have maintained Froude scaling between the model and full scale; that is we have maintained the ratio of the inertial force by gravity force.

So, in order to maintain that we have got similar wave making pattern in the model and full scale; where the length with respect to the velocity is scaled. Now we see that the Reynolds number will be very much different in the model and full scale and because of that the viscous effects will be very much different and in the resistance test we know that the skin friction coefficient is different in the model and full scale.

So, there is a separate scaling involved for the skin friction drag for the ship based on ITTC procedures which is used for resistance scaling from the model to the full scale. Now, because of that the propeller loading at the propulsion point will be different in the model and full scale, because the Reynolds number is very much different and also there are other factors like roughness is different in the model and full scale.

So, because of these reasons we have to make some corrections. So, that the ship self-propulsion point is obtained in the model scale to adjust the propeller loading such that it operates at the shift self-propulsion point not the model self-propulsion point. Because we have to calculate the propulsion factors corresponding to the self-propulsion point of the ship. So, because of these factors the total resistance coefficient of the ship is not equal to the total resistance coefficient in the model.

(Refer Slide Time: 07:01)



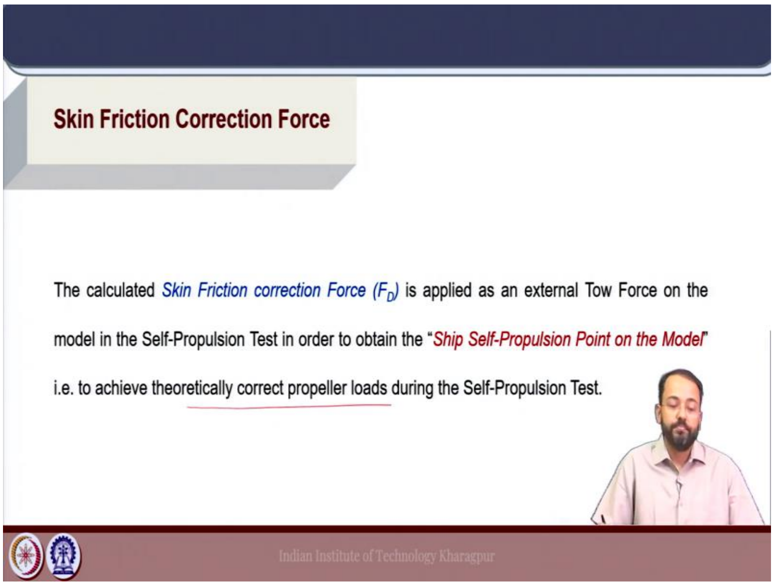
Now due to the difference in Reynolds number and roughness between the model and full scale a skin friction correction force which is denoted as F_D is required to be calculated Now F_D is related to the difference in the friction resistance coefficient between the model and full scale as per these expressions. So, F_D is defined as a coefficient $C_S \times \frac{1}{2} \rho S V^2$ where S with suffix M is the wetted surface area of the model and V_M is the model speed.

Now this coefficient C_S is given by 1 + k, k is the form factor into C_{FM} which is the friction resistance in the model scale minus the same in the full scale and a roughness allowance is also included. So, this skin friction force is required to be calculated to get the full scale propulsion point when we do the model self-propulsion test this part is very important because this force has to be applied on the model and that correlates to the full scale self-propulsion point.

Now C_F can be calculated simply ITTC 57 Ship Model Correlation Line and this is based on the Reynolds number as we have seen in standard resistance calculations and ΔC_F which is the roughness allowance is also given by ITDC based on this formula. Here k_s is the roughness of the hull surface in the full-scale ship and if the value of k_s is not known ITDC recommends this particular value to be used for the calculation of delta C_F which is the roughness allowance.

Now, this skin friction correction is including the friction resistance coefficient between the model and full scale and also the effects of roughness of the full-scale ship. In later revisions of the skin friction correction force ITDC also included correction allowance. This allowance depends on the model test results in the model scale for the self-propulsion test with the values obtained for C trails. So these correlation allowance depends on the facility where the model tests are being carried out and they can also be included in the skin friction correction force which was mentioned in the later revisions.

(Refer Slide Time: 09:42)

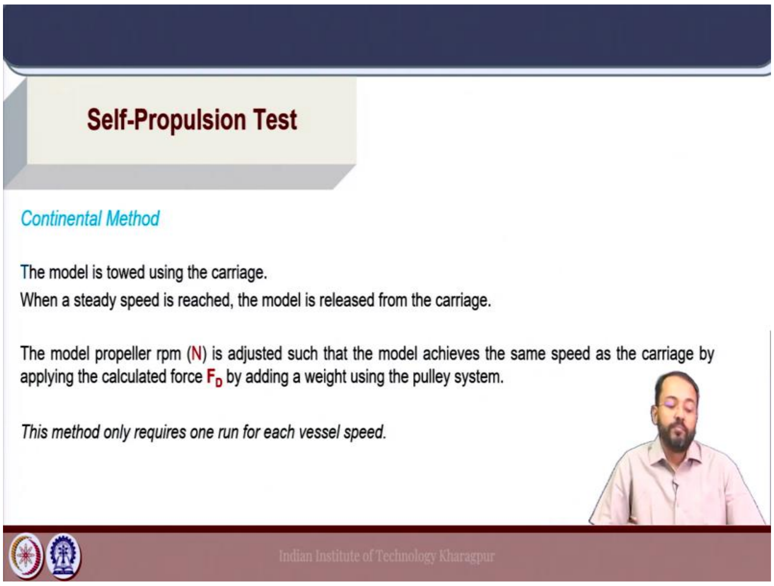


So, this skin friction so this skin friction correction force F_D is applied as an external tow force on the model in the self-propulsion test, why it is done to obtain the ship self-propulsion point on the model.

So, we are doing a model test in the model scale, but we would want to get the propeller loading corresponding to the ship self-propulsion point, because it is the point at which the propeller coefficient should be calculated and the ship powering should be done. So, because we cannot maintain the Reynolds number same between the model and full scale and also to have the effect of the roughness; the skin friction correction force is calculated and it is applied as an external tow force.

So, it gives the theoretically correct propeller loads during the self-propulsion test, which is corresponding to the full-scale propulsion point.

(Refer Slide Time: 11:05)

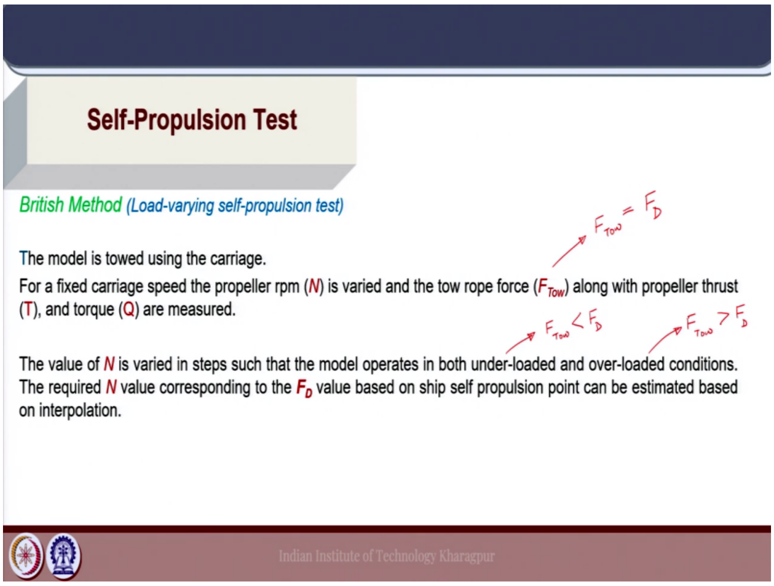


Now, the self-propulsion test can be done typically using 2 standard methods, the first method is the continental method here the model is stored using the carriage, and when a steady speed is reached the model is released. And we maintain the propeller rpm and adjust it in such a way that the model achieves the same speed as the carriage and the force which is calculated F_D the screen friction correction force is applied by a weight using a pulley system.

So, at this particular ship self-propulsion point which corresponds to this calculated value of F_D we are adjusting the propeller rpm, so that the speed of the model is equal to the speed of the carriage and at this balance point the propeller thrust, torque and rpm are measured using a propeller dynamometer. So, for this particular method we use only one run for each vessel speed.

So, for a particular model speed we measure the propeller rpm, thrust and torque using the dynamometer and this corresponds to a particular value of tow force as provided by the pulley system which is calculated based on the skin friction correction force F_D and this gives the self-propulsion point corresponding to the ship scale in the model test.

(Refer Slide Time: 12:46)



In the other method for self-propulsion test which is also called the British method we vary the propeller rpm. So, the model is towed using the carriage which is on the towing tank and for a fixed carriage speed the propeller rpm is varied and the model is connected to the carriage using the resistance dynamometer.

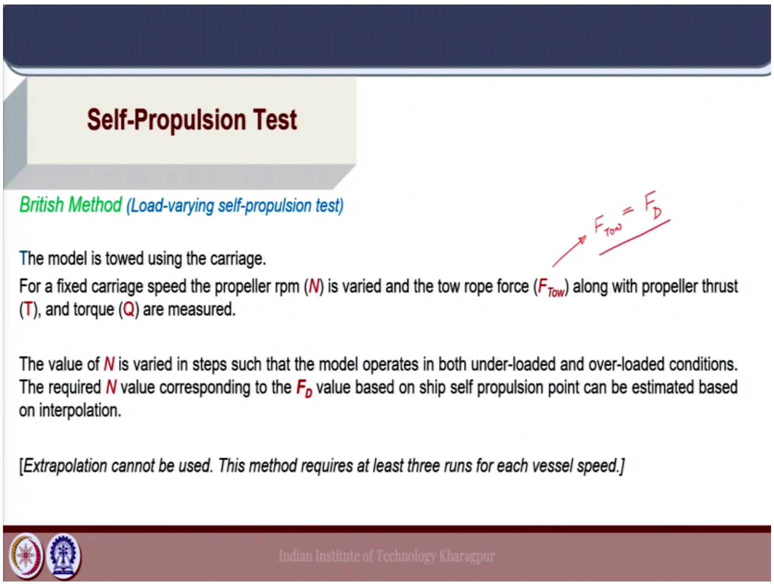
And for varying rpm of the propeller the force exerted is the tow rope force and it is measured by the resistance diameter and apart from that the propeller thrust and torque are measured using the propeller dynamometer, a demonstration of this in our facility will be shown just after this slide. So, here instead of a specific rpm the propeller rpm is gradually varied in steps and for each case the tow rope force or the force exerted at the resistance dynamometer is measured.

And the value is varied in steps in such a way that the model operates in both under loaded and overloaded conditions; that means, we try to achieve the self-propulsion point in the full scale at that condition where F_{tow} this force will be equal to F_D which is the calculated skin friction correction force corresponding to the full scale shift propulsion point. So, here what we are doing is we are varying the rpm.

So, that the propeller is both unloaded; that means, when F_{tow} will be here in this condition F_{tow} will be lower than F_D and in the overloaded condition F_{tow} will be greater than F_D. So, here the value of N is varied in such a way that the value of tow force is varied from a small value which is lower than F_D to a value which is. So, the value of rpm or N here is varied in such a way that the tow force is more.

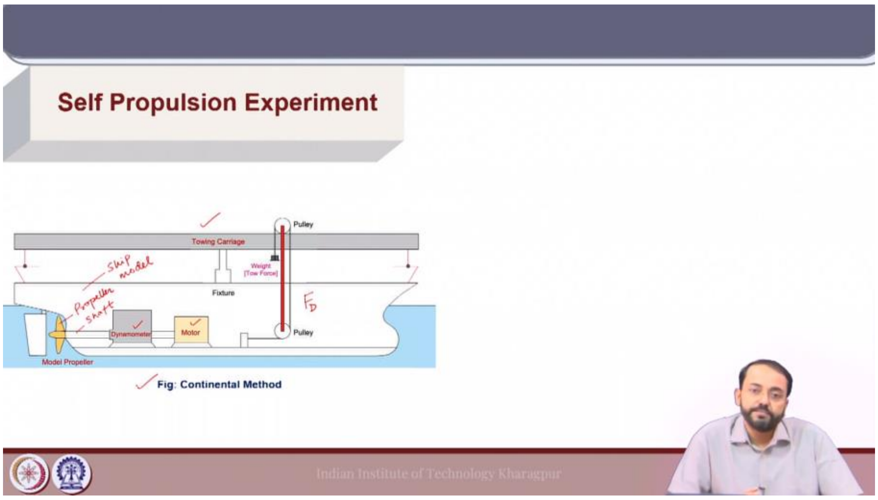
So, the value of the rpm of the propeller N here is varied in such a way that the tow force is both lower and higher than the required F_D or the skin friction correction force. Now, the required value of rpm at the value of the tow force equal to F_D or the self-propulsion point in the ship scale is calculated by interpolation.

(Refer Slide Time: 13:51)



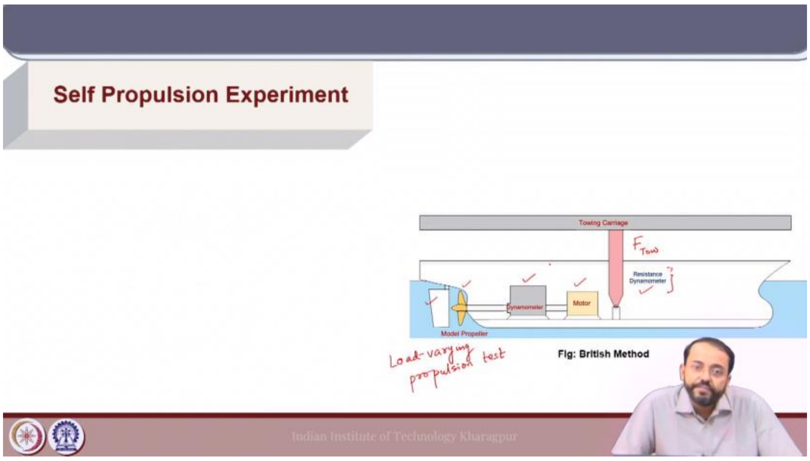
So, at least 3 to 4 runs are taken covering the self-propulsion point and by interpolation, we can calculate the self-propelled rpm. And at that rpm, the thrust and torque values are also obtained from interpolation.

(Refer Slide Time: 15:01)



Let us look into the diagrams for two different methods. First, we have the continental method for the self-propulsion test. Here we have the ship model fitted with a propeller and the propeller is connected via a shaft to the dynamometer and the motor. The motor is giving the required rpm to the propeller and the dynamometer measures the propeller thrust and torque. And the model is connected to the towing carriage here and the carriage is towing the model along the towing tank. Now the friction correction force F_D is exerted with the help of a weight and a pulley system on the model so in this particular method the exact self-propulsion point is considered by applying the value of the calculated skin-friction correction force as the two forces on the model using the pulley and the propeller is running at the specific rpm which propels the ship forward at that specific speed which is the model speed the Froude scale version of the full-scale ship speed.

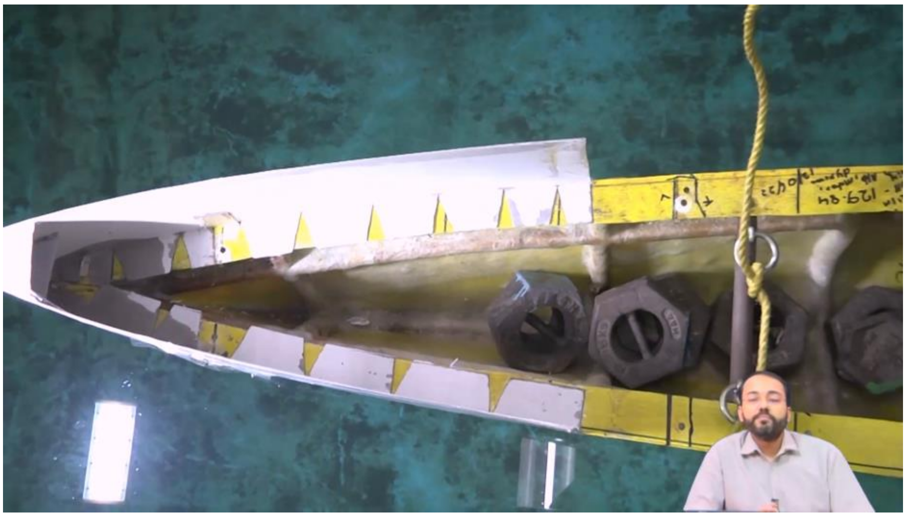
(Refer Time: 16:28).



The next method is the British method which is also called load varying propulsion test here the model is connected to the carriage through a resistance dynamometer and then towed by the carriage at a specific model speed which is the Froude scale version of the ship speed. Let us say for the design condition and the rpm of the model is gradually varied in steps so we have the rpm gradually increasing and as the rpm increases the requirement of the tow force will be less. So the tow force is exerted by this resistance dynamometer and from multiple readings, we can do interpolation to get the self-propulsion point where the tow force is equal to the skin-friction correction force that will be the full-scale ship self-propulsion point on the model and here also we have the motor which is providing the rpm to the propeller here and we have the rudder behind the propeller for the self-propulsion test and the dynamometer is measuring the propeller thrust and torque.

Next, we will see a video of this British method of self-propulsion test from the towing tank facility at IIT Kharagpur

(Refer Slide Time: 18:13)



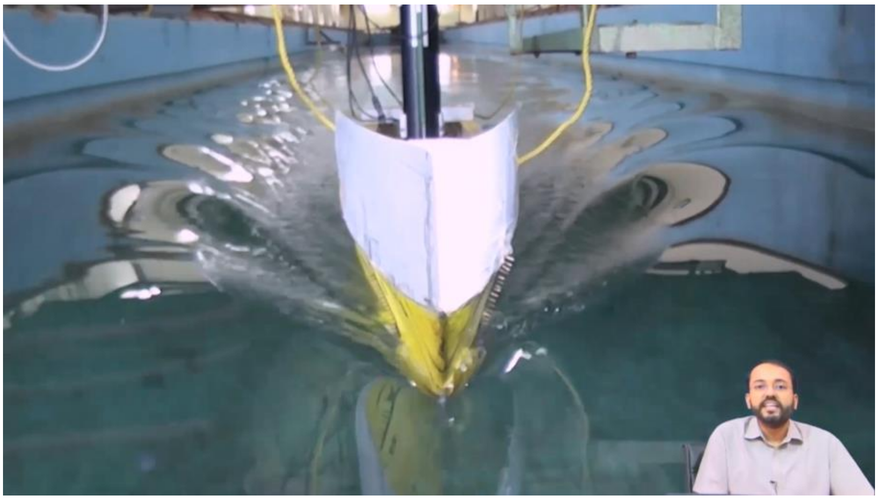
This is the self-propulsion test in the towing tank where the carriage is moving on the tank and it is towing the ship model with a propeller fitted behind and the model is connected to the carriage through the resistance dynamometer the model is ballasted with these weights to the required draft and we have the resistance dynamometer here which is connected to the model these weights are distributed along the length of the model to achieve the desired draft.

This is the self-propulsion test condition where we have the motor and the dynamometer which is connected to the propeller shaft and we have the propeller which is behind the ship rotating here and the rudder behind the propeller. This is a video of the underwater part where the propeller rpm is provided and the ship is moving forward in the self-propulsion test.

So, for this specific model, the propeller is on an inclined shaft and here the model is being towed with the propeller rotating behind at a specific speed. And for each model speed, we will have different sets of propeller rpm increased in steps so that we achieve the self-propulsion point by interpolation as discussed. Now here the speed of the model is increased and that is why the wave-making pattern is very much different. So this is the highest Froude number for which it was tested and that is why the wave-making pattern is different when we increase the Froude number of the vessel.

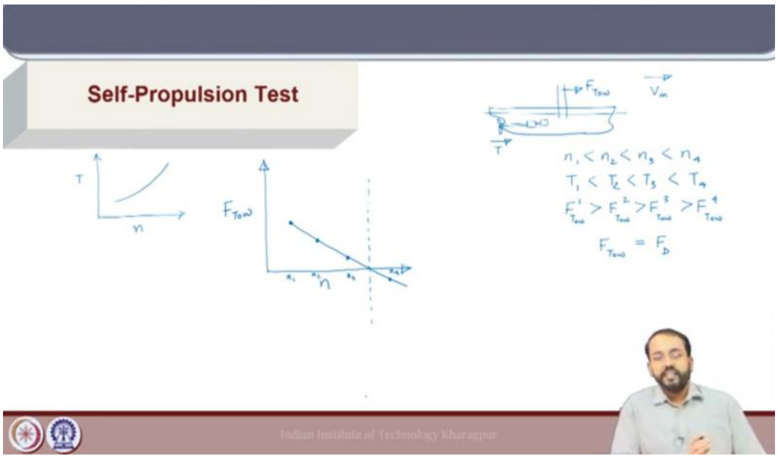
So in this way we have different runs of the model along the tank for each run the speed is kept constant and the propeller rpm is increased in steps to achieve the self-propulsion point.

(Refer Slide Time: 20.34)



So we have the model ship which is propelled with help of this propeller providing a thrust T and we have the resistance dynamometer which is providing a tow force which is connected to the carriage it is moving at a specific speed. Now this propeller itself is connected to a propeller dynamometer and a motor which the propeller dynamometer is measuring the thrust and torque of the propeller. Now for a specific model speed V_M at which the model is moving forward. We increase the rpm of the propeller in steps. The rudder is not shown here for convenience and here as the propeller rpm is increased the thrust from the propeller will increase. Now in all these different rpm conditions, the model speed is constant which is V_M. So when the propeller thrust is very low let us we have four different rpms on a specific run n_1, n_2, n_3, and n_4 in increasing order ok. So when we have the lowest rpm n_1 then the thrust contribution from the propeller will be very low and as the rpm increases the propeller thrust will gradually increase. Similarly, the tow force which is exerted from the carriage on the model to tow the model at a specific speed should gradually decrease. Let say F^1_{tow}, F^2_{tow}, F^3_{tow}, F^4_{tow}. So for the case where the rpm is n_1 lowest rpm the tow force will be highest because the propeller thrust component is low and gradually the tow force will decrease and we have to capture the self-propulsion point where the tow force F2 is equal to the skin-friction correction factor F_D which should be somewhere in between there four points.

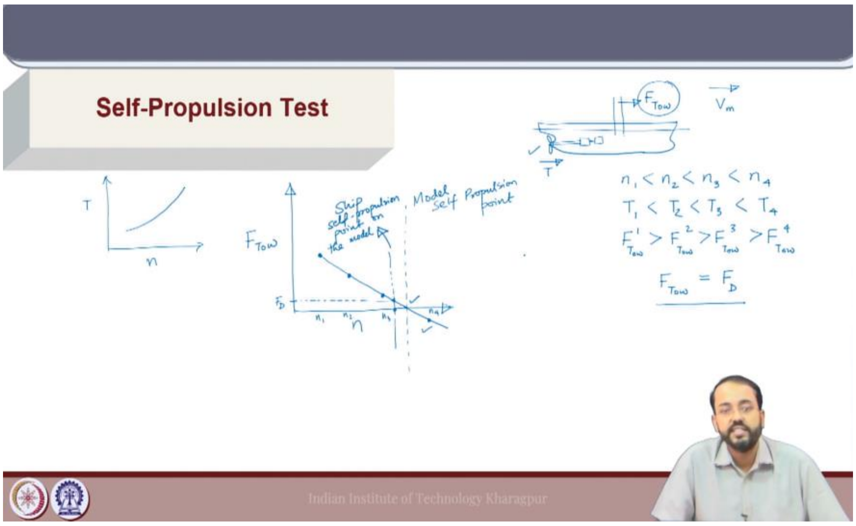
(Refer Slide Time: 23.24)



Now if we plot the propeller thrust versus rpm it will increase as the rpm increases. On the other hand, if we plot the tow force F_{tow} with rpm the tow force will decrease with the rpm. Now let us say these are the four points n1, n2, n3, and n4. Now at the point where the tow force is zero what is the physical meaning? When there is no tow force required to tow the model the thrust is enough for the model to be the profit that is the model's self-propulsion point that means the model itself is self-propelled. But it is very important to remember that this is not the ship's self-propulsion point that we are interested in because the ship powering has to be in the ship self-propulsion point. That is why we have calculated the skin-friction force F_D. So we have to take the point where the value of tow force is equal to F_D, this point. So, let us say F_D has a value here now if we do a interpolation then we can get this particular point and calculate the value of rpm at that particular point.

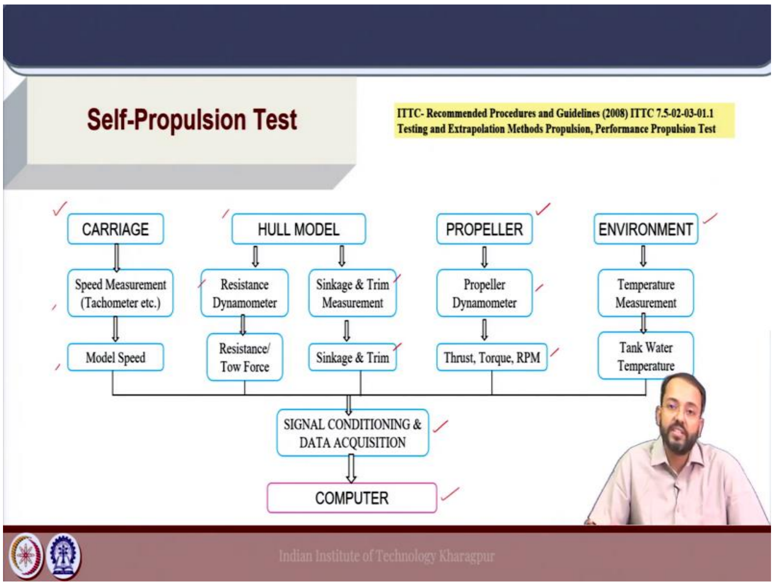
Now, this is the ship self-propulsion point on the model. So, this particular value of F_D when the tow force is equal to F_D that gives the ship self-propulsion point on the model as we have discussed and the rpm corresponding to that gives the correct propeller loading for the self-propulsion test. Now, n4 in this case gives negative tow force. Now, what is the meaning of negative tow force? That means the model is over-propelled. The propeller thrust is already good enough when the tow force is zero at this point then the propeller thrust is already enough to propel the ship. And if still increase the rpm then the propeller will produce more thrust than actually required to propel it. Then the tow force here will be negative.

(Refer Slide Time: 26.49)



Now the points are taken in such a way that the self-propulsion point can be obtained using interpolation. This is how the self-propulsion point is defined with respect to the thrust and the tow force. Which is used for the calculation of propulsion factors from the model test.

(Refer Slide Time: 27:30)



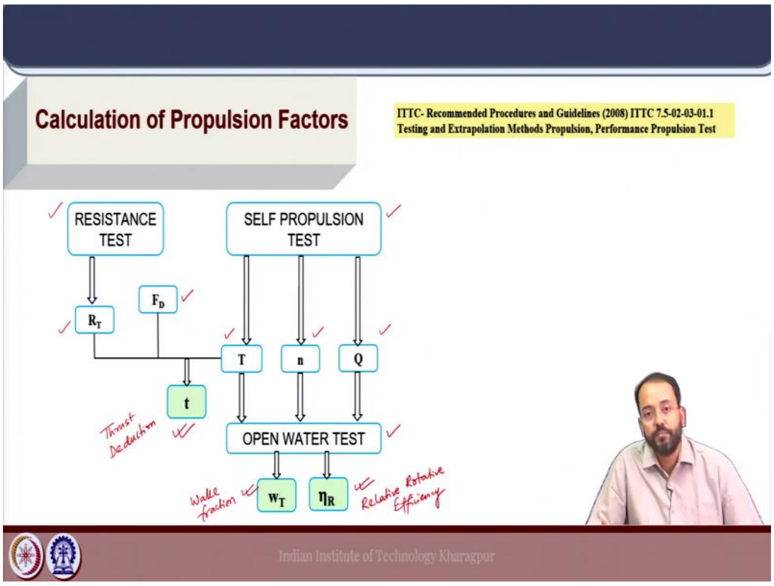
This flow chart shows the data acquisition system from different parts of the self-propulsion test setup as per standard ITTC recommended procedures for model self-propulsion test.

We have the carriage which is towing the ship model fitted with a propeller, in the carriage we have the speed measurement system which measures the model speed. Next on the hull model, we have the resistance dynamometer which is measuring the resistance or the tow force in this case. We also have a sinkage and trim measurement system because the model in a standard self-propulsion test should be free to sink and trim.

So, this sinkage and trim during the test are measured. Now if we move on to the propeller we have the propeller dynamometer which is connected to the propeller and it measures the thrust torque and rpm of the propeller. And finally, we have the environmental factor which is the temperature measurement which is done to calculate the standard density and viscosity of water during the model tests.

So, all these data together are put into the data acquisition system and finally put into the computer for the final calculation of the self-propulsion test parameters.

(Refer Slide Time: 30:00)



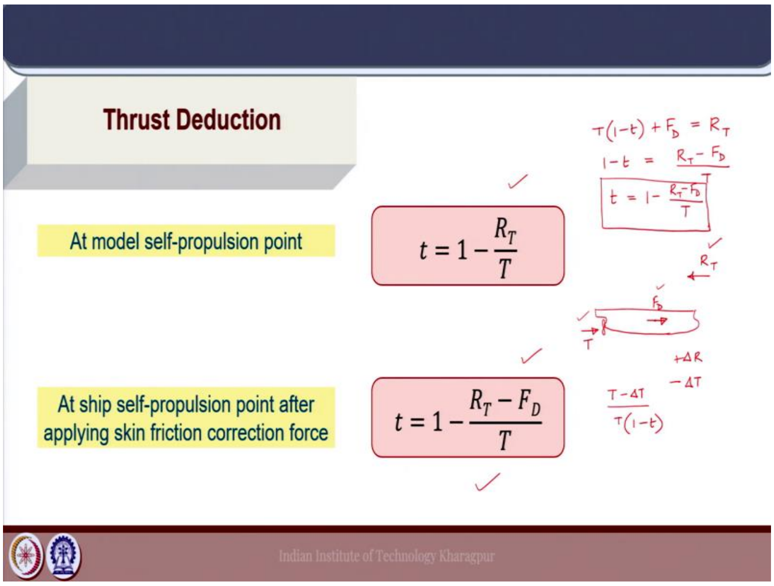
Now, if we look into the calculation of the propulsion factors we have the resistance test which has been done before we have the propeller open water test which was done with only the propeller, we have the self-propulsion test which is done for the ship model with the propeller working behind it. Now what is the output of the resistance test we have the total resistance of the model.

From the self-propulsion test what are the measured values the propeller thrust, rpm, and propeller torque. Now using the resistance that we calculate from the resistance test the total resistance and the propeller thrust from the self-propulsion test. We use the value of F_D which is the skin friction correction force to get the thrust deduction t which is the propulsion factor one of the important factors which is required for the calculation of ship powering.

The next is the use of the thrust and torque obtained from the self-propulsion test we use the data of the open water test to calculate the wake fraction. So, here it is written as W_T which represents the wake fraction calculated using thrust identity we have discussed about thrust and torque identities. And how to apply them to the open water diagram we will again go into these calculations in brief in the next slides and the other propulsion factor here is the relative rotative efficiency η_R.

So, in this way, we can use the resistance and self-propulsion test along with the open water test data to calculate the propulsion factors which will be required for ship powering.

(Refer Slide Time: 35:26)



Now for the thrust deduction, this part is very important to understand that as we have previously written this particular expression, the thrust deduction is related to the total resistance from the resistance test and the thrust measured from the propulsion test at the model self-propulsion point. That means, where the tow rope force is 0 so there is no correctional force.

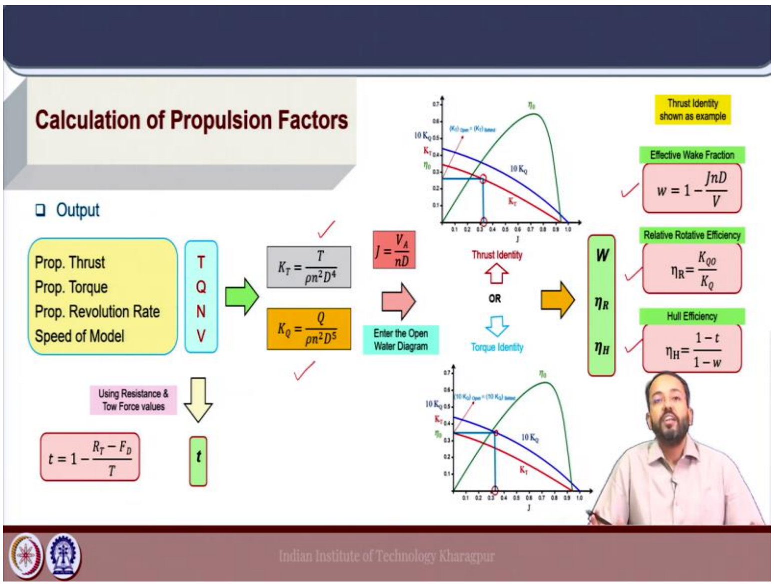
But when we apply the skin friction correction force the self-propulsion point is shifted from the model self-propulsion point to the ship self-propulsion point and here the thrust deduction factor will include F_D which is the skin friction correction force in its expression. So, we have let us say we have the ship model which is in the self-propulsion test and at the resistance dynamometer, we have a tow force which is F_D ok, which is the skin friction correction force.

The thrust provided by the propeller is T and we know that R_T is the total resistance of the model obtained from the resistance test and we have seen earlier that in the hull propeller interaction part of this course that this R_T will increase because of the suction effect of the propeller. So, the resistance test value that we get the total resistance that we get from the resistance test will be increased slightly when the propeller is acting behind the ship.

So, in the self-propelled condition, the resistance will be increased and we take care of that not by an increase of ΔR, but by an equivalent decrease of the thrust by an amount ΔT that we have seen, and to balance for that we write T as T - ΔT ok. Because we are balancing these values T and F_D with the resistance measured during the resistance test, we have to account for that using a factor ΔT which is the thrust deduction and this is mentioned as 1 - t where small t is the thrust deduction factor right.

So, we can write finally, T into 1 - T + F_D is the total force in the forward direction should be equal to the R_T when the model moves forward at uniform speeded. So, this gives 1 - T equal to R_T - F_D/T which gives T equal to 1 - R_T which is this equation. So, the thrust deduction factor during the self-propulsion test can be calculated using the total resistance from the resistance test and the thrust from the propulsion test using the value of F_D.

(Refer Slide Time: 40:50)



So, let us simply look into the calculation of all the propulsion factors together and this will be the summary which is the combination of the self-propulsion test along with the results obtained from the resistance and open water tests.

So, the output of the self-propulsion tests are the propeller thrust torque, propeller revolution rate and speed of the model represented by T, Q, N, and V in the model scale. So, using the resistance and tow force values we can calculate the thrust deduction as we have just seen using this equation. Now, from the measured value of thrust and torque we can calculate the thrust and torque coefficient in the behind hull condition for the propeller.

Now we will use this data to enter into the open water diagram which we have obtained from the propeller open water test. As we have previously discussed there are 2 ways of entering into the open water diagram whether we can either use thrust identity. As we have previously discussed there are 2 ways of entering into the propeller open water diagram one is using the thrust identity and another is using the torque identity.

So, both of these are shown and J is the advance coefficient which is given by V_A/nD and using thrust identity we use K_T calculated from the self-propulsion test to enter the open water diagram here and we can get the corresponding value of J. And if we try to use torque identity we use K_Q measure from the self-propulsion test to enter into the open water diagram and get the value of J. And as we have seen earlier that the value is slightly different in terms of the obtained J and n when we use thrust and torque identities.

Now, a simple example is shown here using thrust identity we can calculate the wake fraction first, let us say we enter the open water diagram using K_T and obtain the value of J. Now the wake fraction now can be calculated by this equation where nD and V are obtained from the self-propulsion test and J is the value which is taken from the open water diagram.

Next, we can calculate the relative rotative efficiency since we are using thrust identity relative rotative efficiency is given by η_R is the ratio of K_{Qo}/K_Q, where K_{Qo} is the torque coefficient obtained from the open water diagram and K_Q is the torque coefficient in the self-propulsion test and finally, we can calculate the hull efficiency η_H by this equation 1 - thrust deduction factor by 1 - wake fraction. Now, this wake fraction is called the effective wake fraction as opposed to the nominal wake fraction which we had measured behind the ship hull.

Now in the wake measurement tests, one can use different ways to measure the wake velocities behind the ship hull and get the average velocity on the propeller plane without the presence of the propeller. So, it is the average value of the velocity at the plane of the propeller measured behind the ship hull, but without the presence of the propeller itself. Now when the propeller is acting behind the ship hull it also changes the flow in the stern part of the ship.

Now, it cannot be measured directly from the experiment, because the propeller is rotating at that particular position; because of this, there is an indirect way which we call the effective wake fraction we use this value of self-propulsion tests and combine it with the open water test values. So, we enter using thrust and torque identity as just shown and we get the effective wake fraction which is a representation of the velocity of the advance of the propeller when it operates behind the ship hull.

So, this is the standard representation of the propulsion factors calculated from the self-propulsion tests in combination with the results obtained from resistance test and open water test. So, this will be all for today’s class in the next class we will go into the calculation for the ship powering using the results of model self-propulsion test.

Thank you.