SHIP PERFORMANCE

CHAPTER - 1

RESISTANCE

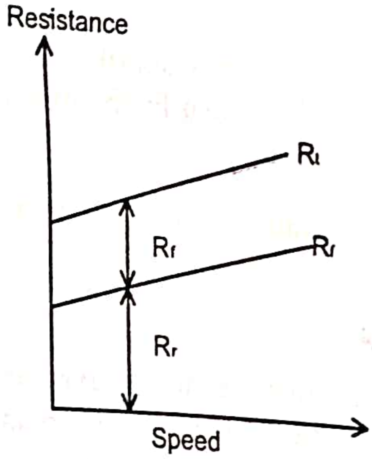
1.1 TYPES OF RESISTANCE

When a ship moves through water at a speed, a resistance is exerted by the water on the ship. If the ship has to continue to travel at that speed, it must exert an equal thrust to overcome the resistance of the water.

For example if the resistance of the water on the ship at 17 knots is 800kN, the ship has to exert a thrust of 800kN if it has to travel at 17 knots.

1.1.1 Total resistance, R_t

It can be divided into frictional resistance, R_f and residuary resistance, R_r. The total resistance is equal to the sum of frictional resistance and residuary resistance. The relationship between resistance and speed is shown in the figure 1.1 which is self explanatory.



$$R_t = R_f + R_r$$

Figure 1.1: Resistance-speed curve

1.1.2 Frictional resistance, R_f

As the ship moves through the water, friction between the hull and water causes a belt of eddying adjacent to the hull to be drawn along with the ship, although at a reduced speed. The belt moves aft and new particles of water are continuously set in motion. The force required to produce the belt of eddying water and to provide the motion is provided by the ship.

R_f depends on speed of the ship, wetted surface area, length of ship, roughness of the hull and density of water.

R_f is given by the formula,

$R_f = f \times S \times V^n \times N$, where f-is the coefficient of friction and depends on L, S, V in knots and n = 1.825 (1 knot = 1.852km/hour)

f-for mild steel hull in sea water is given by,

$f = 0.417 + \left(\frac{0.773}{L + 2.862}\right)$. It can be seen that coefficient, f is reduced as the length is increased.

In a slow or medium speed ship, R_f forms major part and as much as 75% of R_t. Surface roughness will considerably reduce the speed of the ship.

1.1.3 Residuary resistance: R_r

This is divided into resistance caused by formation of streamlines round the ship, eddy resistance and wave making resistance.

Resistance caused by formation of streamlines round the ship is due to change in direction of water. When the water changes direction abruptly or suddenly as in the case of box barges, the resistance may be considerable.

1.1.4 Eddy resistance

It is caused by changes in form. This is small when the ship is designed carefully. The eddy resistance due to rectangular stern frame and single plate rudder is about 5% of the total resistance of the ship.

In a streamline stern frame and a double plate rudder, the eddy resistance is practically negligible.

1.1.5 Wave making resistance

It is the resistance caused by formation of waves as the ship passes through the water. In small and medium speed ships it is small compared with R_r. At high speeds it is considerably increased and is about 50% to 60% of R_t.

This resistance arises from disturbance of the free surface. It implies that U-sections of the ship offer less resistance when compared to V-sections. Normally small form resistances lead to large changes in wave making resistances.

There is no optimum ship form which gives minimum resistance at all speeds but only the best of the form can be selected for any application. Also it has been shown that when the bow and stern systems are out of phase, the wave making resistance is considerably less. It is the principle on which bulbous bow had been developed. The bulbous bow produces less wave making resistance over a limited range of speed and it is most suitable in case of merchant ship which are run over a narrow speed range in full ahead steaming conditions.

One method practiced nowadays to reduce the wave making resistance is the use of bulbous bow. The wave produced in the bulb interferes with the wave produced by the stern resulting in a reduced height of bow waves and reduction in the energy required to produce the wave. The relation between the R_f, R_r and R_t is shown in the figure 1.

R_r follow Froudes law of comparison. The law states that the residuary resistance of similar ships are in the ratio of the cube of their linear dimensions if their speeds are in the ratio of square root of their linear dimensions.

$$\text{i.e}\quad \frac{R_{r1}}{R_{r2}} = \left(\frac{L_1}{L_2}\right)^3 \text{ if } \frac{V_1}{V_2} = \left(\frac{L_1}{L_2}\right)^{\frac{1}{2}}$$

$$\text{or}\quad \frac{R_{r1}}{R_{r2}} = \frac{\Lambda_1}{\Lambda_2} \text{ if } \frac{V_1}{V_2} = \left(\frac{\Lambda_1}{\Lambda_2}\right)^{\frac{1}{6}},$$

Where V_1 and V_2 are called corresponding speeds

At corresponding speeds, $\frac{V_1}{(L_1)^{1/2}} = \frac{V_2}{(L_2)^{1/2}}$, where

$\frac{V}{L^{1/2}}$ is known as the speed length ratio.

It may be seen that at corresponding speeds, the wave making characteristics of similar ships are same. At high speeds, the speed length ratio is high and the wave making resistance is large. To give the same wave making characteristics the corresponding speed of a much smaller and similar ship will be greatly reduced and may not be what is popularly regarded to be a high speed.

Hence, a ship is considered slow or fast in relation to the speed length ratio.

If $\frac{V}{L^{1/2}}^{2}$ is < 1, the ship is slow, V in knots and L in metres.

If $\frac{V}{L^{1/2}}$ is > 1, the ship is said to be fast.

The residuary resistance is usually obtained on the results of model experiments.

1.1.6 Air resistance

The ship also experience resistance due to wind and weather conditions while at sea.

This resistance will comprise of frictional and eddy making components. The air resistance varies as the square of the speed, V. In practice it is difficult to design a smooth form of ship to avoid this resistance. When compared to the cost involved in achieving such a structure, the loss of power is less and hence this resistance is usually neglected.

In full speed condition with no wind, the air resistance is assumed to be about 2 to 4%.When the wind speed is equal to the ship speed and the ship is facing the wind head on, the air resistance is quadrupled and the power consumed to meet out this resistance is considerable and will slow down the ship.

1.1.7 Appendage resistance

Appendages such as rudders, shaft brackets or bossing, stabilizers, bilge keel and duct keels offer their own resistance. Model tests are carried out to calculate these resistances and applied to full scale ship using a different formula than it is applied for the hull proper. These resistances are small and of the order of about 10% that of hull resistance and hence the error in calculating them is not critical.

It is usually assumed that the appendage resistance varies as the square of the speed, V. In addition to the above the ship while in service faces resistance due to waves and spray generated by wind. In rough weather the effect is considerable and often causes a significant fall in speed.

1.1.8 Form resistance

Form resistance is due to the shape of the hull and for example a rectangular shaped barge when sailing encounters much more resistance than a vessel with a Vee shaped stem.

It is not possible to decide absolutely a perfect form while designing. In addition to powering of the ship, the designer has to consider laying out machineries and other constructional constraints. Even while considering the power, one form may be superior to the other at one displacement and speed but inferior at other speed and displacement. Also one parameter cannot be varied without affecting the other.

An allowance is made for such factors and also for the sea conditions when compared to the tank conditions under which the model tests are carried out. This allowance is called ship correlation factor, SCF.

1.2 MODEL TEST

Model tests are based on Froude's law of comparison that if two geometrically similar forms are run at corresponding speeds i.e speeds proportional to the square root of their linear dimensions, then the residuary resistance per unit of displacement is the same.

The model testing tank consists a long tank approximately rectangular in cross section. The tank is spanned by a carriage for towing the model along the tank. Improvements in instrumentation and digital recording of data have improved obtaining the results in an easy and fast manner. The carriage is accelerated upto the required speed, resistance readings and hull sinkages and trim are taken during the speed of constant speed and then the carriage is decelerated. With increasing ship lengths and speeds the requirement for longer tanks has resulted to cope up with acceleration and deceleration of the model.

From the data obtained from above experiment, the following steps are followed for calculating the resistances:

i. Measure the resistance of a geometrically similar model at its corresponding speed.

ii. Estimate the skin friction resistance from data derived from experiments on flat plate.

iii. Subtract the skin friction resistance from the total resistance to obtain the residuary resistance.

iv. Multiply the model residuary resistance by ratio of the ship to model displacements to obtain the ship residuary resistance, R_r

v. Add the skin friction resistance estimated for the ship, R_f to obtain the total ship resistance, R_t.

Once the total resistance of the ship is known, the power required to overcome it is determined. This is known as the effective power, e_p of the ship. The model is tested without appendages such as rudder and bilge keel. An allowance is made for such appendages and also for the sea conditions when compared to the tank conditions. This allowance is called ship correlation factor, SCF.

The effective power, e_p obtained from the model test which is also called effective power, naked, e_{pn} is multiplied by the ship correlation factor to get the true effective power.

1.2.1 Propeller tests in open water

The data required for selection of geometric properties of the propeller to determine the propeller efficiency are obtained by testing the model propellers in open water. This method eliminates the effects of cavitations and the actual flow of water into the propeller behind a particular ship form. The results are compared with different propellers for selecting the best propeller suitable.

The tests are carried out in a tank with the propeller mounted forward of a streamlined casing containing the drive shaft. The propeller is driven by an electric motor on the carriage. Thrust, torque, propeller rpm and carriage speeds are recorded and from these Kt-thrust coefficient, Kq- torque coefficient, J- advance coefficient and efficiency and displacement, Λ can be calculated. Usually runs are carried out at constant rpm and speeds of advance for each run varied.

1.3 SHIP COEFFICIENTS

1.3.1 Admiralty coefficient

The approximation to the power of a ship is obtained at times by a method called Admiralty coefficient method without resorting to model experiments. This is based on the assumption that for small variations in speed the total resistance is expressed by,

$$R_t \, \alpha \, p \times S \times v^n$$

It was seen that $S \, \alpha \, \Lambda^{2/3}$,

Hence, with constant density, $R_t \, \alpha \, \Lambda^{2/3} \times V^n$

But power is proportional to $R_t \times V \, \alpha \, \Lambda^{2/3} \times V^n \times V$

Power $= (\Lambda^{2/3} \times V^{n+1})/$a coefficient. This coefficient is known as **admiralty coefficient.**

Merchant ships are classified as slow or medium speed ships and for such vessels, the value of n may be taken as 2.

Admiralty coefficient, $C = \Lambda^{2/3} \times \frac{V^3}{S_p}$

Where Λ is the displacement, V-speed of the ship in knots, Sp-shaft power in kw.

The admiralty coefficient may be regarded as constant for similar ships at their corresponding speeds. The value of C varies from 350 to 600 for different ships. Higher the value, more efficient is the ship.

For smaller changes in speed, the value of C may be taken constant for any ship at constant displacement.

i.e at corresponding speeds,

$$V \alpha \Lambda^{1/6}$$

$$V^3 \alpha (\Lambda^{1/6})^3 \text{ i.e } V^3 \propto \Lambda^{1/2}$$

$$S_p \alpha \Lambda^{2/3} \times V^3$$

$$\alpha \Lambda^{2/3} \times \Lambda^{3/6}$$

$$\alpha \Lambda^{7/6}$$

$$\frac{S_{p1}}{S_{p2}} = \left(\frac{\Lambda_1}{\Lambda_2}\right)^{7/6}$$

Thus, if the shaft power of one ship is known, the shaft power for a similar ship can be obtained at the corresponding speed.

1.3.2 Fuel coefficient and consumption

The fuel consumption is measured in terms of fuel consumption per unit power called specific fuel consumption in kg/hour. For an efficient diesel engine it is about 0.2kg/ kwh and for steam engines it is about 0.3kg/kwh.

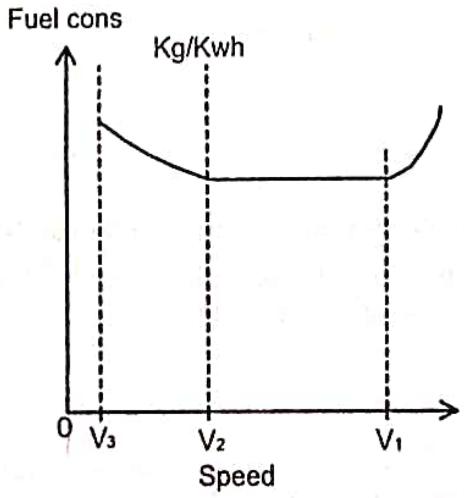


Figure 1.2: Fuel consumption-speed curve

The specific fuel consumption of a ship at different speeds is shown in the figure 1.2. Between V_1 and V_2 the specific fuel consumption is practically constant and if the speed varies in between V_1 and V_2 then,

Fuel consumption/unit time is α to power developed i.e Fuel consumption α Sp

But Sp $\alpha\ \Lambda^{2/3} \times V^3$

Fuel consumption/unit time $\alpha\ \Lambda^{2/3} \times V^3$

Fuel consumption/day = $(\Lambda^{2/3} \times V^3)$/(Fuel coefficient)–tons

The value of fuel coefficient is between 40000 to 120000. The higher the value of fuel coefficient, higher is the efficiency of the ship.

1.4 MODEL TESTS AND SEA TRIALS

Sea trials are carried out after the ship is completed to confirm that the ship has met its specification regarding designed speed. Also, to predict performance during service, to prove that the equipments can function properly in shipboard environment, to provide data that is useful to the ship designer in the subsequent design of ships, to determine the effect on human performance and to confirm the ship meets her design intention with regard to performance.

Two types of trial are carried out. One is of short duration in which the ship responses to a measured sea system are recorded and the other is prolonged period trials in which statistical data is built up of ship response in a wide range of sea conditions.

The first type of trial is carried out to compare ship with model over a range of ship speeds and headings. With this data the long term behaviour of the ship on voyage can be arrived at. The second type of trial is a comparison of actual and assumed behaviour during a voyage or over a prolonged period. The difference is because the ship is not responding to the wave system predicted or the wave systems those are not predicted.

The speed trials are carried out over a known distance. The distances are defined precisely with land marks or in open water by use of accurate navigation position indicators.

The time to traverse the marked distance on shore is accurately noted together with shaft thrust, torque and revolutions. Normally a fine day with little wind is selected for conducting the trial. To reduce the effect of resistance, the use of rudder is kept minimum during the run. At the end of the run, the ship is made to take a large turn around for the next pass.

The trial is carried out for a range of powers upto the maximum the machinery can generate. At each power, several runs are made in each direction to ensure the effect of any tide is eliminated. The mean speed is calculated from the above results and finally the ship's speed is arrived at.

During sea trials also the performance of all equipments fitted on board and various systems are also carried out to ensure they meet the requirement as per specification.

1.4.1 Resistance test facilities and techniques

The facility for model testing is a long tank of rectangular cross section spanned by a carriage which tows the model along the tank, figure 1.3. Improvements have been made in maintaining constant speed, propelling of the carriage, in instrumentation and analysis of data. Digital recording of data and use of computers have reduced the data analysis time to a great extent.

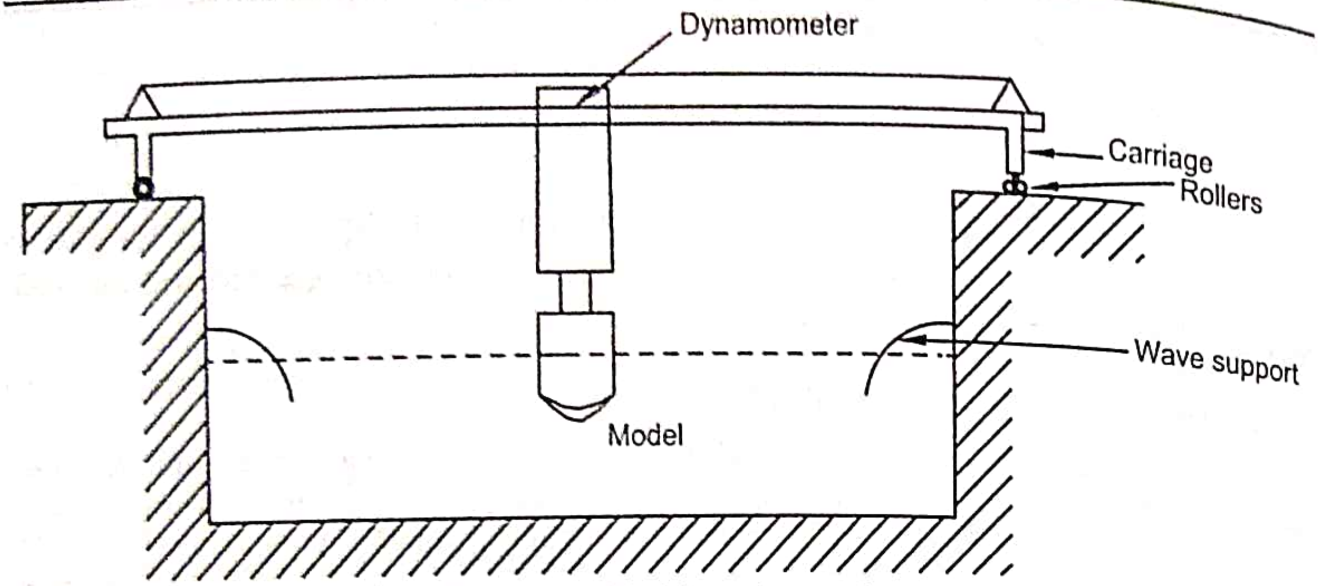


Figure 1.3: Model testing tank

The carriage is accelerated upto the required speed, resistance records and measurement of hull sinkage and trim are taken during a period of constant speed and then the carriage was decelerated. It was experienced unexplained variations in the resistance measured by R.E Frude in repeat experiments on a given model. It was suspected that currents were set up in the tank by the passage of the model causing variations in skin friction resistances due to temperature changes.

It was concluded that a 3% decrease in skin resistance for every 10° F rise in temperature could be adopted for correcting the above with a 55° F as the standard temperature.

After allowing for tank currents and temperature variations, significant variations in resistances were found

1.4.2 Model experiments of hull efficiency elements

These experiments must be carried out with the hull and propeller correctly connected as shown in the figure 1.4. With the model at correct speed corresponding to that of the ship under consideration, a series of run is made over a range of propeller rpm straddling the self propelling point of the model. Model speed and resistance were recorded together with thrust and torque and rpm of the propeller. Results were plotted to a base of propeller rpm as shown in figure 1.5 to find the model self propelling point.

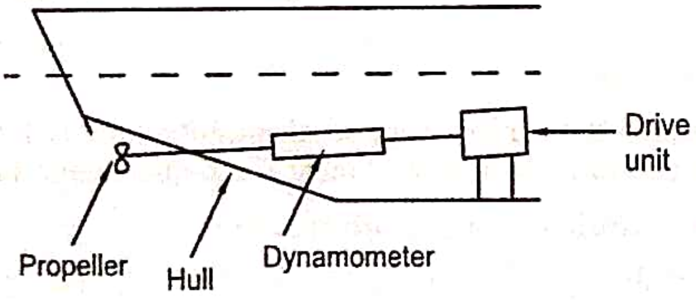


Figure 1.4: Model with propeller in the testing tank

The model propeller then has its thrust and torque measured in open water at a speed of advance estimated to be that of the flow through the propeller when behind the hull i.e making allowance for the wake. By comparing this curve with that obtained in the combined equipment, the correct speed for the propeller in open water can be calculated. The difference between the model speed in the combined experiment and the corrected open water speed is the wake. The relative efficiency follows as the ratio between the torques measured in the open water and combined experiments at self propulsion rpm. This is illustrated in figure 1.5.

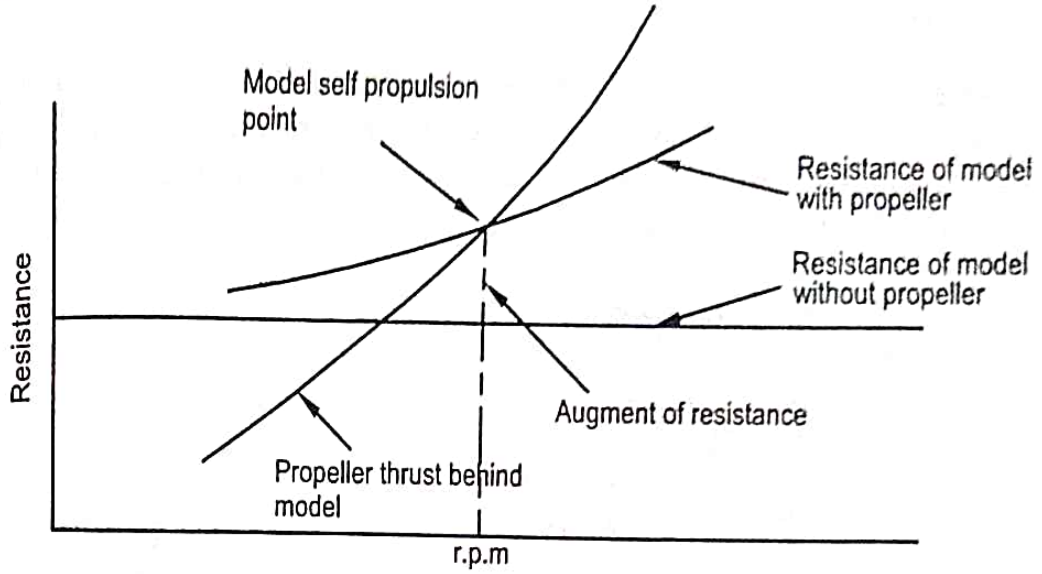


Figure 1.5: Resistance-speed curve with and without propeller

It should be noted that the propeller used in these experiments is made as closely representative of the ship propeller as possible. The hull efficiency elements calculated as above are used with either methodical data or specific cavitation tunnel measurements in order to produce the propeller design.

1.5 PROBLEMS

Problem 1.1: A ship has a wetted surface area of 3500m². Calculate the power required to overcome the frictional resistance at 17 knots if n = 1.825 and f = 0.424.

Frictional resistance, $R_f = f \times S \times V^n$ N

$$= 0.424 \times 3500 \times 17 \times 1.825 \text{ N}$$

$$= 265.218 \text{ KN}$$

Power required = $R_f \times v$, v - in m/sec

$$= \frac{261.218 \times 17 \times 1852}{3600} \text{ kw}$$

$$= 2282.5 \text{ kw}$$

Problem 1.2: A plate towed edge wise in sea water has a resistance of 13N/m² at 3m/sec. A ship travels at 15 knots has a wetted surface area of 4000m².

If the frictional resistance vary as speed to the power of 1.97, calculate the power required to overcome frictional resistance.

$V = 15$knots, $S = 4000$ m²· $n = 1.97$

$R_f = f \times S \times V^n$

At 3m/sec, $R_{f1} = 13 \text{N/m}^2$

A 15 knots i.e $\frac{15 \times 1852}{3600}$ m/sec,

$$R_{f2} = \frac{(13 \times 15 \times 1852)}{(3 \times 3600)} = 83.6\text{N/m}^2$$

$$R_f = \frac{83.6 \times 4000 \times 15 \times 1852}{3600} \text{N} = 2578.224 \text{ KN}$$

Problem 1.3: The frictional resistance per square metre of a ship is 12N at 180m/minute. The ship has a wetted surface area of 4100m² and travels at 14knots. Frictional resistance vary as speed to the power of 1.9. If frictional resistance is 70% of the total resistance, calculate the effective power.

$$\frac{R_{f1}}{R_f} = \frac{12}{\left(\frac{14 \times 1852}{60}\right)}$$

$$\frac{R_{f1}}{R_S} = \left(\frac{180 \times 60}{14 \times 1852}\right)^{1.9}$$

$$R_f = 12 \times \left(\frac{(14 \times 1852)}{(180 \times 60)}\right)^{1.9} = 63.36 \text{ N/m}^2$$

Total frictional resistance = 63.36 × 4100 N = 259776 N

$$\text{Total resistance} = \frac{259776}{0.7} = 371109 \text{ N}$$

$$\text{Effective power} = \frac{371109 \times 14 \times 1852}{3600} = 2670.5 \text{ kw}$$

Problem 1.4: A ship is 125m long, 15m wide floats at a draft of 7.8m. Its block coefficient is 0.72. Calculate the power required to overcome frictional resistance at 20 knots and f = 0.423. Use Taylor's formula for wetted surface area with C = 2.55.

$$\text{Wetted surface area, } S = C \times (\Lambda \times L)^{1/2}$$

$$= 2.55(125 \times 16 \times 7.8 \times 0.72 \times 1.025 \times 125)^{1/2}$$

$$= 3059 \text{ m}^2$$

$$\text{Frictional resistance, } R_f = f \times S \times V^n = 0.423 \times 3059 \times 201.825$$

$$= 306409 \text{ N}$$

$$\text{Effective power} = \frac{R_f \times 20 \times 1852}{3600} = \frac{306409 \times 20 \times 1852}{3600}$$

$$= 3149.9 \text{ kw}$$

Problem 1.5: A ship of 15000t displacement has a residuary resistance of 113KN at 16knots. Calculate the corresponding speed of a similar ship of 24000t displacement and the residuary resistance at this speed.

Λ_1 = 14000t, R_{r1} = 113kN, V_1 = 16knots, Λ_2 = 24000t

$$\frac{R_{f_1}}{R_{f_2}} = \frac{\Lambda_1}{\Lambda_2}$$

$$R_{r2} = \frac{113 \times 24000}{15000} = 180.8 \text{ kN}$$

$$\frac{V_1}{V_2} = \left(\frac{\Lambda_1}{\Lambda_2}\right)^{1/6}$$

$$V_2 = V_1 \times \left(\frac{\Lambda_2}{\Lambda_1}\right)^{1/6} = 16 \times \left(\frac{24000}{15000}\right)^{1/6} = 17.3 \text{ knots}$$

Problem 1.6: Frictional resistance of a ship in fresh water at 3m/sec is 11N/m². The ship has a wetted surface area of 2500m² and the frictional resistance is 72% of the total resistance and varies as speed to the power of 1.92. If the effective power is 1100KN, calculate the speed of the ship.

$$R_f = 72\% \text{ of } R_t,\ R_t = 1100\text{kw}$$

$$R_f = 1100 \times 0.72 = 790\text{kw}$$

$$R_f = f \times S \times V^n$$

$$11 \times 1.05 = f \times 2500 \times \left(\frac{(3 \times 3600)}{1852}\right)^{1.92}$$

$$f = \frac{(11.275 \times 1852)}{(2500 \times 3 \times 3600)} = 0.000773$$

$$R_f = f \times 2500 \times V^{1.92}$$

$$790 = 0.000773 \times 2500 \times V^{1.92}$$

$$V^{1.92} = \frac{790}{(0.000773 \times 2500)}$$

$$V = 12.4\text{knots}$$

Problem 1.7: A 6m model of a ship has a wetted surface area of 7m² and travels in fresh water at 3knots has a total resistance of 35N. Calculate the effective power of the ship 120m long and its corresponding speed. n=1.825, f to calculate from formula $f = 0.417 + \frac{0.773}{L + 2.862}$ and SCF = 1.15.

$$V_1 = 3\text{knots},\ L_1 = 6\text{m},\ R_{t1} = 35\text{N},\ n = 1.825$$

$$R_{t1} \text{ model} = 35 \times 1.025 \text{ N} = 35.875 \text{ N}$$

$$R_f = f \times S \times V^n$$

$$f_1 = 0.417 + \frac{0.773}{L + 2.862} = 0.417 + \frac{0.773}{6 + 2.862} = 0.5042$$

$$R_{f1} = 0.5042 \times 7 \times 3^{(1.825)} = 26.208 \text{ N}$$

$$R_{r1} = 35.875 - 26.208 = 9.667 \text{ N}$$

$$\frac{R_{f_1}}{R_{f_2}} = \left(\frac{L_1}{L_2}\right)^2$$

$$R_{r2} = 9.667 \times \left(\frac{120}{6}\right)^3 = 77336 \text{ N}$$

S & L_2

$$S_2 = S_1 \times \left(\frac{L_1}{L_2}\right)^2$$

$$S_2 = 7 \times \left(\frac{120}{6}\right)^2 = 2800 \text{ m2}$$

$$V_2 = V_1\left(\frac{L_2}{L_1}\right)^{1/2} = 3 \times \left(\frac{120}{6}\right)^{1/2} = 13.416 \text{ knots}$$

$$F_2 = f + \left(\frac{0.773}{(120 + 2.862)}\right) = 0.417 + \frac{0.773}{(120 + 2.862)}$$

$$= 0.417 + 0.0063 = 0.4233$$

$$R_{f2} = 0.4233 \times 2800 \times 13.416^{(1.825)} = 135400 \text{ N}$$

$$R_{t2} = 135400 + 77336 = 212736 \text{ N}$$

$$e_{pn} = \frac{212736 \times 13.416 \times 1852}{3600} = 1468.2 \text{ kw}$$

$$e_p = 1468.2 \times 1.15 = 1688.4 \text{ kw}$$

Problem 1.8: A ship of 12000t displacement has an Admiralty coefficient of 550. Calculate the horse power at 15 knots.

$$\text{Admiralty coefficient, } C = \frac{(\Lambda^{2/3} \times V^3)}{S_p}$$

$$S_p = \frac{(\Lambda^{2/3} \times V^3)}{C} = \frac{1200^{2/3} \times 15^3}{550}$$

$$= 2454.5 \text{ kw}$$

Problem 1.9: A ship requires a shaft power of 2800 kw at 15 knots and the admiralty coefficient is 520. Calculate the displacement, the shaft power if the speed is reduced by 15%.

$$S_p = 2800\text{kw}, \; V = 15 \text{ knots}, \; C = 520$$

$$C = \frac{\Lambda^{2/3} \times V^3}{S_p}$$

$$\Lambda^{2/3} = \frac{C \times S_p}{V^3} = \frac{520 \times 2800}{15^3}$$

$$\Lambda = 8960.5 \text{ t}$$

$$\text{New speed} = 15 \times 0.85 = 17.65 \text{ knots}$$

$$S_p = \frac{\Lambda^{2/3} V^3}{C} = \frac{8960.5^{2/3} \times 17.65^3}{520} = 4575.5 \text{ kN}$$

Problem 1.10: A ship 150 m long, 19m beam floats at a draft of 8m and has a block coefficient of 0.68. If the Admiralty coefficient is 600, calculate the shaft power required at 18 knots. If the speed is now increased to 20 knots and within this speed range the resistance varies as speed to the power of 3, find the new shaft power.

$$\text{Displacement, } \Lambda = 150 \times 19 \times 8 \times 1.025 \times 0.68 = 15980 \text{ t}$$

$$S_p = \frac{\Lambda^{2/3} V^3}{C} = \frac{1598^{2/3} \times 18^3}{600} = 6143 \text{ kw}$$

$$\frac{S_{p1}}{S_{p2}} = \left(\frac{V_1}{V_2}\right)^4 \cdot \text{ since n= 3}$$

$$S_{p2} = S_{p1} \times \left(\frac{V_2}{V_1}\right)^4 = 6143 \times \left(\frac{20}{18}\right)^4 = 9359 \text{ kw}$$

Problem 1.11: A ship of 15000t displacement has a fuel coefficient of 62500. alculate the fuel consumption per day at 15 knots.

$\Lambda = 15000t$, fuel coefficient = 62500, V = 15 knots

$$\text{Fuel consumption} = \frac{\Lambda^{2/3}\times V^3}{62500} = \frac{15000^{2/3}\times 15^3}{62500} = 32.95t$$

Problem 1.12: A ship travels 2000 nautical miles at 16 knots and returns with he same displacement at 15 knots. Find the saving in fuel on the return voyage if the onsumption per day at 16 knots is 28t.

$$\frac{\text{Total consumption}}{\text{day}} = \frac{(28\times 2000)}{16\times 24} = 145.8t$$

$$\text{Total consumption for Return voyage} = 145.8\times\left(\frac{15}{16}\right)^3 = 119.6t$$

$$\text{Saving in fuel consumption per day} = 145.8 - 119.6 = 26.2t$$

Problem 1.13: A ship uses 23t of fuel per day at 14 knots. Calculate the speed if the onsumption of fuel per day is increased by 15%.

$$\frac{\text{Consumption}}{\text{day}} = \frac{\Lambda^{2/3}\times V^3}{\text{fuel coeff}}.$$

$$V_3 = \left(\frac{\text{fuel coeff consumption}}{\text{day}}\right)^{\Lambda 2/3}$$

$$\left(\frac{V_1}{V_2}\right)^3 = \frac{\text{cons.1}}{\text{cons.2}}$$

$$\frac{23}{(23\times 1.15)} = \frac{14^3}{V_2^3}$$

$$V_2^3 = \frac{14^3\times 23\times 1.15}{23}$$

$$V_2 = 14.67\text{knots}$$

Problem 1.14: The normal speed of a ship is 14 knots and the fuel consumption per hour is given by 0.12 + 0.01×V3 tons with V in knots. Calculate the total fuel consumption on a voyage of 1700 nautical miles, the speed at which the vessel must travel to save 11t of fuel per day.

$$\text{Fuel consumption /hr} = 0.12+0.001\times V^3$$

$$\text{At 14 knots fuel consumption/hr} = 0.12+0.001\times 14^3 = 2.864\text{ t}$$

$$\text{Total fuel consumption for voyage} = \frac{1700\times 2.864}{14} = 347.7t$$

$$\text{New fuel consumption/day} = (2.864\times 24) - 11$$

$$\text{New fuel consumption/hr} = \left(\frac{(2.864\times 24) - 11}{24}\right) = 2.405\text{ t/hr}$$

$$0.12 + 0.001\times V_2^3 = \frac{(2.405 - 0.12)}{0.001}$$

$$V_2 = 13.14\text{knots}$$

Problem 1.15: A ship's speed is increased by 20% above normal for 8 hours, reduced by 10% below normal for 10 hours and for remaining 6 hours of the day the speed is normal. Calculate the percentage variation in fuel consumption on that day from normal.

$$\text{Fuel consumption /day} = \frac{\Lambda^{2/3} \times V^3}{\text{Fuel coeff}}$$

$$\text{New fuel consumption} = \frac{\left(\left(\frac{1.2 \times V^3 \times 8}{24}\right) + \left(\frac{0.9 \times V^3 \times 10}{24}\right) + \left(\frac{V^3 \times 6}{24}\right)\right) \times \Lambda^{2/3}}{\text{fuel coeff}}$$

$$\text{Variation} = \left(\left(\frac{1.2 \times V^3 \times 8}{24}\right) + \left(\frac{0.9 \times V^3 \times 10}{24}\right) + \left(\frac{V^3 \times 6}{24}\right)\right) \times \Lambda^{2/3} \times \frac{\text{fuel coeff.}}{\left(\frac{\Lambda^{2/3} \times V^3}{\text{fuel coeff.}}\right)}$$

$$= \left(\frac{9.6}{24} + \frac{9}{24} + \frac{6}{24}\right)^3 - 1 = \left(\frac{24.6}{24}\right)^3 - 1 = (1.08)^3 - 1 = 1.17 - 1 = 0.17$$

% variation = 0.0117

Let normal fuel consumption = c

$$\text{Consumption for 8 hrs} = \left(\frac{1.2V}{V}\right)^3 \times C \times 8 = 13.824c$$

$$\text{Consumption for 10 hrs} = \left(\frac{0.9V}{V}\right)^3 \times C \times 10 = 7.29c$$

Consumption for 6hrs = 6c

Total consumption/day = (13.824 + 7.29+6) c = 27.114c

Normal consumption /day = 24 × c = 24c

Increase in consumption = 27.114c – 24c =3.114c

$$\text{\% increase in consumption} = \frac{3.114c \times 100}{24c} = 12.97\%$$

Problem 1.16: A ships speed was 18 knots. A reduction in speed of 3 knots gives a saving in fuel consumption per day of 20t per day. Calculate the consumption per day a 18 knots.

Let fuel consumption at 18 knots/day = c_1

$$c_1 = \frac{\Lambda^{2/3} \times 18^3}{\text{fuel coeff}}$$

After reduction by 3.0 knots to 15 knots

$$c_2 = \frac{\Lambda^{2/3} \times 15^3}{\text{fuel coeff}}$$

$$\frac{c_1}{c_2} = \left(\frac{18}{15}\right)^3$$

$$c_1 = c_2 \times \left(\frac{18}{15}\right)^3$$

But $c_1 - c_2 = 22$

$$c_2\left(\frac{18}{15}\right)^3 - c_2 = 22$$

$$c_2\left(\frac{18}{15}\right)^3 - 1 = 22$$

$$c_2 = \frac{22}{0.728} = 30.22$$

$$c_1 = 22 + 30.22 = 52.22 \text{ t/day}$$

CHAPTER - 2

PROPELLER THEORY

2.1 DEFINITIONS

Diameter of the propeller, D: It is the diameter of the circle cut by the blade tips.

Pitch, P: If the propeller is assumed to work in an unyielding fluid, then the distance by which the shaft moves in one revolution is called the pitch.

Pitch ratio, or face pitch ratio, p : It is the face pitch divided by the diameter, $p = \frac{P}{D}$

Projected area, A_p: It is the sum of blade areas projected into a plane which is perpendicular to the axis of screw.

Developed area: It is the actual area of the driving faces clear off the boss called, A_d and the area including the boss called, A_b.

Blade area ratio, BAR: It is the developed area excluding boss divided by the area of the circle cut by the blade tip.

$$BAR = \frac{A_d}{\left(\pi \times \frac{d^2}{4}\right)}$$

Disc area ratio, DAR: It is the developed area including boss divided by the area of the circle cut by the blade tips.

$$DAR = \frac{A_b}{\left(\frac{\pi D^2}{4}\right)}$$

Theoretical speed, V_T: It is the distance the propeller advances in unit time.

If the speed is N revolutions per minute,

$$V_T = P \times N \times 60 \text{ m/min.}$$

$$= P \times N \times \frac{60}{1852} \text{ knots}$$

2.2 SPEED

2.2.1 Slip

Slip is divided into apparent slip and real slip.

2.2.2 Apparent slip

Since the propeller works in water, the ship speed will be less than theoretical speed. The difference in speed between these speeds is called apparent slip.

It is expressed as,

$$\text{Apparent slip} = V_T - V \text{ knots}$$

$$= \frac{(V_T - V)}{V_T} \times 100\%$$

Normally V_T is more than V. But however due to current the slip may be negative and V may be more than V_T.

2.2.3 Real slip

It is the difference between the theoretical speed and the speed of advance and is expressed as a ratio or percentage of theoretical speed.

$$\text{Real ship speed} = V_T - V_a$$

$$\text{Real slip} = \frac{(V_T - V_a)}{V_T} \times 100\%$$

The real slip is always positive and independent of current.

2.2.4 Relation between different speeds

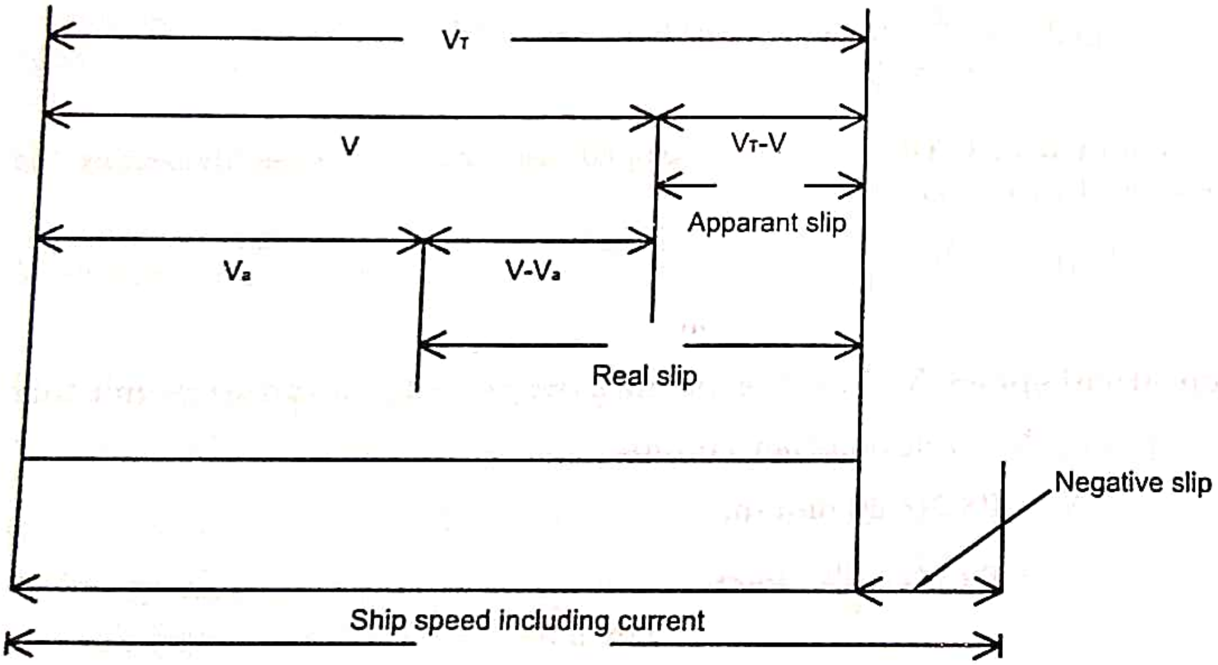


Figure 2.1: Relationship with ship speeds

Let V_T be the theoretical speed, V-be the ship speed and V_a speed of advance. The relationship between these different speeds is shown in the figure 2.1 which is sel explanatory.

2.3 POWER

2.3.1 Wake

The ship in its passage through water sets in motion particles of water in the neighbourhood due to friction of water. The moving water is called is wake.

The speed of the ship relative to the wake is called speed of advance, V_a. The wake speed is often expressed as a fraction of the ship speed.

$$\text{Wake fraction} \quad w = \frac{(V - V_a)}{V}$$

It is obtained approximately from the equation,

$W = 0.5C_b - 0.05$ where C_b is the block coefficient.

2.3.2 Thrust

The thrust exerted by the propeller is calculated by considering the propeller as a reaction machine. The water is received into the propeller disc at the speed of advance and projected aft at the theoretical speed.

Consider an interval of one second.

Mass of water passing through the disc is, $M = \rho \times A \times P \times n$

Where A-is the effective area i.e disc area in m², ρ-density of water, P-pitch of propeller in m, n-speed in revolutions/sec and V_a-speed of advance in m/sec, Change in velocity= $P \times n - V_a$ m/sec

Acceleration, $a = P \times N - V_a$ m/sec², Since the change in velocity has occurred in one second.

But real slip, S $= \dfrac{(P \times n - V_a)}{P \times n}$

$$P \times n - V_a = S \times P \times N$$

$$a = S \times P \times n$$

$$\text{Force, } M = \text{mass} \times \text{acceleration}$$

$$\text{Thrust} = M \times a$$

$$= (\rho \times A \times P \times n) \times (S \times P \times n)\ \rho \times A \times P^2 \times n^2 \times S$$

It may be noted that without slip the propeller will not exert any thrust and increased slip causes increased thrust.

The power produced by propeller is known as thrust power, t_p

$$T_p = \text{thrust, N} \times \text{speed of advance, w m/sec}$$

$$= T \times V_a \times w$$

$$\frac{T_{p1}}{t_{p2}} = \frac{T_1 V_{a1}}{T_2 V_{a2}}$$

If the power remains constant and the external conditions vary, then

$$T_1V_{a1} = T_2V_{a2}$$

Since V_a depends on speed, revolutions/min.

$$T_1N_1 = T_2N_2$$

The thrust absorbed by thrust collars and hence the thrust varies directly as the pressure, t, on the thrust collar

$$t_1N_1 = t_2N_2$$

This shows that if with constant power the ship meets a head wind, the speed will reduce but the pressure on the thrust collars will raise.

2.3.3 Relation between powers

Refer figure 2.2.

Figure 2.2: Relationship with different ship powers

Power produced by engine = indicated power = i_p

Shaft power or brake power,

$$\frac{S_p}{b_p} = i_p \times \text{ mechanical efficiency}$$

Power delivered, $d_p = S_p \times$ transmission efficiency

$$= \text{torque} \times 2 \times \pi \times n$$

Thrust power after considering Propeller efficiency,

$$t_p = d_p \times \text{propeller efficiency}$$

The propeller creates suction at the aft end of the ship in accelerating the water. The thrust exerted by the propeller must exceed the total resistance by this amount.

The relation between the thrust and resistance is expressed as,

$R_t = T\,(1-t)$ where t-is the deduction factor.

2.3.4 Hull efficiency

The thrust power will differ from effective power. The ratio of effective power, e_p and thrust power, t_p is called hull efficiency.

Hull efficiency = $\frac{e_p}{t_p} > 1$ for single screw and is equal to 1 for twin screw.

2.3.5 Quasi propulsive coefficient

QPC is the ratio of e_p to d_p eliminating hull and propulsive efficiency.

$$e_p = d_p \times QPC$$

2.3.6 Overall propulsive efficiency

It is the ratio of thrust power to the indicated power.

$$\text{Overall propulsive efficiency} = \frac{t_p}{i_p}$$

2.3.7 True propulsive coefficient

True propulsive coefficient is the relation between e_p and i_p or S_p

$$e_p = i_p \times \text{propulsive coefficient}$$
$$= S_p \times \text{propulsive coefficient}$$

2.4 CAVITATIONS

The thrust of a propeller varies approximately as the square of the revolutions. Thus as the speed of revolution is increased, there is a considerable increase in thrust. The distribution of thrust over the blade section is shown in figure-8. The pressure at any point on the back of the blade is the algebraic sum of the atmospheric pressure, water pressure and negative pressure of suction caused by the thrust.

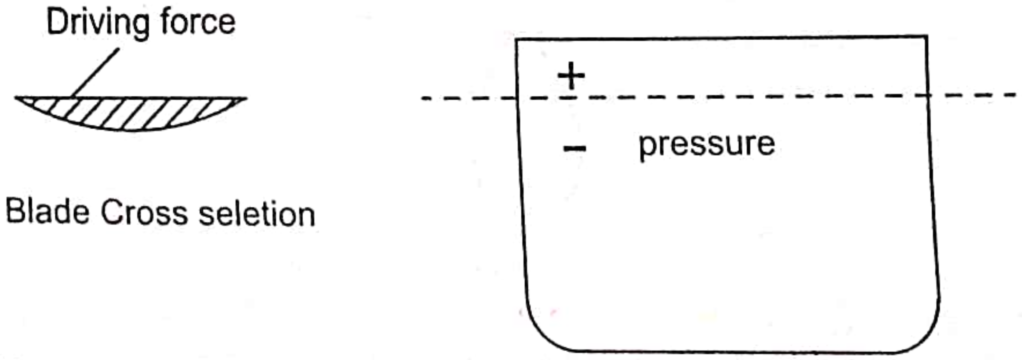


Figure 2.3: (i) Blade cross-section (ii) Pressure distribution on the blade

When the suction at any point is high, the net pressure may fall below the vapour pressure of the water at that temperature causing a cavity or bubble to form on the blade.

This cavity is filled with water vapour and air which associates from sea water. As the blade turns, the bubble moves across the blade to a point where the net pressure (higher) causing the cavity to collapse. The forming and collapsing of these cavities is known as **cavitations.**

When the cavity collapses, the water pounds on the blade material and since the break down occurs at the same position each time, it causes severe corrosion of the blades and may produce holes in the blade material several millimetre deep. It also causes reduction in thrust and efficiency, vibration and noise.

It may be reduced or avoided by reducing the revolutions per minute and by increasing the blade area for constant thrust, thus reducing the negative pressure. Since cavitations is affected by pressure and temperature, it is more likely to occur in propeller operating near surface than in those deeply submerged and will occur more readily in the tropics than in cold regions.

2.5 TYPES OF PROPELLERS

2.5.1 Built and solid propellers (Fixed pitch Propeller)

These propellers are used either in mono-block or in built up form. The mono-block propellers are very commonly used nowadays especially in ocean going vessels engaged in long voyages, figure 2.4. In built up propeller the blades are cast separately and then bolted to the boss separately after machining. This type of propeller is rarely used. Built up propellers were common in earlier days due to difficulty in casting large and quality blades integral with the boss. Also it was found difficult to define the blade pitch in this type of manufacture. In these two aspects the built up propellers were found advantageous.

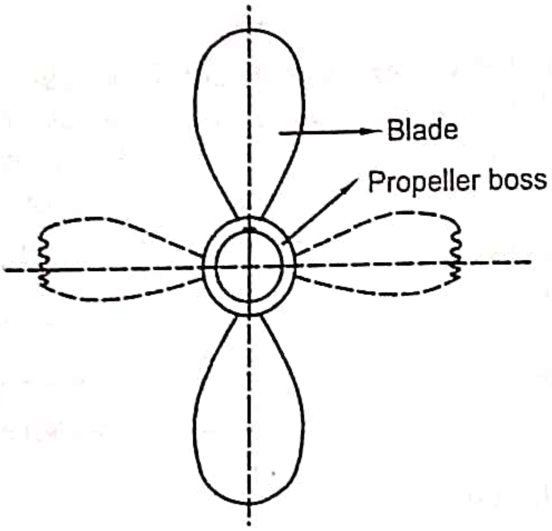


Figure 2.4: Mono block propeller

However built up propellers had large boss diameter when compared to solid propellers which caused cavitation problems in the blade root section.

Mono-block propellers are used in a wide range of application from small propellers in boats to those used in container ships weighing around 130 tons. These propellers range from large four bladed propellers in bulk carrier to highly skewed propellers in merchant and naval applications.

The materials used for manufacture is high tensile brass together with manganese and nickel aluminium bronze. Once cast iron was largely used for manufacture of spare propellers and is no more used due to corrosion problems. Blade numbers vary from two to seven even though in some special applications it is more to solve specific propulsion problem. Normally four or five blades are used in merchant ships.

2.5.2 Controllable pitch propeller

In this type of propulsion the pitch of the propeller can be altered remotely from full ahead to full astern positions. Blades are fitted in bearing rings in the propeller hub, as shown figure 2.5. A servo motor operates a crank pin and sliding shoe to rotate the blades. They increase the manoeuvrability. Engine speed is constant and hence a shaft generator can be run with this arrangement. For these reasons this type of propeller has become popular and has a considerable market share in small vessels such as passenger ferries, tugs, small cargo ships and harbour crafts.

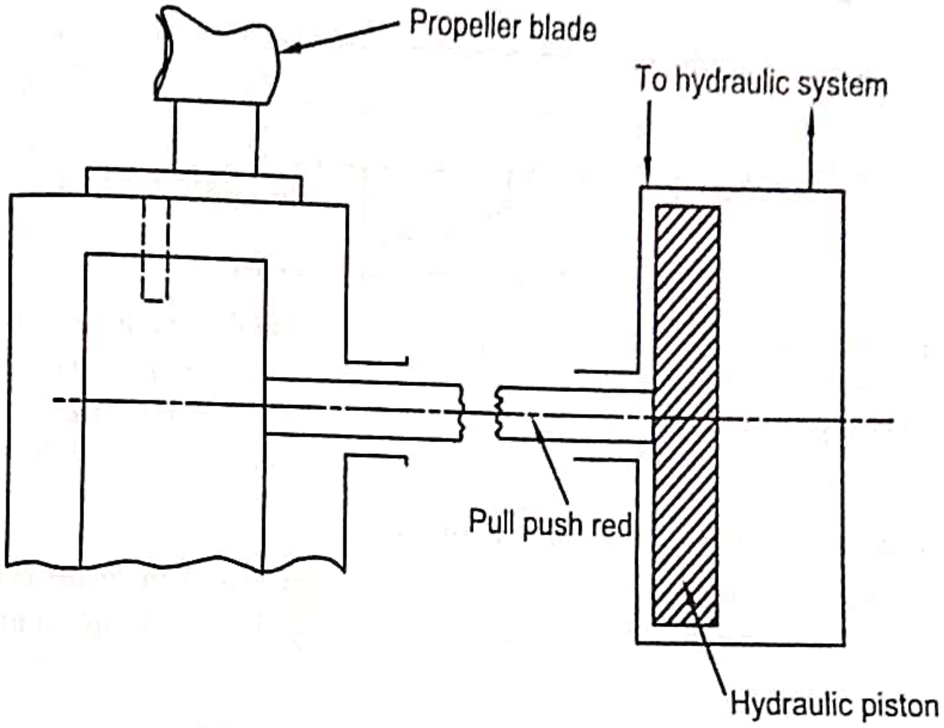


Figure 2.5: Controllable pitch propeller

A tug when towing and during free running, experiences two different loading conditions and similarly, a fishing vessel while free running and while trawling meets two distinctive loading conditions. In case of such vessels which work in two different definite loading conditions, this type of propulsion is ideal. However, it causes difficulties in terms of cavitation characteristics of the propeller by inducing back and face cavitation at different propulsion conditions.

No gear box is necessary for reversing. It is less efficient due to large diameter of the boss. Losses are high and the cost are also of repair and the maintenance cost and also high. For larger powers it is not suitable.

2.5.3 Contra rotating propellers

It consists of two coaxial propellers mounted one behind the other and running in opposite direction, as shown figure 2.6. This system recovers partly the slip stream rotational energy which otherwise be lost in a conventional single screw system. Because of two propeller configuration, contra-rotating propeller is capable of balancing the torque reaction from the propeller. The aft propeller has a small diameter than the forward propeller and the blade numbers in both the propellers are also different and typically four for forward and five for aft propeller are employed. This reduces the vibrations due to blade interference.

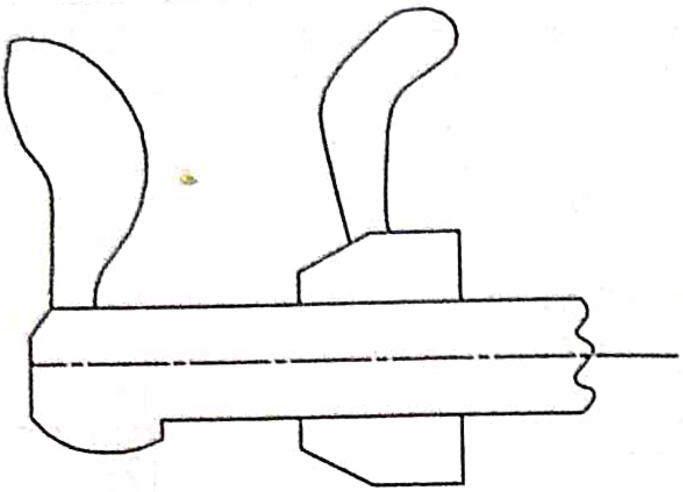


Figure 2.6: Contra rotating propeller

The aft propeller runs in the normal manner and the ford propeller is run by a short hollow shaft which encloses the solid shaft. The propeller efficiency is increased by 10% -12 %. It is high cost and suitable for highly loaded propellers and large single screw tankers. The increased surface area of the combined system reduces cavitations.

2.5.4 Vertical axis or Voith Schinder propeller

A series of vertical blades are set in a horizontal rotor and the rotor is flush with the hull and the blades project down, figure 2.7(a) - 2.7(f). The blades are connected to a control point in the centre.

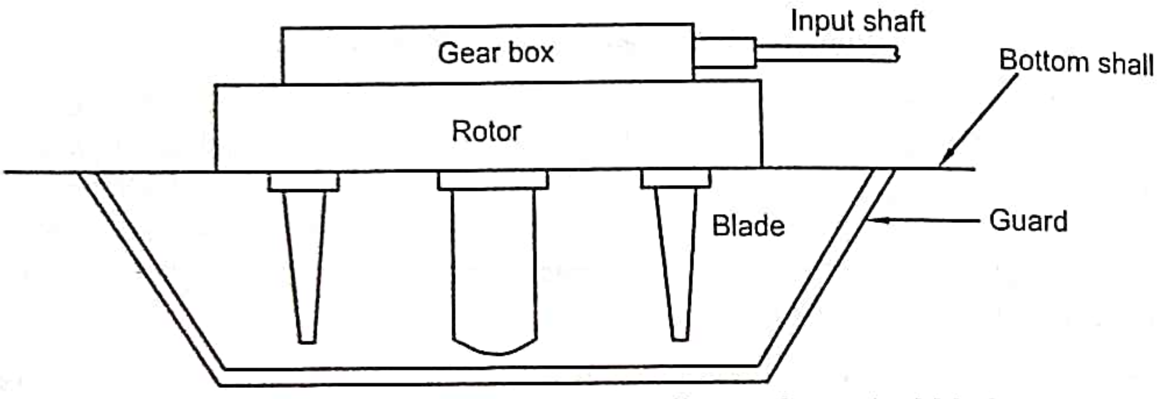


Figure 2.7(a): Voith Schinder propeller with vertical blades

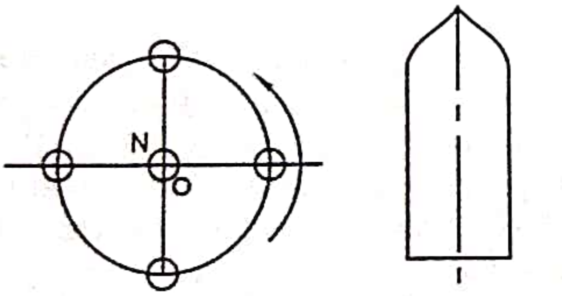


Figure 2.7b: Control point in the centre

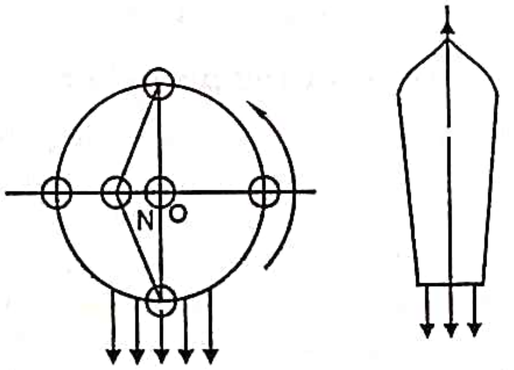


Figure 2.7(c): Control point at port