Chapter 31
Ship squat

What exactly is ship squat?

When a ship proceeds through water, she pushes water ahead of her. In order not to have a 'hole' in the water, this volume of water must return down the sides and under the bottom of the ship. The streamlines of return flow are speeded up under the ship. This causes a drop in pressure, resulting in the ship dropping vertically in the water.

As well as dropping vertically, the ship generally trims forward or aft. The overall decrease in the static underkeel clearance, forward or aft, is called ship squat. It is *not* the difference between the draughts when stationary and the draughts when the ship is moving ahead.

If the ship moves forward at too great a speed when she is in shallow water, say where this static even-keel underkeel clearance is 1.0 to 1.5 m, then grounding due to excessive squat could occur at the bow or at the stern.

For full-form ships such as supertankers or OBO vessels, grounding will occur generally at the *bow*. For fine-form vessels such as passenger liners or container ships the grounding will generally occur at the stern. This is assuming that they are on even keel when stationary. It must be *generally*, because in the last two decades, several ship types have tended to be shorter in LBP and wider in Breadth Moulded. This has led to reported groundings due to ship squat at the bilge strakes at or near to amidships when slight rolling motions have been present.

Why has ship squat become so important in the last thirty years? Ship squat has always existed on smaller and slower vessels when underway. These squats have only been a matter of centimetres and thus have been inconsequential.

However, from the mid-1960s to the late 1990s, ship size has steadily grown until we have supertankers of the order of 350 000 tonnes dwt and above. These supertankers have almost outgrown the ports they visit, resulting in small static even-keel underkeel clearances of 1.0 to 1.5 m. Alongside this development in ship size has been an increase in service speed on several ships, for example container ships, where speeds have gradually increased from 16 knots up to about 25 knots.

Ship design has seen tremendous changes in the 1980s and 1990s. In oil tanker design we have the *Jahre Viking* with a dwt of 564 739 tonnes and an LBP of 440 m. This is equivalent to the length of 9 football pitches. In 1997, the biggest container ship to date, namely the NYK *Antares* came into service. She has a dwt of 72 097 tonnes, a service speed of 23 kts., an LBP of 283.8 m; Br. Moulded of 40 m; Draft Moulded of 13 m; TEU of 5700, and a fuel consumption of 190 tonnes/day.

As the static underkeel clearances have decreased and as the service speeds have increased, ship squats have gradually increased. They can now be of the order of 1.50 to 1.75 m, which are of course by no means inconsequential.

To help focus the mind on the dangers of excessive squat one only has to recall the recent grounding of four vessels:

Herald of Free Enterprise	Ro-Ro vessel	06/03/87
QEII	Passenger liner	07/08/92
Sea Empress	Supertanker	15/02/96
Diamond Grace	260 000 t. dwt VLCC at Tokyo Harbour	02/07/97

In the United Kingdom, over the last 20 years the D.Tp. have shown their concern by issuing four 'M' notices concerning the problems of ship squat and accompanying problems in shallow water. These alert all mariners to the associated dangers.

Signs that a ship has entered shallow water conditions can be one or more of the following:

1. Wave-making increases, especially at the forward end of the ship.
2. Ship becomes more sluggish to manoeuvre. A pilot's quote, 'almost like being in porridge'.
3. Draught indicators on the bridge or echo-sounders will indicate changes in the end draughts.
4. Propeller rpm indicator will show a decrease. If the ship is in 'open water' conditions, i.e. without breadth restrictions, this decrease may be up to 15 per cent of the service rpm in deep water. If the ship is in a confined channel, this decrease in rpm can be up to 20 per cent of the service rpm.
5. There will be a drop in speed. If the ship is in open water conditions this decrease may be up to 30 per cent. If the ship is in a confined channel such as a river or a canal then this decrease can be up to 60 per cent.
6. The ship may start to vibrate suddenly. This is because of the entrained water effects causing the natural hull frequency to become resonant with another frequency associated with the vessel.

7. Any rolling, pitching and heaving motions will all be reduced as the ship moves from deep water to shallow water conditions. This is because of the cushioning effects produced by the narrow layer of water under the bottom shell of the vessel.
8. The appearance of mud could suddenly show in the water around the ship's hull say in the event of passing over a raised shelf or a submerged wreck.
9. Turning circle diameter (TCD) increases. TCD in shallow water could increase 100 per cent.
10. Stopping distances and stopping times increase, compared to when a vessel is in deep waters.

What are the factors governing ship squat?

The main factor is ship speed V_k. Squat varies approximately with the speed squared. In other words, we can take as an example that if we halve the speed we quarter the squat. In this context, speed V_k is the ship's speed relative to the water; in other words, effect of current/tide speed with or against the ship must be taken into account.

Another important factor is the block coefficient C_b. Squat varies directly with C_b. Oil tankers will therefore have comparatively more squat than passenger liners.

The blockage factor 'S' is another factor to consider. This is the immersed cross-section of the ship's midship section divided by the cross-section of water within the canal or river. If the ship is in open water the width of influence of water can be calculated. This ranges from about 8.25b for supertankers, to about 9.50b for general cargo ships, to about 11.75 ship-breadths for container ships.

The presence of another ship in a narrow river will also affect squat, so much so, that squats can *double in value* as they pass/cross the other vessel.

Formulae have been developed that will be satisfactory for estimating maximum ship squats for vessels operating in confined channels and in open water conditions. These formulae are the results of analysing about 600 results some measured on ships and some on ship models. Some of the emperical formulae developed are as follows:

Let

b = breadth of ship.

B = breadth of river or canal.

H = depth of water.

T = ship's even-keel static draft.

C_b = block co-efficient.

V_k = ship speed relative to the water or current.

CSA = Cross Sectional Area. (See Fig. 31.3.)

Let

$$S = \text{blockage factor} = \text{CSA of ship/CSA of river or canal.}$$

If ship is in open water conditions, then the formula for B becomes

$$B = \{7.7 + 20(1 - C_B)^2\}.\ b, \text{ known as the 'width of influence'.}$$

$$\textit{Blockage factor} = S = \frac{b \times T}{B \times H}$$

$$\textit{Maximum squat} = \delta_{max}$$

$$= \frac{C_B \times S^{0.81} \times V_k^{2.08}}{20} \text{ metres, for } \textit{open water} \text{ and } \textit{confined channels}$$

Two short-cut formulae relative to the previous equation are:

$$\textit{Maximum squat} = \frac{C_b \times V_k^2}{100} \text{ metres for } \textit{open water} \text{ conditions } \textit{only},$$

with H/T of 1.1 *to* 1.4.

$$\textit{Maximum squat} = \frac{C_b \times V_k^2}{50} \text{ metres for } \textit{confined channels},$$

where $S = 0.100$ *to* 0.265.

A worked example, showing how to predict maximum squat and how to determine the remaining underkeel clearance is shown at the end of this chapter. It shows the use of the more detailed formula and then compares the answer with the short-cut method.

These formulae have produced several graphs of maximum squat against ship's speed V_k. One example of this in Figure 31.2, for a 250 000 t. dwt supertanker. Another example is in Figure 31.3, for a container vessel having shallow water speeds up to 18 knots.

Figure 31.4 shows the maximum squats for merchant ships having C_b values from 0.500 up to 0.900, in open water and in confined channels. Three items of information are thus needed to use this diagram. First, an idea of the ship's C_b value, secondly the speed V_k and thirdly to decide if the ship is in open water or in confined river/canal conditions. A quick graphical prediction of the maximum squat can then be made.

In conclusion, it can be stated that if we can predict the maximum ship squat for a given situation then the following advantages can be gained:

1. The ship operator will know which speed to reduce to in order to ensure the safety of his/her vessel. This could save the cost of a very large repair bill. It has been reported in the technical press that the repair bill for the *QEII* was *$13 million*, plus an estimation for lost passenger booking of *$50 million*!!

   In Lloyd's Lists, the repair bill for the *Sea Empress* had been estimated to be in the region of *$28 million*. In May 1997, the repairs to the *Sea*

Empress were completed at Harland & Wolff Ltd of Belfast, for a reported cost of *£20 million*. Rate of exchange in May 1997 was the order of £1 = \$1.55. She was then renamed the *Sea Spirit*.

2. The ship officers could load the ship up an extra few centimetres (except of course where load-line limits would be exceeded). If a 100 000 tonne dwt tanker is loaded by an extra 30 cm or an SD14 general cargo ship is loaded by an extra 20 cm, the effect is an extra 3 per cent onto their dwt. This gives these ships extra earning capacity.
3. If the ship grounds due to excessive squatting in shallow water, then apart from the large repair bill, there is the time the ship is 'out of service'. Being 'out of service' is indeed very costly because loss of earnings can be as high as *£100 000* per *day*.
4. When a vessel goes aground their is always a possibility of leakage of oil resulting in compensation claims for oil pollution and fees for clean-up operations following the incident. These costs eventually may have to be paid for by the shipowner.

These last four paragraphs illustrate very clearly that not knowing about ship squat can prove to be very costly indeed. Remember, in a marine court hearing, ignorance is not acceptable as a legitimate excuse!!

Summarizing, it can be stated that because maximum ship squat can now be predicted, it has removed the 'grey area' surrounding the phenomenon. In the past ship pilots have used 'trial and error', 'rule of thumb' and years of experience to bring their vessels safely in and out of port.

Empirical formulae quoted in this study, modified and refined over a period of 25 years' research on the topic, give *firm guidelines*. By maintaining the ship's trading availability a shipowner's profit margins are not decreased. More important still, this research can help prevent loss of life as occurred with the *Herald of Free Enterprise* grounding.

It should be remembered that the quickest method for reducing the danger of grounding due to ship squat is to *reduce the ship's speed*. 'Prevention is better than cure' and *much cheaper*.

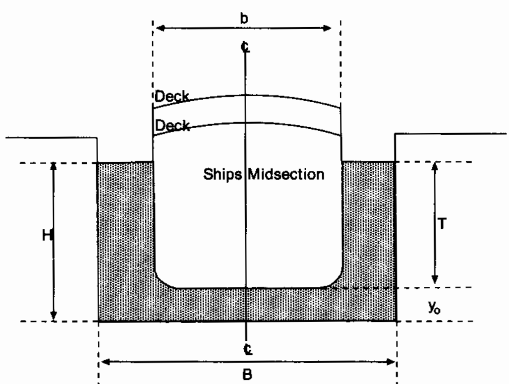


Fig. 31.1. Ship in a canal in static condition.

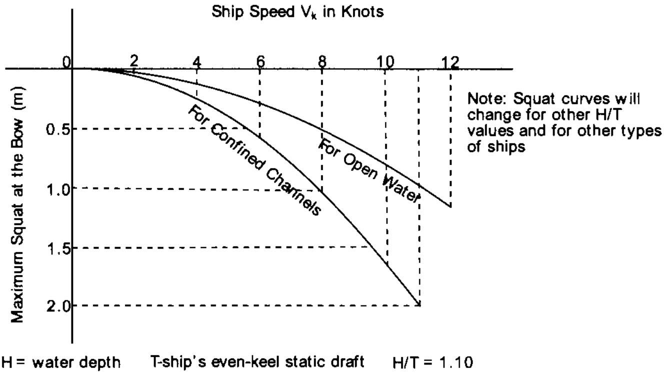


Fig. 31.2. Maximum squats against ship speed for 250 000 t. dwt supertanker.

A_S = cross-section of ship at amidships = b × T.

A_C = cross-section of canal = B × H.

$$\text{Blockage factor} = S = \frac{A_S}{A_C} = \frac{b \times T}{B \times H}.$$

y_o = static underkeel clearance.

$\frac{H}{T}$ range is 1.10 to 1.40.

Blockage factor range is 0.100 to 0.265.

$$\text{Width of influence} = F_B = \frac{\text{Equivalent 'B'}}{b} \text{ in open water.}$$

V_k = speed of ship relative to the water, in knots.

$A_w = A_c - A_S$

$'B' = 7.7 + 20(1 - C_B)^2$ ship breadths

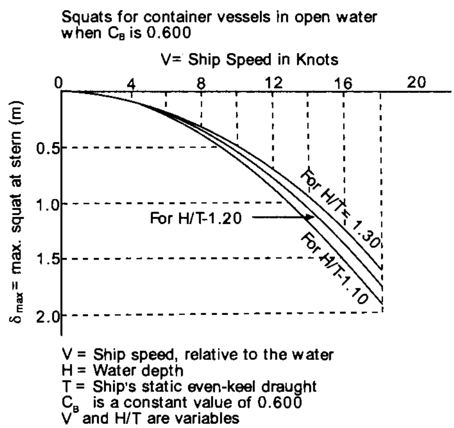
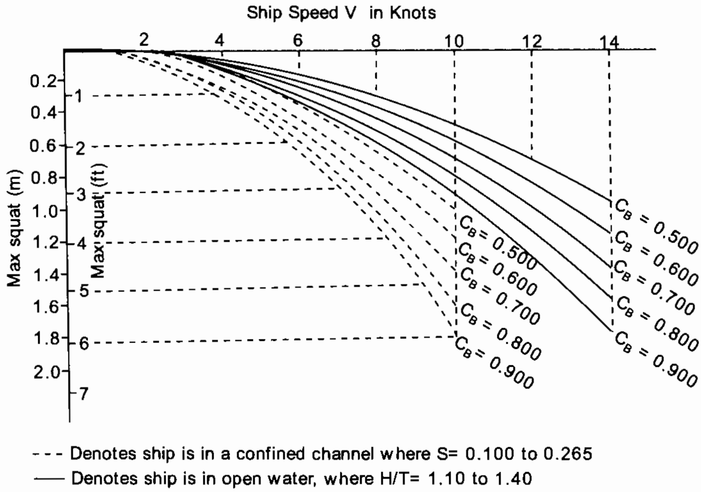


Fig. 31.3



Ship type	*Typical C_B, fully loaded*	*Ship type*	*Typical C_B, fully loaded*
ULCC	0.850	General cargo	0.700
Supertanker	0.825	Passenger liner	0.625
Oil tanker	0.800	Container ship	0.575
Bulk carrier	0.750	Coastal tug	0.500

Fig. 31.4. Maximum ship squats in confined channels and in open water conditions.

Worked example – ship squat for a supertanker

Question:
A supertanker operating in open water conditions is proceeding at a speed of 11 knots. Her $C_B = 0.830$, static even-keel draft = 13.5 m with a static underkeel clearance of 2.5 m. Her breadth moulded is 55 m with LBP of 320 m.

Calculate the maximum squat for this vessel at the given speed via *two* methods, and her remaining ukc (underkeel clearance) at V_k of 11 kts.

Answer:

$$\text{Width of influence} = \{7.7 + 20[1 - C_B]^2\} \times b = \text{'B'}$$

$$\therefore\ \text{'B'} = \{7.7 + 20[1 - 0.830]^2\} \times 55$$

$$\therefore\ \underline{\text{'B'} = 455\text{ m}},$$

i.e. artificial boundaries in open water or wide rivers

$$\text{Blockage factor, } S = \frac{b \times T}{\text{'B'} \times H} = \frac{55 \times 13.5}{455 \times \underbrace{[13.5 + 2.5]}_{\text{(water depth)}}} = \underline{0.102}$$

Method 1:

$$\text{Maximum squat} = \frac{C_B \times S^{0.81} \times V_k^{2.08}}{20} = \delta_{max}$$

$$\therefore\ \delta_{max} = 0.830 \times 0.102^{0.81} \times 11^{2.08} \times \frac{1}{20}$$

$$\therefore\ \underline{\delta_{max} = 0.96\,\text{m}},$$

at the bow, because $C_B > 0.700$.

Method 2:

Simplified approx. formula

$$\delta_{max} = \frac{C_B \times V_k^2}{100}\ \text{metres}$$

$$\therefore\ \delta_{max} = \frac{0.830 \times 11^2}{100} = 1.00\,\text{m};$$

i.e. slightly above previous answer, so overpredicting on the *safe side*.

$$\text{Average } \delta_{max} = \frac{0.96 + 100}{2} = 0.98\,\text{m} \quad y_o = 2.50\,\text{m}$$

Hence, remaining underkeel clearance at bow $= y_o - \delta_{max} = y_2$.

$$\therefore\ y_2 = 2.500 - 0.98 = \underline{1.52\,\text{m}}\ @\ V_k \text{ of } 11\,\text{kts}.$$

Exercise 31

1 A container ship is operating in open water river conditions at a forward speed of 12.07 kts. Her C_B is 0.572 with a static even-keel draft of 13 m. Breadth moulded is 32.25 m. If the depth of water is 14.5 m; calculate the following:
   (a) Width of influence for this wide river.
   (b) Blockage factor.
   (c) Maximum squat, stating with reasoning where it occurs.
   (d) Dynamical underkeel clearance corresponding to this maximum squat.

2 A vessel has the following particulars:
   Br.Mld is 50 m. Depth of water in river is 15.50 m. C_B is 0.817. Width of water in river is 350 m. Static even-keel draft is 13.75 m.
   (a) Prove this ship is operating in a 'confined channel' situation.
   (b) Draw a graph of maximum squat against ship speed for a range of speeds up to 10 kts.
   (c) The pilot decides that the dynamical underkeel clearance is not to be less than 1.00 m.
   Determine graphically and mathematically the maximum speed of transit that this pilot must have in order to adhere to this prerequisite.

3 A 75 000 tonne dwt oil tanker has the following particulars:
   Br.Mld is 37.25 m. Static even-keel draft is 13.5 m. C_B is 0.800. Depth of water is 14.85 m. Width of river is 186 m. Calculate the forward speed at which, due to ship squat, this vessel would just go aground at the bow.

Chapter 32
Heel due to turning

When a body moves in a circular path there is an acceleration towards the centre equal to v^2/r where v represents the velocity of the body and r represents the radius of the circular path. The force required to produce this acceleration, called a 'Centripetal' force, is equal to $\frac{Mv^2}{r}$, where M is the mass of the body.

In the case of a ship turning in a circle, the centripetal force is produced by the water acting on the side of the ship away from the centre of the turn. The force is considered to act at the centre of lateral resistance which, in this case, is the centroid of the underwater area of the ship's side away from the centre of the turn. The centroid of this area is considered to be at the level of the centre of buoyancy. For equilibrium there must be an equal and opposite force, called the 'Centrifugal' force, and this force is considered to act at the centre of mass (G).

When a ship's rudder is put over to port, the forces on the rudder itself will cause the ship to develop a small angle of heel initially to port, say α_1°.

However, the underwater form of the ship and centrifugal force on it cause the ship to heel to starboard, say α_2°.

In this situation α_2° is always greater than α_1°. Consequently for port rudder helm, the final angle of heel due to turning will be to starboard and vice versa.

It can be seen from Figure 32.1 that these two forces produce a couple which tends to heel the ship away from the centre of the turn. i.e.

$$\text{Heeling couple} = \frac{Mv^2}{r} \times B_1Z$$

Equilibrium is produced by a righting couple equal to $W \times GZ$, where W is equal to the weight of the ship, the weight being a unit of force, i.e. $W = Mg$.

$$\therefore M \cdot g \times GZ = \frac{M \cdot v^2}{r} \times B_1Z$$

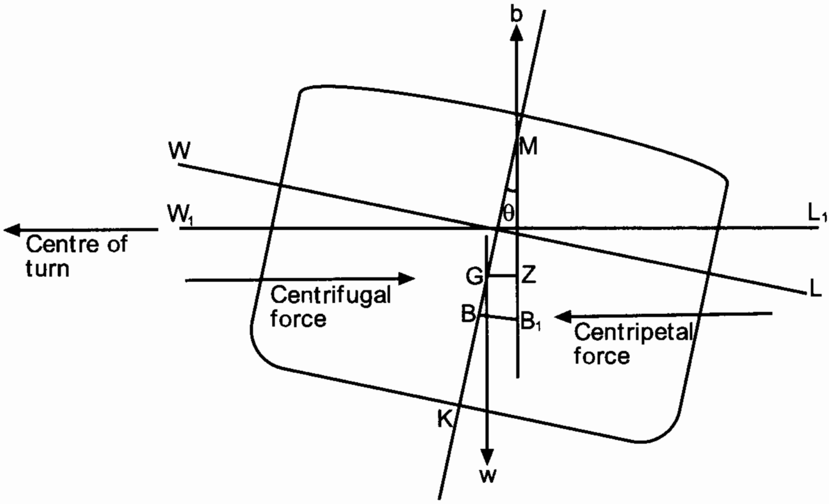


Fig. 32.1

or

$$GZ = \frac{v^2}{g \cdot r} \times B_1Z$$

but at a small angle

$$GZ = GM \cdot \sin\theta$$

and

$$B_1Z = BG \cdot \cos\theta$$

$$\therefore\ GM \sin\theta = \frac{v^2}{g \cdot r} BG \cdot \cos\theta$$

and

$$\tan\theta = \frac{v^2 \times BG}{g \cdot r \cdot GM}$$

Example

A ship turns to port in a circle of radius 100 m at a speed of 15 knots. The GM is 0.67 m and BG is 1 m. If $g = 981\ \text{cm/sec}^2$ and 1 knot is equal to 1852 km/hour, find the heel due to turning.

$$\text{Ship speed in m/sec} = 15 \times \frac{1852}{3600}$$

$$v = 7.72\ \text{m/sec}$$

$$\tan\theta = \frac{v^2 \times BG}{g \cdot r \cdot GM}$$

$$= \frac{7.72^2 \times 1.0}{9.81 \times 100 \times 0.67}$$

$$\tan\theta = 0.0907$$

Ans. Heel $= 5° \ 11'$ to starboard, due to Contrifugal forces only

In practice, this angle of heel will be slightly smaller. Forces on the rudder will have produced an angle of heel, say $1° \ 17'$ to port. Consequently the overall angle of heel due to turning will be:

$$\text{Heel} = 5° \ 11' - 1° \ 17' = 3° \ 54' \text{ or } 3.9° \text{ to starboard}$$

Exercise 32

1 A ship's speed is 12 knots. The helm is put hard over and the ship turns in a circle of radius 488 m. GM = 0.3 m and BG = 3 m. Assuming that 1 knot is equal to 1852 km/hour, find the heel due to turning.

2 A ship steaming at 10 knots turns in a circle of radius 366 m. GM = 0.24 m. BM = 3.7 m. Calculate the heel produced.

3 A ship turns in a circle of radius 100 m at a speed of 15 knots. BG = 1 m. Find the heel if the GM = 0.6 m.

4 A ship with a transverse metacentric height of 0.40 m has a speed of 21 kts. The centre of gravity is 6.2 m above keel whilst the centre of lateral resistance is 4.0 m above keel. The rudder is put hard over to port and the vessel turns in a circle of 550 m radius.

Considering only the centrifugal forces involved, calculate the angle of heel as this ship turns at the given speed.

Chapter 33
Unresisted rolling in still water

A ship will not normally roll in still water but if a study be made of such rolling some important conclusions may be reached. For this study it is assumed that the amplitude of the roll is small and that the ship has positive initial metacentric height. Under the conditions rolling is considered to be simple harmonic motion so it will be necessary to consider briefly the principle of such motion.

Let XOY in Figure 33.1 be a diameter of the circle whose radius is 'r' and let OA be a radius vector which rotates about O from position OY at a constant angular velocity of 'w' radians per second. Let P be the projection of the point A on to the diameter XOY. Then, as the radius vector rotates, the point P will oscillate backwards and forwards between Y and X. The motion of the point P is called 'Simple Harmonic'.

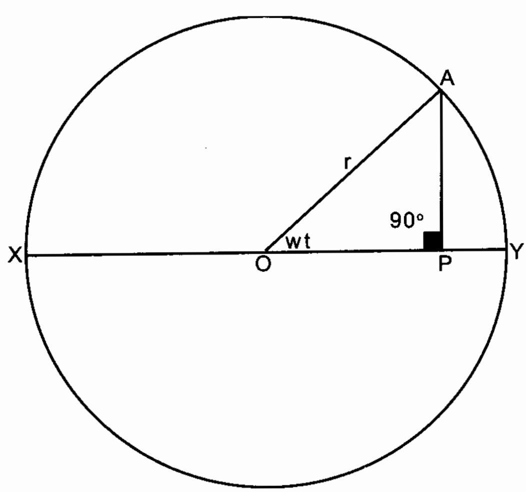


Fig. 33.1

Let the radius vector rotate from OY to OA in 't' seconds, then angle AOY is equal to 'wt'. Let the time taken for the radius vector to rotate through one complete revolution (2π radians) be equal to 'T' seconds, then:

$$2\pi = wT$$

or

$$T = 2\pi/w$$

Let

$$OP = x$$

then

$$x = r\cos wt$$

$$\frac{dx}{dt} = -rw\sin wt$$

$$\frac{d^2x}{dt^2} = -rw^2\cos wt$$

but

$$r\cos wt = x$$

$$\therefore \frac{d^2x}{dt^2} = -w^2x$$

or

$$\frac{d^2x}{dt^2} + w^2x = 0$$

The latter equation is the type of differential equation for simple harmonic motion and since $T = 2\pi/w$ and 'w' is the square root of the coefficient of x in the above equation, then

$$T = \frac{2\pi}{\sqrt{\text{coeff. of } x}}$$

When a ship rolls, the axis about which the oscillation takes place cannot be accurately determined but it would appear to be near to the longitudinal axis through the ship's centre of gravity. Hence the ship rotates or rolls about her 'G'.

The mass moment of inertia (I) of the ship about this axis is given by:

$$I = M \cdot K^2$$

where

M = The ship's mass, and

K = The radius of gyration about this axis.

But

$$M = \frac{W}{g}$$

where

$$W = \text{the ship's weight, and}$$
$$g = \text{the acceleration due to gravity.}$$

$$\therefore I = \frac{W}{g} K^2$$

When a ship is inclined to a small angle (θ) the righting moment is given by:

$$\text{Righting moment} = W \times GZ$$

where

$$W = \text{the ship's Weight, and}$$
$$GZ = \text{the righting lever.}$$

But

$$GZ = GM \cdot \sin\theta$$

$$\therefore \text{Righting moment} = W \times GM \times \sin\theta$$

And since θ is a small angle, then:

$$\text{Righting moment} = W \times GM \times \theta$$

$$\text{The angular acceleration} = \frac{d^2\theta}{dt^2}$$

$$\therefore I \times \frac{d^2\theta}{dt^2} = -W \times GZ$$

or

$$\frac{W}{g} \cdot K^2 \times \frac{d^2\theta}{dt^2} = -W \times GM \times \theta$$

$$\frac{W}{g} \cdot K^2 \times \frac{d^2\theta}{dt^2} + W \times GM \times \theta = 0$$

$$\frac{d^2\theta}{dt^2} + \frac{g \cdot GM \cdot \theta}{K^2} = 0$$

This is the equation for a simple harmonic motion having a period 'T' given by the equation:

$$T = \frac{2\pi}{\sqrt{\text{Coeff. of } \theta}}$$

or

$$T = \frac{2\pi K}{\sqrt{g \cdot GM}} = \frac{2\cancel{\pi}}{\sqrt{\cancel{g}}} \times \frac{K}{\sqrt{GM}} = \frac{2K}{\sqrt{GM}} \text{ approx.}$$

From the above it can be seen that:

1 The time period of roll is completely independent of the actual amplitude of the roll so long as it is a small angle.
2 The time period of roll varies directly as K, the radius of gyration. Hence if the radius of gyration is increased, then the time period is also increased. K may be increased by moving weights away from the axis of oscillation. Average K value is about 0.35 × Br.Mld.
3 The time period of roll varies inversely as the square root of the initial metacentric height. Therefore ships with a large GM will have a short period and those with a small GM will have a long period.
4 The time period of roll will change when weights are loaded, discharged, or shifted within a ship, as this usually affects both the radius of gyration and the initial metacentric height.

Example 1

Find the still water period of roll for a ship when the radius of gyration is 6 m and the metacentric height is 0.5 m.

$$T = \frac{2\pi K}{\sqrt{g \cdot GM}} \qquad = \frac{2K}{\sqrt{GM_T}} \text{ approx.}$$

$$T = \frac{2\pi K}{\sqrt{9.81 \times 0.5}} = \frac{2 \times 6}{\sqrt{0.5}} \text{ approx.}$$

$$= 16.97\text{ s.} \qquad \text{Average} = 17\text{ s.}$$

(99.71 per cent correct giving only 0.29 per cent error!!)

Ans. $\underline{T = 17.02\text{ s}}$

Note. In the S.I. system of units the value of g to be used in problems is 9.81 m per second per second, unless another specific value is given.

Example 2

A ship of 10 000 tonnes displacement has GM = 0.5 m. The period of roll in still water is 20 seconds. Find the new period of roll if a mass of 50 tonnes is discharged from a position 14 m above the centre of gravity. Assume

$$g = 9.81\text{ m/sec}^2$$

$$W_2 = W_0 - w = 10\,000 - 50 = 9950 \text{ tonnes}$$

$$T = \frac{2\pi K}{\sqrt{g \cdot GM}} \qquad GG_1 = \frac{w \times d}{W_2}$$

$$20 = \frac{2\pi K}{\sqrt{9.81 \times 0.5}} \qquad = \frac{50 \times 14}{9950}$$

$$400 = \frac{4 \cdot \pi^2 \cdot K^2}{9.81 \times 0.5} \qquad GG_1 = 0.07\text{ m}$$

$$GM = 0.50\text{ m}$$

$$\text{New } GM = 0.57\text{ m}$$

or

$$K^2 = \frac{400 \times 9.81 \times 0.5}{4 \times \pi^2}$$

$$= 49.69$$

$$\therefore K = 7.05$$

$$I \text{ (Originally)} = M \cdot K^2$$

$$I_o = 10\,000 \times 49.69$$

$$I_o = 496\,900 \text{ tonnes·m}^2$$

$$I \text{ of discharged mass about } G = 50 \times 14^2$$

$$= 9800 \text{ tonnes·m}^2$$

$$\text{New I of ship about the original C of G} = \text{Original I} - \text{I of discharged mass}$$

$$= 496\,900 - 9800$$

$$= 487\,100 \text{ tonnes·m}^2$$

By the Theorem of parallel axes:
Let

$$I_2 = \frac{\text{New I of ship about}}{\text{the new C of G}} = \frac{\text{New I of ship about}}{\text{the original C of G}} - W \times GG_1^2$$

$$I_2 = 487\,100 - 9950 \times 0.07^2$$

$$I_2 = 487\,100 - 49$$

$$I_2 = 487\,051 \text{ tonnes·m}^2$$

$$I_2 = M_2 \cdot K_2^2$$

$$\therefore \text{New } K^2 = \frac{I_2}{M_2}$$

$$\therefore K_2^2 = \frac{487\,051}{9950}$$

Let

$$K_2 = \text{New K} = \sqrt{\frac{487\,051}{9950}}$$

$$K_2 = 7\text{ m}$$

Let

$$T_2 = \text{New T} = \frac{2\pi K_2}{\sqrt{g \cdot GM_2}}$$

$$T_2 = \frac{2\pi 7}{\sqrt{9.81 \times 0.57}}$$

Ans. $\underline{T_2 = 18.6\text{ s}}$

Procedure steps for Example 2

1 Calculate the new displacement in tonnes (W_2).
2 Estimate the original radius of gyration (K).
3 Evaluate the new displacement and new GM (W_2 and GM_2).
4 Calculate the new mass moment of inertia (I_2).
5 Calculate the new radius of gyration (K_2).
6 Finally evaluate the new period of roll (T_2).

For 'stiff ships' the period of roll could be as low as 8 seconds due to a large GM. For 'tender ships' the period of roll will be, say, 30 to 35 seconds, due to a small GM. A good comfortable period of roll for those on board ship will be 20 to 25 seconds.

Exercise 33

1 Find the still water period of roll for a ship when the radius of gyration is 5 m and the initial metacentric height is 0.25 m.
2 A ship of 5000 tonnes displacement has GM = 0.5 m. The still water period of roll is 20 seconds. Find the new period of roll when a mass of 100 tonnes is discharged from a position 14 m above the centre of gravity.
3 A ship of 9900 tonnes displacement has GM = 1 m, and a still water rolling period of 15 seconds. Calculate the new rolling period when a mass of 100 tonnes is loaded at a position 10 m above the ship's centre of gravity.
4 A vessel has the following particulars:
Displacement is 9000 tonnes, natural rolling period is T_R of 15 seconds, GM is 1.20 m. Determine the new natural rolling period after the following changes in loading have taken place:

2000 tonnes added at 4.0 m above ship's VCG.
500 tonnes discharged at 3.0 m below ship's VCG.

Assume that KM remains at the same value before and after changes of loading have been completed. Discuss if this final condition results in a 'stiff ship' or a 'tender ship'.