CHAPTER 30

STABILITY OF THE INTACT SHIP

CONTENTS

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3001. Determination of Stability Characteristics

a. Two things determine the stability characteristics of a ship:

(1) The geometry of the underwater form of the hull.

(2) The loading of the ship.

Of these, the former is determined by the Naval Architect and cannot be altered by the operator. This information is provided by means of hydrostatic data. The latter is planned by the Naval Architect, however its control is the predominate concern of the operator both on a daily and longer term basis.

b. To fully understand the implications of the operator's actions on the stability of the ship it is first important to appreciate the mechanics and principles of ship stability.

3002. Operating Forces

When a ship is floating in water there are three forces operating on the structure.

a. The total weight of all the constituent parts of the ship and contents, which exerts a force vertically downwards through the centre of gravity.

b. The buoyancy force created by the underwater form of the hull displacing water, which exerts a force vertically upwards through the centre of buoyancy.

c. Other forces which cause the ship to move as a result of their action, such as propulsive forces, resistance, wind, waves and changes in loading.

The primary concern of ship stability is to ensure that the first two forces act together in such a way as to provide a stable platform that can cope with the last group of forces without capsize.

3003. Buoyancy

Archimedes' Principle states that:

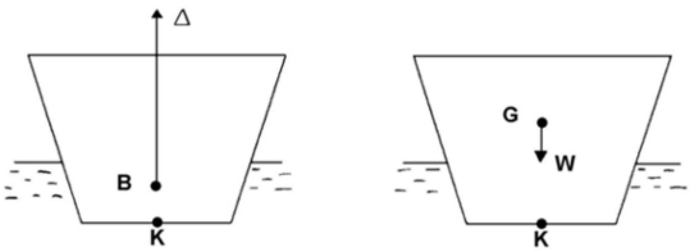
A body fully or partially immersed in a fluid will experience an upthrust equal to the weight of fluid displaced.

This upthrust is called the buoyancy force. In order to calculate the magnitude of this force the Volume Displacement of the ship (∇) and the density of the sea (ρ) must be multiplied to give a value for the Mass Displacement of the ship (Δ).

$$\Delta = \nabla\rho$$

The value of Δ is most easily found from the hydrostatic data for the ship where it is given for various mean draughts (T) in standard seawater of density 1.025 tonnes/m³. The buoyancy force, which is equal to Δ, will act vertically up through the centre of buoyancy (B) that is the centroid of the underwater volume of the hull. Again its position is provided in the ships hydrostatic data for different values of T and expressed as a distance (KB) above the ships keel (K). The buoyant volume of a ship is the volume of the entire watertight part of the hull. That part of the buoyant volume above the waterline is called the **reserve of buoyancy**.

Fig 30-1. Buoyancy and Weight



3004. Weight

The weight (W) of a ship is difficult to measure due to the size of the structure. It is possible to calculate this during the design stage by summing all the individual components but this is impractical for the operator. Instead, finding the total weight relies on the condition of equilibrium the ship adopts when it is freely floating. The weight of the ship acts vertically down through the centre of gravity (G) that again is difficult to find as it depends on the position and weight of all the individual components of the ship. The position of G is found by conducting an Inclining Experiment, the results of which are provided to the operator in the form of the Stability Statement whereby its vertical distance (KG) above the keel (K) is stated for various standard loading conditions. Alterations to these standard conditions to find the position of G for specific loading conditions are relatively simple.

3005. Standard Loading Conditions

Generally ships have three standard loading conditions:

a. **Deep Condition**. The ship is in all respects complete; fully complemented, ammunitioned, fuelled, stored and provisioned.

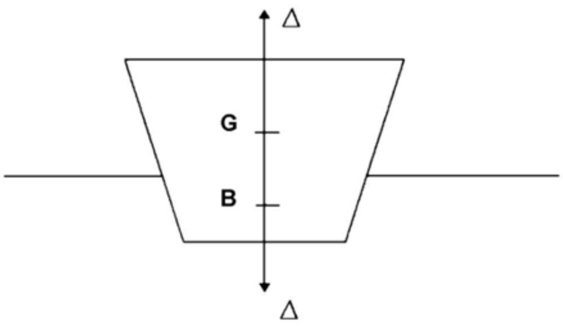
b. **Light Seagoing Condition**. The lightest condition of a ship at sea including any liquid loading restrictions required to meet the minimum stability criteria.

c. **Light Harbour Condition**. The lightest condition of a ship in harbour including any liquid loading restrictions required to meet the minimum stability criteria.

3006. Equilibrium

Under normal circumstances a surface ship would be in a condition whereby it will sink until such time as it reaches a draught great enough to provide an underwater volume displacing enough weight of water to produce a buoyancy force equal to the weight of the ship. Generally this is expressed by describing both the weight of the ship and the buoyancy force produced as being equal to the **Mass Displacement** of the ship (Δ). Although mass displacement is measured in tonnes it is treated as a force neglecting the gravitational constant in all further expressions.

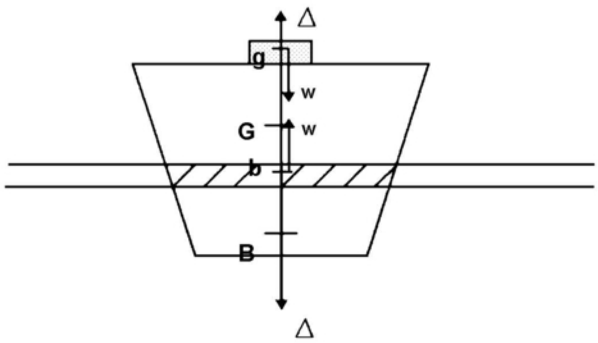
Fig 30-2. Equilibrium



3007. Addition of Weight

The Centre of Flotation (CF) is the centroid of the waterplane at which the ship is currently floating; the ship will trim and heel about this point, which is generally on the centreline and abaft midships. If a weight (w) is added to the ship so that its centre of gravity (g) is above CF, so that there is no heeling or trimming moment, the ship will sink until the increase in draught produces an increase in volume displacement, producing and additional buoyancy force equal to the added weight. An increase of draught in this way, where there is no heeling or trimming moment induced, is called **Parallel Sinkage(s).**

Fig 30-3. Addition of Weight



It can be seen from Fig 30-3 that the buoyancy force created by the additional layer of displaced volume acts through a point b and must be equal to the added weight, w.

3008. Tonnes Per Centimetre Immersion (TPC)

a. For reasonably small additions of weight warships can be assumed to be wall-sided (having vertical side plating). This assumption allows the calculation of parallel sinkage produced by a known addition of weight to be greatly simplified. The weight (in tonnes) required to sink the ship by 1 cm can be found and plotted against the original draught of the ship, this figure is known as the **Tonnes Per Centimetre Immersion (TPC),** and is presented in the ships hydrostatic data for values of mean draught.

b. Given that the TPC for the original draught of the ship is known, the parallel sinkage (s) caused by any addition of weight (W) can be calculated such that:

$$S = \frac{w}{TPC} \text{ (cm)}$$

Particular care should be taken using this expression for large additions of weight, especially where the value for TPC changes considerably in the area of the parallel sinkage. In this case it is prudent to calculate the parallel sinkage using both the TPC at the original draught and the TPC at the new draught and averaging them.

3009. Movement of Centres of Buoyancy and Gravity due to Changes in Loading

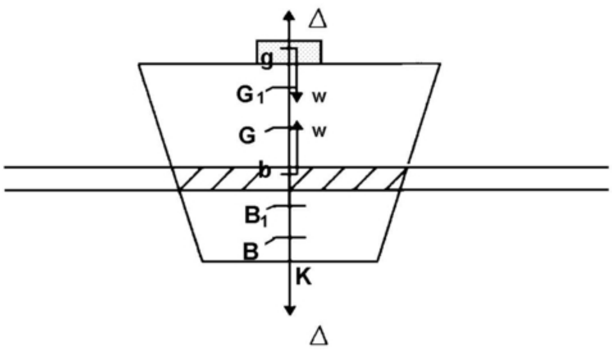
An alteration to the loading of the ship will effect the positions of B and G:

a. B will always move upwards due to the addition of weight, ie towards the centroid of the new slice of displaced volume (b).

b. G will always move towards the centre of gravity of the added weight (g). The opposite is true if the weight is removed.

The new positions of the centre of buoyancy (B_1) and gravity (G_1) can be found by taking 1^{st} moments, multiplying the force by its lever arm, about the keel and dividing by the total mass displacement.

Fig 30-4. Movement of Centres of Buoyance (B) and Gravity (G)



$$KB_1 = \frac{KB.\Delta +. Kb.w}{\Delta + w}$$

where: $Kb = T + 0.5 \times s$

T = original draught

s = parallel sinkage

$$KG_1 = \frac{KG.\Delta + Kg.w}{\Delta + w}$$

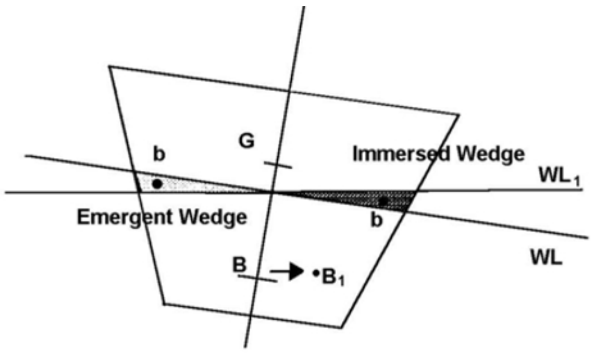
3010. Reserve of Buoyancy

When a surface ship is floating some of its hull is normally above the surface of the sea. If a weight is added the ship will sink further into the sea so that Δ increases. Weight could continue to be added to the ship until such time as its uppermost watertight deck is underwater resulting in the ship sinking. The portion of the ships watertight hull above the waterline is known as the **Reserve of Buoyancy**, and is expressed as a proportion or percentage of the immersed volume. The reserve of buoyancy of a surface warship is of the order of 100% or more and therefore loss of ships by bodily sinking is very unusual.

3011. Transverse Stability

When a ship heels over due to an internal movement of weight or as a reaction to an external force there is no increase in the weight of the ship and hence no increase in Δ. So long as none of the weights making up the total weight of the ship move, ie the ship is secured for sea, G will not move, irrespective of the angle of heel. The weight of the ship, equal to Δ will continue to act vertically down through G. The position of B, however, depends on the shape of the underwater volume of the ship and will move as the ship heels over. As the ship heels over a wedge of additional buoyancy is formed on the lower side and a corresponding wedge emerges from the other side to keep the buoyancy force the same. These wedges have their own centroids and by taking moments it can be seen that the ships centre of buoyancy will move towards the Immersed Wedge (Fig 30-5).

Fig 30-5. Movement of Centre of Buoyancy (B)

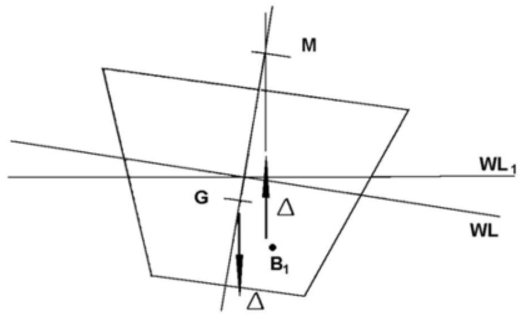


The buoyancy force (Δ) continues to act vertically upwards through the centre of buoyancy that has a new position B_1, but now buoyancy and weight forces are separated and under normal circumstances will attempt to return the ship to the upright position.

3012. Metacentre

The point at which the line of action of the buoyancy force intersects the original vertical centreline of the ship is known as the **Metacentre (M)**, as shown in Fig 30-6. The buoyancy force and the weight under these circumstances continue to be equal to the mass displacement of the ship, as no weight has been added, but now act as a moment couple that will try to bring the ship upright.

Fig 30-6. Metacentre (M)



It can therefore be seen that the ability of the ship to return itself to the upright position is dependant on this moment couple, formed by the movement of the centre of buoyancy, being positive. This moment couple will remain positive whilst the metacentre is above the centre of gravity. The position of M can be found from the ships hydrostatic data at various mean draughts, as a distance (KM) from the keel of the ship.

3013. Righting Moment

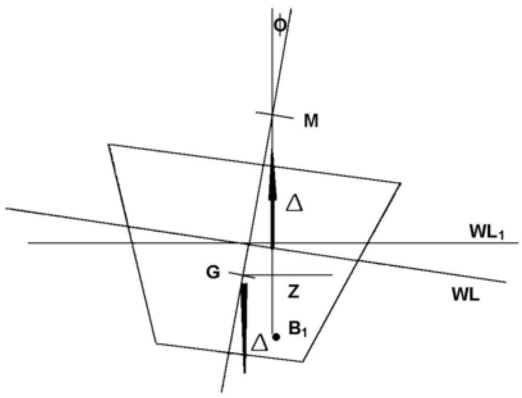
By taking moments about the keel (Fig 30-7) it can be seen that the moment acting to return the ship to the upright position is given by:

Righting Moment = GZ x Δ

now: $GZ = GM \sin\varphi$

so: Righting Moment = $\Delta GM\sin\varphi$

Fig 30-7. Righting Moment



The distance GM therefore provides a measurement of the stability of the ship. It is known as the **Metacentric Height.**

3014. Metacentric Height

a. By examination of the metacentric height and Fig 30-7 it can be seen that three states of stability exist.

(1) **Positive Stability.** If the metacentric height is positive the ship will be stable.

(2) **Neutral Stability.** If the metacentric height reduces to zero, ie G and M coincide then the ship becomes neutrally stable.

(3) **Negative Stability.** If the metacentric height is negative then the ship is negatively stable and will tend to heel to a greater angle.

The size of the metacentric height also indicates the amount of stability a ship possesses; a large positive metacentric height will provide a large righting lever and consequently the ship will be very stable. Conversely a small metacentric height will provide a small righting lever and the ship will be less stable. A ship with a large metacentric height is said to be **stiff** and one with a small metacentric height is known as **tender.**

b. The metacentric height of a ship depends on two things:

(1) The position of G.

(2) The position of M.

The position of G is found by adjusting the value for KG given in the Stability Statement for a standard loading condition, by using the equation at Para 3009 for movements of weights away from this standard condition. The complete method is provided at Para 3026. The position of M is dependant on the position of B as it moves with the angle of heel. The distance of M above B relies on the volume displacement of the ship and the second moment of area of the waterplane of the ship. Calculation of this second moment of area is time consuming and impractical for the operator requiring quick answers to concerns over the ships stability. It is enough to appreciate that the dominant factor in producing a high position for M and thus generally increasing GM is the breadth of the ship and is thus outside the control of the operator. In practice the position of M when the ship is in an upright condition is gained by reference to the ships hydrostatic data for the draught at which the ship is floating. The metacentric height can therefore be found as:

$$GM = KM - KG$$

3015. Stability at Small Angles of Heel

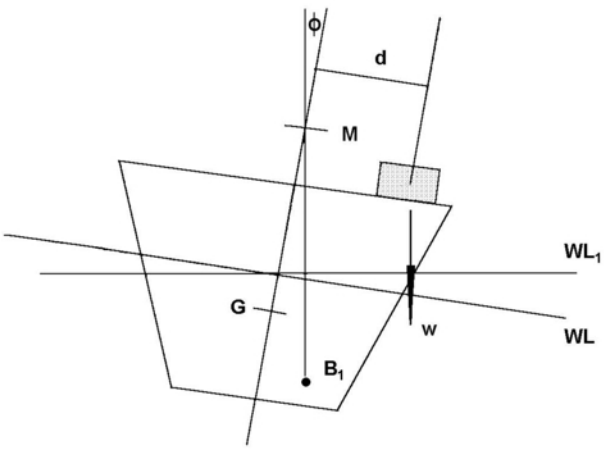
The movement of the centre of buoyancy as the ship heels over is dependent on the shape of the underwater form of the ship and this in turn determines the position of the metacentre and hence the magnitude of the metacentric height. The shape of the ships hull as it heels is not regular and so B cannot be generally expected to move in a regular pattern therefore the position of M will change with heel angle. However, the shape of a ship can be thought of as regular for angles up to 10°, therefore the position of M can be assumed to be fixed for angles of heel within this range. The metacentric height found for the ship in an upright position in Para 3014 sub para b can therefore be used for all angles of heel up to 10°.

3016. Finding the Angle of Heel for Small Movements of Weight

The heeling moment acting as a ship caused by the horizontal movement of a weight is given by:

Heeling Moment = wdcosφ

Fig 30-8. Angle of Heel for Small Movement of Weight



Therefore, to find the angle of heel the heeling and righting moments can be equated to give:

Heeling Moment = Righting Moment

wdcosφ = ΔGMsinφ

$$\text{So } \tan\varphi = \frac{wd}{\Delta\ GM}$$

This equation can now be solved by assuming that GM remains constant for angles of heel up to 10°.

3017. Free Surface Effects

a. Liquid in any compartment, anywhere in the ship, which does not entirely fill the compartment has an adverse effect on the stability of the ship. Such liquid is said to have free surface. As the ship heels, the centre of gravity of the liquid shifts to the low (inclined) side. The result of this can be viewed as either an increasing heeling moment, or a reduction in the righting lever. In practice we normally regard the effect as equivalent to raising the centre of gravity, which has the effect of reducing the metacentric height and hence the righting lever. It can be shown that for small angles of heel the reduction in GM is given by:

Loss of GM = $\frac{i\rho_l}{\nabla\rho_s}$

where:

I = the second moment of area of the liquid surface area about a principal axis parallel to the axis of rotation of the ship.

ρ_l = the density of the liquid concerned.

ρ_s = the density of the seawater.

∇ = the volume displacement of the ship.

The righting lever for the ship can now be assumed to be dependent on this reduced GM, often termed the GM_{fluid}, which is given by:

GM_{fluid} = GM - loss in GM

Calculation of the second moment of area for an irregular shape is time consuming. However many compartments in a ship are rectangular or close to being so and the second moment of area of a rectangle length a (longitudinally) and breadth b (transversely), is:

$I = ab^3/12$

b. This loss of initial stability is entirely dependent on the Second Moment of Area of the free surface, and in particular the breadth. The depth, volume or weight of liquid present plays no part in the formula. Also the loss of GM occurs irrespective of the position of the free surface in the ship. However the position of G is also affected by weight: low down the weight serves as ballast; high up is to topweight, and to port or starboard it is off-centre weight. It can be seen that the worst combination is of a free surfaced liquid high up in a ship causing loss of GM by topweight and free surface effect. This rise in the G can quickly result in a state of loll with the associated loss in stability and requires rapid and correct reactions to be taken to avoid putting the ship in danger of capsize. High free surface effects can easily be caused by water used in firefighting and boundary cooling, many ships have capsized because firefighting water was not pumped out, drained overboard, or drained down. The free surface can rapidly become more dangerous than the fire itself. If the free surface cannot be removed, every effort should be made to divide its breadth. The division need not even be completely watertight to be effective, and mess tables on edge can be most successful. Dividing the compartment into two units of equal breadth reduces the loss in GM by four (division by three would reduce loss by nine, and so on). Conversely, if a free surface area is doubled in breadth, the loss in GM becomes eight times as great. The complete method for assessing stability with a free surface effect is given at Para 3027.

3018. Stability at Larger Angles of Heel

Fundamentally the mechanics involved with stability at larger angles of heel are identical to those previously discussed with the exception that GM can no longer be assumed to remain constant. It was shown in Para 3013 that:

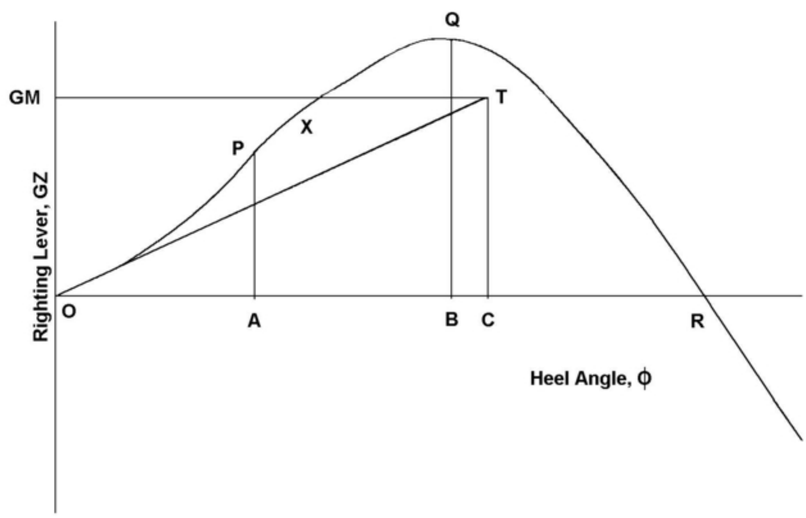
Righting Moment = ΔGZ

This equation still holds for all angles larger than 10° but now account must be taken of the changing underwater form of the hull, which will change the magnitude of GZ for different angles of heel; the metacentre can no longer be thought to be stationary. Determination of the magnitude of GZ involves complicated calculations far beyond the abilities of the average operator. To this end values of GZ are provided for the ship in the form of a **Curve of Statical Stability.**

3019. Curves of Statical Stability

Curves of Statical Stability are provided to the ship as part of the Stability Statement. Normally three curves are presented, one each for the standard loading conditions. The curve shows the value of the righting lever for angles of heel throughout the range of stability of the ship; the righting moment at any angle of heel can therefore be found by multiplying GZ by Δ. The GZ curve for a conventional ship in a normal condition will appear as shown in Fig 30-9.

Fig 30-9. Curve of Statical Stability



Several points and lines have been marked on this figure. They have the following significance:

a. At any angle of heel OA, the ship has a right moment of Δ x PA. It requires a steady inclining moment, such as wind pressure or an off centre weight, of this magnitude to hold her over at this angle.

b. At small angles of heel, the righting lever depends on the metacentric height. This is confirmed in the diagram by the coincidence of the tangent to the curve at the origin 0, and the curve for a few degrees of heel.

c. As the angle of heel increases (about say 10°), the curve shows positive curvature, ie the steepness of the curve increases. At the point X the curvature changes and the steepness decreases. The point of inflexion at X reflects the immersion of the edge of the main weatherdeck.

d. As the heel increases further, the curve becomes horizontal at the angle B of maximum lever Q.

e. Thereafter the curve descends, at first with increasing steepness, then more steadily. It crosses the base line at a point R called the point of vanishing stability, at which there is no righting lever, and beyond which a capsizing lever is set up. This point defines the range of stability of the ship for her particular condition of loading and the angle OR is generally known as the range.

f. Since the greatest righting moment that the ship can exert is Δ x QB, corresponding to the maximum lever QB, it follows that this is the greatest steady upsetting moment that the ship can resist. The angle of maximum righting lever, therefore is the greatest angle of steady heel the ship can take up without capsizing when inclined by a steady heeling moment.

Some of these points on the curve, particularly at higher angles of heel, are somewhat academic as the point at which non-watertight openings are immersed represents a more realistic range of stability for the ship. Generally the non-watertight openings of most concern are the engine downtakes and their angle of immersion will be marked on the GZ curve provided to the ship. Angles of heel past this angle will usually result in unrestricted flooding of large compartments of the ship therefore seriously compromising the stability of the ship.

3020. Adjustment of the GZ Curve for Loading Conditions

It should be appreciated that the value of GZ presented on the curve is dependent on the position of the centre of gravity; this is why the curves are provided for the three standard loading conditions. In practice a ship is unlikely to be operating at a standard loading condition and so alterations have to be made to the curves to ascertain the true behaviour of the ship.

3021. Horizontal Movement of Weights

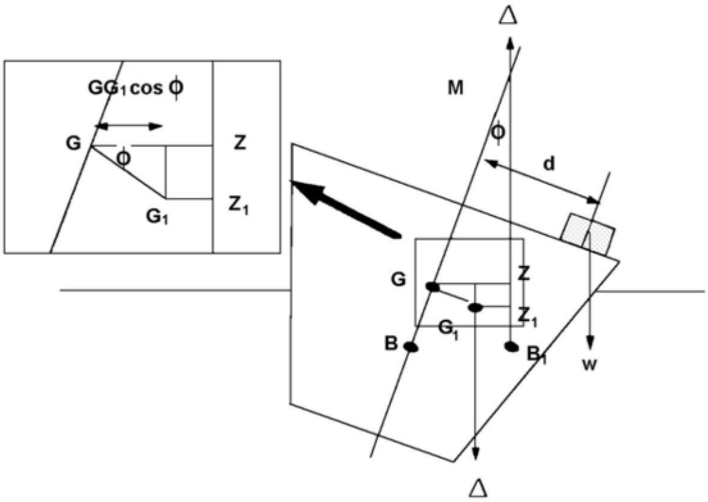
The movement of any weight that constitutes a part of the whole displacement of a ship in a horizontal direction will cause G to move in the same direction. By taking moments about original centre of gravity (G) the distance to the new centre of gravity (G_1) can be found such that:

$$GG_1 = \frac{wd}{\Delta}$$

By referring to Fig 30-10, below, it can be seen that this movement of G will have an effect on the righting lever so that:

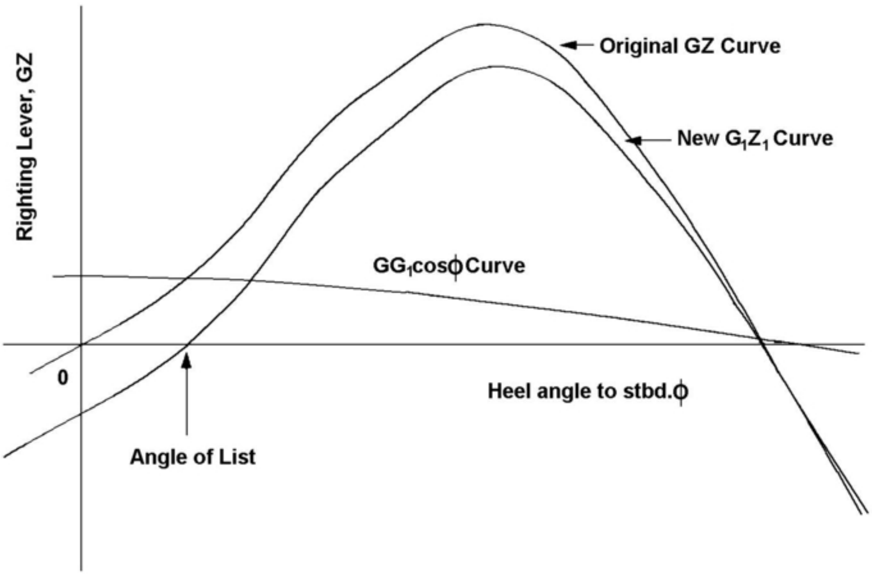
$$G_1Z_1 = GZ - GG_1\cos\varphi$$

Fig 30-10. Horizontal Movement of Weight



Consequently, the modified GZ curve over the range of heel angles can be redrawn by subtracting the curve $GG_1\cos\varphi$ from the original GZ curve. The resulting GZ curve is shown as the 'net righting lever' in Fig 30-11.

Fig 30-11. Net Righting Lever



The movement of the ships centre of gravity away from the centreline will result in the weight force and buoyancy force not being collinear, they will not, therefore, be in equilibrium and the ship will heel over until the 2 points are aligned vertically. The angle of heel will be steady and, so long as the metacentre remains above the centre of gravity, the ship will be stable. This condition of heel is known as **List,** and can be found as the intersection of the net righting lever curve with the x-axis on the curve in Fig 30-11.

3022. Vertical Movement of Weights

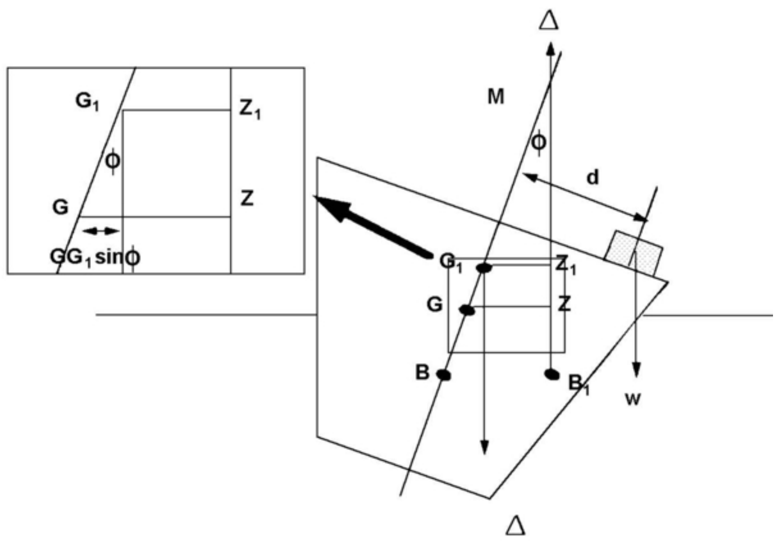
The movement of any weight that constitutes a part of the whole displacement of a ship in a vertical direction will cause G to move in the same direction. By taking moments about the original centre of gravity (G) the distance to the new centre of gravity (G_1) can be found, such that:

$$GG_1 = \frac{wd}{\Delta}$$

By referring to Fig 30-12, below, it can be seen that this movement of G will have an effect on the righting lever so that:

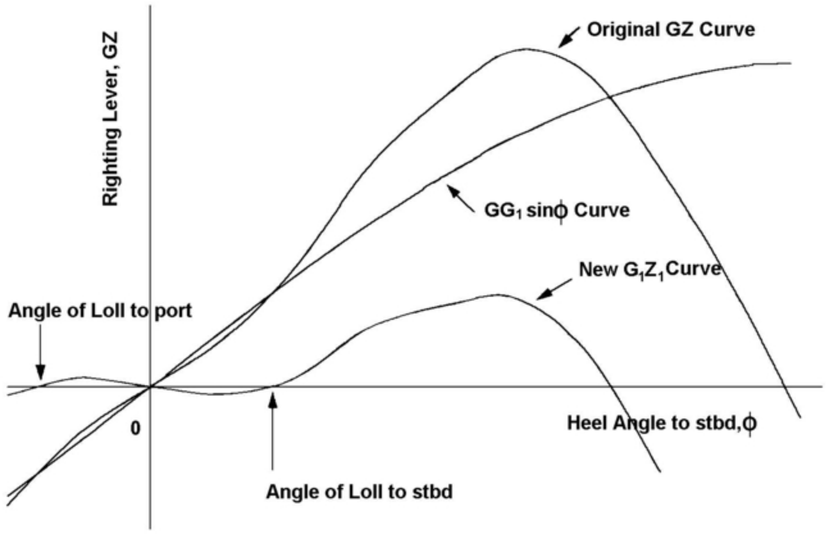
$$G_1Z_1 = GZ - GG_1\sin\varphi$$

Fig 30-12. Effect of Vertical Movement of Weight



Consequently the modified GZ curve can be drawn over the range of heel angles by subtracting the curve $GG_1\sin\varphi$ from the original GZ curve. The resulting GZ curve is shown as the 'net righting lever' in Fig 30-13.

Fig 30-13. Effect of Rise of G



The general effect of the centre of gravity rising in the ship is to reduce the maximum righting lever and range of stability of the ship. However, an interesting case occurs when GG_1 is sufficiently large to take G above M, so that in the upright condition GM is negative. Rather than causing the ship to capsize, which might be expected, depending on the precise hull shape of the ship and the magnitude of the negative GM, a real situation can be reached where the ship will lurch to one side but recover a measure of stability. This is illustrated in Fig 30-13. The angle of heel is known as the angle of **Loll.** While the diagram shows that because of the nature of the GZ curve, the ship should loll to either side, in practice it would have a slight preference to one side (slightly off-centre G, wind direction, etc). Having lolled over to one side a further heeling moment in that direction will be met by a righting lever that rises to a maximum and then tails off to the angle of vanishing stability. The same is not true in the reverse direction; if from an angle of loll a moment is applied to bring the ship upright, this will initially be met with a moment trying to restore the angle of loll. A point is reached before the ship becomes upright where this restoring moment reaches a maximum and the ship will then lurch through the upright and over to the angle of loll on the other side plus a further heel angle brought about by the moment which has been applied. When a ship is in a state of loll, its GZ curve will have become relatively flat, and consequently the effects of this additional moment could be catastrophic. Loll is a very dangerous situation and to be avoided at all costs and if encountered reacted to rapidly. The method for calculating the GZ curve for a more general movement of weight in both a horizontal and vertical direction is given at Para 3026.

3023. Causes Of and Reactions To List and Loll

a. List is caused by an upsetting moment that causes a heeling moment, such as:

(1) An off centre weight.

(2) Any other external force causing an upsetting moment.

b. In order to correct an angle of list:

(1) Remove the off centre weight or moment.

(2) Counter balance the off centre weight or moment with an equal and opposite one.

c. A state of loll is caused by a high centre of gravity. This may be due to one of three causes:

(1) Excessive weight high up, eg flood water in the superstructure, unusual loading.

(2) Insufficient weight low down, eg fuel, other liquids run down too far.

(3) Free surface effects.

d. The correct response is to take measures to:

(1) Reduce topweight.

(2) Increase weight low down.

(3) Reduce free surface effects.

3024. Longitudinal Stability

The mechanics involved in longitudinal stability are fundamentally the same as for transverse stability. However there are several differences that should be noted:

a. The second moment of area of the waterplane is far greater longitudinally than transversely. Consequently the height of the longitudinal metacentre is far greater than the transverse metacentre, in fact approximately 100 times as large.

b. Unlike the transverse case, where the ship is symmetrical about the middle line, there is no axis of symmetry longitudinally and it is necessary to take account of the longitudinal position of the Centre of Flotation, LCF.

c. Angles of trim are generally much smaller than those of heel therefore trim is normally described in terms of the difference between the draughts at the perpendiculars and measured in metres.

In looking at the longitudinal stability of a ship, the main concern is in controlling trim because although the ship is extremely ‘stiff’ longitudinally, it is exposed to much greater moments, due to the large lever arms, when transferring weights fore and aft rather than athwartships. As a consequence of the longitudinal metacentric height being so large the effect of vertical movements of the centre of gravity are insignificant, therefore allowing the assumption that it is constant at each draught. By considering the balance of righting moment and trimming moment in the longitudinal case a simplified formula can be found giving the trimming moment required to cause a change of trim of 1 m between the perpendiculars (BP), such that:

$$\text{Moment to Change Trim 1m BP} = \Delta GM_1 \left[\frac{1}{L_{BP}}\right]$$

The accepted convention is to calculate Change of Trim in centimetres so:

$$\text{Moment to Change Trim 1cm BP} = \frac{D \times GM_L}{100 \times L_{BP}}$$

This formula, therefore, provides a simple solution comparable to that for TPC for parallel sinkage. The Moment to Change Trim 1cm BP (MCT1cmBP) is dependent wholly on the draught of the ship and is provided in the ships hydrostatic data. Now given a moment causing the ship to trim the change in trim of the ship between the perpendiculars can be found as:

$$\text{Change in Trim BP} = \frac{\text{Trimming Moment}}{\text{MCT1cmBP}}$$

Having found the trim change between the perpendiculars the rule of similar triangles can be applied to find the trim change caused at any point along the ships length by:

$$\text{Change in Trim} = \text{Change in Trim BP} \times \left[\frac{(\text{Distance from LCF})}{L_{BP}}\right]$$

This is particularly useful for calculating the new draught extreme at the propellers for example, or predicting draught mark values. The method for calculating the change in trim at any point along the ship is given at Para 3029.

3025. Stability Methods

The following give clear logical methods for solving common stability problems using the information available to the ship.

3026. Addition of Weight and Daily Stability Assessment

In order to assess the stability of the ship on a daily basis (or after changing the loading condition), thus providing a valid datum point prior to further incidents, it is necessary to find GM and Δ for the actual loading condition.

a. Compare actual loading state (tank states, stores, aircraft etc) with a standard loading condition or known datum point. For this example assumes that a weight w_1 has been added Kg_1 above the keel, a weight w_2 has been removed Kg_2 above the keel and a weight w_3 has been moved vertically upwards a distance d_3, compared to the Deep condition.

b. Calculate the actual displacement:

$$\Delta_1 = \Delta_{Deep} + W_1 - W_2$$

c. Find the parallel sinkage caused by the additional weight:

$$s = \frac{W_1 - W_2}{TPC_{Deep}}$$

d. Find the actual draught for Δ_1:

$$T1 = T + \frac{s}{100}$$

e. Find the metacentre from the hydrostatic data at this draught T_1: KM_1

f. Calculate the actual position of G:

$$KG_1 = \frac{KG_{Deep} \times \Delta_{Deep} + Kg_1 \times w_1 - Kg_2 \times w_2 + d_3 \times w_3}{\Delta_{Deep} + w_1 - w_2}$$

g. Calculate the metacentric height:
$G_1M_1 = KM_1 - KG_1$

3027. Addition of Liquids

In order to assess the effect of adding a liquid to a ship currently floating at draught T with a centre of gravity KG, both the effect of the added weight and the effect of any free surface must be taken into account:

a. Find the total weight added:

w = volume x density

b. From hydrostatic data find Δ and TPC at the original draught T.

c. Find the parallel sinkage:

$$s = \frac{w}{TPC}$$

d. Find the new draught:

$$T_1 = T + \frac{s}{100}$$

e. At the new draught T_1 find KM_1 from the hydrostatic data.

f. Calculate the movement of the centre of gravity due to the addition of weight:

$$KG_1 = \frac{KG \times \Delta + Kg \times w}{\Delta + w}$$

g. Calculate the metacentric height after the weight is added:

$$GM_{solid} = KM_1 - KG_1$$

h. Take account of the free surface effects reducing the metacentric height assuming a rectangular compartment; length a, breadth b and the seawater in it of standard density:

$$\text{Loss of GM} = \frac{ab^2 \times 1.025}{12 \times \Delta}$$

i. Calculate the effective metacentric height:

$GM_{fluid} = GM_{solid}$ - Loss of GM

3028. Adjusting the GZ Curve for Movements of Weight

To find the effect on the stability of the ship over the whole range of heel angles due to a large movement of weight, w, and to determine whether the ship is suffering from list or loll the following method should be used to adjust the GZ curve:

a. Resolve the movement of weight compared to a standard loading condition into horizontal (d_{horz}) and vertical (d_{vert}) movements.

b. Find the movement of G in a vertical direction:

$$GG_1 = \frac{w \times d_{vert}}{\Delta}$$

c. Find the movement of G1 in a horizontal direction:

$$G_1G_2 = \frac{w \times d_{horz}}{\Delta}$$

d. Select suitable increments from the original GZ curve (eg 10°) and find values for GZ at each of these angles.

e. Calculate the values of $GG_1\sin\varphi$ and $G_1G_2\cos\varphi$ at each of the selected angles above.

f. Subtract $GG_1\sin\varphi$ and $G_1G_2\cos\varphi$ from the original values of GZ at each selected angle of heel to give a value for G_2Z_2:

$$G_2Z_2 = GZ - GG_1\sin\varphi - G_1G_2\cos\varphi$$

g. Re-plot the curve for G_2Z_2 against angle of heel.

3029. Change in Trim Due to Movement of Weight Longitudinally

To find the change in trim at any point along the ship due to a movement of weight longitudinally:

a. Find LCF and MCT1cmBP from the hydrostatic data for the mean draught of the ship.

b. Calculate the trimming moment, the distance the weight has moved multiplied by its weight; if the weight has been added this is the distance from the LCF.

c. Calculate the change in trim between perpendiculars:

$$\text{trim change BP} = \frac{\text{trimming moment}}{\text{MCT1cmBP}}$$

d. Calculate the trim change at any point:

$$\text{trim change BP} = \frac{\text{trim change BP x distance from LCF}}{L_{BP}}$$