PART I. TRANSVERSE STABILITY

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What Is Stability?

Stability is the ability of a vessel to return to its original condition or position after it has been disturbed by an outside force. Anyone who has been at sea and felt his ship roll, for example, and then right itself (only to roll in the opposite direction and right itself again), has seen stability in action.

Six Motions of a Vessel

The action of a ship in waves is a fascinating, but extremely complex study. No one can predict with exactitude the behavior of a vessel subjected to the forces of wind and weather. Nevertheless, it is possible to study the various motions of a vessel in waves and how these motions are effected by the hull design, the condition of loading, and the characteristics of the ocean waves themselves.

The principal motions of a vessel in waves are (in addition to the vessel's velocity vector):

1. *Rolling* or motion about the vessel's longitudinal axis.
2. *Pitching* or motion about the vessel's transverse axis.
3. *Yawing* or motion about the vessel's vertical axis.
4. *Heaving* or the vertical bodily motion of the vessel.
5. *Sway* or lateral, side to side, bodily motion.
6. *Surge* or longitudinal bodily motion.

Some of these motions are related to each other; others are entirely independent motions. All or most of the motions, however, occur simultaneously and have their effect on the efficient operation of a ship. Although the mariner does not possess complete control over these motions, there is much that he can do to diminish or alleviate their effects.

Figure 1 indicates the types of motion defined above. Stability in these motions is necessary to control and navigate a vessel. For example, it is desirable for a vessel to maintain a constant speed. This would require that the vessel have stability along the *surge* axis of motion. It is also desirable for a vessel to be able to stay on course and not swing wildly from it. This can be construed to mean that the vessel is stable in *yaw* motion or

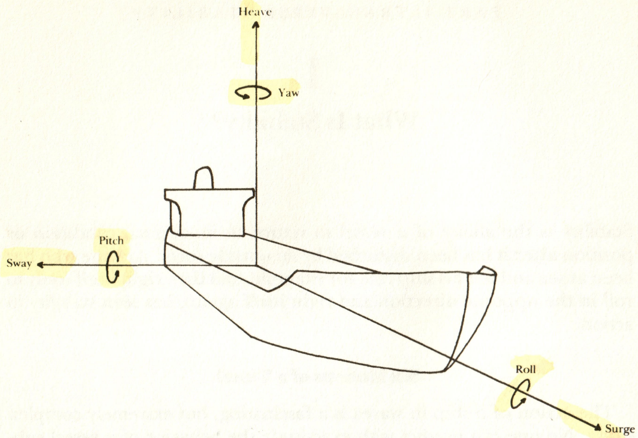


Figure 1. The six motions of a vessel.

heading. We would also like to have a constant *trim* (trim being the difference of the forward and after drafts). For this we need stability in the motion of *pitch.* It is important to minimize a vessel's sideways or lateral motion. This requires a high degree of stability in *sway.* We wish to keep the vessel on the surface at a relatively constant mean draft. To achieve this, stability in *heave* is necessary. Finally, and most significantly, a ship's officer is concerned to keep his vessel from capsizing. Without sufficient stability in *rolling* motion, this goal would be in jeopardy.

In the following table the motions are listed in order of priority along with the type of stability which governs each.

Motions of the Ship and Governing Stabilities

Motion	Governing Stability
1. Roll	Transverse Stability
2. Pitch	Longitudinal Stability
3. Yaw	Directional Stability
4. Heave	Positional Motion Stability
5. Surge	Stability in Motion Ahead or Astern
6. Sway	Lateral Motion Stability

It should be noted that the least stable of the six motions are rolling and yawing while the other motions have a relatively high degree of stability

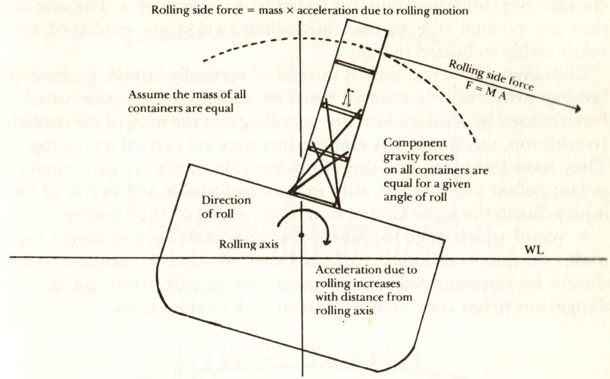


Figure 2. Side force on a container caused by rolling.

when considering the typical merchant-type hull. Yawing can be controlled with a rudder, while rolling must be controlled by the proper distribution of weights aboard the vessel. Although various roll dampening devices do exist and will be discussed later, it must be noted that the motion of rolling and the transverse stability* associated with it are our chief concerns.

The way the vessel rolls is a direct indication of her stability. Let us assume that a vessel has been loaded in such a way as to make her top-heavy. She is then in a *tender* or *cranky* condition. Her roll is slow, and she tends to lag behind the inclinations of the surface of the ocean waves. She has a weak tendency to return to her original upright position, and her stability is poor. Another vessel has a concentration of weight toward the bottom. She is *stiff*; she rolls quickly with large amplitudes; and she has a marked tendency to return to her original erect position which is perpendicular to the surface of the ocean waves. Her stability in the stiff condition is excessive.

To attain stability a merchant vessel should be loaded in such a way as to give her an easy rolling period, neither too fast or too slow. A vessel which rolls too fast stresses the upper parts of her structure, the crew, and,

*When aboard ship, a ship's officer refers to transverse stability, or stability of rolling motion, as simply *stability* because it is this motion of the ship which causes the most concern. When stability is mentioned hereafter in this text, it will refer to transverse stability unless otherwise indicated.

considering container ships, the upper tiers of containers. The side forces that are created due to this fast rolling period are explained by the relationship indicated in Figure 2.

Containers are cross lashed instead of vertically lashed, because cross lashing provides a horizontal restraint which counters the actual side force caused by accelerations due to rolling and the mass of the container. In addition, this is also why empty containers are carried on the top tiers. They have less mass, and therefore, less side forces are generated. The personnel on a fast rolling ship are uncomfortable and in risk of bodily injury due to the same kind of side forces acting on their bodies.

A vessel which rolls too slowly has poor stability and might capsize under certain conditions, such as heavy weather or damage. Thus it should be remembered that an overstable or stiff vessel can be just as dangerous to her crew and cargo as an understable vessel.

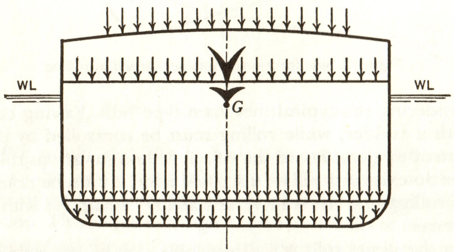


Figure 3. *G* is the resultant of all vertically downward forces of gravity.

Centers of Gravity and Buoyancy

The condition of the vessel as regards stability is determined almost wholly by the location of two points in a vessel: the *center of gravity* and the *center of buoyancy*. Before discussing the relationship between these points it is necessary to define them.

The center of gravity, *G*,: that point at which all the vertically downward forces of weight of the vessel can be considered to act; or it is the center of the mass of the vessel. A ship will behave as if all of its weight (displacement in long tons) is acting down through the center of gravity. See Figure 3.

The center of buoyancy, *B*,: that point at which all the vertically upward forces of support (buoyancy) can be considered to act; or, it is the center of volume of the immersed portion of the vessel. A ship will behave as if all of its support is acting up through the center of buoyancy. See Figure 4.

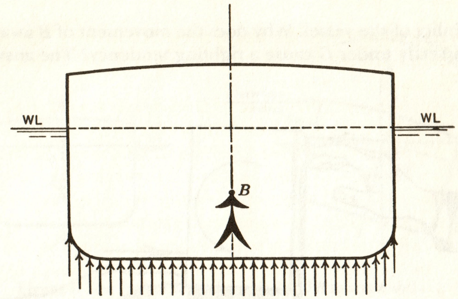


Figure 4. *B* is the resultant of all vertically upward forces of buoyancy.

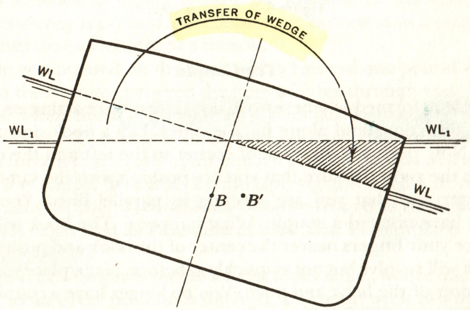


Figure 5. Since *B* is the center of buoyancy of the immersed portion of the vessel. . .

When a vessel is inclined due to some external force, that is, by the action of seas, the center of gravity will remain fixed in its location in the vessel. Of course, if weights are free to move on the vessel, *G* will move too but, for the time being, it is assumed that *G* does remain in its original position. If the vessel does not have a list, this original position is, of course, on the centerline.

When a vessel is inclined, the center of buoyancy will move since it is the center of volume of the immersed portion of the vessel, and a wedge of buoyancy has been transferred from one side of the vessel to the other side. See Figure 5.

It is this movement of *B* which results in a tendency of the vessel to return to its original position. The intensity of this tendency is a measure of the stability of the vessel. Why does the movement of B away from its position directly under G cause a righting tendency? The answer lies in the *couple*.

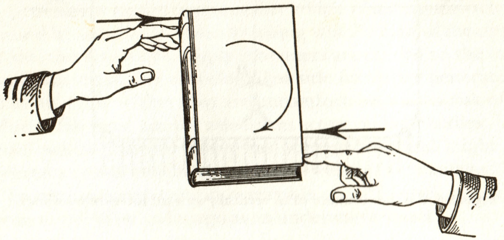


Figure 6. A couple is created.

The Couple

A couple is formed whenever two equal forces are acting on a body in opposite directions and along parallel lines. Lay a book down on a flat surface. Now push the lower right corner to the left and the upper left corner to the right. Be sure that you are pushing with the same force on each finger and that you are pushing in parallel lines. Your fingers' pressure have created a couple. What happens? The book will revolve. Now place your fingers nearer the center of the book and push as before. The book will revolve but not as quickly as before. Next, place your fingers at the center of the book and push. You no longer have a couple and the book will not revolve. See Figure 6.

Returning to the discussion of a vessel, we see by referring to Figure 7 that, when B moves, the lines of force through G and B separate. We now have a couple* exerting a force which tends to rotate the ship back to an erect position.

The couple has been formed by the two equal forces of weight and buoyancy which are acting in opposite directions along parallel lines. The farther these lines move apart, the greater the force of the couple. However, when a vessel is in still water and no external force is inclining her, G

*Since the forces through G and B act vertically upward and downward, when they do not coincide, they must be parallel. Also the forces through G and B are equal. Archimedes' principle (the law of floating bodies) states that a floating body displaces a weight of water equal to its own weight; that is, weight equals buoyancy. Therefore, since we have two equal forces operating in opposite directions and along parallel lines in the same body, a couple exists.

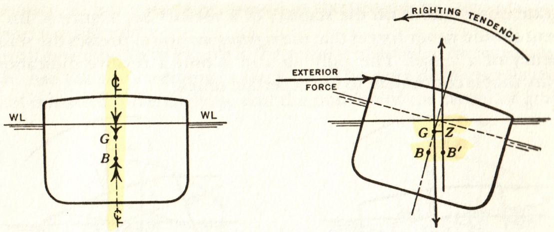


Figure 7. The lines of force through G and B separate and . . .

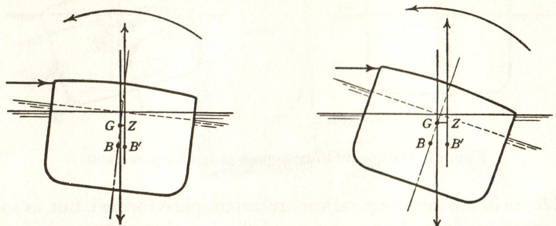
and B are in the same vertical line and no couple is formed. But, as soon as the vessel inclines, B moves toward the low side of the vessel, and a righting tendency is created. All couples are expressed as a certain force (weight unit) times a length, or a *moment*.

Suppose you pushed on the book with a force of one pound with each finger and the distance between the lines of force through your fingers is six inches. Then there is a moment of one-half foot-pound tending to rotate the book. The length, then, is the distance between the lines of force; the force is that of one of the equal forces. In the case of a vessel, the value of the couple is found by multiplying the weight of the vessel (displacement) by the perpendicular distance from G to the line of action of B. This is expressed as a moment in foot-tons. The couple is known as the *righting moment*.

We should now begin to realize what stability is, i.e., where the tendency to return to an erect position is derived, and upon what two things that tendency, or righting moment, depends. The greater the weight of the vessel, the greater the righting moment; the greater the distance from G to the line of force through B, the greater the righting moment.

Referring to Figure 7, we see that it is customary to label as Z the point of intersection of the line of action of B and the line through G to it. The distance GZ is known as the *righting arm*. Thus, if we label the displacement of a vessel Δ, the righting moment may be expressed by the symbols: $\Delta \times GZ$.

The righting arm alone can usually be used as an indication of stability. The reasons for this are very simple. A vessel at any one time weighs or displaces a certain number of tons. Inclining the vessel does not change its displacement. Therefore, the only factor of the righting moment ($\Delta \times GZ$) which changes is GZ, or the righting arm. If GZ doubles, the righting moment doubles; if GZ trebles, the righting moment trebles, etc. It is possible then, merely by the knowledge of the length of GZ, to make accurate observations on the stability of a vessel.* See Figure 8. But the student should never forget that the *righting moment* expresses the stability tendency of a vessel. The righting arm is only a relative indication of stability that is convenient to use at certain times.



GZ=1 ft.
Righting moment is 10,000 × 1, or 10,000 foot-tons.

GZ=2 ft.
Righting moment is 10,000 × 2, or 20,000 foot-tons.

Figure 8. A 10,000-ton vessel rolls . . . and rights.

Initial Stability

Up to this point, we have discussed stability at all angles of inclination and have discovered that the true measure of a vessel's stability is her righting moment and, to a limited extent, her righting arm. If ship's officers were to look up the value of the righting arm in the statical stability curves and multiply it by the vessel's weight he would have the righting moment in foot-tons. This would mean very little to him other than to indicate that the vessel would return to an erect position. He wants a value which will indicate to him directly what the relative tendency of his vessel will be to return to an erect position for small angles of inclination; in other words, he wishes to know how his vessel will roll. Whether or not his vessel is stable at large angles of inclination is not a problem which will confront him frequently. In order to satisfy this need for a simple, concise figure, the ship's officer must know the position of the vessel's *transverse metacenter*.

Transverse Metacenter

This section should be read in conjunction with careful study of Figure 9. The transverse metacenter is a point through which the center of

*Information on the lengths of righting arms for various conditions of loading and angles of inclination are found in the statical stability curves for a vessel. These curves will be discussed in detail in Chapter 6.

buoyancy, *B*, acts vertically upward as the vessel is inclined and *B* shifts toward the low side.

In all cases shown in Figure 9, the vessel is inclined to the same angle; in each case the displacement is the same. The only difference is that the vessel is loaded differently, so that the position of the center of gravity is

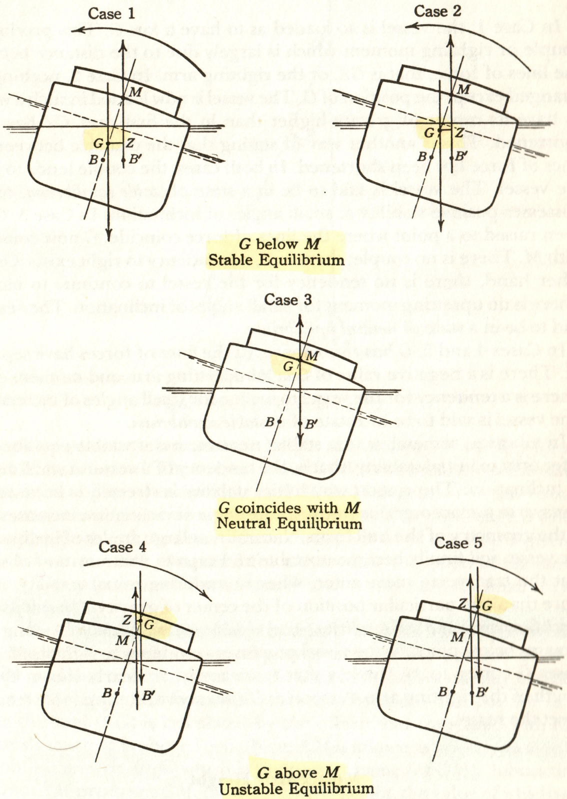


Figure 9. The same displacement; the same angle of inclination, but *G* moves up . . . the student discovers transverse metacenter (*M*), and the equilibriums.

different. The center of buoyancy remains at the same point in each case, because the immersed portion of the vessel is the same. We are already acquainted with three of the four points lettered; *G*, *B*, and *Z*. *M* denotes *transverse metacenter*.

Stable, Neutral, and Unstable Equilibrium

In Case 1, the vessel is so loaded as to have a low *G*. This produces a couple or righting moment which is largely due to the distance between the lines of force, that is *GZ*, or the righting arm. In Case 2, nothing has changed except the position of *G*. The vessel is now loaded in such a way as to have its center of gravity higher than in the first case. *GZ* has been shortened. This is another way of stating that the distance between the lines of force has been shortened. In both cases, the couple tends to right the vessel. The vessel is said to be in a state of *stable equilibrium*, or she possesses positive stability at small angles of inclination. In Case 3, *G* has been raised to a point where the lines of force coincide. *G* now coincides with *M*. There is no couple; therefore, no tendency to right exists. On the other hand, there is no tendency for the vessel to continue to incline. There is no upsetting moment for small angles of inclination. The vessel is said to be in a state of *neutral equilibrium*.

In Cases 4 and 5, *G* has risen above *M*; the lines of forces have separated. There is a negative value of *GZ*; an upsetting arm and moment exist. There is a tendency for the vessel to incline for small angles of inclination. The vessel is said to be in a state of *unstable equilibrium*.

In all cases, remember that stable, neutral, and unstable equilibriums refer only to initial stability, that is, the tendency of a vessel at small angles of inclination. The reason why initial stability is stressed is because the transverse metacenter does move as the angle of inclination increases due to the geometry of the hull form. Naturally, at large angles of inclination, the vessel will finally become unstable and capsize. We may now observe that the transverse metacenter, when considering initial stability, is no more than one particular position of the center of gravity. *It is that point to which G may rise and still permit the vessel to possess positive stability.* As long as *G* remains below point *M*, the vessel possesses a tendency to right itself. The closer *G* comes to *M*, the less that tendency is, as clearly shown by the length of the righting arm. As soon as *G* rises above *M*, the couple tends to upset the vessel.

Metacentric Height

The distance between points *G* and *M*, therefore, is related directly to the length of the righting or upsetting arms. The mathematical expression of this relationship is illustrated in Figure 10, where it is shown that $GZ = GM \sin \theta$. Since *GZ* is a function of righting moment and *GM* is a function of *GZ*, *GM* must be a function of the righting moment. Consequently we can use *GM*, which is called *metacentric height*, as a measure of the initial stability of a vessel.

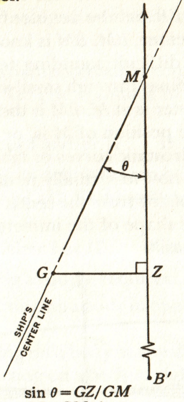


Figure 10. *GM* is a function of *GZ*.

Why can we not use metacentric height as a measure of stability for all angles of inclination? The reason is that *M* does not remain in the same position for angles of inclination over 10 to 15 degrees. For this reason most texts define *M* as the intersection of the line of force through *B* when the ship is erect and the line of force through *B* when the ship is given a *small* inclination. (See Chapter 3 for a thorough discussion of the metacenter.) The expression $GZ = GM \sin \theta$, also, is only valid for small angles of inclination.

For the ship's officer, stability is mainly a problem of finding the position of the vessel's center of gravity because the position of *M* is readily available to him by hydrostatic data in the ship's stability booklet. (Refer to the appendix for a typical stability booklet.) The position of *G* above the keel (*KG*) is calculated by the officer and compared with *KM* (linear distance *M* is above keel). (Note *KM* is known as *height of metacenter* and not *metacentric height* which is the proper name for *GM*.) Subtracting *KG* from *KM* produces *GM*, the metacentric height, the value of which will inform the officer about initial stability, or how the vessel will behave at sea.

Metacentric Radius

For the purpose of explaining exactly upon what the value of *KM* depends, as well as to enable the student of stability to calculate *KM*, it is necessary to point out that *KM* is the sum of the distance from the keel to the center of buoyancy, *KB* and the distance from the center of buoyancy to the transverse metacenter, *BM*. *BM* is known as the *metacentric radius.* Here again we have a difficult sounding term which has very simple meaning. As a vessel inclines through small angles, *B* moves through the arc of a circle whose center is at *M*. *BM* is the *radius* of this circle: hence, metacentric radius. The position of *M* is, or should be, available to the ship's officer on the hydrostatic curves or tables from the curves. Figure 11 will help to illustrate how *M* virtually remains fixed for small inclinations while *B* moves outboard from the centerline.

KB depends upon the shape of the immersed portion of the hull and can be calculated fairly easily.

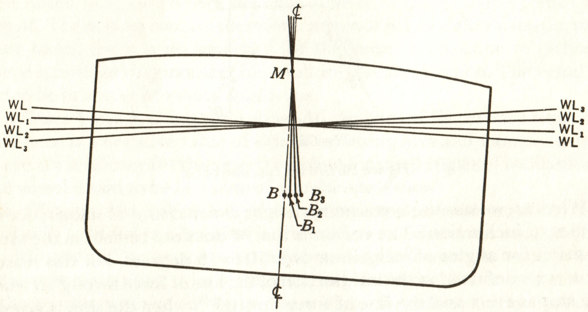


Figure 11. For small angles of inclination *BM* is a radius of a circle having *M* at its center.

Summary

The tendency of a vessel to return to an erect position (called stability) can be determined for all angles of inclination by the value of the righting moment, $\Delta \times GZ$, or solely by the length of the righting arm *GZ*. For small angles of inclination, or initial stability, it can be determined by the distance that *G* is from *M*, or metacentric height. In order to find *GM* it is necessary to find *KG* and *KM*. Where the value of *KM* is not available it may be necessary to find *KB* and *BM*. In succeeding chapters, the calculation of *KG, KM,* and *GM* will be taken up in detail.

Questions

1. Stability by its definition can be considered:

A. Righting moment
B. Righting arm
C. The tendency for the ship to return to an upright position
D. All of the above

2. Center of gravity by its definition can be considered: **I.** The centroid of the displaced volume. **II.** The resultant of all vertically downward forces of gravity.

A. I B. II C. Either I and/or II D. Neither I nor II

3. Center of buoyancy by its definition can be considered: **I.** The centroid of the displaced volume. **II.** The resultant of all vertically upward forces of buoyancy.

A. I B. II C. Either I or II D. Neither I nor II

4. Mathmatically speaking a couple requires:

A. Two equal forces acting on a body in opposite directions and along parallel lines.
B. Any two forces acting on a body in any direction.
C. Two equal forces acting on a body at right angles to each other.
D. None of the above.

5. The couple formed by the center of buoyancy and the center of gravity form what is known as:

A. Metacentric height
B. Metacentric radius
C. Righting arm
D. Righting moment

6. Righting arm is:

A. A couple
B. A moment
C. A distance
D. None of the above

7. Another expression for height of transverse metacenter is: **I.** Metacentric height. **II.** *KM*.

A. I B. II C. Either I or II D. Neither I nor II

8. If *KG* is less than *KM* the ship would be considered to have: **I.** Stable equilibrium. **II.** Neutral equilibrium. **III.** Unstable equilibrium.

A. I B. II C. III D. Neither I, II, nor III

9. Calculate the moment created by a couple with a force of 5 tons which has an arm 2.5 feet.