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A SunCam online continuing education course

Intact Stability of Surface Ships

by

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This course covers the following topics:

What is intact ship stability?

Intact stability is a fundamental part of the calculations for a ship that the Naval Architect does. Fortunately, the calculations are done using specialized computer programs these days, but even the American standard, GHS, could use some updating to the 21st century.
Stability is the ability of a ship to float properly upright in an equilibrium position, at a draft no more than her assigned maximum waterline, and to resist external forces such as normally expected waves and wind while doing so. If you are not an engineer, equilibrium is a condition where two opposing forces acting on a body (in this case the hull), are equal. There are three conditions of equilibrium in ship stability: stable, neutral, and unstable. Stable equilibrium is the condition whereby a floating object returns to its original position when momentarily acted upon by an outside force, such as wind or waves. Neutral equilibrium is the condition where the floating object tends to find a new point of stable equilibrium and stays at that different point when acted upon by a momentary force. Unstable equilibrium is a condition where the floating object tends to keep moving away from a position of stable equilibrium, such as when capsizing. Intact stability is about the condition of an intact ship, that is, it has no damage that results in water leakage into the hull, or as in the case of a sailboat, the ballast does not fall off the hull. Ship trim and heel are affected by moments, or the effect of a weight at a distance. Heel is the result of the moment caused by an off-center weight multiplied by the distance off centerline; the reaction moment is that caused by the buoyant force times the distance the transverse center of buoyancy (TCB) moves to when the ship rolls. The heel angle is the angle at which an equilibrium condition exists where the heeling moment equals the transverse buoyancy moment. Likewise, the trim angle is the angle at which an equilibrium condition exists where the trimming moment equals the longitudinal buoyancy moment.

Here are a few useful terms:

- Allowable KG curve-a graph published in the Stability Booklet showing the calculated KG (vertical center of gravity) height limits at all possible displacements with the sample loading conditions marked below to show that these safely meet the reserve stability requirements to resist wind and waves.

- Baseline-the horizontal reference datum on the centerline, at the bottom of the hull. This is the datum from which all vertical measurements are referenced to. This is shown on all profile and elevation drawings of the ship.

- Capsize- the tendency of a ship to roll over and remain that way or sink when upset by wind, large waves, towlines, or weights hanging over the side. Ships also capsize if they leak water into the hull at a point higher than the double bottom, or when the free surface area of fluids in the hull is large enough to allow large masses of fluid to flow to one side.

- Centerline (CL)-the longitudinal planar axis down the middle of the hull from which transverse distances are measured. This is synonymous with the Baseline at the bottom of the hull and it is shown on all plan views and end view elevation drawings of the ship.

- Center of Buoyancy (CB, or B)-the 3-dimensional location of the resultant effects of the buoyant forces operating against a hull. The longitudinal, transverse, and vertical distances of the center of buoyancy from the various reference datums are abbreviated as LCB, TCB, and VCB.
- Center of Gravity (CG, or G)-the 3-dimensional location of the resultant effects of the weight of an object. The longitudinal, transverse, and vertical distances of the center of gravity from the various reference datums are abbreviated as LCG, TCG, and VCG (or KG for Keel to CG.
- Change in Displacement per Foot (or Inch) of Trim (CDTrim, CD1", or CD1')-As a vessel trims due to weight changes, the displacement changes as well as the trim. Because the ship hull may be finer forward and wider aft or vice versa, the CDTrim will not quite be linear. This value is useful for determining the true displacement of a ship through interpolation with trim that does not fall exactly on the hydrostatic table values for ships with, say, 1' of aft trim, 2', and so on. The metric version of this is CD1cm or CD1dm (decimeter).
- Cross Curves-a graphical set of lines showing the righting arm lengths of the hull at various heel angles. These, or a tabular form, are included in the Stability Booklet.
- Design Waterline (DWL or L(oad)WL)-The waterline draft at which the fully laden vessel is designed to have.
- Displacement (D or Δ)-the weight of a ship, which is equal to the weight of water it displaces, in pounds, long tons (2240 lbs), kilograms, or tonnes (metric ton, 2205 lbs or 1000kg). This is NOT TO BE CONFUSED with a gross ton, which is a volume of 100 cubic feet.
- Downflooding point-any opening above the full load waterline which cannot be closed during normal operation of the ship, which may result in seawater leaking into the ship. These include Engine Room and compartment ventilation openings, tank vents, weathertight doors, opening windows that are normally open, etc.
- Draft-the depth of water displaced by the hull when it is afloat. This is usually measured from the Baseline unless the keel has drag. If so, the maximum navigational draft is deeper than the baseline by an amount shown on the Hull Lines Plan.

- Drag-the term used to describe a keel which slopes down forward or aft relative to the baseline. Drag is usually lower aft than forward. This is not to be confused with hulls such as high-speed powerboats where the bow is deeper than the transom and it has no keel.
- Equilibrium-a ship is considered to be in equilibrium when the resultants of all forces and moments acting on it are zero.
- Fore-and-Aft-the nautical term for forward (towards the bow, or front), and aft (towards the stern, or back end)
- Free Surface Effect-the effect of fluids in tanks and the bilges that are free to shift to the low side when the ship heels. This weight shift negatively impacts transverse stability, and to a much lesser degree, longitudinal stability. The effect on the KG is to raise it by a "virtual" amount that is a factor of the moments of inertia of waterplane are of the free fluid, the specific volume, and the ship's displacement.
- GM-the vertical distance between the Metacenter M and the center of gravity, G. This is a measure of reserve stability.
- Gross Tonnage-a VOLUME measurement of a hull showing the hull and deckhouse volume inside of the framing. It is NOT TO BE CONFUSED with displacement, which is a weight. Although this term is also used for truck and container weights, it has no place being used as a weight in nautical terminology.
- Heel or List: the tendency of a ship to roll to one side of centerline or the other depending on the weights it is carrying. The two words are synonymous.
- Hull Lines Plan-(Also see course 441-How To Read Shipbuilding Drawings, Part 1 for an example) a drawing or geometric computer model showing the hull divided at regular intervals by planes. The traditional Lines Plan, which was developed long before 3D computer models, shows the profile of the hull from starboard, the plan view of the hull from below and the weather deck from above, and sections through the hull looking from forward and aft. The Plan View is split down the centerline with the deck plan above the centerline and hull plan from below shown below the centerline. The Body Plan is split vertically at the centerline and shows the hull sections looking aft from the bow to midships on the right and the view of the hull sections looking from aft to midships on the left. The traditional form of Lines Plan also has a Table of Offsets, which are measured points on the surface of the hull form. These are not pertinent to this course in hydrostatics, although the offsets are measurements at the intersections of the various planes on the Lines Plan. The planes that define the 3-dimensional hull shape by drawing lines of the intersections, are Stations, Waterplanes, and Buttock planes. The lines

resulting from these planar intersections of the hull shape, and which are used to determine the offset measurements are called Stations, Waterlines, and Buttock Lines.

- Hydrostatics-a graphic or tabular format listing of the displacement, LCF, LCB, TCB, VCB, MT1", CDTrim, TPI, and sometimes immersed volume V, for hull drafts from baseline to the maximum allowable draft. These are often calculated for 0 trim, and a few bow-up and bow-down trims that would be commonly seen in use. This is included in the Stability Booklet and is a basis for stability calculations.
- Inclining (or Stability) Test-a scientific test done on a ship to mathematically determine the 3 dimensional location of the Center of Gravity. Long pendulums are set up in the ship, and heavy calibrated weights are moved from side-to-side by a known distance to determine the resulting heeling angle. Alternatively, inclinometers or U-shaped water tubes the width of the ship may be used to measure the change in heel angle due to weight movements. These tests are done upon completion after building, when major modifications are made, and at 5 or 10 year intervals as required by Class or Flag State to confirm the current stability conditions.
- KG-the distance that the ship's center of gravity G is above the baseline, K.
- Long Ton-the standard nautical ton in Imperial units, equal to 2,240 pounds.
- Longitudinal Center of Buoyancy (LCB)- the longitudinal distance of the location of the center of the buoyant forces on the immersed volume of the hull from the vertical datum (FP, AP, or Midships).

- Longitudinal Center of Flotation (LCF)- the longitudinal distance of a point on the top waterline of the immersed hull, measured from the longitudinal reference datum, about which the hull trims when acted upon by the separation distance between the LCG and LCB. It is similar to a teeter-totter pivot point. The LCF is seldom the same distance from the longitudinal reference point as the LCB.
- Longitudinal Center of Gravity (LCG)-the longitudinal distance of the location of the center of gravity of an object in the weight estimate and/or the whole ship, measured from the longitudinal reference datum. If a midship reference axis is being used, distances of weight items and/or the ship forward of amidships are considered negative, and distances measured aft of amidships are considered aft so that aft trim, which is generally desirable, is positive. The different location of this on a hull relative to the LCB is the distance known as the Trim Lever, which see below.
- Longitudinal Reference Datum-In the case of a ship, this reference datum is either the:
  - Forward Perpendicular (FP)-the point where the design draft intersects the Stem. Measurements from the FP proceed aft, and so do the structural frame numbers if

they are shown. American-built ships, except for submarines, generally use the FP or Midship point as the longitudinal reference point;

- Midship (MP)-the point at the ½ length of the Design Waterline (DW, or Load Waterline (LWL). DW and LWL are usually the same thing. This is represented by a Plimsoll Mark symbol on the Hull Lines plan, which looks like a circle with a backwards C to the left and a forward C to the right. The frame numbers do not start from a midship location, but from the AP or FP-this can be a source of confusion sometimes. This location is sometimes used in weight estimates if the stability calculations figure trim about the midship point rather than either perpendicular. Be sure of the direction and start location of the longitudinal reference axis-mistakes due to sign (+ or -) usage are common, particularly if using midships for the start point;
- Aft Perpendicular (AP)-usually the location of the rudder stock, or a specified point between 96% and 97% of the distance aft from the Forward Perpendicular. Longitudinal measurements on vessels and submarines built outside of the U.S. generally proceed from aft to forward, as do the frame numbers for these vessels.

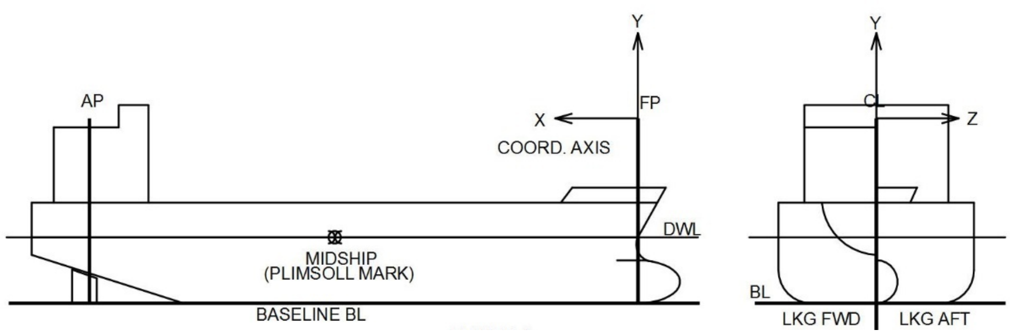

Figure 1: Reference Axes or Datums

- Margin Line-a mathematical border line established near but below the weather deck edge which is used to define the immersion limit of a heeled hull for use in stability and watertight subdivision calculations.
- Metacenter (M)-this is a point similar to the pivot point that a pendulum hangs from. It is always above the CG unless the ship has capsized. The height of the metacenter above the CG is therefore a measure of reserve stability to resist upsetting forces such as wind, waves, and unbalanced weights. The distance of the Metacenter from the longitudinal reference datum is called the longitudinal KM, or KML; the distance of the Metacenter

from the baseline is the transverse KM, or KMT. KML is always longer than KMT. The vertical position of the metacenter changes with displacement and trim, but for any given draft it will always be in the same place.

- Molded dimensions-the longitudinal dimensional distance from a longitudinal reference point to the outer web face of a frame in metal ships, to the nearest face of a frame in wooden ships, or from the centerline to the inside of the shell plating in metal and wooden ships, and to the outside surface of the shell in fiberglass and composite ships. When plates or planks of varying thicknesses are used, the inside surface is smooth, and the outside surface varies in thickness. The opposite is true in fiberglass and composite ships because they are built in a mold that makes for a smooth outer surface.
- Moment To Trim 1 Inch (MT1" or MTI)-the moment (weight times the distance from the vertical reference point) that it takes to cause the hull to trim 1 inch (which is roughly ½" forward + ½" aft from level if using midships for the vertical reference datum). If a forward or aft reference datum is used, the 1" of trim is from level at that point. The metric version is Moment To Trim 1 CM (MT1).
- Port and Starboard- port is the left side of the ship when looking forward, and starboard is the right side.
- Roll Period-the time it takes for a ship to roll from the extreme angle on one side, across to the other angular extreme, and back when a one-time outside force is exerted on it. Generally, the faster the roll period, the more stable the ship is, however typical ranges of roll periods are faster on smaller ships than large ones.
- Sounding-the depth of fluid measured in a tank using a measuring tape or stick. Also, the depth of water under the ship as measured by a sounding lead on a handheld line (rope).
- Specific Volume-the mathematical complement of density. If density is in pounds per cubic feet, specific volume is cubic feet per pound. In metric terms, it is the reciprocal of the specific gravity.
- Stability Booklet-the stability document published by the Naval Architect and usually approved by a Class or Flag State that shows instructions to the Master for how the ship can be operated safely and what the stability limits are. It includes sample loading conditions, a blank sheet for doing manual calculations, the Allowable KG height limits to stay within the required criteria, a set of tanks sounding tables, Cross Curves, and Hydrostatics. Many ships today additionally have a stability loading computer to calculate all ow the loading conditions expected to be encountered.
- Stability Criteria- The various Classification societies and maritime regulatory agencies such as the International Maritime Organization (IMO) of the United Nations, U.S. Coast Guard, American Bureau of Shipping, Marine Coastguard Agency (U.K. Coast Guard),

and other national flag states establish equations and resulting values called stability criteria for Naval Architects to make a mathematical proof that the vessel meets their requirements for "reserve stability". Reserve stability is the safety margin, and is an amount of self-righting ability in addition to the normal operating condition that the ship has. The amount of reserve stability to require has been determined by experimentation, experience in the past, and casualty investigations, and the mathematical analysts at these organizations have developed equations for our use that cover a wide range of vessel lengths and uses. Over time, the various stability criteria have been standardized around the IMO criteria for commercial cargo ships, passenger ships, with some interpretations and local standards allowed for other types depending on their service, such as yachts, barges, tugs engaged in towing, research vessels, school ships, mobile offshore drilling units, and offshore oilfield supply vessels.

- Tank Sounding Tables-these are tables for each tank in the hull showing, at regular intervals like 1" from 0% to 100% full, the weight of the fluid, volume of the fluid, LCB, VCB, TCG, fluid density, and the free surface moment of inertia (FSM) of area of the fluid plane. Sometimes ullage is also shown on deep tanks.
- Tonne-a metric ton, equal to 1000 kilograms or 2,205 pounds
- Tons/Inch Immersion (TPI)- the Imperial unit version of how many long tons of load on the hull that it takes to submerge the hull parallel to the waterline 1 more inch. The metric version is Tonnes/Centimeter (TCM).
- Transverse Center of Buoyancy (TCB)- This is the transverse distance to port (-) or starboard(+) of each item accounted for in the weight estimate that may affect the buoyancy (such as appendages and subtractions to buoyancy), plus the total ship. KB is a stability term that means the height of the total center of buoyancy B of the ship above the keel, K. For the total ship, VCB and KB are used interchangeably
- Transverse Center of Gravity (TCG)-the distance of the center of gravity of an object from the centerline of the ship, or for the total ship.
- Trim: the tendency of a ship to float with the bow or stern down from level depending on the distribution of weights it is carrying and the counteracting buoyancy of the immersed hull volume. Trim is also a specific number which is the mathematical difference between the forward and aft drafts of the ship. For example, if a ship has 3 feet of bow-down trim, the draft at the bow is 3 feet deeper than at the stern. Since most ships are designed to run with a slight bow up trim, this negative trim could stand some correction by changing the weight distribution of cargos and/or fluids to bring the bow up. Trim is a function of the displacement multiplied by the offset distance (trim lever) between the LCG and the LCB.

- Trim Lever-the horizontal distance between the LCB and the LCG.
- Ullage-the measured distance from the top of a tank to the fluid level. The mathematical complement of the sounding of the fluid depth.
- Vertical Center of Buoyancy (VCB, or KB)- VCB is the height above baseline (BL) of each item accounted for in the weight estimate that may affect the buoyancy (such as appendages and subtractions to buoyancy), plus the total ship. KB is a stability term that means the height of the total center of buoyancy B of the ship above the keel, K. For the total ship, VCB and KB are used interchangeably.
- Vertical Center of Gravity (VCG, or KG)-VCG is the height above baseline (BL) of each item accounted for in the weight estimate, plus the total ship. KG is a stability term that means the height of the total center of gravity G of the ship above the keel, K. For the total ship, VCG and KG are used interchangeably.
- Volume (V, sometimes $\tilde{V}$)-the immersed volume of the ship.
- Waterplane Area (WPA)-the area of the waterplane at a specific draft, in square feet (Imperial), or square meters (metric)
- Watertight Subdivision calculations-calculations done to determine the maximum permissible length between watertight bulkheads so that the margin line is not submerged in the event of compartment flooding. Details of this are covered in my Damage Stability class.

As you can see, there are a large number of terms involved in ship stability, but there are a couple of familiar analogies that will simplify things.

An easy way to visualize intact stability is when you sit in a rocking chair. Just sitting in the chair without rocking is like the ordinary operating condition of the ship-the chair leans back a little as it adjusts to put the center of gravity of you and the chair together in a position where the center of gravity is directly over the contact point of the rocker rail on the floor. If you happen to be sitting on the porch in a wind, you may need to adjust your legs just a little to steady the chair. The ship makes a similar adjustment for the weight of itself and the cargo it is carrying, which results in a small bit of heel and trim. The Captain may order the Chief Engineer to add or shift some liquid ballast to level out the heel and trim so that the ship runs level in the water. Because the chair, and a ship, will return to its original position when the upsetting force is removed, this is a case of stable equilibrium.

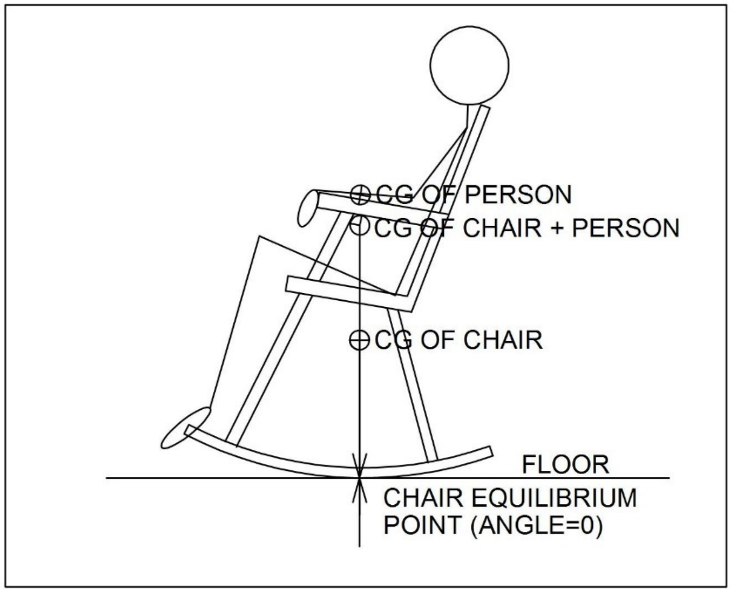

Figure 2: Person and chair at rest

If you then lean back as far as your legs will support you with your feet flat on the floor, you have established an equilibrium condition of stability where the resisting force from the floor to your feet equals the tendency for the chair to want to rock back. This is similar to what a ship in a high wind, or a sailboat experiences-the external force being exerted is from steady wind pressure, and both vessels will heel to an angle where an equilibrium position is again established.

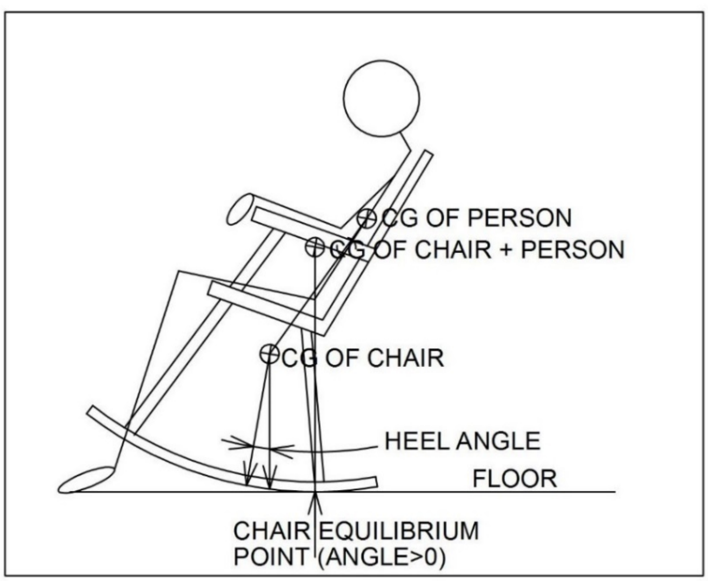

Figure 3: Person with feet resting on floor

If the person in the chair uses the feet to rock the chair back and forth, this is similar to wave forces hitting the side of a ship-it is a repeating outside force that causes a rocking motion in the ship. Notice that there is some rocker rail left behind the person in the chair-this is the reserve stability that the person has left in this condition, just like the ship. The length of the remaining rocker rail is analogous to what is called the "righting arm" in ship stability, and if the righting arm length goes to zero because the combined center of gravity of the person in the chair goes past the edge of the rocker rail, the person and the rocker will fall over backward.

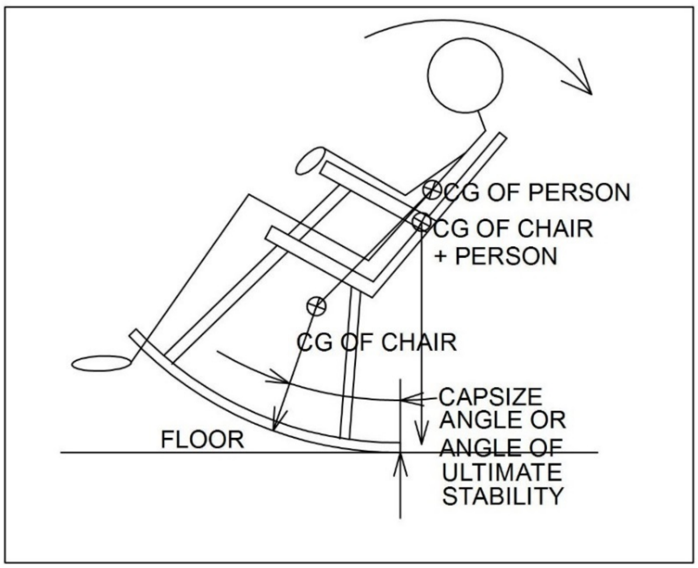

Figure 4: Person falls over backward when rocking too far

Like the person in the chair, the ship will capsize when the righting arm goes to zero. Most ships will lay on their side or turn upside down in this situation, and if there openings in the superstructure such as for engine room ventilation or a weathertight door has been carelessly left open, the ship will take on water and probably sink in the time it takes the crew to get their wits about them to do something to save it. Recent capsizing examples were the Costa Concordia cruise ship off Sardinia and the Golden Ray car carrier off Brunswick, Georgia. Both vessels ran aground in shallow water, which is analogous to rocking over a brick-the grounding raises the center of gravity because of the ground support, which reduces the immersed volume of the hull and therefore the buoyancy helping to keep the ship upright. And, in both cases they improperly ballasted the ship to try and counteract the water leaking into the hull, which further impacted the stability. The specifics of damage stability are covered in my separate class on www. Suncam.com.

Figure 5: Cruise ship Costa Concordia aground and capsized

Figure 6: Car carrier Golden Ray aground and capsized. Note the high-speed hull lines and how they transition to a nearly cubical shape above the waterline.(courtesy News4 Jacksonville)

Video of Austrian battleship capsizing in WW1:
https://www.youtube.com/watch?v=5pSiCjfhUUw

Only special vessels like the USCG 47' Motor Lifeboat or Royal National Lifeboat Institution (UK) vessels can right themselves, since they are specifically designed to be able to do this by having a combination of large volume watertight deckhouse relative to the hull and a low center of gravity, so that when upside down the center of gravity is high, inducing an extreme state of non-equilibrium, which will cause the vessel to roll so that the center of gravity is low again, thereby self-righting the vessel.

Figure 7: USCG 47’ Motor Lifeboat

Figure 8: RNLI Lifeboat

Why are submarines not covered in this class?

Submarines are a special case of intact stability because their centers of gravity and buoyancy are in opposite locations compared to surface ships. Because they can dive and surface, they also have properties which surface ships do not possess, and they therefore operate by a different set of criteria. Submarines are covered in my separate course “Submarine Stability” on www.Suncam.com.

Surface Ship Stability Theory

Ship stability theory is based on an understanding of the interrelationships between the height of the ship's center of gravity G, the metacentric height M, and the center of buoyancy B. Figure 9 shows the transverse case, but there is a similar longitudinal case as well. Stability is also a function of the moment of inertia of area of the waterplane, and it varies in proportion to the 4^{th} power of either the beam (transverse case) or waterline length (longitudinal case). Thus, the wider a ship is, the greater the transverse stability is because the stability improves by the beam to the 4^{th} power. The same happens with the longitudinal case. When damage occurs, stability decreases by a similar proportion, and is thus a dangerous situation.

Metacentric Height and VCG

The metacenter is a point located on the ship's centerline, and it rises or falls depending on the ship's heel angle. It is similar to the pivot point of a swinging pendulum. If the center of gravity G is at a height equal to or higher than M, the ship will capsize. Going back to the rocking chair analogy, if you were to stand in the rocking chair, your center of gravity would be very high relative to the center of gravity of the chair and the metacentric height. The combined weights of the chair and yourself, multiplied by the respective distances from the floor, results in a very high center of gravity G. It takes very little movement to the front or back in this case to topple the chair; a similar thing happens to a ship. If the VCG (or KG) is higher than the available metacentric height M, the ship (and you in the chair) will capsize. In ship terminology, this is when the distance from G to M (GM) goes to zero or negative. The vessel (and the chair) can only stay upright if the GM is positive.

Transverse Stability

Transverse intact stability theory can be visualized with the hull cross-section shown below:

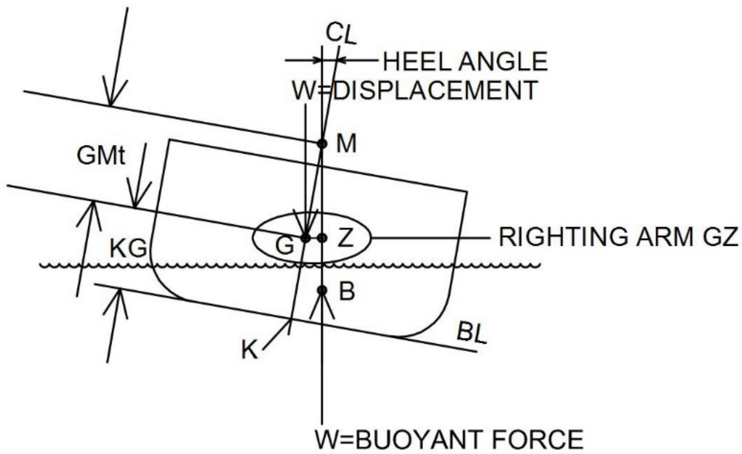

Figure 9: Transverse stability of a ship at a small angle of heel

G represents the position of the center of gravity of the ship. B represents the center of buoyancy of the ship. The value of G equals the value of B by Archimedes' Principle, wherein a ship displaces its weight in water. K represents the keel, or bottom baseline of the ship. The vertical distance from K to G is abbreviated as KG, and it is a measure of how high the center of gravity is above the baseline. Likewise, the distance KB represents the distance of the center of buoyancy above the keel. The horizontal distance GZ is the righting arm for small angles of heel, where GZ approximately equals GM sin (heel angle).

The righting moment is the product of the righting arm length multiplied by the buoyant force (which is equal to displacement). The righting moment is the magnitude of the restoring force that tends to cause the ship to return to its original equilibrium angle once the outside upsetting force subsides. As the ship is heeled by outside forces, the position of G stays the same, but the position of B shifts outboard as the shape of the immersed volume changes due to the heel angle. At the maximum distance that Z can move away from G, we get the peak maximum value of righting arm; as the hull heels further, the location of Z moves back toward G and the righting arm reduces eventually to 0 at the capsize angle.

Longitudinal Stability

Longitudinal stability is similar to transverse, only less important in general use because the transverse case is more critical because of the length versus beam proportions of the ship. Since stability is a function of the moment of inertia of area of the waterplane, it varies in proportion to the 4^{th} power of either the beam (transverse case) or waterline length (longitudinal case). Since most ships have a length/beam ratio of at least 3:1, the longitudinal stability is much greater than the transverse. In the longitudinal case the only time this makes much difference is when the ship floods by the bow or stern, and it immerses the weather deck. In such a case the non-immersed waterplane length decreases, the moment of inertia of area decreases by the 4th power of the decreasing length, and as the compartments below fill up with water, the resulting loss of buoyancy causes the ship to trim down more and more. The famous paintings of the Titanic and Lusitania sinking are good visual examples of this. In both cases the bow flooded past the point where the ships could sustain buoyancy, immersed the foredecks, and they started losing longitudinal stability. As the bow continued to flood, the stern of both ships rose to high angles before the final plunge.

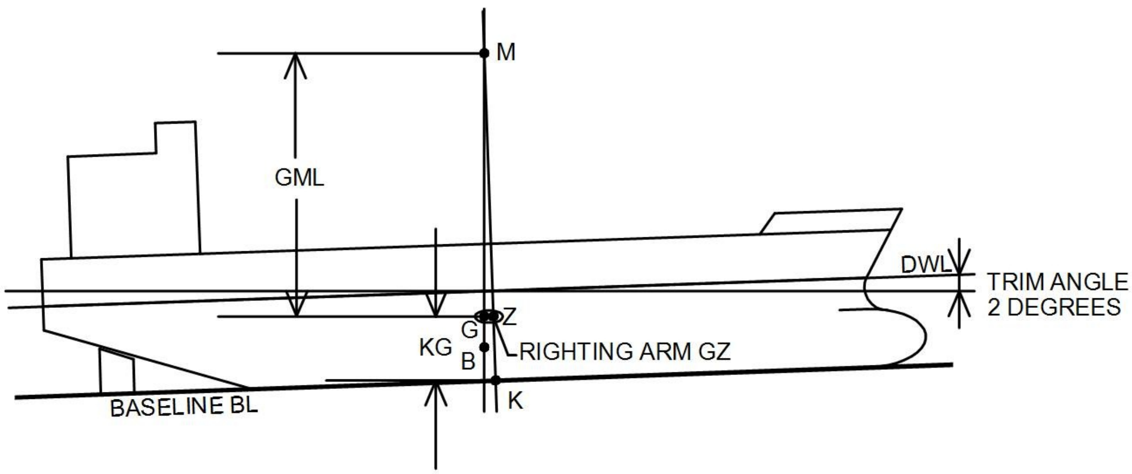

Figure 10: Longitudinal Stability of a Ship At a Small Angle of Trim

How is intact stability calculated?

There are two methods, depending on whether the ship in question is in the design stage or existing. For the design stage, first, the hydrostatics must be calculated for the ship. See my class number 460 "Hydrostatics" on www.Suncam.com for details of how this is done. In the case of a new ship design, there will be a detailed weight estimate that tells the light weight of the unloaded ship, and several loaded conditions such as Departure (100% Load), Mid-Voyage (50% Load), and Arrival (10% Load). (Also see my www.Suncam.com course number 436, Marine Weight Estimation and Control for details of this). In such a case, if an Inclining (Stability) Test has not been performed yet, the numbers being used are strictly for estimation purposes only since the Inclining Test is the true measure of the position of the ship's center of gravity-and the estimates are often low, or better, than the stability turns out to be. Adding a stability margin by increasing the VCG (or KG) by a small amount can be useful here in order to err on the conservative side.

Once the hydrostatics have been calculated by a suitable stability program, there is an existing digital model that has been created to do these calculations. The program will have a stability section where the user will input the displacement, trim or LCG, heel or TCG, and a range of heel angles that the computer model will be heeled to in order to calculate the righting arms and areas under the graphical righting are curve of areas at each incremental heel angle. It is required to input the longitudinal, transverse, and height locations of any openings which cannot be closed during operation of the ship, known as downflooding points, as there are stability criteria that take limitations by these into account. A stability curve looks like this:

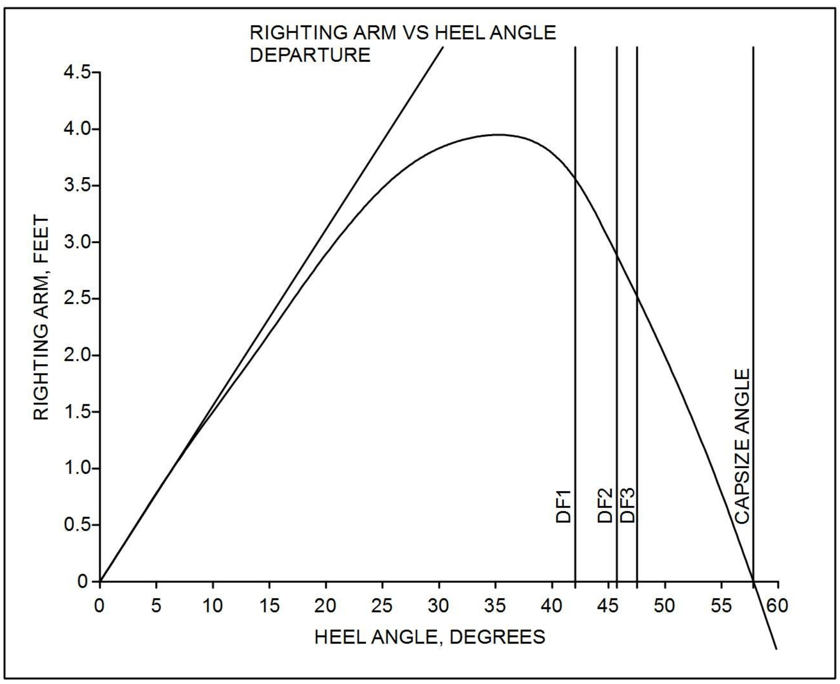

Figure 11: Graphical Representation of Transverse Stability

The graphical presentation of longitudinal stability is similar to transverse, but with trim angle replacing heel angle on the horizontal axis.

Figure 11 is a stability curve for a normal ship in good operating condition. The parabolic curve represents the values of righting arms at different heel angles. The stability increases as the ship heels up to a maximum of about 35 degrees, then starts to fall off. The peak stability tends to occur at the angle where the deck edge starts to be immersed. The downflooding points are all above 40 degrees and the capsize point is over 60 degrees. In this case the KG is low enough, and the buoyancy is high enough to provide the reasonable stability with reserve. To prove this, there are several equations relating area under the curve at specific angles and up to the lowest downflooding point, and there are required minimum values of righting arm. Intact Stability criteria for USCG Inspected vessels are shown in 46CFR Subchapter S, sections 170.160 to 170.173. These apply to various types of ships by function and size, and include criteria for hull reserve stability, weather (wind heel resistance), and International Stability requirements for seagoing ships doing international voyages. For example, using the most general criteria values (170.173(b)) for coastal-sized vessels described as vessels under 100 meters (328') long, and as "Vessels of Unusual Proportion and Form" (vessels other than tugs or towboats) for Figure 11, are:

	Complies?
Initial metacentric height (GM)>=0.49 feet	yes (4.25 feet)
Righting Arm (GZ) of at least 0.66' at angle>30 degrees	yes (3.75'at 30 deg.)
Maximum Righting Arm angle occurs at angle>=25 degrees	yes (37.5 degrees)
Area under RA curve>=10.3 ft-deg. up to 30 degree heel	yes (63.8 ft-degrees)
Area under RA curve to Max. RA angle>=16.9 ft-deg. up to 40 degrees	yes (102.9 ft-degrees)
Area under RA curve to Lowest Downflooding angle	yes (115.2 ft-degrees)
Area under RA curve from 30 degrees to 40 degrees>=5.6 ft-deg.	yes (39.1 ft-degrees)
Area under RA curve from 30 degrees to lowest DF angle>-5.6 ft- degrees	yes (46.3 ft-degrees)

The areas under the RA curve (also called "Righting Energy") are determined as the area under the curve from 0 degrees heel to each specified angle, and thus units are ft-degrees. The metric equivalent of this is meter-radians.

The several sets of criteria presented in Subchapter S vary based on the type of ship and what heel angle the maximum righting arm occurs. I have noted through several decades of use of these criteria on many vessels, that the criteria appear to have been developed for slower, round bilge steel vessels, which are generally deeper draft than aluminum or composite vessels. Both of the latter types often are hard-chine hulls rather than round bilge, because they are lighter and faster than the steel hulls. Consequently, because of their bilge shape and shallower hulls with lesser draft, the hard chine hulls develop their maximum righting arm at lower heel angles and when the criteria require the maximum righting arm to be at a heel angle greater than 30 degrees, this requirement can cause the need to ballast these light hulls to move the maximum righting arm angle. This results in a lower KG and therefore a quicker roll period. This was particularly true with the USCG 47' MLB stability (Figure 7), where we had to lower the KG by design to make it self-righting, with an upper weight limit of 40,000 pounds. The result was a roll period from upside-down (180 degrees) up to upright (0 degrees) in only 5.3 seconds! See further comments about roll periods below. I felt that the use of this criteria was inappropriate for the craft design, but there was no alternative at the time for light, hard chine vessels. There is a high speed stability criteria now under the International Stability criteria and this criteria is allowed to be used instead of the "Unusual Proportion and Form" criteria.

If the ship is existing, and a Stability Booklet and an Outboard Profile or Docking Plan is available, one can read the draft marks or measure freeboards from the Main Deck to the waterline at a number of points along the length of the hull to determine the draft. The Stability Booklet provided by the builder is then consulted to determine the existing state of stability by using the instructions, data contained therein, and calculations of where the overall KG is. In normal cases of loading, the resulting KG will be at or somewhere below the Allowable KG limit shown in the Booklet.

If the ship has a high center of gravity due to improper loading, above the Allowable KG limit, it may have what is called a "loll point" in the stability curve. A loll point is a very dangerous loading condition that gives warning in a peculiar way. A ship with a loll point will not sit upright at rest because from 0 degrees to the loll point, it has negative righting arm; but it will heel to the loll point on either the port or starboard side-in the case below, about 4.5 degrees. Small upsetting forces like wind or waves can cause the ship to rapidly shift to the other side of vertical, in this case rapidly shifting about 9 degrees. This is a clear indication of a ship ready to capsize permanently if a large enough external force was applied to push it past the capsize angle, in this case 30 degrees, and it is an indication of almost non-existent reserve stability.

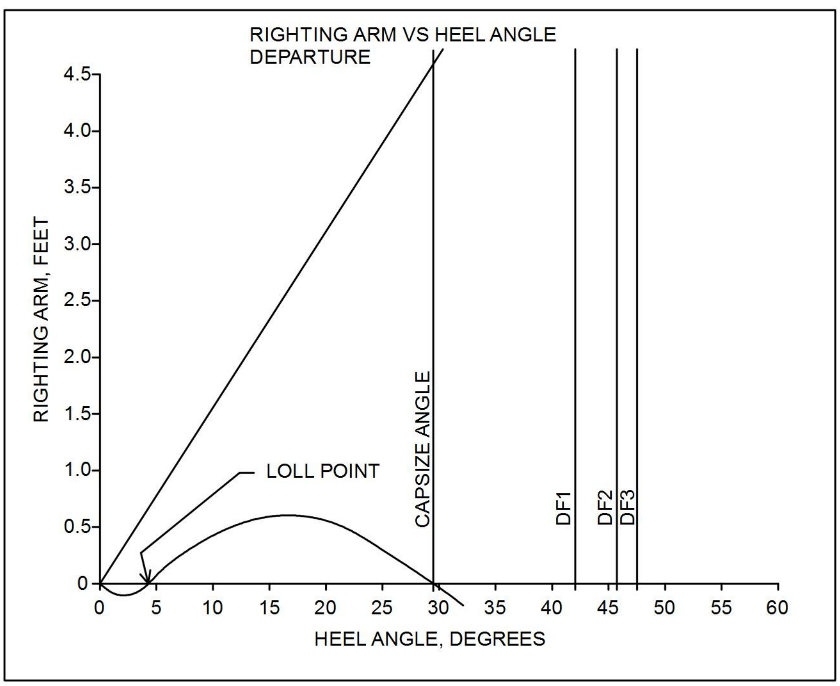

Figure 12: Stability Curve of a ship with a loll point

Roll Periods

A ship's roll period is a function of the transverse metacentric length (GMt) above the center of gravity and the ship's beam. This is like the length of a pendulum arm and the period of the pendulum swing. The roll period is the cycle time that it takes the ship to start a roll from one side, roll to the other side, and return to the start. Roll periods in sailboats are usually quite short since they have a lead or steel ballast fin below the hull to develop a sufficient amount of righting moment to counteract the wind forces on the sails. Large motoryachts over 100' long often have roll periods in the range of 4 to 10 seconds depending on their beam and amount of GMt. Modern cruise ships, on the other hand, in spite of their apparently high center of gravity, usually have gentle 10-20 second roll periods because they are often 92' wide so they can transit the original Panama Canal. Because of their large beam and the waterplane inertia being proportional to the 4th power of it, they have a huge amount of transverse stability and thus can afford to have a high G to lower the roll period without compromising the reserve. Roll periods in this 10-20 second range can be perceived as "comfortable"-shorter roll periods are "stiff" and are difficult to stand on deck in, and longer roll periods are cause for worry in small ships. Since transverse stability develops with the 4th power of the beam, cruise ships have a great deal of reserve stability in spite of their height. This is why they keep getting taller and taller; but they seem to have reached the limit of that on the recent MSC ships that set the balconies of the upper decks inboard of the hull apparently to save weight topside. When there is minimal GMt, the roll period can be very long. I once had to improve the stability on a 140' seismic vessel that had only 2 inches of GMt at the light weight condition, and I measured the (worrying) roll period at 30 seconds as a small boat went by and the wake hit us. Her stability at that point was perilous and she needed 80 tons of steel ballast added into her bottom and an increase in hull strength and allowable draft to lower the KG enough (and thereby increase GM) to meet Class reserve stability requirements. So, the roll period is a good off-the-cuff way to tell how good the transverse stability is. If the ship feels like it isn't going to stop rolling in one direction, it just might not!

The USCG 47' Motor Lifeboat mentioned above is an example of a powerboat with a quick roll period at the other end of the safety spectrum-the original design specs for the prototype required the boat to be capable of self-righting from 180 degrees upside down to right side up, intact or with the pilothouse or survivor compartment flooded, in under 30 seconds. It did the intact self- righting in 5.3 seconds, but I do not know if they actually flooded either of the compartments, risking the electronics, to test the damaged conditions. The builder made well over 100 copies though, so it must have met the damage specs. There is more about this in my class on Damaged Stability on www.Suncam.com. .

Ballast

In many cases, especially after the first Stability Test or after modifications, a ship will need to increase GM to meet required stability criteria. Fixed ballast can usually be added as needed to correct heel and trim, and to lower the overall KG to meet stability criteria requirements in all loading conditions. In the case of a Roll-On Roll-Off passenger ferry I worked on, the concept subcontractor underestimated the height of the ship's KG, and the results of the Inclining Test showed the need for an addition 200 long tons of ballast in the bottom amidships to meet Class requirements-a serious design error. Fortunately, we had just enough additional allowable draft to allow this, and it met contract requirements for the cargo she could carry. When properly ballasted, all loading conditions will fall under the Allowable KG curve shown in the Stability Booklet. For existing vessels undergoing modifications, Class and USCG requirements limit the change in the LCG position to 1% since the last Inclining Test, and displacement changes to between 2 and 10% in order to avoid having to do another Inclining Test. Since the KG usually goes up due to the weight of operational items that collect aboard over time, adding ballast of some sort and/or offloading unnecessary weight items is often necessary. Most ships larger than 100 feet may also have seawater and/or fresh water or wash water ballast tanks specifically located near the bow and stern to control trim, and a pair of transverse tanks to control heel. Many also have water ballast tanks located about amidships to cover light load conditions. These days, with the transfer of invasive species from one ecosystem to another in ballast water a concern, ballast water management has become a reportable and required process on board all ships. The IMO (International Maritime Organization) now requires a 2-fold water ballast management system to be employed on all ships under their requirements. The D1 Standard allowed for ships built before 9/8/2017 is an interim plan good until 2024 that requires ships to replace the water ballast that they took in at the start of the voyage with seawater taken aboard in mid-voyage ocean waters. The D2 Standard, the final requirement, requires all ships to have in place a Ballast Management System which documents test results for living organisms and a ballast water treatment device for killing them. It applies to all ships built after 9/8/2017 and all ships built before that date to have such a system in place at their next survey period.

One of the tricks to making ships with existing seawater ballast systems still usable is to disconnect the seawater inlet(s) to the ballast pump(s), relabel the tanks as "wash water" tanks and carry fresh, but not necessarily drinkable water in them. This water is not quite as dense as seawater, but it has the advantage of leaving the ballast system still usable as a transfer system long as the tanks cannot be filled with seawater, and the fresh water cuts down on interior corrosion. On vessels without a water ballast system, many times this is done by using a watermaker to keep the fresh water tanks full, and transferring fuel between tanks, but as the fuel is burned off, this method is limited, completely so if more than 10% of the total fuel must remain in the tanks as ballast to meet stability, as is common in aluminum motoryachts. Of course, one can almost always add lead, steel, or concrete ballast to lower the KG and/or minimize the amount of liquid ballast, especially fuel, that must be always carried to meet requirements, but the cost of ballast or availability of space or materials is not always convenient. Lead is the densest material, so it takes up the least space, but costs the most; steel is less dense but cheaper and more easily available, but it must be painted or coated in plastic to avoid messy corrosion, and concrete is least dense, pourable, can be made in many densities, is easily available, but must somehow be removable for hull survey inspections if Flag State Inspected or Classed. Cast cement blocks are a good answer for this, and they are very inexpensive but take up a lot of room compared to more dense forms of ballast.

A numerical example of how ballast lowers the KG is as follows:

Displacement before ballast	VCG(KG)	Vert. Moment
3,500 long tons	12.50 feet	3,500*12.50=43,750 ft-lt
500 long tons ballast	2.50 feet	500* 2.50= 1,250 ft-lt
4,000 long tons after ballasting	11.25 feet	45,000 ft-lt

The resultant KG is found by dividing the sum of vertical moments by the total displacement after ballasting, 45,000/4,000=11.25'; thus lowering the KG by 0.75'.

Internal Forces That Affect Stability

Internal forces that affect stability are Free Surface effects of slack fluids, passenger heeling moments, and shifting cargo.

Free Surface Effect

Free Surface Effect is the effect on the vessel's stability caused by the weight of shifting fluids in the tanks and bilges as the vessel is heeled by an outside force. If you held a rectangular box partially filled with water level, and then tilted it to model a heeling tank, you will notice that the waterline is deeper on the lower side of the box. As a result, a volume of water with a triangular cross section of water has been added to the low side and the same amount has been subtracted from the high side of the box. The resulting weight shift causes an effect on the height and the transverse location of the center of gravity of the ship, resulting in a fractional, virtual rise in the KG. If the tank is full to the top, the fluid cannot shift because it is confined by the tank boundaries; if the tank is near empty, all or most of the fluid can shift. There are two ways to calculate the effect on a tank. The first, conservative way applies only to deep tanks where the depth is greater than the width. Simply calculate the transverse moment of inertia of area of the tank ((length*width^4)/12), divide by the specific volume of the fluid, which is the reciprocal of the density, then add up these same values for all tanks that are not completely pressed full or are empty, and then divide that sum by the ship's displacement. The result will be a small number, usually less than a foot or two, to be added to the ship's KG to get the "corrected KG". In actuality, tanks that are pressed full such as fresh water tanks, at departure, do not stay that way for long, and fuel tanks are not pressed up in practice in order to avoid oil spills out of the tank vents. It is traditional to figure full fuel tanks at 95% full in naval service and 98% full in commercial service. Note in this method the free surface effect never varies until the tank is empty, which also doesn't actually happen in practice, since a 10% reserve is kept in the tanks to avoid sucking up water and sludge at the bottom of fuel tanks and to avoid running out of fuel should the voyage go longer than expected.

The more accurate way to calculate Free Surface Effects for shallow depth tanks is to do the calculations above for each tank, then apply the fractional coefficients developed for shallow tanks shown in "Principles Of Naval Architecture" (1988), Volume 1, pages 94-95, published by the Society of Naval Architects and Marine Engineers and various stability regulations. These fractional coefficients are listed for 50% and 95% load conditions, at heel angles from 5 to 90 degrees. They take the depth/width proportions into account, and they tend to reduce the values found by the conservative way in all conditions except where the tanks are much deeper than the width. These tanks tend to increase the calculated Free Surface Effect to a coefficient exceeding 1 because at higher heel angles, deep, narrow tanks start to behave like wide shallow ones. I have found the use of these coefficient tables very useful in calculating the stability of shallow draft vessels which may need to use fresh water, seawater and fuel as ballast to meet stability requirements. So, it is of great importance to be able to accurately calculate the total Free Surface Effect, especially in vessels with wide, shallow tanks. To see methods acceptable to the USCG, see Where To Find Stability Criteria below. If the Free Surface Effects of the liquids in tanks, or other free fluids such as firefighting water are not accurately accounted for, or leaking water starts filling one side, the liquid weight shifts can capsize the ship, as in the case of the S.S. Normandie fire in 1942. Here is a video of the unrestricted free surface effect on transverse stability of a barge loaded with a high center of gravity:
https://www.youtube.com/watch?v=ofylixqKoYo

Passenger Heeling Moments

On passenger vessels it is usual for most of the passengers to congregate on the top deck(s) and as far to one side as possible to get the best view. So, the combined heeling moment of this off-center weight must be accounted for when designing the stability of a passenger vessel. The USCG uses a standard passenger weight of 185 pounds per person, which was recently raised to account for the increasing obesity rate of passengers observed in casualty investigations. In order to pass the stability requirements for passenger vessels, all such vessels must show on their Stability Letter and in their Stability Booklet that they have the required GMt in all load conditions to meet or exceed the minimum requirements for passenger-induced heel. The process is to model the allowable passenger number on each deck, located at 1/4 of the total beam outboard of the centerline of the deck (or, halfway outboard), multiplying the number of passengers by 185 pounds times their distance off centerline at the above location, and sum the resulting moments. This is also similar to the ballast example above, except that the distance is from centerline instead of vertical from baseline.

Minimum required GM for mechanically-propelled or non-propelled vessels except pontoon vessels is required to be: [(W/D)(2/3)(b)]/tan T), where
W=total weight in long or metric tons of persons other than required crew, including personal effects of those expected to be on the vessel;
D=displacement of the vessel in long or metric tons;
b=distance in feet or meters from centerline of the vessel to the geometric center of the passenger deck on one side of centerline;
T=14 degrees or the angle of heel at which the deck edge is first submerged, whichever is less.

Passenger vessels complying with the International Code of Stability need not meet the above but must use 185 pounds per person for passenger weight.

Other types of vessels such as pontoon boats, monohull sailing and monohull auxiliary sailing vessels, and sailing catamarans have separate requirements.

Shifting Cargo

Shifting cargo is a dangerous condition that can rapidly change a stable ship to an unstable one. This happens as a result of:

- Improper stowage and lashing down
- The ship encounters weather and/or waves that are bad enough to heel the ship to high angles, resulting in increased dynamic accelerations of the cargo, failed tiedowns, structural deflections and failures

- Bulk cargos that shift for the above reasons
- Leaking or left-open cross connection valves on transverse pairs or triple tanks
- Tanks that leak into the bilges causing free surface effects not confined by the tanks
- Improper liquid ballast transfer due to incorrect knowledge of tank levels and contents

All of these reasons are pretty obvious, and their effects can be calculated in a manner similar to adding ballast or free surface effects above. Shifting bulk cargos are a little different, though, because recent research into the losses of several of these vessels have shown that the normal friction in bulk cargos which tend to keep them relatively solidified during the voyage, can be significantly reduced if the humidity level in the holds is high, resulting in water condensation that seeps into the cargo, thereby lubricating the individual bits of bulk material and lowering their slide resistance. The same is also true with coal, powder, metal ores, and grain cargos, where moisture and spontaneous combustion can create gasses that bubble up in the material, inflating what was a relatively solid material, and causing the material to behave as a liquid. When this happens, there is a Free Surface Effect that occurs with perhaps a much denser material than the usual tank liquids, and since this effect is a function of the specific volume, the virtual KG addition from it can be significant. And if such a shift happens to all of the cargo holds tilting the ship to one side, the task of manually shoveling all of the shifted cargo or carrying man-portable bags by the thousands is an impossible job at sea. This has been particularly true with nickel ore ships crossing the Pacific. If these ships alternate between loads of light grain and heavy nickel ore, they cannot fill the holds to the top with nickel ore because the ship's cargo volume and weight capacity is limited by the lighter loads of grain it is designed to carry.

External Forces That Affect Stability

Wind Heel

Everyone has seen sailboats heeling in the wind, but what many of those not knowledgeable about sailing do not know is that the heel angle is an equilibrium established by the wind pressure * sail area (a heeling moment) and the ballast * transverse KG offset distance from the center of wind pressure (a righting moment) on the sails, and that the boat will not keep rolling because these moments are equal. Heel-wise, it is just like the balance of a teeter-totter with a light person above the water at the long end, and the heavy person below the water on the short end. Wind force on a powered ship also causes pressure on the ship above the water which results in a small amount of heel in light winds. The USCG requirements for wind heel stability of mechanically-propelled vessels are listed in Code of Federal Regulations (CFR) 46, Subchapter S section 170.170, which must be met to show that the vessel possesses enough reserve stability to meet their requirements for whichever of the categories the vessel will operate in, be they Lakes, Bays, and Sounds, Protected Waters, Partially Protected Waters, or Unprotected Waters (going from least to most required reserve).

The method they use is to first calculate the side profile area of the vessel above the lowest load waterline, and to find the height of the center of wind pressure above that waterline. Next, do the same for the underwater profile, and find the distance of the center of the underwater profile below the same waterline. The sum of the two distances to the centers is the wind heeling arm and this, plus the two areas and the calculated value for wind pressure P must be input into the appropriate equation to get the minimum required GMt.

Minimum GM>=PAH/W*tan(T), where

P=a wind pressure coefficient determined by the operational area and the length of the vessel in feet or meters;

A= projected lateral area in square feet (square meters) of the portion of the vessel and deck cargo above the waterline;

H= the vertical distance in feet (meters) from the center of A to the center of the underwater lateral area or approximately to the one-half draft point;

T= either:

(1) the lesser of either 14 degrees heel or the angle of heel in degrees at which one-half the freeboard to the deck edge is immersed; or

(2) for a sailing vessel, T = the lesser of either 14 degrees or the angle of heel in degrees to the deck edge.

The deck edge is to be taken as the intersection of the sideshell and the uppermost continuous deck below which the sideshell is weathertight.

See the section in CFR46 for further conditions.

Wave Effects-Ordinary Waves and Wakes

Wave affects are caused by unequal buoyancy on one side or one end of a ship as it passes over a wave swell. This is the ordinary cause of rolling at sea, but in the case of large waves, they accentuate the heeling effects. If a ship has a roll period that happens to equal the wave passing frequency, such as in the wake of a passing ship, the effects are even worse, as each passing wave adds energy to cause increasing roll angles until the last wake wave has passed. I have a friend who had a 27 foot powerboat that had the same roll period as passing powerboat wakes-the first wake wave caused it to heel about 20 degrees which it hit on the side; the second roll was about 30 degrees, the third was about 40 degrees, and the fourth was almost 50 degrees! The diesel-powered boats of this make didn't have the problem because the engines were heavy, but his gas engine-powered boat was too light below. The solution was to either add ballast to equal the diesel weight, or to put his full icechest up on the flybridge. The former would lower the roll period, and the latter would increase the roll period away from the exciting frequency. In the case of really large waves, they can crash against the ship, imparting a strong heeling force and possibly causing damage. The USCG does not require calculations for this, but Class design rules for ship structure provide guidance for the design of ships operating in ordinarily expected wave sizes; but at some time in their life a ship may exceed the design parameters.

Grounding

Grounding of the ship lifts it higher in the water at the point of the grounding. This reduces the available buoyancy and raises the virtual KG, similar to a free surface effect. Figures 5 and 6 are examples of this.

End Launching

Ships that are end-launched always experience a similar effect to grounding and it is important that they have sufficient ballast in them and speed down the launch way to overcome the momentary loss of buoyancy and KG effect so that GM does not go to zero. Here is an example of one that did not have enough ballast or speed:

https://www.youtube.com/watch?v=N6TYQZd0HPs

Weights Hanging overboard

A weight hanging overboard will induce two effects: a heeling moment on a ship just as at does on a crane, and a temporary raising of the overall value of KG against the metacentric height, reducing GM. It is important in such cases that any portlights, cargo loading doors, or other openings are closed watertight. The weight multiplied by its distance off centerline produces the heeling moment, and a calculation similar to the ballast calculation above will give the rise in KG. It is therefore important to have a good knowledge of the actual KG of the ship, the weight of the hanging object, and its height above baseline at the highest point. Vessels that lift cargo must meet 46CFR section 173.005 and 173.007.

Ice and Water On Deck

Ice and water both constitute an added weight on deck and in the case of ice, all over the superstructure. Water on deck, if not drained immediately through the freeing ports in the bulwarks and deck drains, also constitutes a free surface effect at a high location. All of these are detrimental to the ship's stability and can create disastrous consequences if not dealt with immediately. They both tend to lower the ship's GM, increasing the possibility of capsizing. In the case of icing, it is imperative that the crew knock off as much ice as they can in order to minimize the accumulation of topside weight, especially if the holds are loaded with water and catch.

Towing Using Cables

Towing using cables creates an overturning moment in the case of side loads, and/or a drag on aft trim. Many tugs have been lost by the barge under tow swinging around the side and pulling the tug over sideways. The USCG has special requirements for reserve stability of towing vessels. Towline Pull criteria are listed in 46CFR section 173.095 for conventional, Voith-Schneider (rotating vertical blades), and azimuthing thruster (Z-drive and azipod)-propelled tugs.

Currents

Currents may affect a ship at anchor by either causing it to drag the anchor, or by creating a sideways heeling force if it shifts the ship so that the current acts sideways, and the anchor holds. Currents combined with wind can compound the issue of side loading, especially if the ship has set a bow and stern anchor as is common in shallow bays where the current runs quickly and reverses.

Where To Find Stability Criteria

The USCG requirements for stability are listed in Code of Federal Regulations (CFR) 46, Subchapter S (sections 170.00 to 174.360). The sections are divided as follows:
Part 170: Stability Requirements for All Inspected Vessels

- Section 170.001 shows applicability to all vessels inspected of built to Subchapter C or E, or is a foreign vessel built under Subchapter O, built on or after 3/11/1996, and notes that vessels built before that date may continue to operate under the rules previously in effect unless they have alterations or repairs done, which then requires them to meet section 170-005.

- Section 170.160 shows applicability of the stability regulations to all vessels but noted exceptional types, which have their own specific requirements shown in later chapters;
- Section 170.165: International Code on Intact Stability references the stability criteria in the International Code Introduction and Part A which must be met for vessels undertaking international voyages, those required to obtain any of four Certificates, and an exception for those vessels not requiring any of the Certificates;
- Section 170.170 defines Wind Heel required GMt requirements as noted above;
- Section 170.173 Stability Criteria for Vessels of Unusual Proportion and Form. These criteria apply to all vessels under 328 feet (100 meters) long except for tugboats and towboats.
- Section 170.285 describes acceptable methods for determining free surface effects for intact stability calculations.
- Section 170.290 describes acceptable methods for determining free surface effects for damage stability calculations. Specifics of Damage Stability are covered in a separate Damage Stability class.
- Section 170.295 describes special consideration for determining free surface effects for passive roll stabilization tanks. These are transverse tanks specially constructed to reduce vessel roll amplitude by using loose water flow calculated to transfer at a rate which will counterbalance the other tank fluids that have flowed to the low side.
- Section 170.300 describes special consideration for determining free surface effects of spoil in hopper dredge hoppers. This is about the watery slurry of dredge spoils (mud, sand, and rock) in the hopper.

Part 171: Special Rules Pertaining To Vessels Carrying Passengers

- Section 171.001 describes general applicability
- Section 171.012 describes other criteria incorporated by reference (which see below)
- Section 171.015 describes how to establish the “margin line” on various hull sheer types
- Section 171.045-057 describes intact stability criteria for various types of vessels
- Sections 171.130-171.155 describe drainage requirements of various vessel deck features

Part 172: Special Rules Pertaining To Various Types of Bulk and Hazardous Cargoes

Part 173: Special Rules Pertaining To Vessel Use

- Section 173.001 describes applicability to vessels engaged in lifting, training (schoolship), Oceanographic Research, and Towing
- Sections 173.005-173.095 describe intact and damage stability criteria for each of the applicable types. Specifics of Damage Stability are covered in a separate Damage Stability class.

Part 174: Special Rules Pertaining To Specific Vessel Types

- Section 174.005 describes applicability to deck cargo barges, mobile offshore drilling units (MODUs), tugboats and towboats inspected under Subchapter I, self-propelled hopper dredges with an assigned working freeboard, oceangoing dry cargo and roll on/roll off ships over 500 gross tons as measured by International Tonnage Convention, 1969, offshore supply vessels inspected under Subchapter L, and liftboats inspected under Subchapter L.
- Sections 174.010-173.360 describe intact and damage stability criteria for each of the applicable types. Specifics of Damage Stability are covered in a separate Damage Stability class.

Subchapter T, Part 178: This describes the stability requirements for various vessels inspected under Subchapter T (passenger vessels under 100 gross tons, under 65 feet (19.8 meters) long, and carries not more than 12 passengers on an international voyage). It mostly refers to Subchapter S, but also includes how a Simplified Stability Test is done for vessels under 65 feet long.

- Section 178.310 describes general requirements
- Section 178.320 describes criteria for various small vessels including monohulls, catamarans, and pontoon vessels
- Section 178.325 describes stability criteria for monohull sailing vessels
- Section 178.330 describes how to conduct a Simplified Stability Test
- Section 178.340 describes stability criteria for pontoon vessels on protected waters

Various Marine Safety Center Guidelines published by the USCG
American Bureau of Shipping Rules For Classing of Steel Ships and many other ship and material types
Various similar Class Guides published by the Marine Coastguard Agency (U.K.)
Cayman Islands Ship Registry regulations, and other Flag States
International Maritime Organization (IMO) Stability Criteria

The IMO is an organization under the United Nations that publishes marine regulations in the form of "Resolutions" of the Marine Safety Committee which cover many aspects of marine commerce. Two that have been adopted by the USCG into their requirements are:

- Resolution MSC 216(82), Amendments To The International Convention For Safety of Life At Sea (SOLAS), adopted 12/8/2006, and
- Resolution MSC 267(85), Adoption of the International Code On Intact Stability, 2008.
- SOLAS is the set of international regulations dealing with requirements for stability, fire resistance and firefighting, bilge systems, lifeboats, liferings, and life preservers, and many other safety aspects that are required for ships doing international travel.

There are also several other stability-related resolutions that deal with specific types of vessels, which can be used as substitutions or "equivalents" in cases where a vessel cannot meet the USCG standards but can meet some other appropriate standard.

Stability Booklet

All maritime regulation authorities require the submittal of stability calculations for approval. Some Flag States have more relaxed stability requirements than the USCG; several for example allow charter motoryachts to operate as passenger vessels with a limit of 12 passengers, a 60 mile offshore limit of operation, and require intact stability calculations only. Oceangoing cargo ships differ, in that they are often required to meet much more stringent criteria because the risks to their operation are much greater. Each vessel is supplied by the builder with a Stability Booklet, or a computer program, which details the following load conditions:

Lightweight (dry ship with no fuel, cargo, water, sewage, passengers, crew, or provisions)
Departure Load (100% cargo, passengers, crew, provisions, fresh water, 95% fuel, hydraulic and lube oil, 10% sewage and shower/sink drain (gray) water
Mid Voyage or 50% Load (100% cargo, crew, and passengers, 50% fuel, 50% water if not having watermakers, 50% sewage and gray water, 50% provisions)
Arrival Load (100% cargo, crew, and passengers, 10% fuel, 50% water if not having watermakers, 100% sewage and gray water, 10% provisions)
The purpose of the Stability Booklet or program is to:

- Give instructions to the Master of how to prepare the ship to go to sea and what safety methods are to be employed in all conditions;
- Show that the vessel meets required stability criteria, both intact, and if required, damage stability;
- Show that the vessel meets required watertight subdivision length in her watertight compartments;
- Provide the officer in charge of stability with the necessary blank forms, hydrostatics, righting arm curves, tank sounding tables, light ship weight and weight centers, and instructions on how to calculate the vessel stability condition for any standard and/or unusual condition of loading;
- Provide the calculations from the latest Inclining Test, and allowable weight and center of gravity margins
- Provide an Allowable KG curve so that the officer can plot the answer to his or her calculation on a graphical representation of the safe and unsafe regions of loading.

The Naval Architect prepares this information and submits it to Coast Guard, Flag State, and/or Class for approval, and once approved it gets issued to the ship. The USCG also issues a "Stability Letter" that states that approval has been given, on what date, with the light ship weight and center of gravity values, allowed cargo load, allowed number of passengers and crew, a record of any fixed ballast aboard, a list of operational limitations if any, such as reserve fuel, seawater, or freshwater ballast which must be carried at all times, and the freeboard measurements.