A SunCam online continuing education course

Hydrostatics, Wetted Surface Area, and Bonjeans Curves

by

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Hydrostatics, Wetted Surface Area, and Bonjeans Curves

This class covers the following topics:

Important reference datums or axes
Useful terms and abbreviations
How Hydrostatics are calculated
What information is contained in the Hydrostatics
How to read a Hydrostatic Table
How to read the Hydrostatic Curves
Differences in accuracy between the two sets of Hydrostatics
Wetted Surface Area calculation
Bonjeans Curves

Hydrostatics are the mathematical properties of a static floating hull. The basis of hydrostatics derives from Archimedes' Principle, which states that a floating or submerged body in water displaces its own weight in water, and so floats or stays neutrally buoyant as the result of an equilibrium condition between the vessel's weight and the buoyant forces opposing it. The hydrostatics are calculated at regular intervals of the ship's draft and for various amounts of fore-and-aft trim, so that the stability calculations can be done and thus the stability condition may be known at any condition of loading. It should be noted that the hydrostatics for salt water and fresh water are different, because of the differing densities of the fluids. Salt water weighs 64 pounds per cubic foot (1.025 tonnes per cubic meter), and fresh water weighs 62.4 pounds per cubic foot (1.00 tonnes per cubic meter), so a ship's draft will be deeper in fresh water than salt, for the same vessel weight, or displacement. The calculated results are published in the Stability Booklet provided by the builder or Naval Architect for use by the ship's officers, and many modern ships now have computerized loading programs that determine the stability conditions and safety limits to operate the ship within.

Important reference datums or axes

The calculation of hydrostatics is referenced to the datum lines as shown below.

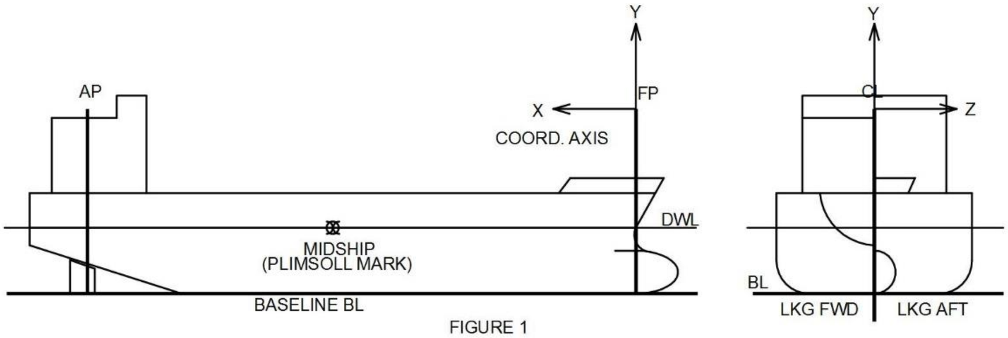

FIGURE 1

Some useful terms and abbreviations are as follows:

Reference Axes-the longitudinal centerline at the base of the ship is called the baseline. All vertical references are made relative to the baseline. This is abbreviated as BL. This is shown on all profile and elevation drawings of the ship.

The Longitudinal Reference Datum in American surface ships is generally at a position near the bow, called the Forward Perpendicular. This is abbreviated FP, and it is usually located at the intersection of the design waterline and the stem (forward-most vertical outline structure of the bow). Measurements from the FP proceed aft, and so do the structural frame numbers if they are shown. Vessels designed and built elsewhere, and all submarines, usually use the aft perpendicular (AP) as the start of the longitudinal reference axis. The location of this historically was where the rudder post was located, but modern ships may have an arbitrary or frame location used for this. 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. The halfway length of the Design Waterline length from the stem to the transom or stern is called the midship point. 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.

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 if they have excessive Free Surface Effect (which see below).

Centerline (CL)-the longitudinal 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, but it is shown on all plan view drawings of the ship.

Center of Buoyancy (CB)-the center resultant point of all buoyant forces operating against a hull. There are longitudinal, transverse, and vertical centers of buoyancy (LCB, TCB, and VCB, or KB, which see below)

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 CD1' 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).

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)

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.

Fore-and-Aft: nautical term for forward (towards the bow, or front), and aft (towards the stern, or back end)

Free Surface Effect-the effect of sloshing liquids in tanks and bilges as the shifting weight of fluids move from side to side, or forward and aft.

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.

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.

Longitudinal Center of Buoyancy (LCB)- the location of the equilibrium point of the buoyant forces on the immersed volume of the hull at a longitudinal distance from the vertical datum (FP, AP, or Midships). The trim of the vessel is caused by a separation of the LCB and the LCG; the longer the separation, the greater the trim. If the LCG is aft of the LCB, the trim is by the stern, or aft.

Longitudinal Center of Flotation (LCF)- a point on the top waterline of the immersed hull, measured from the vertical reference datum, about which the hull trims when acted upon by the separation of the LCG and LCB. It is similar to a teeter-totter pivot (fulcrum) point.

Longitudinal Center of Gravity (LCG)-this is position of the forward or aft location of each item accounted for in the weight estimate, and the total ship, measured from the longitudinal reference axis. 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 positive, so that aft trim, which is generally desirable, is positive.

Metacenter (M)-this is a point similar to the 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. There is a longitudinal metacentric height {KML), and transverse metacentric height (KMT), each of which are like the length of a pendulum arm, and the KML is always longer than the KMT unless the ship is the same length as its width, or it has damaged compartments filling with water.

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.

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).

Tank (Sounding) Tables-these are tables for each tank in the hull showing, at regular intervals like 1" from 0% to 100% full, of the weight of the fluid, volume of the fluid, LCB, VCB, TCG, and the free surface moment of inertia (FSM) of area of the fluid plane. They are similar to the hydrostatics for the entire ship, but only apply to the tanks.

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 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 the immersed hull volume of the total ship and each item accounted for in the weight estimate that may affect the buoyancy (such as appendage like rudders, stabilizer fins, bilge keels, shafts and propellers, struts, and subtractions to buoyancy like seachests, thruster tunnels and moonpools).

Transverse Center of Gravity (TCG)-This is the transverse distance to port (-) or starboard(+) of each item accounted for in the weight estimate, plus 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.

Ullage-the measured distance from the top of a tank to the fluid level. The mathematical complement of the sounding of the fluid depth, or, the measured distance from the inside top of the tank down to the fluid level.

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 Ṽ)-the immersed volume of the ship or volume of a tank.

Waterplane Area (WPA)-the area of the waterplane at a specific draft, in square feet (Imperial), or square meters (metric)

How Hydrostatics are calculated

Before computers, the hydrostatic values were determined by triple integration of the volume using waterplane areas, drafts, section areas, and lengths between sections. It was a very laborious process that took weeks to do using mechanical planimeters and integrator machines. Computers do this in a very short amount of time now in various Naval Architecture-specific programs such as GHS, AutoHydro, NAUTILUS, RHINO, Ship Constructor, FORAN, and others. All programs require the user to develop a wireframe model from offsets or a 3D surface model in the program, input the desired drafts, trims, displacements, and heels, and the program does the rest at the push of a button.

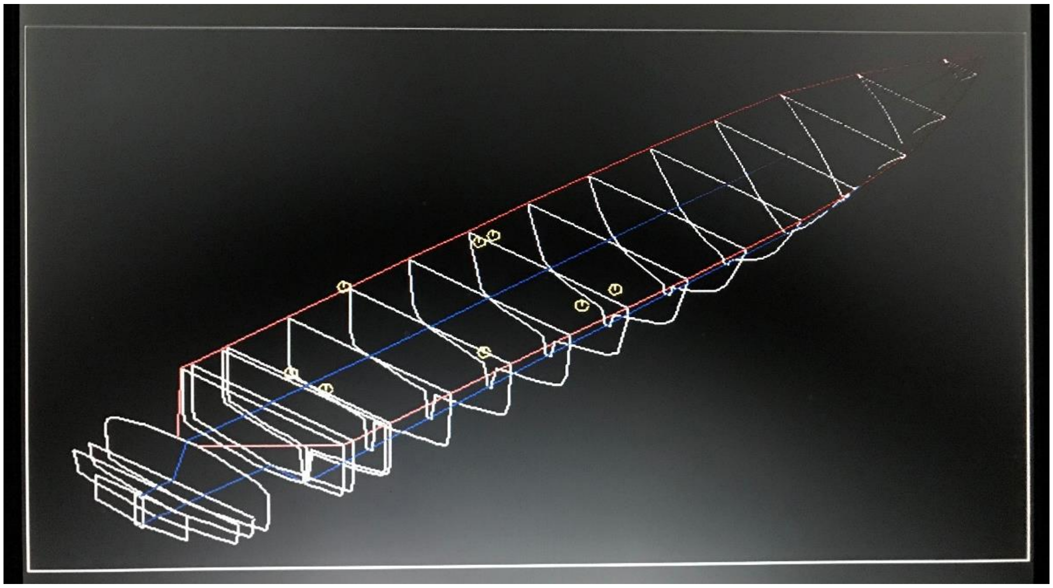

Figure 2: Wireframe hull model of a modern yacht with a swim platform

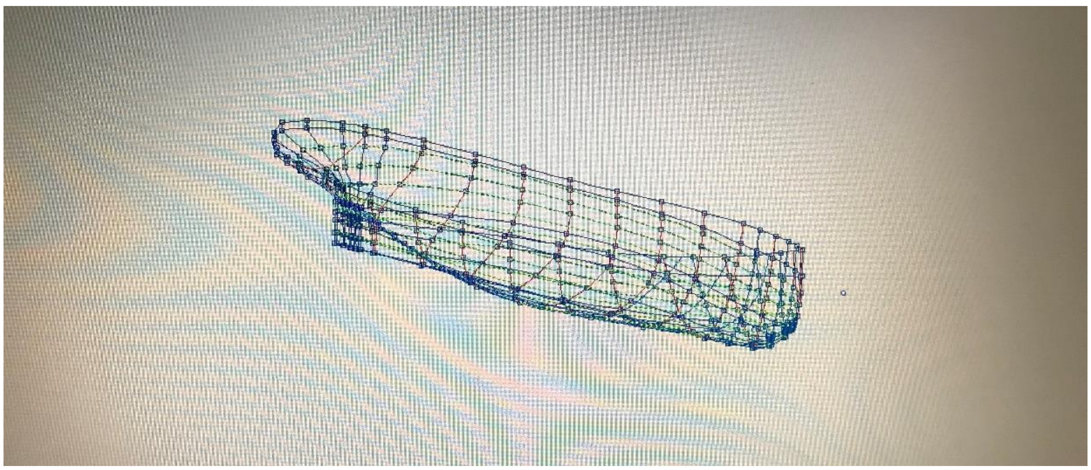

Figure 3: 3D surface model of a tugboat hull

The accuracy of the calculations depend on the number of transverse cuts the computer makes, as directed by the user. You will notice in the wireframe model that there are several closely spaced sections where there is an abrupt change in hull depth; this is so that the computer makes more calculations of section areas in those locations, improving the accuracy of the results. The wireframe model is created by inputting offset points from the hull lines plan developed on a drafting board of in a 3D surface modeling program like ProSurf3. The 3D program can convert a 3D model to a wireframe type for hydrostatic calculation. The close spacing of sections is also the case with the surface model shown towards the aft end, but in the 3D modeling case the close spacing in the skeg at the end of the hull allows the separation of the vertical lines that sweep around the curved stern.

It is common to calculate hydrostatics for 0, 1’, and 2’ forward and aft trims on ships to about 200 feet long, and to higher trims in longer ships to cover a multitude of conditions. Some programs are more capable than others (and cost more) depending on the complexity of the models that can be built and managed, the graphics they produce, the number of interior compartments that can be used, etc. The less expensive simpler programs only do the exterior hull and some appendages such as rudders, keels, bow thruster tunnels, and stabilizer fins. The more professional programs include compartment models with varying permeability (floodability of the compartment) so that intact and damage stability, and allowable watertight subdivision (compartment lengths) can be calculated. The details of how this is done and used are covered in my classes on Intact and Damaged Stability.

What information is contained in the Hydrostatics

A Table of Hydrostatics looks like this:

HYDROSTATIC PROPERTIES
No Trim, No Heel, Fixed VCG = 0.00

LCF Draft	Displacement Weight (LT)	Buoyancy-Ctr. LCB	VCB	Weight/ Inch	LCF	Moment/ In trim	KML	KMT
6.900	291.45	57.63f	4.37	5.93	51.17f	43.20	204.8	16.36
6.950	295.01	57.55f	4.40	5.96	51.02f	43.79	205.1	16.34
7.000	298.59	57.48f	4.43	5.99	50.88f	44.33	205.2	16.32
7.050	302.18	57.40f	4.46	5.99	51.00f	44.22	202.2	16.24
7.100	305.78	57.32f	4.49	6.02	50.86f	44.79	202.4	16.22
7.150	309.40	57.25f	4.52	6.03	50.82f	45.08	201.4	16.18
7.200	313.02	57.17f	4.55	6.05	50.79f	45.36	200.2	16.14
7.250	316.66	57.10f	4.58	6.06	50.77f	45.62	199.1	16.10
7.300	320.30	57.03f	4.61	6.08	50.75f	45.88	197.9	16.05
7.350	323.95	56.96f	4.64	6.09	50.73f	46.13	196.8	16.01
7.400	327.61	56.89f	4.67	6.11	50.72f	46.38	195.6	15.97
7.450	331.28	56.82f	4.70	6.12	50.70f	46.62	194.4	15.92
7.500	334.96	56.75f	4.73	6.13	50.69f	46.85	193.3	15.88
7.550	338.64	56.69f	4.76	6.15	50.69f	47.07	192.1	15.83
7.600	342.34	56.62f	4.79	6.16	50.68f	47.29	190.9	15.79
7.650	346.04	56.56f	4.83	6.17	50.68f	47.51	189.7	15.74
7.700	349.74	56.50f	4.86	6.18	50.68f	47.73	188.6	15.70
7.750	353.46	56.44f	4.89	6.20	50.67f	47.95	187.4	15.66
7.800	357.18	56.38f	4.92	6.21	50.67f	48.15	186.3	15.61
7.850	360.91	56.32f	4.95	6.22	50.67f	48.36	185.2	15.57
7.900	364.65	56.26f	4.98	6.23	50.67f	48.57	184.1	15.52
7.950	368.39	56.21f	5.01	6.24	50.68f	48.78	183.0	15.48
8.000	372.14	56.15f	5.04	6.24	50.81f	48.61	180.5	15.42
8.050	375.88	56.10f	5.07	6.25	50.81f	48.82	179.5	15.38
8.100	379.64	56.05f	5.10	6.26	50.81f	49.03	178.5	15.34
8.150	383.40	56.00f	5.12	6.27	50.82f	49.23	177.4	15.30
8.200	387.16	55.95f	5.15	6.28	50.83f	49.42	176.4	15.26
8.250	390.94	55.90f	5.18	6.29	50.83f	49.61	175.4	15.22
8.300	394.71	55.85f	5.21	6.30	50.84f	49.79	174.3	15.18
8.350	398.50	55.80f	5.24	6.31	50.86f	49.97	173.3	15.14
8.400	402.29	55.76f	5.27	6.32	50.87f	50.15	172.3	15.10
8.450	406.08	55.71f	5.30	6.32	50.89f	50.28	171.1	15.07
8.500	409.88	55.67f	5.33	6.33	50.91f	50.46	170.1	15.03
8.550	413.69	55.62f	5.36	6.34	50.92f	50.63	169.1	15.00
8.600	417.50	55.58f	5.39	6.35	50.93f	50.80	168.1	14.96
8.650	421.31	55.54f	5.42	6.36	50.95f	50.98	167.2	14.93
8.700	425.13	55.50f	5.45	6.37	50.97f	51.15	166.3	14.89
8.750	428.95	55.46f	5.48	6.38	50.98f	51.32	165.3	14.86
8.800	432.78	55.42f	5.51	6.38	51.00f	51.47	164.3	14.83
8.850	436.61	55.38f	5.54	6.39	51.02f	51.64	163.4	14.80

Distances in FEET.-------Specific Gravity = 1.025.-----------Moment in Ft-LT.
Trim is per 115.16Ft
Draft is from Baseline.

Figure 4: Hydrostatic table. Note that it is referenced to the AP as shown by the f's in the LCB and LCF columns.

How to read a Hydrostatic Table

One starts by either reading the draft marks at the bow, stern, and if available, amidships. If the ship is in the design stage, one reads whatever draft they are interested in from the Outboard Profile and Arrangement drawing. Then you read information in the appropriate trim table by looking at the draft column to the left, and then entering between the two drafts nearest to that of interest. The adjacent columns are labeled for values of the draft at the LCF, displacement, LCB, VCB, LCF, Tons/Inch, or TPI, MT1" or MT1', KML, and KMT. Other values can be added, such as VCB, TCB, CDTrim or CDT1" or CDT1', immersed volume V, wetted surface area WS by adding these in the program. To be most accurate, if the trim is not at the amount calculated in the table, all values must be interpolated between two adjacent trimmed tables. Or, let the software do the work by inputting the exact condition values of trim or LCG, draft, heel, and KM. The computer can do all the interpolation is a split second, but if you are a ship's officer and you don't have the program, it's back to manual interpolation.

How to read the Hydrostatic Curves

If you have the Hydrostatic Curves, the interpolation between adjacent drafts is done for you in graphical form, so interpolation between trims only must be done. One can simply draw a horizontal line across the curves at the desired draft, then and read the values for the curves from the scales at the top or bottom and multiplying by the coefficients listed with each curve.

A plot of the hydrostatic data looks like this:

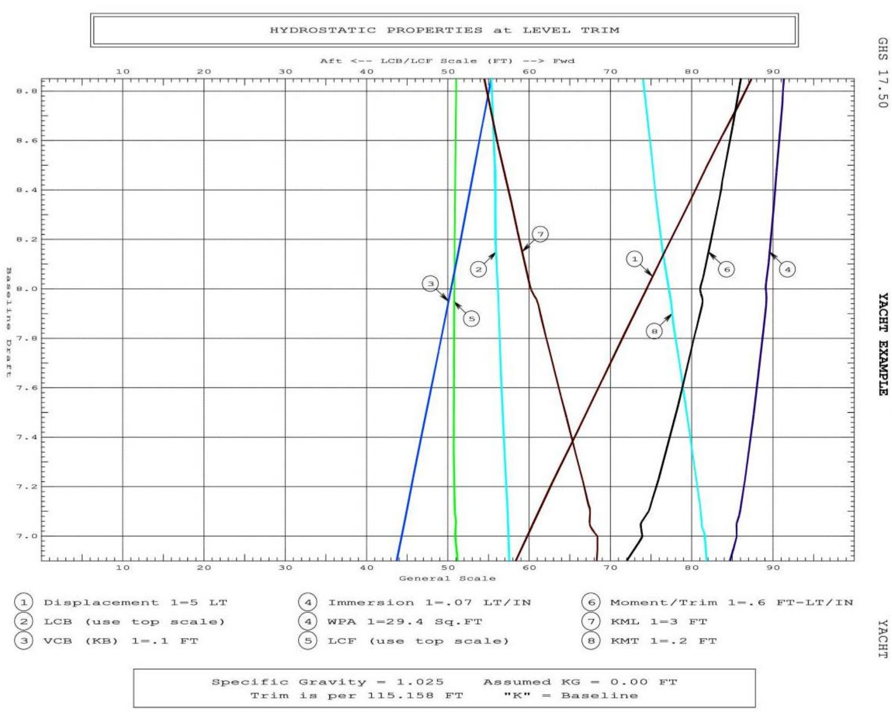

Figure 5: Hydrostatic curves

Differences in accuracy between the two sets of Hydrostatics

If you are not so concerned with being absolutely accurate, then the Hydrostatic Table at the nearest draft will do. The Hydrostatic Tables are good for approximating the values, but it requires interpolation between the listings to get very accurate. The Hydrostatic Curves (also called Curves of Form) drawing does the interpolation for you at each nominal trim by showing the values as lines on graphs, and all you must do is pick the values straight off of the curves at the displacement or draft(s) you calculated. All of the curves for displacement, LCB, VCB, immersed volume V, Waterplane Area WPA, LCF, MT1" or MT1', KML, and KMT are shown on the drawing. The interesting thing to see on the Curves of form is the trends in the various hydrostatic properties as the draft increases-something that is much more difficult to see and understand rom the Table of Hydrostatics. It's kind of like looking at a road map versus using the route map function on your phone-you get a bigger picture looking at the graphic representation.

Wetted Surface Area

Wetted surface area is often shown on Tables and Curves of Hydrostatics at the shipyard because this calculation for various hull depths assists in estimating the amount of hull plating and paint that is needed, and it is information useful in the estimation of hull resistance for powering calculations. However, it is not usually included in the ship's Stability Booklet.

Bonjeans Curves

These are named after a French Naval Architect in the 19th century who was the first to use them. The Bonjeans Curves are a set of graphics that show how total cross-sectional area increases with hull depth at various points along the length of a ship. This is not to be confused with hull section cuts, as shown on the Hull Lines plan. Bonjeans Curves are drawn on a profile of the ship with draft scales forward and aft. They are useful for manually determining the draft of a ship at any point on its length when the trim is excessive. Since computers do this computation today, there is not a lot of use for the manual plotting technique, however these are often used in ship salvage where end compartments are flooded.

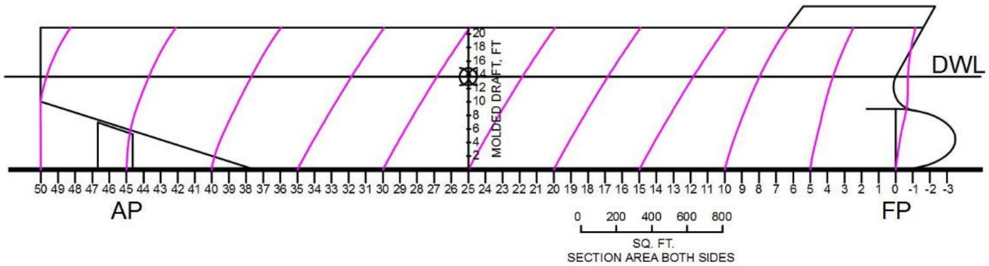

Figure 6: Bonjeans Curves

Once the Hydrostatics are computed, the Stability Calculations can begin.