Stepped Planing Hull Investigation

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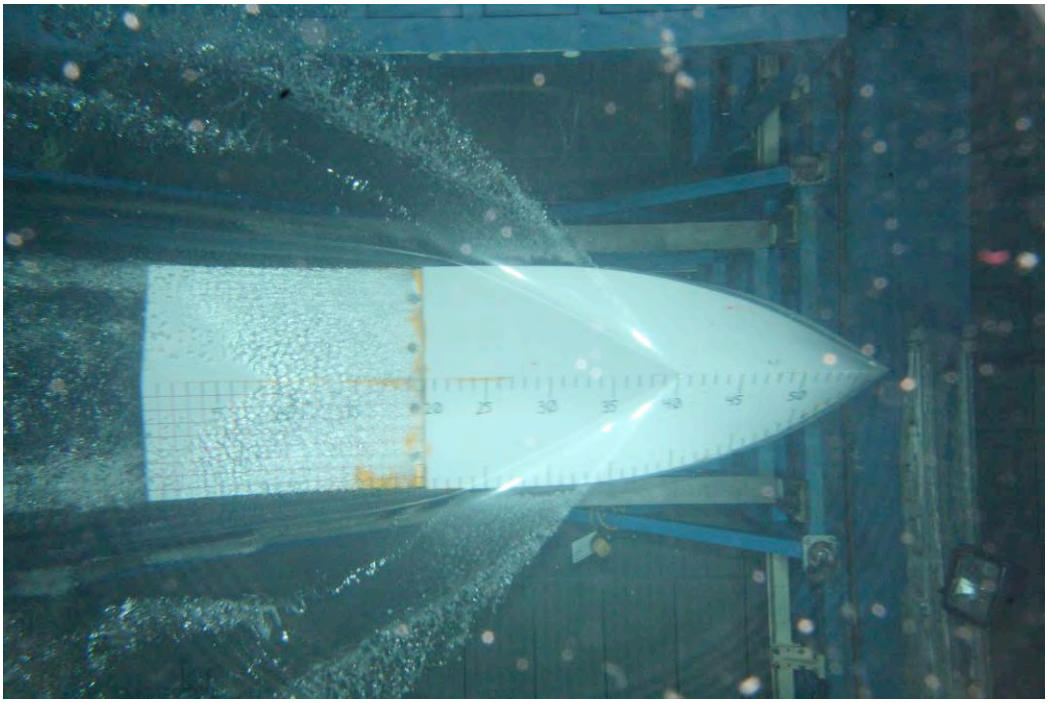

When a vessel travels at high speeds and enters the planing regime of operation, it experiences hydrodynamic forces that provide the necessary lift for it to operate efficiently. The lift forces on the after portion of the hull, however, are almost negligible, and therefore the after portion of the hull does little more than add to the frictional resistance. By introducing a step (or multiple steps) into the hull bottom at the proper location and subsequently ensuring that the flow separates from the hull at the step, a substantial decrease in frictional resistance is realized, provided that the region aft of the step is sufficiently ventilated. By testing both an unstepped and an adjustable stepped version of a generic, 5-foot, prismatic planing boat model at the U.S. Naval Academy Hydromechanics Laboratory, more insight was gained regarding the advantages and disadvantages of operating stepped hulls across the range of speeds.

Introduction

The constant design balance between range, speed, and payload will always present significant obstacles to Naval Architects in their quest for optimally efficient designs. Hull shapes optimized for low speeds and designed to operate in the displacement regime have narrow or pointed sterns that make the hull squat at high speeds. Displacement vessels attempting to operate at high speeds experience extremely high resistances that make high-speed travel completely uneconomical and unpractical. The concept of the planing hull, which operates on the principle of hydrodynamic support, was developed to overcome the inherent disadvantages associated with operating displacement vessels at high speeds. Planing craft are less efficient at low speeds but much more efficient at high speeds. Planing hulls are designed to create positive dynamic pressures (lift) so that the draft decreases when the speed increases. This enables them to ride higher on the waves they create, thus avoiding the increases in drag associated with high-speed displacement hulls. While the common planing hull does show distinct advantages over displacement hulls at high speeds, it is still known to exhibit exponentially increasing resistance as speed increases. The stepped planing hull, which will be covered in detail in the pages to follow, offers a viable, advantageous alternative to the conventional planing hull at higher speeds. The decreased resistances associated with stepped planing hulls allows for one of two things: the increase in a craft's maximum speed or the decrease in engine horsepower and size and thus an increase in cargo-carrying capacity at the design speed.

Stepped Hull Background

The stepped hull is an alternative configuration to the usual high speed planing hull. A stepped hull has a transverse discontinuity located at some point aft of the vessel's center of gravity and center of pressure. The longitudinal location of this transverse discontinuity, or step, is extremely important. To understand the reasoning behind a stepped design, one must understand the hydrodynamic principles of a planing hull. When a vessel planes, the hull bottom will initially intersect the surface of the water at a point called the stagnation point. For vessels with deadrise, the stagnation line will be swept back until it intersects the hard chine on either side, at which point the flow will separate. The region directly aft of this stagnation line is the portion of the hull bottom that provides an overwhelmingly large percentage of the necessary lift due to the large dynamic pressures that are being developed. Clement and Koelbel (1992) have quantified this percentage of the hull's lift at around 90%. The primary lifting surface is typically located in close proximity to the vessel's center of gravity, usually just forward of it. When a vessel is planing, the water pressure on the aft portion of the hull is very low, and therefore it makes a very small contribution to planing lift. It does, however, make a significant contribution to frictional resistance, which is disadvantageous for obvious reasons including poor fuel economy and increased power requirements.

If a transverse discontinuity, or step, of adequate depth is introduced in the hull bottom at the proper location while traveling at a sufficiently high speed, the water flowing along the hull bottom will separate from the forebody at the step. This will leave some amount of the afterbody (the portion of the hull aft of the step) unwetted provided that it can be adequately ventilated (to be explained later). The water that has separated from the step will follow some free surface profile and may reattach to the afterbody. The combination of the lift on the forebody and the lift on the afterbody must be able to support the vessel's displacement. As discussed earlier, the forebody lift, or the lift that is resolved at the vessel's center of pressure, accounts for roughly 90% of the required lift. Therefore, the afterbody must be able to provide the remaining 10% of the lift in order for the vessel to be stable vertically and about a longitudinal axis through the vessel's center of gravity. This lift can be provided by a small wetted portion of the afterbody near the transom. Or, as Clement and Koelbel recommend, a hydrofoil stern stabilizer can be utilized to both provide the necessary lift and to aid in maintaining pitch stability. Essentially the job of the step is to increase the vessel's lift-to-drag ratio by decreasing the drag, the decrease coming from the drop in wetted surface area, and thus frictional resistance, on the hull afterbody.

Testing Scenario

To quantitatively test the theory of stepped hulls, the 15° deadrise model of the NSWC/Norfolk deadrise series was tested free to heave and pitch in the 380-foot tow tank at the U.S. Naval Academy Hydromechanics Laboratory. Instrumentation included a 50-pound block gage for resistance measurements and heave and pitch potentiometers for collection of heave and pitch data, respectively. Figure 1 presents the body plan for the model while Table 1 below details the hull geometry and loading condition.

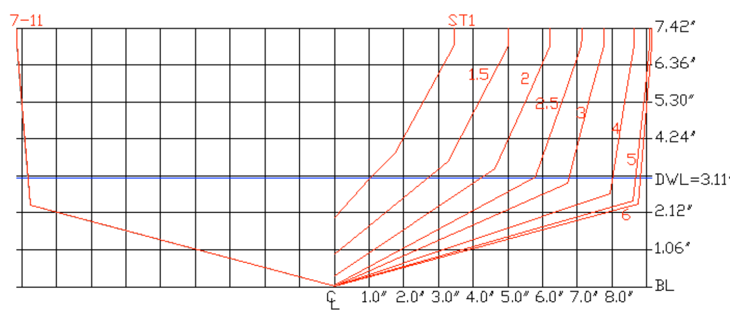

Fig. 1. Body plan.

Table 1. Model Dimensions/Loading	
Length Overall	5.0 ft
Length Between Perpendiculars	4.58 ft
Projected Chine Length	4.8 ft
Max Beam	1.5 ft
Chine Beam	1.45 ft
Deadrise Angle	15°
Displacement	57.45 lb
LCG (fwd of transom)	1.97 ft
KG (above baseline)	0.25 ft
Shaft Angle	10°

Since the thrust produced by the carriage is in the purely horizontal axis, and it was necessary to simulate a shaft angle, ε, of 10° relative to the hull baseline, the unloading force method was used. Prior to each run, an educated guess was made as to how much weight should be unloaded for the speed being tested. After the run, with drag and trim data available, the desired unloading force was calculated using the following equation:

$$Unloading\ Force = (Drag)\tan(\tau + \varepsilon)$$

An error was then calculated between the unloading force used and the desired unloading force. As long as that error did not make up an appreciable portion of the displacement (less than 0.5% was deemed acceptable), than the run was considered valid.

The first series of tests conducted was done prior to any model alterations for inclusion of a stepped design. In results that will be presented later, such data is labeled "Unstepped." The unstepped model data is the baseline for the results; the validity of the stepped hull as a viable or better design alternative is determined by comparing stepped hull test data to unstepped hull test data.

There are many variables that must be considered when discussing a step design. These variables include step shape, step depth, longitudinal location of the step, and method of ventilation. There are three basic possibilities for step shape shown in Figure 2: step pointed aft, transverse step, and the re-entrant vee-step.

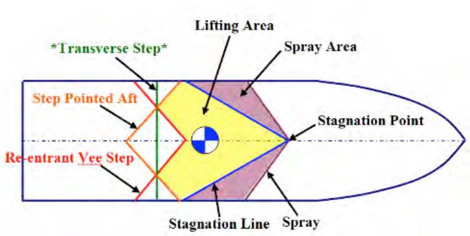

Fig. 2. Step Shape Diagram.

The "step pointed aft" variant is what is found most often in practical design. Most recreational boats have the step pointed aft because it is easier to ventilate. If ventilation is not achieved, regardless of whether or not the vessel is moving fast enough to induce flow separation, flow can get sucked up in the region directly aft of the step. This can cause eddies, additional turbulence, and huge amounts of resistance that would make a step design disadvantageous. The re-entrant vee step is the most efficient step type, but it is also the hardest to ventilate. It is the step type used for Clement's (1992) Dynaplane model. In terms of added wetted area, the "step-pointed-aft" step type adds the most wetted area, the transverse step adds less, and the re-entrant vee step adds the least. Interestingly enough, studies have shown that transverse steps exhibit virtually the same resistance characteristics as steps with an apex pointing in either direction as long as the "centroid" of the step is at the same longitudinal location. Therefore, for the sake of simplicity in fabrication, a transverse step was chosen.

Another significant step variable is its longitudinal location, which is referenced to the transom. The most important issue with step location from a longitudinal standpoint is that the step be located aft of the hull's main lifting area (center of pressure). Usually, this lifting area is very close to the vessel's center of gravity due to the necessity to achieve trim stability. The center of gravity of the model was located 23.63" (1.97 ft) forward of the transom, corresponding to 41.1% of the projected chine length. By locating the step at 35% of the projected chine length forward of the transom, an ample region was provided for the lift area to be effective. The 35% value placed the step at an absolute location of 20.125" forward of the transom. Another important issue with step longitudinal location is that the stagnation line should not cross the step at the design speed. It is desirable for the stagnation line to intersect the chines ahead of the step. Otherwise, if it intersects the step, the heavy main spray that originates at that point will interact with the afterbody in an unfavorable way, resulting in substantial increases in resistance.

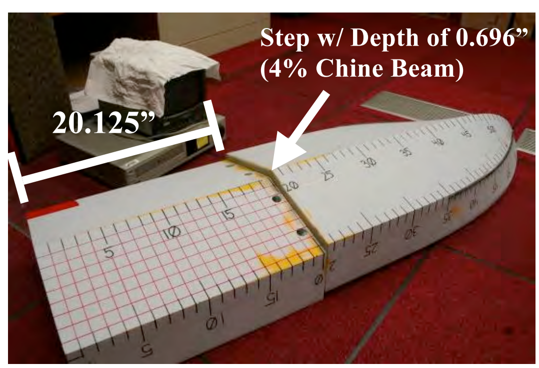

Fig. 3. Stepped Model Orientation.

With limitations on time and tow tank availability, research had to be constrained to the alteration and testing of one major variable dealing with stepped hull design. The variable that was decided upon was step depth. Step depth may, in fact, be the most important variable, provided that the step is located in a reasonable location longitudinally. When a vessel is operated fast enough, large steps provide greater levels of ventilation because the free surface profile of the separated water particles follows a higher, longer trajectory before it reattaches to the aft portion of the hull near the transom. For small steps to achieve similar levels of ventilation aft of the step, the vessel must travel much faster. Thus the idea was to somehow come up with a way to easily vary step depth in between testing sessions so that any step depth could be tested (within reason). One of the most important dimensions of a planing hull is the chine beam, and therefore it is not unusual to base measurements on the chine beam. Several step depths corresponding to even percentage integrals of the chine beam, which measures 1.45 ft (17.4”), were tested. When the model was altered, it was designed so that the step depth would have 1.5 inches of variability. Figure 3 helps to clarify the dimensions that have just been discussed and Table 2 details the various step depths that were tested and their associated chine beam percentages.

Table 2. Tested Step Depths and Associated % of Chine Beam

% Chine Beam	Step Depth
2%	0.348”
4%	0.696”
6%	1.04”

Another extremely important consideration in stepped hull design is the method of ventilation used to ensure that it is air, and not water, that occupies the area directly aft of the step. The two major methods of step ventilation are natural ventilation and pipe ventilation. There is no “right” or “wrong” way to ventilate a step; the important issue is that it gets done. Both methods rely on the physics of pressure differentials being created that essentially allow for air to be sucked in to the void behind the step. For testing purposes, Blount (2009) recommends cutting out a portion of the hull at the intersection of the chine and step in order to facilitate natural step ventilation. The pipe ventilation method involves the insertion of tubes through the hull bottom so that air can be sucked in from above. Since there is no perfect shape or methodology for making a cutout at the chine-step intersection to allow for natural ventilation, the pipe ventilation method was used because it seemed to be the safer, more conservative approach. In order to do so, four holes were drilled in the hull bottom roughly an inch aft of the step. Into the holes, four PVC pipes were inserted, each with an opening diameter of 0.75”. They were spaced roughly equally across the beam of the model so that ventilation could be achieved across the width of the step. The amount of air needed to completely ventilate the region aft of the step was not known, so it was determined that the level of ventilation would be another interesting variable to test. In order to test varying levels of ventilation, caps were purchased for the PVC pipes. Therefore, in addition to the initial test using full ventilation (100% of ¾” holes open), there was a plan for testing the optimum step depth at 0% ventilation (holes capped), 33.3% ventilation, and 66.7% ventilation. Figure 4 shows the pipe system used to achieve afterbody ventilation.

The issue of achieving ventilation brings about another testing issue dealing with the determination of exactly how much ventilation is achieved. It is not the amount of air filling the void aft of the step that needs to be known; instead, it is desirable to know how much of that afterbody surface area is no longer wetted. This provides several valuable pieces of information. First, it allows one to make wetted surface calculations, which are essential for any efforts to scale model data up to full-scale data. Without wetted surface area, it is impossible to come up with a total coefficient of drag for the

Fig. 4. Ventilation Tubes aft of step. (a) 100% open. (b) 0% Open. (c) Holes in hull bottom aft of step.

model. And without full-scale wetted surface area, it is impossible to come up with a full-scale resistance. Second, visualizing how much of the hull afterbody is wetted and how much is unwetted gives a qualitative feel of what is happening in a dynamic sense. For one thing, realizing that much of the hull afterbody is unwetted automatically leads to the impression that there will be comparatively smaller amounts of frictional drag. However, if too much of the hull afterbody is unwetted, it can lead to speed-related instabilities such as porpoising. If the flow does not reattach to the hull at the transom, then there is no way for the after portion of the hull to receive that extra 10-20% of lift that is not provided by the main lifting area and that is meant to stabilize the hull in pitch. This is why Koelbel and Clement (1992) insist on the use of a hydrofoil for the Dynaplane model.

In order to determine wetted surface area for a stepped hull, it is essential to have some method of underwater photography. Armed with this, along with a well-gridded model (especially aft of the step), wetted surface calculations are possible and are not too difficult.

Figure 5 illustrates several important dimensions, the testing apparatus, and the ballasting situation for the stepped hull test program.

Over six days of testing at the Naval Academy Hydromechanics Laboratory in the 380-foot tow tank, 88 runs (data points) were made to fill six complete data sets. Figure 6 on the next page shows the both the unstepped model and the stepped model running at 25 ft/s. Take care to notice the stagnation line crossing the step in Figure 6(b); the effects of this phenomenon will be discussed later.

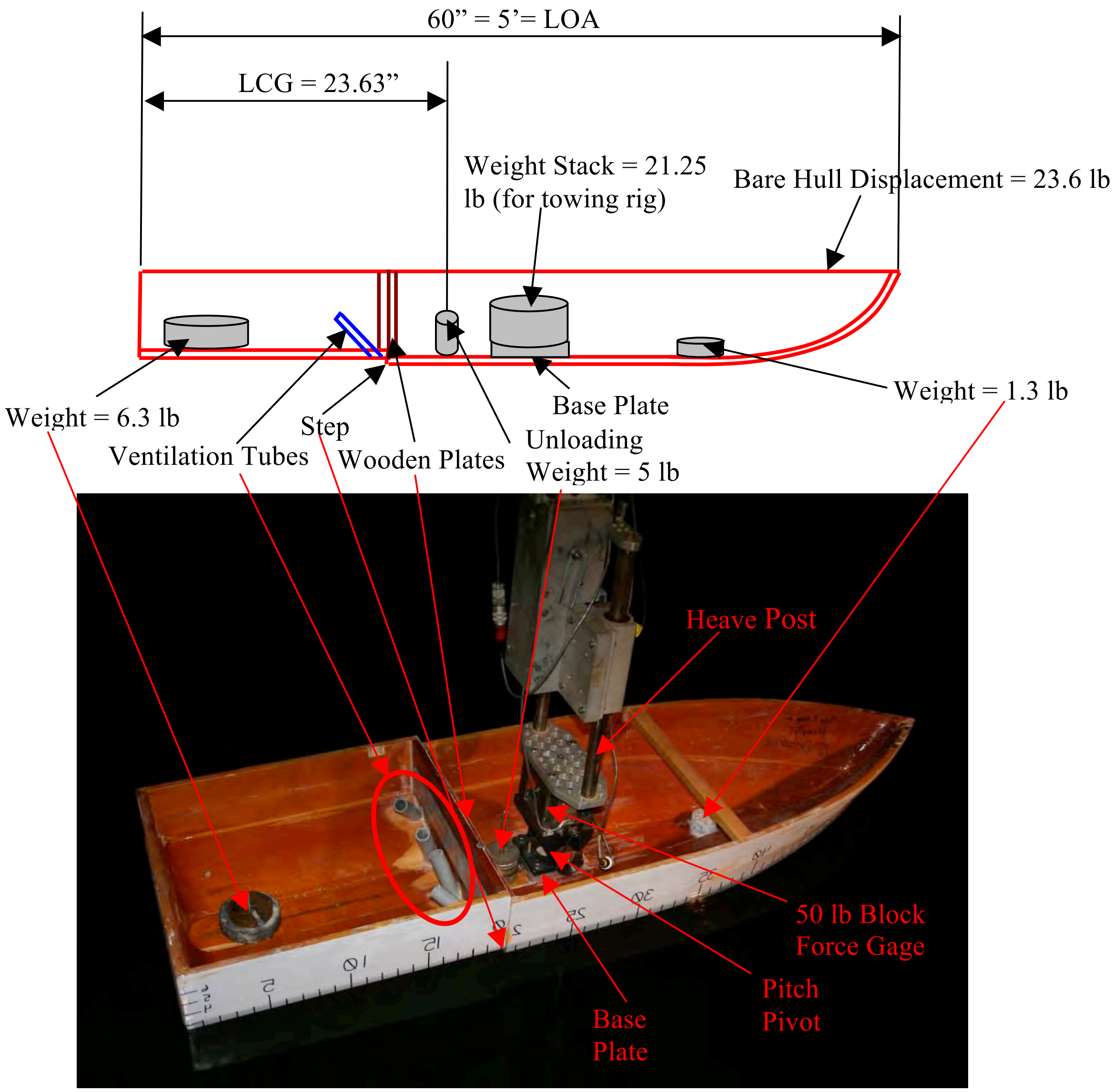

Fig. 5. Stepped Hull Test Apparatus and Ballasting Diagram.

Fig. 6. (a) Unstepped Model @ 25 ft/s. (b) 0.696" Step Model @ 25 ft/s.

Fig. 7. Unstepped Hull running at 25 ft/s.

Figure 7 is a picture that was captured while running the unstepped version of the model at a speed of 25 ft/s.

Heave

Before delving into resistance comparisons and differences in trim, it is useful, especially in the realm of planing craft, to examine the regime in which the vessel is operating. For example, if a vessel is designed to plane, than its resistance characteristics at low speeds in the displacement or semi-planing regimes of operation are not too important. However, if the vessel's operating profile dictates that it is to patrol a certain region at low speeds most of the time while only reaching planing speeds during critical scenarios, than low speed resistance characteristics should be heavily considered. It is for this reason that the model was tested not only at fast, planing speeds, but also at slow, displacement speeds.

The displacement regime of operation is defined as ranging from no speed to the speed at which maximum negative heave occurs. After maximum negative heave has been reached, the

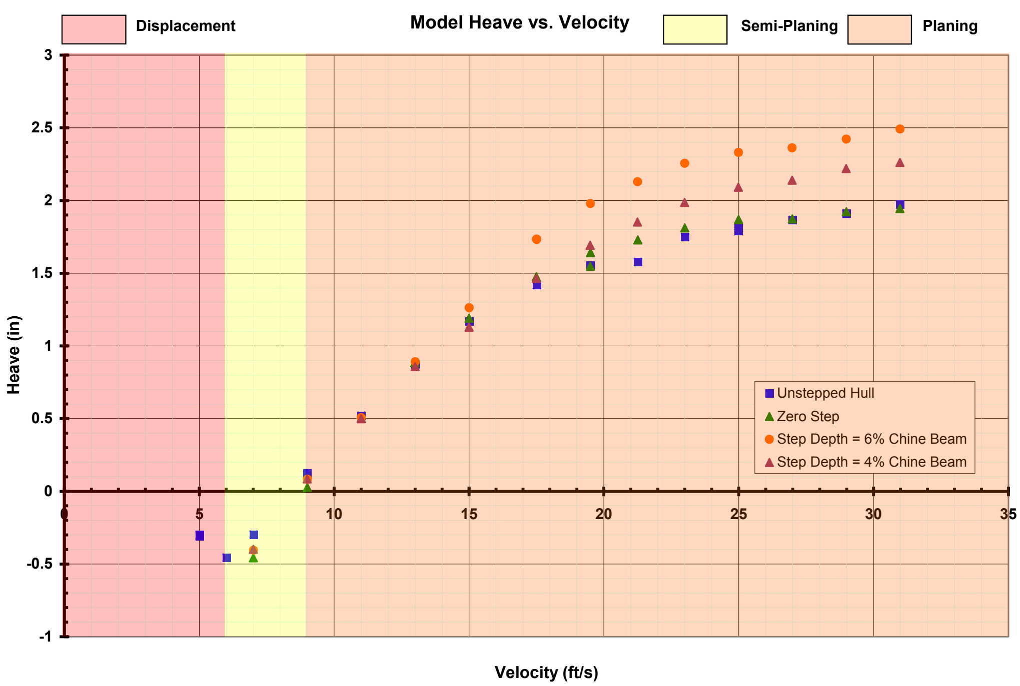

Fig. 8. Model Heave vs. Velocity.

vessel begins to climb its own bow wave, thus forcing heave to become more positive. The region from maximum negative heave to zero heave is called the semi-displacement or semi-planing region of operation. When the heave at the center of gravity goes above zero, meaning that it is higher than the center of gravity in the static condition, then the vessel is said to be planing. In this case, as can be seen in Figure 8, any time the model travels less than 6 ft/s, it is in displacement mode. From about 6 ft/s to 9 ft/s, heave increases again and the model is in the semi-displacement mode of operation. At around 9 ft/s when heave becomes positive at the center of gravity, the model is planing. These three regions are color coded on the graph.

Trim

One of the most important parameters affecting the performance of planing craft is the equilibrium trim angle, which varies with speed. Trim has a major effect on resistance and seakeeping, and it also plays a major role in stability, both transversely and longitudinally. Savitsky and Morabito (2010) point out that wetted surface varies inversely as an exponential power of trim angle. Hence, as the trim angle decreases and more of the forebody enters the water, there is understandably significantly more wetted surface area. This is important because frictional resistance varies linearly with wetted surface area. And a reduction in wetted area is practically the entire basis for a stepped hull design. Hence, at high speeds, where vessels operate at unfavorably low trim angles and wetted surface increases, inclusion of a step would offset that increase in wetted surface area by providing its own decrease in wetted surface at the afterbody.

Since the equilibrium trim angle of planing hulls decreases with increasing speed, vessels attempting to operate at high speeds quickly reach trim angles that are well below the optimum trim angle for minimum resistance. Some designers will introduce a "rocker" at the transom in an effort to increase the vessel's equilibrium trim angle, but this is not a particularly effective method. Stepped planing hulls, as will be explained, allow for operation at a more optimum equilibrium trim angle at high speeds. This is another reason why stepped hulls are often superior to unstepped hulls. Once again, it is important to point out that approximately 90% of the weight of a stepped planing hull is supported by the forebody in the region directly aft of the stagnation point and forward of the step. The remainder of the vessel's weight is supported by the afterbody where it interacts with the wake of the forebody. The longitudinal position of the center of gravity should be located slightly forward of the step in the forebody region, which limits the extent of the forebody's lifting area. Therefore, to support 90% of the vessel's displacement on a relatively small portion of the hull bottom, the equilibrium trim angle must naturally increase to increase the pressure generated on the lifting area. This increase in trim associated with stepped hulls means that, at high speeds, both the forebody and afterbody have less wetted area.
Figure 9 is a plot of trim vs. velocity for each of

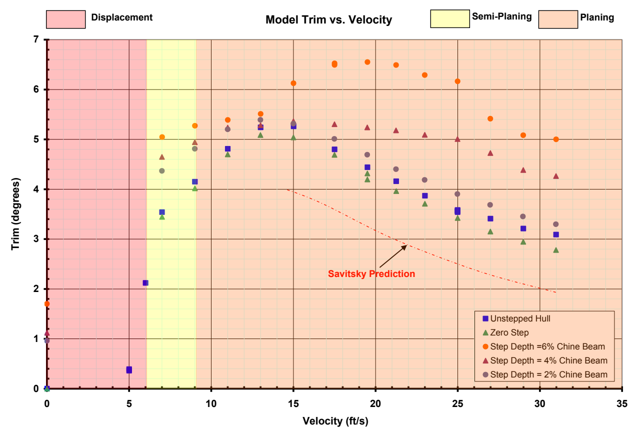

Fig. 9. Model Trim vs. Velocity.

the tested conditions. Please note that the dotted red line on the graph is a prediction and was calculated using Savitsky's Computational Procedure for Hydrodynamic Performance of Prismatic Planing Hulls. It is interesting to point out that Savitsky's prediction method consistently underpredicts the trim over the applicable range of speeds. This could have a lot to do with the fact that the models used in the Savitsky prediction had no faired bow. Trim is extremely sensitive to small things such as how the bow and the hull bottom come together, and this deviation could easily account for the apparent one-degree offset. Trim rises relatively sharply as speed increases through the displacement and semi-planing operating regimes. Each of the tested conditions sees a peak trim at around a speed of 13-20 ft/s, and then trim falls off for the remainder of the curve as speed increases. As discussed earlier, trim increases for the stepped hull relative to the unstepped hull. Additionally, it was discovered that trim increases as a function of increasing step depth. Also, when a step is introduced in the hull bottom, care should be taken to notice and measure the initial static trim that is developed due to the buoyancy that is lost in the after portion of the hull. This causes the vessel to be trimmed bow up while sitting in a stationary position. Figure 8 illustrates the zero speed trim angles for the stepped hull variations.

Resistance

Larger, more advantageous equilibrium trim angles are but a small part of the bigger issue with stepped hulls, the issue of substantially lower resistances at high speeds. They do have their disadvantages at low speeds, however, as one can see from investigation of Figure 11 below, which depicts the resistance-to-weight ratio versus the volume Froude number, which is defined by the equation below:

$$F_{VOL} = \frac{V}{\sqrt{g\nabla^{1/3}}}$$

The volume Froude number is often a better nondimensional indicator than the standard Froude Number based on length because the mean length of the boat changes with changing speed, and therefore there are two primary variables in the conventional Froude number equation, speed and length. F_{VOL} calculates a virtual "length" in the denominator by taking the cubed root of the full-load volume. At volume Froude numbers less than about 2.7, resistance increases with increasing step depth. This is due to the fact that the model is not traveling fast enough for the flow to separate from the step at these low speeds, causing turbulence and, thus, greater resistance. One also will find that it takes faster speeds for the inception of flow separation at the step to occur as step depth decreases. For

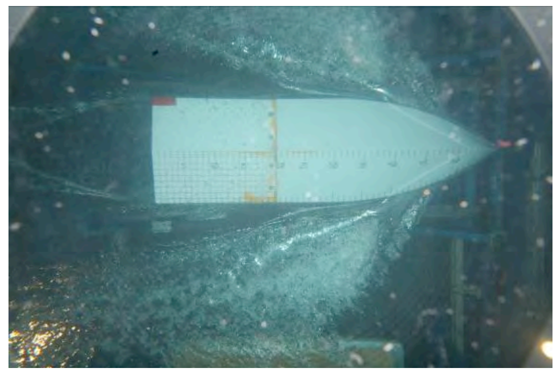

Fig. 10. Step Depth = 2% Chine Beam, Speed = 11 ft/s (F_{VOL} = 1.97). No flow separation, hull afterbody completely wetted.

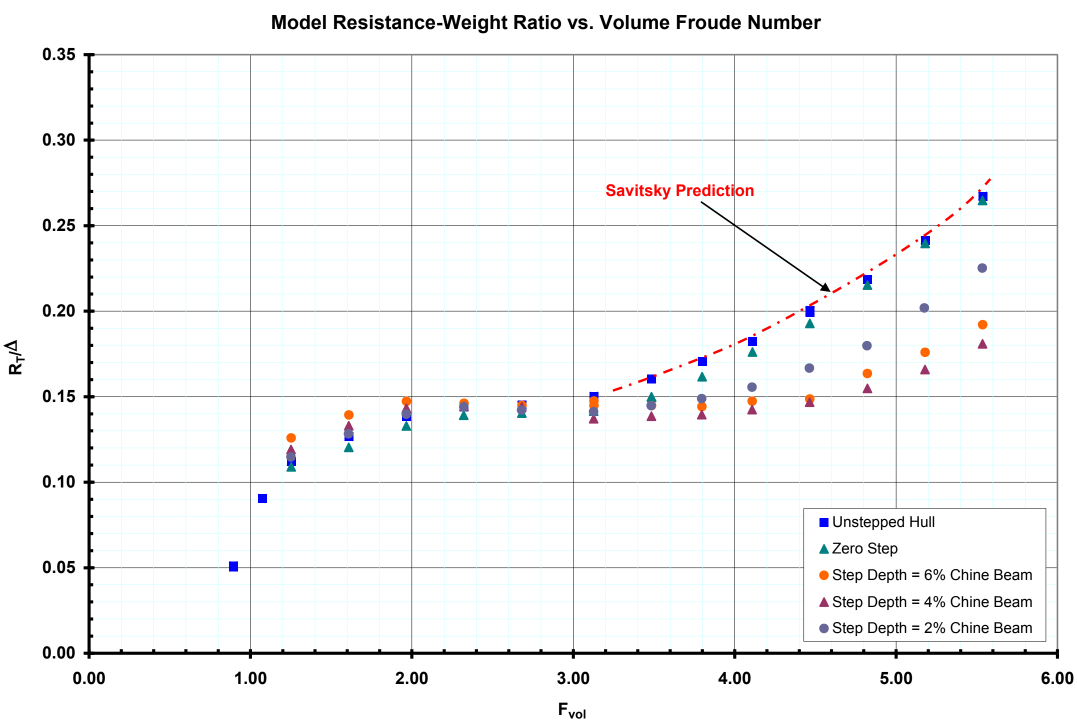

Fig. 11. R_T/Δ vs. F_{VOL}.

the 6% chine beam step and the 4% chine beam step, flow did not separate from the step until 11 ft/s, while for the 2% chine beam step, flow began to separate at 13 ft/s. Figure 10 shows the model with a step depth of 2% of the chine beam running at 11 ft/s. Note that the entire afterbody is wetted, as described above.

In Figure 10, it is interesting to note that all of the points seem to converge at a volume Froude number of about 2.68, which corresponds to 15 ft/s. It is not known if this is purely coincidental or if there is some correlation of this point with the hull form, loading, etc. But it marks the point at which a designer (for this hull, at least) would make the transition from an unstepped hull to a stepped hull. Hence, the design speed would have to be fairly low in this case to consider an unstepped planing boat; after all, the inception of planing occurs at a volume Froude number of 1.6 (9 ft/s). Without considering the possible difficulties associated with constructing a step in the hull bottom, one should only design an unstepped hull for design speeds of $F_{VOL} = 1.6$ to $F_{VOL} = 2.68$. For all F_{VOL} that are higher, a stepped hull should be used.

For volume Froude numbers ranging from around 2.0 to 4.0, the stepped hull curves are remarkably flat in nature. For example, at a step depth of 4% of the chine beam, remarkably, the resistance at 11 ft/s ($F_{VOL} = 1.97$) is greater than the resistance at 23 ft/s ($F_{VOL} = 4.11$), 8.229 pounds to 8.183 pounds, respectively. The same can be said for the unstepped hull curves, but the trend ends earlier at around 3.0, where a drastic difference in resistance starts to be noticed. Note that the unstepped hull was tested twice; one is labeled "unstepped" and the second is labeled "zero step." "Zero step" refers to the data set that was collected after the model was altered; the model was simply retested across the range of speeds with the forebody and afterbody flush (0" step) and ventilation holes covered to test result repeatability and to see if the alterations that were made had any impact on resistance. The two curves seem to correlate fairly well, with the "zero step" tests interestingly showing slightly less resistance over the speed range.

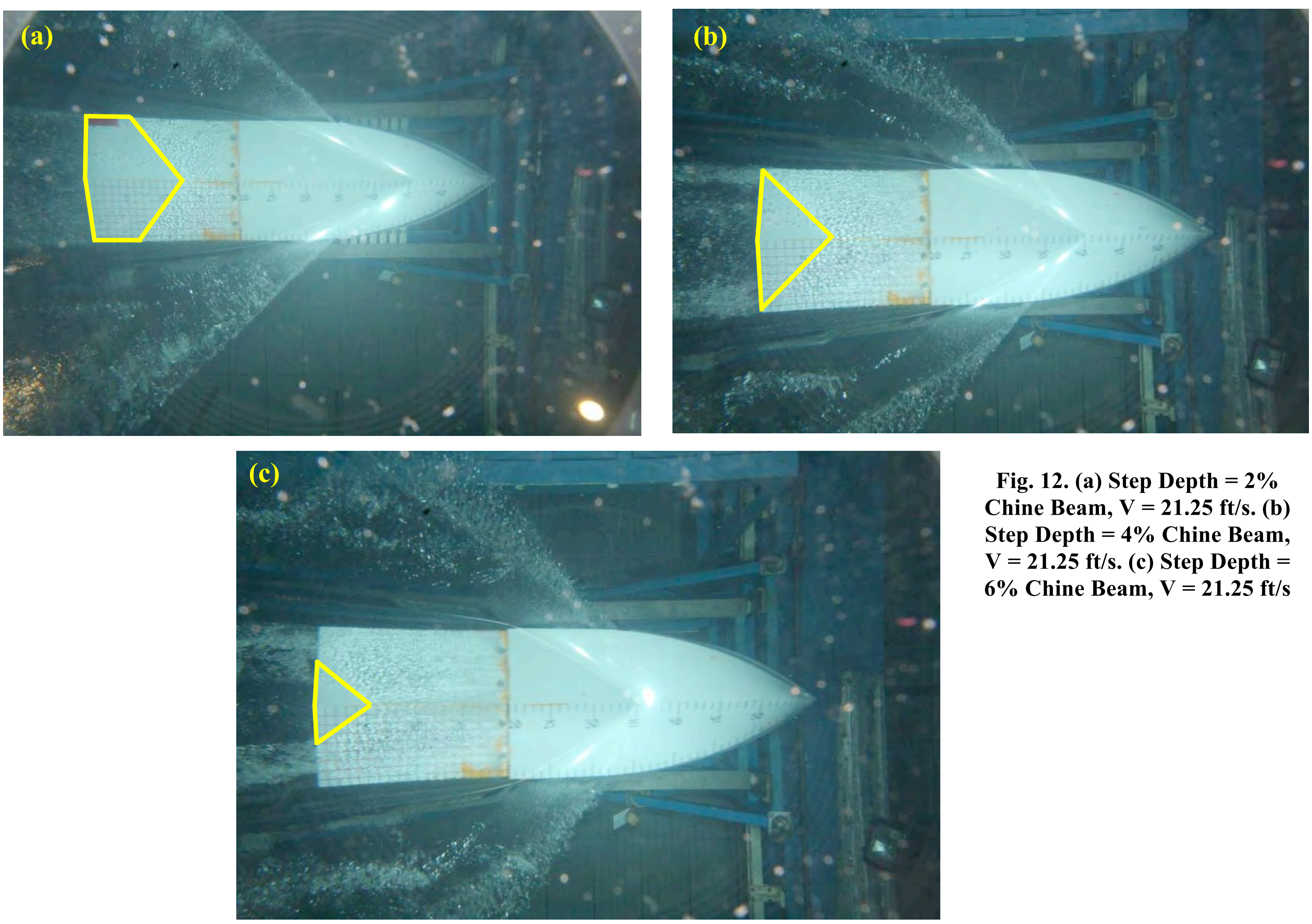

Fig. 12. (a) Step Depth = 2% Chine Beam, V = 21.25 ft/s. (b) Step Depth = 4% Chine Beam, V = 21.25 ft/s. (c) Step Depth = 6% Chine Beam, V = 21.25 ft/s

The only thing that this can be attributed to is a deteriorated model condition (small cracks in the hull bottom) prior to its alteration.

In Figure 11, as with Figure 7, the Savitsky prediction for resistance of the unstepped hull is plotted in red. It is remarkably close to the experimental measurements for the applicable range of speeds that were tested.

Figure 12 is a series of underwater photographs, all taken at a speed of 21.25 ft/s (F_{VOL} = 3.8). In each case, the stagnation line has wetted the chines forward of the step. The three photographs were placed side by side to give a visual illustration of the decrease in wetted surface area with increasing step depth. The area that is ventilated (unwetted) is evident by all of the "bubbles" that appear over that portion of the hull; the wetted area seems very clear with respect to the unwetted area. Outlines of the wetted portion of the hull afterbody (in yellow) have been made for the reader's convenience. It is quite obvious that the wetted area is substantially less for the model with the 6% chine beam step, where the afterbody stagnation line intersects the transom, than for the model with the 2% chine beam step, where the afterbody stagnation line intersects the chines. 90.7% of the hull afterbody is unwetted for the 6% chine beam step, 81% for the 4% chine beam step, and only 49.3% for the 2% chine beam step. Figure 13, a plot of the percentage of ventilation aft of the step versus velocity, depicts this information. Therefore, it is evident that the frictional resistance is the least for the step with the greatest depth, in this case the 6% chine beam step. That is not the case, however, with the overall resistance. In terms of overall resistance, which is the most important factor to consider, the 4% chine beam step is the most effective step, with the resistance being 8.016 pounds (R_T/Δ = 0.14) at 21.25 ft/s. The resistances for the 2% chine beam step and the 6% chine beam step were 8.285 pounds and 8.548 pounds, respectively. It can be concluded, therefore, that the 6% chine beam step produces more extra wavemaking resistance than the 4% chine beam step produces in terms of extra frictional resistance, making the 4% chine beam step the most effective at this speed.

There are several important trends to mention in Figure 13. First, for almost the entire range of speeds once ventilation has been initially achieved, the percentage of the afterbody that is ventilated increases. Second, percentage ventilation aft of the step increases with increasing step height, as mentioned previously and as illustrated visually in Figure 12. The only exception to these two rules occurs when the stagnation line fails to wet the forebody chines and instead intersects the step. As mentioned earlier, this can create a large amount of spray and wake off of the step that can impinge of the afterbody, causing resistance to increase substantially and creating a possibility for longitudinal instability. For this reason, stepped hull designers should definitely consider the relationship between the design speed and the longitudinal step location to ensure that this phenomenon does not occur. During the model experiments, this longitudinal instability, which looks very similar to porpoising, occurred for the 1.04" step at speeds above 27 ft/s. Therefore, it can be concluded that the likelihood of this occurring increases both with increasing velocity and with increasing step depth. Note that once the stagnation line does cross the step, the

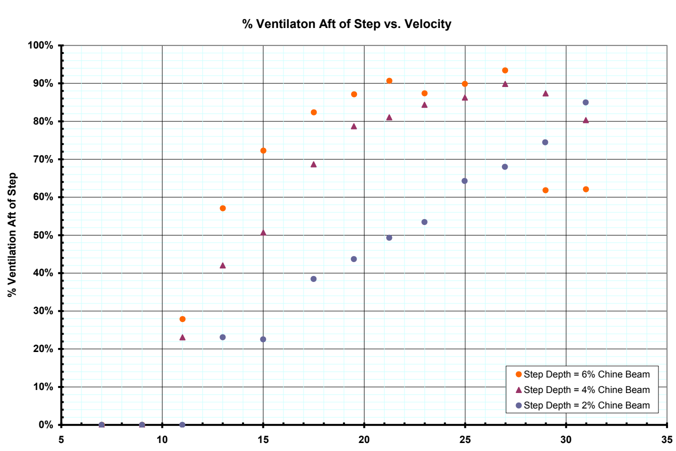

Fig. 13. Percent Ventilation aft of step vs. velocity.

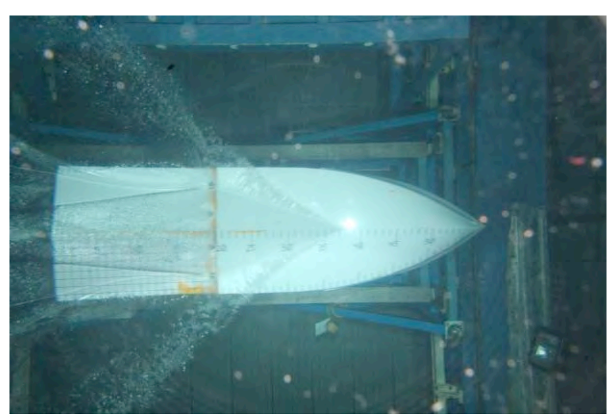

Fig. 14. Step Depth = 1.04", V = 29 ft/s.

percentage of the hull afterbody that is ventilated decreases despite the increasing speed, which bucks the main trend. Figure 14 is a photograph of the model with a step depth of 6% of the chine beam running at 29 ft/s, one of the runs where the instability was readily apparent. Note the huge amount of wetted area that has been added due to the intersection of the stagnation line and the step. Also be aware of the fact that resistance starts to increase again drastically at speeds where this phenomenon occurs.

In general, the 4% chine beam step is the best of the three step designs. It produced the least amount of resistance over the range of speeds, and the difference in resistance at high speeds was greatly magnified. At the highest speed tested (31 ft/s), the drag for this step was 94.2% of the drag for the 6% chine beam step, 80.3% of the drag for the 2% chine beam step, and just 67.7% of the drag for the unstepped hull. Thus, from these tests in calm water, it appears that a stepped hull is far superior to a conventional hull at such high speeds, where a nearly one-third reduction in drag is achievable.

Finally, the method of ventilation used to ensure that the region aft of the step was properly unwetted was tested for the optimum step height of 4% of the chine beam. To do this, the PVC pipes were completely capped, ensuring that no pipe ventilation was occurring and that any possible ventilation would have to be occurring naturally at the step-chine intersection. Upon examination of the results, it is evident that the ventilation method is not too significant for this hull and step configuration. Figure 15 is a plot of simple resistance vs. speed depicting the fact that there is no appreciable difference in resistance between the pipe ventilation method and the natural ventilation method. For this reason, it was not deemed necessary to test the model at intermediate levels of ventilation.

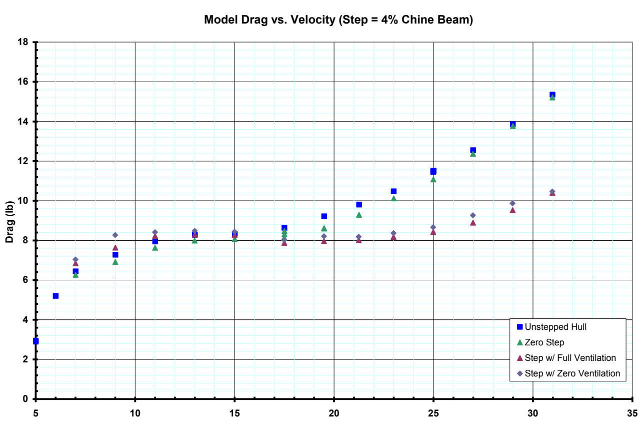

Fig. 15. Drag vs. Speed, Forced vs. Natural Ventilation.

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