Fundamentals of Resistance

DUDLEY DAWSON

Done right, boat design and construction are not simple tasks. There are many opportunities to mess things up, but one area in particular stands out as especially prone to problems.

by Dudley Dawson

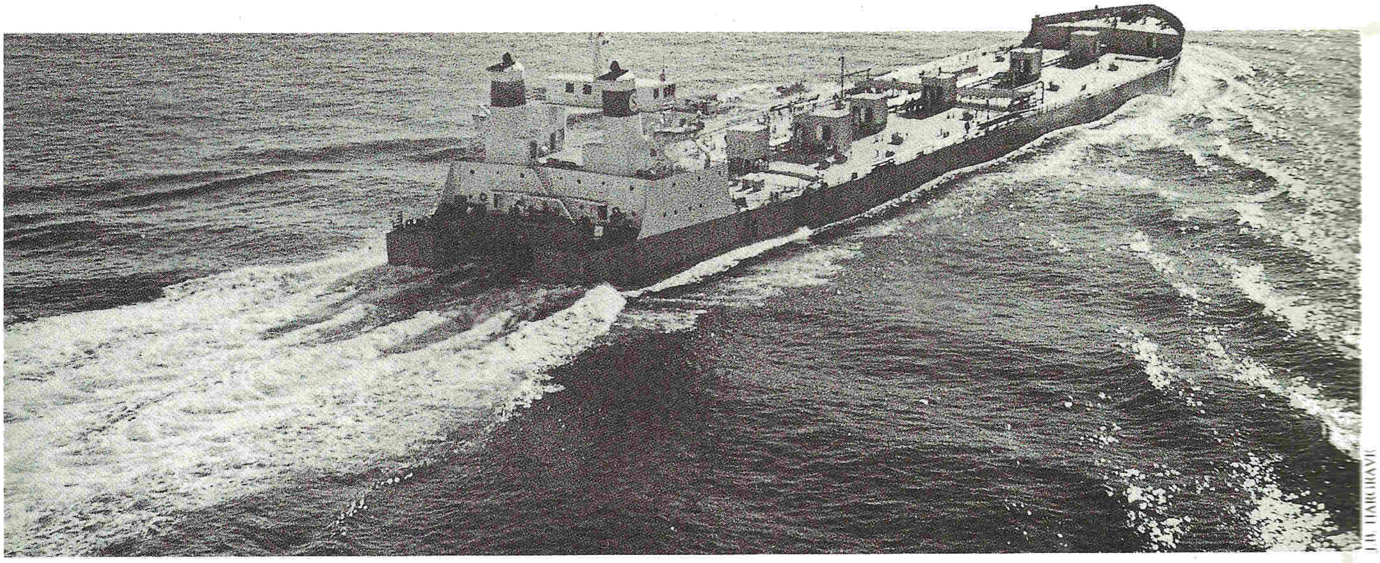
When a boat doesn't make its intended speed, nobody's happy. This shortfall is a major source of disappointment, lawsuits, and ulcers, but it need not be so. The achievement of a speed target rests on two basic components: determining the resistance of the boat, and providing power to overcome that resistance. In an earlier article (*"Faster, Farther, and More Fuel-Efficient," PBB No. 44, page 38*), we covered the subject of propeller and gear selection to deliver the required power efficiently. What remains is an exploration of the basics of resistance. We'll look at the physical components of resistance, as well as the various dimensional and environmental factors involved. To keep things to a manageable size, we won't offer a lot of test data and formulae, as it's a huge topic that's well covered in numerous texts and research reports. We will offer the fundamentals, however, to help you find and understand that detailed data.

Resistance, simply, is a boat's tendency to resist movement. If we want to get anywhere, we have to provide power to match that resistance at whatever speed we want to attain. To do that, we can either guess how much power will be needed and put in a lot of extra iron—not a very good way to handle it—or we can determine the resistance and select a power plant to suit it. Determining the resistance correctly can be done only if we understand what causes resistance, and what can be done to increase or decrease it.

Components of Resistance

Hydrodynamicists divide total resistance into two components to allow analysis of model test data. The first, *frictional resistance*, is the obvious one and is the result of the hull "rubbing against" the water. They've then cleverly named the second component *residuary* (or residual) *resistance*, which is just a fancy term for "everything else." Residuary resistance includes the drag

Above—*A classic pattern of divergent waves is evident in the wake of this planing boat, a 40' Tempest express cruiser.* ***Facing page, above***—*Although they exist on all vessels, regardless of size or speed, distinct patterns of both transverse and divergent waves are most apparent with larger ships having relatively low speed-to-length ratios, such as the 625' tanker* Seabulk Challenger *pictured here.* ***Facing page, below***—*Model tests should be run over a range of displacements, both with and without appendages. The results are then expanded to full size, and can be expressed as either pounds of resistance, or effective horsepower (EHP).*

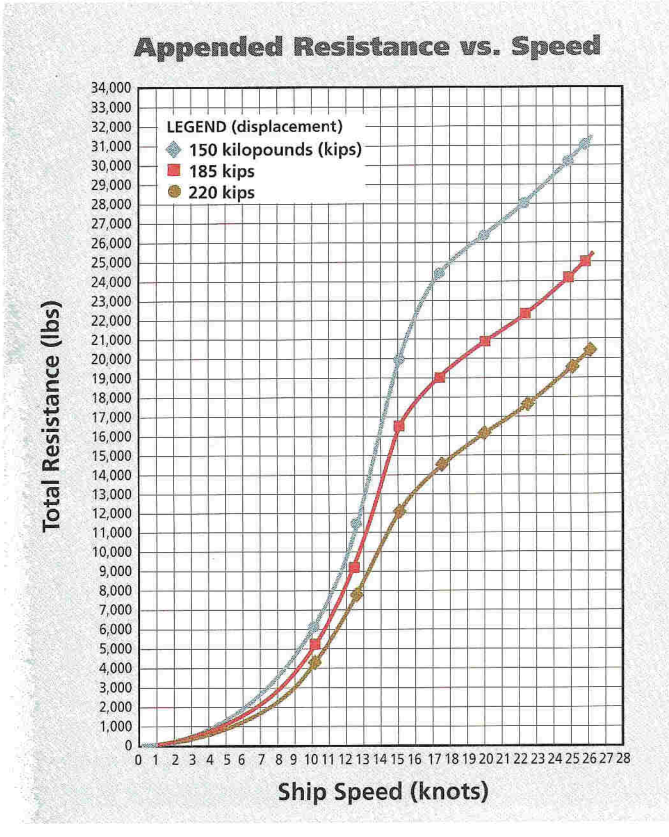


J.B. HARGRAVE

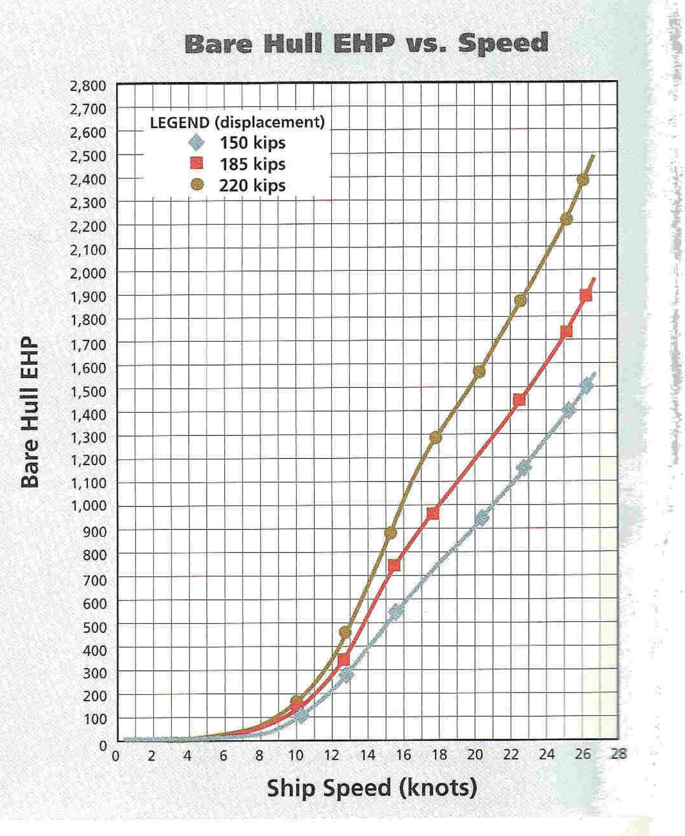
from wavemaking, eddies, and the air drag of the upper hull and superstructure. Drag from appendages (propellers, rudders, struts, shafts, strainers, transducers, stabilizer fins) is sometimes included in model test data and sometimes not, so be sure to ask whether the figures are for bare-hull or *appended resistance*. Resistance due to wind and sea waves is also a component, but these factors are not commonly included in residuary resistance or in model test data. Rather, they are considered as a separate item and are referred to as *added resistance*.

The amount of frictional resistance depends on the amount of hull surface in contact with the water, the roughness of the surface, and the type of flow over the surface and near the surface. Laminar flow generally takes place at low speeds over smooth surfaces. Turbulent flow occurs as a result of increased speed, a rougher surface, or discontinuities in hull/appendage shape. Most boats, of course, experience a mixture of flows at various times. Reducing the amount of wetted surface is an obvious way to reduce frictional resistance, but it's often not practical, as hull shapes must fulfill so many other conflicting requirements. Keep in mind that if you can reduce the boat's displacement by building light, then wetted surface and resistance will also be reduced. Making the surface as smooth and fair as possible is another route to reducing resistance. Antifouling coatings play an important part in this on most boats, and for racing boats, wax or slick polymer coatings are often applied and polished just before the boat is launched.

The wavemaking component is the most substantial part of residual resistance at low speeds, and is a result of the energy expended in creating waves alongside and aft of the boat *(see photo above)*. Originating at points near the bow and the stern, divergent waves radiate out from the sides of the hull at an angle to the direction of travel. The higher



Appended Resistance vs. Speed



Bare Hull EHP vs. Speed

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Right—*Operating at its hull speed of 14 knots, the displacement motoryacht shown here clearly exhibits bow and stern waves with a trough amidships.* ***Facing page***—*Even high-speed sportboats, like this 38' Scarab, share the same resistance components as the slowest tug.*

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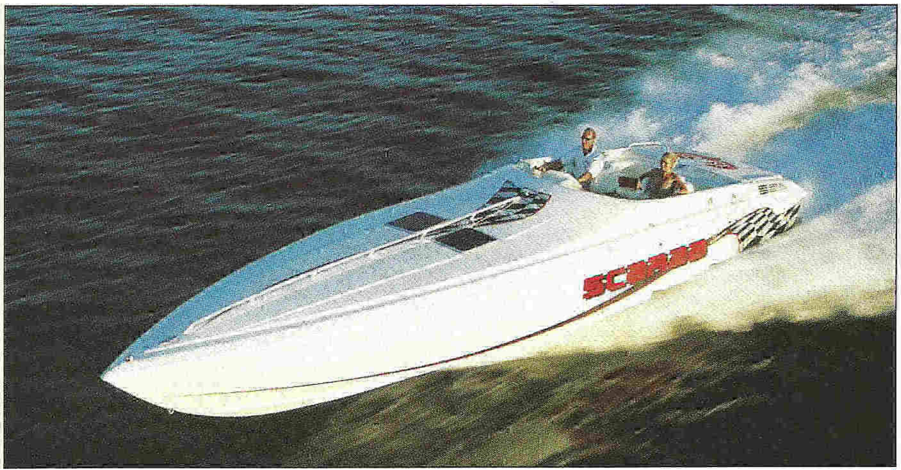


the speed, the lower the angle of divergence *(see photo on page 26)*. Aft of the boat, transverse waves are created perpendicular to the direction of travel *(see photo on previous page)*.

When a displacement hull is traveling near its maximum hull speed, at a speed/length ratio of about 1.33, it has a distinct bow wave and stern wave with a single trough amidships *(see photo above)*. The waves are regions of high pressure on the hull; the troughs, low pressure. The number of wave troughs is inversely proportional to the speed/length ratio, so that at one-half hull speed, there is a bow and stern wave, as well as a wave crest amidships, with two troughs. If you know the waterline length of a boat or ship, you can estimate its speed quite accurately by observing the number of troughs along the length of the hull. Purely displacement hulls cannot exceed their hull speed, and applying more power simply wastes fuel by creating larger waves. Common examples of this are tugboats and fishing trawlers, without a tow, pouring on the coal in an effort to gain some speed. The wake is awesome, but the boat doesn't go any faster.

Eddy-making is a second component of residuary resistance, and is somewhat related to wavemaking in that it expends energy by creating a disturbance in the water. Eddies are the swirls and areas of turbulent water that are sometimes visible, sometimes not, behind blunt or poorly streamlined hull and appendage components. The churning water aft of the transom on a planing hull at low speed is a clear and visible example of eddying. A poorly oriented stabilizer fin or rudder, or a poorly faired transducer, also creates eddies that can go undetected, increasing resistance and robbing a boat of potential speed.

While wavemaking is a major component of residuary resistance for slower boats, appendage drag increases with speed and can become a major factor. It is important to streamline underwater hardware, and reduce its size or eliminate it entirely when possible. On very high-speed boats, getting the appendages completely off the hull bottom can yield substantial reductions in resistance, reportedly up to one-third of total resistance. Surface-piercing propulsion systems take advantage of this by putting only half the propeller in the water, swiveling the drive units to eliminate rudders, and mounting cooling water intakes as small units directly on the drives.

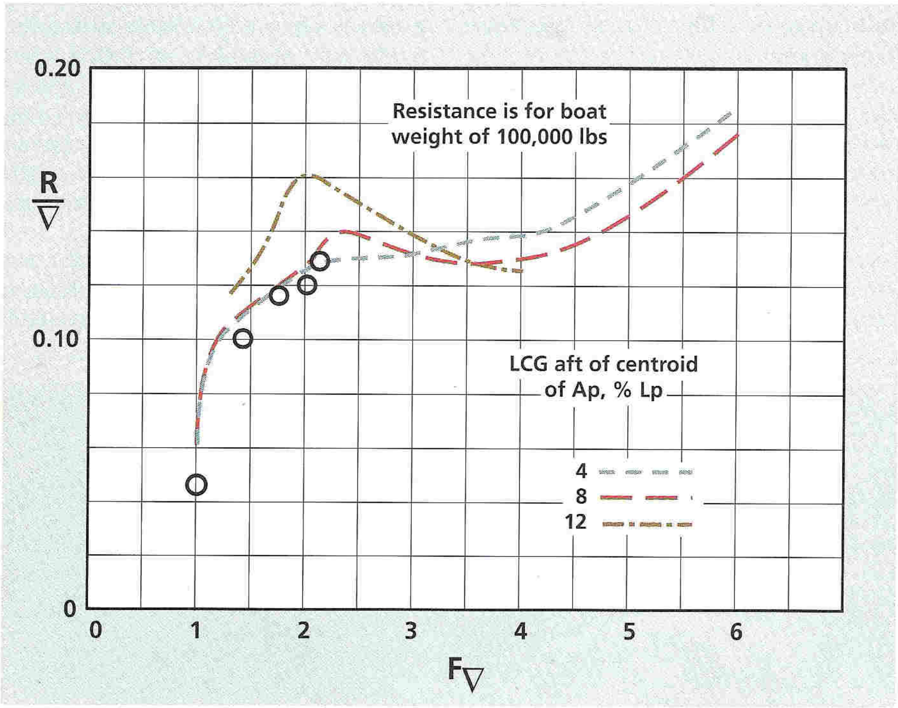
Air drag is not significant at lower speeds. Older cargo ships often had streamlined stacks and swept-back superstructures, but that was more fad than function. Modern ships inevitably have squared-off stacks and houses, which are cheaper to build. As speed increases above 30 knots, however, air drag should be taken into consideration. There's not much you can do about the hull topsides, as there are usually overriding aesthetic and seakeeping considerations. For the superstructure and equipment, however, attention to fairing and streamlining will pay dividends in reduced resistance. Solid bulwarks, towers on sportfishing boats, and brows on flying bridges are common offenders.

Environmental Considerations

Added resistance from wind and sea waves is often unavoidable in the real world, and should be included when determining power options. If you're building a canal boat, waves aren't a big problem, but if it's a ferry that must maintain a fixed schedule on a route where storms are common, that's something else again.

Also, the water itself can have a significant effect on resistance. I think we've all heard a story about a boat that wouldn't

DUDLEY DAWSON



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Top—*At sea, ambient wind and waves increase resistance, compared to that found in calm water or in the model tank.* ***Above***—*Model test results should be compared with relevant known data when possible. Here, a new hull's performance (points) is indicated as superior to a standard Series 62 hullform through the speed range tested.*

run as fast on the ocean as it did when it was tested at some inland location, with the blame being placed on the extra density of salt water. Folks, it's not whether it's salt or fresh, but rather how wide and deep it is. Shallow water or a narrow channel will noticeably increase the resistance of a displacement hull, and will have the opposite effect on a planing boat. If you're building and testing fast offshore boats on a shallow river near your plant, be aware that your customer will never see the boat speed or engine rpm you attained in testing if you don't take this factor into consideration.

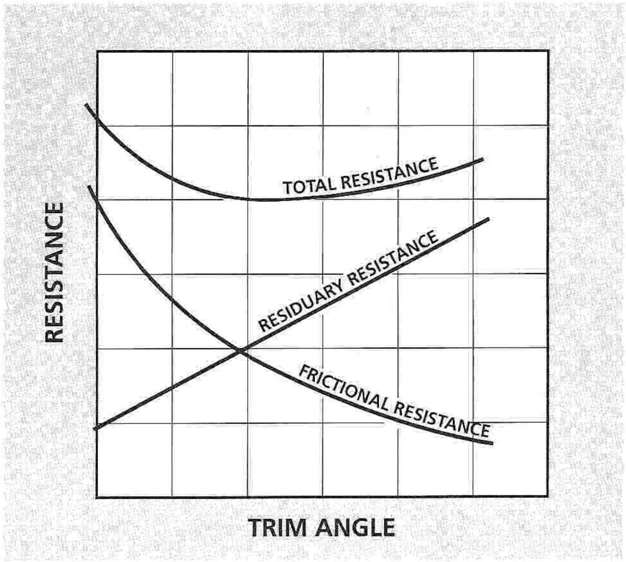
Hull Characteristics

Some hull characteristics lend themselves to direct conclusions regarding resistance. For example, higher displacement always results in higher resistance. On the other hand, some characteristics defy easy categorization. In general, a higher length/beam ratio results in lower resistance, but if the lower beam results in an excessive bottom-loading, or more draft or deadrise, the resistance may increase. It's always a balancing of the various factors and a compromise in the effort to obtain something better. Then, too, there are important seakeeping and safety considerations, as well as aesthetic preferences and the ever-welcome input from the marketing department. I suppose that's why there is no agreement on an ideal hullform, with designers and builders still seeking the Holy Grail—an unattainable "best" hull shape. All we can do is understand the various hull shape factors and their effects, and make educated decisions.

Displacement is usually the single most important factor in resistance. More weight, more resistance, more power required. It's a vicious cycle, so save weight wherever you can. How and where that weight is carried is also important. For evaluation, it's essential that we have a way to compare various boats on an apples-to-apples basis. For displacement hulls, prismatic coefficient (also called longitudinal coefficient) is used as a measure of the "fullness" of the hull. It's the ratio between the actual displaced volume and the volume of a prism the shape of the midship section. There is an optimum prismatic coefficient for each speed/length ratio, with faster boats generally needing higher prismatics. For planing hulls, the size-displacement (or area) coefficient measures bottom-loading as a ratio between the planing area of the hull bottom (inside the chines) and the boat's displacement. With all other things being equal, a higher bottom-loading results in increased resistance. It's easier to compare boats on a dimensionless basis, so this coefficient is normally expressed as the planing area in square feet divided by the volumetric displacement to the ⅔ power: $A_p / \nabla^{2/3}$.

The length/beam ratio is another important consideration in resistance. Generally, higher ratios (narrower boats) mean less resistance, but as mentioned above, other factors enter in, particularly for planing boats. In addition, beam is a critical factor in transverse stability, as well as habitability of the boat. Often, beam must be increased for non-resistance reasons.

The longitudinal center of gravity, or LCG, is important to both displacement and planing boats. For displacement boats, it has a significant effect on wavemaking and can change resistance substantially at certain speeds *(see figure above)*. For planing boats, LCG helps determine running trim angle, which has



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Planing-hull frictional resistance decreases, and residuary resistance increases, with trim angle. Total resistance is the sum of the two, and reaches a minimum at some specific trim angle for each boat weight and speed.

a big influence on total resistance *(see figure at right)*. As trim angle increases, frictional resistance is reduced (less wetted surface) and residuary resistance is increased (more wavemaking). At some point, the optimum trim angle for minimum resistance is achieved. Trim tabs are often used in conjunction with a slightly-aft LCG location to attain maximum speed in calm water, while still allowing a bow-high running angle in heavy weather. A slightly-aft LCG, in conjunction with a low bottom-loading, is also a major factor in avoiding dynamic stability problems *(see "Planing-Hull Stability," PBB No. 31, page 20)*.

The various hull shape factors are, of course, important in many areas other than resistance, and must be considered in the total picture. Among these are draft, deadrise, buttock shape, chine shape in plan, and section shape. Draft is inexorably tied to beam and prismatic coefficient, so you kind of end up with what you get—unless, of course, you have a shallow-water situation where you have to sacrifice that nice big length/beam ratio to gain shallow draft. Mississippi River towboats shouldn't be viewed as examples of minimum hull resistance. Increased deadrise whether on a warped-plane or deep-V bottom, is generally accepted as being a resistance increaser. On the other hand, many swear by the seakeeping characteristics resulting from increased deadrise, and the "maintainable" speed it makes possible offshore. Viewed in profile, buttock-line shape should always be as fair as possible without abrupt changes in direction.

For displacement hulls, particularly at the high end of the speed/length range, some hook down aft is desirable to avoid excessive running trim angle, or "squatting," with its associated wavemaking. For planing boats, however, a straight buttock run is best in most cases. Rocker will cause bow-high running and hook

mum prismatic coefficient in moderate-speed boats, but excessive chine taper should generally be avoided on high-speed boats.

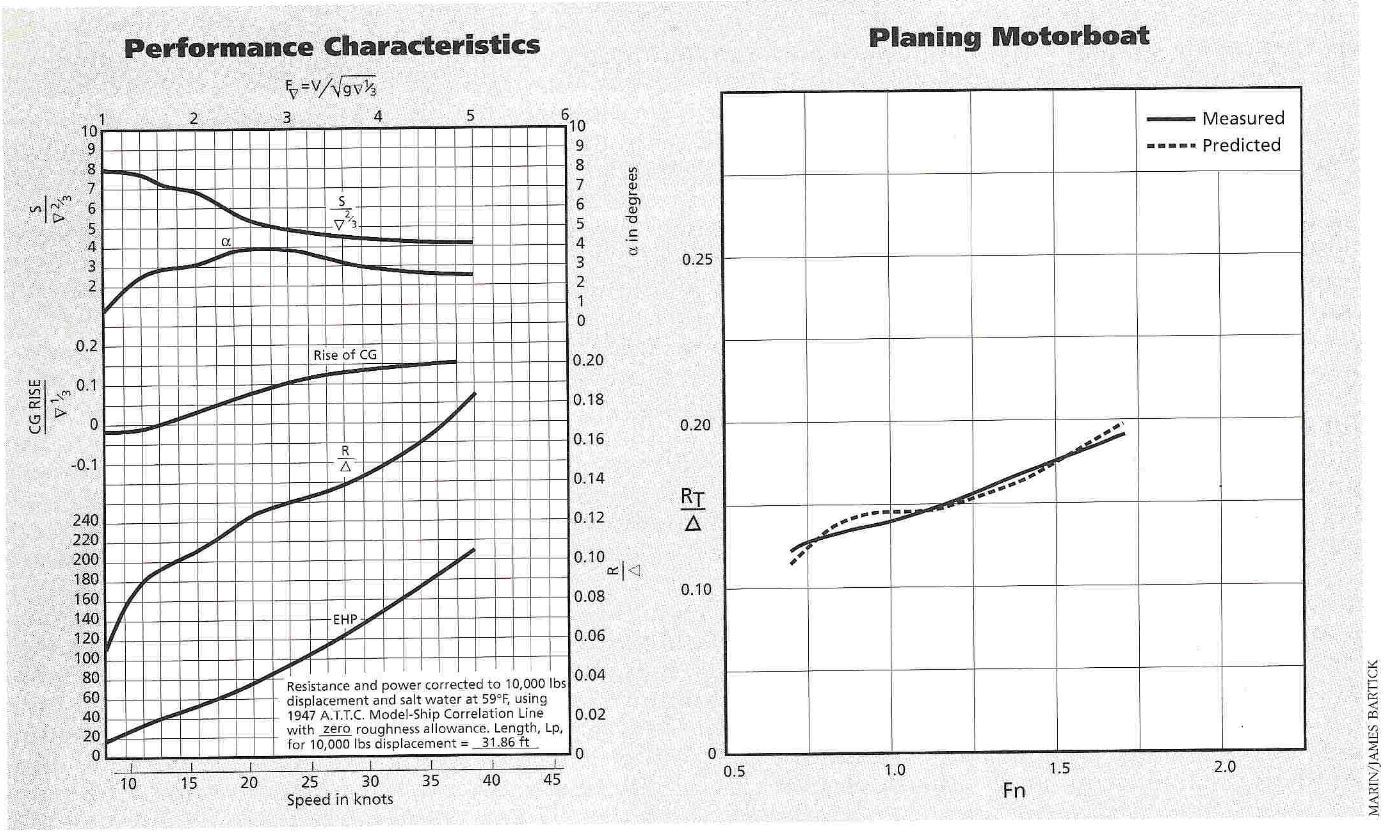
Finally, section shape, and particularly shape forward, is a topic with no lack of proponents for various types: straight, convex, concave, and various combinations such as the "inverted bell." While quite important to impacts and accelerations in waves, section shape is far down the list of important factors in resistance. Even the bulbous bow, so enthusiastically touted for all sizes of "trawler yachts," has for the most part been found ineffective in smaller displacement vessels, up to 80′ or so. I'd suggest you design the bow to whatever seakeeping theory you believe, select deadrise and warp to suit your needs, watch the run of the buttock lines, and the rest of the hull will pretty much fill itself in.

Predicting Resistance Values

The basic methods of determining resistance are from comparison to full-size boats of similar characteristics, from model testing *(see "Model Testing," PBB No. 55, page 32)*, and from calculations based on empirical formulae. If you are building 35′ and 39′ boats from the same mold, and you decide to introduce a 37-footer in the same series, the best data is probably going to be from your own sea trials. If, however, you need to develop a 45′ model with more beam, a different deadrise, and substantially more displacement, don't be tempted to extrapolate the data from the smaller boats. There's plenty of model test data available; it's just a little hard to find if you don't know where to look.

The Society of Naval Architects and Marine Engineers (Jersey City, New Jersey) is a good first stop. Check their Web site at www.sname.org, or call them at 800–798–2188 and request a copy of their publications catalog. Two good SNAME texts on the basics of resistance are *Principles of Naval Architecture*, which is mostly for larger displacement hulls, and *Hydrodynamics in Ship Design*, which is also primarily for ships but has extensive sections on small craft and planing hulls as well. SNAME has several sets of data sheets (see page 34) available: 12 tugs, 9 trawlers, 16 small craft, and miscellaneous larger displacement vessels. The trawler data in these sheets, and in additional SNAME-published research by Nevitt, is based on a standard series, where length/beam ratio, prismatic coefficient, trim, and other factors were varied methodically to study the effect of each individual parameter. The SNAME small-craft data sheets, unfortunately, are only for a collection of unrelated hull forms, but series data for small-craft hull forms is available from other resources.

Each data sheet is complete with lines plan, dimensional specifications, and model test data. There's a companion Technical and Research Bulletin—T&R No. 1-23, "How to Use the SNAME Small Craft Data Sheets for Design and Resistance Prediction"—that is extremely helpful. You'll find that the hull forms are a little dated in some cases, but the theory is still sound, and the T&R bulletin is a good primer on the specifics of using model test data to predict the resistance of full-size boats. SNAME also has many resistance research reports printed in past issues of their magazine, *Marine Technology*, and the annual *Transactions*. Printed



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Left—*Society of Naval Architects and Marine Engineers' model data sheets are available as a set for a variety of planing hulls. Each includes dimensional data and a full set of hull lines, as well as performance data. Though plotted for 10,000 lbs displacement, they can be adjusted for your boat's dimensions and weight.* ***Right***—*Numerical prediction methods using empirical formulae based on model-test data can be quite accurate, as shown by this graph from a MARIN paper by Oortmerssen.*

indices have been published for these, as well as local section papers, dating back to at least 1961.

Several maritime colleges, including Webb Institute (Glen Cove, New York), University of Michigan (Ann Arbor, Michigan), and Stevens Institute (Hoboken, New Jersey), have their own model tanks. They often carry out systematic research which they make available in reports, and very often in technical papers presented through SNAME.

Public and private model towing tanks also carry out and publish research and test information *(see "Model Testing," PBB No. 55, page 32)*. The U.S. Navy is a gold mine of information, and much of their test data and research is unclassified. The snag is sorting out the bureaucracy and getting to the right office. Start with the Carderock, Maryland test facility *(see "Carderock," PBB No. 42, page 39)*, which tests EVERYTHING, and the Suffolk, Virginia-based Combatant Craft Department *(see "A Day in the Life," PBB No. 52, page 42)*, which studies vessels up to about 150′ in length. In addition to the various U.S. research facilities, there are several excellent resources overseas. Among the best for small-craft information are the Maritime Research Institute of the Netherlands (MARIN, Wageningen) and the Wolfson Unit at the University of Southampton (England).

Finally, we get to what may be the most practical and cost-effective solution for most designers and builders of small craft. There are a number of private firms, as well as some of the model tanks, offering consulting services and computer software for resistance prediction. Most are well-advertised here and in other marine magazines, and it would be inappropriate to recommend any particular vendor. I have used at least three of the better-known programs, though, and found them all to be consistently good in resistance prediction (see facing page). Some of the programs are available independently, but most are part of larger design suites; a purchase may depend more on the other features of the software than on its ability to calculate resistance and predict power requirements. As with any tool, you will get more satisfactory results if you understand what you're doing. I wouldn't recommend buying the software and getting into resistance, power prediction, and propeller selection without a good understanding of the basic theory. The empirical formulae on which the software is based need to be applied only to boats fitting within the base parameters set out in the original research and testing. Using cargo-ship prediction methods for an offshore raceboat is a sure route to disaster.

Study a bit of the theory, learn what others have done, and then pick the best method for your particular need: full-size sea trials, model testing, calculations by hand or computer, or in many cases, a mixture of two or three. Even if you decide to hire a consultant to take care of the whole thing, you're better off knowing if what he's proposing makes sense for you. PBB

About the Author: *Dudley Dawson is president of Dawson Marine Group Inc., and a contributing editor to* Professional BoatBuilder. *His firm provides naval architecture and marine engineering services from offices in Greensboro, North Carolina.*