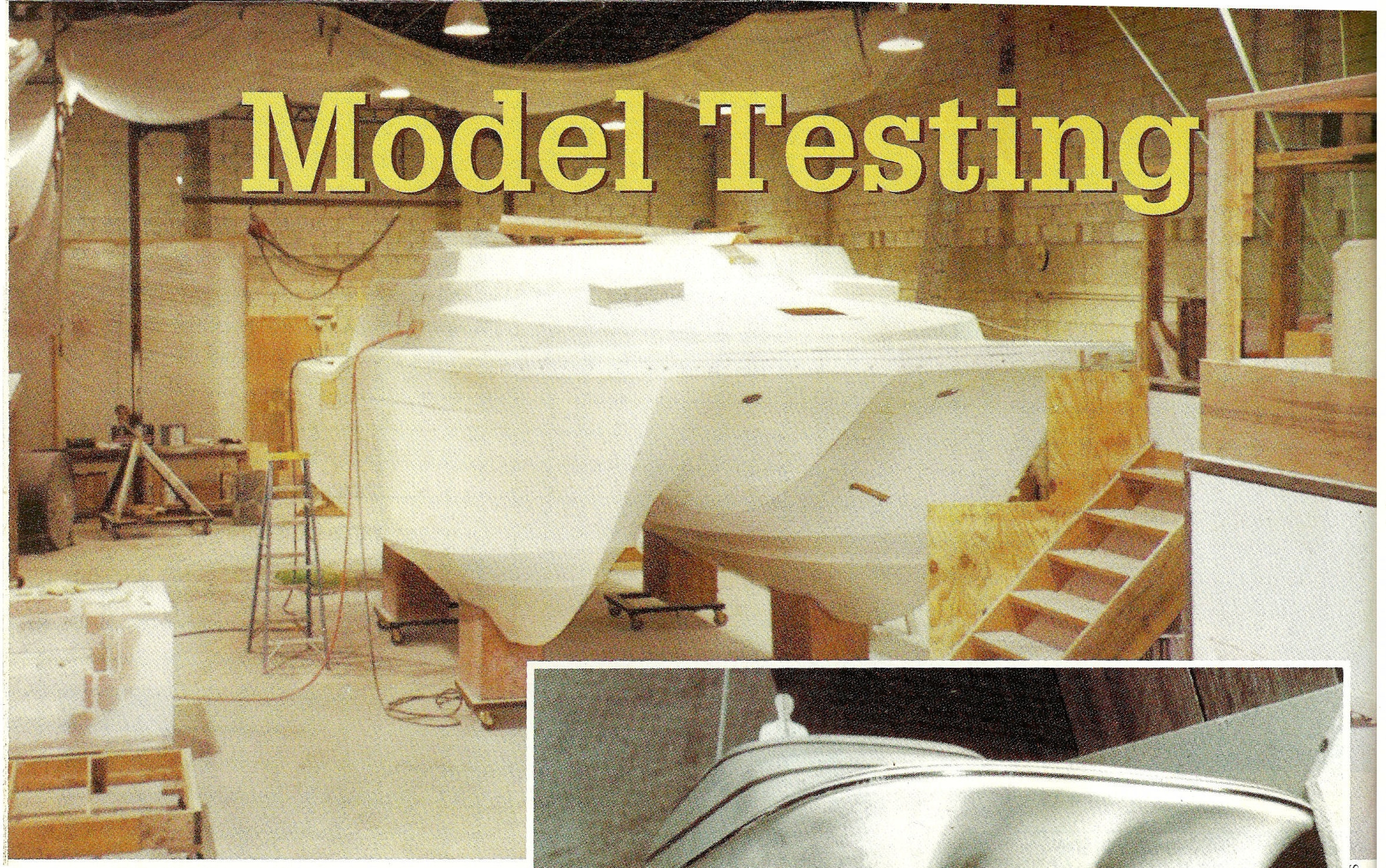
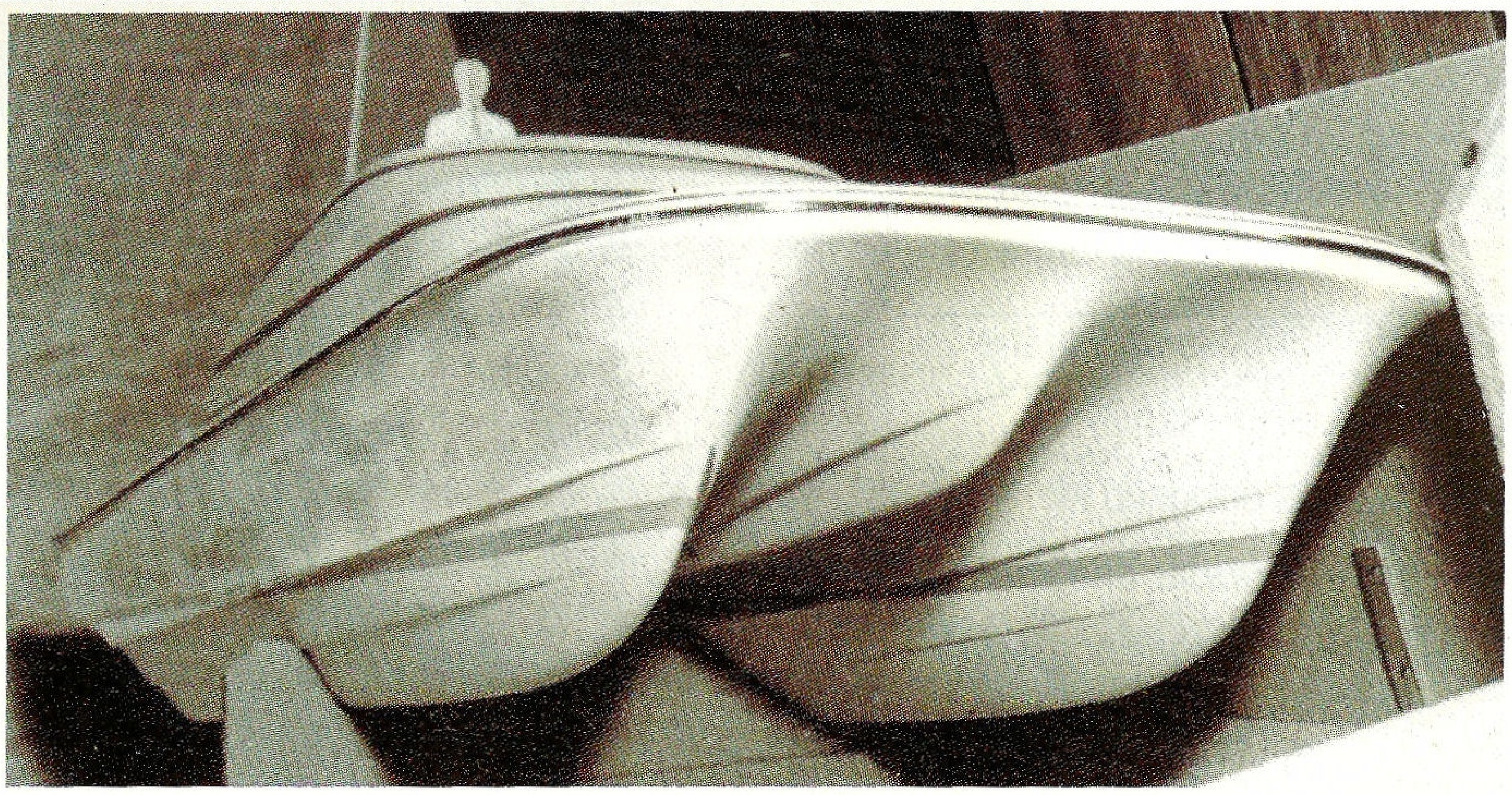
Model Testing





JOHN KILEY PHOTOS

What exactly can you learn from a scale model of a new hullform? And can you accurately test the little boat somewhere other than in a controlled environment?

First of Two Parts

by Richard Akers

You've been building boat models since you were a kid. It's fun, and the results are gratifying. But really, can this kid's stuff be of use to you now? It would be nice if the answer were a resounding "yes," but, like everything else in life, it's not that simple. Models can be as straightforward as carved balsa wood floating in a swimming pool and towed by a fishing pole; or as complicated as five-axis NC-cut structural foam, radio-controlled and propelled by a gasoline motor driving a surface-piercing propeller or even a small waterjet. Results vary all the way from inconclusive to highly useful to the designer.

Why Bother?

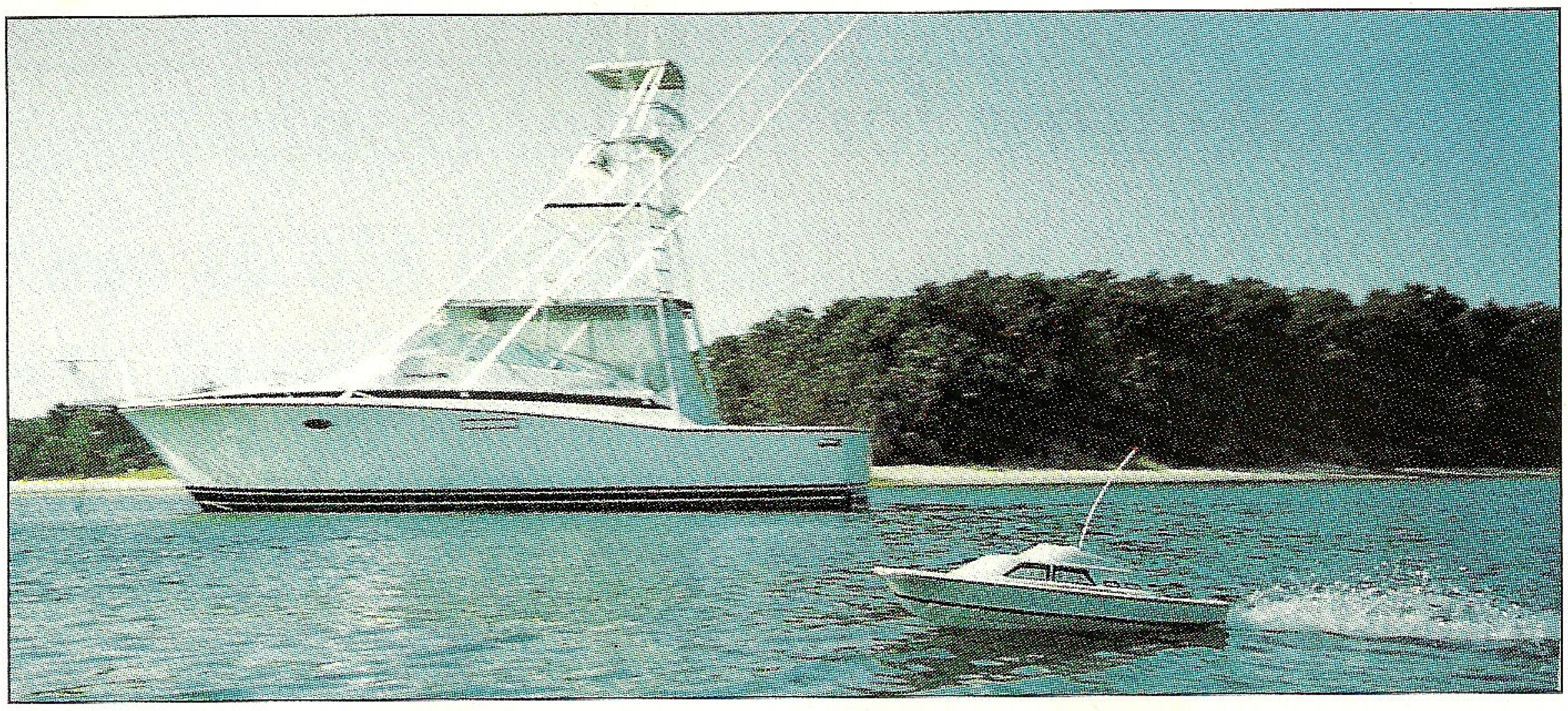
The value of building and testing models depends on your goals. Sometimes it's better to use a free-running model, sometimes a precision model in a commercial towing tank, and sometimes it's best just to use a computer program and skip the model altogether.

The least expensive way to analyze the performance of a new hull is to utilize a computer program, particularly one that has been proven in the commercial marketplace. To estimate the power requirements for a conventional deep-V hull, for example, you can get within a percent or two by using a number of commercial programs. On the other hand, to predict the dynamic stability of a high-speed craft performing a complicated set of maneuvers, you may be out of luck.

When should you consider building a free-running model? The most common answer from naval architects is that they

*Powercat designer John Kiley made five scale models, including the one above **(inset)**, to test various length-to-beam ratios and powering options for a 36′ sportfisherman. The successful full-scale version **(top)** is now being produced by Benchmark Boats (Stuart, Florida). Kiley says he found his models to be useful for both design and marketing purposes.*

Right—*Kiley's radio-controlled composite model runs past the real thing, outfitted with a tower, outriggers, and bridge enclosure.* ***Below***—*Designer Mark Fitzgerald's model of the Adams 36. This handsome working model, which was pond-tested, helped confirm the hullform and establish the styling of the boat's superstructure.*



JOHN KILEY

build models to analyze unconventional, innovative hulls. Few designers expect to predict the power requirements from their models, but they are able to predict the wetness of a planing-hull ride and the basic maneuvering capabilities of their hullform. Furthermore, a number of designers have used models and videos of the tests as marketing tools to promote their professional services.

IF your goal is to:	THEN the value of each of the following is:		
	Free-Running Models	Model in Towing Tank	Computer Programs
Predict Power	Poor	Good	Good
Predict Seakeeping	Poor to Fair	Good (in head or following sea)	Limited
Predict Spray	Fair to Good	Good	Poor
Study Maneuvering	Good	Limited	Low
Market	Useful	Useful	Limited
Study Behavior of Innovative Design	High	High	Low
Test Cost	$$	$$$$	$

Constructing Your Model

Models of boats are by no means a recent idea. Distinguished scientists including Leonardo da Vinci and Benjamin Franklin built and tested model boats. Most of the early designers carved a block of wood until they got the shape they wanted, but that technique is only efficient for small models. Over the years the carved-model technique was refined, becoming the sandwich or layer method that is still common today. A layered model consists of a glued sandwich of many "lifts" of wood, each roughly shaped to match a scale waterline. When the glue is dry, you plane and sand the stack until your model exactly matches the shape of your hull. This type of model can be made with simple woodworking tools, but it is very time consuming, and the models can be quite heavy (which can pose a problem, as we'll see, for models of high-speed craft).

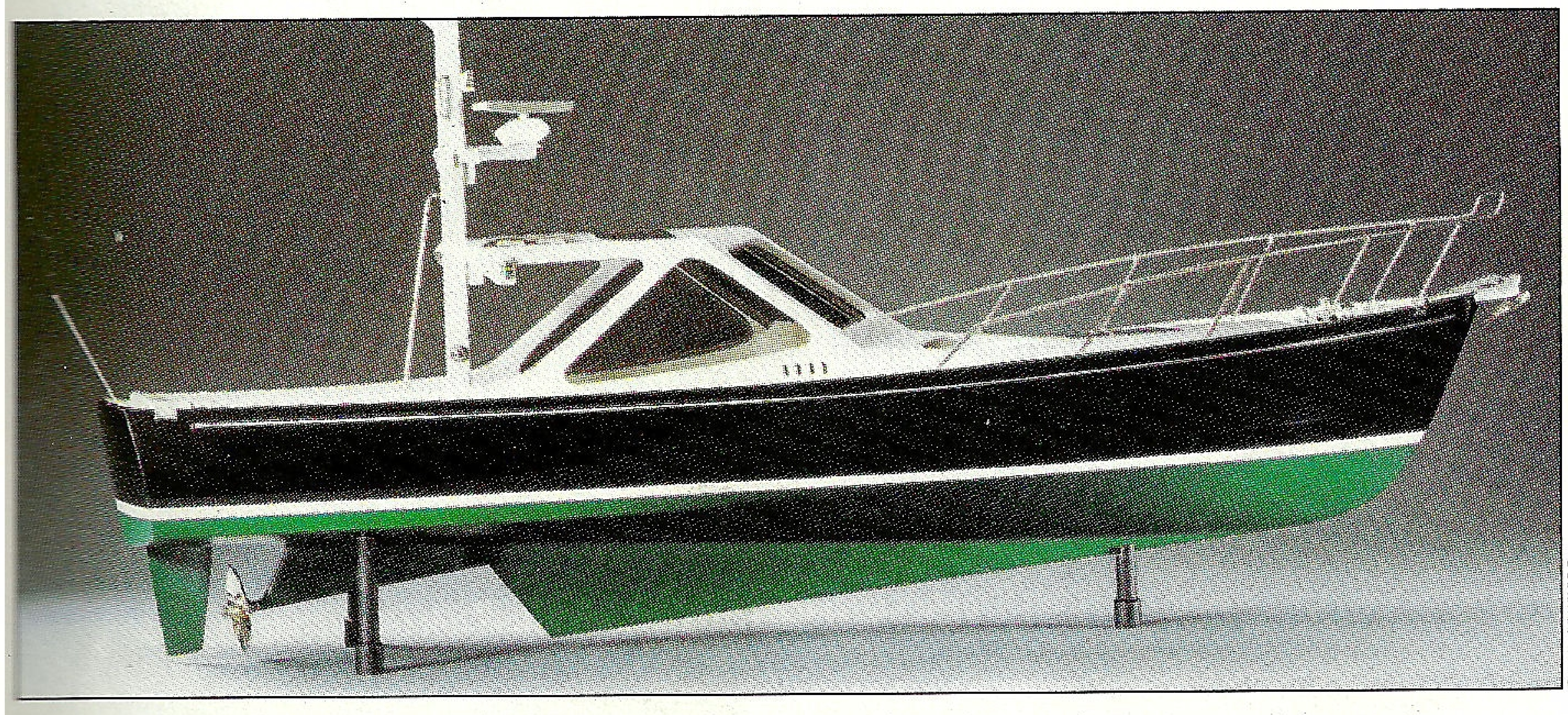
Designer Mark Fitzgerald (Camden, Maine) used the sandwich technique to construct a 54″ model of a 36′ powerboat. He initially powered his model with an electric motor, but switched to a gasoline model-aircraft engine for higher speeds. With this engine Fitzgerald was able to push the model to 13.4 knots, corresponding to 38 knots for the full-sized craft.

Of course, one alternative to the sandwich method is to use conventional building techniques. Several years ago Osterville, Massachusetts-based designer John Kiley was interested in developing a new line of power catamarans (see "Kiley's Cats," PBB No. 47, page 16). Since there was little design data available on power cats, Kiley decided to experiment with his ideas by testing models. He designed a 36″ model and made a mold so that he could try various model powering options. In addition, he was able to adjust the mold for building longer and shorter boats.

Kiley built five models off the single mold. Interestingly, as he built new models, he was able to reduce the models' weight to simulate the flotation of the full-sized craft. To simulate their motion, Kiley had to make light models, so he explored model-aircraft materials. He chose carbon matte, light Kevlar, and high-heat epoxy; following assembly, he baked the models in an autoclave.

The state of the art in model building is to design the model with a computer program and then send the design files to a machine shop (via e-mail, of course). The machine shop cuts the model out of a foam block using a five-axis NC (numerically controlled) router, and ships you the finished product. If all goes well, the model is virtually perfect and the turnaround time extremely short.

Engineer Dave Jansen of North End Composites (Rockland, Maine) has proposed a number of ways of building models from computer-based designs. One possibility is to treat the model as a small boat, carve a mold, and then laminate an FRP shell. There are several alternatives for the mold itself, including carving it out of pattern wood, or out of low-density or even 25- or 30-lb high-density foam. Jansen says that the choice of construction methods and finishes is determined by economics. There is a distinct trade-off between creating an accurate model up front, or fairing it out after the fact. He cautions that most models require a significant amount of



BILL THUSS

Guidelines for Model Boats

1. All of the dimensions of the model, including the propeller diameter, must be scaled to the equivalent dimensions of the full-sized boat with a single model-to-ship scale factor.
2. To avoid the effects of capillary waves, models should be at least several feet long.
3. The weight of the model must be the full-sized weight times the cube of the scale factor.
4. To make it easy to ballast your model, choose a model size such that the weight of the model hull is less than one-third of the scaled weight of the full-sized vessel.
5. If you want your model to pitch, roll, and yaw at the same rate as the full-sized boat, try to distribute ballast in your model following the same weight distribution as the full-sized craft. As an approximation, the weight distributions on most boats can be modeled by placing ballast weights one-fourth of the model length forward and aft of the center of gravity.
6. Add small trip wires (approximately 0.035″ in diameter) about 5% abaft the leading edge of the operating wetted surface. Alternatively, add a row of studs (about 0.12″ in diameter and 0.1″ high) spaced about 1″ apart.
7. Given a full-scale design speed, pick a model speed based on matching the speed-to-length ratio of the model and the full-sized ship. That is, $V_{model} = V_{ship} \times \sqrt{\text{scale factor}}$
8. Install the propeller in your model so that the angle and propeller hub distance below the baseline match those of the full-sized craft.
9. Place the ballast in a powerboat model so that the running trim and heave angle of the model match the expected attitude of the full-sized vessel.

—Richard Akers

hand finishing no matter how accurate the original computer design.

Jeremy Mollica of Mollicam (Merritt Island, Florida), manufacturer of robotic tooling equipment, has constructed foam models for use in commercial towing tanks. Mollica started with an IGES (Initial Graphics Exchange Specification) computer file, cut a soft-foam core, coated the core with syntactic foam, and recut the model. The result was a model that was both precise and light.

A rule of thumb (at least for quotation purposes) is that good models cost $1,000 per foot, and this rule seems to hold no matter how your model is made. For example, a 3′ model will cost about $3,000 and a 6′ model will cost $6,000. Add your design time, and the model costs $5,000 to $10,000, a sizable investment. As one naval architect said, after you have built several models the extra cost of testing them in a commercial towing tank doesn't seem so large anymore.

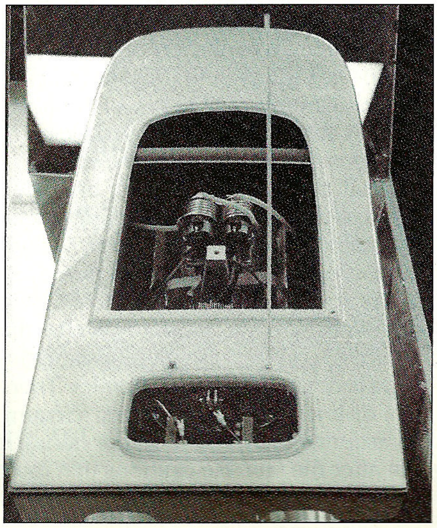
Powering Your Model

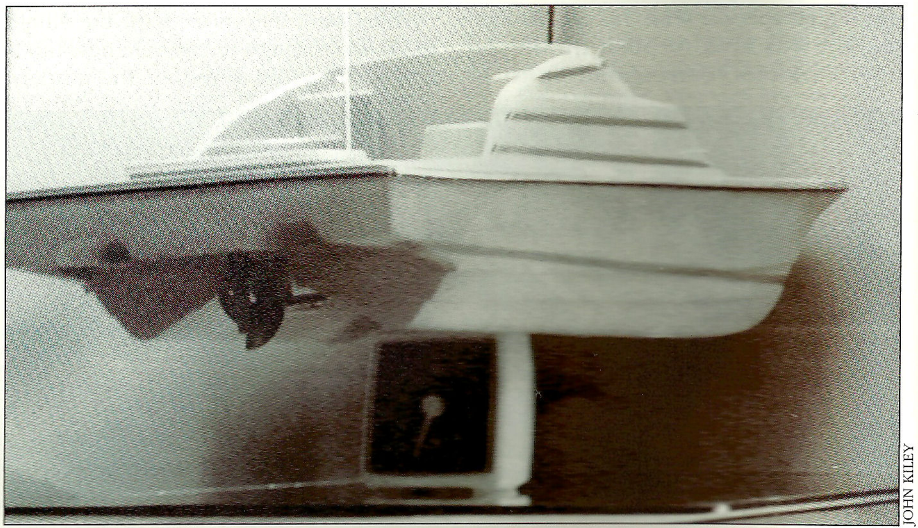
You have three choices for powering your model: tow the model from a boat, propel it with an electric motor, or power it with a gasoline engine. In the first part of this century the well-known yacht designer N.G. Herreshoff tested some powerboat models by towing them from his steam launch. To prevent the wake of his launch from disturbing the wave pattern of his model, Herreshoff built an elevated platform on the bow of the launch. Using a yoke, Herreshoff was able to compare the resistance of two powerboat models. Herreshoff also constructed a resistance wheel with which he measured absolute model resistance. *[For a detailed look at N.G. Herreshoff's half-model construction techniques and collection, see "The Builder's Model," PBB No. 54, page 82—Ed.]*

The design firm Morrelli & Melvin (Newport Beach, California) is well known for its multihulls, both power and sail. When Gino Morrelli and Pete Melvin began considering power catamarans, they, like John Kiley, could find little technical design information. So, to study the effects of different hull configurations Morrelli and Melvin built a number of models and compared them by towing pairs from a yoke.

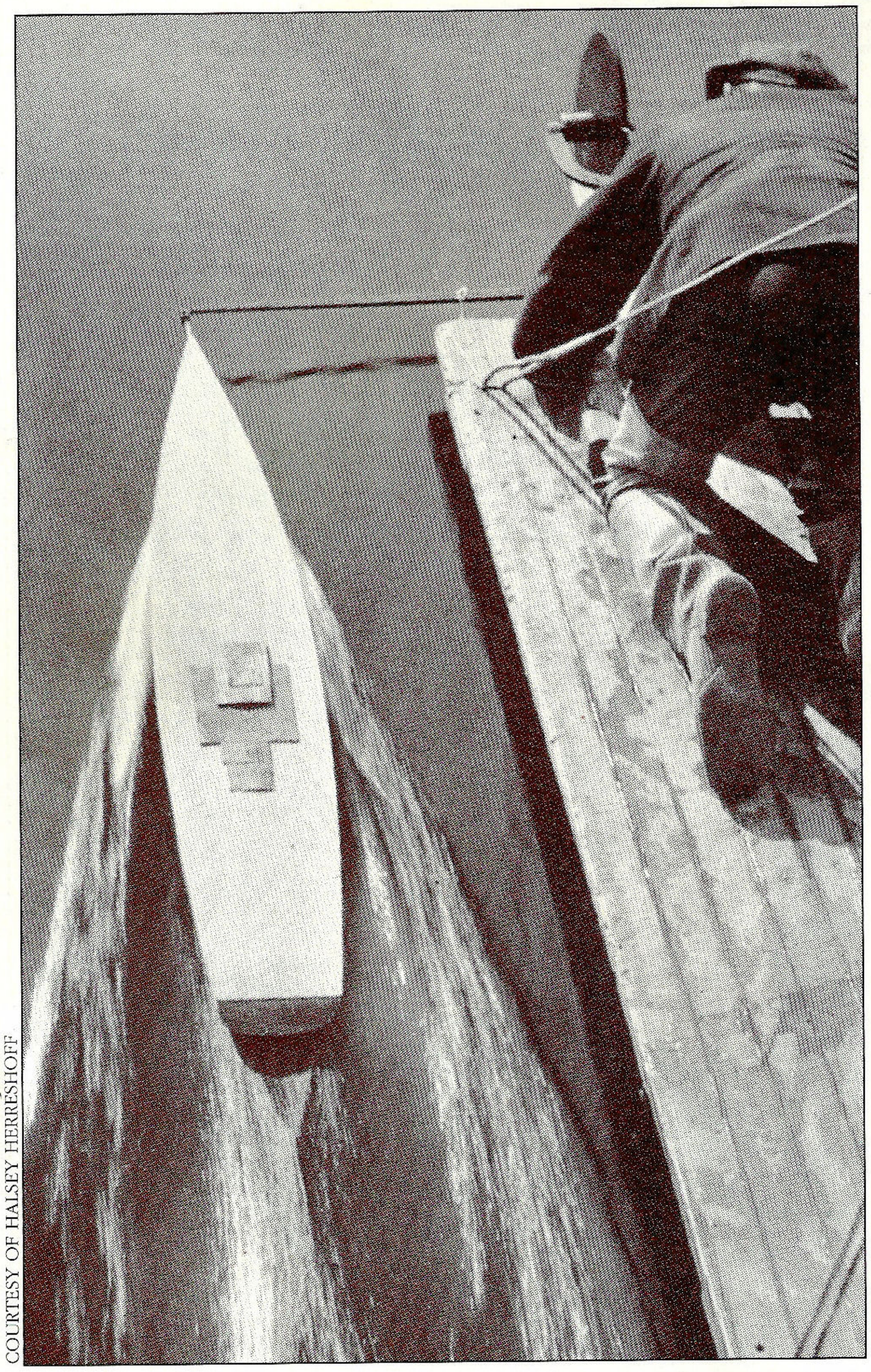
According to Pete Melvin, M&M "modernized" Herreshoff's method by using a carbon fiber shaft for the yoke, monofilament line to tow the models, and a

Two more views of a Kiley power cat model. He initially powered his model with an electric motor, but switched to a gasoline model-aircraft engine for higher speeds. Kiley also used model-aircraft materials for the hull and house to keep the models light for accurate motion simulation.

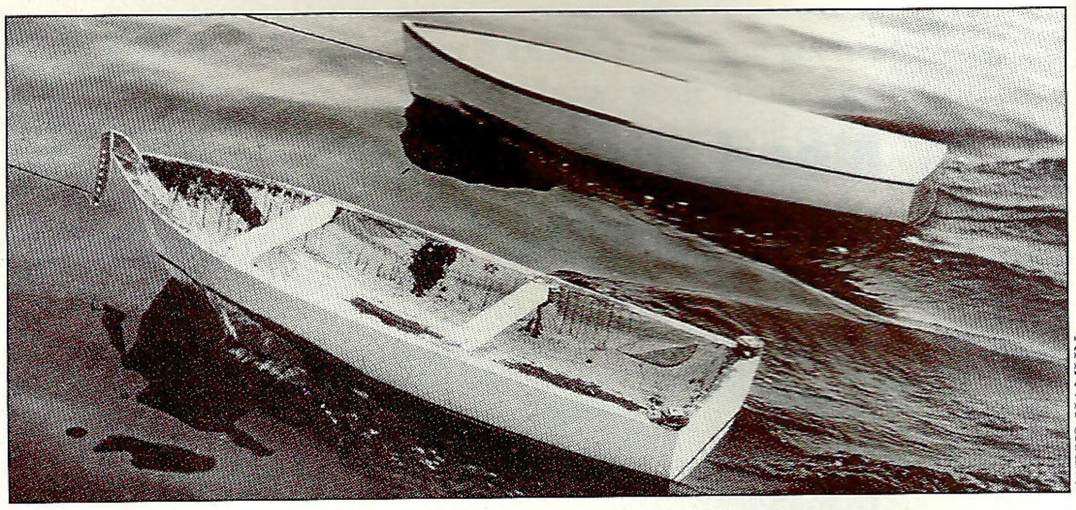




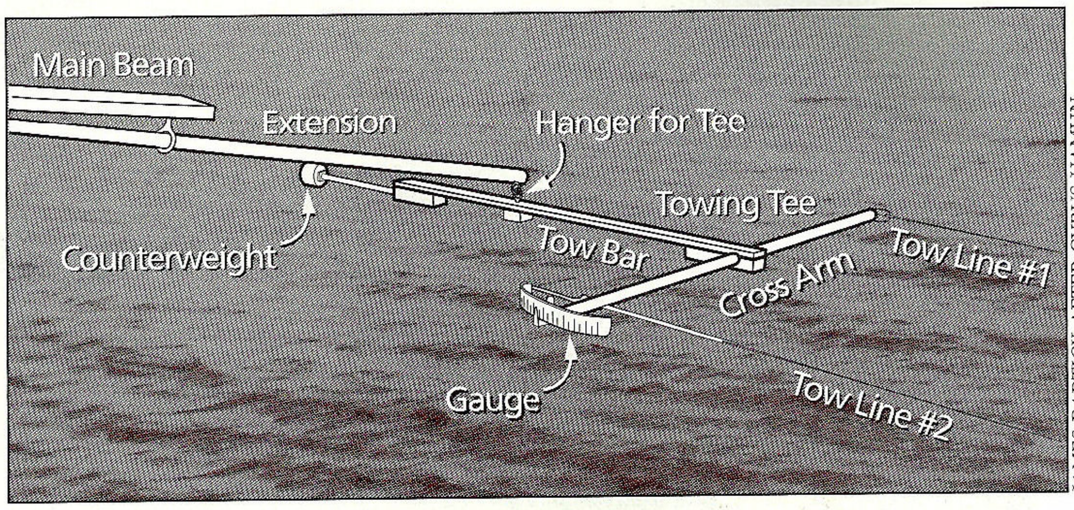
JOHN KILEY



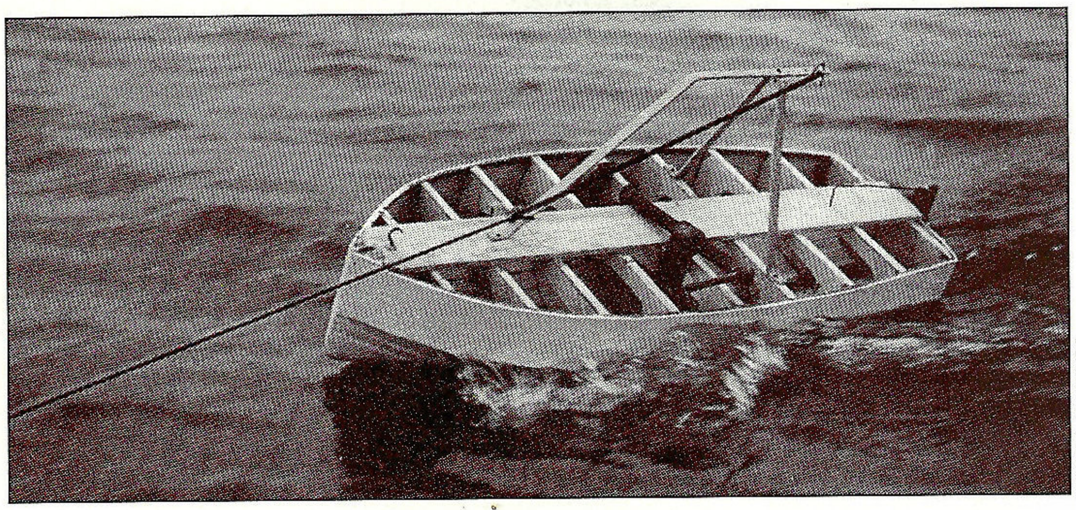
COURTESY OF HALSEY HERRESHOFF



CYRUS HAMLIN



JAMES BARTICK AFTER CYRUS HAMLIN



Left—*N.G. Herreshoff's resistance machine, circa 1915. N.G. suspended a platform from the bow of his own steam yacht, and connected the model via a bridle to a wheel mounted to the platform. A coil spring resisted rotation of the wheel as load was applied by the towed model. This spring stretched to show the amount of resistance based upon the wheel's rotation. Given a sufficient number of test runs and good record-keeping, N.G. was able to develop a reliable database for his designs.* ***Right, top***—*Two models—such as these powerboats designed by Cyrus Hamlin—can be compared by towing them on a yoke or balance beam. The model that lags behind has more resistance. By towing models a designer can study the wave-making characteristics of a proposed hullform and get a sense of how wet the ride will be in the full-sized vessel.* ***Right, middle***—*Hamlin's towing setup.* ***Right, bottom***—*It is much harder to simulate, at small scale, the forces acting on a sailboat hull—but it can be done. This 30" ballasted and towed model is a boat designed by Hamlin, who required his students at Maine's Landing School to build and test models of their designs.*

GPS receiver to estimate speeds (or sometimes they timed a course with a stopwatch). They took great care to make the tests accurate, testing in perfectly calm water and switching the models to alternate sides of the yoke so as to eliminate any built-in testing bias.

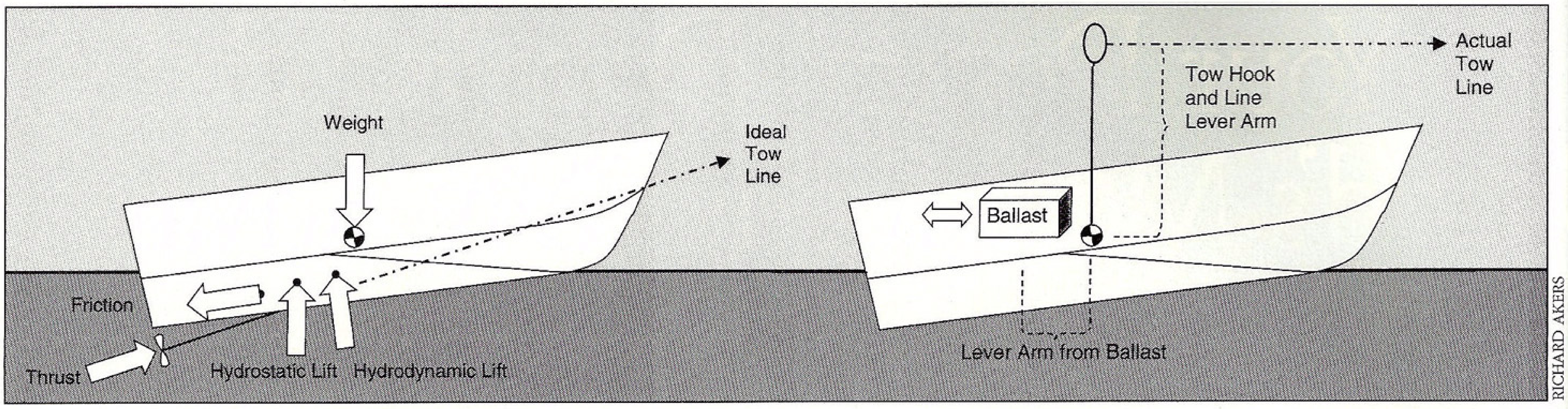
Melvin says that he did not expect results that would scale properly for hull resistance, estimating instead that the actual resistance of the models would probably be 20% or 30% off the scaled resistance of the full-sized craft. But that was all right, he figured, because what they were looking for were primarily qualitative results and, adds Melvin, he and Morrelli were pleased with their findings. They were able to study the speed-power humps and hollows of their designs by comparing pairs of models over a wide speed range.

Naval architect Cy Hamlin (Kennebunk, Maine), author of *The Preliminary Design of Boats and Ships* (Cornell Maritime Press, 1989), advocates the use of electric power for free-running models. Electric power, he says, has a number of advantages, including continuous proportional control, plus reverse and neutral gears. With electric power you can measure the power requirements of your model by measuring the current flow. On the other hand, the power density of batteries is low compared to that of gasoline. If you have a big model and you want it to be quick, you may need to switch to gasoline power.

The popularity of model-boat racing has produced a wide selection of engines and propellers. The model-airplane engines of our youth are still available, but today's model-hydroplane enthusiasts install much larger engines, such as converted weed-whacker (grass trimmer) engines. And, if you haven't looked at model powerboat propellers lately, you'll be surprised at the array of products now available. You can choose from a broad range of propeller diameters and pitches off the shelf, and you can even buy, at a reasonable price, surface-piercing props mounted on gimbaled outdrives.

Balance of Power

A model boat will behave like a full-sized boat only if the model is dynamically similar to the full-sized boat. To be



Left—*The various forces acting on a planing hull must themselves be modeled properly for the model to behave similarly to the full-sized boat.*
Right—*By shifting ballast, you can compensate for the pitching-moment error caused by not towing the model along the actual thrust line.*

dynamically similar, the model must satisfy two conditions: First, all of the dimensions of the model must be scaled to the equivalent dimensions of the full-sized boat with a single scale factor. Second, all of the forces acting on the model must be scaled to those of the full-sized boat with a single factor.

A direct result of the first condition is that the weight of your model must be the weight of the full-sized vessel times the cube of the scale factor. Consider, for example, a full-sized sportfishing boat with a length of 36′ and a weight of 28,000 lbs. If you want to build a ⅛-scale model, your model will have a length of 4′6″ and a weight of 28,000 x ⅛ x ⅛ x ⅛, or about 54.7 lbs. That weight is possible, but light, considering the weight of the building materials, motor, radio controls, and so on.

Now consider building a much smaller 2′ model. This time the scale factor is 2 divided by 36, or 1⁄18, so the model weight must be 28,000 x 1⁄18 x 1⁄18 x 1⁄18 or 4.8 lbs, and that's very difficult to do. The bigger the model, the easier it is to match the weight of the full-sized vessel.

Remember Newton's Second Law of Motion (force = mass x acceleration)? Well, his laws apply to boats as well as apples. If you know the weight of the boat, and you know the forces in every direction, you can predict the acceleration in each direction. In other words, if you can predict the forces in all six degrees of freedom (surge, sway, heave, roll, pitch, and yaw), then you can predict the acceleration that corresponds to these forces. Knowing the acceleration, you can then predict the velocity, and finally the position. For model tests to be useful, you need to scale all six forces as accurately as possible.

The forces on a planing hull include hydrostatic and hydrodynamic lift, friction, the weight of the hull and its cargo, and the thrust force. All of these must be modeled properly for the model to be "similar" to the full-sized vessel.

In full-scaled real life, the thrust force generated by a propeller or waterjet is often not parallel to the surface. So, to model your boat properly you must also apply your towing force along the same line of thrust that you would encounter in the full-sized boat. For a self-propelled model you should install the propeller at the same angle as that of the big boat. For a towed model you could try to design some sort of towing rig that would pull the model both forward and up at the same time, but that is very difficult. An alternative is to have the towline parallel to the water surface and to move ballast weights forward and aft until the running trim and draft of your model approximates that of the full-sized vessel. From a physics standpoint, the results should be the same (ignoring the effect this has on pitching actions).

By shifting ballast you can compensate for the pitching-moment error caused by not towing the model along the actual thrust line.

Figure Skating and Model Boats

Last winter many of us watched diminutive Tara Lipinski win an Olympic gold medal in ice skating. For most spectators, her performance represented an athletic achievement and a thing of beauty. For naval architects, though, her performance also represented a lesson in physics. When Lipinski begins a spin with her arms outstretched, she spins at a moderate rate. As she pulls her arms in closer to her body, she begins to spin faster and faster. Her total weight hasn't changed, nor has she added any energy to her "system." The reason that she spins faster is that her weight distribution (in engineering terms, her "moment of inertia") has changed, and in fact, become lower. Her spinning momentum is fixed and equals her moment of inertia times her spin rate; so when her moment of inertia drops, her speed goes up.

Likewise, if you want the pitch, roll, and yaw motions of your model to match those of your full-sized vessel, the moments of inertia of your model must scale properly to the full-sized boat. You may have your model weight scaled properly, but if your weight distribution is wrong, your model won't act like the full-sized boat. For example, if you have your model ballast spread too far forward and aft, then your model will have a high pitch moment of inertia, which will cause it to be overly sluggish in pitch.

Another rule of thumb is to build a large enough model so that the model's hull weight is only one-third of the scaled full-sized boat weight. This makes it easier to ballast your model correctly, and leaves you enough margin to move your ballast around to match the moments of inertia for pitch, roll, and yaw. If you don't know what your weight distribution will be, you can approximate it by placing your ballast weights symmetrically one-fourth of the boat-length forward and aft of the center of gravity.

Model Sailboats

To accurately model the behavior of a sailboat, you have to scale the forces in all six degrees of freedom. Not only do you need to match the forward resistance, but also the side resistance (since a sailboat always has some sideways slip), the roll resistance, and the yaw resistance. And, just to add to the degree of difficulty, there's this: you need to apply the towing force at the center of effort of the sailing rig, and this force needs to be balanced by a rudder moment to correct for yaw forces.

Designer Bruce King (Newcastle, Maine) expresses strong skepticism that anyone could measure side forces on a scaled-down sailboat from non-tank models. He adds that there are few towing tanks around the world equipped to measure sailboat forces properly. Many don't measure a model's dynamic roll moment, but instead use the static roll moment. King summarizes the technical problem as follows: "The driving factor in testing is to find the center of lateral force, and how it changes with heeling. Especially for larger boats, the balance is critical. What you can handle for a weather helm on a 40' boat would be intolerable on a 100-footer."

Despite his skepticism about model testing, a few years back King towed a sailboat model with tufts, or telltales, on it in a swimming pool. Although he didn't attempt to measure resistance, moments, or side forces, King says his tests allowed him to see that the backwash off the model keel reversed the flow direction, and he felt that he did learn something from the effort.

Tough to Model Resistance Accurately

To predict the resistance of a hull based on model tests, you must consider friction and wave forces. You can match one or the other in scale, but usually not both. In 1868, William Froude proposed breaking the resistance of a ship hull into pieces, and mathematically modeling each piece separately. To use his method to predict the resistance of your boat from model tests, you must:

1. Pick a single scale factor to calculate every model dimension based on the equivalent dimension on the full-sized boat.
2. Pick a model speed (given a design speed) based on matching the speed-to-length ratio of the model and the full-sized vessel. That is,

$$V_{model} = V_{ship} \times \sqrt{\text{scale factor}}$$

Measure the total resistance of the model at this speed.
3. Calculate the frictional resistance of the model based on the model's speed and wetted surface. Subtract this from the total resistance to find the model's wave drag.
4. Multiply the model's wave drag by the scale factor to get the full-sized boat's wave drag. Calculate the frictional resistance of the full-sized vessel using the design speed and your estimate of the wetted surface on the full-sized vessel. Add wave drag and the frictional resistance to get the total resistance.

If you do all of this carefully (and Neptune is on your side), you can predict the full-sized boat's resistance rather accurately. But, as in most endeavors, the devil is in the details. First, what is the wetted surface of your model? You can estimate its wetted surface by measuring its trim and draft, but this can often be off as much as 50% due to wave-making effects.

You can try to estimate the water rise at the bow by watching closely, or you can even put a diver under your model to observe its behavior. John Kiley took underwater photos of his model boats in the swimming pool at Tufts University. (These photos, by the way, became important marketing tools for him later.)

Assuming that you can measure or calculate the wetted surface, how do you know that the water flow on the model boat is the same as on the full-sized boat? Water flow can be smooth ("laminar") or rough ("turbulent"). The friction you get from laminar flow is much lower than the friction you get from turbulent flow.

Unfortunately, your full-sized vessel will be surrounded by turbulent water, while your scale model will have a tendency to run in laminar water. To model the friction properly, you may need to add trip wires, sandpaper strips, trip pins, or other devices to your model. (See the accompanying sidebar on page 34 for additional information.) These devices force the water flow around the model to become turbulent, and result in a better friction match between your model and the full-sized boat.

Gino Morrelli and Pete Melvin tried measuring resistive forces from their models, but with little success. They made a gallant effort, using very accurate spring scales, and towing the hulls with the correct shaft angle. But the scale jitter was so large that they really couldn't read the scale. Melvin says he and Morrelli even went so far as to video record the scale, and then to compute average forces by reading individual frames of video. It was an interesting experiment, but not a fruitful one.

Although the idea of comparing the performance of two models by pulling them through the water is appealing, quantitative results may be questionable. According to naval architect Lou Codega (Alexandria, Virginia), "The differences you should be looking at in a legitimate model test are probably so small that these differences are difficult to find. Trying to measure forces by towing the model behind, say, a Boston Whaler makes the differences impossible to find because of scaling effects." Codega advocates the use of computer software for resistance prediction, and if that is not adequate, then he recommends testing a series of models in a towing tank in a controlled environment.

Naval architect Dudley Dawson (Greensboro, North Carolina) echoes Codega's comments: "Frankly, some of the stuff that's most important to the performance of high-speed boats depends on small details." Dawson adds that it often takes almost as much time and effort to create a good model as to create a prototype, and testing a full-sized prototype will give you more information. Modeling resistance accurately is difficult, and many naval architects would advise you not to try to use your model to estimate the resistance of your full-sized vessel.

Rough-Water Testing

Pete Melvin and Gino Morrelli were concerned about the seakeeping characteristics of their power cats, so they tested models by towing them in a small chop (representing waves for full-sized vessels). Melvin says that these tests allowed them to fine-tune the design of their spray chines to minimize spray.

Mark Fitzgerald is a strong proponent of radio-controlled model tests to study seakeeping characteristics of a new hullform. He notes that there are few commercial towing tanks that can do a good job of simulating beam, quartering, or confused seas; and he feels that it is important to run models in waves for a longer period than is possible in most tanks. He does admit, "A true engineer argues that you can't scale a sea state." In other words, the wave components that make up a given statistical sea state normally cannot be matched by the ripple and chop in a lake or pond. Fitzgerald wryly recounts a failed attempt to create regular waves in a pond, which quickly resulted in a truly confused "sea."

In his lecture series to students at The Landing School of Boatbuilding and Design (Kennebunkport, Maine), naval architect Cy Hamlin lists some of the advantages of open-water model testing, saying: "Runs can be as long as desired to allow the integration of oscillating and varying forces, and allow the buildup of very small forces to a measurable level." Hamlin does concede that it is difficult to measure forces in open-water tests, and that it can be hard to find sea conditions that approximate those encountered by full-sized craft.

Alternatives to Model Testing

There are alternatives to building and testing models. Dudley Dawson uses the computer program NavCad in his design office. Dawson has observed reasonable correlation between the software tools and the performance of full-sized vessels. He further suggests that one alternative to purchasing and learning analysis programs is to ask commercial testing tanks to review designs. Most commercial tank facilities have developed computer software based on their cumulative experience, and they can analyze most common hullforms. Dawson notes that a commercial tank facility could probably give you a powering estimate accurate to within 5%, along with some good advice on seakeeping.

Lou Codega advocates the use of computer programs and analysis tools whenever possible. Codega has collected algorithms from a number of technical papers and implemented them in the form of spreadsheets using the program TK Solver.

Probably the best way to predict the performance of a new hull in a family of hulls is to keep historical records of the performance of existing boats, and to employ that data to predict the performance of new hulls. Dawson is of the opinion that the average production boat builder may tend to skimp on full-scale analysis and recording of data—information that is a lot better and less expensively obtained than model data. Codega has an historical record of the performance of all the boats he has designed over the years. He says that, based on his data and algorithms, he would be disappointed if his speed-power estimates were more than a knot off.

Even the model builders suggest that the use of computer simulation may supplant models in many cases. Dave Jansen of North End Composites states, "As good as the simulation software is getting, it won't be too long before nobody builds models anymore."

Drawing Conclusions

Towed or free-running model boats can tell you a lot about the general behavior of the corresponding full-sized boat. Powerboat models are more useful than sailing yacht models because of the difficulty of matching all of the forces on a sailing vessel. While it is difficult to accurately measure hull resistance, comparative testing can tell you something about the effects of hullform variations on hull resistance. A free-running model is especially valuable when you want to study motions in oblique waves, the shape of the bow wave, and the potential dryness of a ride in the full-sized boat. Model boats and pictures or videos of the boats in action can be a great marketing tool to convince a skeptical public that your ideas are valid. And last but certainly not least: designing, building, and testing model boats is still a heck of a lot of fun. PBB

About the Author: *A graduate naval architect and marine engineer, Richard Akers is the principal of Ship Motion Associates, specializing in marine software for hydrodynamic analysis. He is based in Portland, Maine.*