THE 18th CHESAPEAKE SAILING YACHT SYMPOSIUM

"That Peculiar Property:" Model Yachting and the Analysis of Balance in Sailing Hulls

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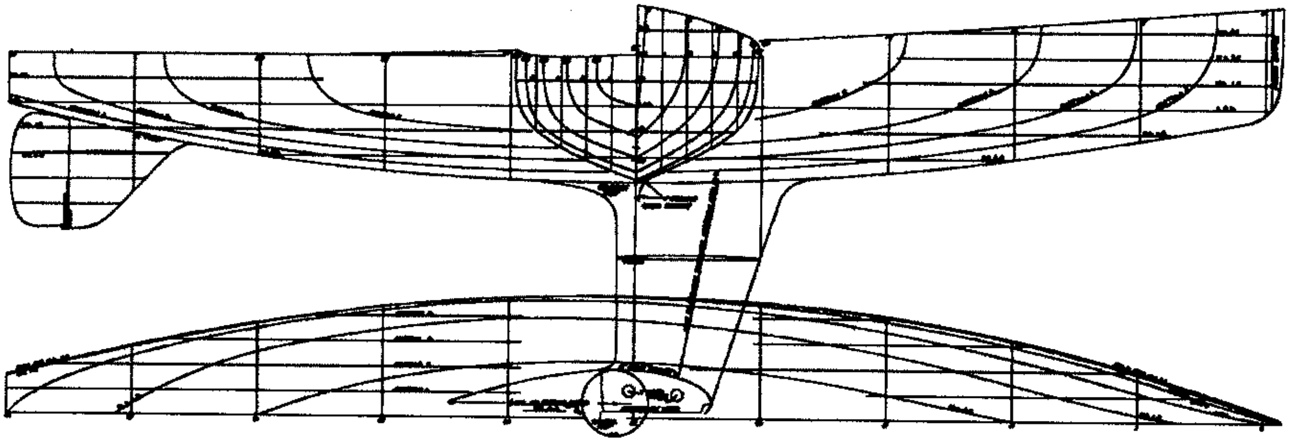

Ted Houk's *Rip Tide*

ABSTRACT

Balance in sailing hulls has been most extensively studied by the designers of free sailing model yachts. This paper describes the nature of free sailing which led to this preoccupation, and then explains the controversial theories of Admiral Turner. The correlation between Turner's criteria for balance and known balanced and unbalanced designs is shown and procedures given for designing boats to those criteria. The paper concludes with speculation about the relationship between theory and practice in this area and suggests areas for further research.

NOTATION

LCB	Longitudinal Center of Buoyancy
LCF	Longitudinal Center of Flotation

INTRODUCTION

The term "balance" is used in two contexts in sailing yacht design. The first, which we will call "rig balance," involves establishing the relationship between the center of effort of the sails and the center of lateral resistance of the hull. The second, which we will call "hull balance," involves the design of a hull shape that maintains a steady course under varying angles of heel. It is this latter sense which is the subject of this paper, what Douglas H.C. Birt[1] called "that peculiar quality known as balance." (Birt, N.D.)

FREE SAILING MODEL YACHTS

For about 100 years before the ascendancy of radio control in the early 1970s, model yachts were sailed "free" of external control. A small but enthusiastic group of individuals continues free sailing in both the U.S. and the

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[1] Later, Douglas Phillips-Birt. We have been unable to locate the source of this reprint.

U.K., and there is a competition between the two countries held every other year.

Beginning in the early 1920s, a consistent set of rules and practices were established for both national and international competition on closed bodies of water:

- Races were conducted as match races in round robin fashion, with each competitor matched against each other competitor at least once.
- Each race consisted of two legs, or "boards," one to windward and one to leeward, running the length of the pond.
- A competitor was awarded three points for winning a windward board and two points for winning a leeward one.
- A boat coming to shore before the end of a windward board could be manually tacked by its skipper or mate with a pole without stopping. A boat coming ashore before the end of a leeward board must be stopped and retrimmed before restarting.

Two forms of self-steering mechanisms were used. Prior to World War II, the dominant mechanism was a mainsheet-to-tiller mechanism called the "Braine Gear." This gear was only used on leeward boards. After World War II various forms of vane steering gears dominated. These gears were "self tacking" in that they would use the angle of heel to automatically set the vane angle to the proper tack when turned while going to windward.

The scoring method placed a premium on high and consistent windward performance. Both self-steering methods relied on rig and hull balance for this. Boats equipped with Braine gear sail to windward on rig balance alone. Boats equipped with self-tacking vane gear have a limited ability to correct for imbalance when going to windward; if the boat turns such that extreme weather helm is required, the wind force can be sufficient to cause the vane to change tacks prematurely and slow the boat. Hull balance therefore is a prime concern for designers of free sailing model yachts. The value of hull balance to full-sized yachts was best summarized by Douglas H.C. Birt:

> *A yacht is balanced if she shows a natural desire to steer straight when heeled. A well-balanced yacht, like a good model, will sail herself under normal conditions with the rudder amidships; variations in the angle of heel will have no effect on the steering, while under the worst conditions she will be light on the helm and show no tendency to run wild.* (Birt, N.D.)

STUDIES IN HULL BALANCE

The earliest analytic statement of hull balance we have found dates from 1887. It appeared in C.P Kunhardt's "Small Yachts" (Kunhardt 1887) which has a chapter entitled "Balance and its Object." In this chapter Kunhardt argues that balance is achieved when the longitudinal center of buoyancy of a hull does not move when the boat heels[2].

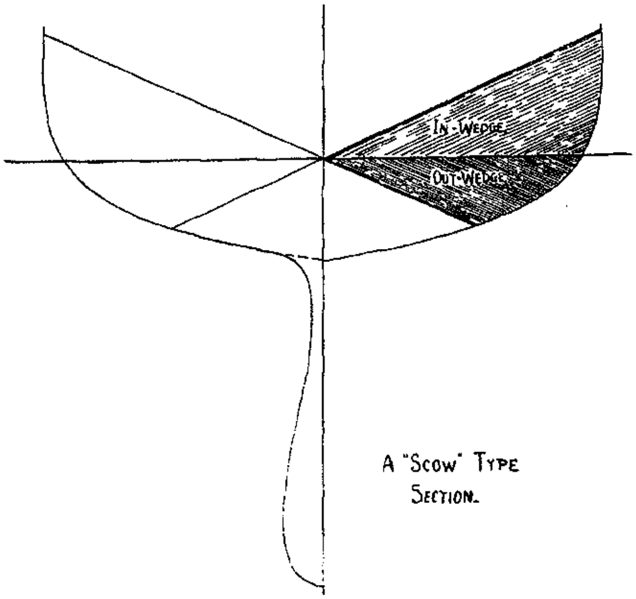

Figure 1. W.J.Daniels' notion of "in" and "out" wedges

The next discussion we have encountered is in a letter to the journal "Model Engineer" in 1902, in which an anonymous author discusses essentially the same principle described by Kunhardt (Anon 1902).

It is generally believed that the first true analytic technique for determining hull balance was devised by the British model yachtsman W.J. Daniels and applied by him to his model yacht *XPDNC*. This technique involved the calculation of "in wedges" and "out wedges" for each section, the "in wedge" being the area immersed when the boat heels and the "out wedge" being the area raised out of the water, as shown in Figure 1. (Daniels and Tucker, 1932)[3]. In later writings Daniels simplified this to determining that the longitudinal center of buoyancy did not move as the boat heels, just as Kunhardt had advocated earlier (Daniels and Tucker, 1952).

Beginning in 1927, then-Captain Alfred Turner of the Royal Navy published a twelve-part series on model yacht

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[2] In the D.N. Goodchild reprint, the term "athwartship position" of center of buoyancy is used, when the context clearly indicates that longitudinal is meant.

[3] Daniels' precedence in this matter is clouded by the publication in 1904 of a series of articles by W. H. Wilson Theobald in "Model Engineer." which describes precisely the same analysis. It is not known whether Wilson Theobald was describing Daniels' work or his own. (Wilson Theobald 1904)

design in the journal "Model Engineer," using his common nom de plume of "Kappa[4]." (Turner, 1927) This is the first description we have found of his later famous and controversial "Metacentric Shelf Theory" of hull balance. Essentially the same material was published in "Yachting" magazine in the U.S. in 1931 (Turner 1931), and "The Model Yachtsman" in 1932 (Turner 1932). The latter paper analyzed the design of the J boat *Enterprise* in the context of his theory. In 1934 he wrote a letter to "Yachting Monthly" in which he summarized his method in "20 points." Point (4) contains the crux of many naval architects' objections to his system:

A yacht balanced statically (i.e., at rest in still water) will balance dynamically underway as far as can be observed experimentally. (Turner, 1934)

His principles were later adopted by cruising yacht designers A.A. Symonds (Symonds 1938) and Harrison Butler (Butler 1945); the latter's designs being well regarded for their ease of handling.

THE METACENTRIC SHELF THEORY

Definition of the Metacentric Shelf

Turner's theory had two parts. The first is the calculation of the metacentric shelf proper. This is a plot of the station-by-station deviation of the station metacenters from the aggregate metacenter of the hull. The various metacenters are located by cutting heeled sections at each station from sheet material and balancing them on a knife edge as shown in Figure 2. The amount of heel is traditionally chosen to be that which puts the boat rail down. The aggregate metacenter is determined by gluing the sections together in a stack and balancing it as shown in Figure 3. (both from Turner 1932).

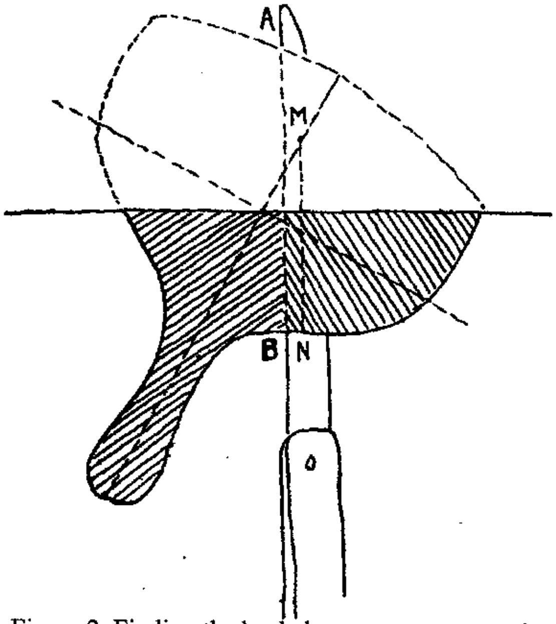

Figure 2. Finding the heeled metacenter at a station

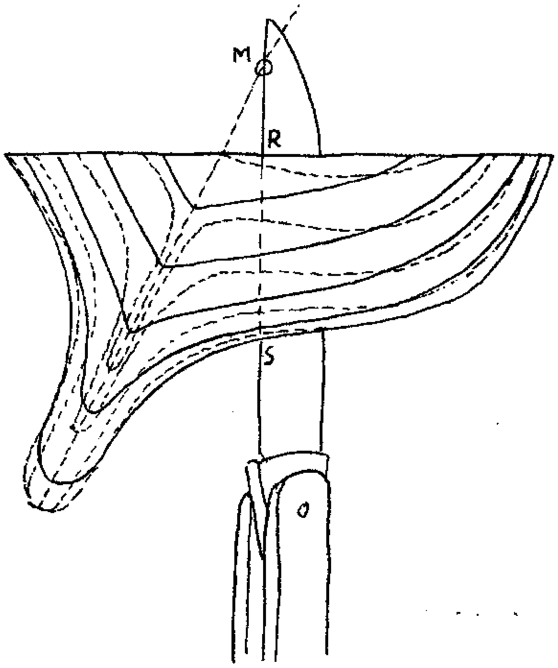

Figure 3. Finding the aggregate heeled metacenter

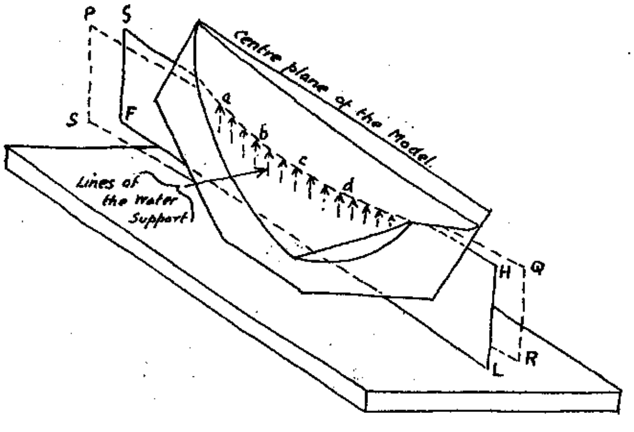

Figure 4. The Metacentric Shelf

The deviation at each station is the distance between the line MN in Figure 2, which a perpendicular from the aggregate metacenter to the heeled waterline, and AB, which is the local metacenter at that station. The distance

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[4] Turner also engaged in extended and lively correspondence, signing himself as "Kappa" or "K."

is signed, i.e., if a deviation to leeward is assigned a positive sign, then one to windward is negative.

Since the line AB in Figure 2 represents the vector of the bouyant force, the integral of the lines forms a plane on which the hull is balanced, to use Turner's analogy, like a child sitting on a fence. This is shown by the plane SHLF in Figure 4. (Turner 1927), which he called the "Metacentric Shelf." The Shelf is typically represented by the line SH, plotted on the load waterline plane[5].

An upright, symmetric hull will have SH running straight down it's centerline. As the hull heels, SH will both change shape and move relative to the hull centerline. Turner argued that if the heeled shelf rotated, as shown by PQRS, the boat would inevitably yaw.

Turner initially insisted that SH remain straight and parallel to the hull centerline as the boat heeled. This criterion severely constrained the hull shape. Later adherents to his methods were satisfied if SH formed a gentle curve whose ends were both on the same side of the aggregate metacenter. That is, if the station-by-station metacenters of the forebody lie to leeward, the station-by-station metacenters of the afterbody should also. As time passed, it became clearer and clearer that this one curve was overly simplistic and not a reliable predictor of hull balance.

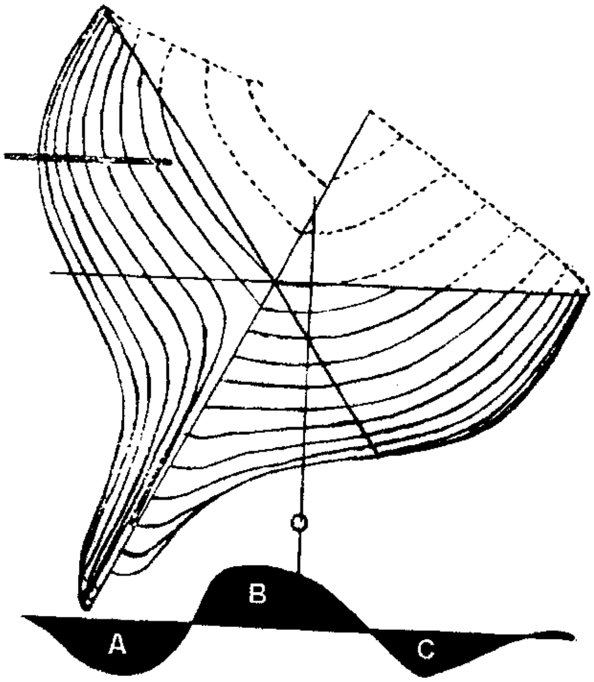

Figure 5. The moment curve for *Yankee*

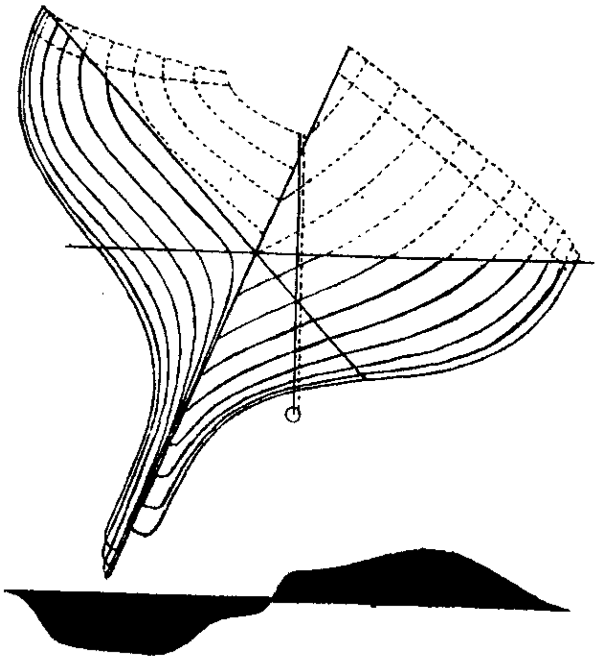

Figure 6. The moment curve for Satanita

The "Moment Curve"

The second part, to which Turner did not give a specific name, is more predictive of hull behavior. This is the curve which results from multiplying the deviation at each station by the immersed area at that station, which Birt calls the "moment curve." These curves have two typical shapes, which can be compared to the characteristics of actual boats to derive some interesting empirical results. . The curve in Figure 5 (Sciarelli, 1970)[6] is that for the 1929 J boat *Yankee*, which was noted for her hull balance[7]. Turner argued that the area under the moment curve for the forebody should equal the similar area for the afterbody, and the sum of the two should equal the area for the midships sections, or in Figure 4 A=C and A+C=B

The curve in Figure 6 is that for the notorious 1893 cutter *Satanita*, which ran out of control during a start sequence and rammed and sank the cutter *Valkyrie II* with loss of one of her crew. This curve exhibits the highly undesirable "crossing" behavior, in which the forces acting on the forebody are on the opposite side of those acting on the afterbody.

The relationship between the curves and the actual behavior of the yacht is argued by Birt:

It is ... a great mistake to regard a ship as a single entity, all the parts wanting to follow each other ... when a

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[5] In all cases of Turner's analysis, it is the shape of the curves, and not their numeric values, which is significant.

[6] These curves were clearly reprinted from some other work which we have been unable to locate.

[7] This may not have been a coincidence. *Yankee* was designed by Frank Paine, whose partner, Norman Skene, was an avid model yachtsman and almost certainly would have read Turner's 1927 articles.

yacht heels it does not necessarily follow that the ends and middle body all want to do the same thing, and and the areas under the moment curve are measures of the amounts by which parts of the hull tend to roll or swing more or less than the hull as a whole. [If] the stern curve C is greater than A curve, both of these lying to the leeward of the axis, [then] the stern wants to swing further to leeward than the bow on heeling, thus forcing the yacht's head up into the wind. (Birt, N.D.)

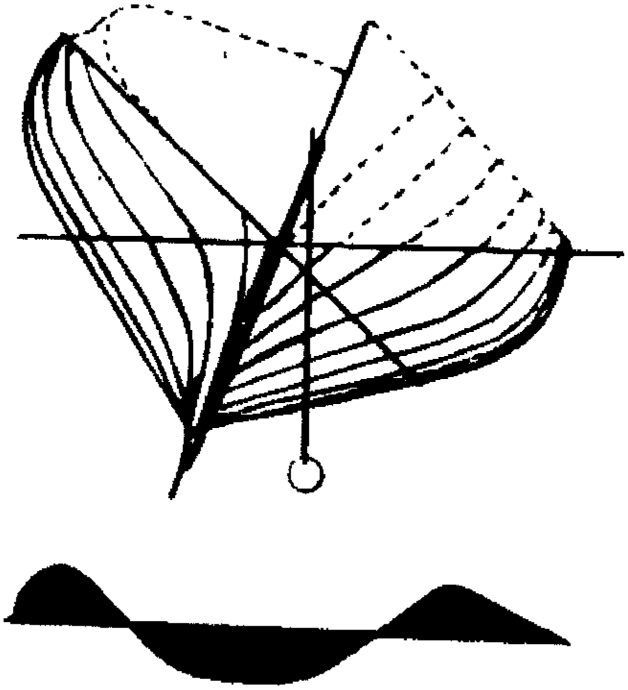

Figure 7. The moment curve for *America*

And of course, if the curve "crosses" as in the case of *Satanita*, the bow will be pushed one way and the stern another, magnifying the yawing effect. This argument is plausible but it is also speculative.

Another two curves of interest are shown in Figures 7 and 8. (Sciarelli, 1970). The Figure 7 curve is for the 1851 schooner yacht *America*, and shows an almost perfect conformance to Turner's criteria. To understand why she shows up well under an analysis devised seventy-five years after her design, one need only consider her pedigree as a New York pilot schooner. These boats raced for business through a busy roadstead, and therefore had to be both fast and handy; after delivering a harbor pilot they were often sailed back short or single-handed, and therefore had to be free of vices. Their evolution was accelerated because they were cheaply built and frequently worn out or lost through collision. It is not surprising that designs rapidly converged on a hull that was both fast and balanced. And, of course, she was designed free of the distortions introduced by rating rules.

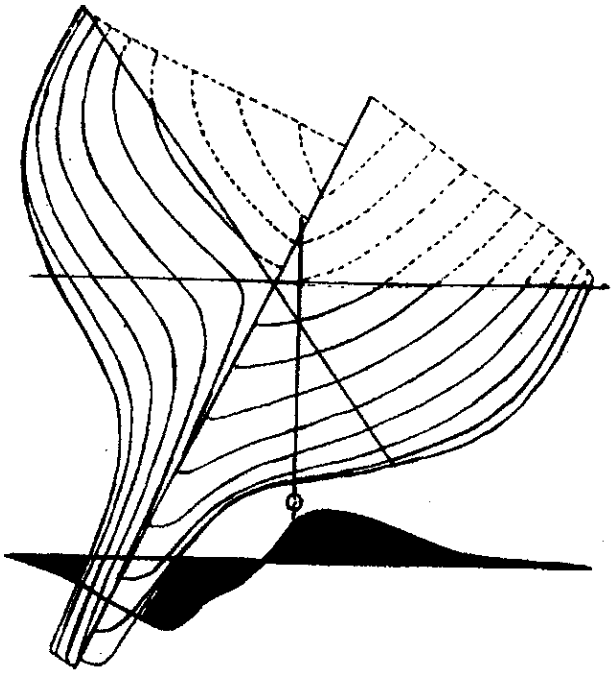

Figure 8. The moment curve for *Whirlwind.*

The curve in Figure 6 is that for the 1929 J boat *Whirlwind*, designed by L. Francis Herreshoff, which exhibits the undesirable "crossing" shape. "Whirlwind" was noted for her difficult handling characteristics. Many accounts ascribe this to the mechanical complexity of her steering gear, but she was asserted as early as 1935 to have an unbalanced hull. (Burgess 1935)[8].

CHARACTERISTIC HULL SHAPES

The advocacy of Turner's analysis methods by cruising yacht designers such as Symonds and Butler has led to a common misperception that the analysis inevitably leads to plodding double-ender hulls of the Colin Archer type. The examples of *Yankee* and *America* should dispel that notion. A further example is that of *Rip Tide*, one of the most successful M Class[9] model yachts ever, shown in the frontispiece. *Rip Tide* was designed by Ted Houk in 1949, and instances were winning races and championships under both a free sailing and radio control until the 1970s. The author has built and sailed a *Rip Tide* both free and under radio and can personally attest to the attractive handling characteristics of the design. Analysis of the hull reveals a moments curve that almost perfectly conforms to Turner's ideal. Correspondence with Houk's son, who watched his father design boats, confirms that the elder Houk used Turner's methods in analyzing and adjusting his designs. (Houk 2006).

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[8] Herreshoff was in the audience when this assertion was made. His reaction, if any, was not recorded.

[9] The M Class rating rule, in its essence, embodies restrictions of 50 in. LOA and 800 sq.in. sail area.

DESIGNING TO THE "TURNER TEST"

Adapting Existing Designs

Anyone wishing to design a hull that passes the "Turner Test" for balance, and which then is very likely to exhibit hull balance in practice, has two options. One is to adapt an existing design to a different rating rule. This option exists because the shape of the moment curve is independent of both scale and station spacing. One can therefore scale sections and adjust the station spacing (which Turner called "concertinaing") of a design to obtain the desired dimensions. The author has done this in adapting the *Rip Tide* design to the constraints of the 36 inch Restricted Class[10]. The resulting free sailing boat tracks to windward through gusts and puffs with the same aplomb as the original.

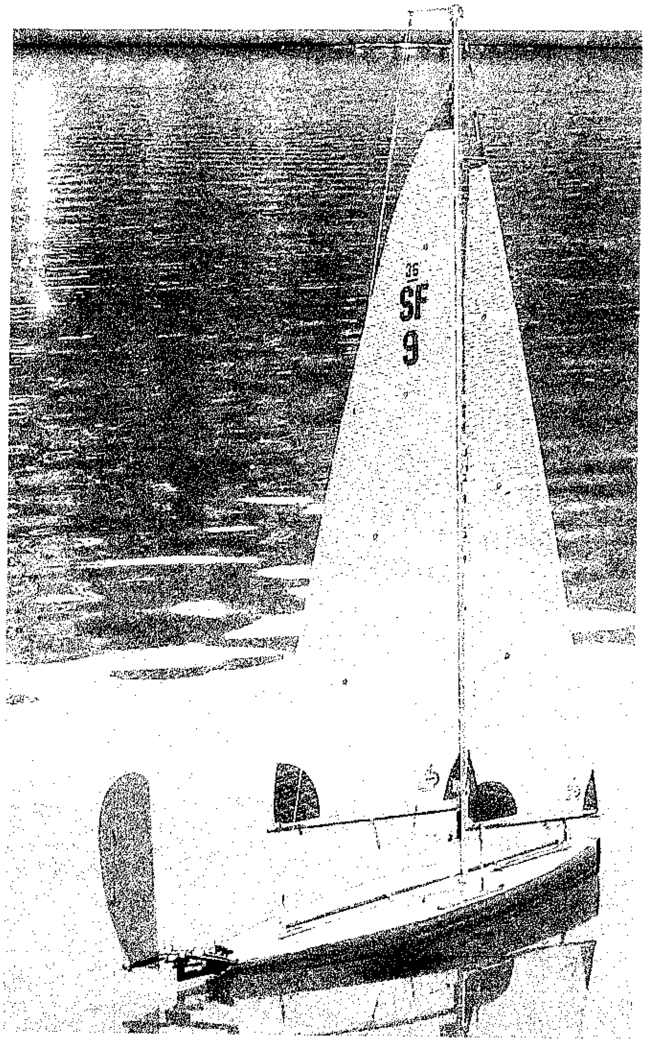

Figure 9. An adaptation of *Rip Tide*

Starting Afresh

The second option is to start with a blank sheet of paper (or computer screen). The process the author uses is based on the notion that a hull is essentially defined by fairness constraints and three "master stations": one at the point of maximum beam, which defines general characteristics such as the prismatic coefficient, one around 25% of the load water line, which defines the forebody, and one around 75% of the load water line, which defines the afterbody.

Referring back to Figure 5, the process is first to devise a hull form such that curves A (forebody) and C (afterbody) have essentially the same area; Birt suggests that deviations of up to 10% are permissible (Birt, N.D.). Curve B is then derived from A and C and the keel shape either adjusted to produce it, or in the case of a fin and bulb design, simply ignored. The easiest way to get the desired result is to arrange that the peak amplitude of A equals the peak amplitude of C. If the peak amplitudes are at the respective master stations, the (area x deviation) at those stations are likely to be equal to within 10%.

It will be recalled that the deviation at the master section is measured from the aggregate metacenter of the hull, which is not known at this time. In order to get the design process started we measure deviations from the hull centerline, adjusting the master section shapes until the two values of (area x deviation) are equal. At this point the intermediate stations can be derived by fairing (or, more likely today, simply read out of a hull design program) and their heeled immersed sections given the "knife edge treatment" to determine deviations from the centerline, and areas measured by a planimeter or by counting squares of graph paper. The resulting (area x deviation) values can be plotted to see if the curves A and C do indeed have equal areas, and intermediate station shapes adjusted if they do not. While such adjustments are highly dependent on hull form, moving the line AB to leeward usually requires adding area just above the waterline or removing area down low; the converse being required to move AB to windward. Games can also be played with tumblehome in the afterbody to obtain the widest possible transom.

The process is tedious but not difficult; as a rule, one can expect that passing the "Turner Test" requires a fuller forebody and narrower afterbody than current fashion dictates. This is shown in Figure 10, the canoe body of a free sailing model designed by the author for a student building and sailing program.

If the area and deviation measurements are captured in a spreadsheet, then a parametric analysis is possible. This is done by adjusting the deviations by a constant amount, which will show the effect of different values of the aggregate hull metacenter on the resultant curves A and C. It is the author's experience that changing these values has little or no effect on the relationship between the two areas and that for the "typical" fin and bulb design the aggregate metacenter is not a factor in the analysis.

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[10] Hull and appendage must fit in a box 37x9x11 inches, all other dimensions unrestricted.

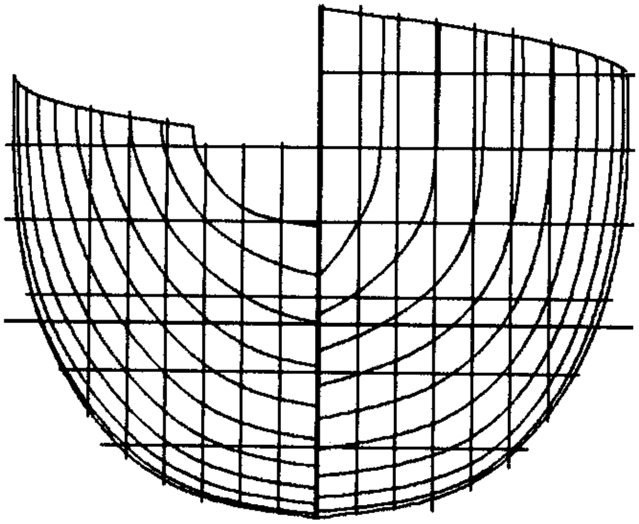

Figure 10. A hull that passes the "Turner Test."

CONCLUSION

The rather unsatisfactory state of our understanding of hull balance and Turner's ideas was summed up by C.A. Marchaj, who, after noting the criticism that Turner only considered hydrostatic factors, quotes K.C. Barnaby as stating:

we may doubt the accuracy of some of [Turner's] reasoning, but the fact remains that boats balanced on his metacentric shelf principle do turn out to be uncannily steady on their course. (Marchaj 1986).

The word "uncannily" nicely sums up the extent of our knowledge.

The evidence from practice is that Turner's method of analysis is predictive at the extremes: hulls that exhibit curves such as that in Figure 5 handle well, those that exhibit curves such as Figure 6. handle badly, and no firm conclusion can be drawn from curves that are in between. It is possible that the shapes of moment curves actually correlate with some other characteristic of a hull which is not directly measured by them. A hint of what this might be was obtained when an extensive analysis of the lines of *Rip Tide* was made by a contributor to an Internet forum (rcsailing) who noted that the LCB and the LCF of *Rip Tide* were very close together and stayed close together when the hull was heeled. This is still only a hydrostatic analysis, and there is a dearth of published information on why such analysis should be predictive of hydrodynamic behavior.

ACKNOWLEDGEMENTS

We are grateful for the contributions of Russell Potts and Theo Houk.

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