THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

Department of Naval Architecture and Marine Engineering

DESIGN CONSIDERATIONS AND THE RESISTANCE OF LARGE, TOWED, SEAGOING BARGES

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In the last decade, ocean-going unmanned barges have become an increasingly important segment of our merchant marine. These vessels, commonly over 400 feet long, and sometimes lifting in excess of 15,000 L.T. dead weight, are usually towed on a long hawser behind a tugboat. Because the barges are inherently directionally unstable, twin outboard skegs are attached to achieve good tracking. Model tests are conducted in order to determine towline resistance and the proper skeg position which renders the barge stable. Skegs, vertical appendages similar to rudders, are placed port and starboard on the rake. They create lift and drag, and move the center of lateral pressure aft, thus tending to stabilize a barge towed on a long line.

At The University of Michigan many such model experiments have been conducted within the past several years. Since these tests have been carried out for various industrial concerns and on specific designs, systematic variations of parameters or other means of specifically relating the results have not been possible in most cases. Nevertheless, on the basis of the results of these largely unrelated tests, recommendations can be made regarding good design practice and some specific aspects can be demonstrated. It is the purpose of this paper to set forth what has been learned from the experience gained. There are two main sections. The first section deals with particular aspects of barge design, including suggestions for advantageous characteristics which reflect observed trends and the results of isolated cases; the second attempts to give means of estimating towrope resistance.

Characteristics of the Models Surveyed

The still water resistance aspects of barge design are not as straightforward as they may first appear. Compromises are frequently made in dimensions or proportions in order to accomodate physical considerations of the restricted waterway parts of a given trade route. Unique cargoes may demand unusual barge shapes or proportions. Also, the problem of directional instability requires compromise. Since many of the barges surveyed were intended to be pushed at least a small portion of their life, the instability correcting skegs were usually a resistance detriment during the pushing operation. Although there are some schemes being promoted to allow pushing in heavy seas, most barges are still towed in the open ocean. For this part of the operation, skegs are required. It is reasonable to assume that a barge which could be pushed all the time would take on a completely different configuration from one which is normally towed.

This paper deals with so-called conventional bulk cargo seagoing barges of generally acceptable hydrodynamic design. In the survey, the results from those models with characteristics reflecting particularly unconventional requirements of possibly outdated characteristics were eliminated. The following criteria were satisfied by all the designs included:

1. L/B between 3.8 and 6.6
2. B/H between 2.5 and 5.0
3. Stern profile rake angle between 15° and 25°
4. $\Delta/(.01L)^3$ between 200 and 400
5. Stern log immersion less than 10% of the loaded draft
6. C_B between 0.78 and 0.92
7. Shallow forefoot
8. Model length at least seven feet in order to minimize scale effects

The survey included a large class of barges.

Hull Form

It was consistently found that certain hull form characteristics yielded acceptable model test results. The following are the important aspects of the entrance, run, and parallel middle body.

Entrance

The shape of the bow is the most significant factor influencing the directional stability of a barge. The entrance may also be the most expensive part of the hull to construct and the most easily damaged. It obviously has a direct effect on the towrope resistance.

Three distinct types of bows are commonly used. The chine bow, or double chine bow, is made up of simple bent plates and usually has straight frames. The ship shape bow is made up of plates of complex curvature and has waterlines ending in distinctly acute entrance angles at the center-plane. Unlike a ship's bow, the stem is not plumb, or nearly so. The spoon bow is also made up of furnaced plates, but has an entrance angle of 180 degrees or slightly less. The name of the bow derives from its spoon-like appearance. These typical bows are illustrated in Figures 1 through 3.

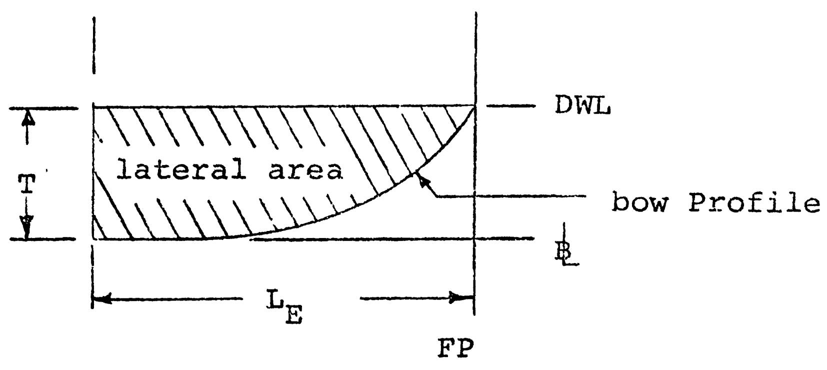
The bare hull resistance, which is that of the barge without skegs but restrained in yaw and side sway, varies among the three types of bows as might be expected. In those cases where comparisons were made, the ship shape bow consistently had the least bare hull resistance. In one case a spoon bow was shown to be superior to a double chine bow when the entrance length, profile shape, and displacement were kept the same. A plausible explanation for this result is the possibility of eddying caused by the chines. It is unlikely that in a given design the bare hull resistance of the three types of bows would vary more than several percent.

Flat sections forward are vulnerable to slamming damage. For this reason the ship shape bow is preferable due to its more nearly V shaped sections.

The authors understand that the cost of bow construction is becoming a less important criterion. Since barges are being built larger in size, they must now be constructed in relatively large, well-equipped yards where equipment for furnacing plates is often available. Therefore the difference in cost of building with simple bent plates rather than furnaced plates is becoming less significant.

Proper design of the entrance is important in obtaining low total resistance of the stabilized barge. Evidence from model tests shows that good towing barges consistently have significantly reduced forward lateral area. The effect of the bow profile being well cut away has been dramatically demonstrated. In one case, the increase in resistance due to the skegs over that of the bare hull was reduced by 30 percent when the entrance profile coefficient was reduced from 0.80 to 0.75. Since the skeg augment is commonly 40 percent, it is apparent that the total resistance can easily be influenced by 10 to 15 percent by proper design of the bow profile.

$$\text{Entrance profile coefficient} = \frac{\text{lateral area}}{L_E \cdot T}$$



Since a higher entrance profile coefficient contributes to increased skeg resistance augment, the ship shape bow may be disadvantageous compared to other bow types. However, since the ship shape bow usually has the least bare hull resistance, the best compromise may still favor it. In another specific case, a spoon bow required six percent less augment than a double chine bow. Since the bare hull resistance of the spoon bow was less than that of the chine bow, the spoon bow was preferable in this example.

Towing bridles constitute another, relatively minor factor in choice of bow design. Towing bridles can be more effective than single lines since they create an additional restoring moment on the hull. The wider the bow deck, the larger, and hence more effective, the bridle moment. For this reason the spoon bow is preferable to the narrower ship shape bow.

Run

Proper design of the barge stern is nearly as important as that of the bow for the most efficient combination of low resistance and directional stability. The stern should be designed to take the greatest possible advantage of the effects of the skegs, since lower total resistance is obtained by utilizing the lift produced by the skegs for stability rather than by designing the stern for greater resistance aft. Few systematic stern variations have been model tested, but observed trends among relatively unrelated designs indicate such specific recommendations as the following:

In profile, the rake should not make an angle with the baseline of greater than about 22 degrees. Also, the transition from the bottom into the rake should not be too severe. A generous radius, two to three times the draft, is recommended. Both of these features tend to minimize the possibility of separated flow in the area of the stern. Besides the obvious increase in resistance due to separation, skeg effectiveness is decreased since the average flow velocity across the skegs is reduced.

Stern log, or transom immersion, should be avoided or at least kept within ten percent of the full load draft since separation behind an immersed transom increases resistance. Also, skegs are normally designed within the envelope formed by the after perpendicular, baseline, and rake, and if the stern log is immersed, skeg size is reduced.

Figure 4 illustrates the desirable features of a well-designed run in profile and body views.

With regard to stern section shape, it seems likely that deadrise promotes an outward flow component which facilitates a negative skeg angle of attack, particularly when there are small amounts of directional instability. On the other hand, deadrise in the rake contributes slightly to directional stability. Possibly, good inflow to skegs outweighs the advantages of deadrise in achieving stability. However, no scientific evidence has been gathered in this regard. The models tested have had little or no deadrise due to their designers' efforts to obtain the maximum displacement without severe transom immersion at the centerplane.

The rake radius, which joins the sides and flat rake, is typically constant throughout the length of the rake. Therefore, the radius can be constructed from simple rolled plates. The dimension of a typical radius varies from two to four feet. However, among the barges surveyed, those which consistently had low skeg resistance augment had larger rake radii immediately forward of the leading edges of the skegs. This feature which permits better flow into the skegs is illustrated in Figure 4.

It is also important in a well-designed stern rake that the full deck width be maintained as far aft as practical.

The sides and transom are joined with a radius which is commonly two feet long. These design characteristics enable the skegs to be placed as far outboard as possible and enhance their effectiveness.

Many vessels have been equipped with a pushing notch. This V shaped wedge cut into the stern on the centerplane allows a tug to become somewhat more integrated into the barge. Recent evidence shows that notches up to 20 feet in length on a 400-foot barge have negligible effects on both resistance and stability. Notches designed for pushing in extremely lightly loaded conditions must have a greater vertical span. This can be obtained either by increasing the fore and aft dimension or by increasing stern log immersion or by a combination of both. Taken to extreme, both alternatives tend to increase bare hull resistance. The latter alternative also reduces skeg size.

Parallel Middle Body

Deadrise is often built into a barge for drainage purposes, particularly in cases of liquid cargo and when there is no inner bottom. There seems to be little other justification for deadrise. If there is an inner bottom, it can be designed with suitable rise. However, a small amount of deadrise, e.g. two percent of the beam, has no noticeable effect on either directional stability or resistance.

Proportions and Form Characteristics

Recently, considerable effort was made to optimize certain characteristic coefficients and proportions of towed barges with respect to resistance. A digital computer regression technique was applied to over 250 data sets of speed and resistance from about 40 model tests. The computer selected the most significant parameters describing each barge. The parameters were then combined with proper coefficients forming an equation estimating the coefficient of residual resistance. The hypothesis was that if a satisfactory equation could be found, then by merely partial differentiating that equation, optimal proportions and characteristics would be evolved. Unfortunately, no equation was found which satisfactorily predicted the resistance for a wide range of barges. The number of data sets was limited due to the broad range of parameters.

In addition, data correlation was attempted by hand. Numberous graphical schemes were tried in an effort to exhibit trends in resistance as functions of proportions or form coefficients. Some trends were discovered and are discussed in the resistance prediction section of this paper, but it was not possible to evolve an optimizing procedure. On the other hand, experience has shown that the following characteristics do consistently yield barges of acceptable resistance per ton displacement and satisfactory towing qualities. These values, in conjunction with the adoption of the hull form recommendations already discussed, should serve as a good starting place in the preliminary design of a prospective barge.

1. $B/T \approx 4.0$
2. $L/B \approx 5.5$
3. $C_B \approx 0.85$

One of the few variations in proportions which was tested at The University of Michigan involved a 23% increase in length. A 75-foot section of parallel middle body was added to a 325-foot barge. The bow, stern, breadth, and draft were not changed. Hence, the form characteristics changed as follows:

L	325	400
L/B	4.92	6.06
B/T	3.43	3.43
C_B	0.85	0.875
$\frac{\Delta}{(.01L)^3}$	291	198

At eight knots the bare hull resistance increased 11.1 percent. The skeg augment decreased from 47.1 percent to 37.7 percent. The adjustable skeg flap remained virtually unchanged; consequently, the skeg drag did not vary appreciably. The resistance per ton in the stable condition decreased 11 percent.

The longer barge had an 11 percent increase in resistance for 23 percent increase in cargo carried, which represents only a three to four percent loss in towed velocity, depending somewhat upon the tug. From this one isolated case, it appears that it is advantageous to increase the L/B and decrease the displacement-length ratio.

Skegs

As previously mentioned, stability can be achieved if enough drag aft can be induced. However, the lateral forces produced by skegs more effectively stabilize a barge.

All of the skegs on the models surveyed were of the so-called "cambered" type. They are usually constructed in two sections so that the trailing portion or flap may be rotated from the deck of the barge. Such a design has several advantages over fixed cambered skegs. During the portion of time that a barge is pushed, the flaps may be rotated so that they are aligned in the flow because directional stability is no longer a problem. This decreases the resistance, and hence increases the speed. In a few cases, the resistance of the hull with the skegs in the flow was actually slightly less than that of the bare hull. Apparently the skegs acted to reduce the eddy resistance. If a barge is under tow with a strong side wind, it may tow dangerously to leeward. The barge may be brought back behind the tug if the windward skeg flap is rotated outboard a few degrees. If a portion of the route is in a congested area, but pushing is not possible, a greater degree of stability and safety can be obtained by increasing the flap angle. When a barge is in a ballasted condition, the flap can be adjusted to a lesser angle for stability. It is interesting to note that a variation in flap angle of only three or four degrees will be the difference between a stable or unstable barge. The variation in drag for a given flap angle, measured relative to the leading portion of the skeg, is seen in Fig. 5. The figure also shows that a barge which is over-stabilized pays an inordinate resistance penalty since the curve is steepest at flap angles just greater than that required for stability.

Usually the leading portion of the skegs and the flaps which were model tested were approximately equal in area. The skeg should be as large as possible to obtain maximum forces and moments. In order to avoid damage, it should not, however, protrude below the base line or extend beyond the transom. Skeg thicknesses are primarily a structural matter, within reasonable limits, for they have little effect on resistance or stability.

In addition to size and shape, skeg position is of primary importance in achieving stability. Since water flows not only from beneath the barge but from the side around the rake bilge into the skeg, the leading portion must be angled outboard as shown in Figure 6. The proper orientation of the leading portion can be determined from flow tests. If the skeg is aligned in the flow with a few degrees of angle attack, the skeg augment is decreased compared to the leading portion positioned fore and aft.

In order that the maximum yaw correcting moment be produced with minimum resistance augment, skegs should be positioned as far outboard as possible. The leading edge of the flap, or the knuckle, should never be placed farther inboard than about 20 percent of the half beam. It is for this reason that the bilge radius should not be excessively large directly athwartship from the skeg, if constructing the skeg coincident with the radius is to be avoided. Figure 7 illustrates, in the case of one model, the resistance penalty incurred by not placing the skegs well outboard. Also shown is the fact that flap angle necessary for stability is increased markedly as the skegs are moved inboard. The additional angle needed contributes to the increased augment. As a practical matter, it is usually not possible to place the knuckle more than 80 percent outboard without having the trailing edge of the flap fall outside the maximum beam.

Other skeg types have been tried in the past, but with varying results. Most of the comparisons made have been between cambered and slotted skegs. In one case slotted skegs were superior, in another there was practically no difference, and in a third case the slotted skegs had higher augment. It is highly desirable that more efforts be made in development of slotted skegs as well as other types. However, it is also true that of the skegs reviewed in Benford's "The Control of Yaw in Towed Barges",[1] the cambered skeg was the most commendable.

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1. Benford, H. "The Control of Yaw in Towed Barges", Gulf Section, SNAME, April, 1955.

Resistance Predictions

There are two logical steps in predicting the resistance of a barge. First, an estimate must be made of the bare hull resistance, and second, an estimate of the skeg resistance augment must be made, both over the operational speed range. Obviously the addition of the two will be the total resistance prediction for the directionally stable barge. Only bare hull resistance is applicable to the pushing condition when properly positioned skegs with adjustable flaps are used. It would be very helpful to the naval architect to have a method of calculating the estimated performance while the design is in the preliminary stage.

Bare Hull Resistance

Several empirical methods of obtaining resistance estimates have been tried, employing resistance data from previously tested models. As previously mentioned, no satisfactory results were generated by the computerized regression analysis to predict residual resistance coefficients for a wide variety of barges. There have been numerous attempts to plot barge parameters as functions of various resistance coefficients and to use three dimensional form factors. Many of the results exhibited overall trends, but in no case could additional trends within the scatter of the data be established. Figure 8 shows residual resistance coefficient plotted against block coefficient for bare hull only. As elementary as these plots are, no more satisfactory result was obtained. The bands shown in the figure contain at least 80 percent of all data analyzed. The degree of optimism, in terms of how well an individual design incorporates the recommendations of the hull form section of this paper, will determine where in the bands the barge designer selects a C_R value.

The skin friction resistance may be determined with the 1947 A.T.T.C. coefficients since the residual resistance coefficients were determined using that line. As a practical matter, within the accuracy of the graphs of C_R, it would be equally acceptable to use the 1957 I.T.T.C. coefficients for full scale values of frictional resistance. In most cases of predicting barge resistance, the practice has been to use a correlation allowance of C_A=0.0004.

A quite accurate approximation of wetted surface area is given by the formula:

$$S = 36.7\ \Delta\ \frac{(B + 2T)}{BT}$$

where Δ is in L.T.S.W. Of the barges surveyed for this paper, about 95 percent had wetted surface areas within one percent of that given by the formula.

Skeg Resistance

The skeg augment amounts to from 25 to 60 percent of the bare hull resistance. Particularly difficult barges to stabilize, e.g. converted ships, may have as much as 150 percent skeg augment. However, low percentage augment is not necessarily a good feature, since it may be due to a poor stern design of high resistance which aids in stabilizing. Also, a barge with low bare hull resistance will have a greater percentage augment than a hull of higher resistance if the actual skeg drag is the same in both cases. Typically percentage augment is not a function of speed for any given barge.

The skeg augment data of the barges surveyed correlated to an even lesser extent than did bare hull resistance. This is in part due to the human element involved in ascertaining when a model is stable. Generally, stability is considered to be obtained when a model varies no more than a beam width off the intended course when towed on a line about three times the model length. In addition, the oscillations must be damped.

Full scale motions ought to be somewhat less, due to boundary layer scale effects and hence higher average flow velocities across the actual skegs.

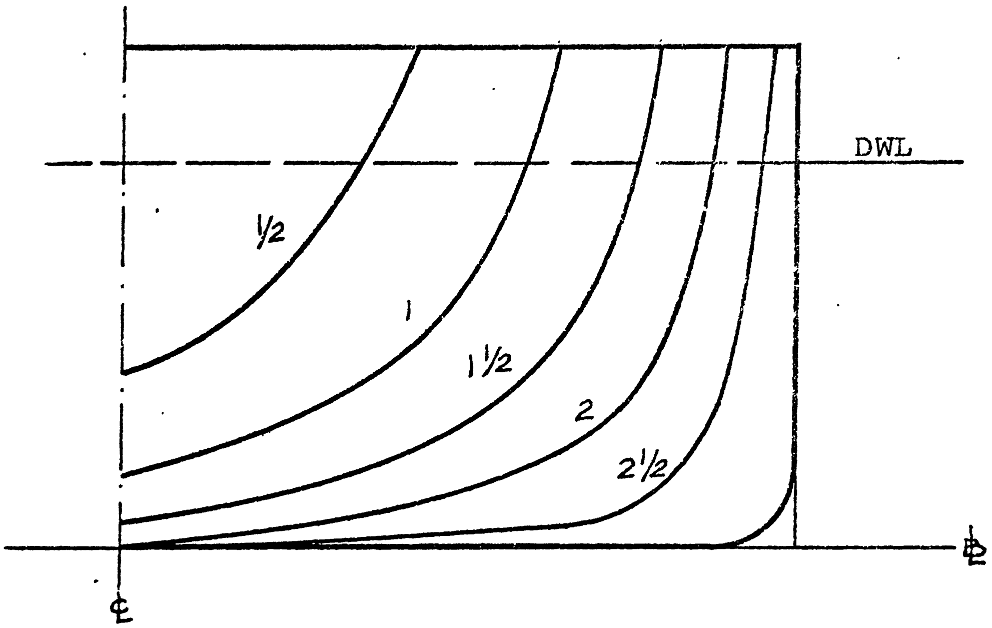
The most effective method of predicting skeg augment is in terms of speed decrease rather than in resistance increase. Among all models surveyed, the speed decrease over the bare hull speed was between 7.3 and 9.3 percent regardless of the original speed or form parameters. The data were examined at four different speed-length ratios and 70 percent of the points fell between eight and nine percent speed decrease. The median of all data was 8.46 percent.

To estimate the total resistance, the designer needs to determine the bare hull resistance as already described, graphically construct the bare hull resistance curve, and shift it to the left at constant resistance by 8.5 percent to allow for skeg augment. It may be desirable to adjust the shape of the bare hull curve and repeat the shifting process until the skeg resistance augment is nearly a constant percentage of the bare hull resistance throughout the speed range.

It is hoped that this paper will serve as a guide in the design of large ocean-going barges. The authors have attempted to relate what they have learned from having conducted many barge model tests over the last several years. Without the funding supplied by the Society of Naval Architects and Marine Engineers, Interstate Oil Transport Company, and George B. Drake, many of the experiments conducted in order to investigate specific facets of barge design would not have been possible. The technical guidance of Professor R. B. Couch and the editorial efforts of Mrs. Carol Rosenberg are specifically acknowledged.

Figure 1

TYPICAL SHIP SHAPE BOW



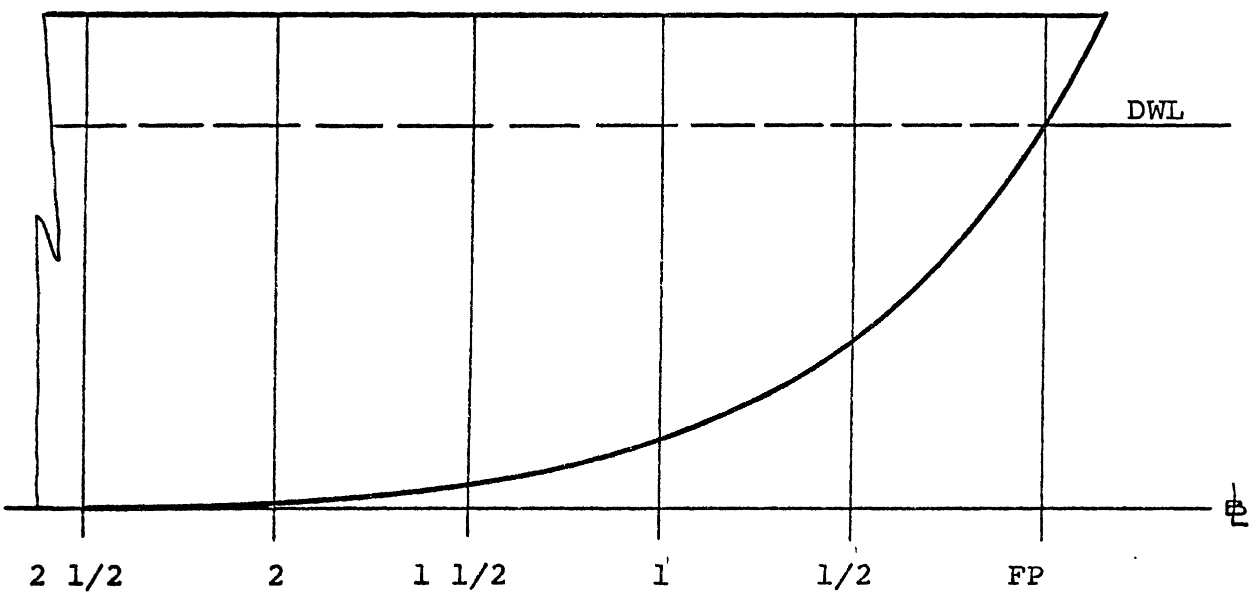
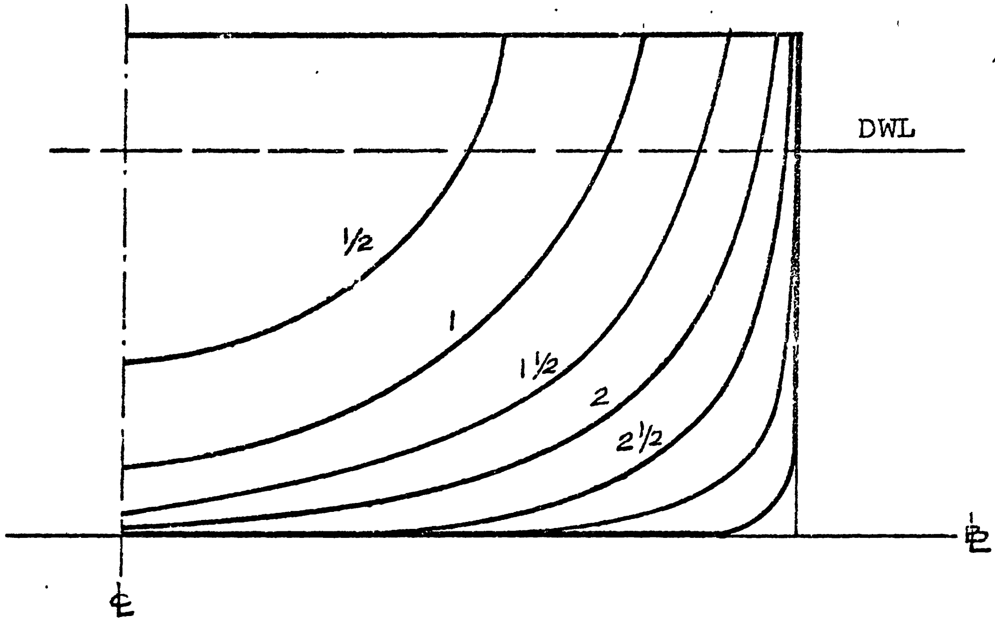


Figure 2

TYPICAL SPOON BOW



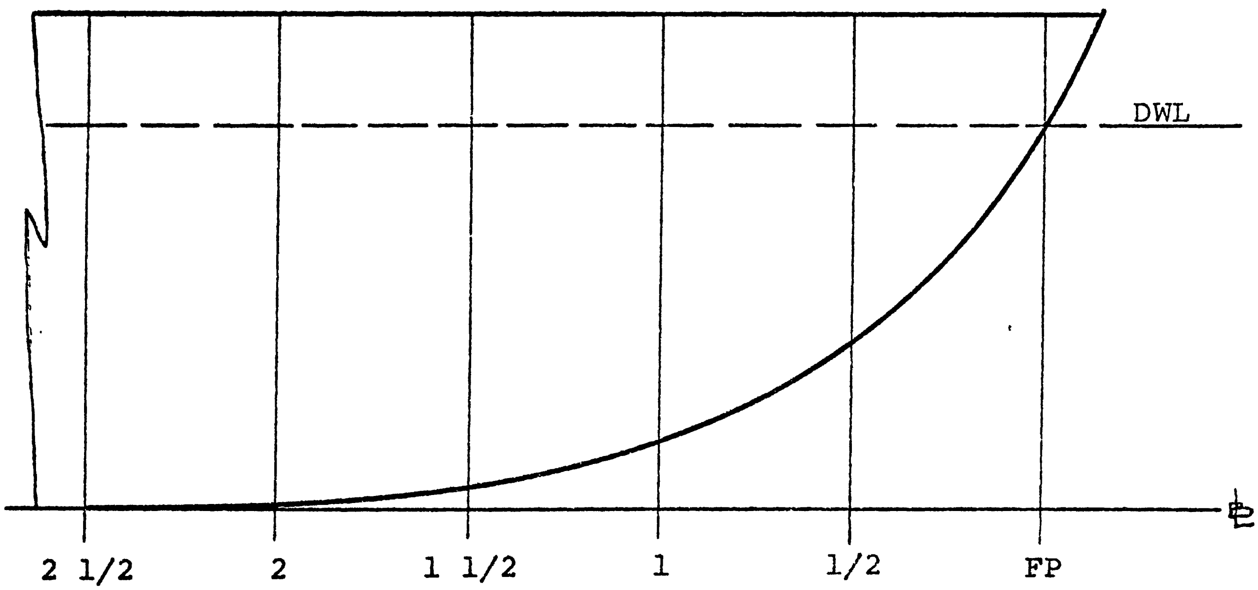
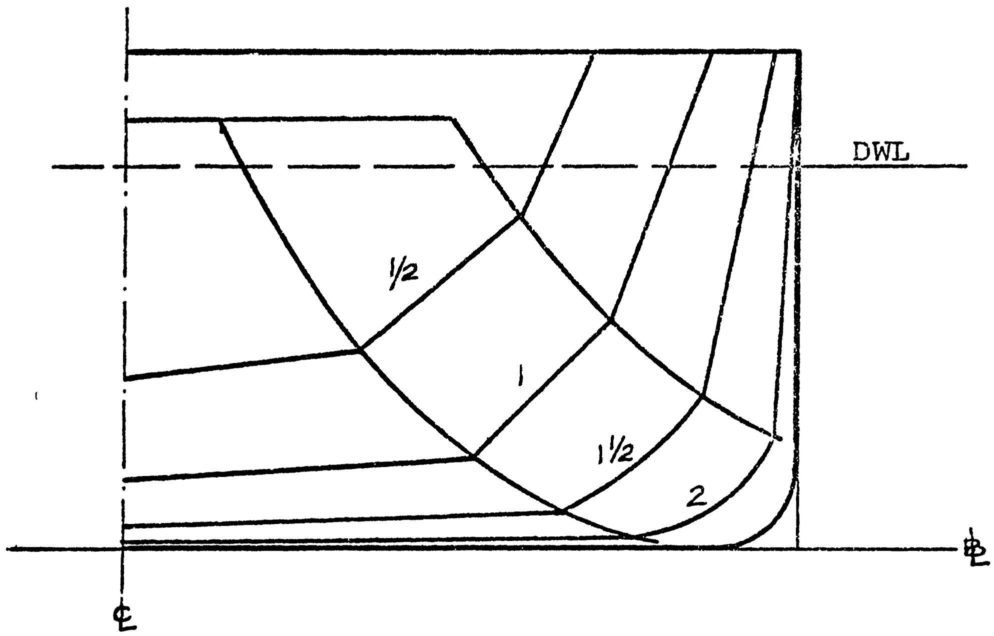


Figure 3

TYPICAL DOUBLE CHINE BOW



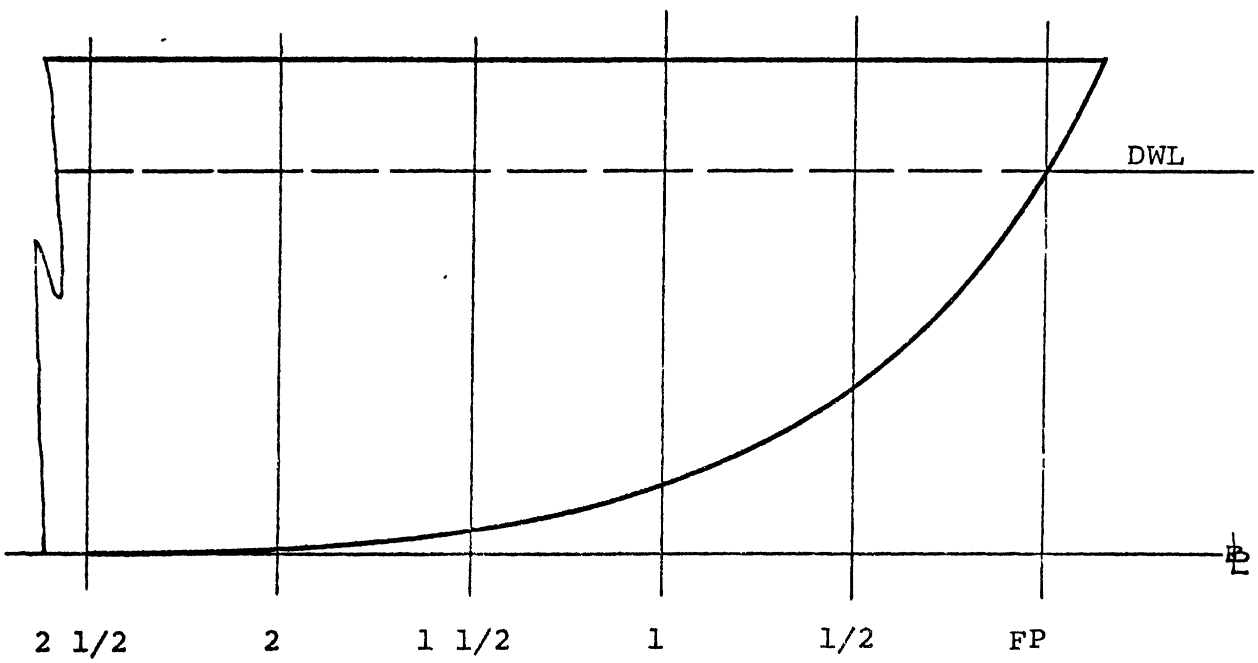


Figure 4

RECOMMENDED STERN RAKE DESIGN FEATURES

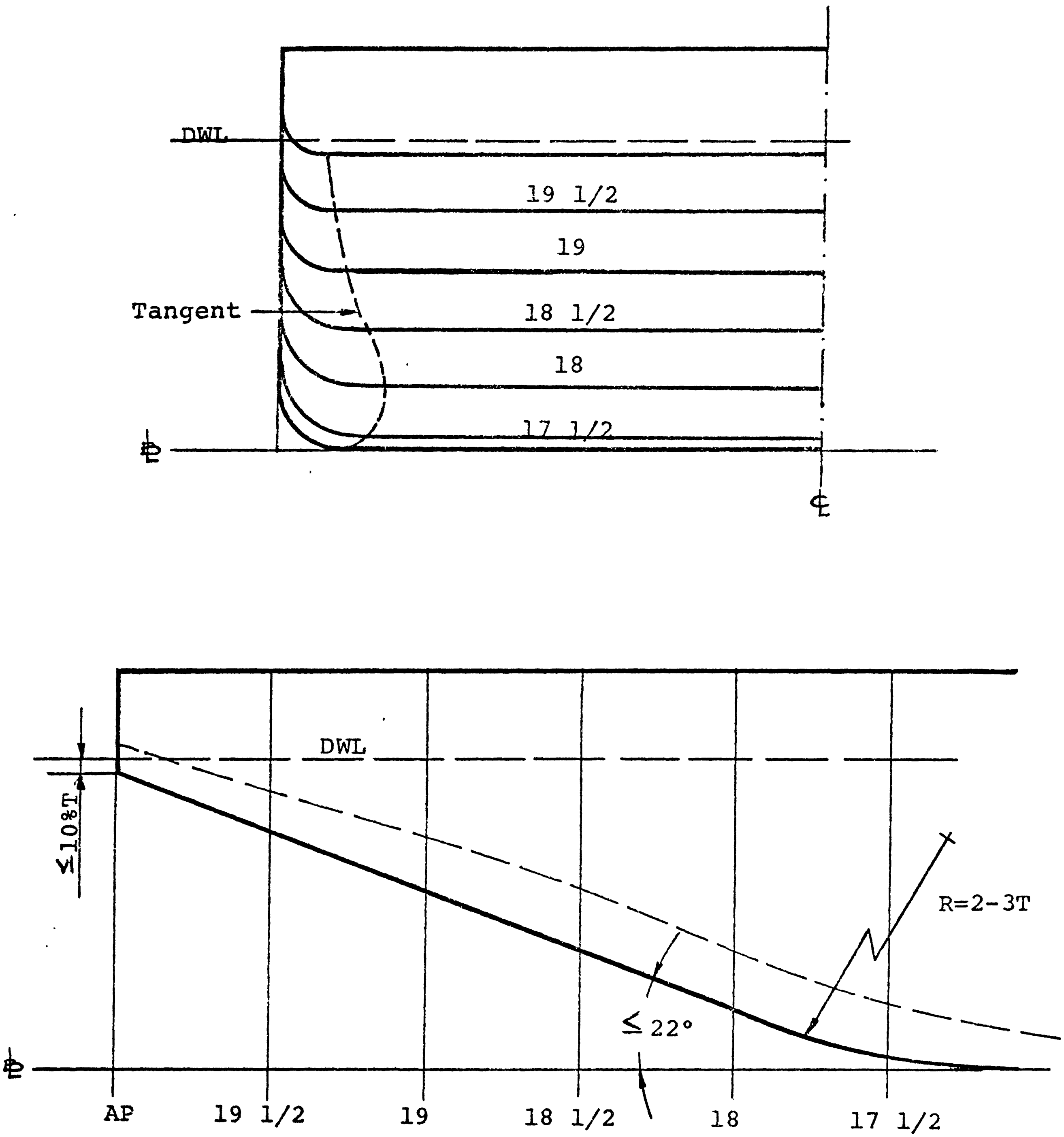
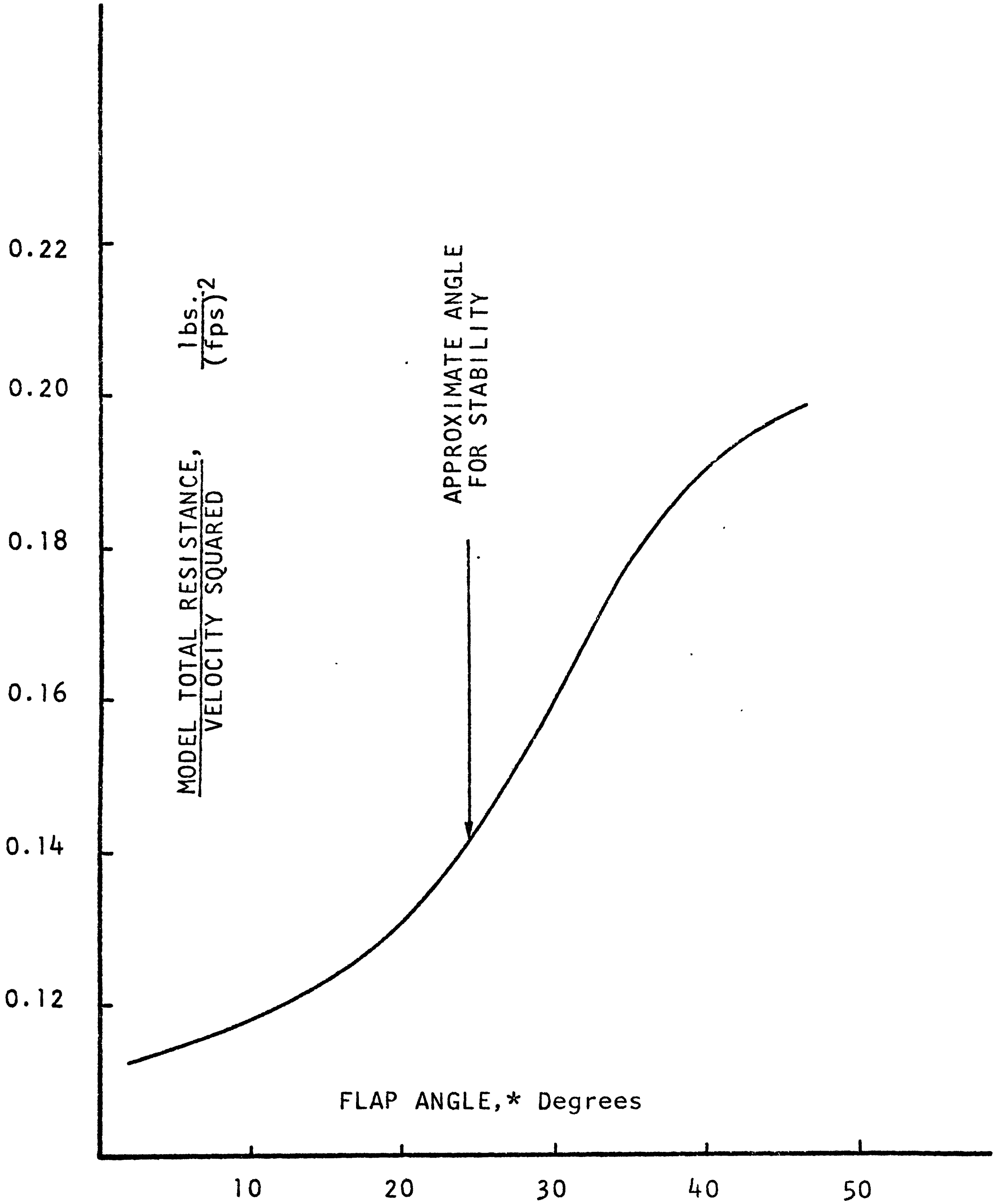


Figure 5

EFFECT OF SKEG FLAP ANGLE ON RESISTANCE



* Measured relative to leading portion

Figure 6

CAMBERED SKEG

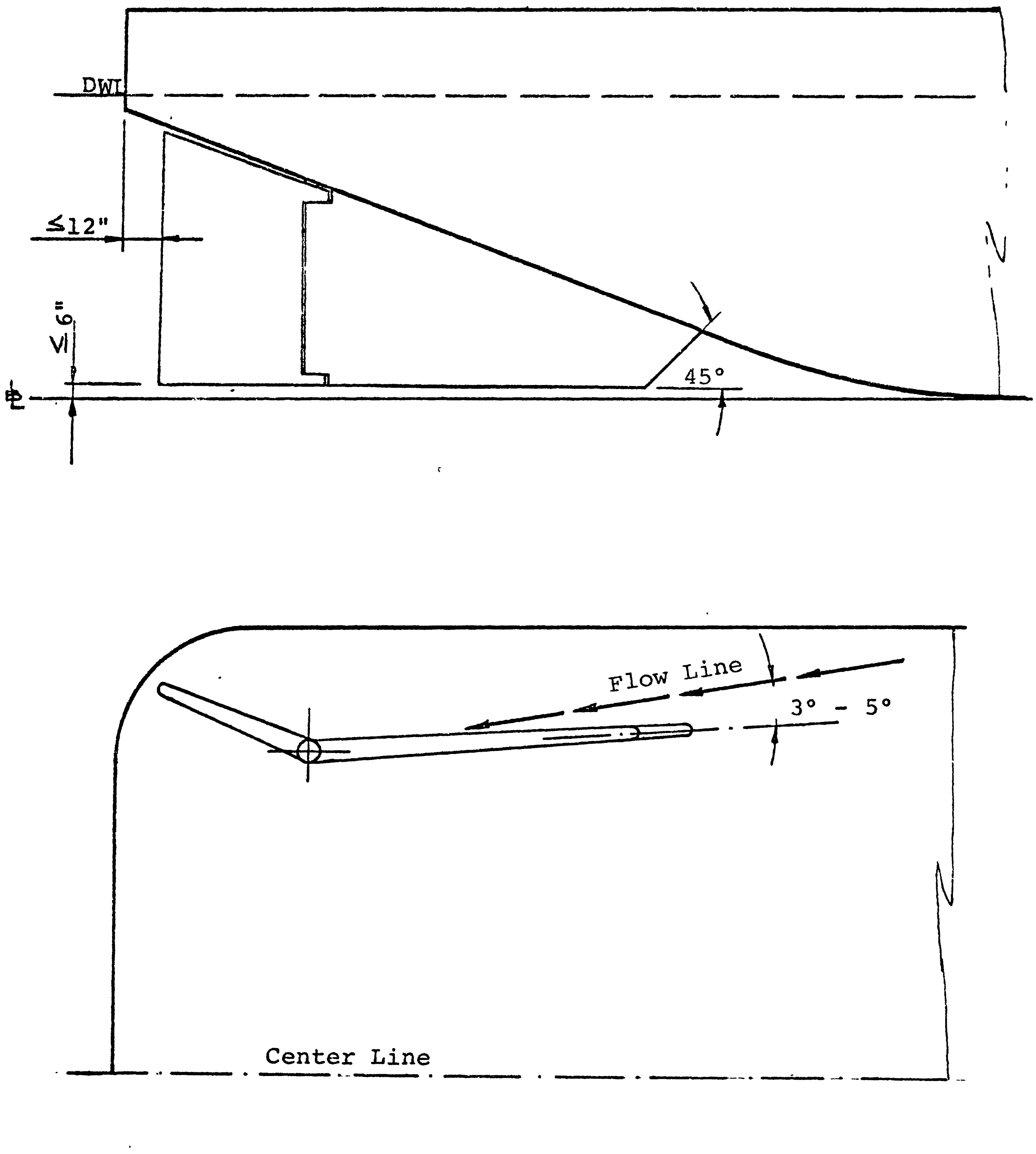


Figure 7

EFFECT OF OUTBOARD SKEG POSITION
ON RESISTANCE AND FLAP ANGLE

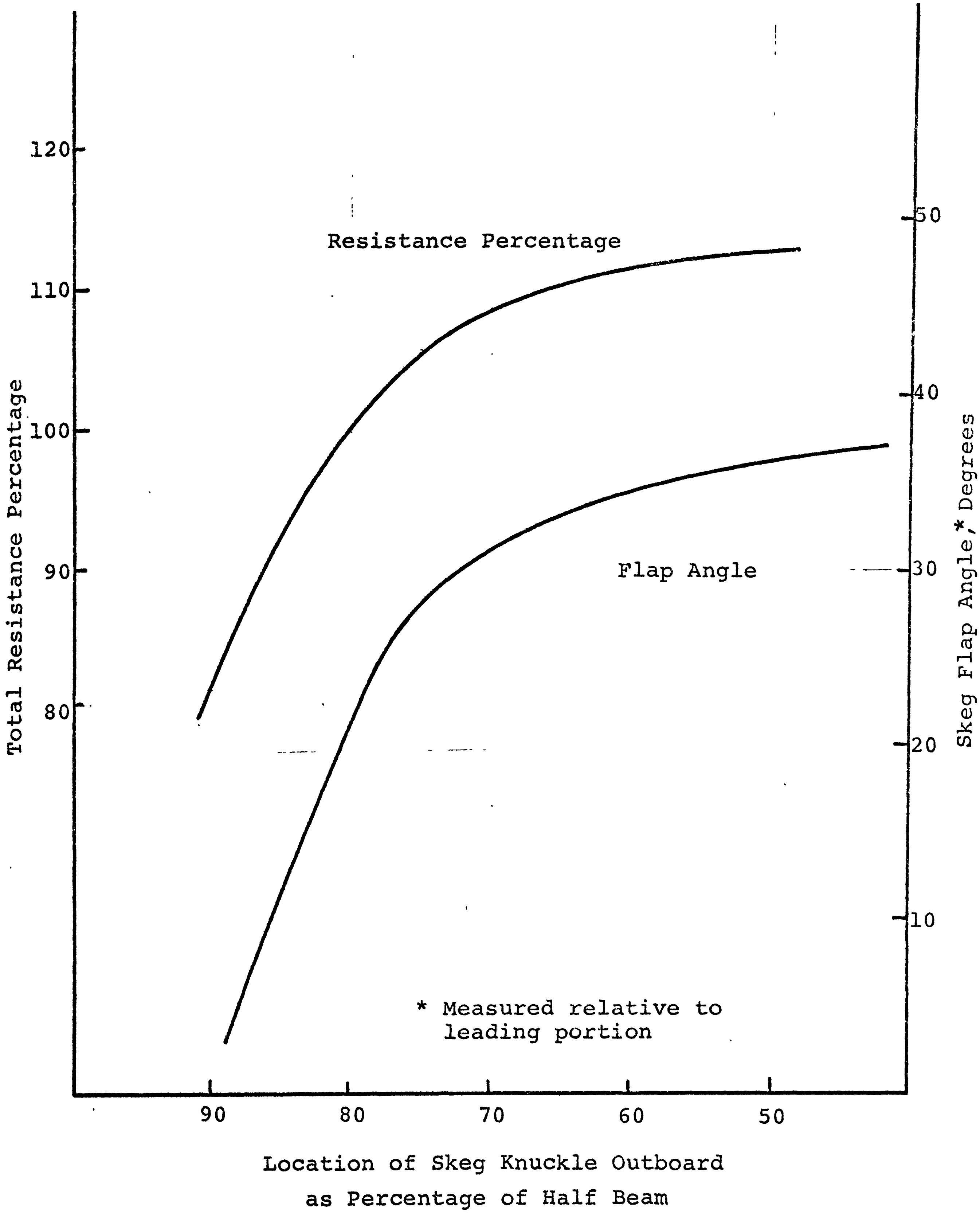


Figure 8

RESIDUAL RESISTANCE COEFFICIENTS, $C_R = \frac{R_R}{\frac{\rho}{2} S V^2}$,
VERSUS BLOCK COEFFICIENT FOR
BARE HULL