Hydrodynamic Design of Planing Hulls

By Daniel Savitsky[1]

The elemental hydrodynamic characteristics of prismatic planing surfaces are discussed and empirical planing equations are given which describe the lift, drag, wetted area, center of pressure, and porpoising stability limits of planing surfaces as a function of speed, trim angle, deadrise angle, and loading. These results are combined to formulate simple computational procedures to predict the horsepower requirements, running trim, draft, and porpoising stability of prismatic planing hulls. Illustrative examples are included to demonstrate the application of the computational procedures.

FUNDAMENTAL research on the hydrodynamics of planing surfaces has been actively pursued in both this country and abroad for well over 40 years. The original impetus for this planing research was primarily motivated by the hydrodynamic design requirements of water-based aircraft and to a somewhat lesser extent by the development of planing boats. In recent years, however, the research emphasis has been on planing forms with application to planing boats and hydrofoil craft.

Some of the earliest experimental studies on prismatic planing surfaces were made by Baker [1][2] in 1910 but the first comprehensive experiments which received wide attention were those of Sottorf [2]. These were followed by investigations of Shoemaker [3], Sambraus [4], Sedov [5], and Locke [6]. The efforts of these researchers resulted in a large accumulation of test data describing the hydrodynamic characteristics of constant-deadrise prismatic planing surfaces operating at fixed trim, fixed mean wetted length, and constant speed. To make these data suitable for practical use it was desirable to establish empirical equations which would express the relations between the many planing variables and the hydrodynamic lift, drag, pitching moment, and wetted area. Under sponsorship of the Office of Naval

Nomenclature

C_f = friction-drag coefficient = $D_f \cos \beta / \frac{\rho}{2} V_1^2 \lambda b^2$

C_{L_0} = lift coefficient, zero deadrise, = $\Delta / \frac{\rho}{2} V^2 b^2$

$C_{L\beta}$ = lift coefficient, deadrise surface, = $\Delta / \frac{\rho}{2} V^2 b^2$

C_{L_d} = dynamic component of lift coefficient

C_{L_b} = buoyant component of lift coefficient

C_p = distance of center of pressure (hydrodynamic force) measured along keel forward of transom = $l_p/\lambda b$

C_v = speed coefficient = $V/(gb)^{1/2}$

R_e = Reynolds number, = $V_1 \lambda b/\nu$

λ = mean wetted length-beam ratio = $\frac{(L_k + L_c)}{2b}$

λ_1 = mean wetted length-beam ratio based on area below undisturbed water surface

where

b = beam of planing surface, ft

D_f = frictional drag-force component along bottom surface, lb, = $D \cos \tau - \Delta \sin \tau$

g = acceleration due to gravity, = 32.2 ft/sec^2

L_c = wetted chine length, ft

L_k = wetted keel length, ft

l_p = distance from transom to point of intersection of hydrodynamic-force vector with keel (measured along keel), ft

V = horizontal velocity of planing surface, fps

V_1 = mean velocity over bottom of planing surface, $f(\tau, \lambda)$, fps

β = angle of deadrise of planing surface, deg

Δ = load on water, lb

ν = kinematic viscosity of fluid, ft^2/sec

ρ = mass density of water, w/g

L_b = hydrostatic lift component, lb

also

D = total horizontal hydrodynamic drag component, lb

D_p = resistance component due to pressure force, lb

d = vertical depth of trailing edge of boat (at keel) below level water surface, ft

N = component of resistance force normal to bottom, lb

a = distance between D_f and CG (measured normal to D_f), ft

f = distance between T and CG (measured normal to T), ft

T = propeller thrust, lb

ϵ = inclination of thrust line relative to keel line, deg

c = distance between N and CG (measured normal to N), ft

L_1 = difference between wetted keel and chine lengths, ft = $(L_k - L_c)$

L_2 = difference between keel and chine lengths wetted by level water surface, ft

L_m = mean wetted length, ft = $(L_k + L_c)/2$

w = specific weight of water, pcf

γ = angle between spray root line and keel line measured in plane parallel to keel, deg

τ = trim angle of planing area, deg

LCG = longitudinal distance of center of gravity from transom (measured along keel), ft

Φ = angle between the keel and spray edge measured in plane of bottom, deg

A_s = total wetted spray area, sq ft

VCG = distance of center of gravity above keel line, measured normal to keel, ft

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[2] Numbers in brackets designate References at end of paper.

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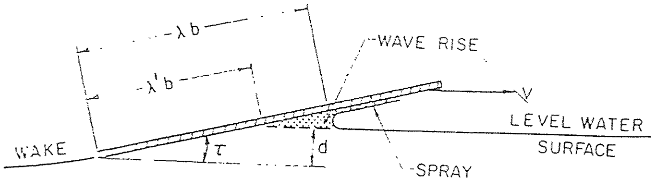

Fig. 1 Wave rise on a flat planing surface

Research, U.S. Navy, the Davidson Laboratory of Stevens Institute of Technology, in 1947, undertook a theoretical study and empirical-data analysis of the phenomenon of planing. This study produced 16 technical reports (listed in the Appendix), which consider planing-surface lift, drag, wetted area, pressure distributions, impact forces, wake shape, spray formation, dynamic stability, and parallel planing surfaces. Where possible the ONR sponsored research utilized existing planing data and theoretical results but in many areas additional experimental results and new theoretical analysis were provided by the Davidson Laboratory.

In 1949, Korvin-Kroukovsky and Savitsky [7] published a summary report on the then completed studies of planing lift, drag, and wetted area and, in 1950, Murray [8] utilized these results in developing a computational procedure for predicting planing performance. In 1954, Savitsky and Neidinger [9], continuing the ONR study, developed an extensive set of empirical planing equations which increased the range of applicability to parametric planing variables well beyond those developed in [7].

The purpose of the present paper is to utilize the results of the studies of [9] to describe the elemental hydrodynamic characteristics of prismatic planing surfaces and then to combine these results to formulate simple computational procedures to predict the horsepower requirements and porpoising stability of prismatic planing hulls. Some of the material of [9] is repeated in this paper since [9] had a limited distribution and is currently out of print.

Hydrodynamics of Prismatic Planing Surfaces

A knowledge of the elemental hydrodynamic characteristics of simple planing surfaces is necessary prior to undertaking the design of specific geometric planing boats. In this section of the paper attention will be given to the development of equations for wetted area, lift, drag, center of pressure and stability limits of hard-chine prismatic surfaces in terms of deadrise angle, trim angle, and forward speed. The prismatic planing surface is assumed to have constant deadrise, constant beam and a constant running trim for the entire wetted planing area. Variations from these conditions will be discussed in the section on design procedure. Only hard-chine planing forms are considered in this paper since, at present there is a scarcity of basic planing data on round-bottom forms.

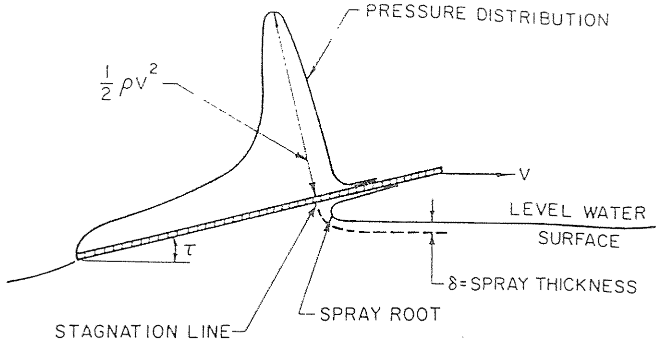

Fig. 2 Typical pressure distribution on flat planing surface

The planing coefficients and symbols used in the subsequent analysis are based on Froude's law of similitude and are the same as those used in the analysis of water-based aircraft and hydroskis. Each symbol is specifically defined in the section on nomenclature. It will be noted that the beam is the prime nondimensionalizing dimension rather than the length of the boat which is usually considered by the naval architect. The justification for this is that for planing hulls, the wetted length of the boat varies with trim, loading, and speed while the wetted beam is essentially constant. Moreover, it is possible to change the overall length of a planing boat without changing its hydrodynamic characteristics at high speed.

Shape of Wetted Area of Planing Surfaces

A separate analysis is given of the shape of the wetted area for flat-bottom and deadrise planing surfaces.

Wave Rise for Flat Planing Surfaces

In the case of planing surfaces with no deadrise (flat-bottom planing surfaces), water rises in front of the surface, thereby causing the running wetted length l to be larger than the length defined by the undisturbed water-level intersection with the bottom l_1, Fig. 1. Wagner [10] had made a mathematical study of the flow at the leading edge of a planing surface of infinite length and found that the rising water surface, mentioned in the foregoing, blends into a thin sheet of water flowing forward along the planing surface. This sheet is the source of spray in a planing surface and the region of its origin has been designated by Wagner as the "spray-root" region. Fig. 2 shows the spray root and the pressure distribution resulting from it. The term wetted area, as used in this paper, designates that portion of the wetted area over which water pressure is exerted and excludes the forward thrown spray sheet. The wetted area used in this sense is often designated in the literature as the "pressure area" and geometrically, includes all the wetted bottom area, aft of a line drawn normal to the planing bottom and tangent to the curve of the spray root. This line is clearly discernible from underwater photographs. As seen in Fig. 2, the stagnation pressure is developed

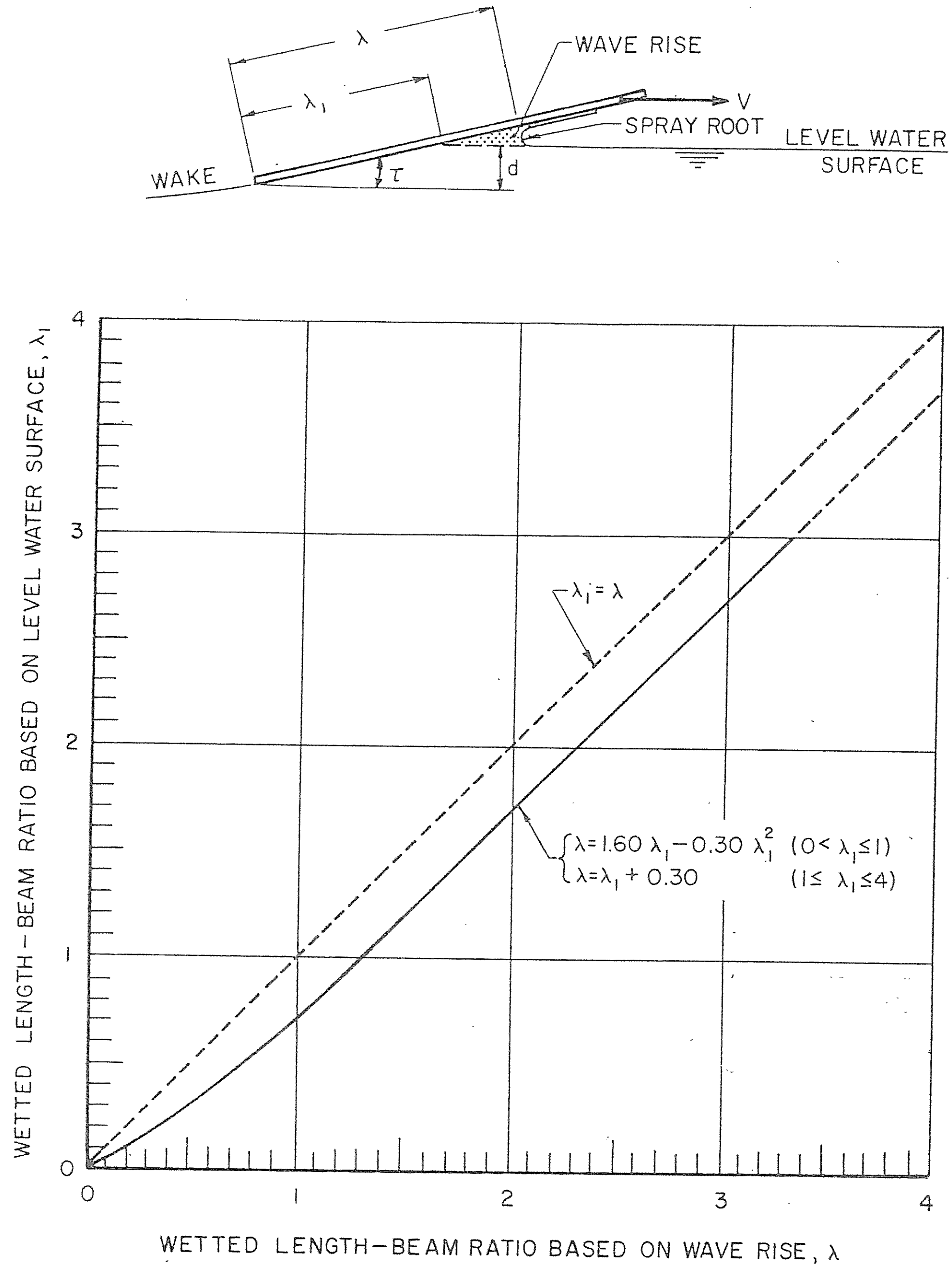

Fig. 3 Wave-rise variation for flat planing surfaces

at a short distance aft of the spray-root line. At very small values of trim angle the stagnation line and spray-root line are nearly coincident. As the trim angle increases, the stagnation line moves farther aft of the spray-root line.

Flat-plate, wetted-length data from all available sources are shown plotted in the form of λ versus λ_1 in Fig. 3. Here λ represents the running mean wetted length-beam ratio (l/b) and λ_1 represents the calm-water length-beam ratio obtained from the relation $\lambda_1 = d/b \sin\tau$, where d is the depth of the trailing edge of the planing surface below the level water surface during a planing run. It is seen, from Fig. 3, that, for the range of test parameters considered, the wave rise on a flat-bottom planing surface is only a function of the running wetted length. The mean curve fitted through the test data is defined by the following empirical equations:

$$\lambda = 1.60\,\lambda_1 - 0.30\,\lambda_1^2 \qquad (0 \le \lambda_1 \le 1)$$

and

$$\lambda = \lambda_1 + 0.30 \qquad (1 \le \lambda_1 \le 4) \qquad (1)$$

The empirical wave-rise relation is given in the form of

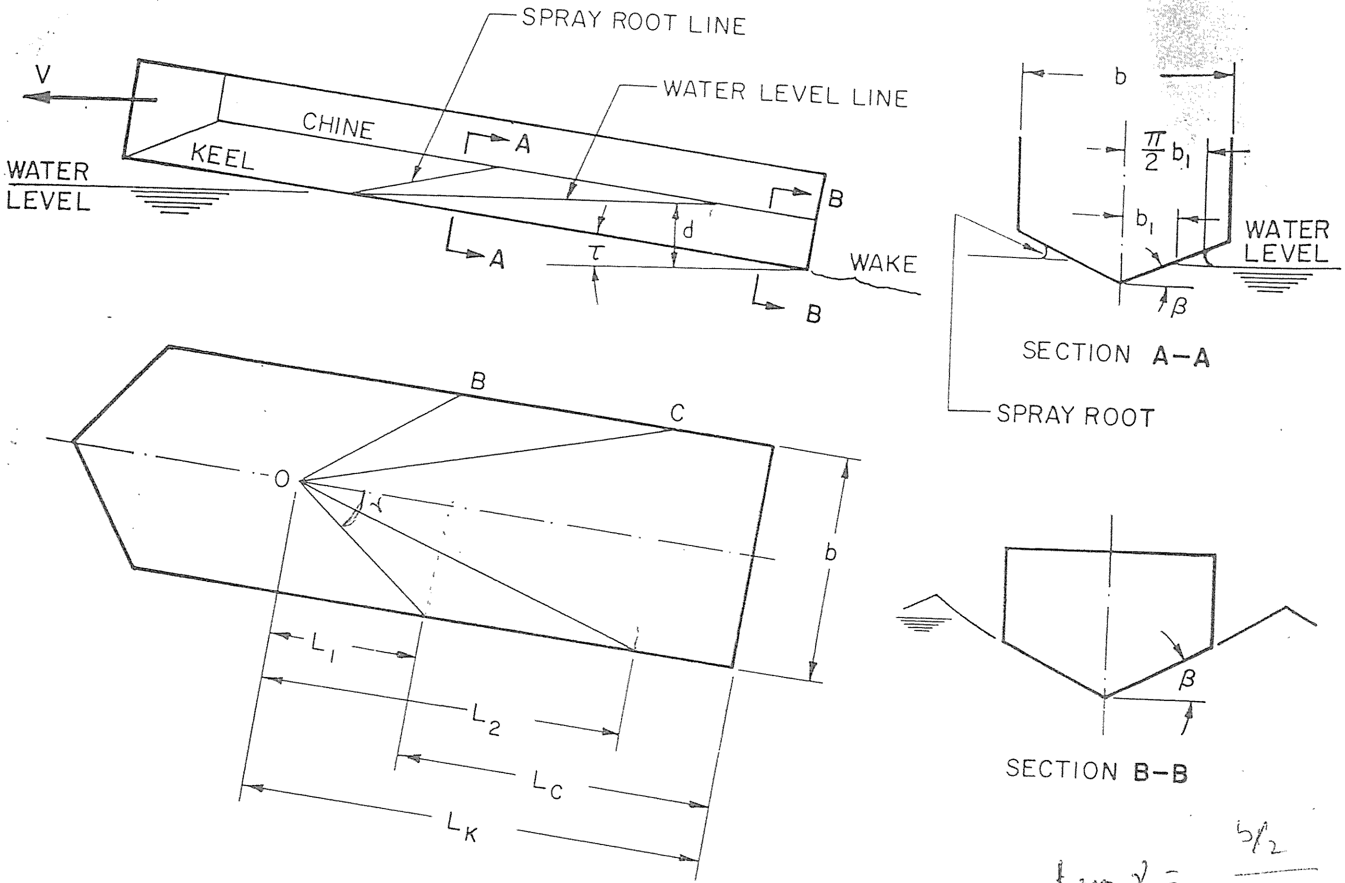

Fig. 4 Waterline intersection for constant deadrise surface

$$\tan\gamma = \frac{b/2}{\frac{b\tan\beta}{\pi\tan\tau}} = \frac{\pi\tan\tau}{2\tan\beta}$$

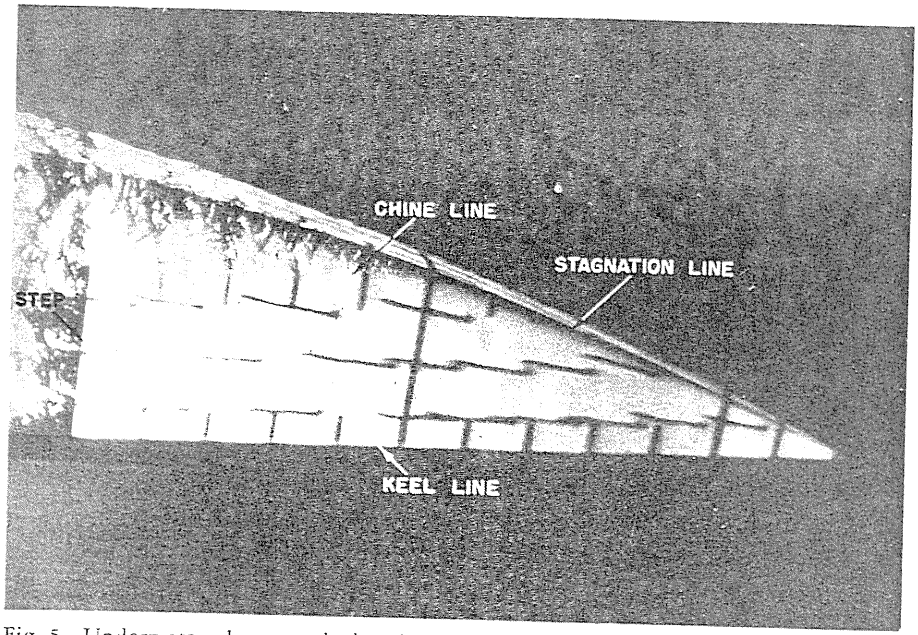

Fig. 5 Underwater photograph showing arrangement of tufts over bottom illustrating direction of fluid flow

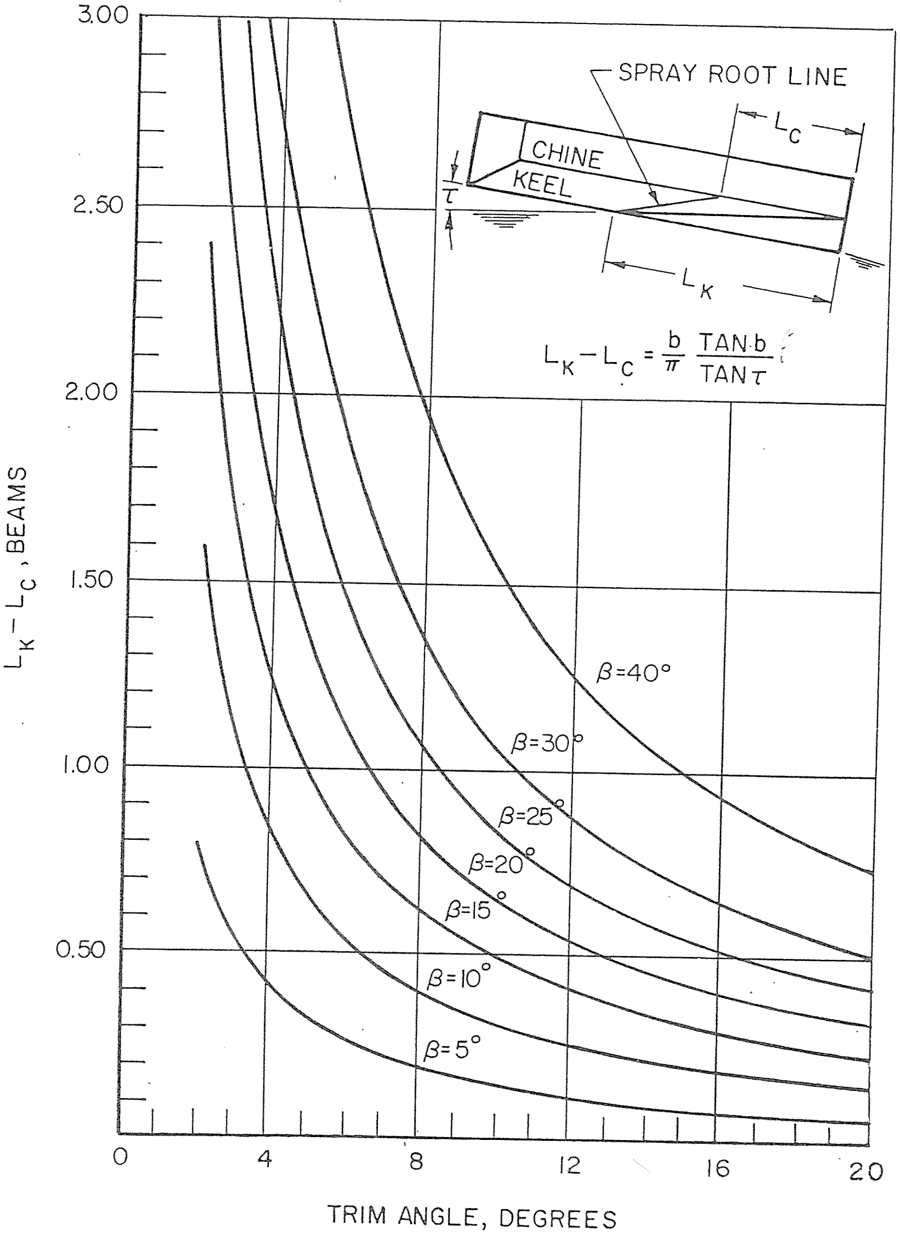

Fig. 6 $L_k - L_c$ versus trim and deadrise

two equations since, for the average planing case, λ_1 is usually larger than unity and thus the equations are reduced to the very simple form of $\lambda = \lambda_1 + 0.30$. An empirical wave-rise equation similar in form to (1) was also developed by Smiley [11].

As with all empirically developed equations, some bound must be placed on the parametric range of applicability of the results. The discussions in [9] conclude that (1) is applicable in the trim range from 2 to 24 deg; $\lambda \leq 4.0$; and $0.60 \leq C_v \leq 25.00$.

Wetted Pressure Area of Deadrise Planing Surfaces

In the case of Vee-shaped planing surfaces, the intersection of the bottom surface with the undisturbed water surface is along two oblique lines (*O-C*) between the keel and chines, Fig. 4. Up to a trim angle of approximately 15 deg there appears to be no noticeable pile-up of water at the keel line. For larger trim angles Chambliss and Boyd [12] indicate a slight pile-up of water at the keel. Aft of the initial point of contact, *O*, there is a rise of the water surface along the spray root line (*O-B*) located ahead of the line of calm water intersection. The location of the spray-root line is easily seen from underwater photographs such as that shown in Fig. 5. It is generally found that the spray-root line is slightly convex, but since the curvature is small, it is neglected. Thus the mean wetted length of a deadrise surface is defined as the average of the keel and chine lengths measured from