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Preface

It has become clear over the last several decades that most students of engineering, and most graduates of engineering, in general, do not have the interest in or the knowledge of the theoretical fundamentals needed to be fully functional in applied engineering science. This knowledge is seriously needed for purposes of marine design and engineering. There is all too often a fallback on "canned" routines without even so much as a vague acquaintance with the physics of the computation. The effort of this book is a reconciliation of order or reversal of structure. It is a book of physical examples involving a sampling of the important naval architecture/marine engineering problems that today's engineers do not engage well enough. This book has a somewhat reversed structure. For example, it does not include "self-contained, ready-to-use" computer programs which have become popular in many college texts. Instead, this alternative approach is to emphasize the relevant physical modeling principles at the first level, filling in with the mathematical/theoretical details to support the physical understanding, leading to more effective rational analysis and engineering production.

This book addresses principles involved in the design and engineering of planing monohull power boats. Problem areas in need of better understanding leading to better design/engineering are identified. These areas are within the topics of boat resistance, seaway response, and propulsion, three topics in the field of planing craft that are well recognized, but not well understood and not so rationally treated in new boat development programs.

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Boat Hull Hydrodynamics

Introduction and Background

Planing craft, particularly in the extensive worldwide boating industry, are the vastly dominant water craft type.

"Planing" of a water craft occurs on accelerating to a sufficiently high speed. When such speed is initiated from rest in calm water, the hull bow angle is forced to increase upward, thereby increasing the angle of incidence of the boat bottom relative to the water surface. This incidence angle, interacting with the increasing boat speed, produces increased dynamic pressure on the boat bottom, which lifts the boat progressively further upward in elevation toward the level of the water surface. There is normally some overshoot: on reaching the level of the surface. The trim angle then decreases back toward equilibrium, with perhaps some oscillation, as the boat settles-in to steady planing on the calm water surface.

Decisions required in the rational design of planing craft, particularly with regard to two aspects, are particularly difficult to conclude with precision: these aspects are planing speed and seaway motions (slamming). High speed and low seaway dynamics are the primary attributes sought in any new planing craft design undertaking, but they are conflicting. The characteristic most needed for low resistance, and consequently, high speed, is the weight located aft toward the stern of the boat. But weight aft tends to result in high impact acceleration when traversing waves. Further, weight aft can lead to "porpoising" instability, which is an oscillatory pitch motion in calm water accompanied by slamming oscillation. Conversely, weight forward results in reduced bow impact acceleration in waves, but also gives a long waterline, imposing higher resistance, and therefore reduced speed. So weight aft for high speed and weight forward for low wave impact are conflicting attributes. There are appendages, hull form variations, and operating procedures that can be employed to help with the design dilemma imposed. A principal one used on almost all planing boats is decrease in bottom "deadrise" angle progressively from bow to stern. A sharp angle forward at the boat stem tends to promote "knifing through" the seaway in the bow where the vertical slam motions tend to be highest. Conversely, the relative flatness in the lines aft help to achieve good lift per unit surface area in the stern region, and good lift-to-drag ratio overall while allowing shorter boat length.

A planing craft is, in a comparative sense, small in size and high in speed. In both senses, the relative scaling of size and speed is via the dimensionless Froude number: $F_{nL} = \frac{U}{\sqrt{gL_w}}$, where U is the craft forward speed, L_w is its wetted length, and g is the acceleration of gravity. Planing exists most clearly for high F_{nL} where U is high and L_w is small. But with the craft wetted-length changing as the boat speed changes, in cases, drastically, the Froude number is usually best redefined as the dimensionless (half) *beam* Froude number: $F_{nB} = \frac{U}{\sqrt{gZ_{\text{ch}}}}$, Z_{ch} being the wetted half-beam, or maximum chine offset. The maximum wetted chine offset is typically much less variable with speed than is the wetted length, particularly, in the calm-water planing regime.

Froude number is also a measure of gravity wave-making and it is derived and used primarily on that basis. With regard to both planing and wave-making, free-surface wave-generation diminishes to low level in both the high and low Froude number limits, with largest ship-generated waves in the intermediate region around $F_{nL} = 0.6$. At high Froude number, with $F_{nL} \gg 1$, where planing craft usually run when operating near design speed, the water surface acts as a relief surface of vanishing pressure. Here, far-field gravity wave-making is traditionally taken as zero for planing prediction and design development.

The equations of motion of planing craft are derivable from Newton's Law in terms of the six degrees of freedom (DOF) of rigid-body-dynamics. These are the three DOF in the vertical-fore-and-aft plane: heave, pitch, and surge, and the three in the horizontal-fore-and-aft plane: sway, roll, and yaw. It is the principal vertical plane DOF that are, generally speaking, the most important in understanding and designing planing craft; the characteristics and related effects of these three vertical plane DOF are the focus of this book. The three horizontal DOF are treated as secondary and are generally established as acceptable if the critical vertical plane response is established as acceptable. At any rate, the equations of motion that must be solved for the respective motions are always constructed by application of Newton's Law applied simultaneously in all active degrees of freedom. Of course, the field has learned by analysis, and experience, what approximations and simplifications in the general theory are permitted for success in the applications of planing craft design engineering. That explanation and demonstration is also a purpose of this book.

It has been said that any concept explanation of complex physical processes is best started in terms of the simplest configuration that embodies the basic physics at issue, and then proceeds upward in sorting out the physical complications, systematically, step by step, until a useful working knowledge is gained, demonstrated, and applied. This concept explanation of planing boats is applied here, beginning with the simple prismatic box illustrated in Fig. 1.1.

Chapter 1
Conceptual Monohull Planing in Calm Water

Planing in its simplest useful form starts with a prismatic box of rectangular cross-section, with length L larger than the cross-sectional dimensions, B and D, in Fig. 1.1. The coordinate system is the right-hand rectangular system located at the bow stem (0,0,0). The block, of Fig. 1.1, is itself a prismatic form capable of planing on its bottom, but very primitive planing, with low lift/drag ratio.

First, adding the weight of an engine aft in the empty box, along with some structure, locates the center of gravity, x_{cg}, aft of $x = L/2$. Take the added weight as symmetric with $y_{cg} = 0$ on the vertical-longitudinal center plane; let the weight magnitude be less than γLBD, where γ is the specific weight density of the displaced water. With proper care in assuring transverse stability, the box then floats motionless with small bow-up trim angle, α, transom draft, Ht, and zero heel (Fig. 1.2). The wetted length may also be slightly reduced, with an overhang above the water free-surface forward. While the wetted volume is now no longer prismatic, the wetted sections are of self-similar rectangular shape, which is important in the generalization of the box to boats.

On powering-up by engaging the engine and propeller, forward movement occurs, which will become planing on the flat bottom if the engine has enough power to overcome resistance in achieving high enough speed. With sufficient speed, the trim angle of the flat bottom develops the lift to overcome the weight and raise the boat up toward the surface. This powering-up will be accompanied by trim and draft changes and perhaps a first-order wetted length change. The trim increment either steepens or flattens from the zero-speed hydrostatic attitude, depending on the history of the speed development. At any rate, a new wetted length accompanies the new draft and trim to develop dynamic equilibrium as a function of speed. Consider the y-axis now relocated to the forward end of the water plane, with x positive aft from the adjusted stem position due to the trim.

This box clearly qualifies as a planing hull form, albeit a highly primitive one. Any degree of bow bluntness reflects a poor design hydrodynamically, as the bottom flow will separate transversely with y-symmetry (in the mean) immediately under the blunt bow, accompanied by a pressure drag building as the incoming

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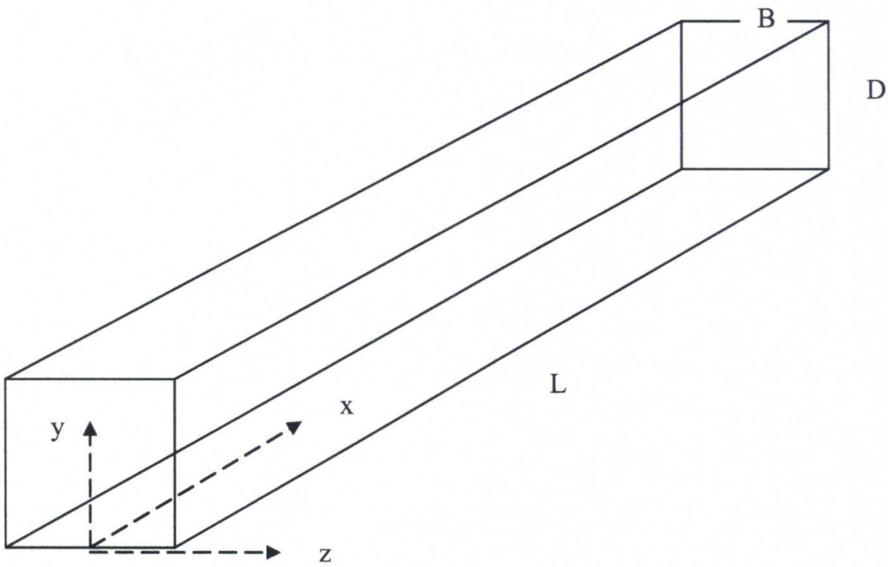

Fig. 1.1 Weightless prismatic box, for illustrating the development of the surface geometry of prismatic planing

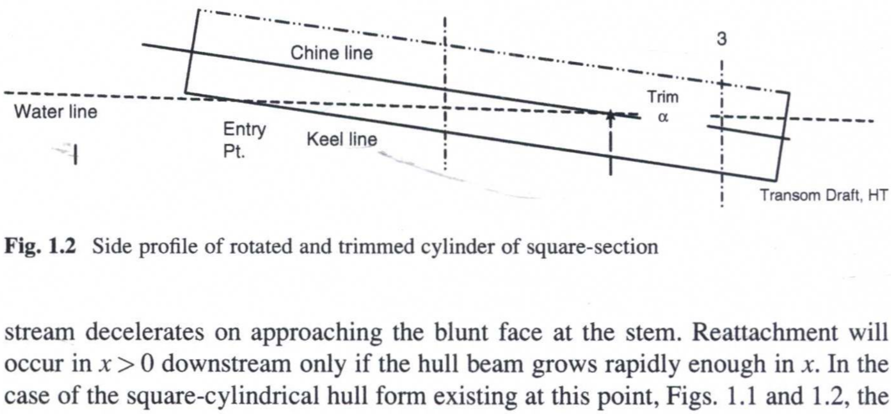

Fig. 1.2 Side profile of rotated and trimmed cylinder of square-section

stream decelerates on approaching the blunt face at the stem. Reattachment will occur in $x > 0$ downstream only if the hull beam grows rapidly enough in x. In the case of the square-cylindrical hull form existing at this point, Figs. 1.1 and 1.2, the flow would separate at the blunt stem and theoretically not reattach, to first order. In this case, any lift developed would have to be by way of axial bow impact and secondary flow downstream of the blunt bow. The lifting flow and pressure would be of secondary magnitude, requiring large trim to develop the equilibrium hull lift on the flat bottom, probably at a low, sub-planing speed.

In general, the chine is a fore-and-aft flow trip that runs continuously from stem to stern down the vessel side above the keel. The term "chine-unwetted (CUW)" refers, for the general craft, to the region of the surface forward where the flow is accelerating up the side hull, led by a relatively thick spray sheet. On reaching the chine at some section x, the flow encounters the chine, the flow separates, and the "chine-wetted (CW)" flow phase commences. It continues until full separation occurs at the transom. Most intensity of the dynamic pressure on the hull bottom develops in the CUW region by way of the upward flow acceleration in the forebody. A second-order fraction of the lift develops as CW on the after-bottom. In general, the hull is not wetted above the chine. In the specific case of the "planing box" of Fig. 1.1, because of the blunt entry, the bow separation point and the stem entry point effectively coincide. This makes the downstream box flow entirely CW. The drag of the box would be, to the lowest order, the viscous/turbulent drag on the box wetted sides and bottom and the bow plate pressure drag and would be found to be excessive compared to that achievable with streamlining and separation delay.

As a next step in refining Fig. 1.1 box into a legitimate planing hull form, eliminate the constant width flat bottom by simply rotating the box 45° about its longitudinal axis, while maintaining its weight distribution as fixed (Fig. 1.2). The wetted prismatic planing surface is now that of a self-similar cylinder of triangular section below the waterline. Self-similarity, or just similarity, means that the cross-section has the identical triangular shape at all x such that the cross-sections vary with only a single dimension, say, in this case, the half-beam $Z_{ch}(x)$; Z_{ch} simply changes the size of the triangle but not its shape. With this 45° rotation from prismatic into similarity, an apex angle of 90° exists at the keel, 45° to either side. This defines the deadrise angle $\pm\beta(x)$; $\beta(x) = 45°$ in Figs. 1.2 and 1.3 for all x, symmetrically on both sides of the vertical center plane. This simple rotation and trim has eliminated the flat bottom in favor of a V-bottom, with β constant in x. With the bow overhang shown in Fig. 1.2, the entry is sharp due to the overhang; without the overhang some bow bluntness would remain. Conventionally, any bow bluntness is eliminated forward by increasing the deadrise angle to approach ±90° for a relative knife edge at the stem; this is favorable for wave entry as addressed under "Background." Conversely, $\beta(x)$ is often reduced in the stern region to serve the alternative competing interest of low resistance and small motions in waves. $\beta(x)$ is usually reduced in a continuous manner as x approaches the stern. $\beta(L)$ may be as low as 10° at the transom. $\beta(L)$ as high at 30° is seen in the interest of wave impact but is draggy in calm water; β as high as 45° would rarely be encountered. Note from Fig. 1.2 that a similarity flow would exist up to the chine wetting point, x_{cw}, after which the lines are non-similar.

Figure 1.2 lines, depending on the craft weight, W, and the x_{cg}, will, unlike the square box section, have a significant length of CUW flow for dynamic lift development. The lift development would be forward in supporting the craft weight at reduced (planing) draft.

Figure 1.3 is a cross-section in terms of the relative waterlines obtained by rotating the water about the z-axis through the trim angle α, rather than rotating the hull surface; the rotated water surfaces are denoted 1, 2, 3. The relative water surfaces of Fig. 1.3, being easier to draw than the rotated hull surfaces, are useful for visualization.

Figure 1.4 is a prediction of the multiple cross-sections of the USN 10MRB. It is viewed in the y-z cross-section relative to the steady planing design waterline at the

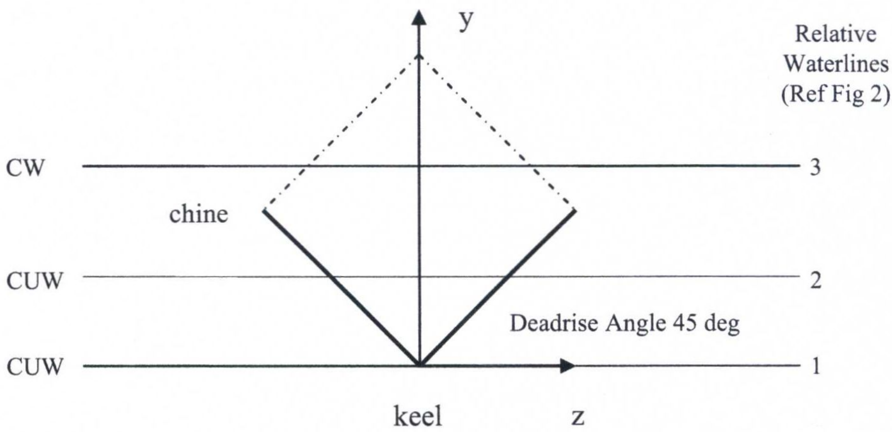

Fig. 1.3 Rotated box section in terms of trim of relative waterlines

design speed of 33 knots. The flow calculation is complete other than the "wave rise," a higher-order graphic that is not shown.

These stacked sections of Fig. 1.4 are collectively called the *body plan* of the craft lines. Note from Fig. 1.4 that the minimum section depth is at the stem, and is zero there by definition, and as in Fig. 1.2 sketch, and the maximum depth is at the transom. Note that this vessel is running chine-wetted (CW) over much of its afterbody; the chine corresponds to the locus of points at $z = Z_{ch} = 1.0$. Also note that the chine offset has contracted minimally on approaching the stem. Since the x-distance covered by the sections collectively corresponds to the running wetted length, the implication of Fig. 1.4 depiction is that the stem is dry, so that the incidence angle α places the keel above the water surface forward. Unlike Fig. 1.2, lines of Fig. 1.4, while simple in character, would not be self-similar because of the regions of convergence forward and with the chine-wetting aft.

In reiteration, note particularly the following in Fig. 1.4:

1. The plot covers the running wetted hull surface from the waterline entry to the transom.
2. The deadrise angle, β, is constant at 21° over this wetted region but, although not seen, is sharper further forward ahead of the entry point at $x = 0$.
3. At unwetted sections further forward in the overhang, the β angle steepens to approach 90° at the prow (material stem).
4. Figure 1.4 plotted points are most highly concentrated in the sections where the chine wets at x_{cw}.
5. Figure 1.4 was from a planing analysis performed on the performance of the USN-10MRB.

It is also instructional to view the body plan as the boat moving steadily forward with speed U, with the sections passing by a fixed observer (Fig. 1.5). What the observer sees, for sight fixed on a vertical-transverse space plane at x_i, is the

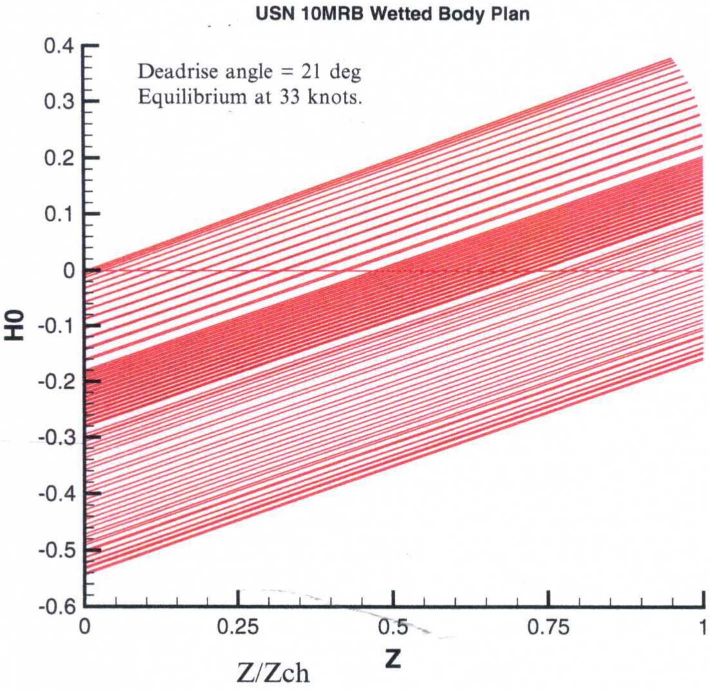

Fig. 1.4 USN 10MRB body plan, planing at 33 knots

sequence of sections in the body plan falling vertically downward with speed $U\sin\alpha$ (x_i) as they come by and slam through the water surface, at times t_k:

$$t_k = \frac{x_k}{U} \tag{1.1}$$

where t_i is the time at which the section at x_k impacts the surface, with $x_k = t_k = 0$ at stem entry.

Planing Boat Hydrostatics

Since zero speed in calm water is the beginning state for acceleration to planing, it is, therefore, considered appropriate to delay planing particulars with a consideration of planing boat hydrostatics. Many a planing craft design has been deemed unsuccessful due its inability to plane. Such a problem is usually hydrostatic in origin, with the boat simply being unable to "climb out of the hole" created at hydrostatic equilibrium. For such a case, the boat may have adequate power for planing on the water surface, but inadequate power to raise itself to the surface from zero-speed hydrostatic equilibrium.

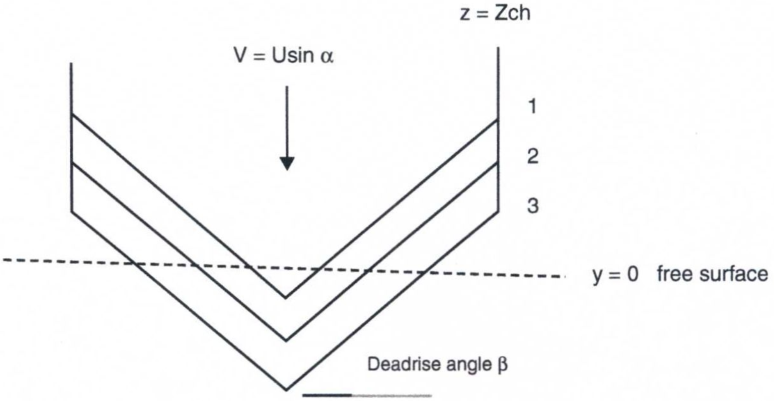

Fig. 1.5 Body plan—self-similar wedge sections impacting with speed $V = U\sin\alpha$ through the water surface at $y = 0$

Floating at zero speed, hydrostatic equilibrium is by Archimedes principle. It requires that the boat weight, W, equals the weight of the water displaced or buoyancy, B, and that the longitudinal center of gravity of the boat weight, x_{cg}, is equal to the longitudinal center of buoyancy, x_{cb}, of the displaced water, i.e., the center of gravity and the center of buoyancy lie on the same vertical line.

Figure 1.6 is a three-dimensional perspective of the "rotated box" self-similar hull form of wetted length, ℓ (refer to Figs. 1.2, 1.3, 1.4, and 1.5). Similarity is maintained if the box is either flattened or steepened as it is rotated so that the deadrise angle is constant lengthwise but different than 45°. Constant deadrise CUW sections are important in greatly reducing calculation time with the similarity flow, as is shown further along.

In this analysis the chine is taken as unwetted (CUW) so the waterline lies between the keel and the chine over the full length at hydrostatic equilibrium.

For trim angle α, the depth $h(x)$ of the keel in the plane of x is

$$h(x) = x\tan\alpha, \tag{1.2}$$

and, for β being the constant deadrise angle, the transverse offset of the chine from the x-axis is

$$z_c(x) = h(x)\cot\beta \tag{1.3}$$

The full wetted cross-sectional area at x is then

$$A(x) = z_c(x)h(x) = x^2\tan^2\alpha\cot\beta \tag{1.4}$$

Integration in x over the wetted length produces the displaced volume, multiplied by ρg results in the displaced water weight, B, equivalent to the boat weight:

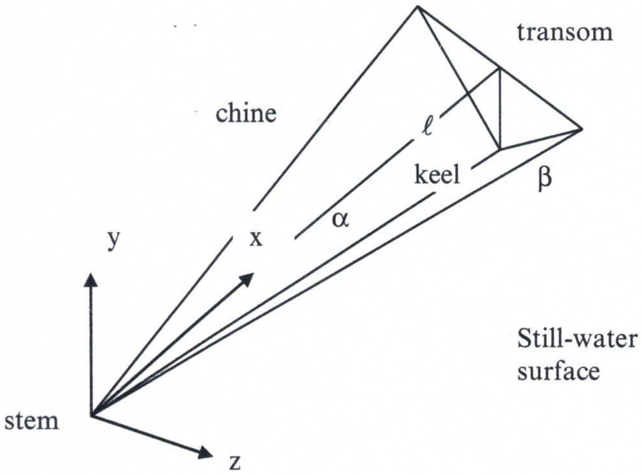

Fig. 1.6 Self-similar wedge hull at still-water equilibrium: rotated rectangular prismatic box analogy (CUW)

$$W = \frac{1}{3}\rho g \ell^3 \tan^2\alpha \cot\beta \tag{1.5}$$

Here, β is known (45° for the box rotation), but α is one of the two unknowns that must be determined by satisfying the condition of static equilibrium; the other is the wetted length ℓ.

Vertical force equilibrium requires from (1.5), that

$$B = W = \frac{1}{3}\rho g \ell^3 \tan^2\alpha \cot\beta \tag{1.6}$$

Moment equilibrium about the z-axis gives

$$Mz = Bx_{\text{cb}} = Wx_{\text{cg}} = \frac{1}{4}\rho g \ell^4 \tan^2\alpha \cot\beta \tag{1.7}$$

Hydrostatic Solution

Equations (1.6) and (1.7) are the two equations of static equilibrium needed to find the two unknowns ℓ and α. First temporarily eliminate α by dividing (1.6) by (1.7) to achieve simply