INTRODUCTION

The planing hull form is perhaps the oldest, simplest and most extensively employed member of the family of modern marine vehicles discussed in this special Journal edition. Appropriate application of modern technology has resulted in the development of planing hull forms which are devoid of the hydrodynamic problems that have stereotyped planing craft as underpowered rough-riding vehicles. Modern planing hulls are designed to avoid the so-called "hump problems," demonstrate good behavior in a seaway, have substantial useful load fractions, and have a potential for growth up to displacements which have established them as effective members of naval units.

As shown by Mazza [1], in the 1970-1983 period, 327 fast attack units and 1471 patrol craft have been constructed and exported worldwide, thus establishing these smaller warships as "most popular" in the international market. Their excellent cost-effectiveness ratio, simplicity of operation, miniaturized electronics, and relatively heavy fire power have attracted the attention of many navies—particularly those operating in restricted waters as well as newly formed navies which consider the fast attack and patrol craft as their first ship in establishing an effective naval fleet.

The commercial usage of the planing form is primarily in the recreational area where, in the United States alone, annual production of recreational planing boats number in the thousands. In recent years the philosophy in designing these craft has moved from a preoccupation with high calm water speed to a serious effort to apply modern technology to substantially improve their seakeeping abilities. The modern planing hull now has surprisingly good seakeeping characteristics with little deterioration in calm water performance.

It is expected that the planing hull form will continue to find increasing utilization in military and commercial applications, particularly as research in this "traditional" hull form is continued. In this chapter we will describe the platform, discuss its special attributes and limitations, review the current and potential applications, summarize the state of technology, discuss the productivity and supportability and project future developments.

The material in this chapter is extracted from several sources such as presented in Reference [2] augmented by the generous contributions of many internationally recognized authorities in the technology of planing hulls. The editors wish to especially acknowledge the following individuals whose unselfish personal efforts contributed substantially to all aspects of this chapter:

Mr. Donald L. Blount — Naval Sea Combat Systems Engineering Station
Mr. P. Ward Brown — Davidson Laboratory, Stevens Institute of Technology
Mr. Timothy J. Chalfant — Uniflite, Inc.
Mr. Timothy Graul — Graul Marine Design
Mr. Michael Jones — Naval Sea Combat Systems Engineering Station
Mr. Joseph Koelbel, Jr. — Advanced Marine Enterprises, Inc.
Mr. Seabury C. McGown — Murray Crisis-Craft Cruisers West, Inc.
Mr. Jackie Morris — Naval Sea Combat Systems Engineering Station
Mr. John K. Roper — Roper Associates, Inc.
Mr. Ted Sladek — International Marine Co.
Mr. Jim White — U.S. Coast Guard

HISTORICAL EVOLUTION OF PLANING HULL FORM

Light displacement, high-speed, small combatant ships and ocean-capable patrol craft have been part of the world's navies since World War I. The Second World War brought substantial refinement and continued development which saw hard-chine hull forms evolving to equal status with the round-bilge forms so prevalent earlier. Great Britain, Germany, the United States and Russia, at this time, began to develop the early parentage of planing hull forms as we know them today.

To capitalize on the impressive German World War II E-Boat capabilities, two British prototypes called the Bold class were completed in 1948. Pathfinder, was produced in round bilge form, while its sister vessel had a
planing hull with hard chines. *Pathfinder* was the last British round-bilge planing boat built, all successors being hard-chine designs.

A succession of follow-on efforts was undertaken by the British, and the early 1960s marked the real opening of the high performance gas turbine propulsion era with the *Brave* class which was designed for a 50-knot speed requirement, with a specific weapons payload identified.

When U.S. PT-boat (Patrol Torpedo Boat) needs became obvious in the early 1940s, the British Navy's Packard-engined, Thornycroft-designed MTBs served as parent vehicles from which the 80-foot *Elco* and 79-foot Higgins PT-boats evolved through the war years. The U.S. Navy's post-World War II program was late starting and consisted of developing a new class of PTs. Capitalizing on both foreign and U.S. World War II experience, this program spawned a family of four 95-foot aluminum PT-boats which first saw service in the early 1950s. Each boat was different from the others but one had round bilge and the other three had hard chines. The speed capabilities of the three hard chine vee-bottom boats were nearly identical, ranging from 44 knots to 48 knots. The round bilge was slower at 38 knots but was more stable and easier riding in a seaway. All three hard chine boats exhibited varying degrees of pounding and directional instability at various headings in waves where the average of the one-third highest was 4.5 feet and higher.

In the mid 1960s, the British and U.S. navies achieved similar positions with respect to their high-performance patrol craft configurations. A similar evolution was occurring in Germany and the USSR. Their programs had produced the West Germany *Jaguar* class PTF, the USSR *Osa* class PTF(G), and *Nanuchka* class PGGP.

The 139-foot *Jaguar*, with a 23-foot beam and displacing 190 tons, has a round-bilge forward but becomes hard-chine in approximately the after one-third of the hull. Diesel propelled, this class achieved about 40 knots. The *Osa* class PTF(G) is a 127-foot hard-chine, 240-ton boat with a 22-foot beam and is estimated to be 4 knots slower than the *Jaguar* class. The *Nanuchka* class PGGP, at nearly 1000 tons with LOA of 198 feet and a 40-foot beam, is thought to be unique among the modern large high-performance craft in having a hard chine hull configuration.

In mid 1970, the U.S. Navy undertook an advanced planing hull research program aimed at improving seakeeping first while retaining as much speed as possible and at improving the lift-drag ratio of the hull through the mid-speed range of the speed envelope. This led to the development of a high length-beam ratio, high beam loading, double chine, moderate deadrise hull which met all the specified requirements of good seakeeping and good lifting efficiency. This prototype hull, identified as CPIC-X (Figure 7) became the U.S. "benchmark" design which met the conflicting demands for the best compromise of high speed and seakindliness in one hull form with minimum cost and complexity. The hull design features which achieved this performance are described in the technology section of this chapter.

The concept of a relatively small, fast, inexpensive carrier of a potent weapon at sea is not new, but a dramatic demonstration of this capability occurred on 21 October 1967. The event was the sinking of the Israeli *Eilat* by Styx missiles launched from an Egyptian *Komar* class patrol boat at a range of about 12 nm. The small boat concept has become most attractive to many of the smaller and newly-independent nations who are acquiring fast, heavily armed small combatants from Great Britain, France, Germany, the Scandinavian countries, the United States and the USSR. Furthermore, modern technology is now available to incorporate seakeeping and endurance with the speed, maneuverability, low profile, and low relative cost which are characteristic of these modern, very powerful vehicles.

Unfortunately, the aggressive and successful planing hull research program which was initiated by the U.S. in the 1970s subsided in the late 70s when the U.S. Navy decided to emphasize acquisition of large combatants capable of transiting the world's oceans.

**DESCRIPTION OF THE PLANING HULL CONCEPT**

The planing hull is designed specifically to achieve relatively high speed on the surface of the water. Although it is not essential to the concept of planing, rough water operation has become an important capability for most useful planing hulls, and this aspect of their design will be reviewed.

Speed on the water surface is closely related to the size of the vessel and the installed power. Length is the principal dimension used to define speed-size relationships at low speeds because the resistance of the hull to motion through the water is especially dependent upon the formation of surface waves which, of course, move at the speed of the hull. Surface waves have a fixed relation between their speed and their length. This is sometimes expressed, in English units, as the wave speed in knots divided by the square root of the wave length in feet and this ratio is always equal to 1.34 (except in very shallow water). The speed/length ratio of a displacement vessel is similarly defined as its speed in knots divided by the square root of the waterline length in feet. Therefore, when a vessel moves at a speed/length ratio \( V_l / L \) of 1.34 it creates waves whose length is equal to the waterline length of the vessel. This critical speed is also stated in dimensionless form using the Froude number, \( F_r = V / L \). Therefore, \( V_r / L = 1.34 \). The value of \( V_r / L = 1.34 \) marks the upper limit of true displacement operation and the beginning of "high speed displacement" operation. The reasons for this are given in the next two paragraphs.

Below \( V_r / L = 1 \) and as shown in Figure 1, marine craft span two or more waves (of their own bow wave train), the changes in draft and trim are small, and power requirements are modest. In this speed regime the hull is supported entirely by buoyant forces. Up to a \( V_r / L \) of 0.90 the drag is predominantly frictional. The hull is tapered at the stern and curved upward toward the waterline, to minimize flow separation which is another source
Figure 1. Wave Patterns vs. Speed-Length Ratio.

of drag. This is typical of slow, heavy vessels as shown in Table 1. Above \( V_K/\sqrt{L} = 0.94 \) the wavemaking drag becomes increasingly important. At about \( V_K/\sqrt{L} = 1.20 \) it begins to increase at a very high rate. At about \( V_K/\sqrt{L} = 1.34 \) wavemaking becomes a virtual barrier to further increases in speed for the true displacement hull form (Figure 2). This is because the increased local velocities caused by the rounded hull form result in negative pressures which cause the vessel to settle deeply and to trim down by the stern. The ship is literally climbing the back of its own bow wave.

Table 1 shows approximate representative ratios for the general type of vessel shown. This table shows typical values for Froude numbers and speed/length ratios as well as lift/drag ratios for a wide range of ships and craft. Note that low speed (low speed/length ratio) is generally associated with high lift/drag ratios whereas high speed craft tend to have much lower lift/drag ratios.

At \( V_K/\sqrt{L} \) above 1.34 it is therefore necessary to depart from the “canoe stern” or “counter stern” of the low speed types and to make the buttock lines flatter terminating in a transom stern. This hull form avoids the negative pressures that occur when a true displacement hull is overdriven and causes the flow to separate cleanly at the stern, thus keeping the separation drag to a minimum. As the design speed of the vessel is further increased even straighter buttock lines are required and the transom must be broader and more deeply immersed (but round bilge sections may still be employed). This high speed displacement (or semiplaning) regime extends from \( V_K/\sqrt{L} \) of about 1.3 to about 3.0. These speed regimes are depicted graphically in Figure 3.

A systematic series of high speed displacement hulls (Series 64) the parent form of which is shown in Figure 4a, was tested by Yeh [3] at speed-length ratios up to 5.0. In analyzing the results, Yeh makes the following statement regarding high speed displacement operation:

“The dropping off of residuary, i.e. wavemaking, resistance coefficients and close spacing of \( R/\Delta \), i.e. wavemaking resistance per ton of displacement (proportional to D/L), contours between the speed/length ratios of 2.0

Table 1. Vessels Typical of Various Froude Numbers.

<table>
<thead>
<tr>
<th>Length</th>
<th>Speed</th>
<th>Drag-</th>
<th>Lift-</th>
<th>Type of Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Froude Number</td>
<td>FSL</td>
<td>Drift</td>
<td>Lift</td>
<td>D/L</td>
</tr>
<tr>
<td>0.15</td>
<td>0.5</td>
<td>0.001</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>0.24</td>
<td>0.8</td>
<td>0.002</td>
<td>500</td>
<td>125</td>
</tr>
<tr>
<td>0.30</td>
<td>1.0</td>
<td>0.005</td>
<td>200</td>
<td>125</td>
</tr>
<tr>
<td>0.33</td>
<td>1.1</td>
<td>0.008</td>
<td>50</td>
<td>125</td>
</tr>
<tr>
<td>0.39</td>
<td>1.3</td>
<td>0.02</td>
<td>50</td>
<td>125</td>
</tr>
<tr>
<td>0.45</td>
<td>1.5</td>
<td>0.03</td>
<td>33</td>
<td>125</td>
</tr>
<tr>
<td>0.54</td>
<td>1.8</td>
<td>0.05</td>
<td>20</td>
<td>125</td>
</tr>
<tr>
<td>0.98</td>
<td>3.3</td>
<td>0.10</td>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td>1.34</td>
<td>4.5</td>
<td>0.14</td>
<td>7</td>
<td>125</td>
</tr>
</tbody>
</table>

Naval Engineers Journal, February 1985
Figure 3. Speed Regimes.

Figure 4a. Typical High Speed Hull Forms.

Figure 4b. Typical High Speed Hull Forms.

(F_N = 0.5) and 3.0 (F_N = 0.9) mean that a small increase in horsepower will bring a higher return in speed in this speed range than in any other speed range, except at the very low speeds. The leveling off of the residuary resistance coefficients and their magnitudes after the speed/length ratio of 3.0 (F_N = 0.9) indicate that the wave resistance is no longer an important factor. The frictional resistance, however, remains the dominant factor, and its magnitude is about twice as large as the form drag. Therefore, for ships designed to operate at speed/

length ratios over 3.0 (F_N = 0.9), it is highly desirable to keep the wetted surface to a minimum.

It is precisely this factor that makes the planing type of hull, shown in Figure 4b, desirable at high speeds. The manner in which it generates lift (discussed below) causes it to rise bodily above its static flotation level and to trim up by the bow thereby reducing the wetted surface significantly.

Since the formation of waves is less significant and not primarily influenced by hull length above semiplaning speeds, the length Froude number is no longer very useful as a measure of the speed-size relationship and the volume (or displacement) Froude number F_v = \sqrt{V/\rho g L^3} is frequently used. Figure 5 shows a plot of drag/lift ratio against Froude number for several slenderness ratios (L/D). The curves represent the state of the art for efficient planing hulls at their design speeds and do not represent any one hull throughout the speed range. It can be seen that the curves all cross in a small area around F_v = 3.3, indicating that slenderness ratio, and hence the length, has little effect on the specific resistance at this Froude number. At lower speeds longer hulls have a great advantage over shorter ones and (from other data) high speed displacement or semiplaning configurations have an advantage over full planing configurations, to be described below.

At higher speeds, as noted above, the planing type of hull is required. These facts are illustrated dimensionally in Figure 6, where the line marked “Upper Bound Displacement Hulls” represents F_v = 3.3, the limit of speed.
above which the high speed displacement type hull form may be more efficient depending on the length and weight (slenderness ratio) of the vessel. The shorter the hull, at constant weight (the lower the slenderness ratio), the lower the speed at which the planing type hull can be considered. This range of lower limits, shown in Figure 6 as the family of curves labeled "Lower Bound Planing Hulls," corresponds to a range of length Froude numbers from 0.84 to 1.10. This range is also shown in Figure 3.

The chief characteristic of the planing hull is effective flow separation, not only at the transom as in the high speed displacement ship, but also at the sides. Effective flow separation is necessary to prevent the formation of negative pressure areas on the bottom of the hull. This is usually accomplished with a hard chine configuration, one type of which (Series 62) is shown in Figure 4. Greater deadrise and/or more rounded transverse sections can be used if effective flow separation is achieved by proper placement of spray rails. The longitudinal shape (buttock lines) must have no convexity aft of the bow sections. This basic rule may be violated occasionally when local longitudinal convexity (rocker) is added in the transom area—particularly in high speed recreational craft. The negative pressures developed by this "rocker" geometry provides a bow up trim moment to the craft and thus prevents the craft from running "too flat" at high speeds.

When a planing hull is driven beyond the displacement speed range it initially trims down by the stern like the other types, but because it is a "lifting surface" it develops positive hydrodynamic pressures as speed increases thus generating dynamic lift. As the hydrodynamic lift increases with increasing speed the amount of hydrostatic (buoyant) lift decreases so that the total lift remains constant and is equal to the craft weight. At full planing speeds, $V_K/\sqrt{L} > 3.0$, the wavemaking resistance, which effectively becomes a speed barrier for a displacement ship, actually decreases for a planing craft as the speed increases.

Although primarily adapted to high speed operation, useful planing hulls, with few exceptions, must be able to operate successfully in the high speed displacement (semiplaning) and low speed (true displacement) regimes, and importantly in rough water as well. The hull form which best meets these requirements has a relatively high length-beam ratio (greater than 5) to reduce impact accelerations at high speed and to reduce trim and therefore resistance in the transition speed range. The high slenderness ratios associated with these proportions produce low resistance at low speeds. A good planing hull will also have moderate deadrise (about 15 degrees) aft increasing to high deadrise (about 45 degrees) forward combined with fine lines in the bow. These characteristics further reduce slamming at all speeds, and minimize rough water resistance. The only disadvantage that must
MODERN SHIPS & CRAFT

be accepted is a small increase in resistance at low dis-
placement speeds and at full planing speeds compared to
hulls optimized for either of these speeds. This is an
acceptable penalty considering the all around good per-
formance that is achieved, particularly the ability to run
with good efficiency throughout the entire speed range.

The theoretical and analytical considerations just de-
scribed permit definitive model testing with dependable
scaling, with high confidence in both the hull form and
its full scale performance prediction. The way is then
open to intelligent selection of hull material, construction
techniques, and choices of scantlings and propulsion
components.

Hull construction can be of welded steel with light
alloy superstructures (particularly for the larger sizes); of
all-aluminum welded structures, of glass fiber reinforced
plastic (particularly for the smaller sizes), or of wood.

The vast majority of conventional planing hulls are
powered by diesel engines driving fixed pitch propellers
via reversible reduction gears. More recent high perform-
ance designs use gas turbine power plants for high speed
operation and separate diesel engines for slow speed and
maneuvering economy. Commercially available sub-
cavitating propellers with high blade area ratio are used
in the speed range up to approximately 35 knots. At
higher speeds, special so-called "transcavitating" pro-
pellers are required. Transcavitating propellers combine
features of both conventional and supercavitating pro-
pellers, giving good efficiency over the entire speed
range. All these features will be discussed in greater de-
tail in the following sections of this chapter.

SPECIAL ATTRIBUTES AND LIMITATIONS

The modern planing hull is a relatively inexpensive
high speed platform capable of carrying potent military
payloads. Development and eventual utilization of large
size planing vessels can be achieved at a substantially
reduced cost as compared to other types of advanced
naval vehicle concepts.

Attributes

Principal capabilities of a planing hull from the tech-
nological viewpoint are listed below.

- The basic smooth and rough water hull hydrodynamic
  technology is sufficiently advanced to enable reliable
  preliminary performance predictions to be made.
- Model-prototype performance correlation is sufficiently
  well-documented to establish model testing as a reliable
  design and evaluation procedure.
- Planing hulls generically do not have serious naviga-
tional draft limitations.
- The hard chine planing hull has more inherent roll
damping, particularly underway, than a round bilge
hull, which effectively reduces roll motions in a sea-
way. Active roll fin stabilizers are easily added to the
vessel to further reduce roll motions in the displacement
speed range. This allows for comfortable long-term op-
eration at these speeds.

- Planing vessels properly designed for seakeeping can
  retain a large portion of their calm water operational
  speed capability in moderate to severe sea conditions.
  For instance, at a speed of 37 knots, a 100-foot planing
  hull was able to perform its mission in waves of signifi-
cant height up to five feet.
- Hull construction can follow normal shipyard practice
  and will not require aircraft-type fabrication tech-
niques.
- Much of the required structural technology is in hand
  and no unresolvable structural design problems are en-
visioned.
- The large useful load fraction (approximately 40 per-
  cent) of a well-designed planing ship provides sufficient
  fuel for long transiting capabilities at low speed without
  refueling and at medium speeds with refueling enroute.

Limitations

Principal limitations of a planing hull from the technol-
yogy viewpoint are listed below:

- The lift-drag ratio at very high speeds (V<sub>W</sub>/V<sub>L</sub> > 4.0)
is less than comparably size hydrofoils and SES craft.
- The seakeeping performance in high sea states will
  never be the equal of hydrofoil craft but is nonetheless
  quite acceptable for reasonable operating periods.
- The planing hull has been traditionally stigmatized as a
  small boat with small payload and no rough water ca-
pability. Although recent technology advances in plan-
ing hull design have negated these perceived
limitations, some time will be required for general ac-
ceptance of these possible improvements.
- Commercial and state user agencies tend to buy off-the-
shelf recreational boats and modify them to meet their
needs. Unfortunately the best and latest hull technology
is usually not incorporated into these available hulls.

CURRENT APPLICATIONS

U.S. NAVY

In the last 4 to 5 years the combat role of planing craft
has been deemphasized. This is mainly due to the great
expans of ocean over which the United States is required
to make its presence known. Earlier experience with
small fast warships has caused the U.S. Navy to decide
that these ships pose too many restrictions considering
long-term open-ocean seakeeping and weapons carrying
capability. The U.S. philosophy today is to build comba-
tants capable of transiting any of the world's oceans and
carrying a vast assortment of weapon systems. Unfortu-
nately, with this philosophy, problems can arise when it
is necessary to engage in limited warfare in areas where
the larger ships cannot operate close to shore or in the
inner harbors or rivers. The primary uses today of plan-
ing craft within the U.S. Navy are as patrol craft, inser-
tion craft, riverine craft and ships' boats.

Patrol Craft

Limited patrol in shallow waters and around islands as
well as some coastal patrol is undertaken by Navy small
boat groups. These missions are usually performed to intercept terrorists and drug runners or to ensure safe passage of personnel going from ship to shore. Currently the Navy's primary patrol boat for this mission is a 65-foot PB.

**Insertion Craft**

These craft are used for operations which require the insertion of advance troops such as commandos, guerilla operatives, or other special forces. They are required to be of low profile, fast, seaworthy, and capable of being davit-launched at sea. At present the Navy uses various inflatable craft and a specially designed 36-foot fiberglass hull for such applications.

**Riverine Craft**

Riverine craft were used during the Vietnam War to patrol the delta and many rivers of South Vietnam. The enormous numbers of boats in this region required the Navy to modify or build boats to interdict this traffic. Craft used included the 31-foot PBR, 50-foot PCF, 95-foot Osprey and many converted LCM-6 and LCM-8 landing craft. Other riverine craft were used to provide firepower and landing capability during the many assaults. These craft included the ASPB, LCM-6 Monitor, 36-foot Mini ATC and any other small craft capable of supporting a small caliber weapon.

**Ships' Boats**

Tests are presently being conducted and prototypes built of a light-weight inflatable craft with a rigid V-hull made of fiberglass. This craft is officially known as a rigid inflatable boat (RIB) and will be deployed on combatant ships, such as frigates and cruisers. It was originally designed in England for the Lifeboat Service to transit the surf zone and proceed at high speed through rough seas. They have a conventional fiberglass deep V-hull with a larger diameter inflatable tube around the gunwale. This has proven to be a very seaworthy and stable design. As an example, these craft have been davit launched at 12 knots in a sea state 3. They will be used for boarding, search and rescue, and personnel and supply transport.

With the present U.S. Navy philosophy, the future does not look promising for further planing craft development beyond the present inventory with the exception of one or two larger craft for special missions. Those missions which could be handled by planing craft will probably be accomplished by more sophisticated and expensive vessel types such as the SES and hydrofoil.

**FOREIGN MILITARY**

The present and future applications of planing craft in foreign navies are distinctly more positive than in the U.S. Navy. Foreign navies have placed great emphasis on the use of small naval combatants, as attractive alternatives to larger ships. This is due to the escalation of shipbuilding costs, the institution of the 200-mile territorial limit, and the entry of "third world" nations into modest naval programs.

The emphasis on small ships has resulted in an impressive number of these high speed vessels in foreign service [5]. Reported characteristics in 1979 indicate over 2,700 vessels under 200 feet LOA in active service worldwide with the following distribution:

<table>
<thead>
<tr>
<th>LOA, ft</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>61-70</td>
<td>11</td>
</tr>
<tr>
<td>71-90</td>
<td>19</td>
</tr>
<tr>
<td>91-110</td>
<td>7</td>
</tr>
<tr>
<td>111-130</td>
<td>44</td>
</tr>
<tr>
<td>131-150</td>
<td>11</td>
</tr>
<tr>
<td>151-170</td>
<td>4</td>
</tr>
<tr>
<td>171-190</td>
<td>2</td>
</tr>
<tr>
<td>191+</td>
<td>2</td>
</tr>
</tbody>
</table>

The largest concentrations by overall length are 127 feet (30%) and 87 feet (16 percent).

It is also interesting to examine the distribution as a function of speed shown in the following table:

<table>
<thead>
<tr>
<th>Speed, knots</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤20</td>
<td>1</td>
</tr>
<tr>
<td>21-30</td>
<td>32</td>
</tr>
<tr>
<td>31-40</td>
<td>35</td>
</tr>
<tr>
<td>41-50</td>
<td>25</td>
</tr>
<tr>
<td>51+</td>
<td>7</td>
</tr>
</tbody>
</table>

The speed distribution indicates the following:

- **Low Speed:**
  - 30% of the vessels travel at speeds ≤ 20 knots.
  - 32% of the vessels travel at 21-30 knots.
  - 35% of the vessels travel at 31-40 knots.

- **High Speed:**
  - 25% of the vessels travel at 41-50 knots.
  - 7% of the vessels travel at 51+ knots.

This distribution indicates a shift towards high-speed vessels, which are better suited for modern naval operations.

**Figure 8. Smooth Water Performance.**

Naval Engineers Journal, February 1985
MODERN SHIPS & CRAFT

The smooth water performance characteristics of the craft reported were used to calculate transportation efficiencies and a dimensionless speed \( F_v \) from which representative data were plotted in Figure 8. The greatest number of craft have maximum speeds above the "planing hump speed" of \( F_v = 1.5 \) with a high concentration in the semiplaning region of \( 1.5 < F_v < 3.0 \). There are also an impressive number of "pure planing" craft operating at \( F_v > 3.0 \). This is important in identifying the trends of hull form as they change with increasing \( F_v \).

As discussed by Mazza [1], the international market for small warships has grown explosively between 1970 and 1983. It became a multibillion dollar annual market in the 70s. Many factors contributed to this surge in interest. Typical are:

- The rapid development of new generations of weapons systems which caused significant changes in naval tactics that highlighted the use of small combatants.
- The creation and expansion of completely new navies, particularly in the evolving countries.
- Depressed shipyards, pressed by the world wide decline in orders for merchant ships which turned their attention to the international market for small combatants.
- The growing importance of offshore resources and the consequent creation of the 200 mile EEZ (Exclusive Economic Zones) thereby creating new surveillance requirements.

During this period, the average displacement of warships has decreased from 1,100 tons in the 60s to 800 tons in the 70s mainly as a consequence of the fast attack craft's development and diffusion. There is indeed an international trend towards greater utilization of smaller surface vessels. The European industries dominate the export business with the German and French yards being the leaders, and the most popular size fast attack craft is in the 250-300 ton range.

U.S. COAST GUARD

The U.S. Coast Guard is a unique branch of the armed services in that it has well defined roles and missions in maritime safety, search and rescue, aids to navigation, environmental protection and law enforcement under the Department of Transportation in times of peace, while maintaining a state of military readiness to function under the Department of the Navy in times of war. The Coast Guard currently uses a variety of planing hull boats in carrying out these missions.

The largest number of boats are classified as light utility boats (UTL). These are nonstandard, less than 25 feet in length, purchased from the boating industry by district commanders to meet the specific needs of the individual Coast Guard districts. There are over 1,000 UTLs of various types, and the overwhelming majority of them are planing hulls. These boats are used for short range search and rescue, law enforcement, port and environmental safety, marine environmental response, recreational boating safety, and the servicing of short range aids to navigation. Wartime missions for them will remain essentially the same, but one would expect some change in emphasis. For example, the number of harbor patrols for port safety will probably increase.

A clearer picture of the current use of planing boats may be obtained by reviewing some of those in service. Five examples will be considered: Two multimission boats, two specific mission boats and a new ship's boat.

The 30-foot utility boat MkIII (UTM) is of fiberglass and is used for search and rescue, and law enforcement, in moderate sea states. It has an overall length of 30 feet, a 10-foot 7-inch beam and a 2-foot 10-inch draft at an operating displacement of 6 tons. The 30-foot UTM is powered by a single 270-horsepower Cummins VT8-370M, or 280-horsepower Cummins UT6-250M, diesel engine. It has a maximum speed of 25 knots. There are 365 of these boats in service.

The 41-foot utility boat (UTB) is built of aluminum and is also used for search and rescue and law enforcement in moderate sea states. It has an overall length of 40 feet 8 inches, a 13-foot 6-inch beam, and a 4-foot 9-inch draft at an operating displacement of 12.8 tons. It is powered by a pair of either 280-horsepower Cummins V903M, or 320-horsepower Cummins VT903M diesel engines. The maximum speed is between 22 and 26 knots. There are 201 of these boats in service.

The 30-foot surf rescue boat (SRB) is of fiberglass and is used for search and rescue in moderately heavy seas and surf. This boat was designed to have a faster transit speed than more traditional surf rescue boats. It has an overall length of 30 feet 4 inches, a beam of 9 feet 4 inches and a draft of 3 feet 7 inches at an operating displacement of 4.6 tons. It is powered by a General Motors 375 horsepower 6V92T diesel engine and has a maximum speed of 28 knots.

The 55-foot aids-to-navigation boat (ANB) is aluminum and is used to provide quick response servicing of lightweight aids to navigation. This is a work boat with length overall of 58 feet, a 17-foot beam and a 5-foot draft at an operating displacement of 28.8 tons. It is powered by a General Motors 170-pair 540-horsepower General Motors 12V-71 TI diesel engine and has a maximum speed of 22 knots. There are 20 of these boats in service.

The Coast Guard is in the process of equipping each of its cutters with an Avon 6-meter rigid hull inflatable boat (RHIB). The 6-meter RHIB has a fiberglass, deep-vee planing hull to which is attached a synthetic rubber, inflatable flotation collar. It is powered by a pair of 70 horsepower outboard motors. It can carry from two to ten persons and has a maximum speed of 25 to 35 knots. The boat can be launched and recovered from a cutter while underway using a single point davit. There will be 124 of them in service.

The Coast Guard has a fleet of 26 "Cape" class, 95-foot patrol boats (WPB), and 53 "Point" class, 82-foot patrol boats (WPB) in commission. They have conventional patrol boat displacement hulls and are capable of operating in the high speed displacement regime, i.e., speed/length ratios of from 2.0 to 2.5. The 95-foot WPBs were built from 1953 through 1959. The 82-foot WPBs were built from 1960 through 1970. These boats should start to be replaced at the end of this decade.
Federal guidelines for major acquisitions require the consideration of alternative system designs for the replacement of the present WPB capability. This means a consideration of various types of advanced marine vehicles. Speed, the ability to maintain speed in a seaway, and seakeeping will be major factors in evaluating any vehicles. Good seakeeping qualities may lead to the consideration of deep-vee, or double chine planing hulls. Thus more easily powered for attainment of planing speeds. On the other hand some boats, although designed to over 100 tons in displacement. The majority are in the 16-foot to 30-foot size range. Annual production in this size range numbers in the thousands of units. Quantities in sizes over 30 feet decrease with increased length with less than 10 boats per year in the 90 to 100 foot category. Recreational boat types are:

- Runabouts, mostly 16 to 25 feet, maximum 60 feet
- Sportfishing boats, inland and coastal water sizes 16 to 45 feet, and offshore sizes 25 to 80 feet
- Cruising boats, from 25 feet to 100 feet
- Sports racing, from 16 feet to 60 feet

The future of the recreational boat business and planing craft production as the major part of it, depends largely on basic national economic conditions. Purchase, maintenance, and operating costs for recreational craft fall into the category of discretionary expenses and require a healthy economy to be sustained. Another aspect of the recreational boat market is that it is not large enough or mature enough to support development and production of engines designed and built primarily as marine propulsion units. Almost all marine propulsion engines are built as a spin-off of automotive or industrial engines. Therefore, the availability of marine propulsion engines at prices low enough to be affordable for recreational boats requires that there be some other larger commercial need for such engines so as to provide the manufacturer with the incentive to produce the basic engines for conversion to marine applications. For instance, many recreational boats use gasoline engines in the 380- to 425-cubic-inch range. As Detroit down-sizes automobiles, these engines may become unavailable for marine use because the underlying automotive market will no longer have a need for them. Most commercial planing boats are designed around existing power plants and the type and quantity of boats built is a function of the availability of engines at reasonable prices.

Work boat applications are the second most numerous application for planing craft. The following are typical of the various applications:

- Offshore oil rig crew boats, 50 to 120 feet
- Commercial fishing boats, 25 to 50 feet
- Charter fishing boats, 36 to 60 feet
- Pilot boats, 35 to 60 feet
- Fire boats, 30 to 80 feet
- Oil spill clean-up boats, 16 to 50 feet
- Hydrographic survey boats, 25 to 50 feet
- Landing craft type cargo boats, 25 to 50 feet

Crew boats are probably the most significant of the non-recreational types used today in the U.S. Planing craft are suitable for this service inasmuch as speed is important, payloads are not excessive, and endurance requirements are reasonable. Production, which fluctuates with the fortunes of the offshore oil drilling business, is currently low, but it has been significant over the past 20 years and can be expected to continue to be a major application of planing boats.

Other applications as listed above hardly represent a major industry, but they do represent a variety of different usages each with its own special needs. The requirements of these other usages are such that they can often be satisfied by less expensive and/or more durable displacement type craft. However, in those instances where craft size is not too large, thus permitting planing speeds with the available lightweight power plants, or where high speed is essential to the mission, planing craft are employed. Generally their use is suitable where payloads are moderate and endurance requirements are low as in the case where runs are short allowing frequent refueling. Patrol boats are a quasi-commercial type of planing craft. Users include various local, state and federal gov-
MODERN SHIPS & CRAFT

ational agencies such as harbor police, fisheries enforcement, customs, parks and recreation, etc. In the United States patrol boats are generally small, 25 to 50 feet in length. Missions which would require larger craft are usually handled by U.S. Coast Guard vessels of a displacement or semidisplacement type.

In the U.S. most patrol boats are adaptations of boats originally designed to be recreational boats and are built to recreational boat standards. As a consequence they are often not ideally configured for this application and are not as durable as their military patrol boat counterparts. On the other hand, they are relatively inexpensive.

In Europe and Asia one sees more harbor police launches than in the U.S. and they are generally custom-designed and built for patrol use. They are recognizable different in configuration from recreational boats and have a no-nonsense appearance. Some of the most technically advanced are built in Italy using hull forms and other technology closely akin to those of offshore racing boats.

Patrol boat requirements can be expected to increase in the future as governments continue to increase their involvement in various water oriented activities. Such applications should employ the best and latest technology and provide an impetus for advancing the art. However, if recent experience continues to be the norm, such will not be the case. Most nonfederal agencies do not have the expertise to design or prepare suitable specifications to obtain the best in the way of patrol boats. So long as patrol boats are purchased by the user agencies the same way they purchase typewriters, agencies will continue to get off-the-shelf recreational boats not ideally suited for patrol boat applications.

POTENTIAL APPLICATIONS

The design of high speed craft has recently become one of the most active areas of naval architecture. The 200-mile fishing limit, recognized since 1 January 1977 by virtually all nations, imposes national jurisdiction over nearly 10 percent of the world's ocean areas. These areas have become the Exclusive Economic Zone of the coastal states who wish to protect and exploit their potential offshore wealth, which includes fishing as well as oil and other natural resources. It has been estimated that 90 percent of both living and natural resources in and under the sea are within the 200 mile limit and that world demand for patrolling coastlines could require up to 600 additional high speed vessels. Such factors when coupled with mounting aspirations of emerging nations, have given rise to a world-wide interest in planning craft capable of acceptable operations in a seaway.

From a totally military point of view, high speed planning hulls armed with powerful surface-to-surface missiles, self-protected with surface-to-air missiles and close-in defensive weapons and countermeasures, and fitted with modern electronics systems will be entering service in the world's navies in ever increasing numbers. As noted earlier this enthusiastic interest in the use of small, fast, patrol craft with devastatingly capable missile systems was in part precipitated by the sinking of the Israeli destroyer Elat in 1967. Since that time, second generation antiship missile systems have appeared which operate from lightweight fixed launchers. In addition, gun armaments have experienced rapid developments with the introduction of effective and accurate fire control, increasing rates of fire, and high precision munitions. Various caliber guns are available which can be effective even against aircraft and incoming missiles and which are compatible with planning hulls.

As discussed by Dorey [27], sensors, computation and display facilities, and electronic warfare systems now form an integral part of the weapon outfit of any warship, and their availability in forms compact and light enough to be installed in high speed planning craft can make this class an effective warship.

Developments now in the technology pipeline using microminiaturation for all forms of electronics equipment will have a dramatic effect on the "packing factor" of the black boxes which comprise the weapons systems of today. When the effects of such change are ultimately felt in all facets of the combat system design for small warships, the day of the multimission small warship truly will have arrived.

It is further expected that the demands of commercial and recreational markets will continue to expand. Further, with greater needs for good seakeeping performance, modern technology will be applied to develop hull forms which will satisfy this demand.

STATE OF TECHNOLOGY

SMOOTH WATER PERFORMANCE

Planing craft hydrodynamic technology is based primarily upon experimental data obtained from tests of prismatic planning surfaces such as those reported by Savitsky [6] and results of hull series tests such as illustrated by Series 62 reported by Clement and Blount [4]. This technology has been synthesized into simplified empirical equations which are easily used in design. The following discussion of the smooth water characteristics of planing craft is based upon analytic considerations, model test results, and full scale data.

Hydrodynamic Lift

The lift on the planing surface is attributed to two separate effects. One is the positive dynamic reaction of the fluid against the moving planing bottom, and the second is the so-called buoyant contribution which is associated with the static pressures corresponding to a given draft and hull trim. At very low speeds, the buoyant lift predominates, while at high speed, the dynamic contribution predominates. A plot of lift coefficient as a function of mean wetted length/beam ratio for a range of speed coefficients is given in Figure 9 for a zero deadrise surface. The correction for deadrise is given in Figure 10. The important hydrodynamic characteristics demonstrated are:
The lift coefficient, $C_{L}$, increases as the exponential power of trim angle and as the square root of the mean wetted length/beam ratio, according to the following equation (for zero deadrise surface):

$$C_{L0} = \frac{1}{\pi} \frac{(0.0120 \lambda^{1/2} + 0.0055 \lambda^{5/2}/C_{V})}{\varepsilon}$$

where:
- $\tau = $ trim angle, degrees
- $\lambda = $ mean wetted length/beam ratio
- $C_{V} = $ speed coefficient $= V/\sqrt{gb}$
- $V = $ speed, ft/sec
- $b = $ beam of planing surface, ft
- $g = $ acceleration of gravity, ft/sec²

All other parameters being constant, the hydrodynamic lift varies as the square of the beam.

The planing lift is predominately due to dynamic bottom pressures when the speed coefficient $C_{V}$, a Froude number defined above, is greater than 10.

The effect of deadrise angle is to reduce the lift coefficient, all other factors being equal.

Hydrodynamic Drag

The hydrodynamic drag of the bare hull is composed of pressure drag due to lift forces acting normal to the bottom, and to viscous drag acting tangential to the bottom in both the pressure area and in the spray area which is located immediately forward of the pressure area. These drag components, at full planing speed, are best illustrated in Figure 11. It has been found that these drag/lift ratios are only slightly dependent upon speed (except as speed influences trim) and mean wetted-length/beam ratio. These are the hydrodynamic characteristics illustrated:

1) The drag/lift ratio is primarily dependent upon trim angle with the optimum trim at approximately 4 degrees.

2) At trim angles of less than 4 degrees, the viscous drag due to bottom friction dominates, while at larger trims, pressure drag due to dynamic lift generation dominates. For typical hull forms, low trim angles will also immerse the bow, further adding to the total resistance.

3) The drag/lift ratio increases significantly with increasing bottom deadrise—especially at low trim angles.

4) For trim angles less than 4 degrees, the drag/lift ratio decreases with increasing trim angle. This is a beneficial feature that reduces the drag penalty due to overloading since, all other parameters being equal, planing hull trim angles increase with increased loading.

5) If the sole design requirement was to provide minimum power at high speed in smooth water, then it would be concluded, from Figure 11 that a flat-bottom hull planing at a trim angle of approximately 4 degrees would be the ideal combination of hull form and trim attitude. Unfortunately, this selection would be unacceptable for several practical reasons:

   a) At high speed, the combination of $\beta = 0$ degrees and $\tau = 4$ degrees most likely will result in longitudinal instability—"porpoising."
b) When operating in a seaway, the flat bottom hull will develop severe wave-impact accelerations (as discussed in a subsequent section on seakeeping).

c) Trim angles less than 4 degrees are desirable to reduce wave-impact accelerations (as discussed in a subsequent section on seakeeping).

6) Early planing hull designs were guided almost entirely by the requirement for high speed in calm water so that low hull deadrise angles were used and loaded to attain optimum trim angle. Modern planing hull design is so dominated by seakeeping considerations that reasonable compromises in smooth water performance are not only tolerated but sought. Consequently, good planing hull forms will have moderate deadrise at the stern (approximately 15 degrees) increasing to high deadrise (approximately 50 degrees) at the bow. To achieve the desirable low trim angles in rough water, provision is made to shift ballast or fuel into bow tanks. If this design feature is not possible, then transom flaps are installed to reduce the trim as necessary. These trim control techniques allow for setting the optimum trim angles in both calm and rough water. Design procedures for selecting the size and deflection of trim flaps are given by Savitsky and Brown [7].

The results of systematic series tests (Series 62 and 65) have been synthesized into the results given in Figure 5 which show the drag/lift ratio for efficient planing hulls as a function of speed for various slenderness or displacement/length ratios. The curves, which are for a displacement of 100,000 lbs, represent the state of the art for efficient planing hulls and do not represent any one hull over the entire speed range. At \( F_r = 2.0 \), corresponding to the cruise speed range for most naval craft, the longer hulls have substantially less resistance than the shorter ones. There is only a small effect of slenderness ratio at \( F_r = 3.0 \) and a moderate increase in resistance with increasing slenderness ratio for \( F_r \geq 3.0 \). It can also be seen that the long hulls have little or no hump drag but do have greater resistance at high speed.

**Center of Pressure and Trim**

Because trim angle is such a critical planing parameter, as discussed above under lift and drag, trim control devices such as transom flaps or longitudinal transfer of fuel or ballast are used to achieve the desired running attitude. For example, low trim reduces impact accelerations at high speed in head seas, high trim is required for maximum speed in smooth water and for operating in following seas.

The center of pressure of planing hulls is calculated by means of a semiempirical equation given in Figure 12. It shows a variation in center of pressure from 33 percent of the mean wetted length forward of the transom at low speed to 75 percent forward at high speed.

**Equilibrium Conditions**

For a planing hull having a specified length, beam, deadrise, displacement, center of gravity, and thrust line, there is a relation between running trim angle and speed at which the hull is in equilibrium. This equilibrium trim angle is easily computed using the basic hull technology just described and determines the drag/lift ratio of the boat as plotted in Figure 11. Typical curves of trim and resistance as a function of speed for conventional planing craft are demonstrated in Figure 13 for hulls of various length/beam ratios. It is seen that, as speed increases, the craft trim and resistance increase to a so-called “hump” value and then decrease as the speed is further increased. The hump trim and resistance decrease with increasing length/beam ratio and are barely noticeable at high length/beam ratios.

It is interesting to observe that, at volume Froude numbers (\( F_v \)) between 2.5 and 3.5, the drag is essentially constant and independent of length/beam ratio so that increases in installed power will result in relatively large increases in speed. At volume Froude numbers greater than 3.5 to 4.0, the drag will moderately increase as the length/beam ratio increases.

Simply stated, when given a fixed displacement, the designer should attempt to configure the planing bottom to be as long and as narrow as possible—consistent with the requirements of internal arrangements and transverse stability. Fortunately (as will be shown) a high length/beam ratio hull is also very desirable for good performance in a seaway.

A review of proportions of past planing hull designs indicates that the preponderance of constructed boats had
length/beam ratios between 3 and 5, with large numbers of commercial and recreational craft being in the ranges between 3 and 4. It is these craft which experience pronounced hump trim and high resistance characteristics—a performance pattern which even nautically-oriented observers so typically associate with planing boats. In recent years, the design trend has been to length/beam ratios in excess of 5.0—even at the expense of compromising the internal arrangements. This results in a substantial reduction or even elimination of the “hump” problem, as well as a substantial reduction in drag in the preplaning speed range.

**ROUGH WATER PERFORMANCE**

Perhaps the greatest demand imposed on today’s designers of planing hulls is to develop hull forms with good operational capability in a seaway. Traditionally, planing hulls have been characterized as small boats with no rough water capability. It should be recognized however, that such hulls were designed almost entirely for high speed in calm water—culminating in a hull form and loading combination which resulted in unacceptable seakeeping qualities in even moderate sea states.

Recent research in planing hull seakeeping technology have quantified the relations between hull form, loading, speed/length ratio, sea state and the expected added resistance, motions, and, most importantly, wave impact accelerations [7]. In fact, the designer now has the tools to optimize the planing hull for specified operational requirements in both smooth and rough water. An example of such an optimization was given by Savitsky, Roper, and Bezen [8].

A brief summary of the most important seakeeping technology and its effects upon planing hull design is given below.
Wave Impact Acceleration

The accelerations from impacts in waves are not linearly dependent upon wave height. As a consequence, the linear superposition techniques developed for seakeeping analysis of displacement ships are not applicable to planing hulls at high speeds. Model tests must therefore be carried out in irregular seas. Based on Fridsma’s analysis of model tests in irregular waves, the average impact acceleration at the center of gravity of a planing hull operating in irregular head seas having a Pierson-Moskowitz spectrum, can be represented by the following empirical equation [7]:

\[
\bar{a}_{CG} = 0.0104\left(\frac{H_{1/3}}{b} + 0.084\right)^{\frac{5}{3}} - \beta (V_K/\sqrt{L})^2 (L/b)/C_a
\]

where:
- \(\bar{a}_{CG}\) = average center of gravity acceleration, g’s
- \(H_{1/3}\) = significant wave height, ft., (average of \(1/6\) highest waves)
- \(\tau\) = equilibrium trim angle, deg
- \(\beta\) = deadrise angle, deg
- \(V_K\) = speed, knots
- \(L\) = load waterline length, ft
- \(b\) = beam, ft
- \(C_a\) = beam loading coefficient, \(\Delta/\rho b^3\)
- \(\rho\) = weight density of water, lbs/ft³

The average 1/Nth highest acceleration, \(\bar{a}_{1/N}\), is related to the average acceleration \(\bar{a}\):

\[
\bar{a}_{1/N} = \bar{a} (1 + \log N)
\]

Therefore, the 1/3 highest and the 1/10 highest are, respectively 2.1 and 3.3 times the average acceleration.

The limits of applicability of these empirical equations are identified in Reference [7].

Several interesting and useful design conclusions result from an examination of the impact acceleration equation. All other conditions being equal:

1) The impact accelerations are linearly dependent upon equilibrium trim angle. Hence, they are easily reduced by a reduction in trim angle through the use of ballast transfer or trim flaps.
2) The impact accelerations for equal trim angles are inversely proportional to the deadrise angle—large increases in deadrise result in large decreases in impact acceleration.
3) The impact accelerations vary inversely with beam loading coefficient \(C_a = \Delta/\rho b^3\) or as the cube of the beam. Thus, even a 10-percent decrease in the beam is expected to reduce the accelerations by nearly 30 percent. A recent planing hull design incorporated a double chine hull as shown in Figure 14. The upper chine provided the beam necessary for roll stability at low speed and the lower chine, which caused flow separation during the impact process, provided the narrower beam desirable for reduction of wave impact loads. Full scale test results for the hull form were presented by Blount and Hankley [10].
4) Although it appears from the impact equation that acceleration increase with increasing \(L/b\), the ultimate effect is to reduce the accelerations. Increasing \(L/b\) for a given hull displacement leads to a reduction in beam

which, in turn, increases \(C_a\) by the cube of increasing \(L/b\), thus resulting in a reduction in impact loads.
5) Accelerations are proportional to the significant wave height in irregular seas and increase as the speed squared.

Figure 15 presents a graphical representation of the trim and deadrise effects upon the 1/10-highest impact accelerations expected to be experienced by a 200-foot planing hull running at 50 knots in seas of 10-foot significant wave height. If a reduction in impact acceleration were the only operational consideration, a planing hull would be designed with high deadrise; a longitudinal weight distribution such that the craft would run at a very low trim angle; and a narrow beam to obtain a high beam loading. Unfortunately, while this combination of design and operating parameters would indeed yield small im-

Figure 14. Body Plan for Modern Double-Chine Planing Hull.

Figure 15. CG Impact Acceleration in Head Seas.
impact accelerations, it will also develop large hydrodynamic resistance and have reduced internal volume. An acceptable design must establish the best compromise between resistance, impact acceleration, and total useful volume. The technology for developing a design philosophy for such effective trade-offs is in hand.

The actual average 1/10-highest acceleration levels as a function of non-dimensional wave height obtained in full-scale trials of planing hulls operating at $F_{0} = 3$ is shown in Figure 16. The upper curve is representative of hulls with lower deadrise and beam loading—typical of planing craft designed a decade ago. The lower curve shows the trend for modern, more useful planing hulls designed with moderate to high deadrise and beam loading. It is seen that recent hull designs experience less than one-half the acceleration levels measured on earlier planing forms. For the 20-degree-deadrise hull specified on Figure 15, $H_{1/3}^{1/3} = 0.37$ and, from Figure 16 it is expected that at 50 knots, the 1/10-highest CG acceleration will be approximately 1g—a rather modest load for a 50-knot speed capability. Future seakeeping research should result in additional reductions in “g” loadings while still maintaining practical hull form.

**Speed Loss in a Seaway**

In addition to demonstrating reduced impact accelerations, it is also essential that the speed loss in waves be acceptably small. The results of recent model tests, of a hull form such as shown in Figure 14, have indicated only modest resistance increases in irregular seas. These data have been used to predict the speed loss in waves at constant power and the results are shown in Figure 17. It is seen that, for $H_{1/3}^{1/3} = 0.35$ (corresponding to a 10-foot wave for the 200-foot planing hull in Figure 15), the speed loss is approximately 17 percent. Although Figure 17 indicates only a small reduction in speed loss with increasing $F_{0}$, there are other combinations of hull loading and form which result in larger speed losses when $F_{0}$ is increased. However, for most high length/beam ratio planing hulls with moderate deadrise, the speed loss in a seaway is primarily dependent upon significant wave height, and to a much smaller extent, upon planing speed.

Relative to the effect of geometric form, it has been found from model tests that the speed loss in waves increases with decreasing deadrise angle and/or decreasing trim angle—particularly if substantial bow immersion is associated with low trim.

**Pitch and Heave Motions in a Seaway**

The pitch and heave motions in a seaway are usually largest in the displacement speed range when the wave encounter period equal to the natural period in heave and/or pitch. At planing speeds, the motions are essentially constant with speed, being approximately one-half those in the displacement speed range. For high length/beam
ratio hull forms, the pitch motions are expected to be tolerably small. Figure 18 shows the expected 1/10-highest pitch amplitude as a function of speed for a 200-foot planing hull operating in seas with an 11-foot significant wave height. These plots are based on the results of recent model and full scale tests scaled to a 200-foot planing craft [10]. It is seen that, for speeds in excess of 35 knots, the 1/10-highest pitch amplitude is only about ±3 degrees.

Roll Motions in a Seaway

Recently, attention has been paid to reducing the rolling motions of a planing craft in the preplaning range in order to provide a more stable platform for military systems and to improve habitability. The problem has been to increase the hydrodynamic roll damping which is inherently small even for hard chine planing hulls. Active roll-fin-stabilized systems have been used with good success at speeds in excess of 10 knots when roll stabilization was necessary. The effectiveness of active roll fins, whose area was approximately 1 percent of the hull waterplane area, is demonstrated in Figure 19. These results are based on recent full-scale trials for a ratio $H_b/V_{k} = 0.50$. It is seen that, in beam seas, the roll motions were reduced by a factor of 2, in bow quartering seas by a factor of 2.2, and in stern quartering seas by a factor of 4. Such large attenuations in roll improve the mission effectiveness and the crew's efficiency. The speed loss due to the added drag of the roll fins is easily accepted in light of the added stabilization and comfort they provide. Also, at planing speeds, the fins can be retracted to eliminate this appendage drag.

Habitability

Criteria for evaluating the effect of ride quality on the performance effectiveness of crew members in high speed marine vehicles continue to be reviewed but, as yet, there is no agreement on any one standard. For the purposes of this paper, reference is made to the International Standards Organization standard reported in MIL-STD-1422B and by Von Gierke. This criterion uses vertical accelerations and frequencies of occurrence as a measure of human tolerance. Criteria are shown in Figure 20 where curves of 1/3-octave RMS g's are plotted against center frequency of the 1/3-octave bands for tolerance levels corresponding to 1, 2.5, 4, and 8-hour durations. The ISO standard is for center frequencies greater than 1 Hz and corresponds to levels of fatigue-decreased proficiency. Von Gierke's criterion is for center frequencies less than 1 Hz and corresponds to 15-percent motion sickness incidence.

Superposed on this curve are measured acceleration levels for a high length/beam planing hull of moderate deadrise operating at speed/length ratios of approximately 2, 3, and 4 in an irregular wave having a significant wave height of approximately 30 percent of the hull beam. It is seen that, using these criteria, the accelerations encountered at high speed indicate a tolerable ride up to 4 hours duration. This evaluation is substantiated by personnel aboard even though observers not on the boat felt the visual appearance including the flying spray indicated a rough ride.

DIRECTIONAL STABILITY/MANEUVERABILITY/CONTROL

Directional stability, maneuverability, and control have received little research attention during the entire period of planing hull development. There have been rotating arm tests on specific hulls to enable performance
predictions to be made, but, there is currently no published procedure for estimating the hydrodynamic derivatives required for a reliable prediction of coursekeeping stability, longitudinal stability, and turning.

In the low speed range, the craft may be statically unstable on course because the bow has not yet trimmed up. However, with active rudder control, it can be made dynamically stable. In the planing speed range, when the craft has positive trim, it usually has static and dynamic stability. If instability does exist at planing speeds, it is easily eliminated by increasing the skeg area at the expense of a minor increase in drag.

At very high planing speeds the trim decreases so that portions of the convex bow become exposed to high water velocities. If the convex geometry of the bow (both transverse and longitudinal) is severe, large negative pressures will develop and possibly result in roll and/or yaw instabilities. In some instances the judicious placement of longitudinal “spray” strips may correct the problem, but this is not always the case.

Directional control rudders, either mounted flush under the hull bottom or stern-mounted in a surface-piercing position, are of such size and vertical location as to develop adequate coupled yaw and roll moments to cause the boat to heel into the turn and are located in the wake of the propellers whenever possible. High speed turning diameters are in the order of 10 times the boat length and are mainly dependent on the rudder characteristics. In the displacement speed range, the turning diameters are considerably less—especially for twin propeller installations where asymmetric thrust can be used to assist turning. An important hydrodynamic consideration in rudder design is the avoidance of cavitation and ventilation of these control surfaces if high speed tight turns are to be achieved. Chord-wise fences on the stern-mounted rudders can prevent ventilation. Cavitation inception is delayed to higher speeds by the traditional means of reducing rudder thickness and lift coefficient.

Because of the usual roll-yaw moment coupling, a roll bias due to unbalanced engine torque on narrow beam planing hulls can require some rudder deflection in order to keep the boat on straight course. The addition of a fixed trailing edge tab on the outboard edge of the transom will provide a roll moment to counter this engine torque, avoiding the necessity for rudder deflection to maintain a straight course.

Longitudinal instability (porpoising) has not been a serious problem. If it does occur, it can be corrected by means of trim flaps which reduce boat trim or forward movement of the center of gravity which also causes the boat trim to decrease.

### Propulsors

Given the option to select an optimum thruster, one will find a preponderance of fixed-pitch conventional-section propellers on most craft operating up to speeds of 35 knots. However, above speeds of 30 knots the trend is to use cambered section blades with transition to supercavitation sections at about 40 knots and above. The majority of applicants utilize these fixed pitch propellers on inclined shafts with maximum shaft angles of 15 degrees in low speeds and 10 to 12 degrees at 40 knots. Some newer designs of very high speed craft utilize right angle (inboard/outboard) drives or surface propellers. Many of the right angle drive units are installed so as to permit the propeller to operate in a surface mode. Experimental data indicate that above 30 knots, a 10 to 15 percent increase in speed is normal by changing from a submerged propeller to a surface propeller with no other changes. It can be projected that surface propellers will become commonplace as the drive system mechanism becomes more reliable.

Although a number of other propulsor types (i.e. ventilated propellers, partially-submerged propellers, waterjets, etc.), do offer some promising performance features, their application to planing craft has been limited so that operational experience is also limited.

### Subcavitating Propellers

Conventional subcavitating propellers of commercial manufacture are most commonly used on planing craft up to speeds of approximately 30 knots. Above 30 knots, these propellers have had serious erosion problems. Through custom design and close tolerance manufacturing the useful speed of these propellers may be increased to approximately 35 knots.

Propeller characteristics are obtained from standard series propeller charts, such as the Gawn-Burrill series [11]. This series covers a range of blade area ratios and pitch-diameter ratios for a series of cavitation numbers.

The developed blade outlines are of elliptical shape and the sections are ogive (flat face, circular-arc back, and sharp leading and trailing edges). While demonstrating good performance characteristics in the fully wetted condition, these sections sustain serious thrust breakdown and losses in efficiency when cavitation occurs. Figure 21 demonstrates the thrust breakdown for expanded blade-area ratios of 0.50 and 0.80 for cavitation numbers down to 1.0 (28 knots). It is seen that large propeller diameters and large blade-area ratios are required to reduce the propeller loading ($K_p$) and, hence, delay thrust breakdown at high speeds. This is an impractical solution for the designer since struts, low RPM, and large reduction gears are required, especially if a gas turbine power plant is used.

The Gawn-Burrill series test data do not extend to design speeds beyond 38 knots. However, as indicated by DuCane, it is believed that, even for the highest blade-area ratios, cavitation will no longer be avoidable and severe thrust and torque breakdown accompanied by efficiency losses will occur, spreading gradually to higher advance ratios (lighter propeller loadings) with reduced propeller cavitation numbers.

### Fully-Cavitating Propellers

Since planing hulls often operate at speeds in excess of 35 knots, propeller cavitation will be unavoidable. For-
Fortunately, there is a propeller series available which is designed to accommodate cavitation without the serious performance deterioration associated with the ogive propeller. This is the Newton-Rader [13] propeller which has cambered sections such as shown in Figure 22. For typical advance ratios at design speed, the propeller develops a cavity which extends over more than 85 percent of the blade surface and beyond the trailing edge. They are frequently referred to as “fully-cavitating” or “transcavitating” as distinct from the supercavitating propellers. Figure 23 compares the efficiencies of the Gawn-Burrill and Newton-Rader propellers at a cavitation number of 0.50. At the usual design values of advance coefficient $0.7 \leq J \leq 1.0$, the shaded area represents the gain in efficiency associated with the Newton-Rader propeller. At $J = 0.80$, for example, there is a 22-percent gain in efficiency even though the blade-area ratio of the Newton-Rader propeller is only two-thirds that of the Gawn-Burrill propeller. Further, there is no significant compromise in efficiencies at low speeds when the propeller is fully wetted.

The use of a fully-cavitating propeller permits an increase in loading, resulting in smaller propeller diameters and higher RPM. Although this usually causes a reduction in propeller efficiency, the overall propulsive coefficient (OPC) may actually increase due to the reduction in appendage drag associated with reduced shaft angle and shorter strut lengths. In addition, there should be a weight reduction associated with smaller reduction gears, propellers, shafts, etc.

Figure 21. Cavitation Characteristics of Gawn-Burrill Propeller.

Figure 22. Blade Sections for Newton-Rader Fully Cavitated Propeller.

Figure 23. Comparison of Gawn-Burrill and Newton-Rader Propellers at Low Cavitation Number.

---

Naval Engineers Journal, February 1985
Most Newton-Rader propellers installed on fast patrol boats have been constructed of high-tensile, nickel-aluminum bronze; have had blade-area ratios of approximately 0.7; and a working stress level of less than 15,000 psi. This compares with 80,000 psi ultimate tensile strength of the material. Blade erosion has been minimal even for extended service at speeds up to 55 knots. The American Bureau of Shipping has certified a Newton-Rader propeller designed for a high speed planing yacht. These propellers have been fabricated by foundries that normally produce small boat propellers in large quantities. The price has been very modest. Design procedures useful in selecting the optimum Newton-Rader propeller are given by Blount and Hankely [10].

**Propulsive Coefficients**

Propulsive data, the transfer functions which describe hull-thrust interrelations, are essential for accurate speed-power predictions. Hadler and Hubble [14] developed and presented analytical models for propulsive data for single, twin, and four screw planing craft as a function of shaft angle. These data agree very well with a collection of model and full-scale experimental propulsive data reported by Blount and Fox [15].

Reference [15] relates to conditions of minimal propeller cavitation. The quantitative effects of cavitation on propulsive data are ill-defined although it has been observed that for cavitation numbers less than 1.7, cavitation effects are important modifiers of propulsive data and correlation factors so that full-scale speed-power performance will be less than predicted when neglecting cavitation. For the cavitated case, the required power should be calculated by the methods described by Blount and Fox [15] along with correlation experience reported by Blount and Hankley [10].

**Hull Shape Details**

Having described the effect of major hull proportions, loading, speed, etc., on the planing craft behavior, it is now of some interest to discuss hull shape details and their evolution over the years.

When planing speeds became possible around the turn of the century, due to the introduction of higher horsepower lighter weight engines, the hull form of the typical small launch evolved quickly from that of a rowing or sailing craft toward one with a broad stern and straight after buttocks. These characteristics kept the stern from “squatting,” making higher speeds possible. But spray was a problem because a sheet of water would run well up the side before separating from the hull. For many years this was not only accepted but considered smart; more than one advertiser proudly pictured his craft racing along “with a bone in her teeth.” The disadvantages of this phenomenon, i.e. deck wetness, increased resistance, and instability (in roll, pitch and yaw), were occasionally recognized over the years and attempts were made, sometimes successfully, to solve them by the application of spray rails. Correctly placed spray rails are indispensable in the design of high speed round bottom boats because they provide for the flow separation which is necessary at the boundaries of a planing surface.

In parallel with the development of the high speed round-bottom boat was the development of the high speed vee-bottom boat. The vee configuration, especially in the favored form with rather low deadrise and hollow sections, inherently provided for flow separation and good lift, but the characteristics which provided good lift in smooth water provided a hard, pounding ride in rough water.

Both round bottom and vee bottom boats retained a high length/beam ratio into the twenties. However, starting in the thirties there was an accelerating trend toward greater beam, primarily for reasons of increased internal volume and greater stability to carry the tophamper associated with increased cruising accommodations. Typical round bottom and vee bottom hull forms of the fifties are shown in Figures 24 and 25 respectively.

In due course many other hull forms were tried; for example, inverted vee, inverted vee with beveled chines, a W-shaped bottom, inverted bell sections, the so-called cathedral hulls, and many complex variations. Examples of all these are still being built. However, it is interesting to note that those designers and builders who observed
their designs carefully and made improvements with each successive model are developing their designs along converging lines. As round bottom hulls were developed for greater speed and as vee bottom and cathedral hulls were developed for better seakeeping, they all tended to converge toward the same general hull shape, an example of which is shown in Figure 26, depicting a design of the sixties.

The incorporation of high deadrise was a major breakthrough in planing boat design. This took place in the 1950s when the first “deep vee” was built. An approximation to the body plan of this boat is shown in Figure 27. Prior to this, designers generally believed a boat had to be flat to plane although sea plane model data to the contrary had been available for decades. Another belief then current and still held by many is that, for good planing efficiency, the deadrise should be constant, that is, the hull should be a monohedron. Indeed, the “breakthrough” boat shown in Figure 27 is a monohedron. But, any monohedron can be improved because, for good seakeeping and handling, the amount of deadrise desirable in the bow is greater than that required at the stern, and the resistance penalty for a moderate amount of warp in the bottom is small, if any. In addition, too much deadrise at the stern reduces transverse stability, both at rest and when planing.

When comparing the relative merits of round and vee bottom boats it should be noted that some well-known studies have come to false conclusions because they compared a good design of one type with a poor design of the other type. It is important to point out that with proper sections and with spray rails for effective flow separation, a round bottom boat can be designed for both good rough water performance and good planing performance. In the same way, when the sections of a vee bottom boat are developed for good seakeeping and spray rails are located for good flow separation, it will be very similar to the highly developed round bilge boat. In particular, one type does not necessarily need more deadrise than the other.

**Design Techniques**

Although the design of planing hulls rests on a preponderance of science it still requires some intuition. A good example is the calculation of hydrodynamic performance in smooth water. The optimum planing surface to carry a given load at a given speed can easily be calculated. The problem for the designer is that the lowest resistance planing surface is always too wide for its length to be practical, and too small to be either useful or stable. The utilization of very efficient planing surfaces requires the use of more than one such surface per vehicle, spread out either laterally for roll stability as in the catamaran or longitudinally for pitch stability as in the stepped boat, or both. The higher the speed the more specialized the design must be. Currently the ultimate seems to be a modern development of the hydroplane (invented many years ago) which rides on small areas of its sponsons and is balanced in pitch by riding on the propeller. At top speeds of over 150 mph and frequently over 200 mph, aerodynamic forces aggravate the already severe stability problems. Rough water operation is out of the question. In the design of boats of this type intuition coupled with experience predominates, but it is only in these extreme designs that highly efficient planing surfaces can be utilized. In some cases, efficient planing surfaces can be further improved by cambering their trailing edges. Cambering, which is amenable to calculation, increases the average pressure under the surface and thereby reduces the wetted area.

The point here is that boats (usually monohulls) which are intended for purposes other than racing must be artfully designed with greater length and beam than would be possible with the optimum planing bottom. This usually causes them to run at lower trim angles and have greater wetted areas than optimum. Whereas a perfectly flat surface is most efficient, some deadrise is required to provide good banking in turns, and a great deal more is required for good rough water ability. The way in which the intended service of the craft influences the choice of hull characteristics, and hence the possible technological advancement, will now be discussed:

**Craft Types, Their Limitations and Capabilities**

Each craft type, taken here in the four broad categories of pleasure cruisers, ocean racers, crew boats, and patrol
boats, has certain limitations that define the state of the art. Principal among these is rough water capability. In the case of pleasure cruisers the conflicting requirements among which a compromise must be reached are these: it is necessary to maximize the accommodations (volume) for a given length. This dictates a wide, deep boat, and many pleasure boats tend in this direction. But, for good seakeeping the hull should be long and narrow and because of stability requirements, the narrowness dictates that the boat must be low. For reasons such as this the cruising types, however comfortable and/or profitable they may be, do not define the state of technology for planing hulls.

Ocean racers seem to be locked into a single type of deep vee hull with virtually constant deadrise. However, they have brought about great advances in the design, construction, and installation of equipment and fittings suitable for use in such a rugged, high “g” environment. The limitation now seems to be the amount of punishment the crew is willing or able to take.

The hull form of crew boats has likewise become quite standardized. It is usually an approximately developable shape with moderate deadrise and somewhat more variation of deadrise with length than seen in ocean racers. Practical considerations such as cost of acquisition and operation limit the size (power) of engines and hence the speed of the boat. In most cases the actual speed of operation is about 25 knots and it is seldom over 30 knots. Therefore, crew boats do not define the state of technology for planing hulls.

The most significant advances in the hull form of planing boats have been made in the design of naval patrol boats. These applications require moderately high speeds (although not as high as those of ocean racers) and the ability to maintain these speeds in water rough enough to cause the postponement of an ocean race. The hull form that was considered best for this purpose in the 1970s was simply a logical extension of the trends described in the history given earlier. This design, shown in Figure 14, incorporates features of both Figure 26 and Figure 27. The double chine, evident in the afterbody, is not an essential feature of the concept but facilitates the incorporation of several other features. This design has excellent seakeeping characteristics and good resistance characteristics. Recently a hull has been designed and model tested which not only has low vertical accelerations in rough water but which also has low resistance over the speed range. This is shown on Figure 28.

The model test revealed one area in which improvements can be made. It was observed that the exceedingly fine bow knifed into the water so easily that wave impact occurred, not on the bottom but under the topside flare. The fineness of the bow also necessitates greater freeboard than normally expected. The obvious development is to make the sections a little fuller so that when pitching into a wave there will be two light impacts rather than one larger one (even though in this design the single larger impact is much less than that experienced by the average planing boat). The question is whether or not these changes can be made without impairing the resistance characteristics which are probably due to the fine bow.

Figure 28. Recent hull design with both low vertical accelerations in rough water and low resistance over the speed range.

**Hull Form Development**

The concomitant characteristics of a fine bow and a relatively far aft location of the center of gravity brings up a problem with planing boat stability which is not yet fully understood. There seem to be two distinct cases. One, involving only transverse stability, was encountered as early as the 1950s. The other, which has only come to light in the last decade (except for some round bottom boats), involves both transverse and longitudinal stability. It is exhibited, as far as is known, by boats with centers of gravity unusually far forward and which have, consequently, very full waterlines and large longitudinal buttock curvature at the bow.

The former case seems to involve too much deadrise at the stern and too high a center of gravity. When a boat becomes unstable in this mode it usually just lies over until it planes stably on one side of the bottom.

The latter case is more serious because a boat, apparently planing stably in a normal attitude, may unexpectedly drop its bow to about zero trim and then, just as suddenly, roll over on its side and/or develop a yaw. At this writing the phenomenon seems to be due, at least in part, to extreme convexity of the waterlines and buttock profiles at the bow. Because so little is known about this problem it will only be said that this is a fertile field for experimentation and research.

**Structure**

**Structural Loads**

The most severe loads on a planing boat are the loads on the hull bottom due to the combined effects of the advance of the boat into waves and the heaving and pitching motions. The resultant pressures are called impact pressures. The maximum pressure of each impact exists only momentarily and over a small portion of the hull bottom. The location on the hull, the size of the area affected and the magnitude of maximum impact pressure vary with each wave encounter. A typical impact pressure distribution on a hull bottom is shown in Figure 29—note the very large peak pressure and the small area over which it acts. Thus, the average pressure over large areas...
It appears, however, that the Heller-Jasper method is the most favored. In general maximum impact pressures are encountered in the area from approximately 0.3L to 0.5L aft of the bow and to approximately 50 percent of their maximum at the bow and 25 percent at the stern.

Several well-proven methods are available to predict the bottom loads on planing craft. The work of Heller-Jasper [16] and Allen-Jones [17] yield bottom design pressures based on known craft impact accelerations. Spencer's [18] work, which deals exclusively with aluminum crew boats, gives bottom design pressures based on typical crew boat performance and dimensions. These local bottom loads are more critical in design than overall bending loads. Longitudinal hull bending moments can be estimated using the work of Heller-Jasper. Design loadings for the remainder of the structure (hull sides, decks, bulkheads, superstructures, etc.) are normally based on hydrostatic heads. Spencer's work provides a useful summary of these loadings. U.S. Coast Guard Navigation and Vessel Inspection Circular No. 11-80, provides guidelines for loadings on aluminum passenger vessels having deep-vee hull forms, lengths from 60 to 130 feet, and speeds up to about 25 knots.

Classification societies' procedures are not based on loadings for the specific craft and usually result in heavier structures when compared with the "tailored" design procedures described above.

It is not to be concluded that there is universal agreement on the magnitude and distribution of pressures to design planing hull structure-components. Most designers tend to use methods with which they have had success. It appears, however, that the Heller-Jasper method is the most favored.

**Structural Design**

The structural design of planing craft is a very straightforward procedure. Suitable materials are available, design tools are at hand, and successful examples abound. A conventional planing craft can be constructed successfully from any of the recognized structural materials (aluminum, steel, wood, composites). Ideally, the special qualities of the material selected should match the special requirements of the craft in question. Since most planing hulls are designed by the builder, the selection of material is heavily influenced by the builder's facilities and capabilities.

Once design loads are determined, the analysis of the structure of a planing craft is a matter of recognizing the limitations of the selected material and using good engineering practice. It is important to consider all loads, identify all load paths and check the associated stresses and deflections to ensure that the structure is adequate but not overdesigned. When determining the characteristics of the major structural units (bottom, side, deck, bulkheads, superstructure) it is important to consider the structure as a whole and to provide structural continuity so that loads and stresses are transmitted and distributed smoothly throughout. In the process, it is often possible to simplify the structure by reducing the variety of structural components and by spacing them uniformly. This makes it easier to order materials and prevents many construction mistakes.

Since local loadings are usually more critical for planing craft than overall bending loads, it would appear that structural weight can be reduced by using small panels and thin plating. Such an approach can lead to a complex structure with many parts which is expensive to fabricate. This trade-off between cost and weight is difficult to evaluate accurately. It is usually resolved by considering shipyard capabilities and designing the lightest structure which the builder(s) involved can fabricate using existing techniques.

A comparison of structural weight versus overall length as a function of hull material was made by Sharples [26] where it was shown that the steel hulls are substantially heavier than aluminum hulls. Their use is, of course, justified based on lower cost and their fire-resistant qualities.

Based upon a survey of existing boats, it appears that the methods for selecting design loads and the materials used in construction are related to the displacement and speed of the craft. Figure 30 provides some empirical boundaries. It is seen that, for relatively low displacements, the GRP material is most commonly used. For displacements between approximately 45 and 100 LT and less and speeds in excess of 25 knots, aluminum is the preferred material. For larger displacements, steel is the most common material.

It is important, in the early stages of any design, to coordinate the structural arrangement and the general arrangement of the craft. This minimizes structural weight and enhances structural continuity by incorporating the main propulsion and armament foundations as well as tank bulkheads into the primary structure of the craft. It also reduces the number of non-structural bulkheads. It is also important to minimize the total enclosed volume.
with the limits of space and subdivision requirements. This helps to reduce not only structural weight but also
the weight of other systems (piping, wiring, HVAC, etc)
which are volume related.

While adequate methods for estimating design loads
are available, it would be of great value to have a method
of predicting design pressure distributions which takes
into consideration the local geometry of the craft. As
planing craft become larger (L/B increases) overall bend-
ing loads will become more critical. More data are
needed to help evaluate the loads. Advances in composite
materials, particularly for non-cored materials, offer op-
portunities for significant structural weight reductions.
The challenge here will be to effect these improvements
at reasonable cost.

As to the loadings commonly used, the smaller craft
generally use "rules of thumb" which have been devel-
oped empirically over the years to the point where the
number of failures has reached an acceptable level and
must be considered good design for the craft to which
they are applicable. The high speed boats must rely more
on experimental data and empirical design methods such
as Heller-Jasper, Jones-Allen and Spencer. These meth-
ods should produce good-to-excellent results. For the
higher length and tonnage, standard naval architectural
practices such as those of the classification societies will
be adequate as long as high speed (30+ knots) and severe
structural weight fraction restrictions are not required.
Otherwise use must be made of experimental data and
analytical methods.

USEFUL LOAD FRACTIONS

The trends for useful load fraction as well as weight
fractions for structure, machinery, and other fixed
weights for four existing planing hulls are shown in Fig-
ure 31. The term useful load includes military payload,
ship fuel, potable water, ship's complement and effects,
and stores. It is seen that useful load fraction increases
with displacement so that, extrapolating to 600 tons, the
useful load can be as large as 45 percent of the full load
displacement.

SURVIVABILITY

Survivability of planing craft can best be described as
the capability of the boat to endure and remain afloat
after exposure to a variety of predictable perilous situa-
tions such as extreme sea states, damage by fire, hostile
action, underwater explosion and structural damage.
The features of hull design which influence seakeeping
have already been discussed and model tests are an ac-
cepted method for evaluating survivability in extreme
seas. Weapons attack includes missiles, medium and
small caliber projectiles and, in the case of riverine craft,
small arms fire. Damage can also come from blast bombs
and underwater explosions.

As previously stated, the design of high performance
 craft is usually governed by operational considerations of
power, speed, range and payload. Naval architects and
designers are faced with having to choose power plants
and propulsors as close to model test and calculated re-
sults as possible. This means that power margins of 35 to
50 percent used in big ship design are not feasible for
high performance craft. Therefore, in many cases, sur-
vivability considerations become secondary. Neverthe-
less, a hazard analysis should be conducted as part of the
design effort with trade-offs and compromises docu-
mented.

Specific features which contribute to the survival of
craft are:

a) arrangement of vital systems
b) structural protection
c) damage control
d) compartmentation
e) ordnance stowage

Arrangement of vital equipment and systems should be
such that parallel equipment is located in compartments
as far from one another as practical to preclude the pos-
MODERN SHIPS & CRAFT

sibility of flooding adjacent compartments and destroying an entire system when the craft is hit by weapons fire or underwater explosion. If separation is not possible and an armor material can be used, then the equipment should be centralized. This centralized compartment should be sheltered behind as much armor and non-vital equipment as possible.

Structural protection would require the use of heavy ballistic armor, watertight and fire resistant bulkheads and damage tolerant primary structures. Ballistic protection against large weapons would be prohibitive because of the weight penalty, but watertight and fire resistant bulkheads are usually part of the design from the beginning and are therefore available for structural protection.

Damage control is designed into the craft with the use of systems such as damage repair equipment and stowage; shock mounting of equipment; bilge pumps; fire detection and extinguishing; and counterflooding. Normal practice by the U.S. Navy in small craft design has been to provide damage control equipment and stowage according to set rules. Delicate equipment is shock mounted according to equipment manufacturers instructions. Fire detection and extinguishing systems are sized and installed in conjunction with compartment use and size, with Halon being the most prevalent extinguishing agent. Flooding capability is usually limited to the forepeak and compartments with longitudinal watertight bulkheads.

Compartmentation is used to meet stability criteria and as part of damage control. Present criteria set a two-compartment standard of subdivision which requires that the floodable length be great enough to allow any two adjacent compartments to be flooded without loss of the craft due to foundering, and, in addition, that the craft retain sufficient stability in the damaged condition to keep the final hull trim angle within defined limits.

Ordnance stowage should be in compartments below the waterline as far as practicable. This becomes more difficult the smaller the craft becomes.

In conclusion, adequate survivability is difficult to design into small, fast combatant craft. All of the factors should be weighed and as much as possible should be incorporated into the design from the beginning. These craft will not accept heavy weight penalties, therefore, it challenges the naval architect and designers to incorporate innovative ideas to ensure survivability.

PRODUCIBILITY AND SUPPORTABILITY

The technology for constructing metal and fiber reinforced plastic planing hulls is well advanced and has been successfully applied. A summary of some of these construction techniques and the supportability of crafts constructed of these materials is discussed below:

Aluminum Hull Construction

Aluminum is an ideal material from which to construct fast patrol craft because it is readily available and easily fabricated into strong, lightweight structures without the need for exotic assembly techniques. Aluminum is homogenous, has omnidirectional strength characteristics, is highly corrosion resistant, is easily formed and joined, and can be assembled into hulls without the necessity for expensive tooling. If production volume warrants, very effective labor-saving techniques and equipment are available which can greatly decrease the manhour content of the end product. In sheet or plate it can easily and quickly cover large hull surfaces. The internal stiffening structure may be varied in size and location depending on craft configuration and service. Because of its formability, weldability, and easy handling properties, very complex hull forms can be produced.

Welding is one thing; welding aluminum is something else again, and welding an aluminum boat is an art and skill strictly unto itself. A great deal of training is necessary if one is to become a skilled aluminum shipyard welder. The availability of reliable, compact welding equipment was, more than any other factor, responsible for the growth of the aluminum boatbuilding industry. Welding has now reached a very high level of development. The latest "pulsed arc" equipment enables high quality welds on lighter gage sheets than had been possible previously. As technology proceeds at its present rapid pace, it is expected that even more efficient welding methods will be used. High frequency and electron beam welding processes are two which are presently being developed.

By far the most reliable method of inspecting welds is by x-raying (radiography). Just to say that a weld shall be "x-ray quality" is meaningless; the standards to which the x-rays are to be inspected must be clearly specified. The classification societies all publish such standards.

Where x-raying is not feasible, dye penetrant inspection may be used for surface defects. A dye is brushed over the welded area, then the excess wiped off. The dye is usually a fluorescent color or is visible under "black light," readily revealing surface irregularities and cracks. A major problem with dye penetrant inspection is that all traces of the dye must be removed before any subsequent welding is done, and it will bleed through paint.

A skilled weld inspector can tell by the visual appearance of welds whether any of the common superficial defects exist, such as undercuts, cracks, arc strikes, cratering, cold laps and surface porosity. Welds should be regular, uniform and have proper crown or contour.

The aluminum companies and welding equipment suppliers are valuable sources of information and guidance which should not be overlooked by those involved in aluminum design, fabrication, and maintenance. The vast array of alloys, hardnesses, sheet and plate thickness and widths and special extrusions which were offered by the aluminum companies just a few years ago are no longer economical to produce. The industry in the U.S.A. has basically standardized on alloy 5086 sheet and plate for marine applications.

The basic methods of cutting aluminum are shearing, sawing, and plasma cutting. Shearing and sawing are normally employed by shipyards of all sizes with well known procedures and equipment.
The plasma cutting process was developed in 1955, but has come into widespread use only recently. Plasma arc cutting heads for "electric eye" burning machines can cut stainless steel and other metals as well as aluminum. Far more exotic cutting machines with multiple-head torches, controlled by numerical tapes developed from computerized lofting, are also becoming very widely used in boatbuilding. Using plasma arc with numerical control, burning speeds on the order of 180 to 240 inches per minute (4½ to 6 meters/minute) are possible, and an excellent quality of cut is obtained.

The basic forming processes employed in boat construction include rolling, progressive bending, flanging, and forming or straightening shell plates or panel assemblies on a bumping or forming press.

For commercial and military craft, the longitudinal framing system is most often used. Here, the principal shell stiffeners are disposed longitudinally and are supported by transverse web frames and bulkheads. Longitudinal framing usually results in a stronger, fairer hull which requires fewer manhours to build than does one which is transversely framed.

Some builders use the floating frame system, where the transverse web frames do not directly contact the shell plating, instead supporting the shell longitudinals only. Other builders favor the "deep web" system, where the web frames are notched to pass the longitudinals, or the longitudinals are intercostal to the webs. For simplicity in fabrication, uniform web frame space is generally used.

Aluminum boats normally incorporate two types of longitudinal framing: primary shell stiffeners and deep longitudinal girders which (a) support the loads of main propulsion engines, fuel tanks and strut legs, and (b) afford additional hull girder stiffness.

Longitudinal shell stiffeners may either continue through watertight bulkheads and/or frames or may be intercostal. The effort required to fair a longitudinally framed hull where the longitudinals pass through the bulkheads is considerably less than with intercostal longitudinal framing, and there is no chance of misalignment on opposite sides of the bulkhead or web frame. However, many yards find it easier to form and handle the shorter intercostals.

Shell plating can be installed in single sheets from keel to chine and chine to shear for smaller craft, but straking is necessary in the larger sizes. Aluminum plate is economically available in the U.S. in widths up to about 96 inches. Beyond that, there are considerable delays in rolling and shipping, and premium prices must be paid.

Inverted Construction

It is most efficient to construct an aluminum hull through the shell plating stage in the upside-down position. In this way, transverse and longitudinal framing can be set up and shell plating can be wrapped around the hull unobstructed by supporting structure. Gravity will help with the plating job, external shell seams can be welded flat, and there is far less accumulation of debris inside the hull.

Once the hull is welded, either before or after installation of the deck, it can be rolled over to an upright position using either trunnions welded or bolted to the ends of the hull or nylon straps or cables wrapped around it.

There are several systems of supporting the hull structure in a jig during fabrication. These include:

Ladder Jig: Transverse frames are clamped or bolted to steel uprights which accurately locate the web frames and bulkheads and (in some cases) longitudinal girders. The jig uprights normally support the frame floors and horizontal cross bars support the upper ends of the frames near the sheer. The jig is arranged so that adequate clearance is provided between the sheer of the boat and the shop floor to permit easy access of workmen. A disadvantage of this fabrication technique is that considerable overhead clearance is required to lift the hull clear of the jig.

Grid Jig: A variation on the ladder jig which consists of a series of flat bars standing on edge and spaced at the transverse frame spacing of the hull. Extensions of the transverse frames above the sheer, or separate temporary extensions welded to the frames, are then bolted to the flat bars, after they have been aligned on the vertical and longitudinal reference centerlines. If the hull has a sheer bar and a straight sheer, the jig can be even simpler; just a large flat plate.

Deck Jig: Another very practical jig consists of an inverted framework to support the vessel's deck: either a series of transverses or longitudinal sets at the proper camber and sheer, or both. Deck plating is first welded together (using automatic equipment if available), then trimmed to the plan of the deck. Deck stiffeners are installed, then the transverse bulkheads and web frames are erected on the deck itself. Temporary bracing is used to hold frames plumb and in the correct lateral alignment.

Combinations and Variations: In a production setup, it may be most efficient to employ separate jigs for the construction of decks. After the hull is turned over, the deck assembly is mated to the hull.

Upright Construction

Some builders have successfully employed upright construction whereby a bottom frame grillage subassembly is constructed, then dropped into the shell plating which is supported by a female or pin jig. With a shallow hull where the bottom can be a separate subassembly this method may have merit.

Subassemblies

The higher the production rate, the greater the demand for breaking work down into small units. It is desirable to shop-fabricate as many hull components as possible into modules or subassemblies and then bring them together at the point of assembly. Items which lend themselves to shop or bench fabrication include struts, shaft logs, transverse frames, bulkheads, engine foundations, transoms, keels/stems, skegs, deck fittings, deckhouses,
MODERN SHIPS & CRAFT

consoles, boarding platforms, tanks and the like. Economies effected by these means generally are reflected in greater values to the buyer.

There is very little justification for building aluminum hulls in more than one module except in the much larger sizes, i.e., above 150 feet.

FIBERGLASS REINFORCED PLASTIC (FRP)

Fiberglass, or more specifically fiberglass reinforced plastic (FRP), is the most popular material for planing boats today. FRP offers ease of construction by semi-skilled labor, durability (including complete resistance to corrosion), relatively light weight, and reasonably low material cost.

The most common materials for FRP construction are:

- **Reinforcement** — Fiberglass mat consisting of randomly oriented short glass fibers rolled together in a felt-like mat, weight is specified in ounces per square foot and common weights are 1 oz psf, 1 1/2 oz psf and 2 oz psf; fiberglass roving which is a coarse woven material using flat bundles of glass fiber strands for both warp and fill, weight is specified in ounces per square yard and common weights are 18 oz psy and 24 oz psy.

- **Laminating resin** — The most common are isothalic and orthothalic polyester resins pre-pregnated with copper naphthanate and catalyzed with methyl ethyl ketone peroxide. Most commercial construction employs general purpose (non fire-retardant) resin whereas military and commercial hulls subject to USCG inspection use fire-retardant resins. Fire-retardant resins cost approximately 1.5 times that of general purpose resins.

- **Core materials** — The most common are polyurethane foam, polyvinyl chloride foam, end grain balsa wood and douglas fir plywood. Densities used vary from 6 pcf to 30 pcf.

There are some materials less commonly used but gaining acceptance to reduce weight and/or to increase strength. Usage is limited to date because they are considerably more expensive and less understood. These include:

- **Vinylester laminating resins** — Provide considerably greater strength after prolonged immersion in water and are therefore attractive for use in the submerged portion of hulls. Its use permits reduction in scantlings therefore reducing weight. Cost is less than 2.5 times that of non-fire-retardant general purpose polyester resin.

- **Non-woven reinforcement materials** — Provide higher reinforcement content inasmuch as the bundles of fibers are not woven together and there is less space per ply to be filled with resin yielding low resin content ratio laminates. Some non-woven reinforcement materials are unidirectional and are used where strength is required in only one direction thus saving the weight of the unneeded fill yarns of a woven material. Multidirectional non-woven material is available in what is known as triaxial configuration consisting of three plies of unidirectional material typically with one central ply oriented with the strands parallel to the length of the roll sandwiched between plies with strands oriented plus 45 degrees and minus 45 degrees to the central ply.

- **Aramid fibers** (Dupont trade name Kevlar) — These fibers are much lighter than glass for the same strength, i.e., much stronger in tension; minor flexural strength increase, but weaker than FRP in compression. Fiber weight is approximately 42 percent lighter than the equivalent glass and laminate weight is approximately 33 percent lighter than conventional FRP. Vinylester resin is recommended for use with aramid fibers. Aramid fiber costs approximately 7 times more per pound than fiberglass.

- **S-Glass** — Conventional fiberglass is made of so-called E-Glass. So-called S-Glass is stronger but not generally available and is more expensive.

- **Carbon fibers** — These fibers are much lighter than glass for the same strength. Laminate weight reduction can be 50 percent or greater compared to conventional FRP. Carbon fiber costs are 30 times more per pound than fiberglass.

A very limited number of planing craft hulls have been built using these so called high technology materials. Some boats have used them throughout the entire structure, but more frequently they are used only for highly stressed portions. Their use not only increases material costs but also in some instances dictates more costly fabrication methods. Usage is thus limited primarily to recreational racing craft where cost is not an overriding consideration.

Construction Methods

Boat building with fiberglass is accomplished by a variety of techniques. The most popular procedure today is hand layup where workers apply and saturate layers of fiberglass material to a pre-gel-coated open female mold. Some smaller craft builders in the high volume commercial industry use chopper guns to apply a thickness of resin mixed with randomly chopped glass fibers to the same type of molds. This method relies heavily on the skill of the machine operator to maintain consistent skin thickness eliminating alternating thin spots or excessive buildup. “Chopped” hulls are not as sound or strong as those made of layered woven material. More sophisticated procedures than hand layup include resin injection molding and resin transfer molding where reinforcement is captured in closed molds and resins are injected under pressure. These techniques require more extensive and highly stiffened closed tooling or matched molds to maintain shape during resin injection. They are cost effective only when considering volumes of hundreds of parts per year. Resulting parts are usually lighter, often stronger, and tighter tolerances can be maintained.

Tooling for the more popular open mold technique is usually a female version of the part to be molded. The mold is stiffened with external ribs, frames, and often cored skins. Large hull and deck molds can be mounted in pits in the ground which allow workers to climb inside or they can be mounted in giant rollers, facilitating rotation, so workers may lay up one side at a time while standing on the floor. Costs of such special tooling run about 25 to 50 percent more than typical fixed tooling, excluding plug. Plug costs could be two to four times...
more than part cost, depending on construction technique. Some manufacturers use one-off techniques to build plugs and incorporate the tooling into a vessel, recovering the one-time expense.

Fiberglass reinforced plastic as a construction material lends itself to compound curves and complex shapes. Simple open molds require draft of 1.5 to 2.0 degrees to prevent capture of parts in the mold. Sharp corners are not practical in simple molding procedures where a minimum of 1/8-inch radius is required to allow forming reinforcement material during layup. The more exotic procedures achieve sharp corners with great expense. When parts to be built require closed sides or return curvature, as does a hull with tumble home, split molds or multipiece molds are used. These molds have bolting flanges built into mating surfaces which uncouple to allow part release.

Common lay up procedures use precut "dry" material layered in molds by hand then saturated with resin using spray guns and hand rollers. Builders of larger vessels (70 to 100 feet) make use of resin impregnators which saturate the reinforcement as it comes off the roll which is suspended over the mold. Hand work is still required to affix and deaerate the material. After saturated material is positioned in the mold, some manufacturers cover the uncured composite with a plastic sheet or "bag," seal the perimeter and draw a vacuum on the plastic. This forces air and excess resin out of the laminate. Vacuum is held until curing is complete. The disadvantage of this method is that it requires saturated material and the vacuum-bag to be in place while the resin is still in a liquid state, normally only 45 to 60 minutes. However, for a single critical layer like core material the procedure is ideal to guarantee a complete bond.

Relatively recent plastics technology includes the development of a presaturated reinforcement material which allows unlimited working time. This material, however, must be refrigerated until its use. After all laminate layers are cut and positioned in the mold, a vacuum is drawn, and the whole apparatus is wheeled into an oven or autoclave where curing begins when heat is applied. This procedure requires a sophisticated facility and materials are expensive to purchase and store.

The proper amount of heat is required for complete curing of even conventionally saturated material. Normally, multilayered laminates generate adequate heat or exotherm during the chemical reaction to effect cure. In cases where there are many layers of material (more than about six) or when a coring material is incorporated, layup must proceed in stages, allowing intermittent catalytic reaction or "kicking" to take place and exotherm to dissipate. Core material insulates and traps the heat against the mold surface. Extreme heat will accelerate the reaction in spots causing shrinkage, laminate distortion, and possible stress concentration.

Builders must cognizant of materials and procedures and plan cycle times carefully to maintain consistent quality and homogeneous integrity. Material suppliers are familiar with their products and can aid builders in proper use and procedures.

For more information on fiberglass construction techniques, see References [19] through [26].

Economics

The variety of fiberglass planing craft for commercial service is almost endless. For one-off custom configurations fiberglass lends itself to piecewise assembly and finish work. However, this approach is costly—perhaps 20 percent to 100 percent more from a labor standpoint than the premolding of parts. A rule of thumb of molding is that break-even amortization of tooling and mold occurs at six production units. Production fiberglass planing craft hulls cost between $3 and $4 per pound to produce. Approximately half the cost is material, when conventional products are used, and half is labor. Customized production can sometimes double the labor figure, not including engineering and overhead requirements to support such efforts. Conventional materials would include general purpose resins and E-type glass fiber material. Special purpose products such as fire-retardant resins, vinylester and epoxy resins, S-type glass, unidirectional weaves and aramid fibers cost more.

Data requirements for military small craft are voluminous but comprehensive, even by today's information-hungry standards. This practice provides the customer with a complete package which is not privileged information to a unique contractor. This ultimately benefits both contractor and government, standardizing products and methods. However, depending on the completeness of the basic design provided by the Navy, at least 500 hours and as many as 2000 hours are required per contract for engineering support and drafting services to comply with specifications for drawing packages.

Small commercial vessels, intended to carry passengers for hire, normally require U.S. Coast Guard certification. Modest data requirements prior to construction and intermittent inspection procedures raise contract costs by increasing labor usage and overhead and interrupting production. Engineering support in these cases is usually less than 500 hours. Customized commercial vessels not requiring certification can often be adapted from existing designs and molds with much lower support requirements. Depending on the manufacturing facility and methods used, learning curves for fiberglass craft are approximately 85 percent. Fabricator labor is generally non-union and semiskilled. A large percentage of the work force may be in training, provided that key personnel are experienced.

Operating costs for fiberglass boats include annual antifoulant replacement, cosmetic refurbishment, and the routine machinery maintenance found on other craft. Typical costs for painting and refurbishment are generally less than routine preventative maintenance costs for steel or aluminum vessels. This includes two coats of bottom paint and one coat of paint on hull topsides, deck and superstructure. However, only the harshest service would require yearly recoating of above-water surfaces. Normally, gel-coated or epoxy coated surfaces merely require periodic polishing and waxing to remove oxidation and maintain their high-gloss finish.
MODERN SHIPS & CRAFT

Facilities

Facilities for fiberglass boat construction must meet a mixture of legal and practical environmental requirements. Legally, facilities must comply with safety and ventilation regulations set down by OSHA. Noxious styrene monomers are critical to plastic resin workability but must be purged from layup buildings by some sort of forced ventilation. Environmentally controlled areas, avoiding temperature extremes and high humidity, produce the best and most consistent results. Also, the cleaner the area, the lower the likelihood of material contamination and the better the cosmetics of the end product. A well-lighted facility is essential but direct ultraviolet rays may sporadically accelerate resin cure and upset the hardening process. High volume builders need high ceilings to allow separation of parts from molds without requiring mold movement from the layup area. Also, large doors allow access and egress of large fiberglass parts.

Supportability

Fiberglass reinforced plastic is a common enough medium today in boat building to provide the vessel owner and the designer adequate assurance of longevity and service. Adequate repair of FRP craft can be performed with semiskilled labor, rudimentary tools and a few key yet readily available materials. However, a professional service facility or a production plant will attain greater efficiency and cosmetic perfection with more proficient personnel, sophisticated tooling and elaborate techniques. For example, resin, fiberglass and gel-coats may be applied by hand with a simple paint brush and finished with grinder and sandpaper. The professional will utilize spray equipment, forms and fixtures, and more exotic finishing tools to accomplish a better looking product in half the time. Ultimately structural integrity could be equivalent between both fixes. Navships Document 0982-0190-0010, "Manual for Major Repairs to Glass Reinforced Plastic Boats" is one source of information about field repair published by the Navy.

STEEL

High tensile steel has a strength-weight ratio similar to typical marine aluminum alloys. Because of minimum gage constraints, however, it may not be attractive for small craft since it will result in heavier hulls relative to other materials. Recent studies by R. Allen of DTNSRDC indicate that high tensile steel may indeed be attractive for large, high-speed planing hulls with displacements in excess of 500 tons. Because minimum gage, and not strength, is the governing consideration for small hulls, mild steel is used primarily for these hulls. Relative to cost considerations, it appears that, although heavier, steel hulls will be cheaper than aluminum. Planing hulls built of steel are more widely available abroad—particularly for speeds less than approximately 35 knots.

The construction techniques for steel hulls are well-known and will not be discussed in this chapter. It would appear that, world-wide, there is more boat building and repair capability for steel than for other construction materials.

CONCLUSIONS

There is an expanding international interest in the use of fast patrol boats particularly as the nucleus of naval units in developing new nations. In addition, the introduction of the Exclusive Economic Zone of coastal states has required the acquisition of large numbers of these high speed craft to protect and patrol their off-shore wealth. The commercial and recreational utilization of planing hulls expands each year.

Fortunately, the recent developments in planing hull technology have demonstrated that high speed hulls can now be developed and constructed with the following characteristics:

- Impressive seakeeping characteristics in comparison with the older designs, when hull form proportions and loadings are properly selected for the sea state and speed of interest.
- Structural weight fractions as low as 22 percent of full load displacement.
- Useful load fractions approaching 45 percent of full load displacement.
- Elimination of the traditional "hump" trim and resistance penalties.
- Simplicity of design which permits ease of fabrication, the use of available propulsion systems, readily available engines, and proven propellers capable of speeds up to 50 knots.
- Avoidance of special control systems.
- Various choices of construction materials.
- Well-established design, construction and repair techniques available world-wide.

Quantitative projections of costs of planing hulls are impossible to discuss in these inflationary times. However, there are major considerations which should reduce the cost of planing craft relative to other members of the advanced vehicle family. These are:

a) The number of shipyards (world wide) which are capable of building planing hulls is relatively large and continues to increase. This should result in more competitive bids and a favorable price to the customer. In contrast, there are only limited numbers of manufacturers capable of constructing ACV, SES, hydrofoil, etc.

b) The required structural technology is in hand and hull construction can follow normal shipyard practice. In fact, many of the traditional builders of displacement ships are easily expanding into the fast patrol boat market.

c) There are no special control or operational systems nor special support or maintenance procedures required in planing hulls.

d) With the elimination of "hump" speed characteristics through proper hull design, it appears that constant pitch, foilly cavitated propellers can be used throughout.

140 Naval Engineers Journal, February 1985
the speed range. These propellers are easily fabricated in existing foundries.
e) The absence of "hump" will also enable economical slow speed operation on one relatively small engine and, with the ability to bring on line (in sequence) multiple engines, the result will be an operating profile where engines can be set to run at their best fuel rate.

The final decision on cost will be dependent upon careful analysis to establish trade-offs between capital costs, operating costs, maintenance costs, and value of the mission to be performed. A reduction in maximum speed, for instance, can result in a reduction in the number of engines required, and this decision will have a significant impact on cost, especially if high powered expensive gas turbines are being considered.

REFERENCES


Naval Engineers Journal, February 1985 141