Bicentennial Marine Symposium, The Royal Institute of Marine Engineers, Sydney, Austrialia, January 1988, pages 87-100.

SWATH: THE PAST THE PRESENT AND THE FUTURE

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SUMMARY

This paper traces the development of the SWATH (Small Water-Plane Area Twin Hull) concept from early ideas through to some of the vessels which are now in service.

Attention is drawn to some of the principal features of SWATH vessel design and their effects on the performance of the vessel. In particular, the options available regarding the choice and location of propelling machinery together with the associated problems are considered and solutions which have been adopted or proposed are reviewed.

The problems of comparing widely different types of marine vehicles are then discussed. A quantitative analysis of the relative performance of SWATH vessels and craft of other types (e.g. monohulls, catamarans, hydrofoils, etc.) is then quoted and analysed for a range of different sea states.

Finally the paper reviews the other advantages and disadvantages of SWATH vessels compared to the alternatives and suggests the types of employment in which SWATH vessel features show to their maximum advantage.

1. INTRODUCTION

From about the time when sail gave way to steam, engineers and naval architects have sought methods to reduce the motion of ships in a seaway. The solutions proposed during the last century were many and varied: some did not get past the drawing board; some stopped at the model test stage; while some such as the swinging saloon on the Bessemer (Fig.1) in 1875 (1) were tried out full size, such was the designer's confidence.

Limited success in reducing rolling was achieved initially with bilge keels (2) and then with anti-rolling tanks (3), which have been subsequently further developed during the present century. More effective in reducing rolling while underway has been the fin stabiliser first fitted by Dennys in 1936 (4) and subsequently developed over a number of years and fitted to large numbers of both passenger ships and warships.

However, little has been done to reduce the pitching motion of monohulls (or indeed catamarans); some benefits can be achieved by suitable lines or by reducing free-board at the ends of the vessel (e.g. Bessemer and wave-piercing catamarans), but such benefits are small in overall terms. The very high longitudinal GM and consequently the large forces associated with pitching motions make it difficult to visualise any economical method being developed.

A requirement by the US Navy for a small vessel that would have mininum motions in large waves led to the ideas of the joint author of this paper, T.G. Lang, being developed (5). The first of several patents was issued in 1971 and covers all the features of modern SWATH vessels (Fig. 2). Earlier patents had been issued - the earliest in 1905 - for vessels having some SWATH-like characteristics and have been illustrated in an earlier paper by the authors (6).

The first modern SWATH vessel built was the US Navy's SSP (stable semi-submersible platform) Kaimalino. This vessel was subjected to wide-ranging series of tests and trials which have been described in detail (7, 8 & 9); the design tools developed (e.g. (10) by a member of Lang's Group) have been used intensively by later designers.

Although many conceptual designs were subsequently developed in the USA, particularly for the US Navy, only three small 64 ft vessels have since been built there, all for private interests - the Betsy ex-Suavelino in 1981, the Halcyon in 1985, and the Chubasco in 1987, all licensed under Lang's SWATH patents. A 3500-ton T-AGOS SWATH is now being constructed by the McDermott shipyard under a US Navy contract.

However, inspired by the Kaimalino, Mitsui in Japan have built five SWATH vessels: a small experimental 19 ton craft Marine Ace, a 343 ton passenger ferry Seagull (ex Mesa 80), a 286 ton survey vessel Kotozaki, a 3500 ton diving support vessel Kaiyo, and finally a small pleasure craft, Marine Wave. Mitsubishi has built a survey vessel Ohtori.

SWATH vessels have much in common with the many (nearly 200) semi-submersibles employed in the offshore hydrocarbon industry principally for exploratory drilling, but the essential difference is that the SWATH always operates at about the same draft with the hulls fully submerged whether stationary or underway, whereas the drilling semi-submersible will operate with its hulls fully submerged when stationary, but will deballast and have its hulls only partially submerged when on passage (when it becomes in effect a catamaran). Thus the SWATH is unique among existing marine vehicles in offering a steady platform, both underway and at rest in seaway.

Table 1 compares the principal advantages of different types of marine vehicles.

Table 1

	Steady under way	**Steady at rest**	**High speeds**	**No speed reduction in waves**	**Shallow draft**	**Dwt carrier**
SWATH	+	+	+	+		
ACV			+		+	
SES			+		+	
Catamaran			+		+	
Monohull					+	+
Hydrofoil	+		+	+		
Semi-submersible		+				

2. FEATURES OF SWATH DESIGNS

Four features of SWATH designs will be discussed:

(a) Side struts

The Kaimalino has two struts on each side whereas most other SWATHs have been built with one continuous strut on each side.

The advantages of the two struts per side are:

(i) lower motions at rest
(ii) lower strut side loads
(iii) less need for automatic control at high speed
(iv) lower power required for dynamic positioning

Regarding the last point, it should be noted that when working in the offshore hydrocarbon industry experience shows that a semi-submersible can only work on its preferred heading about 50% of the time (11).

The advantages of a single continuous strut per side are:

(i) simpler structure
(ii) less hull shaping for optimised drag
(iii) more space in struts with better accessibility to lower hulls

Thus the choice between one or two struts per side will be determined primarily by the intended operations of the vessel.

(b) Arrangement of stabilising fins

Fixed stabilising fins at or near the aft end of the submerged hulls are essential to counteract the Munk pitching moments and provide dynamic stability, but the fitting of active fins forward ('canards') and activating the aft fins is an option which becomes highly desirable at higher speeds, and in cases where the reduction of motion to a minimum is important.

The fins can be controlled manually or by means of an automatic motion control system. With the fins locked in position the SWATH will have much smaller motions than a monohull of comparable displacement at all headings in rough seas except possibly following and quartering seas where long period pitch and heave motions can occur at higher speeds. Manual control can improve the performance substantially; the best results can be obtained by automatic controls.

The automatic control system for the Kaimalino was installed after one year of operation and subjected to extensive testing. The results were published by Higdon (12) who commented that even further motion reduction could be achieved with improved controller design. Nevertheless, in the well-known trials (8) with a 378 ft, 3000 ton US Coast Guard cutter, the 88 ft Kaimalino proved to have the lesser motions in a seaway. Subsequent work by Caldeira-Saraiva and Clarke of BMT (13) predicted very significant reductions in the pitch and heave of Kaimalino by the use of an improved controller, further work being envisaged into including lateral motions also. The improvements claimed at a speed of 15.5 knots based on the Subjective Motion Indicator (SMI) - a quantitative measure of the effect of ship motion on human beings - are striking:

Uncompensated SWATH	SMI = 2.00
Existing compensator	SMI = 1.37
New compensator	SMI = 0.04

This study thus indicates the potential of SWATH designs to provide a steady platform, and the importance of automatic controller design in association with the ship design.

(c) Propelling machinery arrangements

In determining the type and position of the propelling machinery, a factor of major importance is the minimisation of weight. The gas turbine is therefore very attractive as a prime mover, and the Kaimalino was so equipped. However, the subsequent increases in the price of fuel coupled with the relatively heavy fuel consumption of a gas turbine has limited its attractiveness on economic grounds, except for the higher design speeds.

High speed, lightweight diesel engines have been chosen for the majority of SWATHS now in service (Table 2, below).

In all vessels built to date, except the Chubasco, the prime movers have been located within the box structure. The advantages of locating the engines in the lower hulls would be:

(i) minimum noise and vibration in box structure (passenger ships)
(ii) elimination of intermediate drive problems, weight, etc.
(iii) minimises KG

The advantages of location in the box structure are:

(i) accessibility for operation/maintenance/replacement
(ii) minimum noise and vibration in lower hulls (warships)

While at first sight the possibility of small, light, high-powered gas turbines fitted in the lower hulls might appear an attractive solution, problems can arise in accommodating the large inlet and exhaust trunking required.

The intermediate drive from a prime mover in the upper hull to the propeller shafts in the lower hulls presents an interesting engineering problem, which has been solved in a number of ways in existing vessels:

TABLE 2

Vessel	Prime Mover	Drive to propeller shaft
Kaimalino	gas turbine	chain drive
Suavelino	diesel	shafts and bevel gears
Halcyon	diesel	belt drive
Chubasco	diesel	engines and gearboxes below
Marine Ace	petrol	shafts and bevel gears
Seagull	diesel	shafts and bevel gears
Kotozaki	diesel	shafts and bevel gears
Kaiyo	diesel	electric
Marine Wave	diesel	shafts and universal couplings
Ohtori	diesel	shafts and bevel gears

Chain drive was selected for the Kaimalino because alternative systems were inferior in either cost or weight; at the time the US Navy was having problems with its 'Z' drive for hydrofoils.

In the design of the small Halcyon it was found that an 'off the shelf' V-belt type of drive had both cost and weight advantages over a right-angle gearbox transmission system (i.e. bevel gears). Such belts, which have low noise levels, are only available to transmit comparatively low powers, although quite adequate for this small vessel.

However, on the Suavelino, of similar size, the engines drive shafting through bevel gears. This system has also been adopted on the larger SWATHs; to minimise weight and to keep the KG as low as possible the shaft and gears run at high speed, with reduction gearing in the lower hulls driving the propeller shafts. The smaller Marine Wave has the engines placed well forward driving inclined shafts linked to the propeller shafts (which are also somewhat inclined), universal couplings linking the inclined shafts to engines and propeller shafts.

The Kaiyo, the largest SWATH built to date, has a diesel electric drive. This arrangement normally carries a weight and space penalty, but bearing in mind the comparatively low speed and power of this vessel (12 knots, 3440 KV) this was presumably considered acceptable, especially since the vessel is dynamically positioned on station and electric drive to the main propellers obviously facilitates their integration into the system as well as reducing the total power otherwise required to be installed.

In warships, and some other applications, there is a need for comparatively low cruising power, and, for short periods, a high 'sprint' power. A recent design study for a SWATH frigate (14) solved this with a gas turbine in each lower hull to provide the sprint power, driving through reduction gearing and a clutch, similar to a 1971 SWATH frigate design referred to in Ref 23 of (5). For cruising, diesel generators are mounted in the box structure driving electric motors on the shafts – to minimise noise it is proposed to use water-cooled DC motors powered through thyristor convertors.

Mention is also made in this recent study of the possibility at some time in the future of using superconducting generators and motors, and certainly superconducting motors were built for trial purposes by GEC in the USA in 1971 intended for SWATH and similar high-speed vessels. The Japanese are working on superconductive electromagnetic propulsion; their advertising literature shows a futuristic SWATH so equipped. In view of the recent breakthrough in the development of higher temperature superconducting materials, this approach may be very attractive.

(d) Steering arrangements

Because of the wide separation of the propellers a SWATH can be steered very effectively at low speads by propellers alone. However, in the event of. a failure of one propeller a powerful steering system becomes essential,such as in the Kaimalino where the rudders are mounted immediately abaft the propeller.

Most SWATHS built to date have a similar arrangement. Due to the inevitable slimness of the side strut at its aft end to meet hydrodynamic considerations,some structural problems are encountered in order to provide adequate support in an athwartship direction for a rudder hung beneath it.

The Kaimalino has its rudders arranged in the propeller race, with the rudder supported by, and through, a horizontal box girder running aft from the main strut, complicating the design of the strut.

The frigate study (14) and some previous US Navy studies, have proposed a submarine type rudder forward of the propellers, which is a convenient solution structurally but not so good hydrodynamically.

The choice of rudder location will be determined primarily by the intended operation of the vessel.

3. PERFORMANCE OF SWATH VESSELS

The authors' earlier paper (6) examined the relative performance of different types of commercial marine vehicles in calm water by plotting Cd/E against a non-dimensional speed U (see Appendix 1 for the derivation and meaning of these expressions). The most efficient vehicle will have the lowest value of Cd/E and it will be noted from Fig. 3 that even in smooth water conditions there is a small but significant range over which SWATH vessels appear the most efficient, the limiting-line curves showing the best performance based on the information plotted. This has been derived from published information perhaps produced on several differing assumptions, so caution should be exercised in using these limit lines, which are intended to indicate general trends rather than definite limits.

A comparison of the performance of different types of marine vehicles in varying sea conditions is shown in Fig.4. Using values of U from the diagram for a given value of $h/\Delta^{1/3}$ enables a diagram to be produced similar to Fig.3 by comparing efficiencies in a seaway (see Appendix 1). Figs. 5 and 6 show such diagrams for $h/\Delta^{1/3}$ = 0.5 and 1.0 and it will be noted that when $h/\Delta^{1/3}$ = 1.0 the SWATH limit line is below a displacement monohull at all values of U. Fig. 4 does not include a curve for planing catamarans in a seaway since we have been unable to find published data, but we believe that it would probably be similar to SES craft. We believe that $h/\Delta^{1/3}$ = 0.5 represents about the worst seas in which an ACV or SES could maintain speed, since in worse conditions the accelerations would exceed 0.1g so that the crew would probably reduce speed. (The speed reductions in Fig. 4 result from added power requirements due to motion and wave action and not human comfort or structural considerations.) Thus the curves for ACVs and SESs in Fig. 6 are somewhat theoretical.

Figs. 7, 8 and 9 have been drawn from Figs. 3, 5 and 6 to show the areas (in terms of speed and displacement) in which SWATH vessels might be the most efficient commercial marine vehicles for the three sea states used. Of course, the displacenent of the different types of marine vehicle may not be the same for the same service, e.g. to carry a certain number of passengers at a certain speed. However, for the same service we could assume that cargo deadweight and outfit weight would be similar; the more efficient vehicle for a given speed and displacement will have a lower engine power and weight in the terms of our analysis, hence lower fuel requirements and weight which would help offset any saving of hull structure weight that a 'less efficient' vehicle may (or may not) have.

Some studies in America (15) have indicated that if the improved seakeeping ability of SWATH vessels is ignored, the displacement of a SWATH vessel built to the same requirements as a monohull would be about 30% greater.

However, a particular study showed that if both SWATH and monohull warships were designed to be fully operational in sea state 6, the monohull would have to be increased in size by 70%, the SWATH remaining unchanged. The SWATH warship would thus be about 76% of the displacement of the enlarged monohull.

Figs.7, 8 and 9 should therefore be of some help in identifying the areas in which SWATH wlll be the most efficient in terms of power and therefore fuel consumption.

In considering actual applications for SWATH vessels, capital costs will also have to be taken into account. Indeed, we believe that the only true comparison between different types of marine craft would be that based on a particular service requirement (specifying also weather conditions, maximum allowable motions, etc.) for which an optimum design of each type of craft was produced with full costings (both capital and operating). Only then could an accurate comparison be made on economic grounds,which must be the ultimate basis for comparison.

The American Navy studies (15) indicate that SWATH designed for the safe warship mission requirements as a traditional monohull but ignoring seakeeping abilities would cost some 17% more: if, however, seakeeping ability is taken into account and the size of the monohull increased to give the same performance as already described then the SWATH is some 9% less costly.

Our own conclusions are that the extent to which the capital cost (and to some extent the operating cost) of a SWATH vessel differs from that of a monohull designed for a similar service will depend upon the extent to which the sea-keeping abilities of the two vessels are taken into account. If designed for calm water conditions the SWATH will be the more expensive both to build and to operate in calm water; as the sea state for which the vessels are designed is increased, the difference in cost will decrease and soon reverse.

In general we believe SWATH vessels will cost less than hydrofoil boats, air cushion vehicles, or surface effect ships having similar payloads.

4. CONCLUSIONS: THE FUTURE OF SWATH VESSELS

In Table 1 we have summarised the areas in which each type of marine vehicle can show advantages. The lack of motion both underway and at rest in a seaway, together with the ability of a SWATH vessel to travel at high speeds, is a combination of qualities not shared by any other marine vehicle. The nearest is the hydrofoil, which does not, however, exhibit similar lack of motion when stationary or travelling at low speeds in a seaway, which could be an important disadvantage. It also has problems in becoming foil-borne in a seaway after it has stopped for any reason.

The four areas in which we are most confident that the advantages of SWATH vessels over all alternatives will ensure their future use are:

(1) Passenger vessels, where the virtual elimination of sea-sickness is a very real benefit. The absence of speed loss in waves will enable schedules to be planned with confidence and to be maintained in poor weather conditions. Also the lack of motion when stationary will enable regular services to be maintained to exposed piers, offshore platforms, etc.

(2) Offshore patrol, fishery protection, etc, where the ability of even a small SWATH vessel to fly a helicopter off and on in rough seas would enable it to patrol effectively a far larger area than could be covered by any other single vessel without a helicopter, and where the SWATH vessel can be designed for comparatively low cruise speeds and high 'pursuit' speeds.

(3) A range of warship types, especially where operational functions require a steady platform in a seaway such as operation of helicopters and/or VTOL aircraft, etc, and where the seakeeping ability of a SWATH vessel would enable it to operate over a much wider range of sea states, e.g. minehunters.

(4) Oceanographic and survey vessels, etc, handling equipment on the seabed where a simple semi-submersible is not suitable because of the time ballasting and deballasting at each stationary position, and/or where a relatively high transit speed is required.

It is, of course, very disappointing that the development of SWATH vessels has been so slow. The extensive research that has been done and the undoubted success of the Kaimalino should have been sufficient encouragement for the construction of many more such vessels of ever increasing size. It may be that the slump in shipping worldwide, the apparent belief that SWATH vessels are much more expensive than monohulls (which they are not if mission effectiveness in a seaway is considered), together with a reluctance to be a pioneer in a time of general recession, have all been factors in this situation.

However, we remain convinced that it is only a matter of time before SWATH vessels are no longer regarded as novel and are built in substantial numbers for many applications, especially the applications that we have described.

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APPENDIX 1

Using an approach developed in Ref 16, the most general performance-related variables are vehicle speed V, full load weight W, and propulsion power P. The variable ρ is the fluid density, and g is the acceleration of gravity. A nondimensional parameter Q which expresses these variables as a single parameter is:

$$Q = \frac{P\, g^{2/3}}{W^{2/3}\, \rho^{1/3}\, V^3}$$

Q may be looked upon as an optimization parameter which, if minimized, provides a vechicle possessing minimum power for a given displacement and speed. Let the vechicle power be expressed as:

$$P = \frac{D\, V}{E}$$

where D = drag and E = propulsive efficiency. Also, let the drag coefficient be defined as:

$$C_d = \frac{D}{(W/\rho g)^{2/3}\, \rho\, V^2/2} = \frac{2\, D\, g^{2/3}}{W^{2/3}\, \rho^{1/3}\, V^2}$$

where W/ρg is the fluid volume displaced by W. Substituting these expressions into the equation for Q:

$$Q = \frac{C_d}{2\, E}$$

In other words, the optimization criterion is 0.5 times the drag coefficient divided by the propulsive efficiency of a vehicle.
Similarly, if it is desired to let U be a nondimensional velocity expressing the velocity V as a function of the vehicle weight W, then:

$$U = \frac{V\, \rho^{1/6}}{g^{1/3}\, W^{1/6}}$$

where U can be shown to be a Froude number based on volume. Consequently, a graph of Q versus U can be transformed into C_d/E versus volume Froude number, or alternatively into $P/W^{2/3}V^3$ versus $V/W^{1/6}$ where ρ and g are expressed as constants.

The wave height may be expressed nondimensionally as H where:

$$H = \frac{h\, \rho^{1/3}\, g^{1/3}}{W^{1/3}}$$

and h = significant wave height in a given sea state. H may alternatively be transformed into $h/W^{1/3}$ by expressing ρ and g as constants.

It is noted that C_d/E is a nondimensional term that can be calculated using metric units or English units where:

$$C_d / E = 1.9761\ \text{KW/MG}^{2/3}\, V_m^3$$

$$C_d / E = 10.716\ \text{SHP/LT}^{2/3}\, V_k^3$$

where KW is total shaft power in kilowatts, MG is displacement in megagrams, V_m is speed in metres/sec, SHP is shaft horsepower, LT is long tons, and V_k is speed in knots. Similarly, the displacement Froude numbers can be calculated using the following expressions:

$$U = V / \sqrt{g\, \nabla^{1/3}} = 0.3210\ V_m/\text{MG}^{1/6}$$
$$U = V / \sqrt{g\, \nabla^{1/3}} = 0.1647\ V_k/\text{LT}^{1/6}$$

Performance in a Seaway

Since Cd/E varies inversely as V^3 and U varies as V, the formula for the limit lines for calm water conditions shown in Fig 3 can be changed for different sea conditions by substituting:

$$y_1 \left(\frac{V_1}{V_0}\right)^3 \text{ for } y_0$$

and

$$x_1 \left(\frac{V_0}{V_1}\right) \text{ for } x_0$$

where x_0, y_0, V_0, are the calm water valves and x_1, y_1, V_1 are the rough water values. The value of V_0/V_1, for any nondimensional wave height $h/\Delta^{1/3}$ can be obtained from Fig 4.

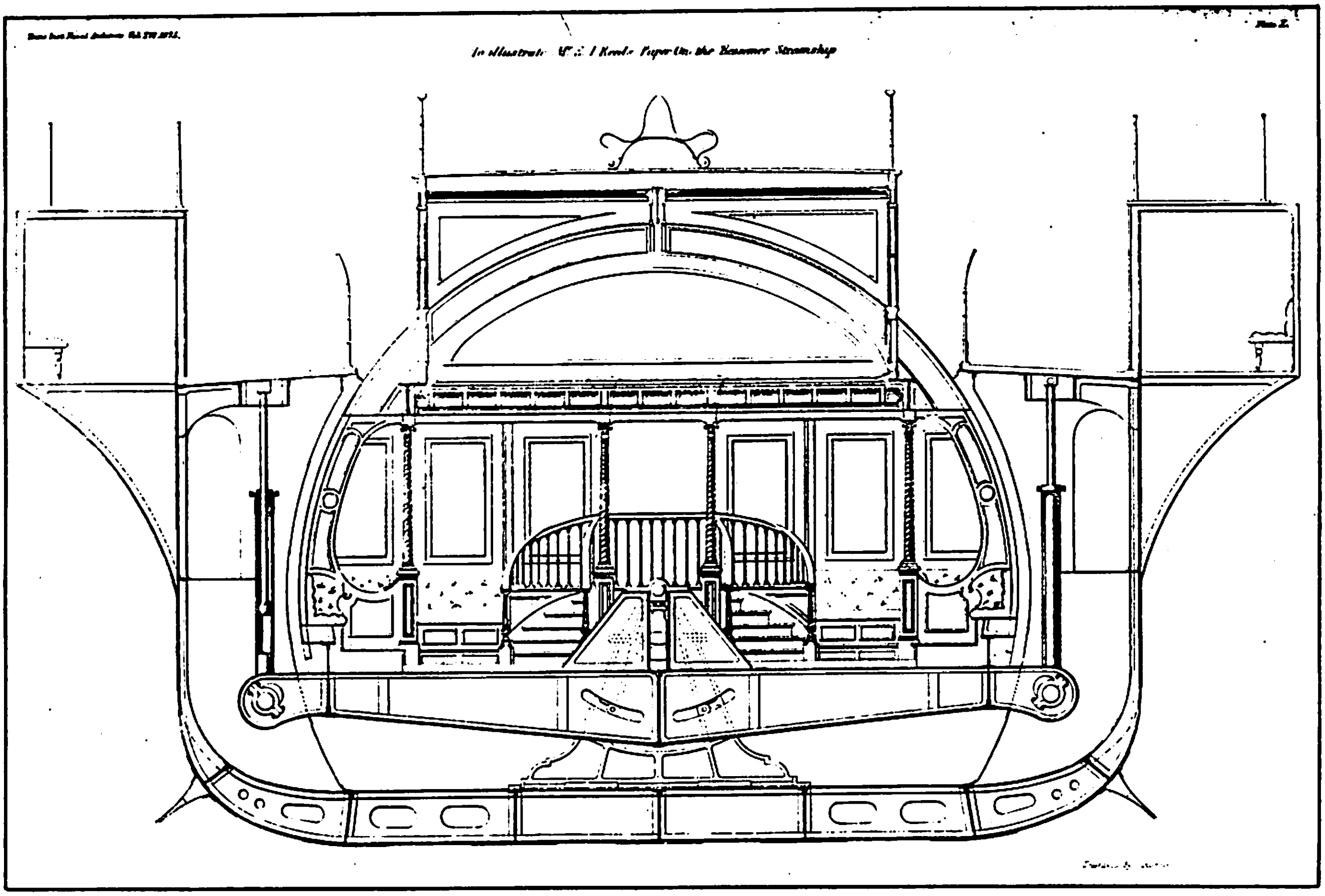

FIG. 1 SWINGING SALOON OF THE BESSEMER STEAM SHIP

United States Patent

[11] 3,623,444

[72] Inventor Thomas G. Lang
5354 Calle Vista, San Diego, Calif. 92109
[21] Appl. No. 20,204
[22] Filed Mar. 17, 1970
[45] Patented Nov. 30, 1971

[54] **HIGH-SPEED SHIP WITH SUBMERGED HULLS**
18 Claims, 36 Drawing Figs.

[52] U.S. Cl. .... 114/61, 114/66.5 H
[51] Int. Cl. B63b 1/10
[50] Field of Search 114/61

[56] References Cited
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Primary Examiner—Andrew H. Farrell
Attorneys—Richard S. Sciascia, Ervin F. Johnston and Thomas G. Keough

ABSTRACT: A high-speed ship is formed of at least one elongate hull section submerged completely beneath the water's surface supporting a platform above the surface waves by a plurality of struts dependent from the platform to provide support and stabilization by reason of their configuration and location. High-speed dynamic pitch stability is ensured by including a stabilizer member on the aft portion of the submerged hull having a horizontally oriented control surface sufficiently sized to locate the greatest composite, vertical pressure surface substantially aft of the ship's centroid. Controlling the angle of the stabilizer member in accordance with changing wave conditions and speed provides a highly stable cargo transport capability as well as superior weapons platform.

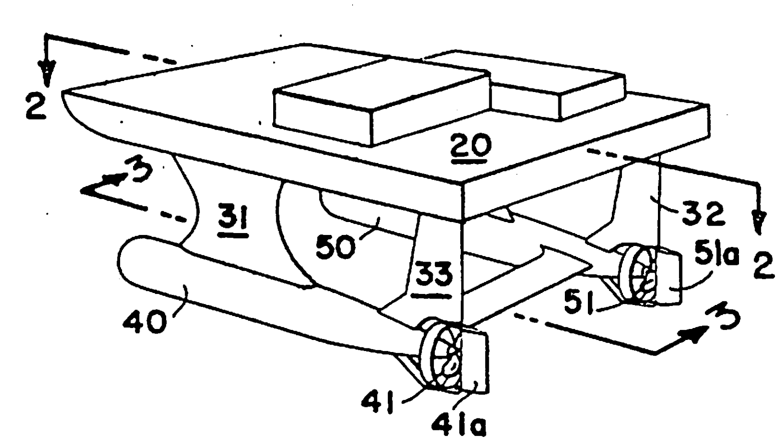

FIG. 2 US PATENT #3,634,333 BY T.G. LANG ON SWATH SHIPS. 11/30/71

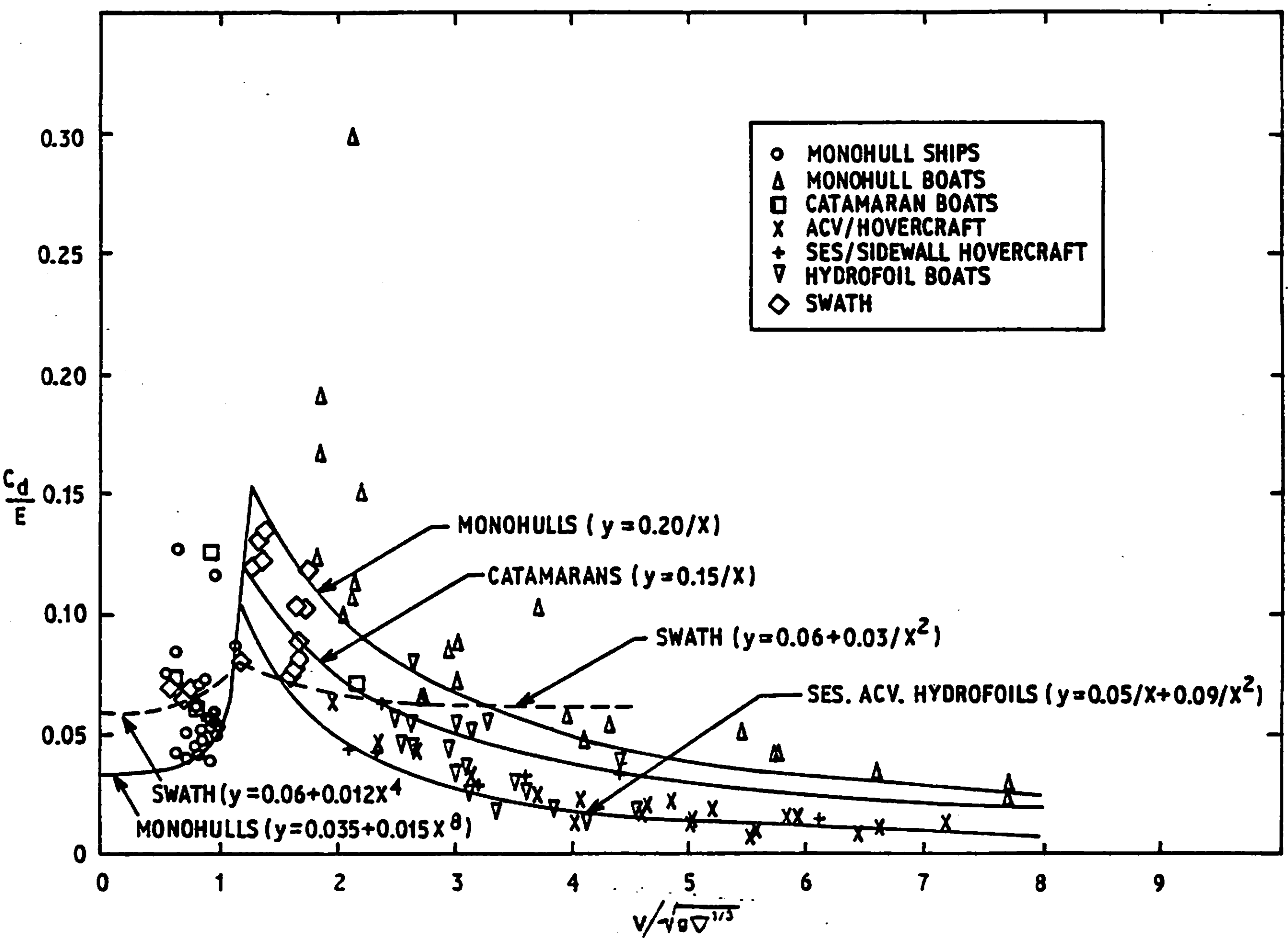

FIG. 3 RELATIVE PERFORMANCE OF MARINE VEHICLES IN CALM WATER

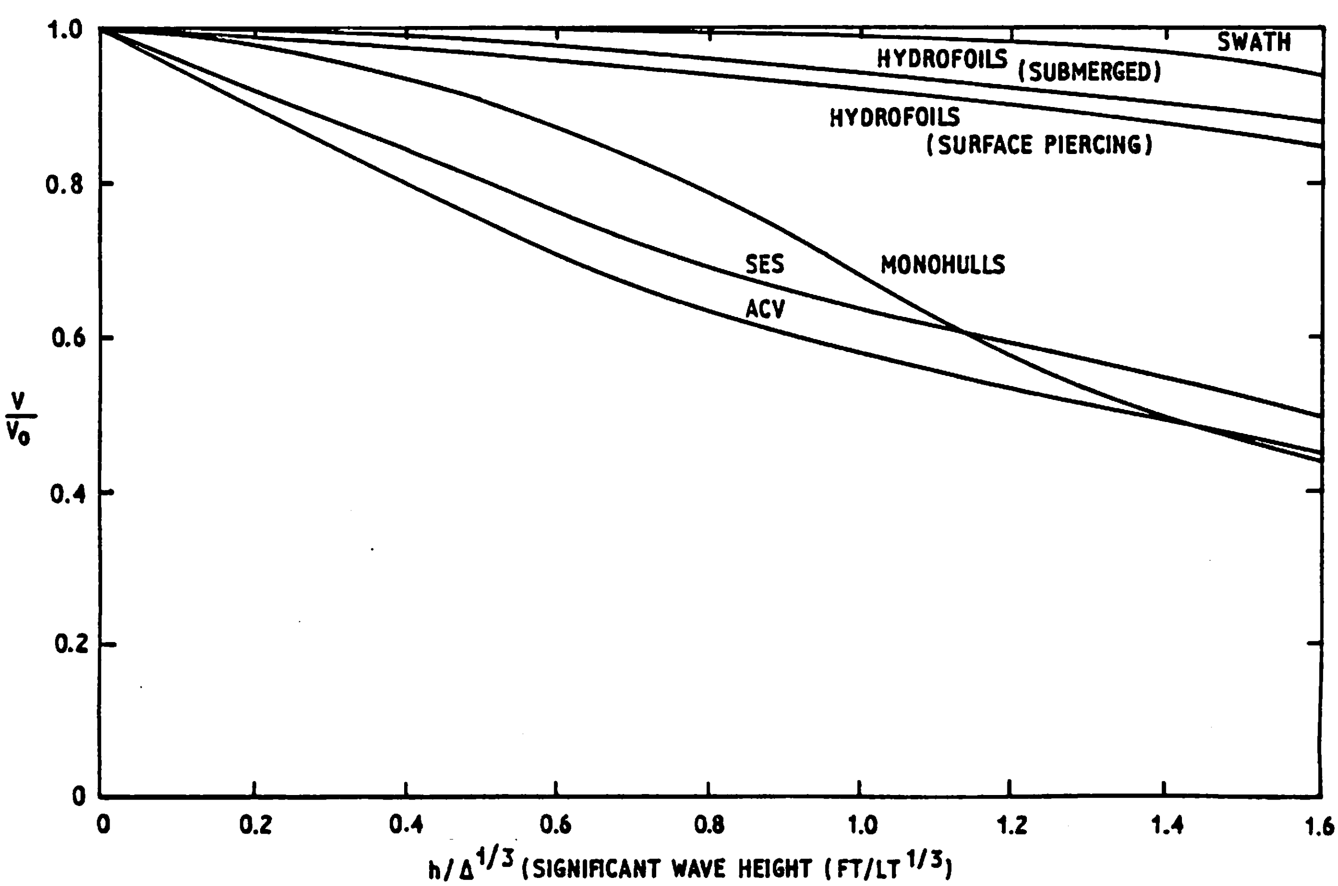

FIG. 4 SPEED REDUCTION IN WAVES

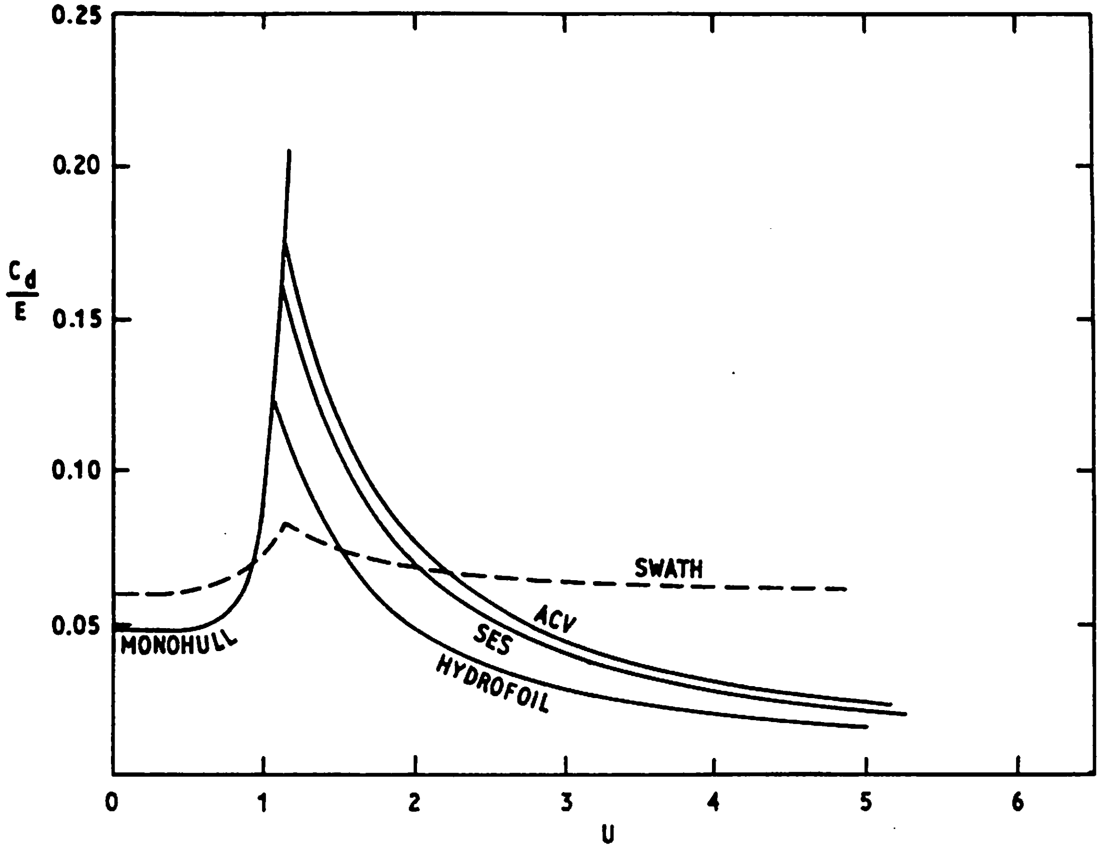

FIG. 5 RELATIVE PERFORMANCE OF MARINE VEHICLES IN SEAS $h/\Delta^{1/3} = 0.5$

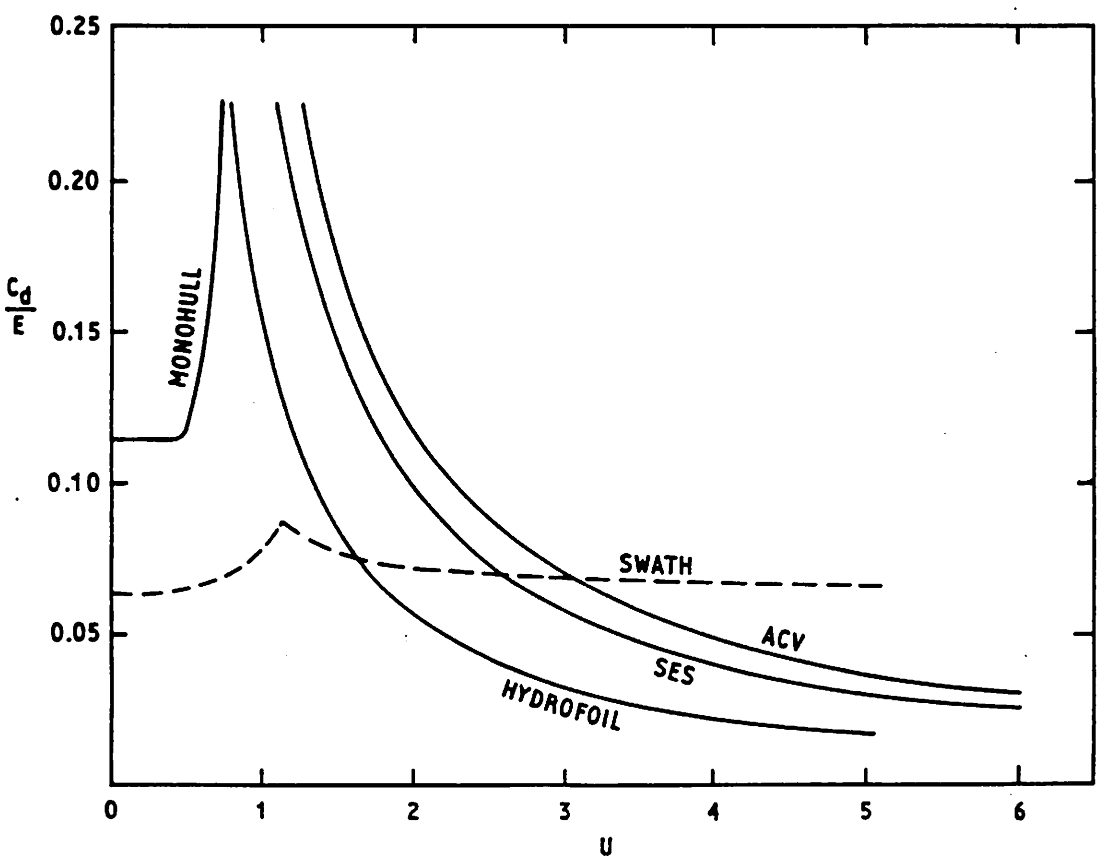

FIG. 6 RELATIVE PERFORMANCE OF MARINE VEHICLES IN SEAS $h/\Delta^{1/3} = 1.0$

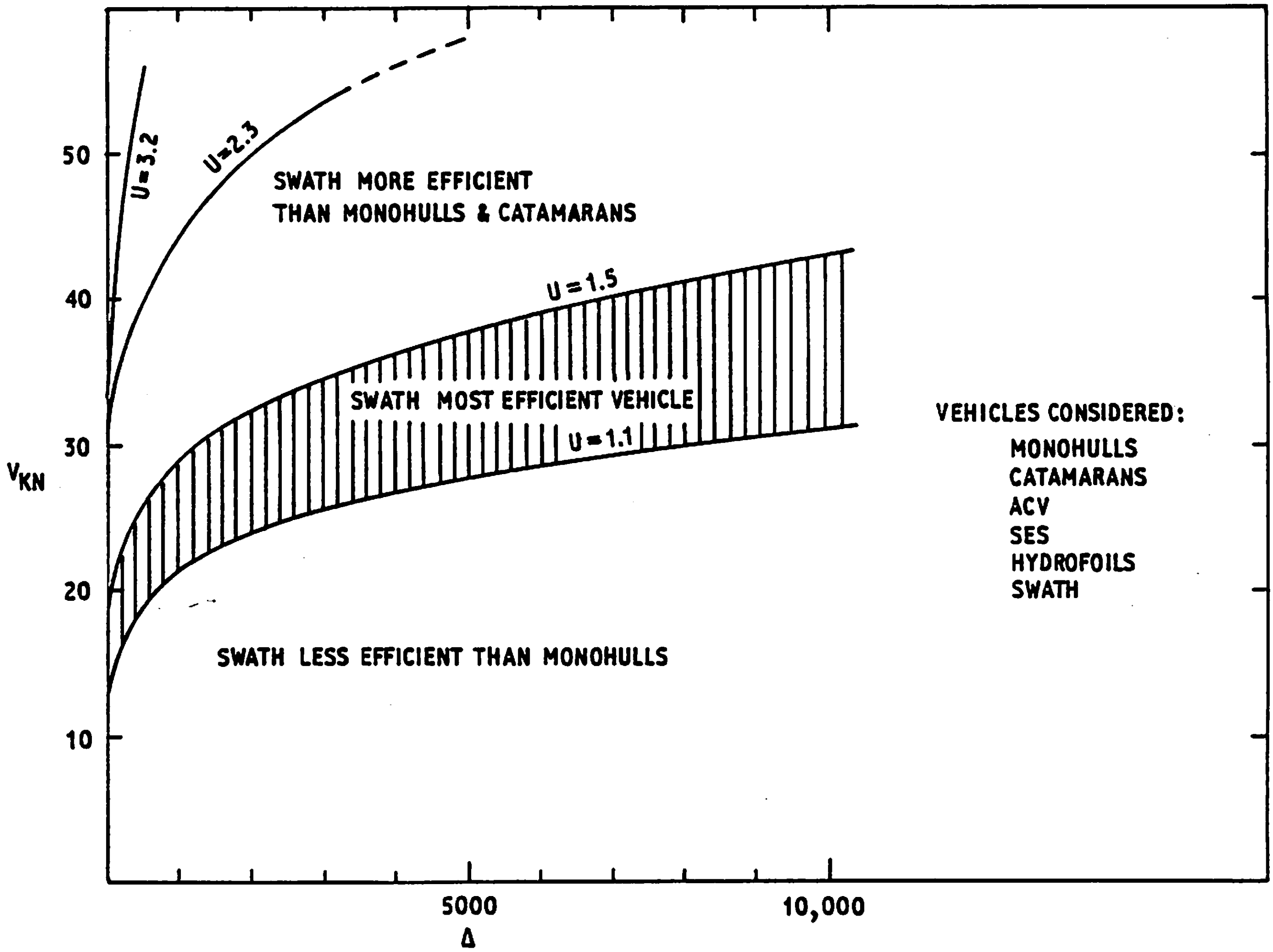

FIG. 7 PERFORMANCE IN CALM WATER

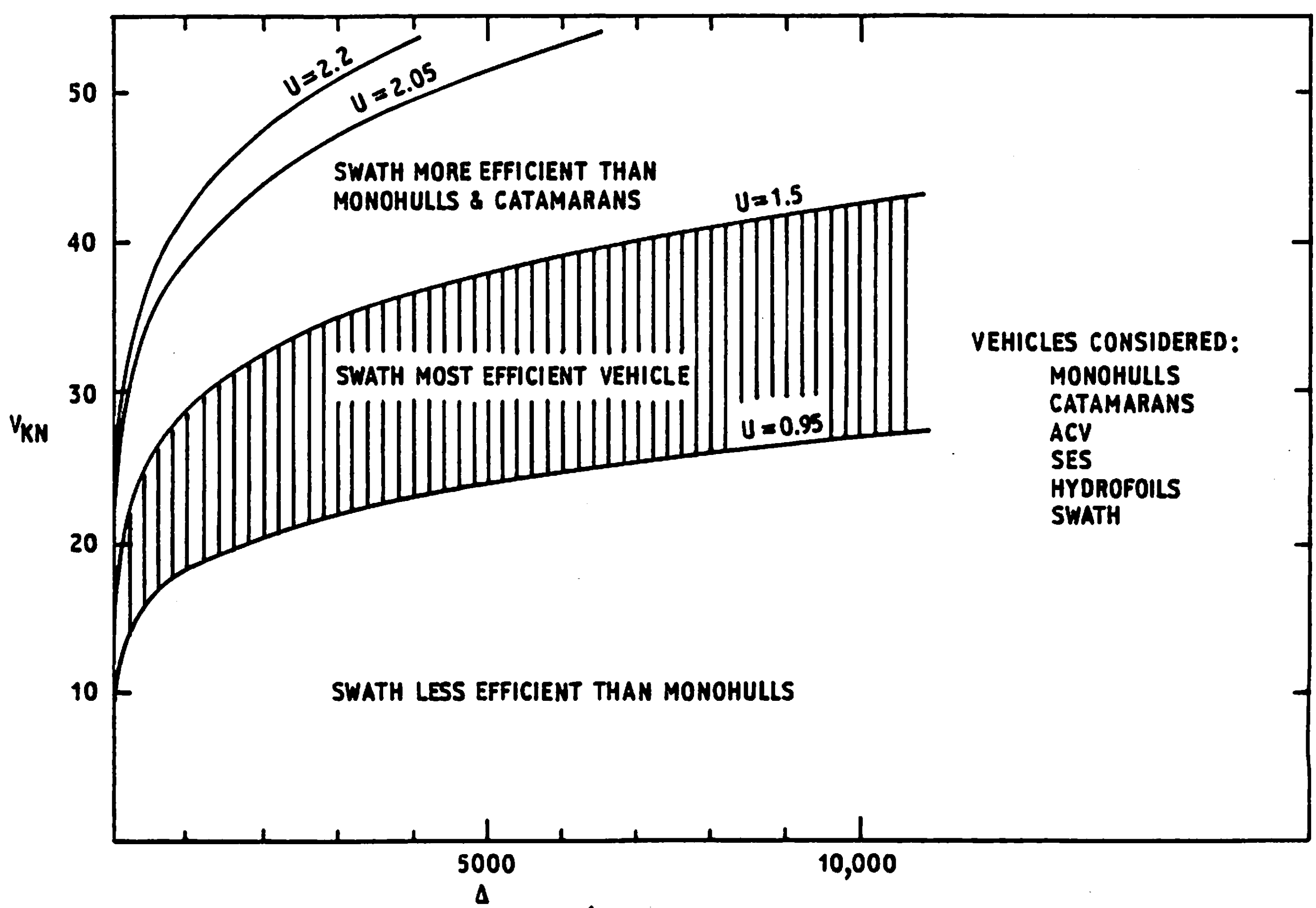

FIG. 8 PERFORMANCE IN A SEAWAY ($h/\Delta^{1/3} = 0.5$)

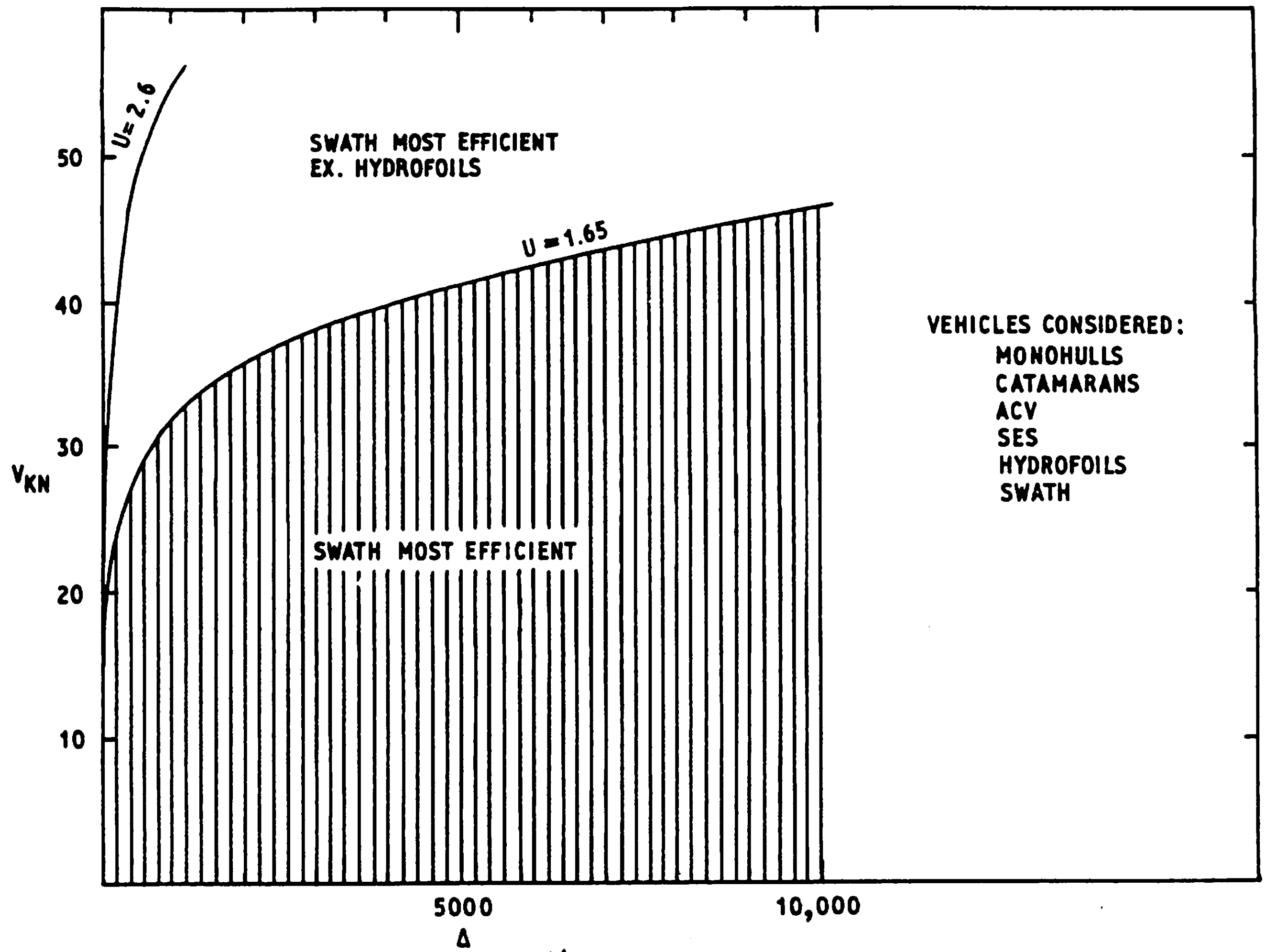

FIG. 9 PERFORMANCE IN A SEAWAY ($h/\Delta^{1/3} = 1.0$)

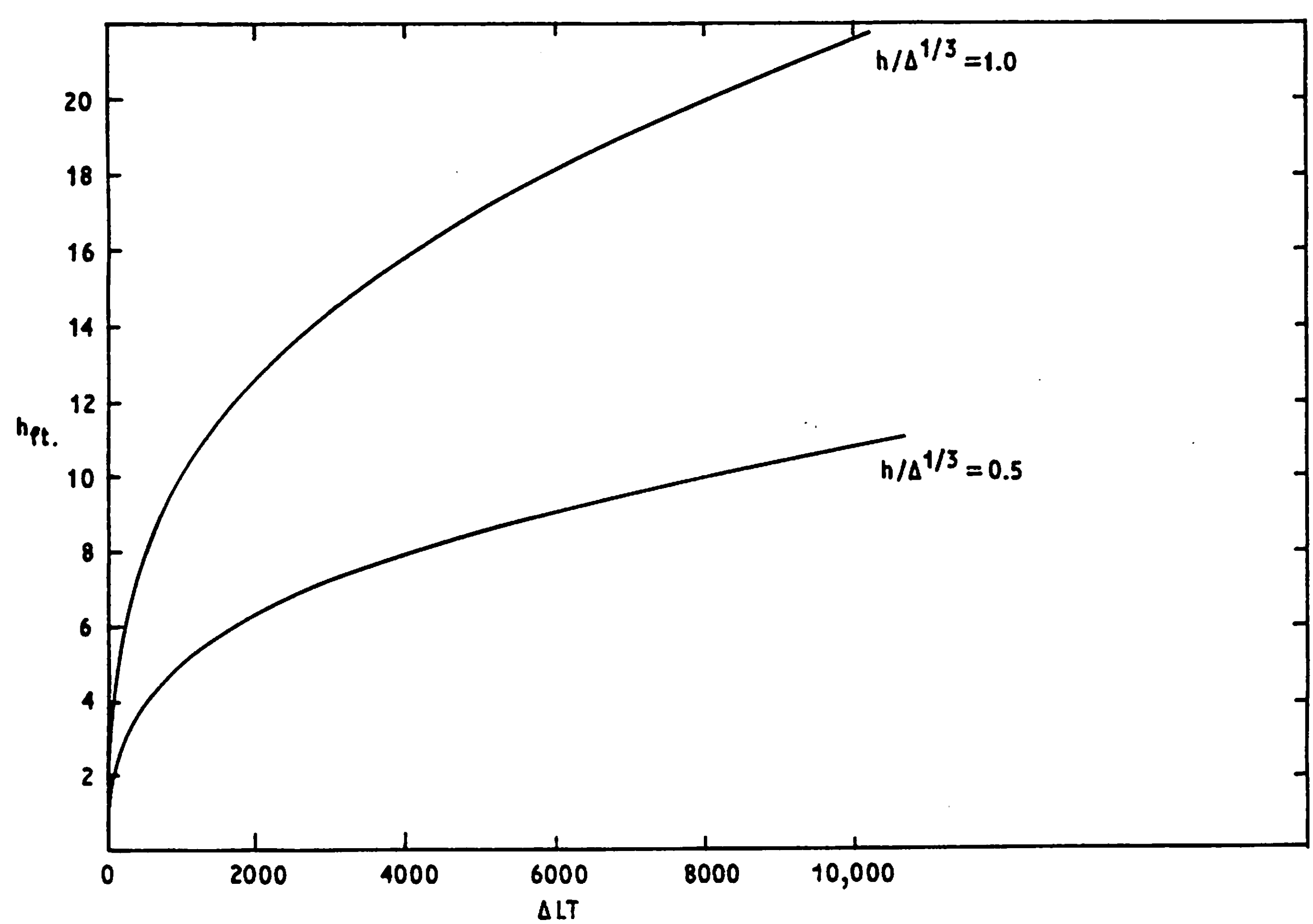

FIG. 10 PLOT OF WAVE HEIGHT AGAINST DISPLACEMENT