HYDRODYNAMIC DESIGN OF AN S^3 SEMISUBMERGED SHIP

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ABSTRACT

The S^3 semisubmerged ship concept is described, and hydrodynamic characteristics are presented. Variations of the basic form are discussed and results of model tests and theory are presented on static and dynamic stability, drag and power, motion in waves, and effectiveness of an automatic control system for motion reduction. The results show that an S^3 is inherently stable at all speeds, well damped in all modes, and should provide a near-level ride in high sea states if equipped with an automatic control system. Furthermore, an S^3 should have less drag than a monohull at the higher design speeds.

INTRODUCTION

Military and commercial users of ships are continuously searching for new design concepts which would provide improved speed, range, payload ratio, seaworthiness, or reliability. Such improvements are preferably to be attained at reduced cost, although cost tradeoffs are the general rule. Since monohulls have long been the most widely used hull form, it is generally accepted that their lead position is not easily challenged.

The large monohulls can carry a very large payload ratio, they have a long range at moderate-to-high ship speeds, and they offer good seaworthiness at a relatively low initial and operating cost per unit of payload. The small monohulls, on the other hand, have other advantages, such as: low unit cost, more flexible utilization resulting from greater numbers for a given total cost, more frequent scheduling, less net cost when small payloads are required, and less target value in the case of military applications.

Unusual ship designs such as hydrofoils and various types of air-supported vehicles have already taken over some of the missions performed earlier by monohulls. These types of craft are high performance vehicles, and tend to be used when higher speed is important, such as certain passenger craft and special military applications. These craft require considerable power, are more complex in design, and are therefore more costly than monohulls.

There is a need for a new type of small displacement ship which has low cost, has all the desirable features of small ships, and yet has many of the desirable features of large ships.

One new type of displacement ship which has been receiving considerable attention lately, especially in the oil drilling industry, is called a semisubmersible. Typically, semisubmersibles are low-speed ships having two or more submerged cylindrical hulls with several vertical cylinders supporting a platform well above the water. These craft have been found to withstand very high sea states and winds, and exhibit small motion in waves relative to monohulls.

The term S^3 refers to a certain class of related semisubmerged ship designs and their characteristics. The S^3 semisubmerged ship concept discussed in Reference 1, and shown in Figure 1, belongs to the family of semisubmersibles; however, it is designed to provide low drag at higher speeds, and to have good seaworthiness not only at rest, but underway. An S^3 tends to fill a gap in ship design since it can be small, having all of the advantages of small ships, and yet have the speed, deck space, and seaworthiness of large ships.

The S^3 Concept stemmed from designs of the writer dating back to the 1950's. This concept was introduced at the Naval Undersea Research and Development Center (NUC) in 1968, where it has been under active investigation ever since. The S^3 is not the only higher-speed semisubmerged ship concept, however. Several other types have been designed, as discussed in Reference 1, including a single-hull version conceived by Lundborg dating back to 1880, a multihulled version described by Blair in 1929, a twin-hulled version by Creed in 1945, the Trisec by Leopold at Litton Systems in 1969 (Ref 2), and more recent versions called Modcats designed by Pien at Naval Ship Research and Development Center (NSRDC) (Ref 3).

DESCRIPTION

The typical design of an S^3 semisubmerged ship, shown in Figure 1, consists of two parallel torpedo-like hulls which support an above-water platform by means of four well-spaced streamlined vertical struts. Stabilizing fins attached to the aft portions of the hulls provide pitch stability at higher speeds. The water plane area and spacing of the struts provide static stability in both roll and pitch. Small controllable fins called canards may be placed near the hull noses. These canard fins can be used in conjunction with controllable stabilizing fins at the rear to provide motion control over heave, pitch, and roll. If rudders are placed in each of the four struts, motion control over yaw and sway can be obtained, especially when an S^3 travels obliquely to waves. It should be noted that an S^3 design is inherently stable at all speeds, without the use of control surfaces.

Some of the advantages of the S^3 hull type relative to a monohull are: greatly improved seaworthiness, both at rest and underway; reduced wave drag at higher speeds; greater deck area and internal volume; certain advantages of the unusual hull shape for placement of a central well, mounting sonars, carrying small craft, placement of propulsors, and potential for modular construction; improved propulsive efficiency and greater cavitation resistance;

greater topside weight capacity; and the potential for a near-level ride in high sea states.

These advantages are to be weighed against the disadvantages. The primary disadvantage is the increased structural weight due to its relatively dispersed design form. Other possible disadvantages include the large draft, and the need for ballast control over trim.

Many variations of the typical design shown in Figure 1 are possible. The strut thickness and chord lengths can vary, the hull lengths and diameters can change, the hull cross-sectional shape can vary, the rudders can be located behind the propellers, the sizes and positions of the stabilizing and control fins can be varied, and the ship can be propelled by means other than propellers, such as pumpjets. Still other S^3 variations from the typical design form are presented in Figure 2; these include a two-strut and a six-strut, twin-hulled design, and several types of single-hulled designs. There is no "best" S^3 hull form, since the form will vary as a function of size, mission, and design constraints.

The primary objective of this paper is to describe the basic characteristics of an S^3 so that it can be compared with other types of ships for various types of applications. To do this, the drag and power, stability, motion in waves, and automatic control characteristics will be discussed.

DRAG AND POWER

In calm water, ship speed is a function of drag, and is therefore limited by the installed power. The maximum speed may be less in the higher sea states, since speed may be limited either by ship motion or by increased drag due to waves. In the case of monohulls, speed limitations in the higher sea states can be severe.

In order to compare the drag and power of a wide variety of ship forms, sizes, and speeds, the following equations are used:

$$\text{drag coefficient} = C_D = \frac{D}{\nabla^{2/3} \frac{\rho}{2} V^2} = C_{D_f} + C_{D_r}$$

$$\text{power} = P = \frac{D \cdot V}{\eta} = C_D \, \nabla^{2/3} \, \frac{\rho}{2} \, V^3/\eta$$

$$\text{displacement Froude number} = F_\nabla = \frac{V}{\sqrt{g \nabla^{1/3}}} = \frac{V \rho^{1/6}}{g^{1/3} \, \Delta^{1/6}}$$

$$\text{hull efficiency} = E = \frac{\Delta \cdot V}{P} = \frac{\Delta}{D} \cdot \eta$$

$$\text{range} = R = \frac{\Delta_f}{\Delta} \cdot \frac{\Delta}{D} \cdot \eta \cdot \frac{1}{SFC} = \frac{\Delta_f}{\Delta} \cdot E \cdot \frac{1}{SFC}$$

where D = drag, ∇ = displaced volume, ρ = mass density of water, V = speed, η = propulsive efficiency, g = acceleration of gravity, $\Delta = \nabla\rho g$ = displaced weight, Δ_f = weight of fuel, and SFC = specific fuel consumption = weight of fuel consumed per unit power per unit time. The units used may be any consistent set. The term C_{D_f} is the frictional drag coefficient, and is assumed to be purely a function of Reynolds number; the term C_{D_f} reduces as the size or speed increases. The term C_{D_r} is the residual drag coefficient; it includes the wave drag and all other sources of drag except frictional drag, and is assumed to be purely a function of F_∇.

Figure 3 is reproduced from Reference 1, and shows the approximate hull efficiency E at maximum speed for a variety of ship types as a function of displacement Froude number F_∇ in calm water. Hull efficiency is an important parameter since the equation shows that it is directly proportional to range. Note that the hull efficiency of an S^3 is somewhat less than that of a monohull at low F_∇, but somewhat greater than that of a monohull at high F_∇ where monohull wave drag becomes large. The reason for this result is that an S^3 has a greater frictional drag than a monohull due to its increased wetted surface area, but has less wave drag at higher speed due to its unusual hull form. A C_D of 0.05 and an η of 0.80 have been used for the S^3 curve in Figure 3 at $F_\nabla = 2.0$, with C_D/η reducing slightly at lower F_∇, and increasing slightly at higher F_∇ to reflect reduced propulsive efficiency. The propulsive efficiency η is somewhat greater for an S^3 than for monohulls since the boundary layer inflow to the propulsors will be more axially symmetric; therefore, the S^3 propulsors can be more completely wake adapted, as in the case of torpedoes where propulsive efficiencies of 85% to 90% are not uncommon. The line shown in Figure 3 for monohulls is the locus of the highest measured values of E. In rough water, the value of E for monohulls will reduce considerably, as shown later, while E for the S^3 ship will not change appreciably.

The dashed lines in Figure 4 show the measured C_D from model tests. The model data relate to a small-craft S^3 design. The solid lines are the estimated drag coefficients for several 3000-ton ships, including an improved low-wave-drag four-strut S^3, and the estimated C_D of an improved two-strut design taken from Reference 3. Notice that the values of C_D for the 3000-ton ships are significantly lower than those of the small models, primarily due to the Reynold's number effect on frictional drag and the use of thinner struts. The wave drag portion of the estimated value for the S^3 ship was calculated by Dr. R. B. Chapman of NUC using linearized thin ship theory in which all strut-strut, strut-hull, and hull-hull interactions were included. This same theory has provided excellent agreement with a large number of tests conducted on various struts, strut-hull combinations, and complete S^3 models. Reference 4 by Dr. Chapman contains data for estimating the spray drag of surface-piercing struts at high speeds.

Figure 5 shows the ratio of the drag in waves to the drag in calm water for tests on a 5-foot model of a DE-1006 destroyer (Reference 5), and for tests on a 5-foot model of an S^3. The drag of the destroyer model increases by factors of five or more in waves, while waves are shown to have no significant effect on the drag of the S^3 model.

Figure 6 shows the power required for a 3000-ton, four-strut S^3 compared with the estimated power requirements for a hydrofoil, a high-speed surface effect ship and a destroyer. The results show that the S^3 requires significantly less power than either a hydrofoil or SES at speeds up to around 50 knots.

A photograph of a model of a 3000-ton S^3 is shown in Figure 7, together with a list of some of its estimated characteristics.

STABILITY

A wide variety of model tests have shown that the S^3 is inherently both statically and dynamically stable. In regard to static stability, the metacentric height in roll can be calculated from the equation

$$GM = \frac{I}{\nabla} - BG$$

where $I \doteq \frac{b^2}{4} A$ = moment of inertia of the total waterplane area A,

b = strut center-line spacing,

∇ = displaced volume, and BG is the distance upward from the center of buoyancy to the center of gravity. Large topside loads can be carried even with a small waterplane area due to the substantial transverse and longitudinal strut spacing.

Tests in large waves and high simulated winds have shown that GM in roll should be around 3/4 of the hull diameter (alternatively, approximately 8% of the beam), although values as little as 1/4 of the hull diameter are acceptable. Tests indicate that motion in beam waves reduces as the roll GM increases, contrary to some monohull results. However, since both wave drag and structural weight increase as the strut waterplane area and spacing increase, the roll GM should be made no larger than necessary.

The metacentric height in pitch is calculated from the same equation as for roll, except I now refers to the longitudinal area moment of inertia. Tests to date on S^3 models have shown that motion in waves reduces as the pitch GM increases. In other words, the struts should be well-spaced in the longitudinal direction. This is one of several reasons why the four-strut configuration was selected as a typical (but not the only) design form for an S^3.

Figure 8 shows typical waterplane areas for a monohull, a catamaran ship, a two-strut low waterplane ship, and a four-strut S^3. Note that the S^3 has the greatest static stability in both roll and pitch per unit waterplane area because the waterplane area is concentrated in the four corners of the ship where it is most effective. Another advantage of the four-strut configuration is that it has less virtual mass in the transverse direction than the two strut design, and therefore will have less motion and hydrodynamic loading in beam seas.

One of the first questions explored in a series of S^3 model tests conducted in 1969 concerned the dynamic stability of an S^3. Figure 9 shows pitch data obtained on several 5-foot model configurations tested in calm water in the General Dynamics Aeromarine Test Facility model towing basin in San Diego, California. The hull diameters were 4 inches. Figure 9 shows that all models were stable at all test speeds except the non-S^3 model designated C + N which had no stabilizing fins. Thus, these tests showed that the S^3 stabilizing fins were necessary for dynamic stability at F_∇ greater than about 0.9. This result was in good agreement with S^3 design theory which shows that the dynamic instability of bare hulls will overcome the static stability provided by the struts above some critical speed unless stabilizing fins are incorporated.

A very useful device to further investigate the dynamic stability of an S^3 is the 5-foot radio-controlled model shown in Figure 10, which was tested in 1970. This model was stable under all test conditions and controlled well. All motions were well damped at rest and highly damped when underway. It operated well in waves and wind at all angles, although the greatest motion occured in large following waves. Figure 11 shows an 11-foot model built and tested at the Naval Ship Research and Development Center in 1971. This model performed similar to the 5-foot model suggesting that model tests and the known scaling relationships are valid.

MOTION IN WAVES

During the 1969 towing tests, various S^3 model configurations were tested in 4-inch X 80-inch waves in head and following seas. The non-dimensional pitch and heave amplitudes for two S^3 models in head seas are shown in Figure 12 together with the pitch and heave amplitudes of a 5-foot model of a C-4 monohull ship. Note that the motion of the S^3 models is significantly less than that of the monohull model. The S^3 models were also tested in a variety of wave lengths, and no resonance was found in head seas.

The test results in following waves showed significantly more motion, as seen in Figure 13. The monohull was not tested in following waves. The wave height was equal to the hull diameters, so the waves were relatively high. Tests in 2-inch waves showed considerably less motion. Data taken on the lift force and pitching moment indicated that small control surfaces and an automatic control system would significantly reduce motion in following seas.

Tests at rest in beam seas showed that the roll of the S^3 models was significantly less than that of the monohull model, and no resonance occurred at any of the wavelengths tested.

AUTOMATIC CONTROL SYSTEM

The combined use of horizontal canard control fins near the noses of the hulls, and controllable stabilizing fins near the aft end of the hulls, provides motion control over heave, pitch, and roll in high sea states.

Figure 14 presents computer results obtained by Dr. D. T. Higdon of NUC showing the reduction of heave and pitch in head waves which is achieveable by automatic stabilization of an S^3 ship similar in shape to the radio-controlled model of Figure 10. The already small motions are reduced by a factor of four or more.

Figure 15 shows the computer results for motion reduction in following waves. In this case, the result is much more dramatic. Heave is reduced by factors of twenty or more, and pitch is reduced by factors of five to ten.

SUMMARY

A considerable number of model tests, theoretical studies, and design studies have been conducted on the S^3 concept. The results show that the S^3 is highly stable and seaworthy (both at rest and underway), more efficient at higher speeds than conventional ships, and will provide a near-level ride if automatically controlled in high sea states. Also, many advantages result from its unusual hull form for various kinds of military and non-military applications.

REFERENCES

1. Lang, T.G., "S^3-- New Type of High-Performance Semisubmerged Ship," American Society of Mechanical Engineers, Paper No. 71-WA/UnT-1, Winter Annual Meeting, Nov 28 - Dec 2, 1971.

2. Leopold, R. "A New Hull Form for High-Speed Volume-Limited Displacement-Type Ships," Society of Naval Architects and Marine Engineers, Paper No. 8, Spring Meeting, May 21 - 24, 1969.

3. Stevens, R.M., "New Dimensions in Naval Catamarans," American Society of Naval Engineers, ASNE Day Meeting, May 4 - 5, 1972.

4. Chapman, R.B., "Spray Drag of Surface-Piercing Struts," Naval Undersea Research and Development Center, TP-251, September 1971.

5. Sibul, O.J., "Ship Resistance in Uniform Waves," Institute of Engineering Research, University of California, Berkeley, California, Report No. NA-64-1, January 1964. AD # 606272.

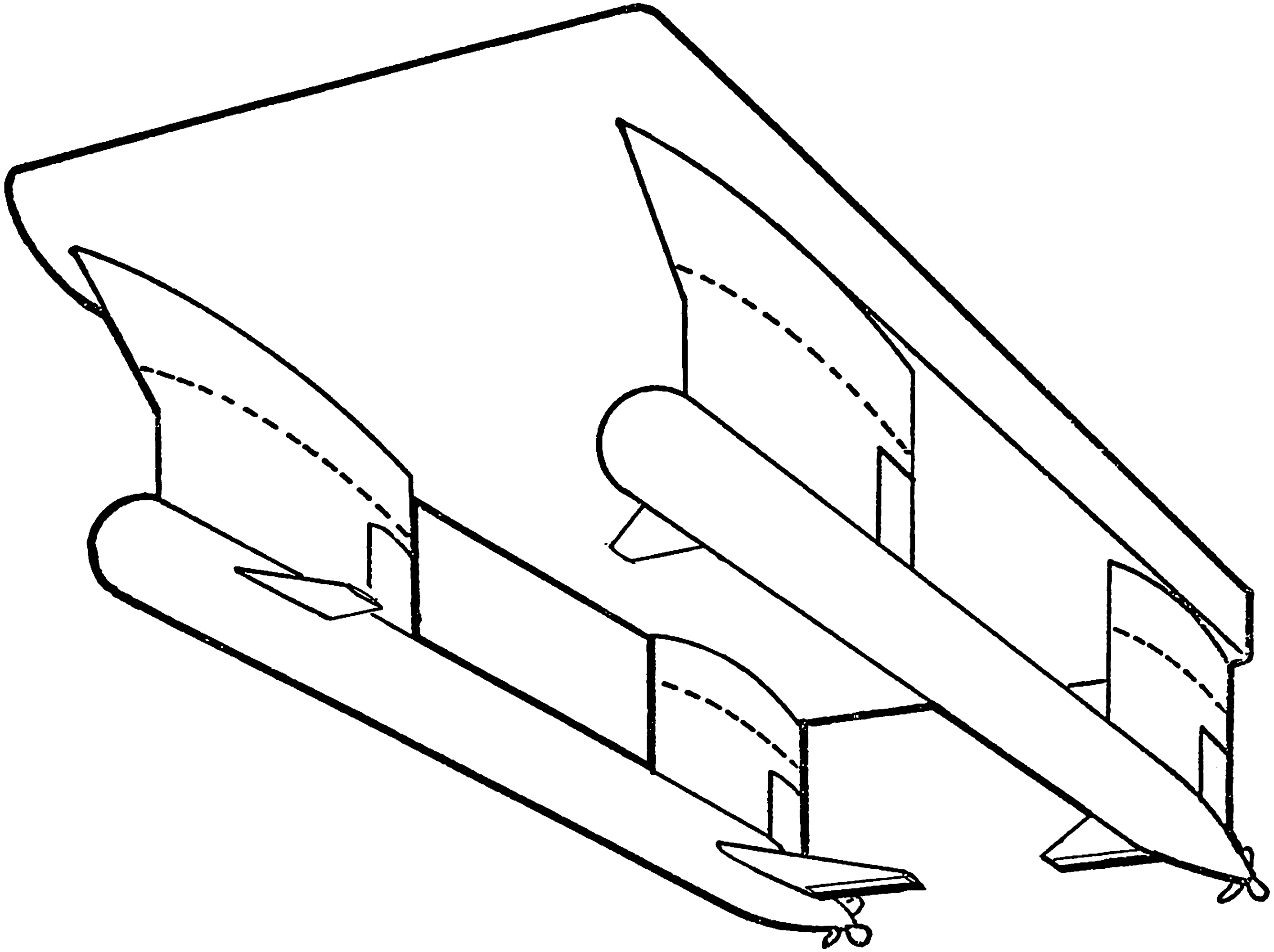


Figure 1.
BASIC S^3 SEMISUBMERGED SHIP CONCEPT

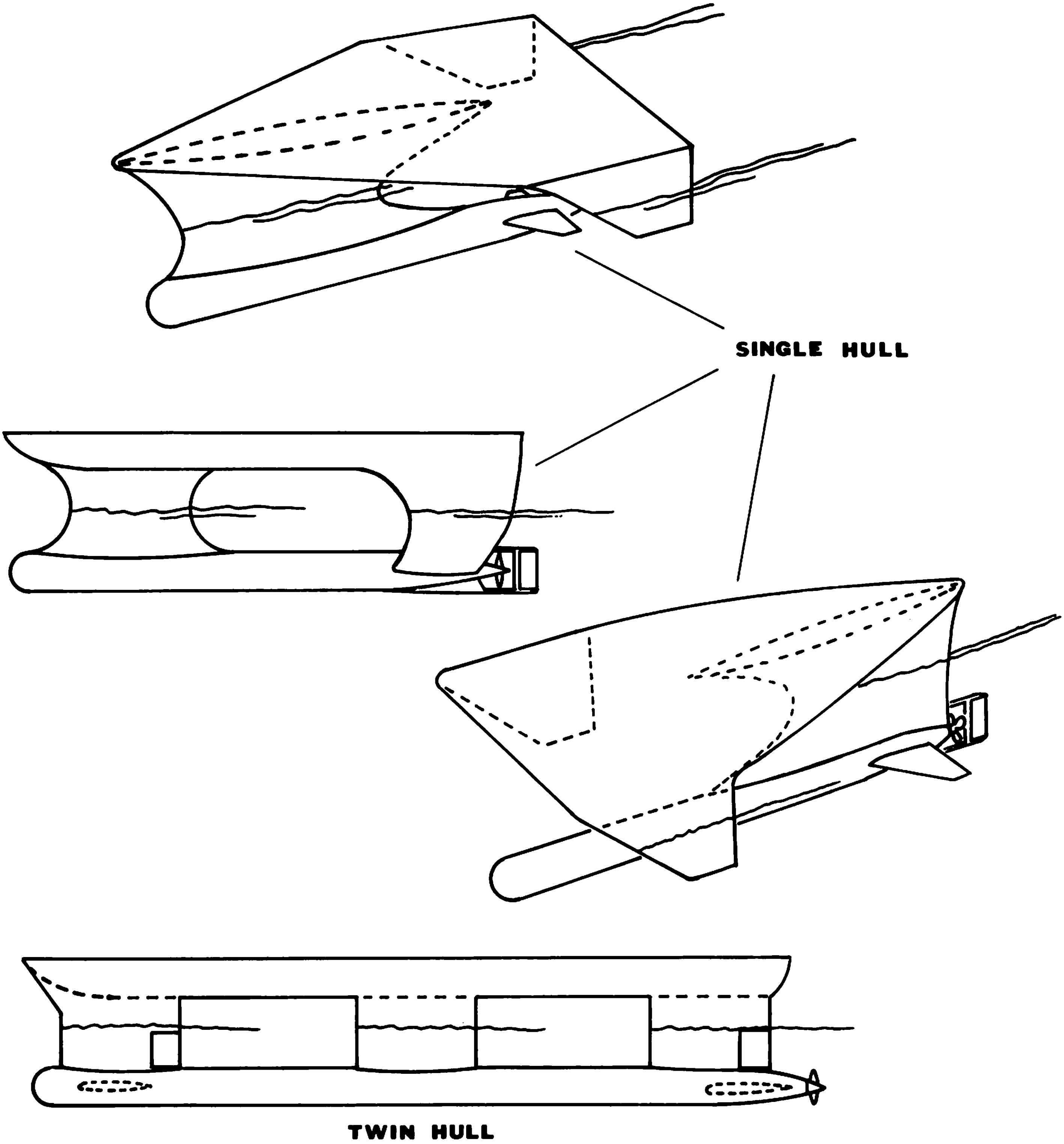


Figure 2.
ALTERNATIVE DESIGNS OF THE S^3 CONCEPT

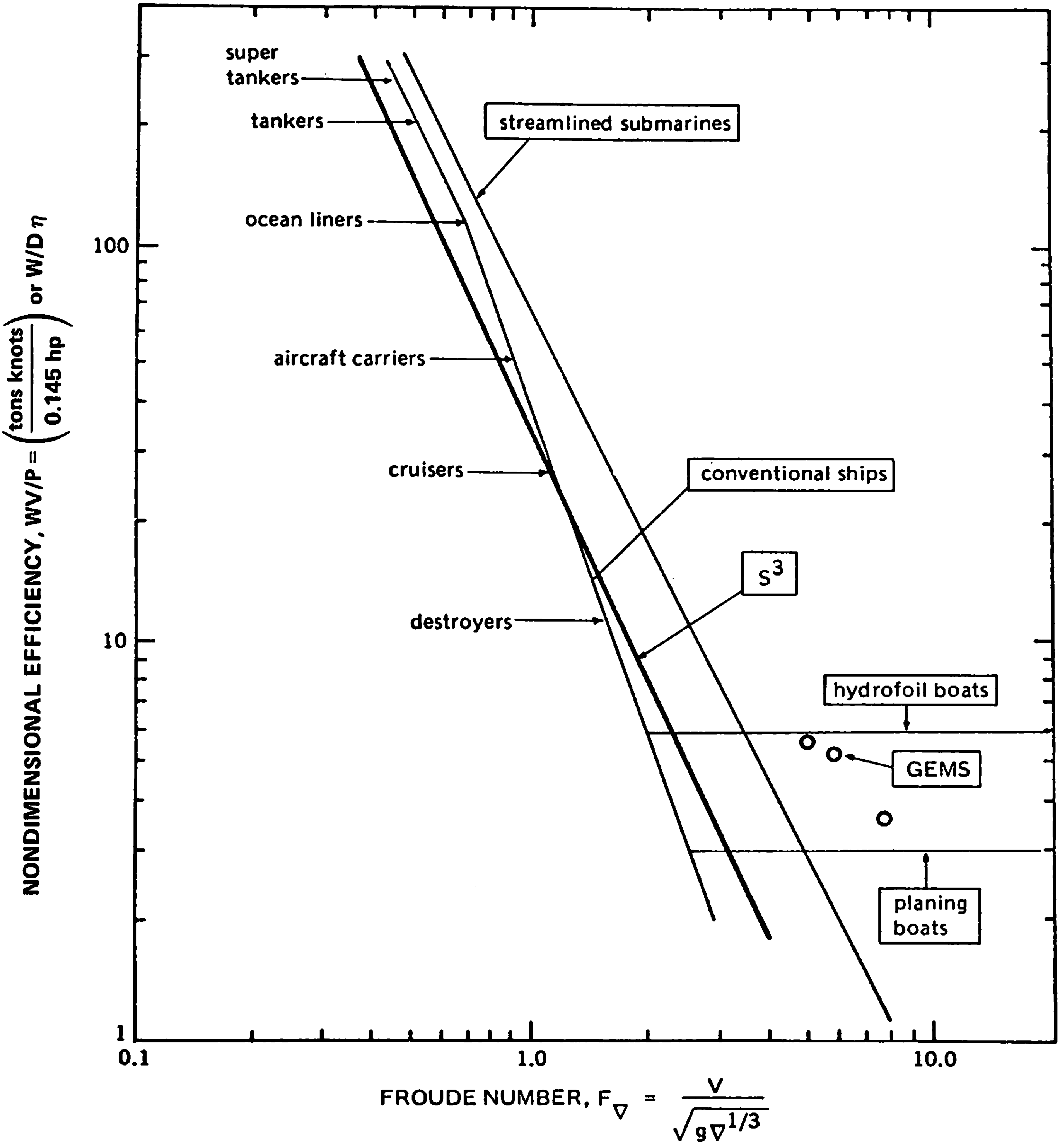


Figure 3.
HULL EFFICIENCY OF VARIOUS SHIP TYPES

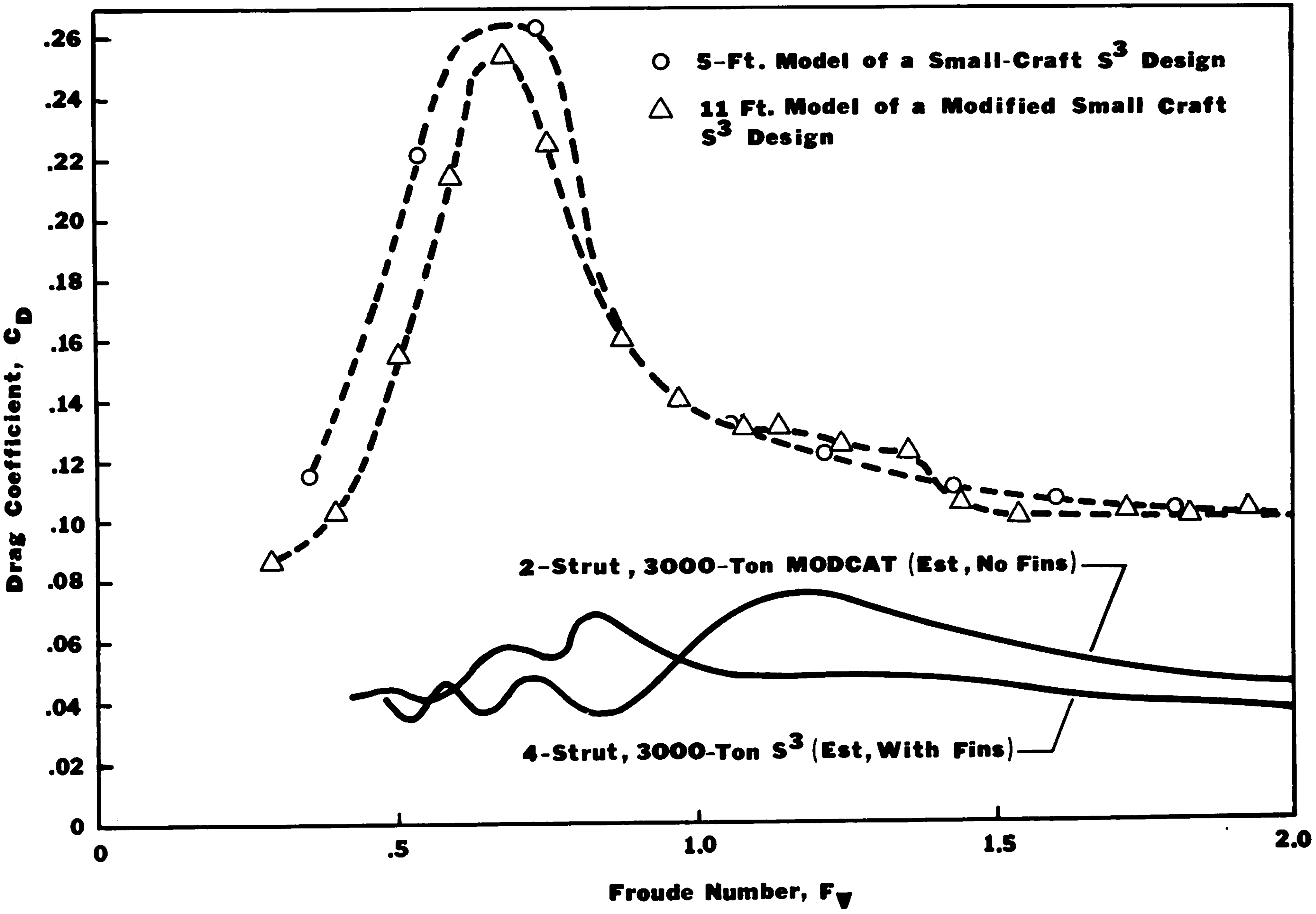


Figure 4.

DRAG COEFFICIENTS OF VARIOUS S^3 MODELS AND 3000-TON SHIP DESIGNS

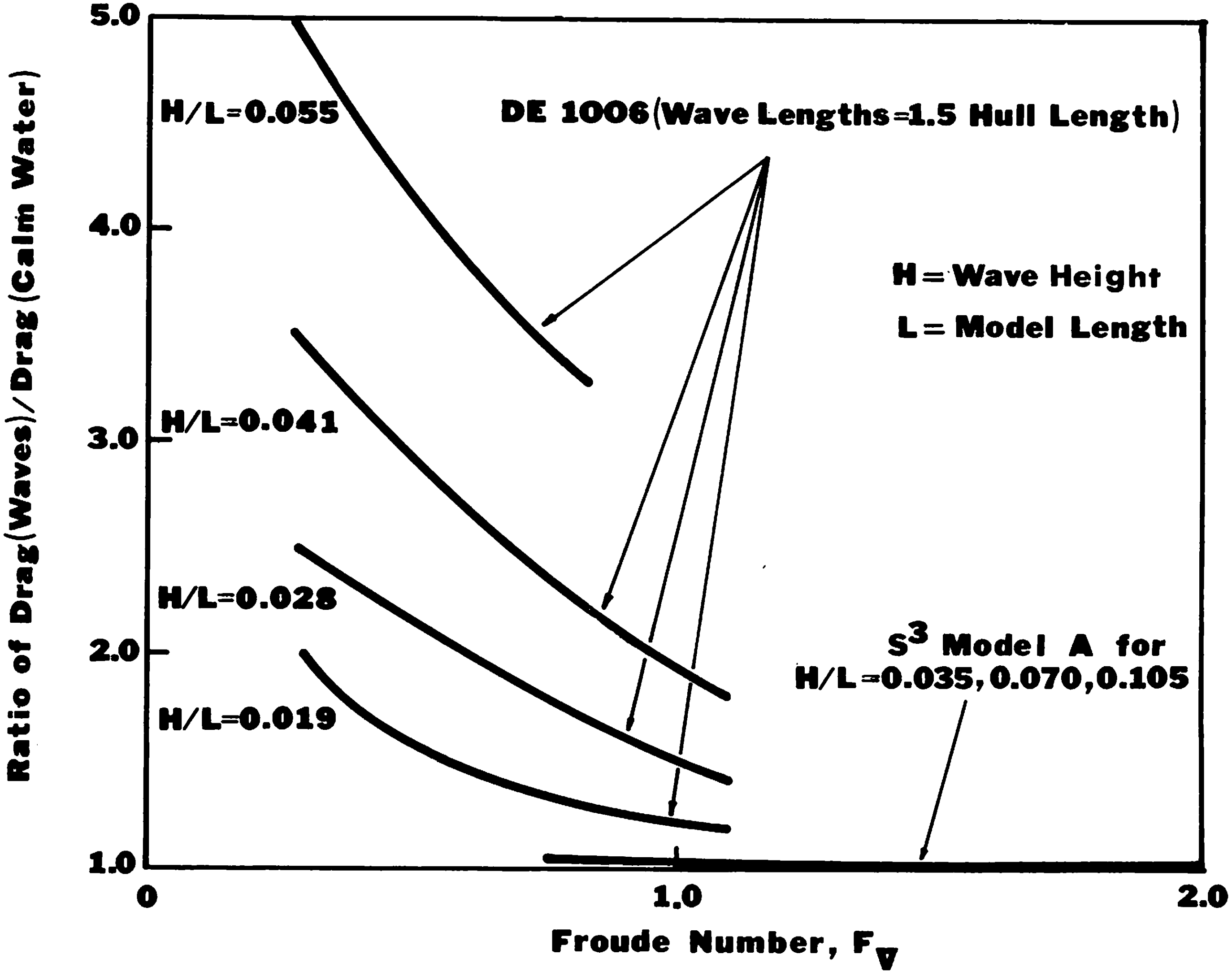


Figure 5.
EFFECT OF WAVES ON THE DRAG OF FIVE-FOOT DESTROYER AND S^3 MODELS

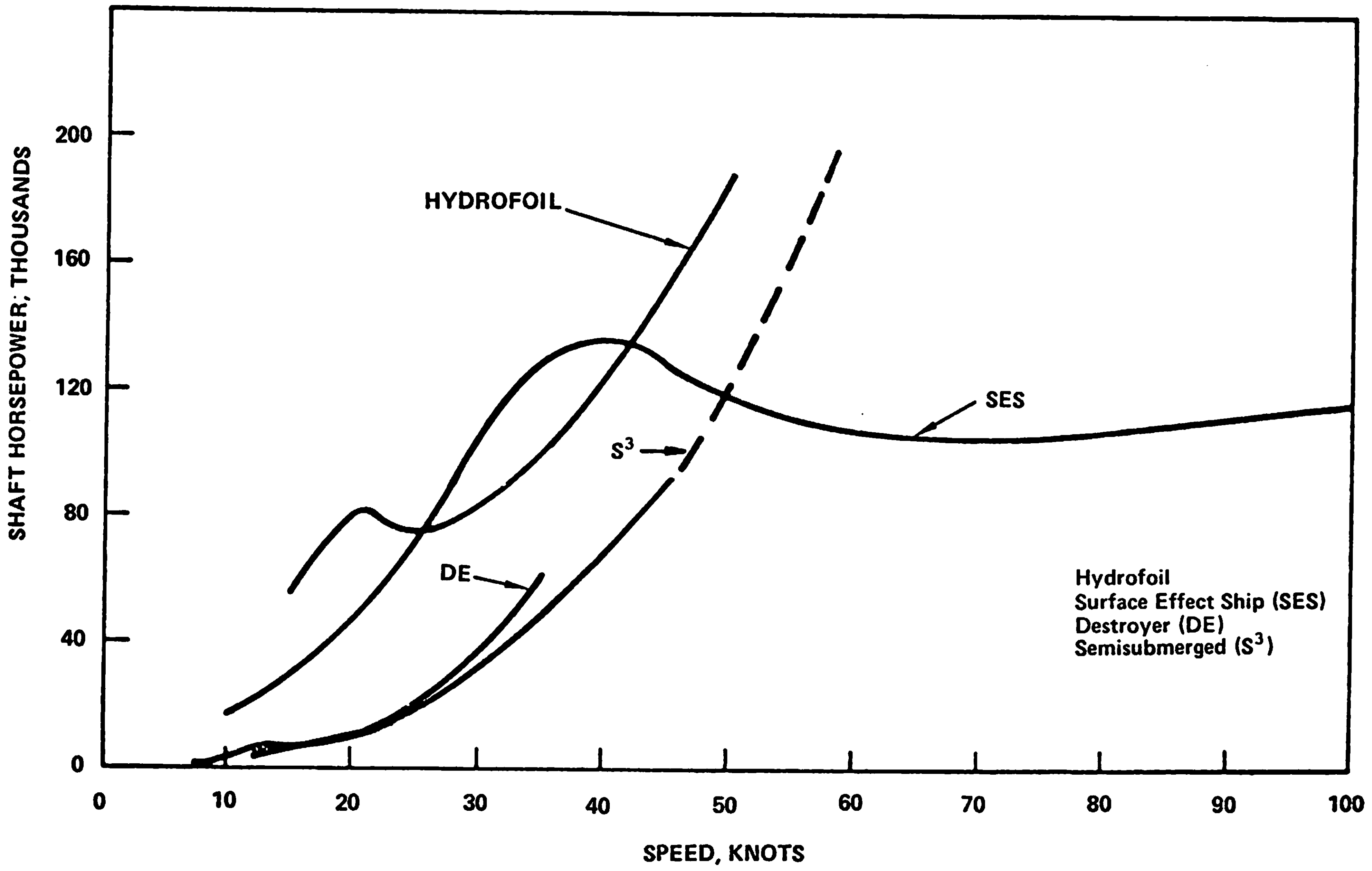
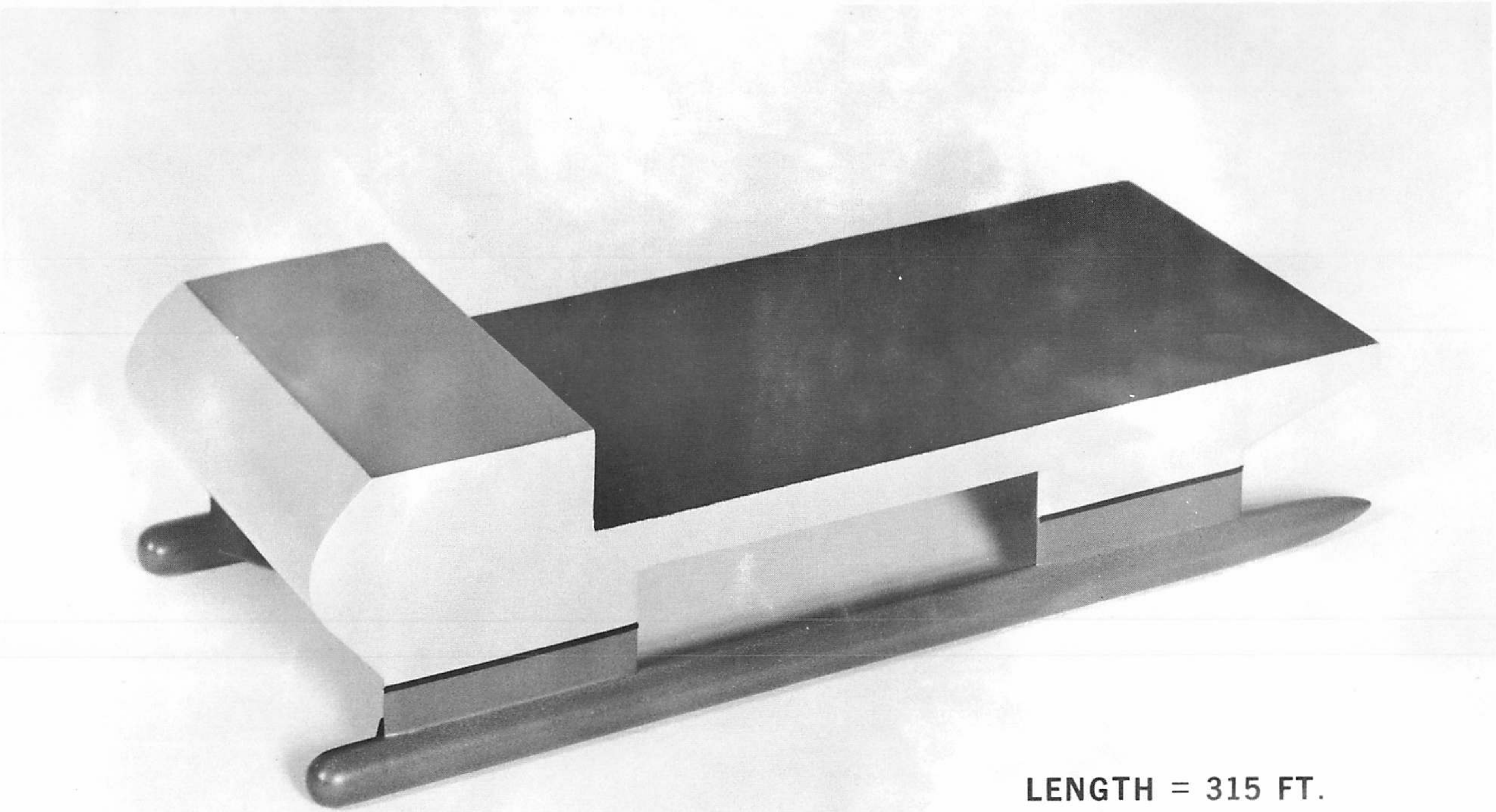


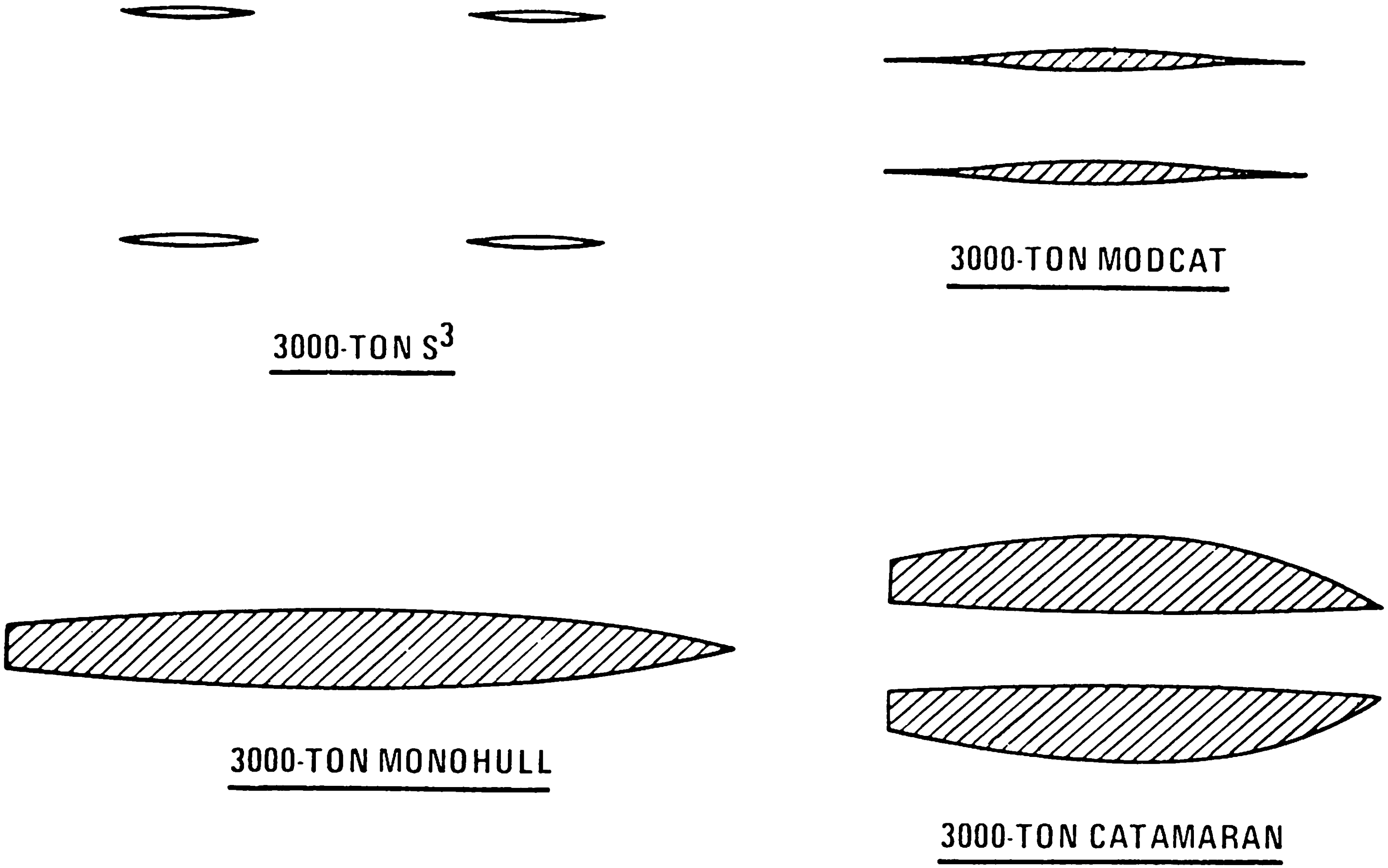
Figure 6.

POWER REQUIREMENTS FOR VARIOUS KINDS OF 3000-TON SHIP DESIGNS



LENGTH = 315 FT.
BEAM = 137 FT.
HULL DIAMETER = 14 FT.

Figure 7.
MODEL OF A 3000-TON S^3 SHIP



3000-TON S^3

3000-TON MODCAT

3000-TON MONOHULL

3000-TON CATAMARAN

Figure 8.
WATERPLANE AREAS OF VARIOUS SHIP TYPES

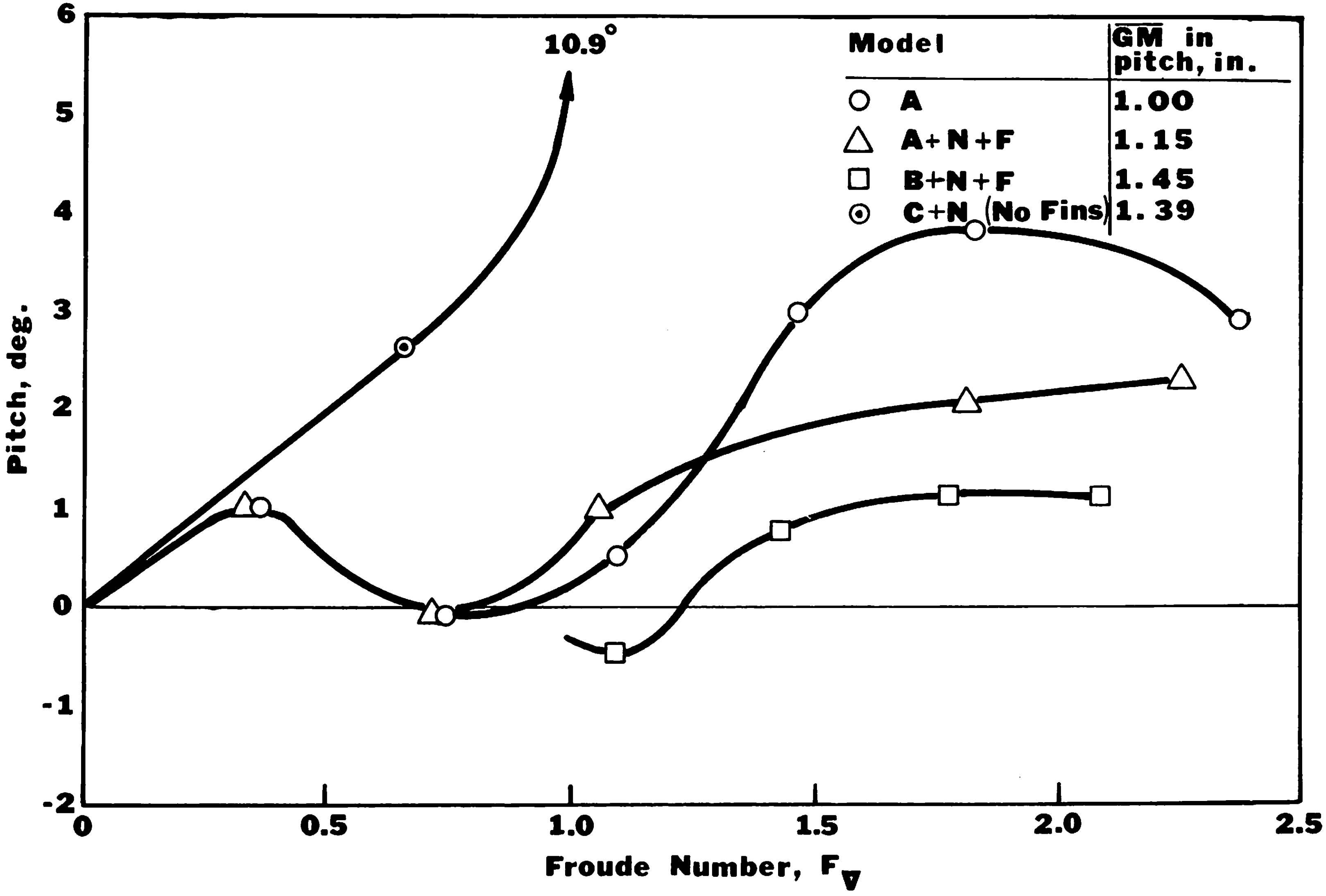


Figure 9.

PITCH IN CALM WATER OF S^3 MODELS AS A FUNCTION OF DISPLACEMENT FROUDE NUMBER

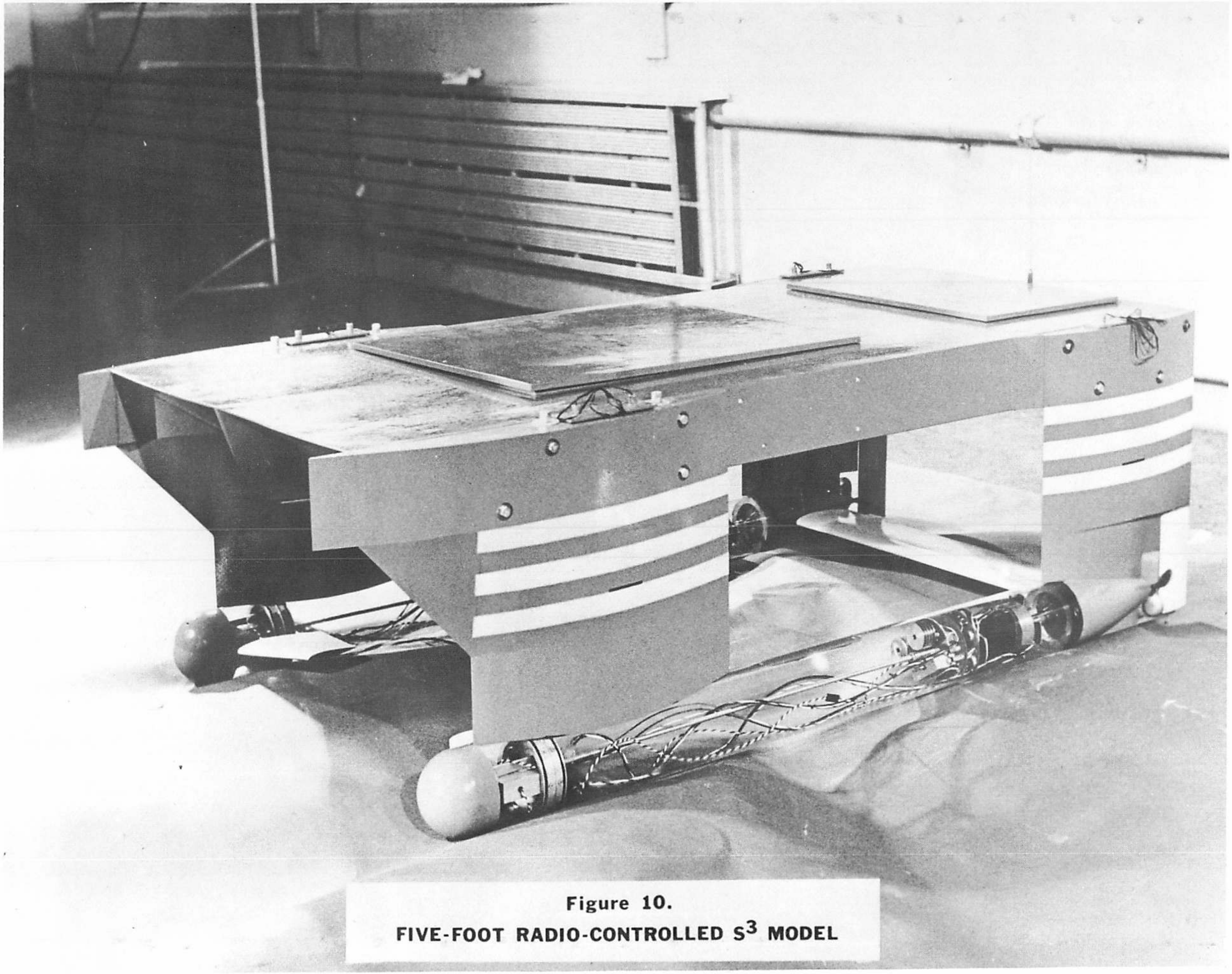


Figure 10.
FIVE-FOOT RADIO-CONTROLLED S^3 MODEL

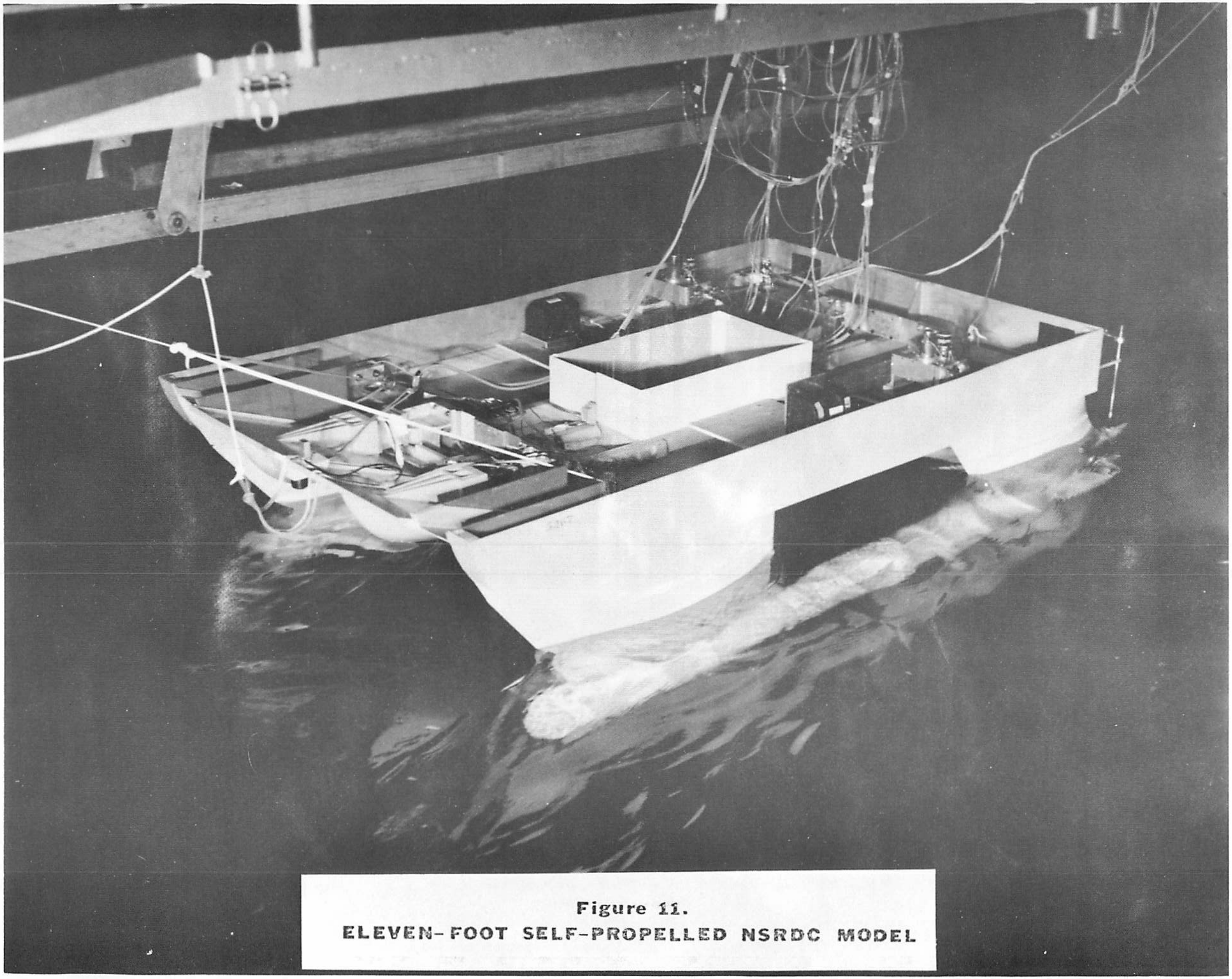


Figure 11.
ELEVEN-FOOT SELF-PROPELLED NSRDC MODEL

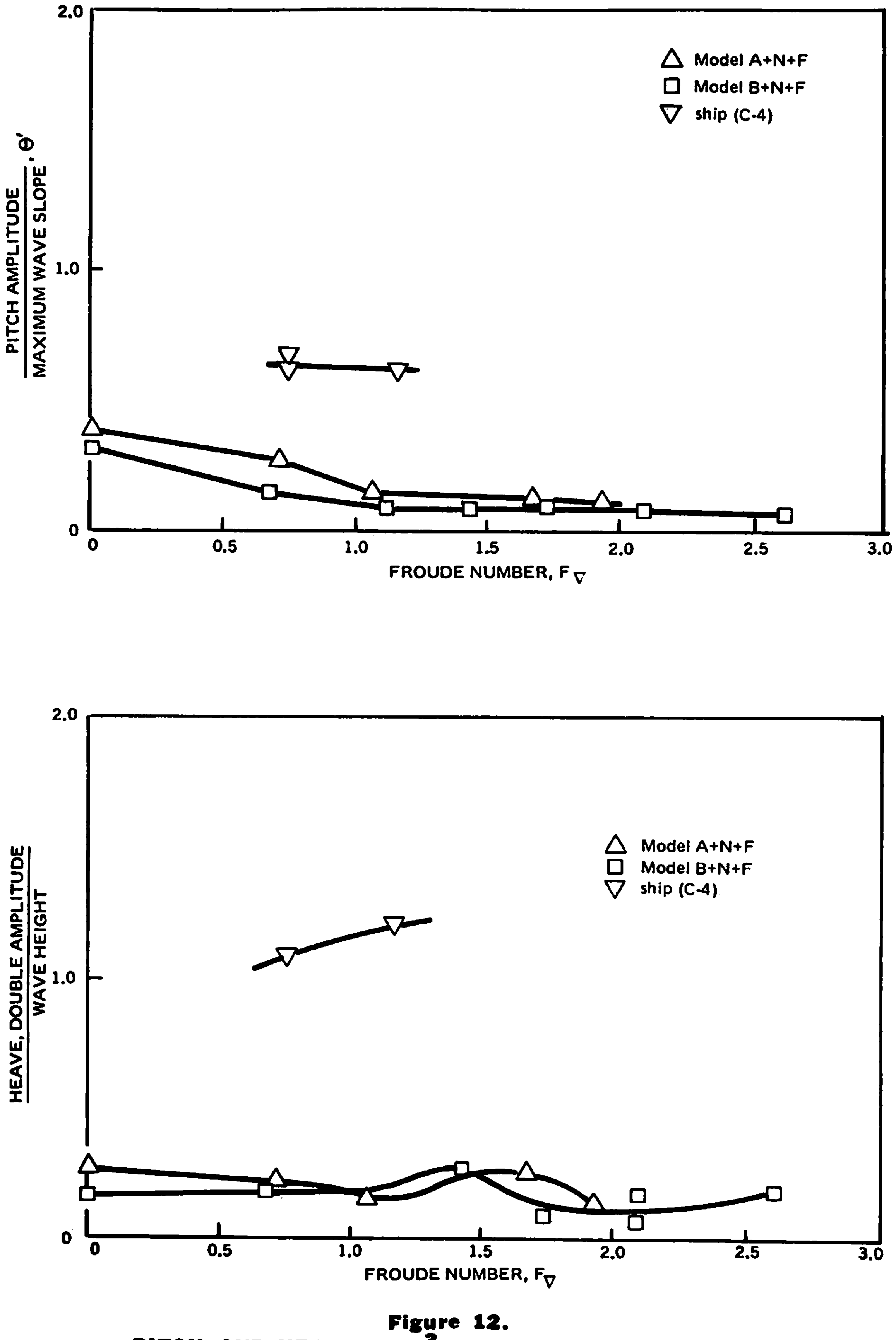
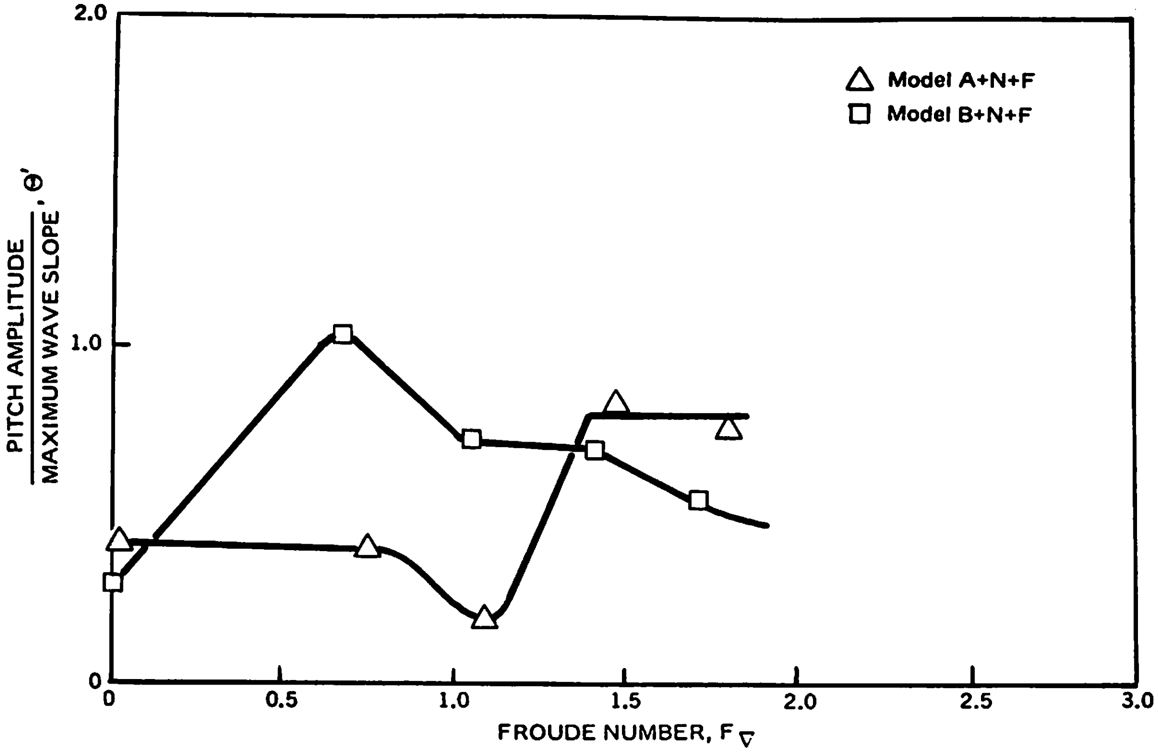


Figure 12.
PITCH AND HEAVE OF S^3 MODELS IN HEAD SEAS



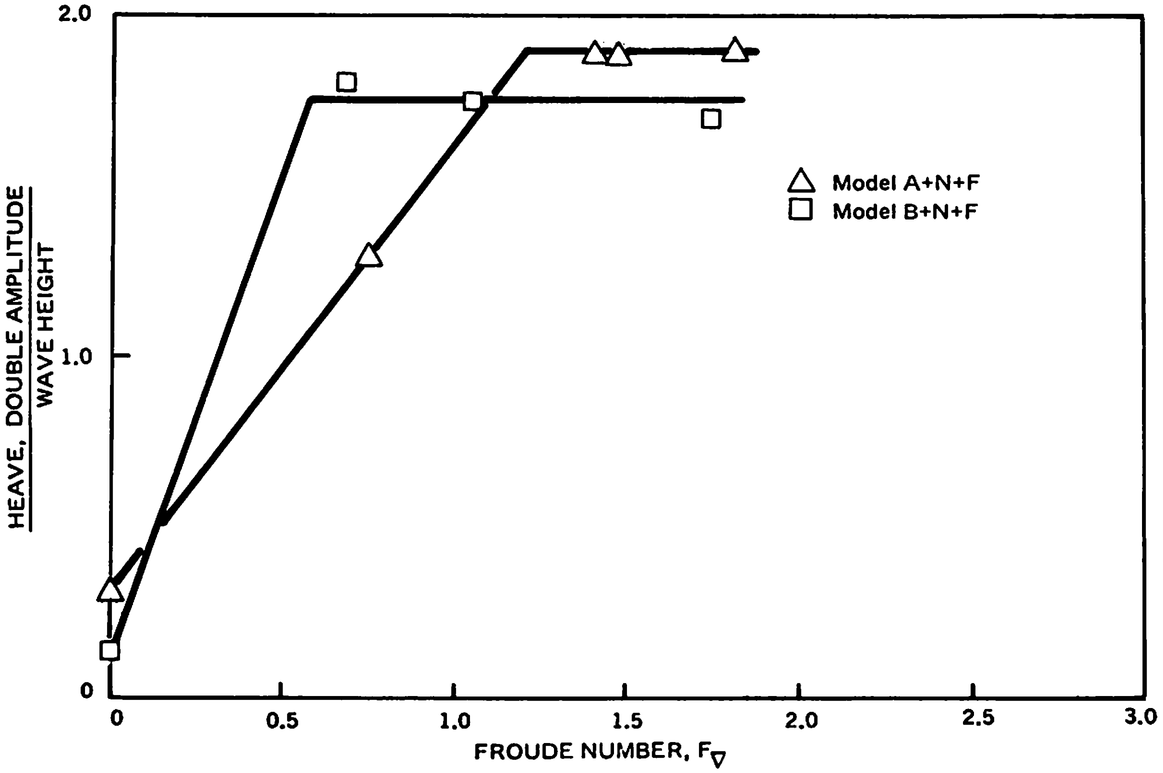


Figure 13.

PITCH AND HEAVE OF S^3 MODELS IN FOLLOWING SEAS

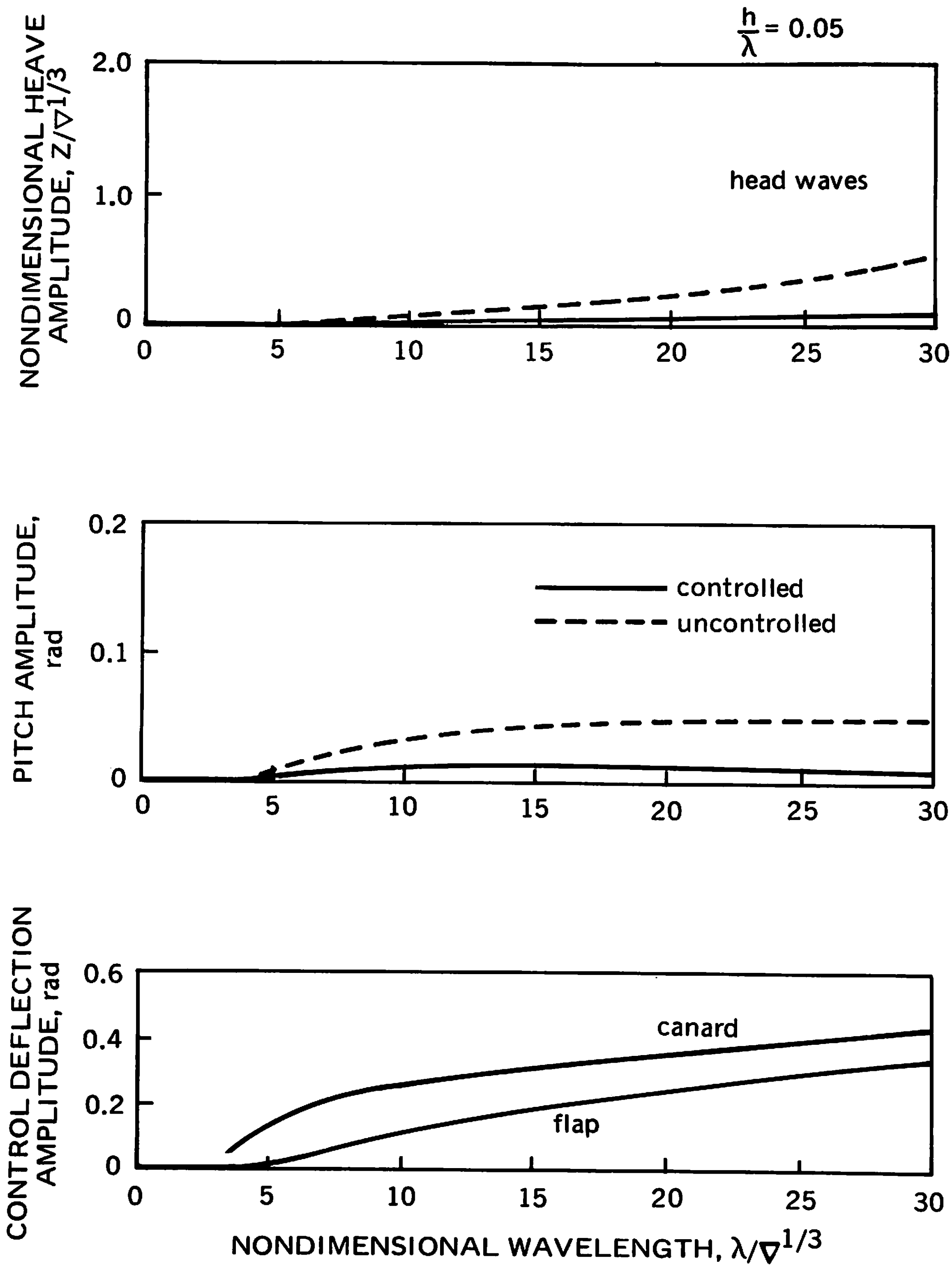


Figure 14.

EFFECTIVENESS OF AUTOMATIC CONTROL IN HEAD SEAS AT $F_\nabla = 1.65$

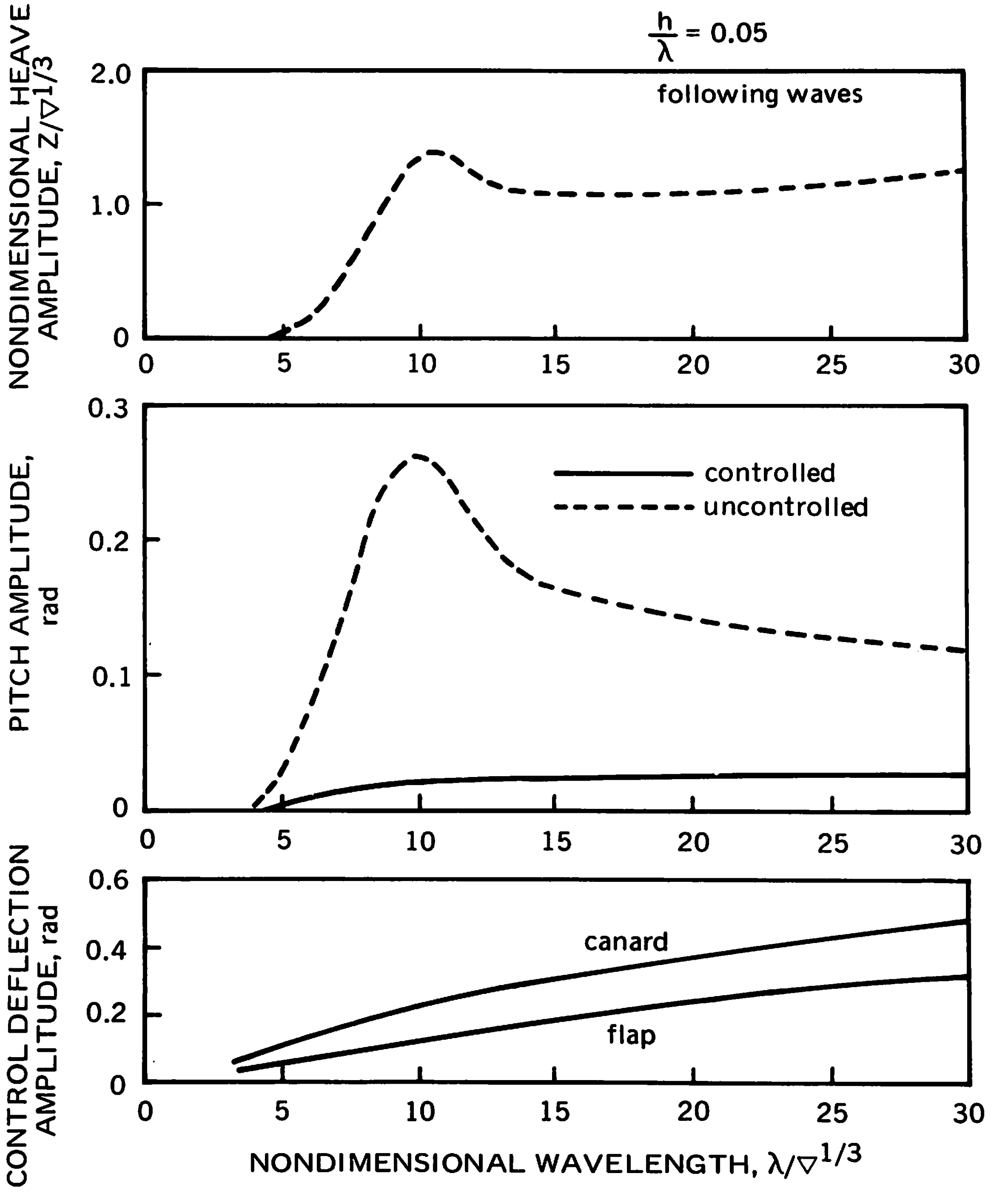


Figure 15.

EFFECTIVENESS OF AUTOMATIC CONTROL IN FOLLOWING SEAS AT $F_{\nabla} = 1.65$