SEMISUBMERGED SHIPS FOR HIGH-SPEED OPERATION IN ROUGH SEAS

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To evaluate methods to obtain high speed at sea without large increases in ship size, several hull configurations were surveyed; in particular semisubmerged craft designed to operate at or just below the surface. By increasing judiciously the amount of submerged hull-volume, both high-speed resistance and pitching motions in rough seas can be reduced.

The hull configurations that were surveyed included a craft that resembles a surfaced submarine, a slender ship with large bow and stern bulbs, and a craft (semisubmerged) that is similar to a shallow-running submarine with a permanent surface-piercing strut for air supply and exhaust. The semisubmarine, potentially, can exceed submarine speeds because of its low resistance and good sea performance. In addition, the air-breathing power plant of the semisubmarine weighs less and requires less space than a nuclear power plant.

The study of the calm-water stability characteristics of the semisubmarine at intermediate and extreme speeds shows that depth and directional stabilization can be achieved with tail fins of reasonable size, except at low and intermediate speeds, where stabilization by fin area alone is not attractive; however, active controls readily can provide operation at constant depth in calm water. Analog computer studies show a peculiar dependence upon the distribution of stabilizing surfaces and other parameters. Therefore, precise and extensive model tests are required to explore the near-surface dynamics of this craft to fully develop its advantages.

INTRODUCTION

The successful development of the true submarine has resulted in a craft that can remain submerged almost indefinitely and operate at high speeds in a three-dimensional realm of steadily increasing depth. When a submarine runs far below the surface, surface wavemaking resistance is virtually eliminated; the remaining resistance is caused almost entirely by skin friction. Although a submarine can be made squat in comparison with a surface ship to minimize the ratio of wetted surface to volume, its surface area is greater than that of a comparable surface ship. This is a disadvantage at moderate speeds; however, at high speeds, this disadvantage is more than compensated for by the elimination of surface wavemaking. Power is directly proportional to speed cubed, even at high speed; therefore, speed is limited only by the weight and size of the power plant.

The development of the submarine puts a new light on the problem of surface ship design. During World War II, the submarine and the destroyer were evenly matched. This is no longer true. Submarines have distinct advantages in speed and maneuverability, particularly when seas are rough. In addition, submarines have added advantages in evasiveness because they operate in a three-dimensional realm. To meet the challenge of the submarine, naval architects must develop high-performance surface ships. This problem has frequently been viewed with pessimism. It has been said that the only way to cope with the submarine is to go above the surface, as with a hydrofoil craft, or to go below it with another submarine. In this view, ships on the surface can only be fast if they are large, which increases cost.

There is another viewpoint, however, that suggests the need to give serious attention to the possibilities of more radical types of small surface craft that might be able to attain high speed even in rough seas.

POWER REQUIREMENTS

Figure 1 shows three directions for seeking higher ship speed than can be obtained with a conventional surface ship – for example, a destroyer. One direction is to go well below the surface to eliminate surface-wavemaking resistance. Another is to stay on the surface but to reduce surface-wavemaking resistance drastically with a longer and more slender hull. The third is to raise the hull above the surface with either a planing-type hull or hydrofoils.

In addition, Fig. 1 shows that there are a multitude of different possible types of craft, with successively larger submerged volumes, that can be designed to operate at the air-water interface. Other possibilities have been suggested by Boericke [1].

It is of interest to consider the comparative powering problems of these diverse waterborne craft. Because it is difficult to determine reliable figures for the propulsive coefficients, the comparison of the power required for these craft (Fig. 2) is based on effective horsepower (EHP). Displacement is a reasonably good index of size; therefore, EHP's have been estimated for the craft shown in Fig. 1. Each craft is assumed to have a displacement of 2844 tons, which corresponds to the displacement of a DD-692 class destroyer. This displacement was selected as the desirable maximum displacement for high-speed craft.

Figure 2 is a rough comparison of the calm-water resistances of these waterborne craft at speeds up to 70 knots. The craft that has the lowest resistance is an ideal, deep-running submarine with a minimum of appendages, optimum hull form, and an assumed length-to-diameter ratio of 7.0. Not only is a deeply submerged submarine the lowest in resistance of any type of craft, but even at 60 or 70 knots the EHP is far from astronomical.

For an ideal submarine form (H) running with its center 1-1/4 diameters below the surface (that is, the upper surface of the submarine is 3/4 diameter below the surface) there is a pronounced hump in resistance that corresponds to the maximum wavemaking speed. The submarine is close enough to the surface to produce a surface wave that causes this rise in EHP. As the speed of the submarine increases further, the wavemaking resistance becomes a decreasingly important part of the total resistance.

For an ideal submarine (about 210 feet long) with a strut (about 30 feet long) piercing the surface (G) there is a sizable increase of EHP, which rapidly goes up with speed. Information is still rather sketchy on the resistance of struts piercing the surface, but the plotted values are believed to be roughly correct. The disturbance of flow by the strut is not

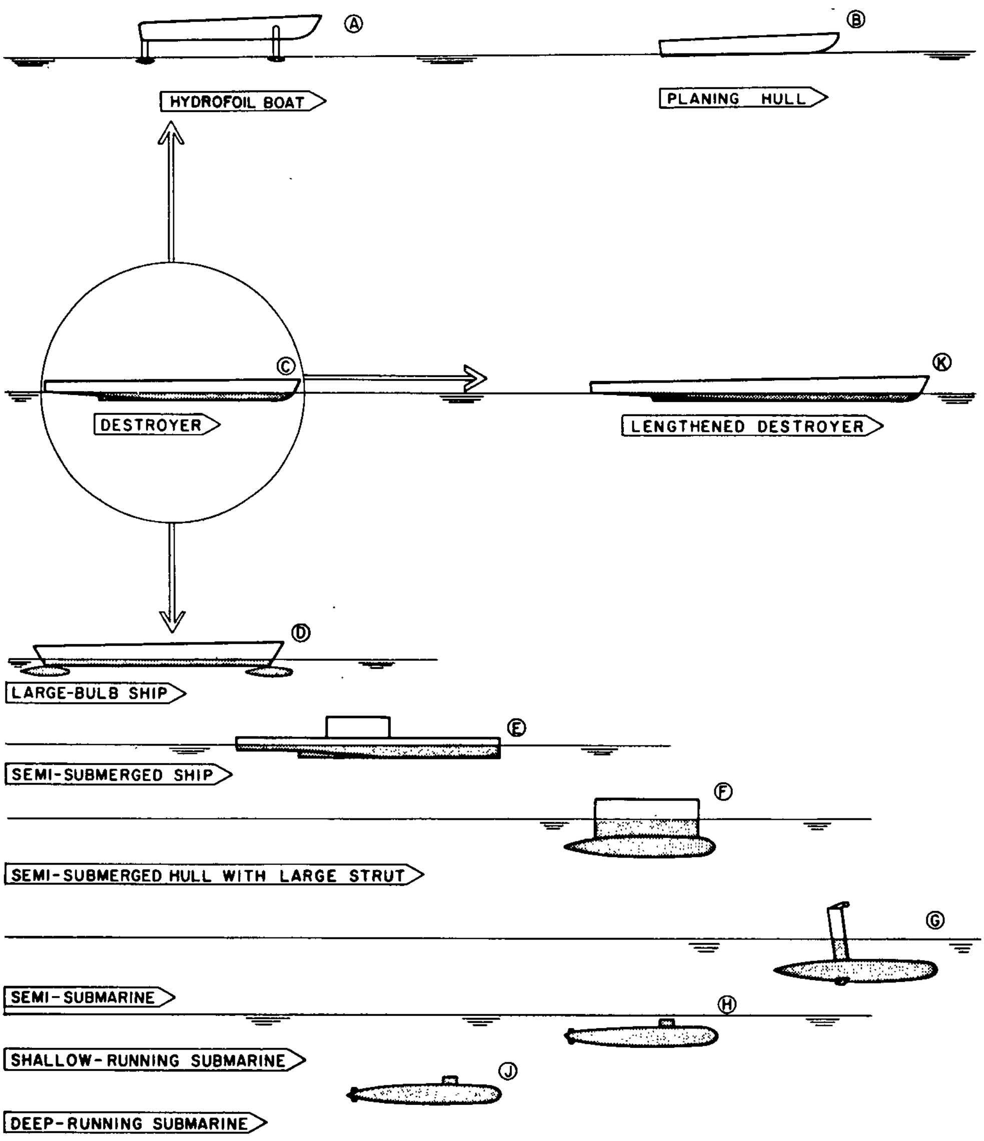

Fig. 1. Possible directions for seeking higher speeds at sea

wavemaking resistance in the usual sense (because the speed is very high for the length of the strut), but there is separation of flow, ventilation, and even cavitation that cause a very large increase in resistance, usually designated spray drag, which shows very emphatically the reason for trying to make the strut as small as possible.

For a typical destroyer (C), the EHP is considerably higher than for a submarine with a small strut, especially as speed goes up. In addition, this ship is slowed more than a submarine in rough water.

Figure 2 also shows that a surface ship could achieve very high speeds if it were designed to be much more slender than a destroyer (K). This would reduce the surface

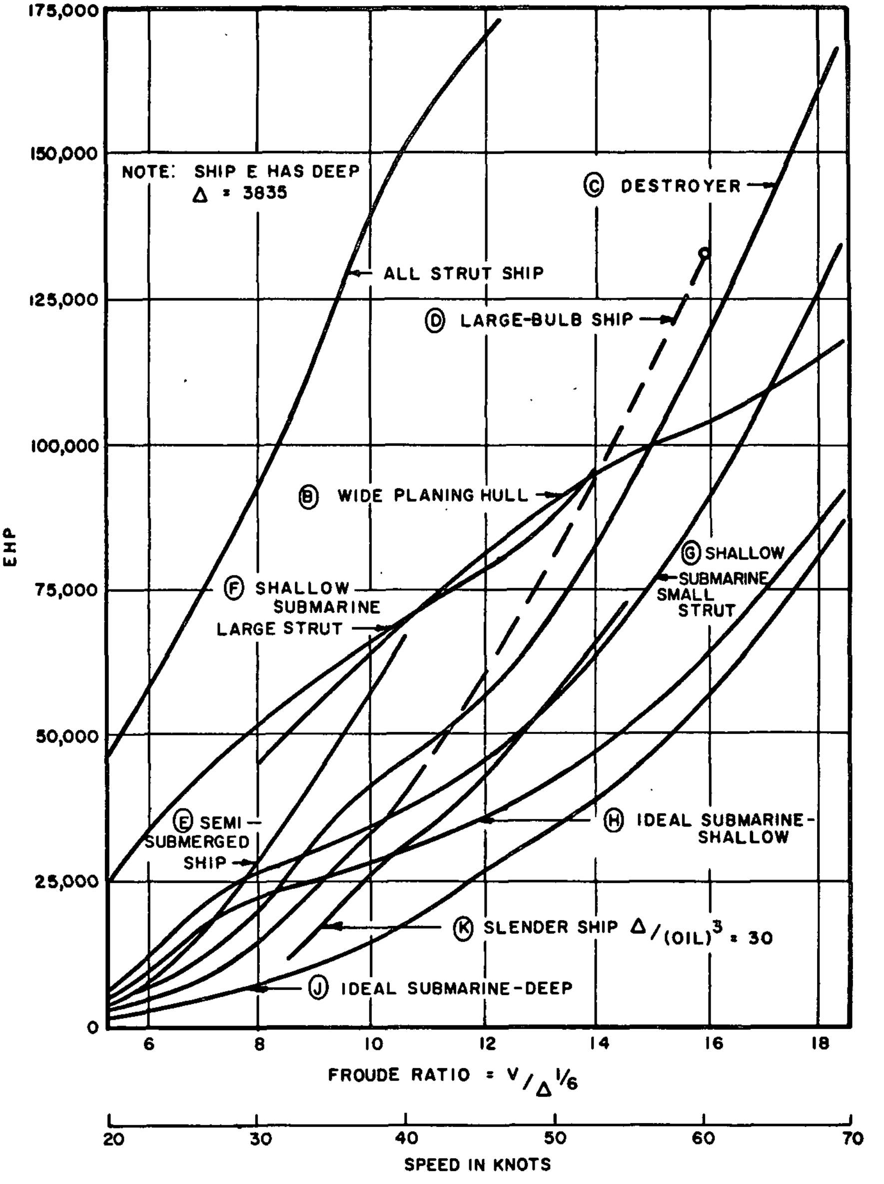

Fig. 2. Effective horsepower required versus speed for a group of bodies with $\Delta = 2844$ tons

wavemaking resistance and thus compensate for increased frictional resistance. As the speed of this ship goes up, the EHP curve almost coincides with the curve for the shallow-running submarine with a small strut. This suggests the latter type of craft has no resistance advantage over a slender destroyer designed specifically to go at very high speed. However, the very slender destroyer would run into trouble at high speed in rough water, and the near-surface ship with strut may have advantages.

A submarine with a very large strut (F), as suggested by Boericke [1] and investigated by Mandel [2], shows comparatively high resistance, especially at high speeds. An all-strut ship – that is, a ship of the same displacement and about the same draft as the others but with its entire hull extending through the surface – has a very high EHP. Figure 2 also indicates that a large planing boat (B) of optimum-breadth would be better only at very high speeds (near the limit of this figure).

The semisubmerged hull form (E), reported by Lewis and Odenbrett [3], and the slender hull with large bow and stern bulbs (D) are capable of high-speed supercritical operation in rough seas with comparatively small pitching motions. The first of these ships, (E), shows rather poor calm-water EHP performance at deep rough-water draft, but the latter, (D), is remarkably good up to the limit of the speed range so far tested.

Therefore, a number of types of craft intermediate between conventional ships and submarines are feasible that promise remarkably low power requirements. However, the larger the proportion of the hull that is submerged, the more difficult the ship design problem becomes; available hull volume is curtailed and problems of transverse stability (static) become increasingly difficult with greater submergence. The cost of the craft can also be expected to increase correspondingly. Hence, it is desirable to consider and compare all types of craft thoroughly to determine the most satisfactory compromise for any particular need.

ROUGH-WATER PERFORMANCE

Of course, it is not enough for a surface or near-surface craft to show favorable calm-water resistance at high speed. If it is to compete with a deeply submerged submarine, the ship must be able to maintain good speed in rough-storm seas. This may be, in part, a powering problem. However, in high-speed craft, it is usually mainly a matter of avoiding or minimizing ship motions and indirect effects – such as wet decks, slamming, propeller racing, local high accelerations, etc. The ideal craft, therefore, is one that provides the best compromise between low-resistance characteristics and outstandingly good performance in rough water – capable of high speed in any sea condition.

(As background for the discussion of the problems of rough water performance, the balance of this section has been adapted from Ref. 4.)

Ship motions at sea are usually resolved into six components for study: the angular motions of roll, yaw, and pitch and the translatory motions of heave, surge, and sway. Some are more troublesome than others, but when one or two are reduced the others are apt to become more noticeable. Rolling has received particular attention ever since steam replaced sails and the steadying effect of canvas was lost. Because the forces involved in rolling are small, it has proved feasible to reduce these amplitudes drastically by various antirolling devices. The simplest device is the bilge keel, which has been generally accepted in shipbuilding for many years. Its effectiveness can be explained on the basis of the theory that irregular storm seas contain many regular component waves of a wide range of periods superimposed on one another. A ship will respond much more violently to one particular band of wave periods (or frequencies) than to any others. This period is the natural rolling period of the ship. Consequently, the most serious rolling occurs in the natural period of the ship and, therefore, may be classed as synchronous rolling. In any oscillating system, simple damping is always effective in reducing synchronous oscillation. Therefore, by increasing the damping of roll, the bilge keel markedly reduces serious synchronous rolling.

Another damping device is the passive antirolling tank system, in which there has been a notable resurgence of interest recently. Such tanks installed in naval auxiliaries have proven to be remarkably effective. Important features are their low installation cost and equal effectiveness hove to and at forward speed. However, reduction rather than elimination of rolling is the best that can be expected.

For moderate and high-speed vessels, a much more effective method of reducing rolling appears to be controllable fins. These devices are so effective that the rolling problem appears to have been solved in principle, except for low-speed vessels for which an activated tank or gyroscope system is applicable. This does not mean that further research is not needed. There are problems of the interaction or coupling of other motions, particularly yaw, of obtaining increased effectiveness with reduced weight and cost, of avoiding structural failures of fin shafts, etc. Furthermore, the system for the control of roll must be coordinated with the system for the control of yaw, that is, the steering gear and gyro-pilot.

Heaving and pitching motions are the most difficult to overcome and present the most serious problems because they involve large vertical accelerations and cause shipping of water, slamming, and propeller racing. Furthermore, when other motions are controlled or reduced, they become even more noticeable. Consequently, attention will be focussed on these symmetrical modes of motion, assuming that methods are available for solving the other motion problems.

Model research in regular-head seas has brought three important facts into prominence [5]: (a) the amplitudes of motion are greatest in the vicinity of synchronism between the period of encounter and a ship's natural period of oscillation, (b) phase relationships leading to wet decks and slamming also are characteristic of synchronism, and (c) waves appreciably shorter than the length of a ship do not cause serious motions even at synchronism. On the basis of these general facts, there are two possible methods by which significant reduction of pitching and heaving amplitudes can be sought: avoiding synchronism with waves of ship length or longer, and reducing the magnification effect, which causes increased amplitudes near synchronism.

Although damping devices such as bow fins can reduce the magnification of motions somewhat, the most effective method of reducing motions is by avoiding synchronism. In a regular swell, this undesirable condition can be avoided by changing either course or speed. If the speed is changed, synchronism can be avoided by an increase or a decrease. If the speed for pitch synchronism is the critical speed, slowing brings the ship into the subcritical range; increasing speed brings the ship into the supercritical range. Figure 3 (from Ref. 5) shows the relationship between pitching period and speed for synchronism in head seas. For other headings, a simple cosine correction must be introduced. The curves that define the conditions for synchronous pitching show that (a) the longer the wavelength, the higher the critical period, and (b) in any particular wavelength, the lower the ratio of $T_p/\sqrt{L}$, the higher the critical speed.

When a ship encounters irregular storm seas, the situation does not remain so simple. Oceanographers have shown that storm seas can be considered as composed of a great many regular-wave trains of varying length and direction of travel, all superimposed on one

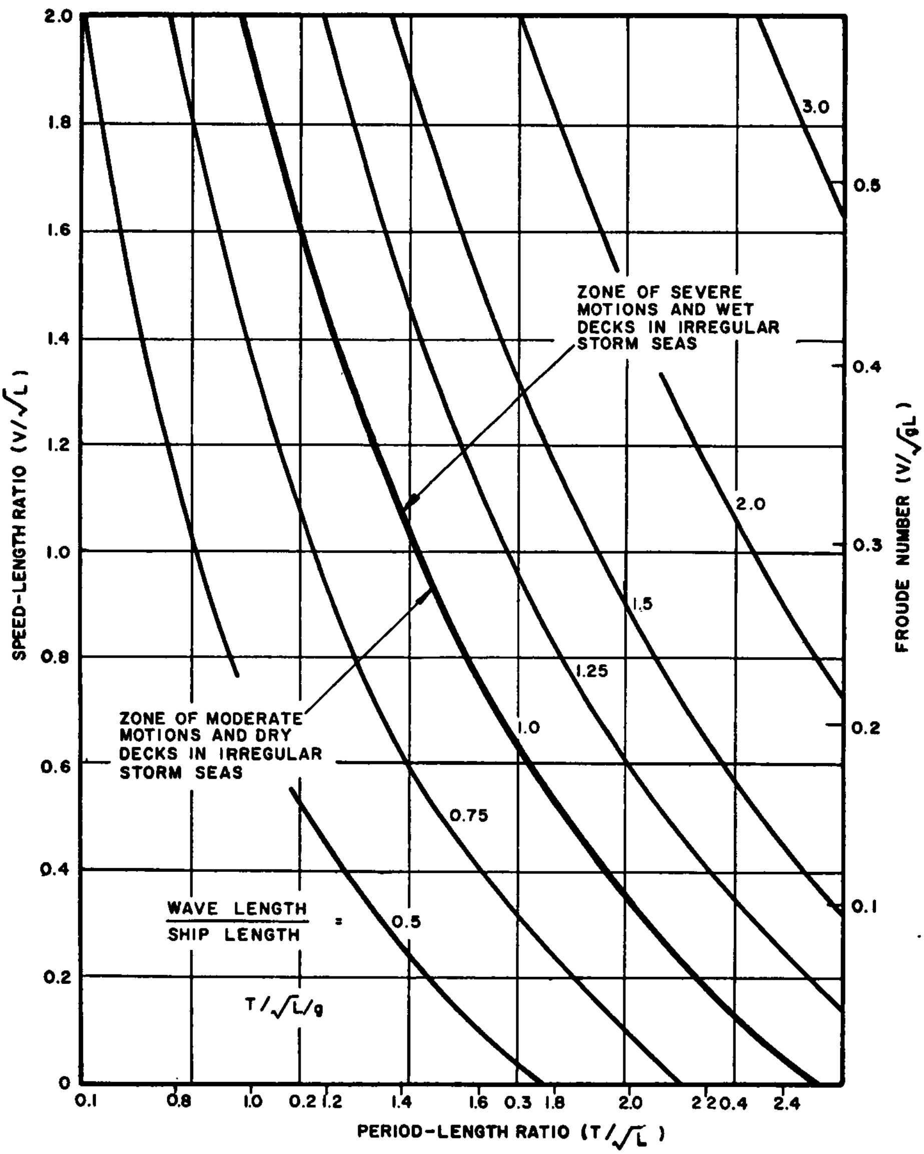

Fig. 3. Theoretical speed-length ratios for synchronous oscillation in regular-head seas of different lengths (from Ref. 5)

another [6]. They also have confirmed the observations of seamen that shorter waves are formed first in a storm. As the wind continues to blow, longer components are formed without seriously affecting the smaller components. For a particular wind velocity, the sea reaches a limit when it attains its fully developed state. If the wind increases in strength, not only are the component waves believed to be higher, but – when the fully developed state is reached – longer components also will be present.

If a ship is able to attain a speed sufficiently high that its period of encounter with the longest important wave component is shorter than the natural pitching period, the ship will be in the supercritical condition for that particular storm. Most ships can attain this condition only in moderately heavy seas – that is, in light winds or in stronger winds of short duration. In general, whether or not a ship can attain the supercritical condition depends both on the sea state, indicated by wind velocity and duration, and on the ship's natural pitching period. Speeds for supercritical operation are shown for the case of head seas in Fig. 4, which is taken from Ref. 5. At other headings, the ship must reach even higher speeds to attain the supercritical condition.

Because short waves are present in both severe and moderate storm seas, it is impossible to avoid synchronism with all component waves by reducing speed. However, model tests have shown that waves appreciably shorter than the ship do not cause serious motions even at synchronism. Therefore, speeds that are low enough to avoid synchronism with waves of ship length and longer cause moderate motions. This condition may be termed the subcritical range. For head seas, it depends mainly on the ship length and the natural pitching period, that is, on the ratio $T_p/\sqrt{L}$, as shown in Fig. 3. At times, all ships must reduce speed in storm seas to attain the subcritical condition of moderate pitching.

In following seas, most ships steaming at ordinary speeds are always in the subcritical range. This explains the advantage of heaving to with wind and sea astern, provided that the ship can be kept under control. However, Mandel [7] has pointed out that unusual ship forms intended for supercritical operation in head seas may encounter critical conditions in following seas.

SUPERCRITICAL OPERATION IN ROUGH SEAS

It has been shown in Ref. 5 that for most ships the most promising method of reducing pitching and heaving motions is to use hull proportions that raise the critical-speed limit and permit higher subcritical speeds. This means increasing the length in relation to displacement, which results in a reduced period-length ratio, $T_p/\sqrt{L}$. A ship can then go at higher speed before synchronous response to waves of near ship length is experienced (Fig. 3).

Thus, in Ref. 8 a model 25 percent longer than a conventional DD-692 destroyer, but with the same displacement, had $T_p/\sqrt{L} = 0.20$ instead of 0.25. It was concluded that in a storm in which the conventional destroyer could attain a speed of 20 knots ($V/\sqrt{L} = 1.0$), the longer vessel could attain a speed of 30 knots or $V/\sqrt{L} = 1.4$ (Fig. 3). The longer destroyer was an abnormally slender ship, with $\Delta/(L/100)^3 = 30$. Tremendous problems of stability, structure, and hull arrangements would be encountered in the design of such a ship. It hardly seems feasible, therefore, to think of large increases of speed to 50 or 60 knots by going further in the direction of longer and thinner ships.

The most promising direction then to obtain really high speeds in head seas, where motions are most severe, is to aim at supercritical operation. At the same time, care must be

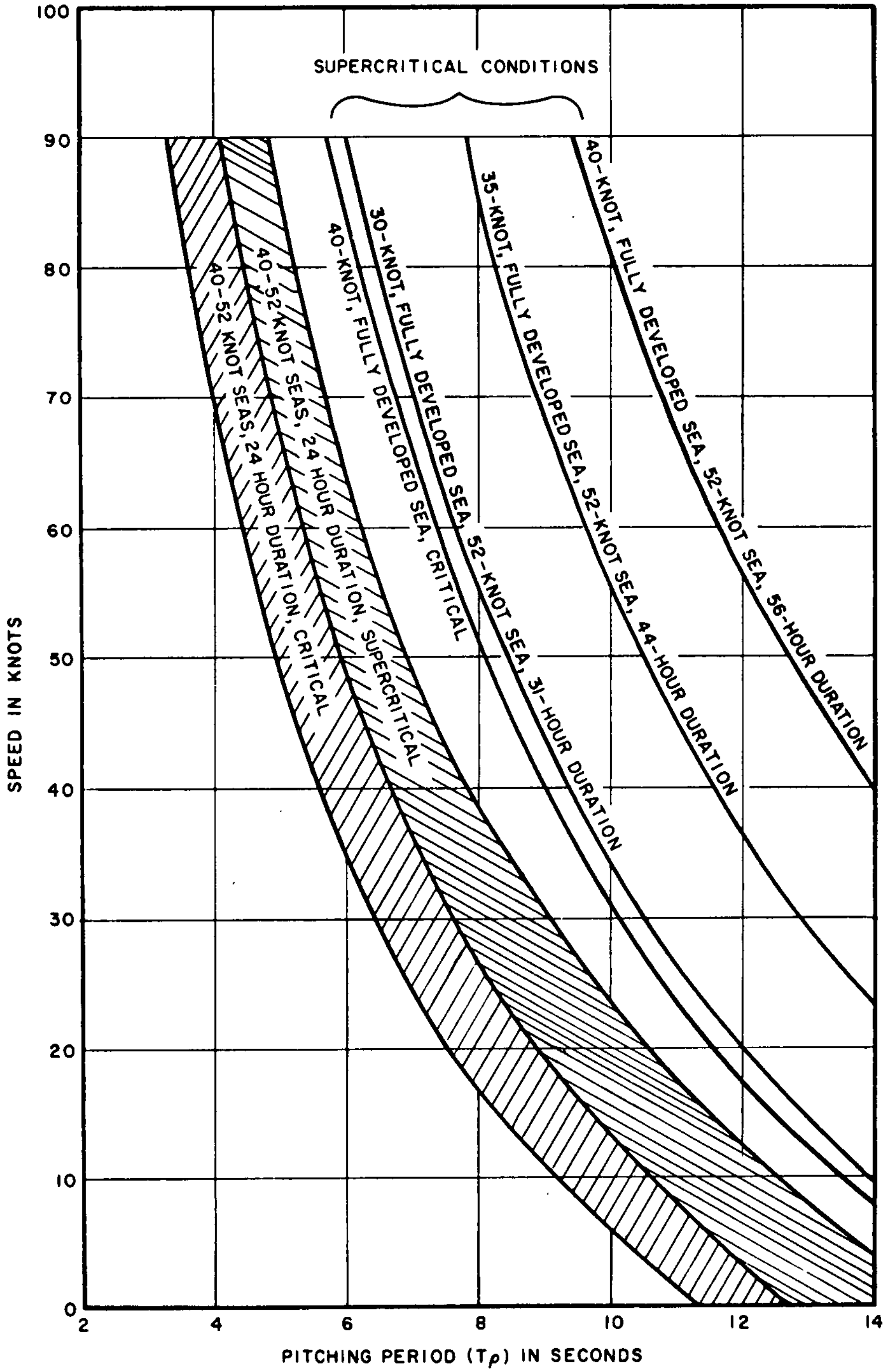

Fig. 4. Ship speeds for critical and supercritical operation, based on a Neumann ideal spectra (from Ref. 5)

exercised to remain in the subcritical speed range in following seas. The basic idea is simply to attain high ship speed and a long, natural pitching period. The problem of high speed involves the question of reducing wavemaking resistance, which has already been discussed.

To consider all the possible means of increasing the natural pitching period (T_p) it is well to examine the equation given in Ref. 5:

$$T_p = 2\pi \sqrt{\frac{\nabla}{gBL}} \sqrt{\frac{C_k^2 + C_j^2 k_{yy}}{C_{IL}}} \tag{1}$$

in which ∇ is displacement volume, g is acceleration of gravity, B is breadth, and L is length. The coefficient C_k is the inertia coefficient so that the longitudinal mass moment of inertia $I_L = \nabla e (C_k L)^2$, or $C_k = I/L \; J_L/\nabla e$; $(C_j^2 k_{yy})$ is an analogous coefficient of virtual inertia by which $\nabla \rho L^2$ must be multiplied to give the longitudinal mass moment of inertia of the entrained water. C_{IL} is the coefficient of longitudinal waterplane inertia defined by the relationship

$$BM_L = \frac{L^3 B}{\nabla} C_{IL}.$$

From Eq. (1) it can be seen that the following trends increase the natural pitching period:

1. Increase of displacement
2. Reduction of length or beam
3. Increase in virtual inertia $(C_j^2 k_{yy})$
4. Reduction in waterplane inertia (C_{IL})
5. Increase in mass moment of inertia (C_k).

Because a ship in supercritical operation tends to plunge through the waves rather than to ride over them, it is difficult to attempt to keep water off the foredeck. Accordingly, low freeboard and a heavily built deck is one way to cope with shipping of water, which at the same time permits a very narrow waterline. The body plan in Fig. 5 illustrates a possible design for a supercritical ship of this type, (*E*) of Fig. 1, a ship like a surfaced submarine, made longer and more slender to attain high surface speed. The normal waterline would be used for good weather operation; in bad weather, large peak ballast tanks would be filled to lengthen the pitching period by increasing the displacement, by increasing the radius of gyration, and by reducing the waterplane area (items 1, 4, and 5 above). Characteristics are compared with a typical destroyer in Table 1.

This semisubmerged model had $T_p/\sqrt{L} = 0.38$ in the deep-draft condition. Results of tests in regular- and irregular-head seas [3] confirmed theoretical expectations that a supercritical condition of moderate motions could be attained at speeds of 35 to 40 knots in moderately rough irregular-head seas (Fig. 6). Heaving motions were more pronounced than

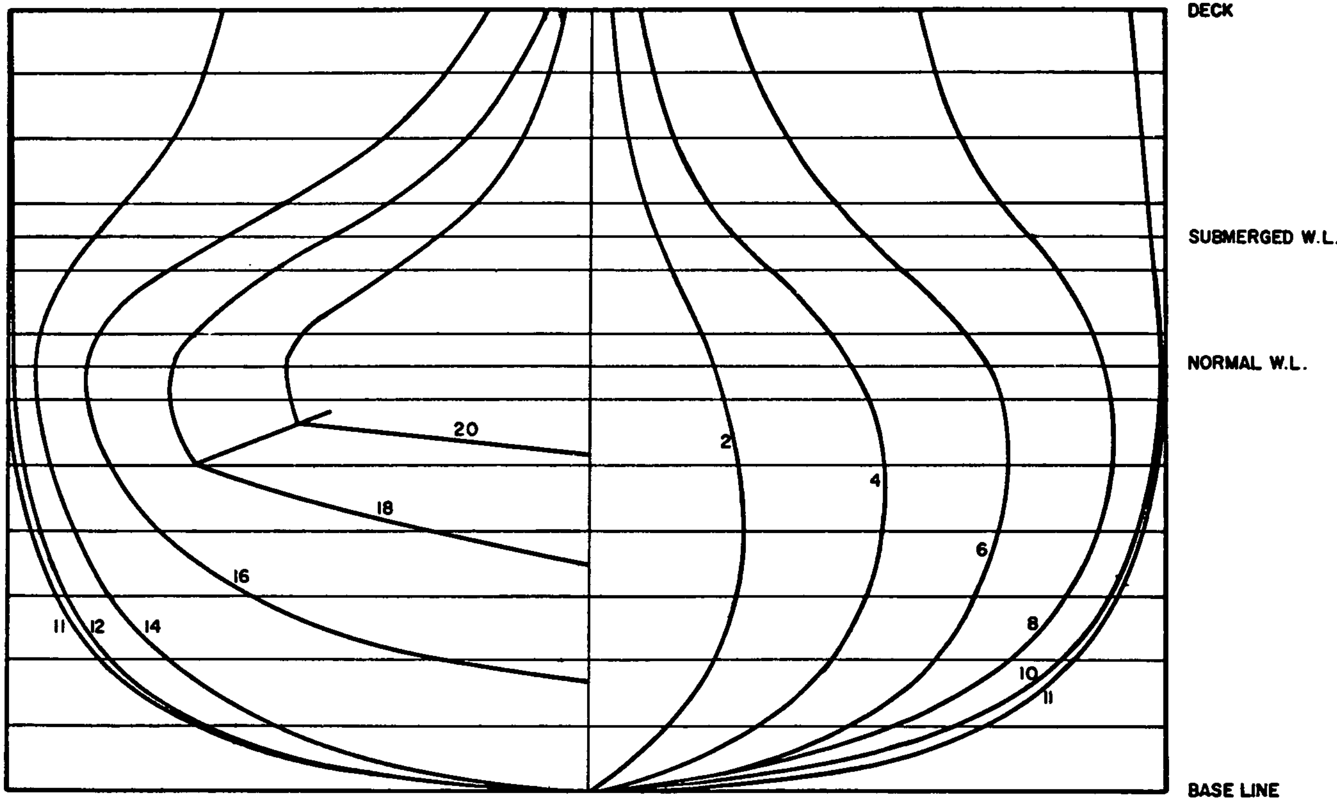

Fig. 5. Body plan of proposed semisubmerged ship for high speed supercritical operation (from Ref. 3)

Table 1
Characteristics of Unusual Ship Forms

Item	DD-692 Destroyer	Semisubmerged Ship	Large-Bulb Ship
Length overall (ft)	391	383.0	441
Length on WL (ft)	383.6	383.0	346
Length of each bulb (ft)			94.7
Beam (ft)	40.8	36.4	34.4
Draft (ft): hull, normal displ.	14.1	13.0	17.2
bottom of bulb, normal displ.			36
hull, deep displ.		17.0	
Displacement (long tons):			
hull, normal	3471	2770	2480
bulbs			991
total			3471
deep		3835	
$\Delta/(LWL/100)^3$	62	68*	84
Waterplane coefficient	0.77	0.57*	0.64
Longitudinal gyradius	0.24 L	0.27 L*	0.30 LWL
Natural pitching period, T_p (sec)	4.9	7.9*	8.9
Period-length ratio, $T_p/\sqrt{LWL}$	0.25	0.40*	0.48
Natural heave period (sec)	5.1	6.5*	6.3

*At deep draft.

pitching, but heaving accelerations were not unusually high in spite of the high average frequency of wave encounter. In irregular waves, the highest single value of heave acceleration was 0.45 g at 25 knots and 0.26 g at 40 knots. The reason for these moderate values was that the motion occurred primarily in the natural heaving period.

No following-sea tests were run, but the natural pitching period is such that subcritical operation is anticipated at speeds up to 45 knots. However, as previously noted, the power requirement at deep draft is exceedingly high, even in calm water, for practical considerations. Furthermore, wave impact on the superstructure would be a serious structural problem, and it might be necessary to raise the deckhouse up on columns to permit the waves to pass under it. Hence, though this type of craft looks interesting as a supercritical ship, there are serious problems to be solved to make it practicable.

Another type of supercritical craft is the slender hull with large bulbs mentioned earlier, (D) of Fig. 1. Available results of a model investigation of such a ship now under way at the Davidson Laboratory will be summarized. The objective here was to increase the natural pitching period by increasing the virtual mass moment of inertia of the hull, without incurring a resistance penalty in the process. That is, k_{yy} of Eq. (1) was greatly increased. The bulbs appear to be too deeply immersed to provide appreciable benefit in the form of damping of motions.

The hull form selected was the well-known ideal form developed by Wigley [9] for which the theoretical wavemaking resistance has been calculated. In this form, the underwater sections are parabolic, the waterlines are sinusoids, and the above water form is wall-sided. For the shape of the bulbs, a body of revolution was selected with length/depth = 5. Theoretical wave resistance of this type of body has also been calculated. The size of each

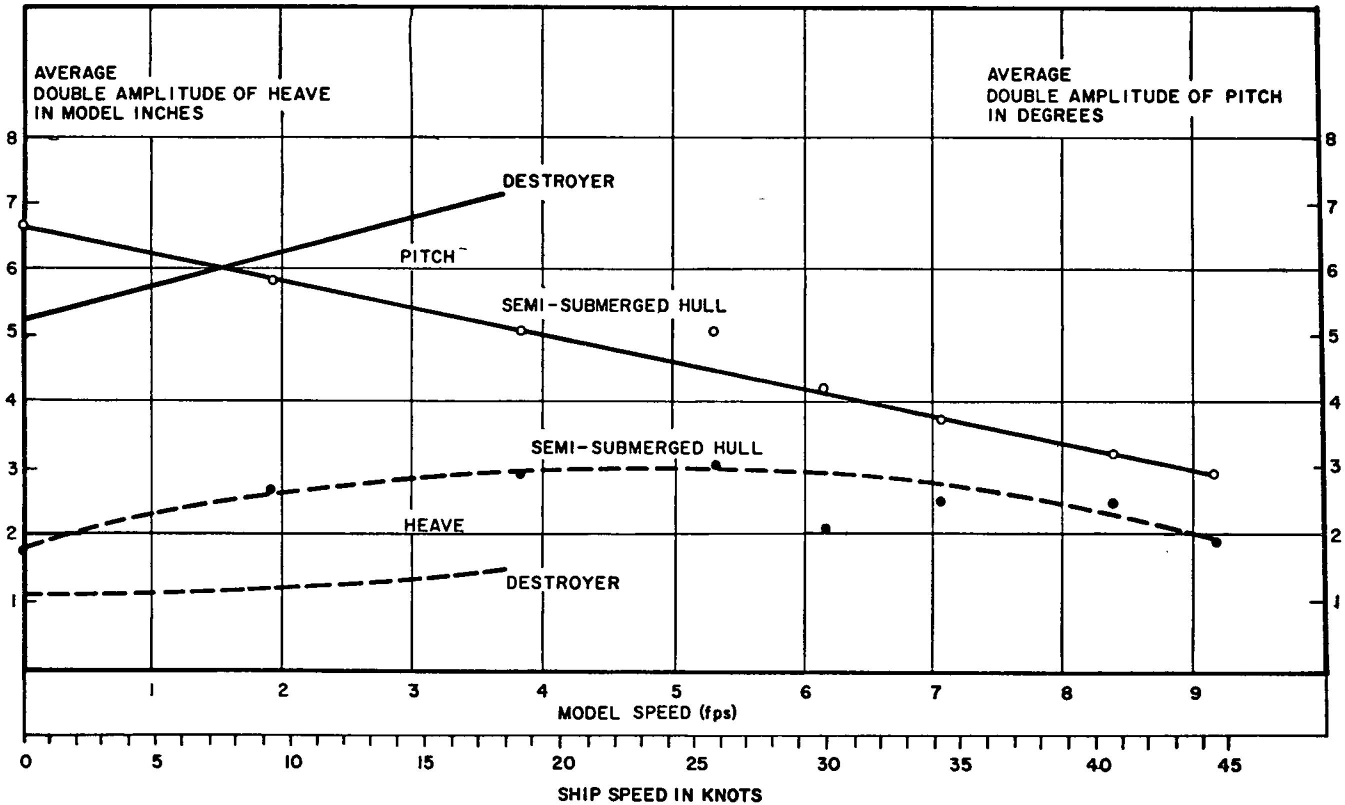

Fig. 6. Pitching and heaving motions in irregular waves with a significant height of 21.6 feet (from Ref. 3)

bulb was fixed at 20 percent of the volume of the hull alone. Thus, both bulbs represent 28.6 percent of the total displacement. The bulbs were attached to the hull in a manner that permitted their fore and aft location to be varied.

Figure 7 shows the model with 40 percent of the length of the forward bulb extending forward of the FP and 60 percent of the aft bulb extending aft of the AP. Full-scale characteristics of the large-bulb ship are given in Table 1, and compared with those of the typical destroyer and semisubmerged hull.

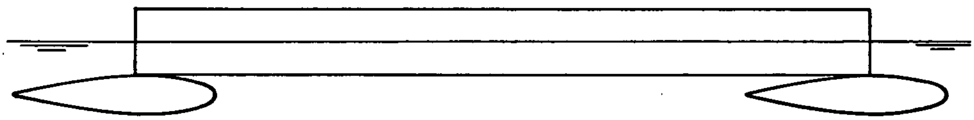

Fig. 7. Slender ship with large bow and stern bulbs

At present, neither the testing nor the analysis in this project has been completed. Results presented here are preliminary and subject to further evaluation when the testing program is completed. Because the forward position of the bow bulb showed the least resistance of the positions tested, it was selected for the regular 2.0L wave tests. Figure 8 compares the pitching motions of three types of ships. The worst pitching motions for the large-bulb model occur at about the speed for synchronous motions, 2.4 fps or 9.8 knots. At intermediate speeds, the motion of the large-bulb model was somewhat greater than the semisubmerged model, but at high speeds it was somewhat less.

Figure 9 shows one real shortcoming of the model. Worst heaving motions occur in the vicinity of 34 knots ship speed, where the amplitude approaches 2-1/2 times the amplitude of the wave. Synchronism for heave occurs at 6.8 fps or 28 knots ship speed. While the heaving was severe, maximum acceleration amidships accompanying the motion was 0.45 g in an $LWL/41$ wave, no worse than the semisubmerged model. However, the large heave amplitudes may actually cause the middle body of the ship to emerge from the water at speeds where maximum heaving motions occur. Nevertheless, this type of craft appears to offer real potentialities of high speed in rough water, and research is continuing on possible means of improving performance further. It has the advantage over the semisubmerged design in having less hull-volume limitations, and sufficient freeboard and flare can be provided forward to keep water off the foredeck.

SEMISUBMARINE

Characteristics

Finally, we may consider the possibility of larger proportions of submerged hull. Mandel has considered a hull with a surface-piercing fin almost as long as the hull ((F) of Fig. 1) with some success [2]. However, it is believed that the power requirements are excessive and that the only hope for success with this type of craft is to reduce the fin to the absolute minimum. Mr. E. Frankel stated at the Seminar on Ship Behavior at Sea, Stevens Institute of Technology, June 1960, that a model is now being investigated at M.I.T. in which the fin has been reduced to about 1/6 the length. Resistance and control problems for such a craft ((G) of Fig. 1) are now being investigated at Stevens.

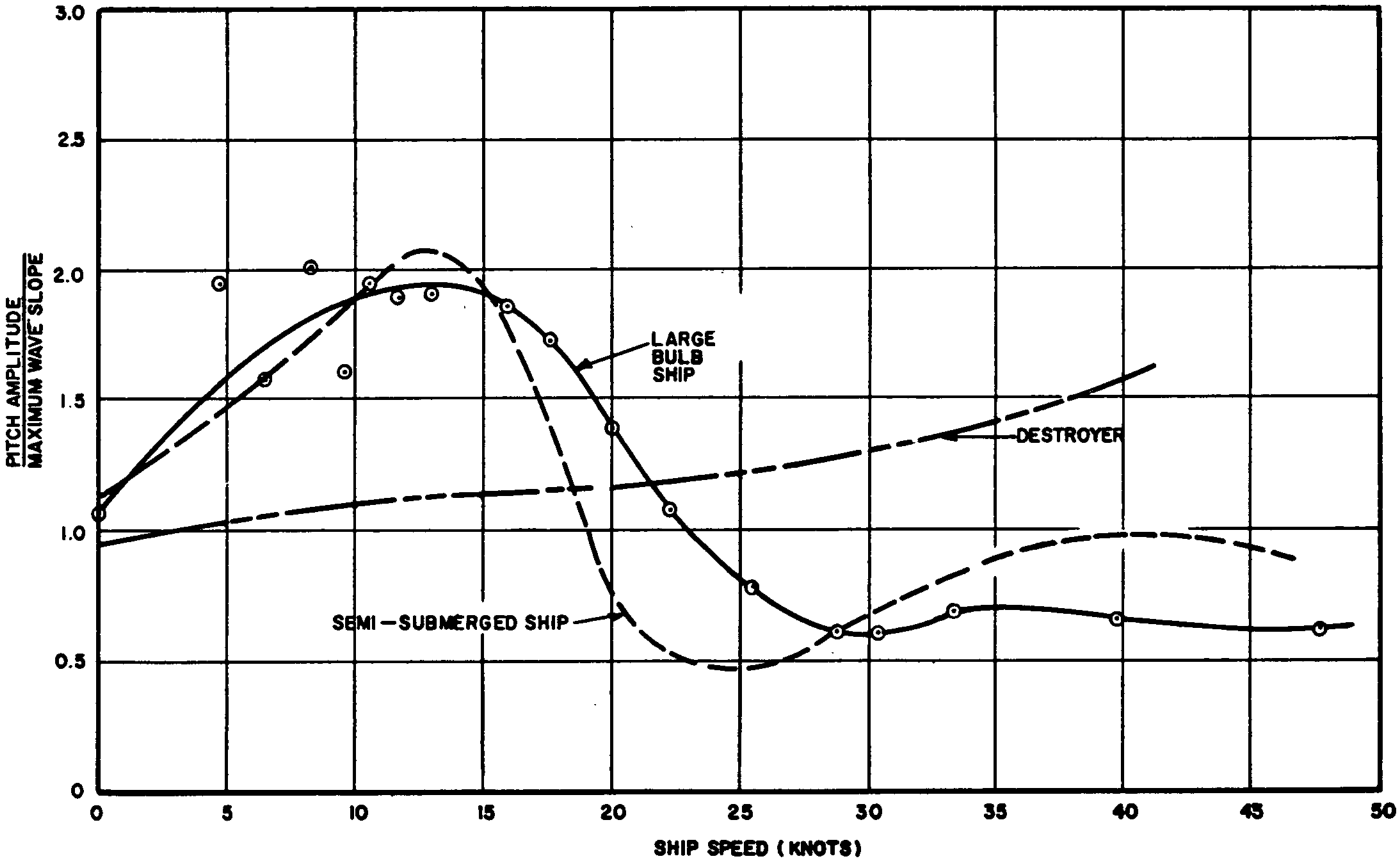

Fig. 8. Pitching motions in regular 2.0*L* waves

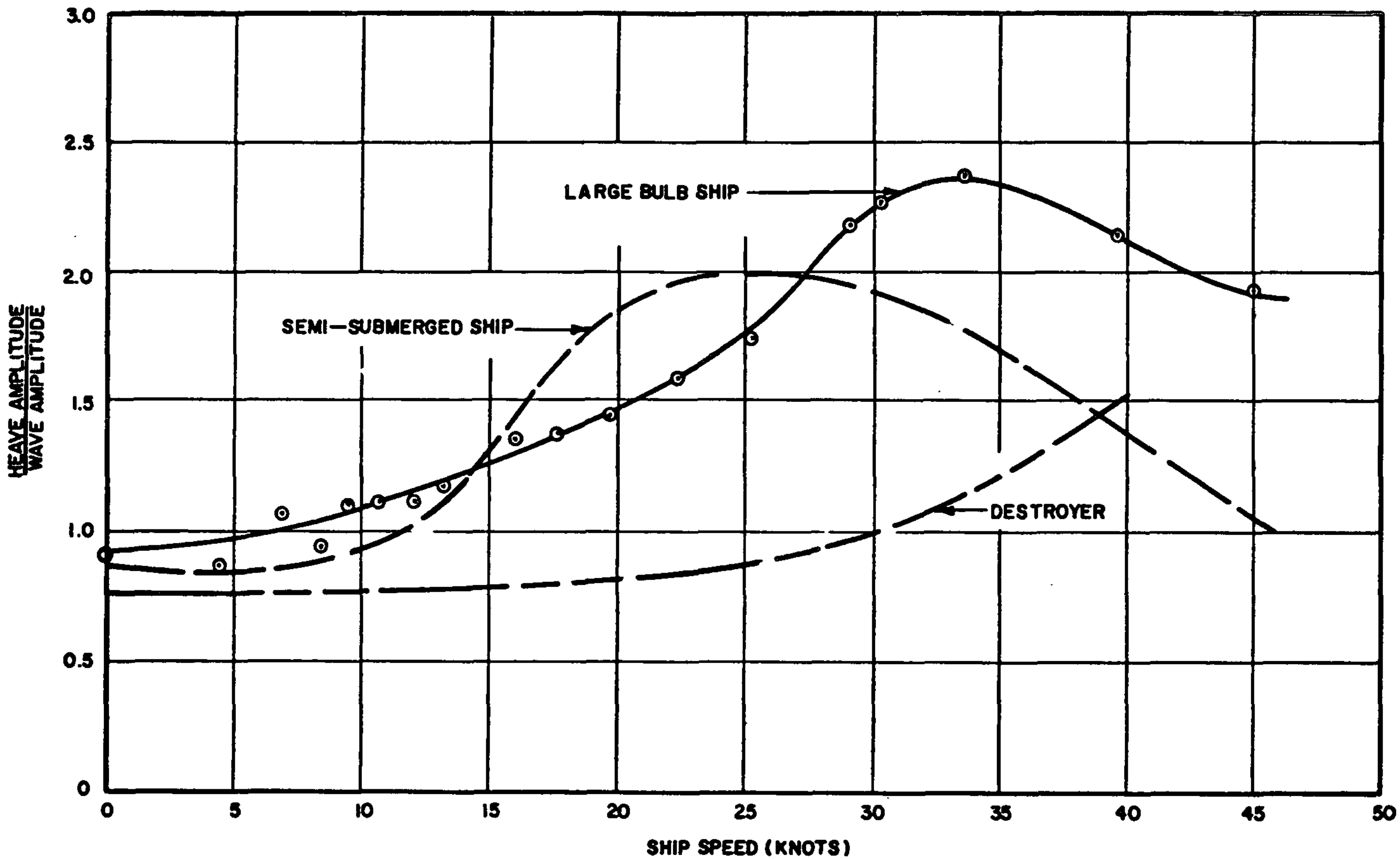

Fig. 9. Heaving motions in regular 2.0L waves

Before discussing control problems, it is important to consider in what way this craft would be better than a submarine. The question is, why should we take the trouble of having a strut piercing the surface, paying the penalty of additional resistance? In short, why not use a submarine? The answer is, for the moment at least, that there seems to be no doubt that the weight and size of nuclear power plants are greatly in excess of air-breathing plants of comparable power. In fact, the weight and space requirements of the present type of nuclear power plant seem to be two or three times as great as air-breathing plants. Furthermore, we have seen definite possibilities that the weight of air-breathing power plants can be further reduced. One of the most helpful developments here is the hydrofoil craft which, regardless of its own merits, is certainly stimulating the development of lightweight power plants that would make the air-breathing submarine even more advantageous.

Because the high-speed near-surface craft with surface-piercing strut (semisubmarine) has not been previously discussed in the literature and because of the many interesting technical problems associated with this type of ship, the balance of this paper will deal with this particular craft.

The appearance of the semisubmarine might be roughly as shown in Fig. 10. It would have a submarine-like hull, but not designed for high hydrostatic pressures. The strut would have to go high enough above the surface so that the crests of the waves would not cause difficulty. Its main function would be to take air down into the hull and carry exhaust gases out. It would be necessary to accept from the very outset the need for control devices, for we cannot expect it to run at a constant depth below the surface, even in calm water. The reason for this is, of course, that there are surface interaction effects. Any body moving at high speed, or even at moderate speed, below the surface experiences forces (which can be resolved into a moment and force) related to the wavemaking on the surface. These forces probably reach their maximum at the condition of maximum wavemaking resistance, but they are still present at very high speed. Fortunately, the effects at very high speeds appear tentatively to be generally favorable. To explore this problem at the Davidson Laboratory, simplified linear equations of motion have been set up and solved on an analog computer.

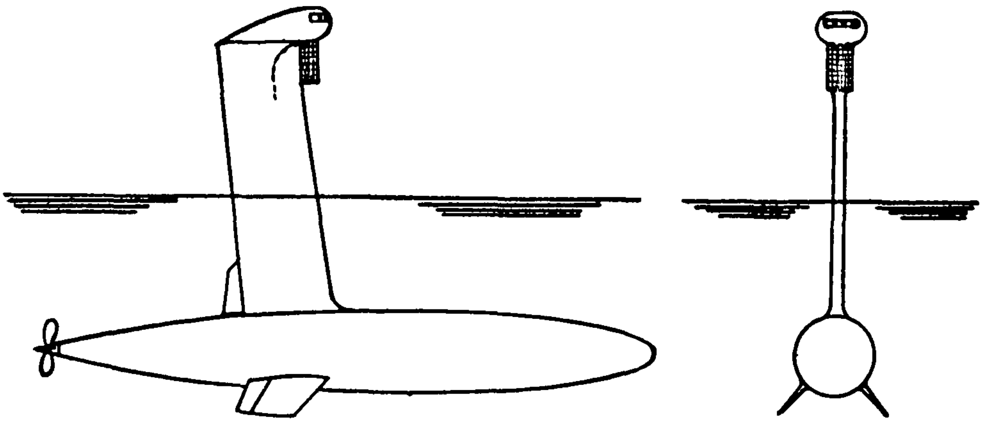

Fig. 10. High speed semisubmarine

Design Problems

It should be noted that the control of a semisubmarine involves more than a problem of stability in the usual sense. Suppose the heading of a stable ship is disturbed downward; if the craft is stable, it will steady down on a new course that will take it deeper and deeper. Similarly, if it is displaced upward, it will steady down on a new course upward so that it will eventually break surface. The ship should have a tendency to come back of its own accord to the original course and depth. This quality is here referred to as depth stability. It will be shown later that this can best be achieved by means of control surfaces with automatic control, which can keep the ship running level. This problem appears to be roughly the same difficulty as the control of completely submerged hydrofoils on a hydrofoil boat. It will be discussed in more detail in the next section.

If there is a large surface-piercing fin, or a smaller fin near each end of the craft, it may be expected that the increase or decrease of buoyancy associated with changes in immersion would assist in the depth control of the body. However, with a single minimum fin, the buoyancy effect appears to be small and reliance must be placed on dynamic control. A small amount of positive overall buoyancy would be desirable in the submerged condition for safety in case of power or control failure.

The next problem, after the consideration of maintaining a level course under a calm sea, is the behavior of the ship in a rough sea. Here we find that the head-sea case is no problem. The runs on the analog computer indicated that this particular design had a pitching period of about 20 seconds, or at least when it was disturbed it oscillated in a period of about 20 seconds, which is a sort of dynamic, natural pitching period. It signifies a very low response to outside disturbances, so that the high frequencies encountered in head seas will not cause motions of any consequence in the craft. However, in following seas we may expect that it will run into the critical zones of Fig. 1 of Ref. 7. The problem of providing vertical control so that the ship will run level or approximately so will be discussed further in the next section. In long waves it may be desirable for the ship to contour the surface, moving up and down, just as a hydrofoil craft must do.

Another problem to be investigated is that of lateral control and turning. A fore and aft location for the strut must be determined which, in combination with other fins, will provide satisfactory directional stability in a horizontal plane and at the same time will not lead to serious heeling in a turn. This problem can easily be investigated by the use of conventional model tests on a rotating arm. Recent work by Strumpf suggests that an arrangement of two fins as shown in Fig. 10 might be the most satisfactory solution in combination with the surface-piercing strut.

In addition to the purely hydrodynamic problems discussed, there are many other design problems to be solved, including the following:

1. Compact, lightweight air-breathing power plant,

2. Air supply and exhaust,

3. Structure of surface-piercing strut,

4. Static transverse stability,

5. Minimization of resistance by selection of optimum hull proportions and obtaining the best balance between depth and strut drag,

6. Automation of operation to minimize crew requirements.

Because of the high ship speeds and relatively low thrust loading considered, it does not appear difficult to obtain a conventional propeller of good efficiency. A single shaft should be used to obtain a high propulsive coefficient. There are virtually no limitations on propeller diameter (other than construction) and rpm may be selected to give a good efficiency along with low machinery weight. Submergence depth enters into the cavitation criterion to some degree, but there appears to be no difficulty in avoiding cavitation up to 45 or 50 knots. Cavitation is a problem for control surfaces, however.

The installation of a high-power propulsion plant dictates a minimum weight and space allowance. Gas-turbine main engines seem to satisfy these requirements. For naval purposes the ship must be able to achieve a high speed for short time intervals and must also be able to cruise at a considerably reduced speed for long time intervals. A single gas-turbine engine does not have the ability to operate efficiently over this considerable power range. Hence, to achieve high engine efficiency, multiple engines should be considered. At top speed all engines would be running. For this operation, engine life is a prime consideration. At low speed, fewer engines would be running and the idle ones could be disconnected from the reduction gear with a fluid coupling to facilitate maintenance and to eliminate windage losses.

The reduction gears to reduce the turbine shaft speed to a practical propeller speed involve very strict weight and, more important, space limitations. These considerations suggest an epicyclic gear train with high surface hardness and high K factor. This type of gear should have the ability to transmit power efficiently over a large range of powers. Even so, the gearing will undoubtedly be the largest single item of machinery weight.

Another possibility for reduced weight is to design a ducted type of propeller operating at very much higher rpm, perhaps in the supercavitating range. This would permit a drastic reduction of gear weight.

Air supply and turbine exhaust involve serious engineering problems to minimize pressure losses and yet keep the surface-piercing strut to minimum size. In any case, the ducting will certainly be a big item in machinery weight.

It is proposed that a compact control station be located at the top of the surface-piercing strut for good visibility. Permanent ballast of about 10 percent of displacement might be necessary to provide satisfactory static transverse stability.

Basic trends of semisubmarine characteristics have been studied in a preliminary way in connection with work of the Panel on Naval Vehicle Systems, Undersea Warfare Committee, National Academy of Sciences-National Research Council. Tentative design features of a series of craft of varying size were worked out on the basis of certain assumptions regarding technical potentialities [10]. These assumptions will be summarized before presenting the results.

Resistance

Resistance was estimated from model tests of simple bodies of revolution, with axes 1-1/4 diameters below the surface. An Ogive strut was selected, the size was established by the estimated engine air requirements. A length of 14 percent of ship length was used for the series. Strut resistance was calculated from Ref. 11, neglecting the elimination of tip losses by the attachment of the strut to a hull. The characteristics that were selected were not necessarily optimum.

The complication of a controllable pitch propeller was not considered necessary; however, for backing and for emergency propulsion, small auxiliary screws were assumed driven by medium-speed diesels. The speed that can be achieved with this propulsion will be around 5 or 6 knots.

For these tests the following characteristics were selected.

Hull-Form Coefficients – Length/beam ratio = L/B = 7.0; submergence beam ratio = h/B = 1.25 (to centerline); prismatic coefficient = $C_p = \nabla/(\pi/4)B^2L$ = 0.650; wetted surface coefficient = $K_s = W.S./\pi BL$ = 0.774.

Ogive-Strut Coefficients – Thickness/chord ratio = t/c = 0.167; submergence/chord ratio = h/c = 1.30; c/L = 0.139.

Machinery – Main engines: GE converted aircraft engines, type MS240B, MS240A, 6000 rpm; reduction gears: double reduction, epicyclic type, small with low weight (estimated on the basis of Timmerman second reduction gears); overall fuel consumption: 0.55 /SHP-hr at V = 45 knots and 0.58 /SHP-hr at V = 20 knots.

Propulsion – For this study the top speed was chosen at 45 knots and the cruising speed at 20 knots. The propeller and propulsion characteristics chosen (not necessarily optimum) were as follows:

	Δ = 6000	Δ = 3000	Δ = 1500	Δ = 750
Propeller diameter	21.5 ft	16.8 ft	13.4 ft	10.0 ft
Shaft rpm	200	250	300	400
Propeller efficiency at 45 knots	74%	75%	76%	76%
Assumed hull efficiency	140%	120%	120%	120%

The appendage resistance allowance chosen was 10 percent in all four cases. All propellers were checked for avoidance of cavitation.

Weights

Assumed hull, machinery weights, and other data are shown in Table 2.

For any vehicle, whether for military or commercial service, the basic characteristics of interest are speed, range, and payload. Various types of plots can be prepared to show the relationship among these variables for different craft. However, for ASW purposes the particular need seems to be for a top speed between 45 and 50 knots and a cruising speed between 15 and 20 knots. Hence, in the present study fixed speeds have been assumed and trends have been determined of range versus payload for a family of vehicles of different sizes. The results are shown in Fig. 11.

The plot shows that for fixed speed and size, the payload available for weapons, detection gear, etc., varies inversely as range. And for any given range, the larger the ship the greater the payload must be. To be more specific, it appears that a 1500-ton craft for

Table 3
Weight Data for Semisubmarine Series [10]

Displacement (Δ) in tons	6000	3000	1500	750
Length (L) in feet	272	216	171.5	136
Beam (B) in feet	38.8	30.8	24.4	19.4
SHP	130,000	70,000	40,000	25,000
Weights in Tons				
Steel weight (0.35 Δ)	2100	1050	525	262
Outfit weight (0.10 Δ)	600	300	150	75
Salt-water ballast (0.05 Δ)	300	150	75	38
Lead ballast + margin (0.10 Δ)	600	300	150	75
Main propeller machinery	300	183	114	82
Crew and all stores	71	56	43	32
	3971	2039	1057	564
Deadweight = payload + fuel	2029	961	443	186
More Optimistic Design*				
Payload + fuel	2820	1360	655	299

*All weights reduced by 20 percent.

example, could perhaps carry a payload of about 100 tons over a range of 2500 to 4500 miles (including 10 hours at 45 knots). The larger ships could carry much more.

Even better results and higher speeds might be attained with high-rpm and supercavitating propellers. Although the design data given are only tentative, it is hoped that the suggested trends show the potentialities of unusual naval craft if the same level of technical effort is applied as in current hydrofoil boat designs.

CONTROL OF NEAR-SURFACE BODIES

The depth control of a body moving at high speed below, but close to, the water surface is an interesting problem. Therefore, it may be of value to summarize the theoretical work carried out so far for both the calm-water and following-wave cases. It is hoped that this will serve to clarify the problem and to specify areas that require research.

Dynamic Stability in Calm Water

The following analysis considers only small disturbances of equilibrium conditions, which the craft is assumed to have when proceeding at a constant speed (U) along a path

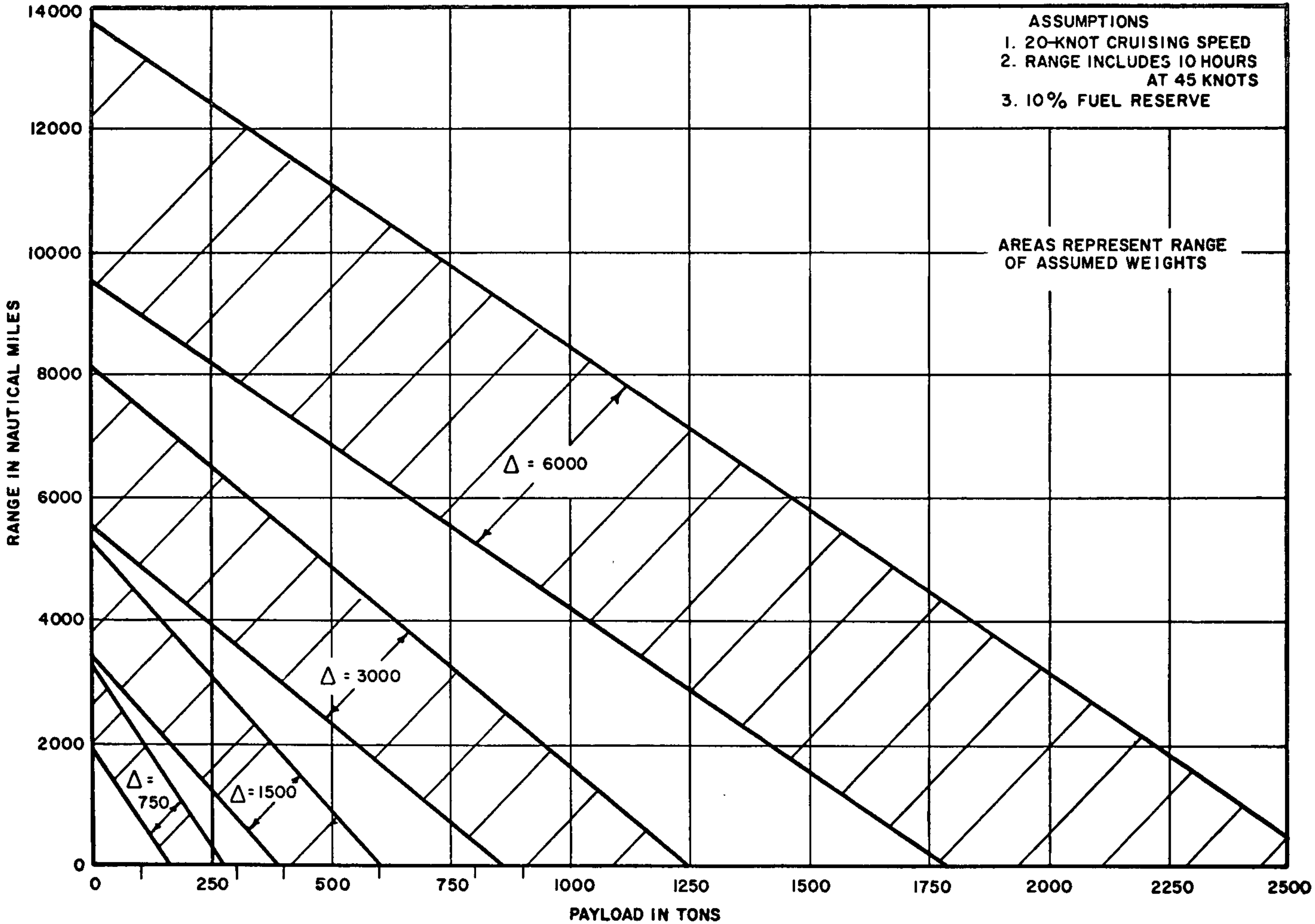

Fig. 11. Payload as related to range of a semisubmarine

($z_o = h$) parallel to the undisturbed free surface. For the heave and pitch analysis assume that there are no lateral excursions.

Stated briefly, the equations of motion for heave and pitch are

$$m'(\dot{w}' - q') = Z'(w', q', \dot{w}', \dot{q}', \dot{z}_o, \theta) \tag{2}$$

$$I_y'\dot{q}' = M'(w', q', \dot{w}', \dot{q}', z_o', \theta) \tag{3}$$

where m' is the nondimensional mass of the craft ($2m/e\ell^3$), w' is the vertical velocity of the center of gravity in fraction of speed (U, positive downward), q' is the nondimensional angular velocity about the transverse (y) axis, z_o' is the instantaneous distance from the free surface to the center of gravity in fraction of the length of the craft (ℓ, positive downward), θ is the pitch angle (positive nose-up), I_y' is the nondimensional mass moment of inertia about the y axis ($I_y' = I_y/(e/2)\ell^5$), Z' is the nondimensional total vertical force (force $1/2e\ell^2U^2$), M' is the nondimensional total pitching moment (about the y axis), and the dots above a symbol indicate differentiation with respect to nondimensional time ($s = Ut/\ell$).

Motion near the free surface induces forces and moments that are dependent upon the distance (x_o) and possibly on the pitch angle (θ). These dependencies are, of course, not present when the ship is deeply submerged.

When the ship is near the free surface, the force and moment become dependent on z_o. There is also a possible dependence of the force and moment upon θ, which does not arise in the case of deeply submerged bodies. In view of the dependence on depth below the surface, it is advantageous to write the equations with respect to an axis system (x_o, y_o, z_o) that is fixed in the free surface, rather than with respect to a system (x, y, z) that is fixed in the body as is usually done. Expanding the right sides of Eqs. (2) and (3) in Taylor expansion and retaining only the linear terms yields:

$$(Z_{\dot{w}}' - m')\ddot{z}_o + Z_w'\dot{z}_o' + Z_{z_o}'z_o' + Z_{\dot{q}}'\ddot{\theta} + (Z_q' + Z_{\dot{w}}')\dot{\theta} + (Z_w' + Z_\theta')\theta = 0 \tag{4}$$

$$M_{\dot{w}}'\ddot{Z}_o' + M_w'\dot{Z}_o' + M_{z_o}'Z_o' + (M_{\dot{q}}' - I_y')\ddot{\theta} + (M_{\dot{w}}' + M_q')\dot{\theta} + (M_w' + M_\theta')2 = 0 \tag{5}$$

where all the coefficients are derivatives with respect to the indicated subscripts (except m and I_y). To obtain Eqs. (4) and (5), the kinematic relation between the motion referred to axes fixed in the craft and those fixed in the water surface has been used; therefore,

$$w = \dot{z}_o + \theta, \quad \text{and} \quad q = \dot{\theta} .$$

In principle, these equations can be solved analytically, but the results are somewhat unwieldy. They can also be solved on an analog computer. In our study we have attempted to glean some understanding from the analytical approach and have also used an analog for more rapid exploration of the influence of fin area and control on the response of the body when disturbed as it cruises at 30, 40, and 60 knots at a depth of 1.25 diameters (to the centerline). The following discussion will first reveal what has been learned from the hand-turned mathematics and will be followed by a recounting of the results of the analog studies.

Equations (4) and (5) represent a pair of linear coupled equations in z_o and θ of the form

$$\begin{aligned} L_1 z_o + L_2 \theta &= 0 \\ L_3 z_o + L_4 \theta &= 0 \end{aligned} \tag{6}$$

where $L_{1,\ldots,4}$ are the linear second-order operators displayed in Eqs. (4) and (5). The solution for either z_o or θ involves integration of single, fourth-order, linear differential equations of the following form:

$$(L_1 L_4 - L_2 L_3)\begin{Bmatrix} z_o \\ \theta \end{Bmatrix} = 0 \tag{7}$$

where (upon omission of the primes and the subscript o on z)

$$\begin{aligned} L_1 &= (Z_{\dot{w}} - m)D^2 + Z_w D + Z_z \\ L_2 &= Z_{\dot{q}} D^2 + (Z_q + Z_{\dot{w}})D + (Z_w + Z_\theta) \\ L_3 &= M_{\dot{w}} D^2 + M_w D + M_z \\ L_4 &= (M_{\dot{q}} - I_y)D^2 + (M_{\dot{w}} + M_q)D + (M_w + M_\theta) \end{aligned} \tag{8}$$

and $D = d/ds$.

Thus, the equations for z and θ are in the form

$$(aD^4 + bD^3 + cD^2 + dD + e)\begin{Bmatrix} z \\ \theta \end{Bmatrix} = 0 \tag{9}$$

and the solutions are of the form

$$z = h + \sum_{i=1}^{4} z_i e^{\sigma_i s}; \qquad \theta = \sum_{i=1}^{4} \theta_i e^{\sigma_i s} \tag{10}$$

where h is the original depth and the σ_i's are the roots of the quartic equation

$$a\sigma^4 + b\sigma^3 + c\sigma^2 + d\sigma + e = 0. \tag{11}$$

For stability, or no exponential divergence, a, b, c, d, and e must each be greater than zero. In addition, for no oscillatory divergence

$$bcd - (ad^2 + b^2 e) > 0.$$

The last inequality is Routh's discriminant, which requires the real parts of all complex roots to be positive.

At this point we must note that stability as used here refers to directional and depth stability, that is, depth stability means that after an arbitrary excursion in either z or θ,

$$z \to h \quad \text{as} \quad t \quad \text{or} \quad s \to \infty$$

and directional stability means

$$\theta \to 0 \quad \text{as} \quad t \quad \text{or} \quad s \to \infty .$$

This is to be distinguished from the case of the deep-operating submarine, where the body is considered stable as long as it does not go into a diverging trajectory but settles on a new path that is straight but not in the same direction as that prior to the disturbance.

If we note that $M_{\dot{w}}$, $Z_{\dot{q}}$, M_θ are small and that $Z_\theta = 0$ (as may be proved for the doubly symmetric body under consideration) the coefficients of the characteristic equation take on the relatively simple form

$$\begin{aligned}
a &= 1 \\
b &= -\left(\frac{Z_w}{M_2} + \frac{M_q}{N_y}\right) \\
c &= \frac{1}{M_2 N_y}\left[M_q Z_w - M_w \cdot (m + Z_q)\right] - \frac{Z_z}{M_2} \\
d &= \frac{1}{M_2 N_y}\left(M_q Z_z - M_z Z_q\right) \\
e &= \frac{1}{M_2 N_y}\left(M_w Z_z - M_z Z_w\right)
\end{aligned} \tag{12}$$

where $M_2 = m - Z_{\dot{w}}$, the virtual mass in direction z, and $N_y = I_y - M_{\dot{q}}$, the virtual mass moment of inertia.

It can be noted that a, b, and c are the same as will be found in the equation of motion for the deeply operating body, with the exception of the term $-Z_z/M_2$. The quantity d is seen to be an effective damping coefficient that is arrived at by coupling the damping force and moment derivatives with the free-surface force and moment derivatives, and e is an effective spring constant arrived at by a similar coupling of the static force and moment derivatives with Z_z and M_z. It is now necessary to say something about the characteristic of Z_z and M_z as functions of Froude number [12]. The force rates (Z_z and M_z) arise from the asymmetry of flow about the body when it is moving parallel to the water surface. At very low

Froude numbers, the surface acts as a rigid ceiling, which causes a suction or attractive force and virtually zero moment. This attractive force is considered negative because the positive direction is downward. Because this attractive force becomes less negative as z increases, Z_z is positive at low Froude numbers. At high Froude numbers, the reverse is true, that is, the force is one of repulsion and Z_z is negative. The force rate changes sign at a Froude number of $F = U\sqrt{g\ell} = 0.55$. Again, with increasing Froude number the moment changes from a small bow-up moment ($M_z < 0$) at low Froude numbers, to a bow-down moment ($M_z > 0$) for all Froude numbers greater than about 0.33.

Physically, the vertical attractive force at low Froude numbers tends to be destabilizing because any excursions toward the free surface will cause this force to increase. At high Froude numbers, the repelling effect is stabilizing. If we consider the effect of M_z in the absence of the force, then the moment is destabilizing at low Froude numbers and stabilizing at high Froude numbers in regard to simple exponential divergence. However, large values of M_z can lead to oscillatory divergence or instability.

The magnitudes of Z_z and M_z at 30 knots ($U/\sqrt{g\ell} = 0.62$) are significantly different from their values at 40 and 60 knots so that we may expect, and do find, a considerable difference in the stability or the fin area required for stability over this speed range. Although, other derivatives can be expected to be Froude-number dependent, such as M_w, M_θ, $M_{\dot{q}}$, Z_w, and $Z_{\dot{w}}$, they have very weak variations with Froude number at the submergence ratio and over the Froude numbers considered.

Exponential Instability

To establish stability criteria, consideration must be given to the requirement that each of the coefficients a, b, c, d, and e of the quartic equation in σ be positive. Equation (12) shows that a and b are positive; Z_w and M_q are both negative. Figure 12 is a graph of b as a function of tail area; note that b is large.

The coefficient c is composed of three terms; the last term is found to be small and, because the two remaining terms are composed of those derivatives which are considered to be independent of Froude number, the relation for stability arising from $c > 0$, that is,

$$M_q Z_w - M_w(m + Z_q) > 0 , \tag{13}$$

is exactly that required for the body when operating deeply submerged. Figure 13 is a graph of c as a function of fin area; a fin area of 220 ft^2 is the minimum required to prevent exponential divergence. In computing the changes in the various coefficients as a function of fin or tail area, a conservative lift rate of 2.0 was chosen to take into account the attrition expected from partial cavitation.

An inspection of the equation

$$d = \frac{1}{M_2 N_y}\left(M_q Z_z - M_z Z_q\right) \tag{14}$$

shows it to be positive for high Froude numbers but negative for those ranges of low Froude numbers where M_z is negative. Thus, this term can cause exponential divergence at low

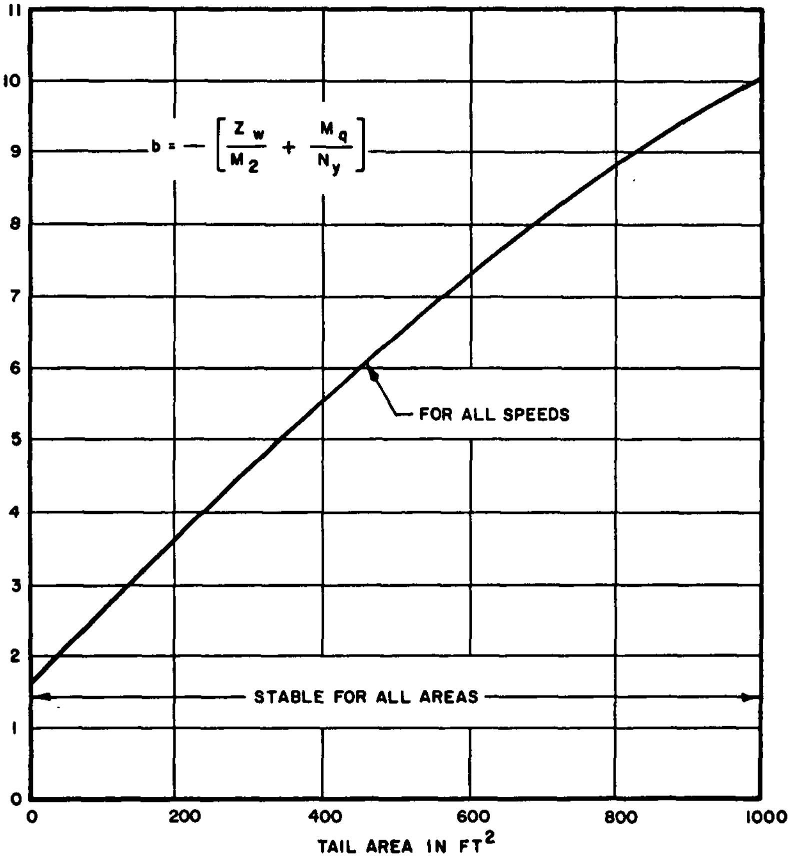

Fig. 12. Coefficient b versus tail fin area

Froude numbers but is not troublesome in regard to this type of instability at high Froude numbers. However, for Froude numbers where M_z is maximum, the attending increase in d can contribute to oscillatory instability. Figure 14 is a graph of d as a function of tail area.

The coefficient

$$e = \frac{1}{M_2 N_y}\left(M_w Z_z - M_z Z_w\right) \tag{15}$$

is negative for zero tail area. Figure 15 shows that the minimum tail area to prevent exponential divergence at 60 knots is 255 ft^2. Thus, the free-surface effects at high speed require a bit more tail area than the condition imposed by c for deep operation.

Oscillatory-Exponential Instability

If a pair of the roots of the quartic characteristic equation are complex, either damped or undamped sinusoidal oscillations will occur subsequent to an initial disturbance, depending

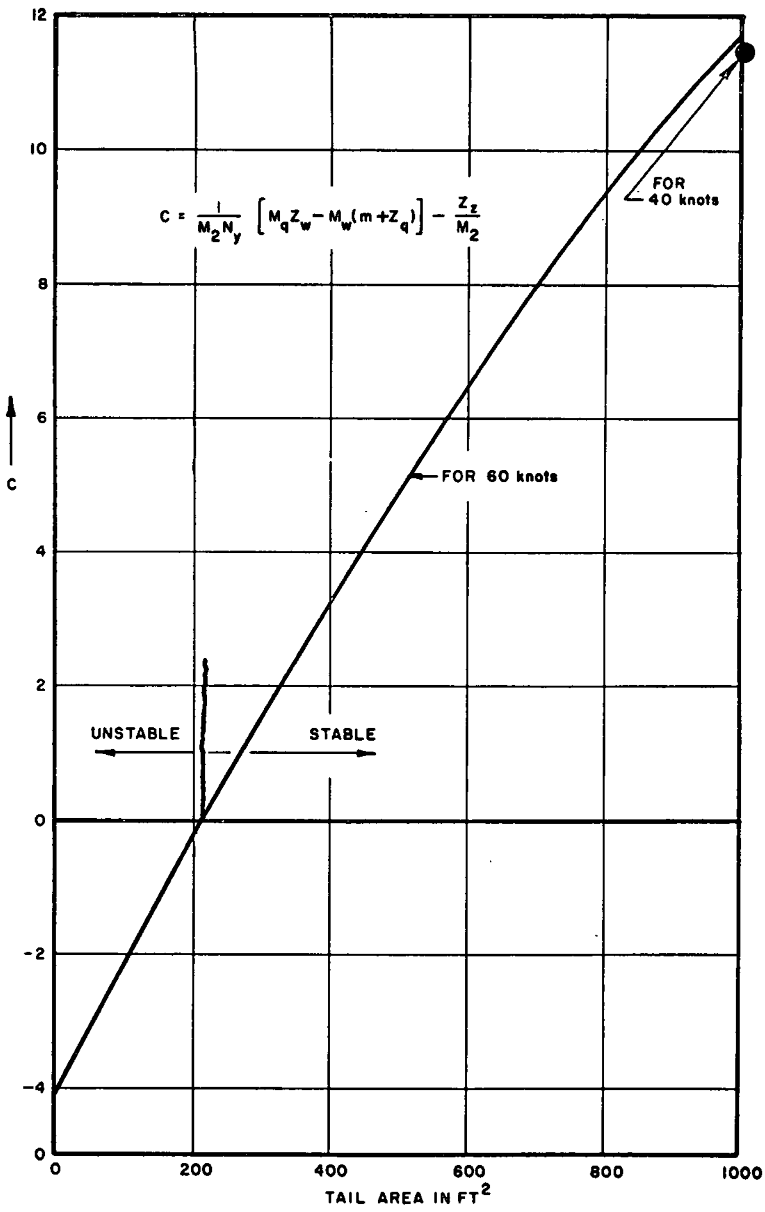

Fig. 13. Coefficient c versus tail fin area

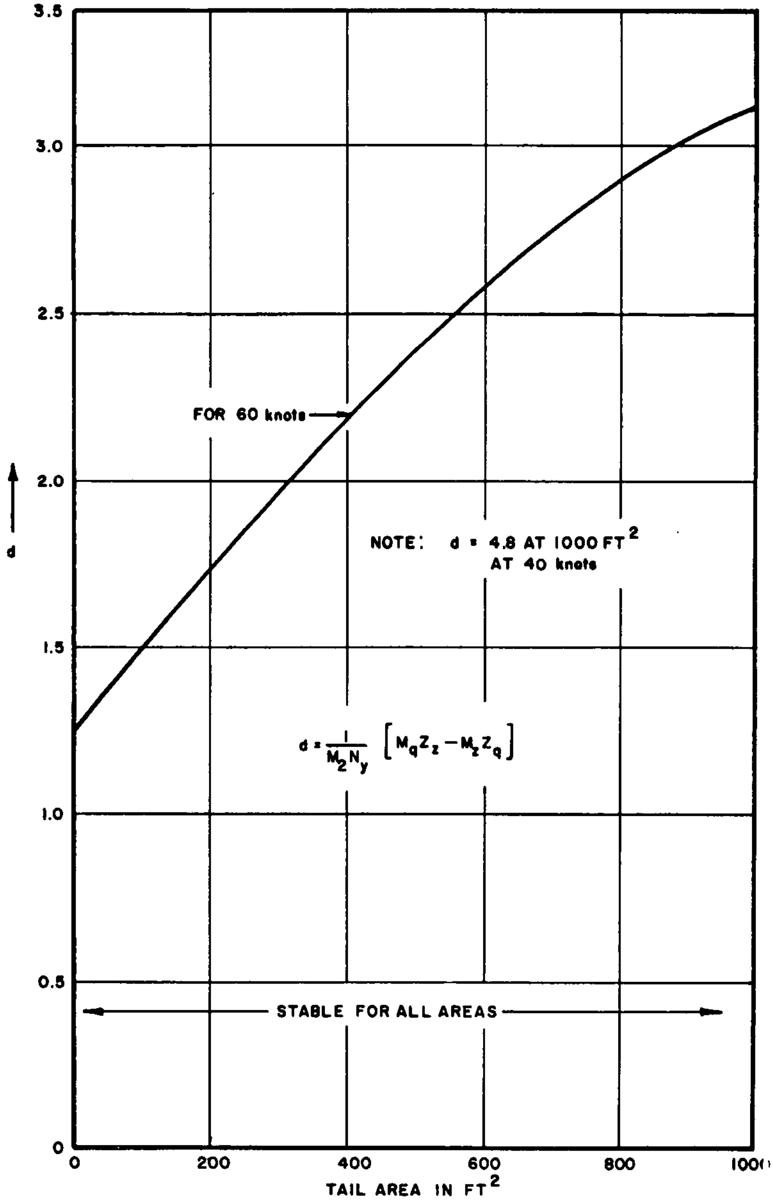

Fig. 14. Coefficient d versus tail fin area

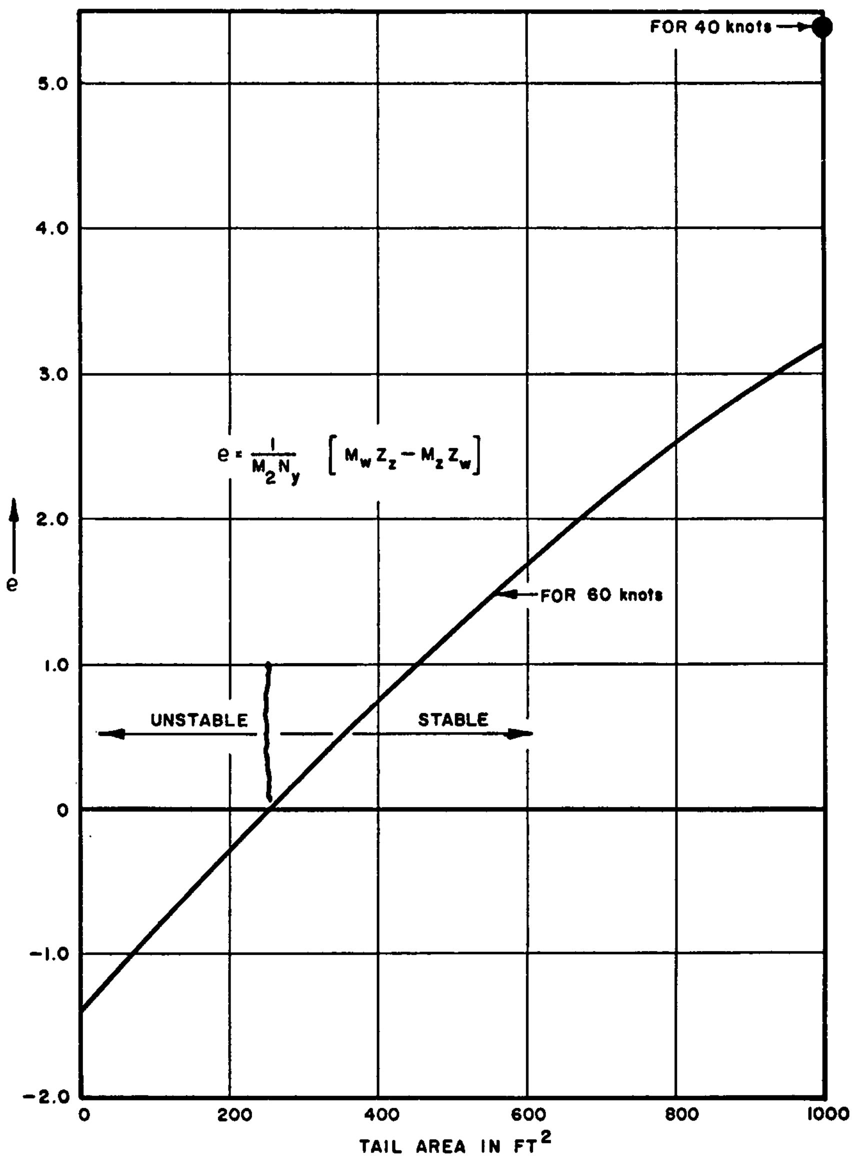

Fig. 15. Coefficient e versus tail fin area

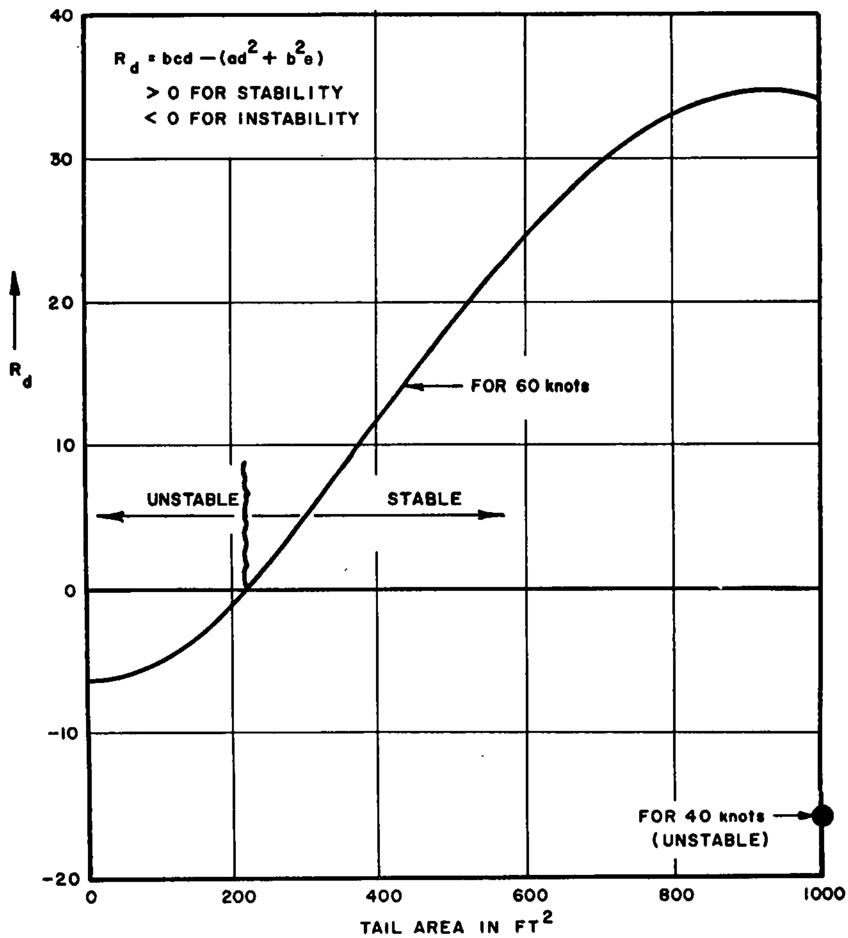

Fig. 16. Variation of the condition for oscillatory stability, R_d

upon whether the sign of the real part of this complex root is negative or positive. Routh's discriminant (R_d) provides the following relationship, which the coefficients must satisfy for stability.

$$R_d = bcd - (ad^2 + b^2e) > 0 . \tag{16}$$

It can be seen that the quantities d and e, which represent coupling of the free surface effect with the body damping and static force rates must not become overly positive or the product bed will be overcome and oscillatory instability will result. Inspection of Fig. 16 shows that Routh's discriminant is positive at 60 knots for tail areas greater than 200 ft^2, but that even a tail area of 1000 ft^2 is insufficient at 40 knots. The loss of stability with decreasing speed is due mostly to the large change in M_z which, with some assistance from Z_z, produces a 12-fold change in the coefficient e, thus making it much more positive (even for a tail area of 300 ft^2) and resulting in a negative value for Routh's discriminant. It is also to be noted that increasing b, which is really the deep-water effective damping coefficient (depending on Z_w and M_q), will cause oscillatory divergence. This is also a surprising result, which stems from the coupling of the body coefficients with the free surface spring terms (M_z and Z_z). Thus, making the body overly stable for deep operation provides a very stiff effective spring coefficient (e), which appears to be most responsible for divergent oscillatory oscillations.

Results of Analog Studies

Exploration of the influence of fin area, distribution of fin area, the sensitivity to certain coefficients, and the effectiveness of control can quickly be assessed by an analog computer. The results of such studies are discussed in the following subsections.

Responses with Fixed Fin Areas – Results of the analog studies of responses with fixed fin areas can be friefly summarized as in Table 3.

Table 3
Analog Computer Results for Fixed Fin Areas

Speed (knots)	All Fin Area Aft	3/4-Area Aft, 1/4-Area Forward	1/2-Area Aft, 1/2-Area Forward
Fin Area = 300 ft^2			
30	Divergent oscillations	–	–
40	Divergent oscillations	–	–
60	Damped oscillations	–	–
Fin Area = 1000 ft^2			
40	Slightly divergent oscillations	Damped oscillations	Divergent oscillations
60	Lightly damped oscillations	–	Heavily damped oscillations

Since the case of 300 ft^2 of fin area has been discussed, the following remarks will be directed toward giving some rationalization of the curious result of very slight stability at 60 knots with 1000 ft^2 of fin area aft as compared with very marked stability when this area is split into half forward and half aft. To begin with, this large area was selected as an intuitive attempt to stabilize against the oscillatory instability at 30 knots without regard to its implications on the stability of the deeply operating submarine. An inspection of the criterion of stability for deep operation,

$$M_q Z_w - M_w(m + Z_q) > 0 ,$$

which is essentially the quantity c, shows that by adding too much tail fin, $m + Z_q$ can be made negative (by making Z_q so negative that it overwhelms m) and, at the same time, making M_w change from positive to negative so that the second product in the above inequality contests with the magnitude of the positive product $M_q Z_w$. Thus, it is possible to alter the stability in deep operation little beyond a certain maximum by a piling-on of fin area. At the same time, the quantity b increases enormously, and though b plays a minor role in determining stability in the deep operating case, in this case of coupled motion in the neighborhood of the free surface, it is very disadvantageous to make b large. This can be seen by again referring to Routh's discriminant

$$bcd - (ad^2 + b^2 e) > 0$$

which shows that the quadratic behavior of b can be overriding, provided the value of e is not too small.

As we take area from the stern and put it on the bow, c decreases only about 20 percent, b is large and does not change, and e decreases by a factor of 8 (d changes but is not decisive). Thus, the role of M_w (which has, with equal areas forward and aft, a destabilizing tendency with regard to deep operation) is to provide a much softer effective spring value e to this fourth-order system and thus permit quick decay of oscillations.

Control Effectiveness – The foregoing has shown that exponential instability will exist at Froude numbers below 0.3, that excessive tail area is not the answer at $F \approx 0.6$, and that reasonable tail area will only stabilize at $F \approx 1.2$ (which corresponds to an unlikely speed of 60 knots). This leads to the necessity of applying controls that obviously would be needed anyway for rough-water operation. A systematic study of the effectiveness of controls proportional to z, $\dot{z}$, θ, and $\dot{\theta}$ could and should be made to arrive at the best combination. In view of the shortness of time available for this study, computer runs were made only for a control function proportional to $\dot{\theta}$. An all movable control area of 300 ft^2 is considered to be actuated without time lag according to the equation

$$\text{Tail Angle} = \delta = k\dot{\theta}'.$$

When the gain factor k was varied to determine a suitable value, it was found that $k = 1.0$ is just enough at 30 knots to prevent divergent oscillations and that a value of $k = 2.0$ gives good control, requiring a tail angle of about twice the maximum pitch angle. Results of computer runs for this gain factor ($k = 2$) at different speeds are as follows, the values listed being the ratios of amplitudes of any cycle to that of the previous cycle:

Speed (knots)	$k = 1$	$k = 2$
30	0.92	0.35
40	0.30	critical damping
60	critical damping	critical damping

It therefore appears possible to control the craft in calm water over the speed range investigated by means that are quite reasonable. A more thorough analysis that involves the use of z, $\dot{z}$, and θ may well reveal a still more effective means to achieve controllability.

Sensitivity of the Analysis, and Recommendations Regarding Stability and Control – Runs were made on an analog computer to investigate the sensitivity of the response of the

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stable system to variations in the virtual (or effective) mass and virtual mass moment of inertia. It was found that the rate of decay of stable oscillations is not sensitive to virtual mass nor to virtual moment of inertia, which is in contrast to studies on deeply submerged bodies. Also for the case of 60 knots with 300 ft^2 of tail area, the sensitivity of the response to variations of M'_w and Z'_w of ±20 percent was determined and found to be quite small. Because several of the stability characteristics of this craft are so profoundly different from those for which experience has been built up, it would seem worthwhile to conduct model tests to check the predictions made here and at the same time to widen the scope of the study. This might be done through the use of an ultrasensitive motion-following apparatus or with the use of freely operating models. Certainly, the stability in the horizontal plane will be very important, particularly in view of the excitation in roll and yaw that will be provided by the long strut. These programs should be backed up by rotating-arm experiments to determine static and rotary derivatives near the surface and also by oscillator tests to determine the influence of heave and pitch frequencies. Seaworthiness investigations must also be made, particularly for the case of following seas, where critical operation may be encountered.

CONCLUSIONS

The possibilities of small, fast ships operating on or near the surface appear excellent.

To permit the design and development of such craft, energetic research should be undertaken in the following hydrodynamic problems:

1. Propulsion by means of high-rpm machinery,

2. Drag of surface-piercing struts,

3. Forces and moments on high-speed bodies near the surface,

4. Depth control of near-surface bodies in following waves,

5. Optimization of control surface arrangements on submerged bodies,

6. Lateral control of a near-surface body with surface-piercing strut.

Parallel research and development should be carried on in other areas that affect the design of high-speed craft, particularly in the area of lightweight power plants.

The Navy should be encouraged to design and build experimental limited-purpose ships, not intended to undertake normal operational duties in the fleet. These ships would be of inestimable value in guiding future research, development, and design.

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DISCUSSION

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The subject of this Symposium is, of course, devoted to problems of hydrodynamics of high performance ships. Thus far during the Symposium, however, I have heard a great number of discussions concerning economics and propulsion and even some structural topics, as well, and therefore I hope the organizers of the Symposium will not chastise me too greatly if I too digress, if only briefly. I hope that the authors will also forgive me if I give you a little story that is incidental, more or less, to the subject of the paper, but which, nevertheless, has some bearing. One final remark by way of introduction: The paper by Professor Mandel was on the hydrodynamics of a deep-diving submarine, which design was carried through at my Institute. I hope that by my discussion, which is going to be very brief, you will not get the impression that our institute is concerned only with such very unusual types of vessels.

What I want to get to is the following consideration: The common yellow mineral known as sulphur exists in great abundance throughout the world, particularly along the gulf coast of the United States and Mexico, and in France and Italy. Sulphur is mined by the so-called Frasch process in which hot water is pumped down into the ground and the sulphur is forced out in molten form. This sulphur is then usually piled up in very large heaps in which it solidifies. Then one places a dynamite charge in the sulphur and blows off big chunks which are then loaded either on barges or on railroad cars and transported to other parts of the world. We began to think of a different means of transporting sulphur and for this we needed to know something about its structural properties, but we found out that even the largest sulphur producers in the world had little or no knowledge concerning the mechanical properties of sulphur. To make a long story short, sulphur is as strong as fairly high-grade Portland cement concrete: it has a very high compressive strength and a moderately good tensile strength. Our idea was, and we have investigated only certain of the economics involved here, to bring the sulphur up in molten form and to cast it in the form of a ship or boat and "sail" it to some other port or destination.

Because of its high compressive strength sulphur has some desirability for a semisubmerged boat. Unfortunately, its low tensile strength would require some reinforcing material, but since we had concrete barges during the war, why not a sulphur barge? To reduce wave impact forces and to improve operation in rough seas, why not a semisubmerged boat made of sulphur? It might be found rather than self-propelled, perhaps in train, and thus result in very large savings in transportation costs.

So, while I am not talking about particularly high performance ships of the semisubmerged type, and while I am talking about commercial aspects rather than military, I thought you might be amused by these speculations and considerations, bearing somewhat on the subject of semisubmerged ships, that we have been talking about. The stability studies and other considerations of the authors will certainly be of extreme interest to us if we pursue this subject further.

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