THE HYDRODYNAMICS OF HIGH-SPEED HYDROFOIL CRAFT

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A general discussion of some important hydrodynamic problems associated with the operation of high-speed hydrofoil craft is presented. The difficulties that arise from the necessity to either avoid cavitation or design for supercavitating operation, and at the same time to deal with those high-gust loadings that accompany flight in a seaway are emphasized. Theoretical results pertaining to the effect of a seaway on foil loadings and cavitation inception are given, as well as results describing the influence of the free surface on inception speed. The importance of flaps is stressed and new theoretical results concerning flap effectiveness in both sub- and supercavitating flows are presented. Finally, the effect of near-surface operation on the lift-drag ratio of supercavitating foils is discussed and some new theoretical results are given.

INTRODUCTION

I should like at the very beginning to state two warnings. The first concerns the title of this paper which was poorly and immodestly selected. Rather than "*The* Hydrodynamics of High-Speed Hydrofoil Craft" it should read "*Some* Hydrodynamics of High-Speed Hydrofoil Craft." In excluding from discussion many important problems, I have sought to emphasize others which are, in my opinion, most needy of discussion at this time. The second warning is addressed to the very small number of you who not only expect from me but even look forward to highly mathematical content. I am sorry to announce that not a single integral sign is to be displayed here. For this reason, I have already been accused of a kind of scientific degeneracy. Such a charge must, of course, be vigorously denied and I hasten to point out that between the lines and behind the figures lies, I think, enough mathematics to satisfy all but the most jaded theoretician.

The hydrofoil boat together with the airplane has been evolving now for over 50 years. It has appeared in many and varied configurations and performed with mixed success; until recently its future as a marine vehicle remained uncertain. The inevitably growing need for high-speed transport over water would seem to be well enough recognized at this time, however, so that the serious and continued development and use of the hydrofoil boat may be considered safely assured.

The advantages of the hydrofoil craft over displacement or planing craft for high Froude number operation is well-known. Only the edge jet vehicle (or hydroskimmer or ground effect machine as it is sometimes called) offers competitive performance and then, we believe, only in large sizes, say several thousand tons displacement. In Fig. 1 are outlined on a

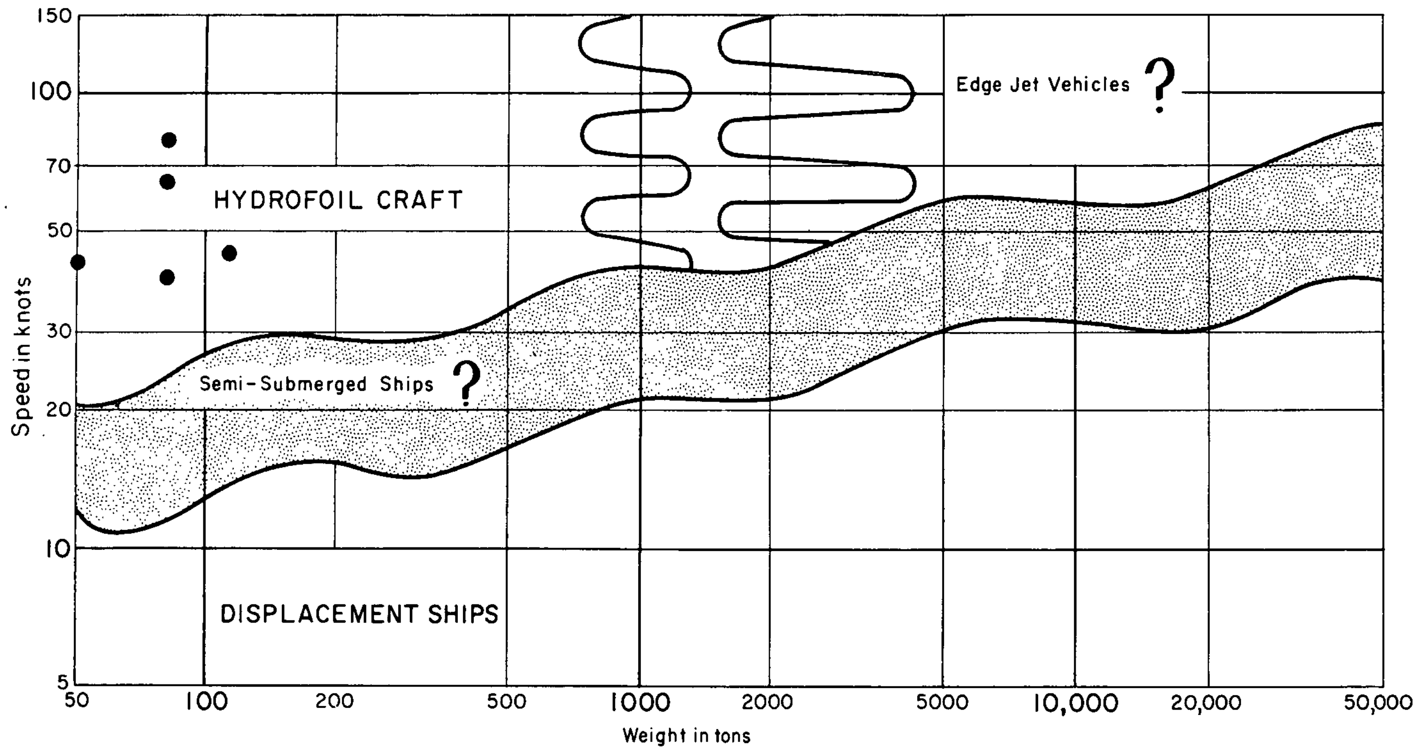

Fig. 1. Optimum operating regimes for seagoing vehicles

speed versus displacement diagram the regions in which various marine vehicles, including semisubmerged ships in addition to those already mentioned above, would seem to offer optimum powering performance. This diagram is based on available data [1, 2] and powering calculations we have carried out at Hydronautics, Incorporated. Also shown are design points for various hydrofoil boats that have been constructed or are under construction. Study reveals that both with regard to needs and capability, the hydrofoil boat seems particularly fated for high-speed operation, that is for speed in excess of 40 and perhaps as high as 120 knots.

The engineering problems involved in the design and construction of high-speed hydrofoil boats are exceedingly severe with respect to power plant, transmission, structure, and hydrodynamic aspects. It is the purpose of the present paper to discuss some of the important hydrodynamic considerations involved, to underline certain problems, and generally to give perspective to the situation that the hydrodynamicist faces.

Both sub- and supercavitating craft intended for sustained operation at sea are considered. It is emphasized that high-speed craft involve very high static foil loadings and additional severe seaway loadings. The hostility of the sea environment is strikingly illustrated through comparison with the atmospheric environment through which the airplane flies. The problem of preventing cavitation on subcavitating craft is discussed and the effect of seaway motions on inception is predicted. The importance of flaps for loads and motion control is underlined and some new theoretical results relating to the effect of the free surface on two-dimensional flap effectiveness for both sub- and supercavitating foils are presented. Other new theoretical results pertaining to the effect of the free surface are also given and, in particular, its beneficial influence on lift-drag ratios of two-dimensional supercavitating foils is revealed.

Many staff members of Hydronautics, Incorporated, have participated in the preparation of the results indicated above.

WING LOADINGS

Considering the essential similarity between the hydrofoil boat and the airplane, it is natural to compare the problems that have faced their development and, of course, to take maximum advantage of mutually useful and pertinent information and experience. This last statement will almost universally be translated as meaning that the naval architect should take advantage of the knowledge of the aeronautical engineer—as, most naturally, he often does. Of course, seacraft and aircraft operate in vastly different environments. Whereas air is so light that it is still a matter of amazement to many that anything substantial can support itself therein, every successful hydrodynamicist early acquires a great deal of respect for the weightiness of his own particular subject. A consequence of this difference in densities is illustrated in Fig. 2. In interpretation of this figure it is useful to recall that the wing or foil loading (displacement over foil area) equals the wing lift coefficient (C_L) multiplied by the dynamic pressure q, $(\rho U_0^2/2)$, and that the optimum lift coefficient for a given design depends primarily upon hydrodynamic considerations relating to minimum powering requirements; practical design lift coefficients for both seacraft and aircraft lie in the range 0.1 to 0.35. The very much larger wing loadings experienced by high-speed seacraft in comparison to those for supersonic aircraft are apparent from the figure. It is striking that the wing loadings of 60-knot-plus seacraft are at least one and almost two orders of magnitude larger than for aircraft of contemplated design. At the same time, the hydrodynamic demands for thinness of underwater structures are just as severe as in the

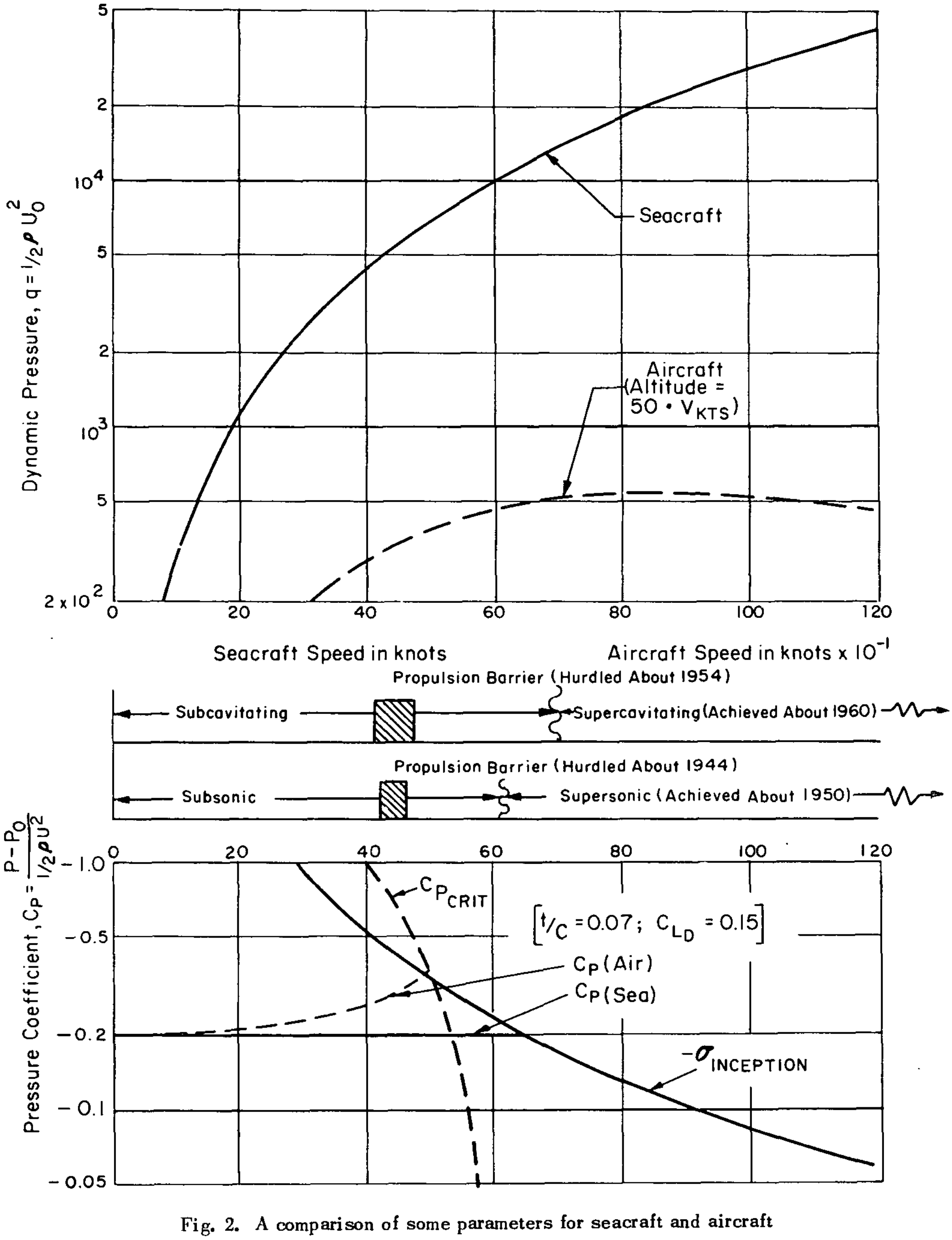

Fig. 2. A comparison of some parameters for seacraft and aircraft

case of aircraft; for either a supercavitating or supersonic foil of given length, drags are incurred proportional to the square of the foil thickness. It is rather difficult to put this comparison on a quantitative basis, but suffice it to say that a 5 percent diamond-shaped strut has the same drag coefficient (about 0.1 based on thickness) operating at mach number 2.3 in air, as when operating at 60 knots and 5 feet submergence in water while ventilated to the atmosphere.

Similarly, for subsonic or subcavitating foils a great premium is placed on structural slenderness, since the speeds which may be attained in either case without impairment in operation increase with thinness of structure. An attempt is made to illustrate this fact in Fig. 2 (bottom) where the critical pressure coefficient for aircraft and inception cavitation number for seacraft are plotted, together with the minimum pressure coefficient for a wing of about 7 percent thickness ratio and 0.1 lift coefficient. Such a wing would encounter, according to Fig. 2, drag rise and buffeting difficulties at 500 knots plus in air and 65 knots plus in calm water. However, a wing of 4 percent thickness and 0.1 lift coefficient could probably achieve about 530 knots in air and 80 knots in calm water before impairment of operation. The crucial observation to be made is that the seacraft structural designer must thin his wings at design dynamic pressures and wing loadings some 20 to 50 times greater than would exist in the case of an aircraft.

It is interesting, having put the static loading problem in some perspective, to note some analogies between propulsion and hydrodynamic problems for the airplane and hydrofoil boat. In these analogies, which it will be immediately recognized cannot be taken too literally, high-speed problems incurred in air due to the finite speed of sound become equivalent to difficulties caused by cavitation in water. In both media, screw propellers are commonly used at low speeds, with their use being finally impaired unless radical change in form is made at speeds of the order of 400 knots in air and 40 knots in water. The propulsion barriers that existed as a consequence, have both been successfully hurdled at this time, by the introduction of jet propulsion in one case, and of the supercavitating propeller in the other [3, 4]. It is taken for granted that high-speed hydrofoil craft will utilize supercavitating propellers with efficiencies at design in the range 0.65 to 0.72.

At speeds somewhat higher than those at which the low-speed screw propeller runs afoul of efficiency loss and severe vibration, the supporting foils of vehicles in both media begin to suffer those same difficulties, and at speeds in excess of 750 knots in air and 75 knots in water, it is almost essential that the design of wings and foils be based on entirely different principles than for low speeds. As is indicated in Fig. 2, the first hydrofoil craft utilizing supercavitating foils is being test flown this year (1960); it has been designed and constructed by Dynamic Developments, Inc., of Babylon, New York, under contract to the Office of Naval Research of the U.S. Navy. The cavities attached to these foils are not, of course, filled with water vapor, but are ventilated through the free surface to the atmosphere.

THE HOSTILE SEA

In a very important respect and in addition to considerations of static wing loading, the sea is a much more difficult, even hostile, environment in which to fly than the atmosphere. Most naval designers and ship's passengers have acquired an appreciation for the severity of the wind-driven motions which must statistically be expected to exist near and on the ocean's surface; and all of us who allow ourselves to be transported from place to place in aircraft have awareness of the turbulence in the atmosphere—we may even have observed

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that such turbulence is generally much more intense near the ground than at high altitudes. I do not think, however, that ever before has a quantitative comparison of gust intensities just beneath the surface of the sea, and in the atmosphere been made. In Fig. 3, the horizontal axis represents the root-mean-square of the vertical velocities (in feet per second) either in air or water, and the vertical axis the probability of exceeding a given value of root mean square velocity. Shown plotted are curves for the North Atlantic at a 5-foot depth averaged the year around and curves for averages for the atmosphere at low altitudes (0 to 10,000 feet) and moderate altitudes (30 to 50,000 feet). The values for air have been taken from Ref. 5. The values for the North Atlantic at 5-foot depth were theoretically derived from experimental all-year observations of significant wave heights in the North Atlantic made by the U.S. Weather Bureau, and have been taken from Ref. 6. It will be observed that a root-mean-square value of 1 foot per second is exceeded only 17 percent of the time at moderate altitudes in the atmosphere, 53 percent of the time at low altitudes, and 89 percent of the time at a depth of 5 feet in the North Atlantic. For an rms value of 3 feet per second, the respective percentages are 3, 16, and 28 percent. Only for high-intensity gusts (which occur infrequently) is the atmosphere at low altitudes statistically gustier than the ocean. The intensity of motions in the sea of course varies with depth of submergence, and in Fig. 4 this dependence is shown for a sea generated by a 20-foot-per-second wind, which about corresponds to a state 3 sea. It is to be noted that the rms vertical velocity is about twice as great at the surface as it is at 5-foot submergence and is further reduced about 50 percent as the depth increases to 10 feet.

The motion of the environment induces loads on the vehicle structure and subsequent rigid body motions and structural flexing. The seacraft, operating as it does in such close proximity to the sea surface must maintain its altitude relative to the instantaneous sea surface within very strict limits lest the hull impact or the foils and propeller broach. For that reason it is generally desirable for the craft to "follow" or respond to waves which are as long or longer than the craft itself. Both surface-piercing and variable-incidence foils are designed with such response in mind. Of course, the actual response of the vehicle to a certain sea will particularly depend on the frequency with which it encounters the waves that compose that sea. It so happens that the spectrum of a real, fully-risen, wind-generated sea seems to be sharply peaked, most of the energy residing in waves traveling with a celerity close to the wind speed and with corresponding lengths [7]. The consequence of this fact is that a boat traversing such a sea will sense a dominant frequency of encounter, which will depend on the wind speed that generated the sea, the boat's speed, and its direction relative to the wind. In Fig. 5 is plotted this frequency of encounter versus boat speed from motion into (to the left) and with (to the right) the wind, for wind speeds from 7 to 23.5 knots, corresponding to sea states from 2 through 5. These curves are based on studies made by F. Turpin and M. Martin [8]. It is to be noted that a response to frequencies, ω, in excess of 2.5 radians per second or about 0.4 cps (averaging the "with" wind and "into" wind encounters) is required for a 60-knot boat operating in state 5 sea, and even more rapid responses for faster craft. The rms accelerations experienced by a boat responding to such a sea are 0.707 $\omega^2 H_0$, where H_0 is the semiamplitude of the vehicle's heaving motion relative to fixed axes.

Such accelerations must themselves be limited especially on account of human comfort limits. It turns out, in fact, that our tolerance to vertical accelerations is quite small. Shown in Fig. 6 are curves based on recent studies of factors influencing hydrofoil boat handling qualities by P. Eisenberg [9] which delimit acceleration and frequency ranges for which vertical motions are perceptible, uncomfortable, and intolerable. If an rms acceleration of 0.15 g is taken as an upper design limit, then in a state 5 sea, H_0 could not exceed about 6 inches. However, the rms wave semiamplitude in the same sea is about 3 feet and the 10 percent highest waves have an rms semiamplitude of 5.4 feet. It would seem that

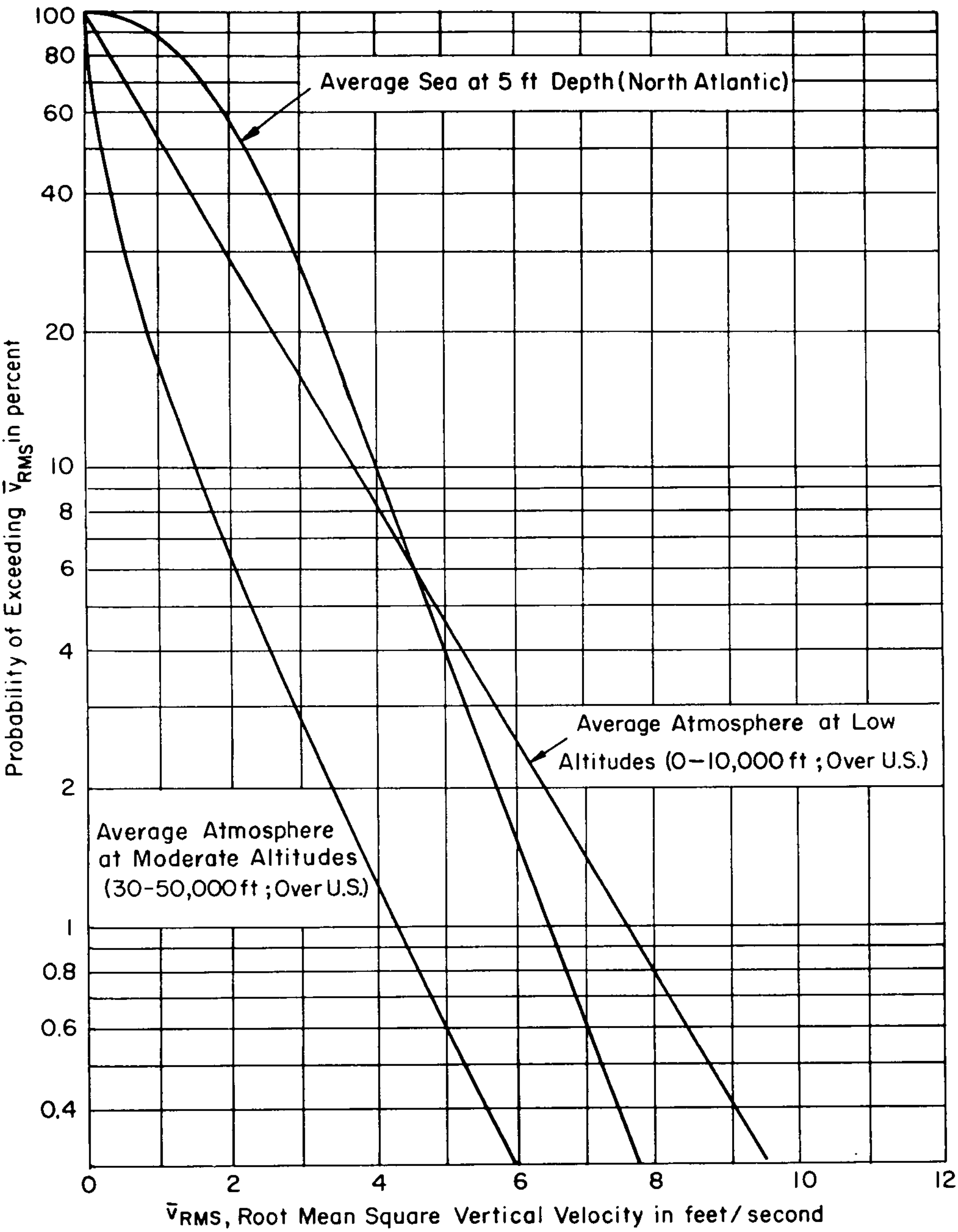

Fig. 3. Statistical vertical velocities at sea and in the atmosphere

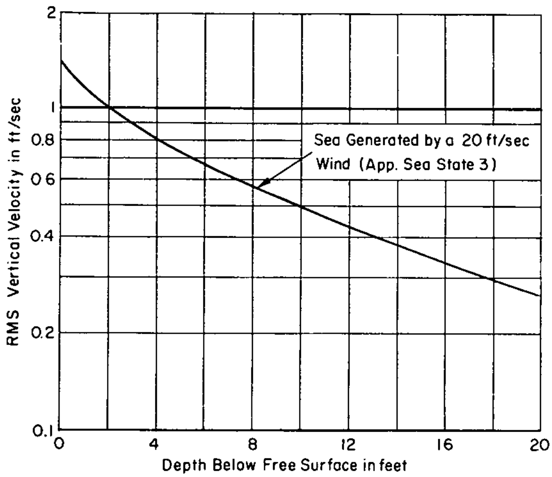

Fig. 4. Effect of depth on vertical velocities in a seaway

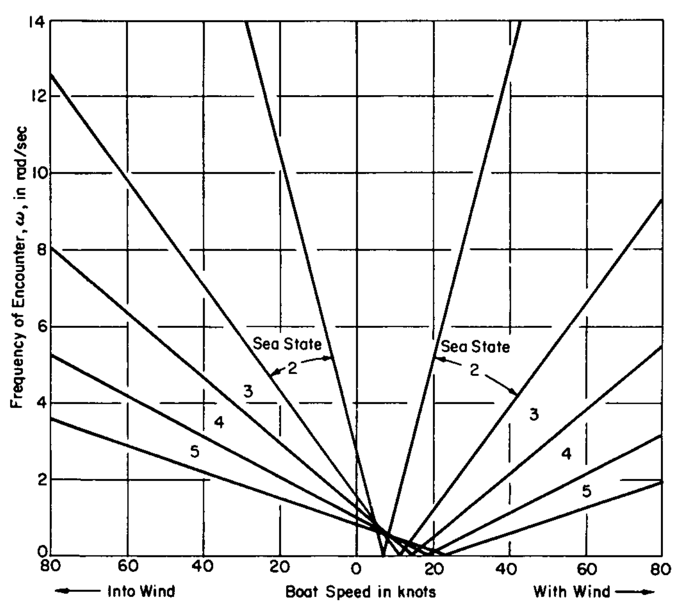

Fig. 5. Frequencies with which a boat encounters waves of various sea states corresponding to various wind speeds

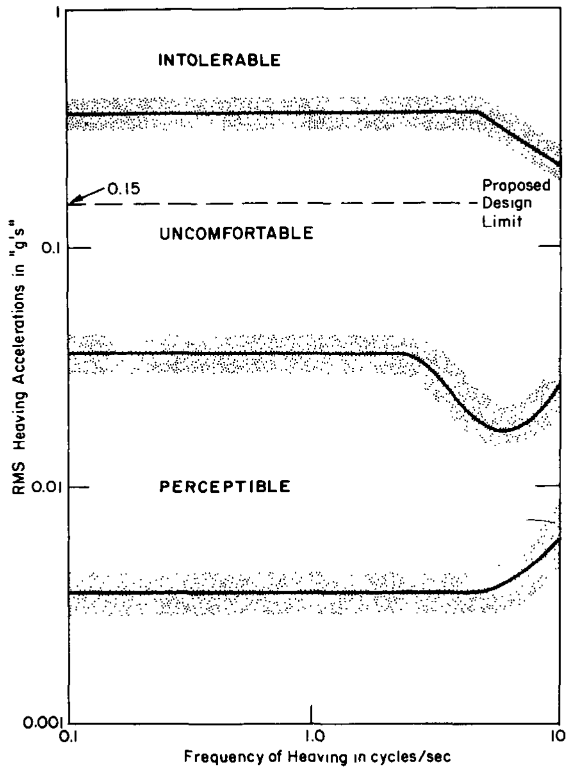

Fig. 6. Human sensitivity to heaving oscillations

such a sea cannot, for reasons of comfort alone, be followed to any extent, but must be plowed. Such an effort, of course, requires a boat with sufficient hull clearance and foil submergence for the hull to pass over crests and the foil system to extend under wave troughs. Variable incidence foil systems particularly recommend themselves for plowing, since a typical surface-piercing foil would during such motions experience fluctuations in load due not only to the orbital subsurface velocities associated with waves, but also to changes in wetted area.

It is of interest to calculate the fluctuating loads acting on a plowing fully submerged foil system, without trim changes, flap or spoiler actuation (in other words, a passive foil system), in order that the problem of controlling these loads by one or another of the means just mentioned can be properly assessed. These loads will actually depend on the rigid body motions of the vehicle and the structural flexing. Aircraft experience [10, 11] would lead us to believe that such dynamic effects tend to increase the loads calculated on the basis of a rigid structure and quasi-static analysis such as we make here. Thus, alarming as our results may be, they are probably not to be relieved by more rigorous calculations, but only through a relaxing of the sea conditions that we have referred to. The dynamic g loadings (in addition to static loadings) induced by the seaway on a fully submerged wing are, according to quasi-static and rigid-body theory, approximately equal to

$$(C_{L_\alpha}/C_L U_0)\bar{v}$$

where C_{L_α} is the foil lift curve slope, C_L is the equilibrium lift coefficient, U_0 is the speed of advance, and $\bar{v}$ is the seaway-induced vertical velocity. If rms g loadings are desired, then rms values of $\bar{v}$ are to be used in computation. The quantity

$$C_{L_\alpha}/C_L U_0$$

at design speed is a characteristic of the craft, while the quantity $\bar{v}$ depends on the environment. Clearly, if minimum dynamic loadings are desired, then the parameter

$$C_{L_\alpha}/C_L U_0$$

should be minimized in design.

In Fig. 7 are shown calculated values of this parameter as a function of speed, for a family of subcavitating and supercavitating hydrofoil wings. The former was selected with wing lift coefficients, thickness ratios, and aspect ratios varying from 0.35, 0.11, and 7 (respectively) at 45 knots to 0.15, 0.05, and 3.3 (respectively) at 70 knots and in such a way as to maintain approximately constant wing stress and satisfy cavitation inception considerations at each speed. The operating depth of submergence is for all wings taken as one mean foil chord. The supercavitating wings were taken in two versions, utilizing in one case thin low-drag foil sections ($t/c \approx 0.08$) with aspect ratios and lift coefficients ranging from 5 and 0.18 respectively at 60 knots to 3.4 and 0.16 respectively at 90 knots, and in the other case thicker foil sections ($t/c \approx 0.16$) with aspect ratios and lift coefficients ranging from 8.1 and 0.26 at 60 knots to 5.6 and 0.23 at the higher speed. All of the supercavitating wings considered are designed for approximately equal maximum nominal stress and are optimized with respect to lift-drag ratios.

The dynamic loads parameter is seen to be generally larger for subcavitating wings, mainly as a result of the higher sectional lift curve slopes of subcavitating foils relative to supercavitating sections. It will be recalled that at infinite depth, the former are about

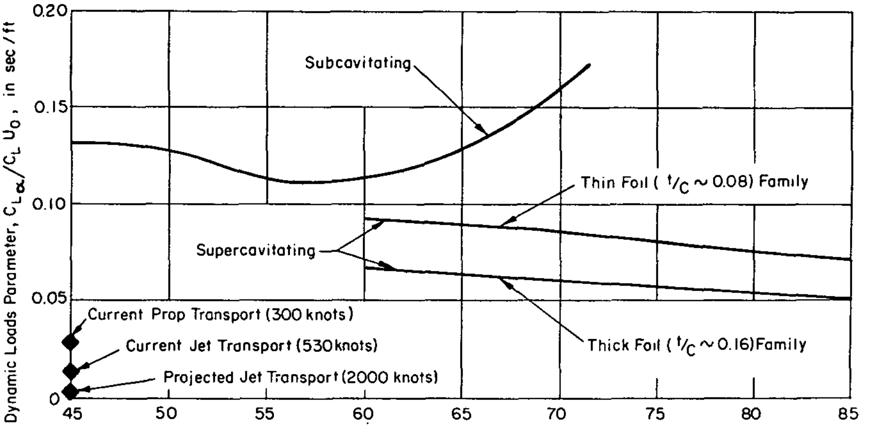

Fig. 7. Dynamic loads parameter $C_{L_\alpha}/C_L U_0$ for a family of hydrofoil craft

four times the latter in value. The proximity of the free surface tends to reduce this ratio, however, and for the wings considered, the C_{L_α} were in an average ratio of about two to one. The increase in the dynamic loads parameter for subcavitating craft between 60 and 70 knots is entirely due to the decrease in lift coefficients demanded in order to prevent cavitation inception. For the optimized supercavitating wing families a general decrease in dynamic load parameter accompanies and is due to increasing speed. The family with thicker foil sections enjoys a smaller value of the parameter because of higher optimum lift coefficients. The values of

$$C_{L_\alpha}/C_L U_0$$

for three transport aircraft [12] are also shown on the vertical ordinate and are seen to be considerably smaller in value than for the best supercavitating wing at 85 knots; the speed of these aircraft range from 300 to 2,000 knots.

The results of the calculation of the dynamic loads parameter shown in Fig. 7 and which have just been discussed, are combined with earlier statistical results, Fig. 3, relating to the character of the North Atlantic and of the atmosphere, to determine the probability that a particular craft with passive foil system (no load alleviation) will suffer dynamic rms g loadings exceeding a certain level. These new results are shown in Fig. 8. The extremely marked effect of decreasing values of dynamic loads parameter,

$$C_{L_\alpha}/C_L U_0$$

in reducing the probability of high g loadings is to be noted. As this parameter varies from a value of 0.04, which is a little less than for the best supercavitating wing at 90 knots, to a value of 0.12 which is a little less than for the subcavitating wing at 65 knots, the probability of exceeding an rms g loading of 0.2 increases from 4 to 70 percent.

The results for aircraft utilizing the low-altitude gust probability curve of Fig. 3 for the propeller transport and the high-altitude curve for the jet are interesting in themselves, but they have been especially included in order to afford through comparison a striking illustration of the magnitude of the dynamic loads problem that must be faced by the designer of seagoing high-speed hydrofoil craft.

LOAD ALLEVIATION AND FLAPS

The results shown in Fig. 8 make it abundantly clear that extremely effective load-alleviating devices must be provided if the design limit of 0.15 g rms vertical acceleration set according to comfort criteria is to be met. These devices must counter vertical orbital velocities in both upward and downward directions and for 60-knot plus craft at encounter frequencies of the order of 2.5 radians per second and higher. If load alleviation is sought through tail foil trim control, then angular accelerations leading to vertical accelerations in excess of the design limit would, according to our calculations, seem to be implied. As an alternative, control of lift at the main foils without essential change of trim suggests itself and has the additional advantage of affording more rapid response than in the case of trim control.

The use of flaps has especially been considered, and in that connection we present here the results of recent calculations on the behavior of two-dimensional flaps for both subcavitating and supercavitating foils, both operating at very high forward speeds. It must

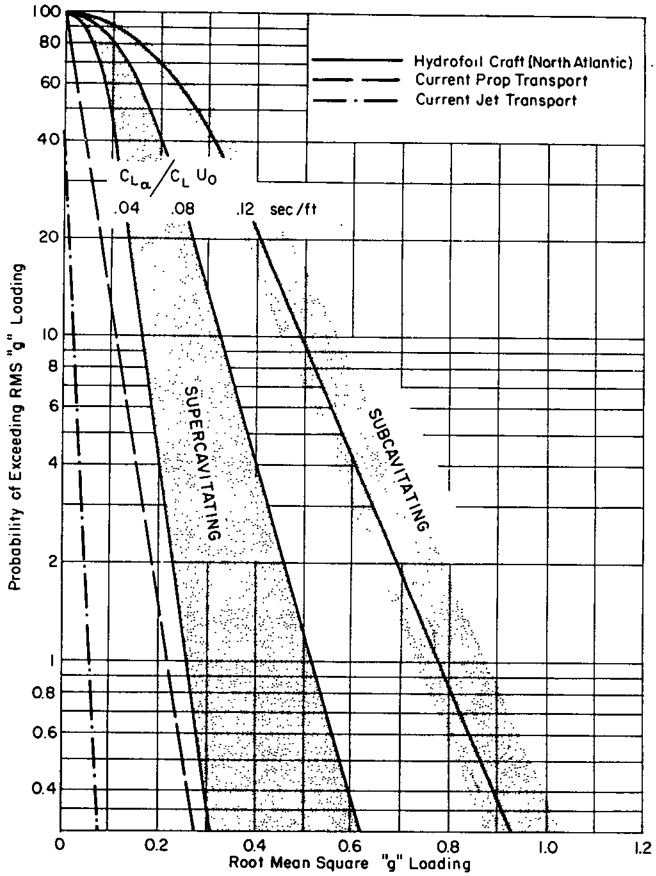

Fig. 8. Statistical dynamic loading for seacraft and aircraft

be understood that the values of flap effectiveness and hinge moments shown must be suitably modified in practice to take into account real fluid and finite aspect ratio effects; these results do, however, show the magnitude of the effect of near surface proximity.

In Fig. 9 (left) are given curves of subcavitating flap effectiveness versus flap-chord ratio for depth-chord ratios from zero to infinity. A composite curve for a range of flap-chord ratios, graphically illustrating the near surface effect is also given in Fig. 9 (right). The important conclusion is that theory predicts about a 4-percent loss in flap effectiveness relative to infinite depth at one chord submergence, and a 13-percent loss at 1/2 chord depth. The loss at zero submergence in the planing condition is 50 percent. These calculations assume that no cavitation occurs on the foil in the vicinity of the hinge; such occurrence would of course lead to loss in flap effectiveness. The results for surface effect on subcavitating flap effectiveness were obtained by my colleague C. F. Chen in a very interesting way. He determined that a particular flow reversal theorem which had previously been derived for flows without free surfaces [13] was applicable in the present case, and he was thus able to calculate the force on a flapped foil in terms of the flow about a flat plate at incidence under the free surface; the latter flow is exactly the flow about the lower foil

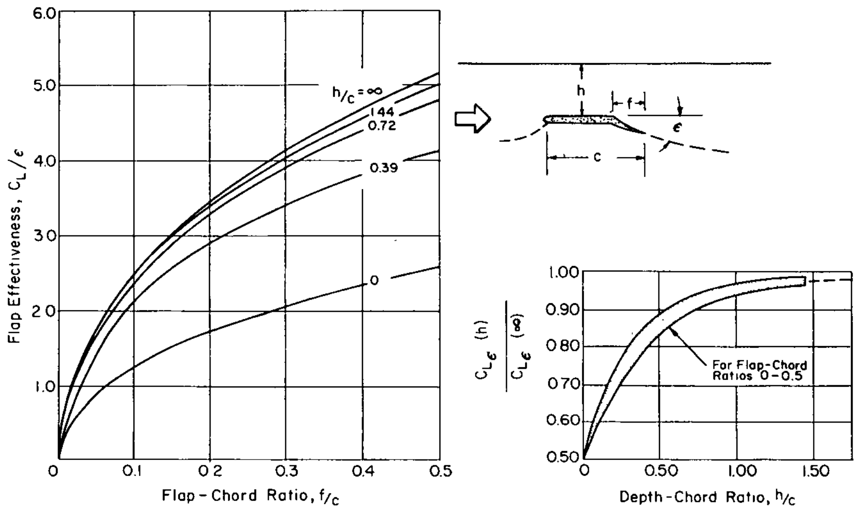

Fig. 9. Free surface effect on two-dimensional subcavitating flap effectiveness

of a two-dimensional biplane and has been known for decades [14]. This calculation constituted the first application to my knowledge of flow reversal theorems for flows with a free surface.

The flap effectiveness of supercavitating flaps at a given depth and for a particular flap-chord ratio is less than that of subcavitating flaps, but the difference in effectiveness decreases with depth and finally disappears at zero submergence. This situation corresponds to the fact that subcavitating flap effectiveness decreases as the free surface is approached whereas supercavitating flaps become more effective. J. Auslaender [15] has recently developed pertinent theory and calculated the performance of supercavitating flaps including the effect of the free surface. In Fig. 10 are presented curves of flap effectiveness versus flap-chord ratio for depth-chord ratios of 0, 1, and infinity. The results for infinite submergence had been obtained previously [16], at which time it was observed that supercavitating flaps at infinite depth reached a maximum value of flap effectiveness for flap-chord ratios less than one. It will be observed in Fig. 10 that for a flap-chord ratio of 0.25, the supercavitating flap gains 17 percent in effectiveness at 1 chord submergence (relative to infinite depth) and 47 percent at 0 submergence in the planing condition. Also, presented as Fig. 11 are hinge moment coefficients for supercavitating foils composed of a forward flat section operating at various angles of incidence δ, followed by a 25-percent flap, all operating at a depth of 1 chord. These results and many more of the same nature have been obtained by Auslaender using linearized theory for zero cavitation number [16-19]. It is presumed that practical foils will be ventilated to the atmosphere and thus operate at a cavitation number close to zero, so that the present results are meaningful practically.

The action of flaps or other load alleviation devices must, of course, be supervised by a suitable sensing and control system. Such systems, involving acoustic wave sensors and similarly sophisticated devices—plus the ubiquitous black box or two—are apparently under active development. I will not dare to say anything about these things, but it is perhaps worth speculating in the present context that high-speed boats must mainly plow through rather than respond to the sea, and that the alleviation of dynamic loads, rather than the

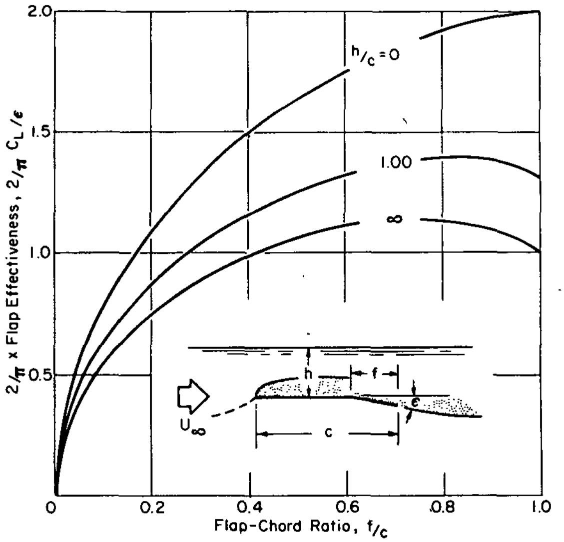

Fig. 10. Free surface effect on two-dimensional supercavitating flap effectiveness

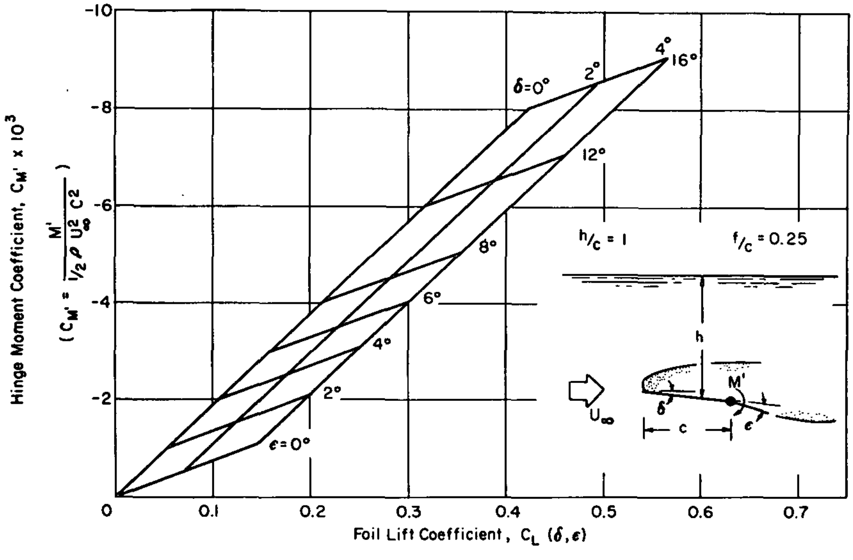

Fig. 11. Supercavitating hinge moment coefficient

control of motions, becomes the task that must be successfully accomplished by the flaps, black boxes, etc.

CAVITATION SUPPRESSION

As boat speeds increase beyond 40 knots the danger of cavitation occurrence on foils, vertical struts, and propulsion nacelles rapidly increases. Because of the erosive effects of cavitation it does not seem attractive to design for operation with small regions of local cavitation occurring on the underwater structure, nor does it seem really feasible to allow extensive cavitation short of supercavitation because of the buffeting that very often accompanies such "transcavitating" flows [20]. The designer must thus strive to suppress cavitation, a process which as earlier mentioned leads to underwater structures which become increasingly thin.

A great deal has been written about the estimation of minimum pressure coefficients on hydrodynamic bodies, and I will here only add several small straws to the camel's back. The first concerns the point that it would seem to us generally dangerous in design, even in the earliest stages, to consider the inception properties of components by themselves rather than in combination. This might seem to be a rather obvious remark, but nevertheless there has been considerable discussion of the inception properties of components, and very little on combined configurations. In Fig. 12 are shown theoretical inception speeds for a modified spheroidal nacelle and a NASA 16 series strut both separately and in combination, as a function of pod length-diameter ratio. The strut maximum thickness was assumed to be 1/6 of the nacelle diameter and its length 67% of the nacelle length; since such a nacelle may at times operate in practice right up to the free surface, the calculations were made for zero depth although the relieving effect of the free surface was not taken into account. These calculations were made for illustrative purposes only, and although thought to be realistic, do not necessarily represent optimum configurations; further they neglect the influence of the propeller and horizontal foils should they be called for, and the additional influence of pitch and yaw. Even so the relation between component and configuration inception speeds is indicated.

In considering the inception speeds of components it would seem very important that the effect of wave motions be taken into account, for the minimum pressure coefficients of high-speed foil and strut sections are very sensitive to incidence and yaw. Shown as Fig. 13 is an estimation of the probability that local cavitation will occur on a hydrofoil wing of aspect ratio 4, with Series 16 sections of 4-percent thickness and a design lift coefficient of 0.15, while operating at 5-foot depth in the average North Atlantic environment described in Fig. 3; it was assumed that cavitation occurs during motions involving fluctuating angles of attack for values of rms angle of attack equal to steady inception angles, and this is believed to be a conservative assumption. It is observed that this wing, which could according to theory make 70 knots in calm water, will cavitate over 50 percent of the time during year-round operation at speeds as low as 50 knots, and over 75 percent of the time at 60 knots. These predictions of average performance do not, of course, show how inception speed varies with sea state, so in Fig. 14 is presented (solid line from the left) a curve of inception speed versus sea states (and corresponding wind speed) for the wing described above, assuming again that the rms angle of attack corresponds to the steady inception angle. The dashed curves are based on the slightly different assumptions that the average of one-third highest and maximum angles of attack in the seaway correspond to the steady inception angle. It is of interest to know how much faster than inception speed a wing may be driven before the cavity grows long enough to cause serious buffeting, and the right-hand

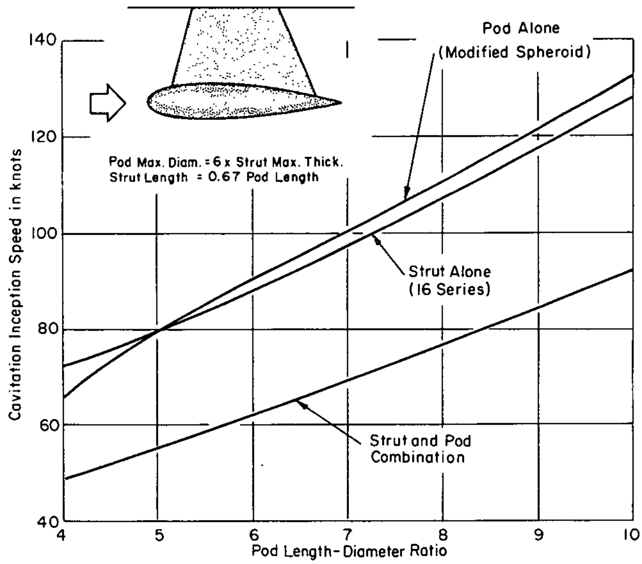

Fig. 12. Cavitation inception speeds for streamlined pods and struts

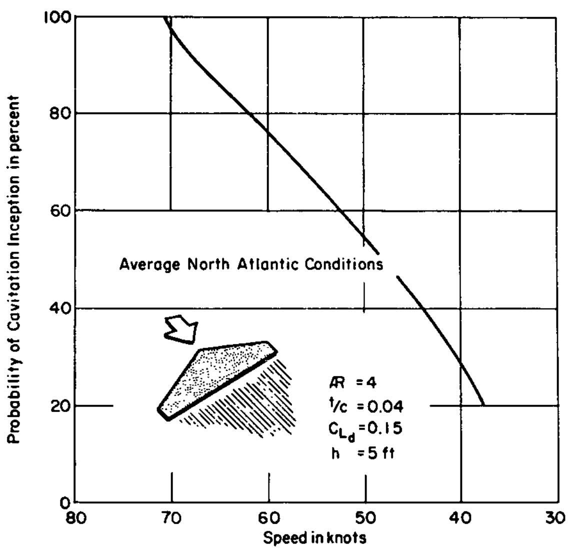

Fig. 13. Probability of cavitation inception vs speed for North Atlantic operation

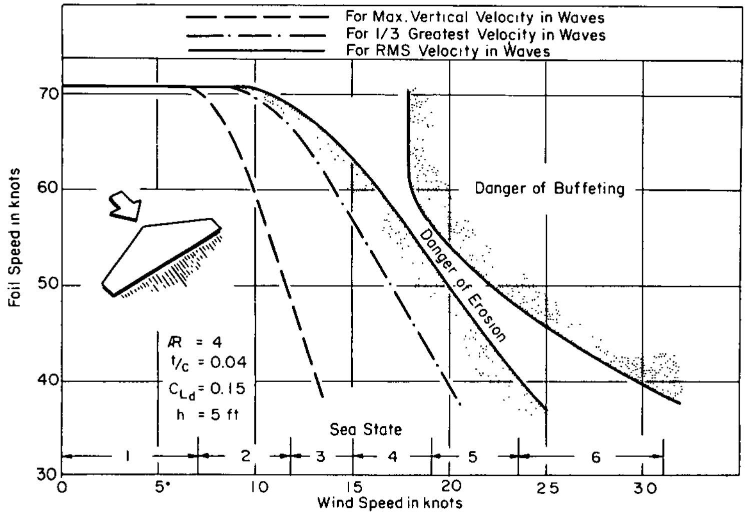

Fig. 14. Wing cavitation inception vs sea state

boundary in Fig. 14 outlines the region of forward speeds and sea state wherein severe foil vibrations might be expected; this prediction is entirely theoretical as far as operation in a seaway is concerned, being based on observations under steady angles of attack [20].

In order not to end this discussion of cavitation suppression on too despairing a note, I would like to present as Fig. 15 the results of calculations that we have carried out on the effect of the proximity of the free surface on the minimum pressures due to the thickness portion of a thin plane wing, and on the minimum pressures acting on spheroïdal bodies of revolution. For the smaller depth-diameter ratios, the latter refer particularly to the pressures on the upper portion of the body. These calculations indicate that very modest gains in inception speed may result in practical cases due to the proximity of the free surface.

SUPERCAVITATING OPERATION

It has already been pointed out that the propulsion of high-speed hydrofoil boats depends upon the utilization of supercavitating propellers, and it would seem clear, in addition, that the 70-knot-plus potential of these craft will depend upon the utilization of supercavitating foils and struts. A great deal has recently been written about practical bodies operating in cavity flow, and particularly good references to this work are the collective papers presented at the second Office of Naval Research Symposium on Naval Hydrodynamics (1958), which was the immediate predecessor of the present Symposium.

The Langley Laboratory of the (U.S.) National Aeronautics and Space Administration have in the past conducted especially valuable theoretical and experimental studies of supercavitating wings and struts operating in ventilated condition [17-19, 21]. These results provide at least a lower bound to the values of lift-drag ratios to be attained for high-speed craft, and it is believed that further significant increases in foil efficiency will be realized, if at all, only as the result of detailed and intensive research.

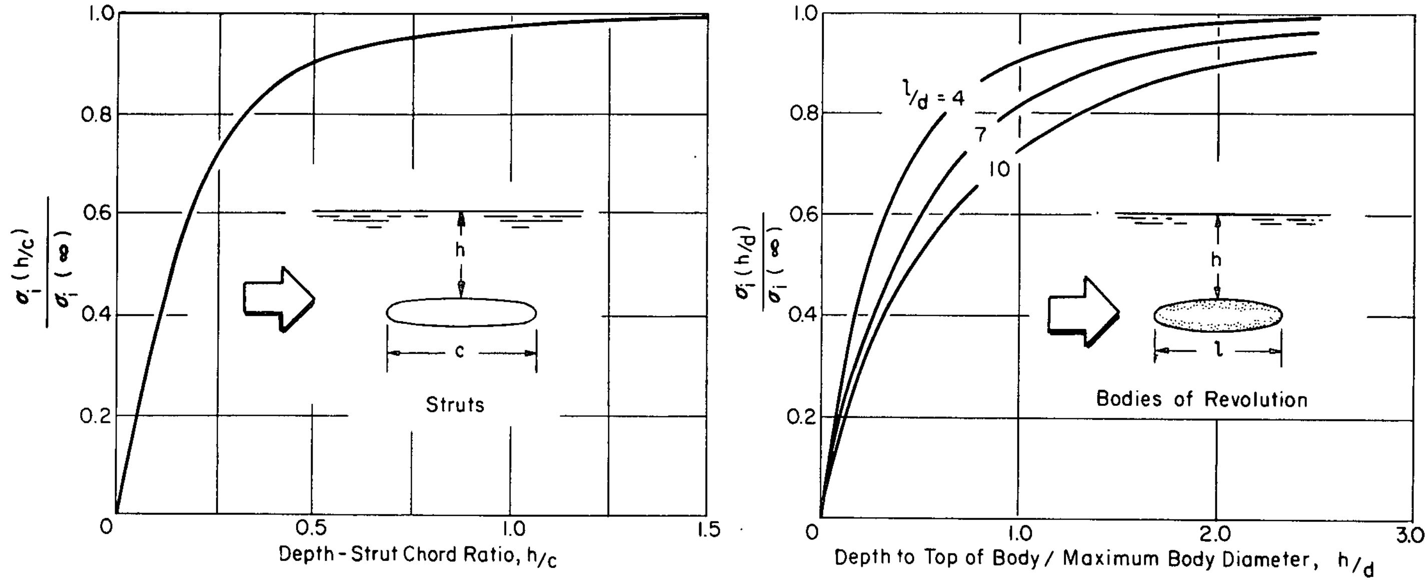

Fig. 15. Inception cavitation coefficients, σ_i, as affected by the near surface

For foils of optimum design, the sum of induced and cavity drags seems to be considerably greater than the friction drag. The division of induced and cavity drag depends very much on the wing aspect ratio, the cavity drag being generally larger and thus more important for aspect ratios of 2 or 3 and higher.

Theoretical studies [16, 17], now confirmed by experiments [18, 22], have led to the design of low-drag supercavitating foils such as are used in propeller design. We have recently developed a theory and made calculations to reveal the effect of near-surface proximity on the shape of optimized low-drag foils, and on the resulting lift-cavity drag (L/D_c) ratios. It may be recalled that I had some time ago shown that, according to linearized theory, there exist for supercavitating foils at infinite submergence, optimum values of L/D_c, inversely proportional to the foil lift coefficient. These ideal optimum ratios are not realized in practice partly because of the necessity to design foils of sufficient strength, and thus develop lift from incidence as well as camber; nevertheless, these ratios do provide information as to the efficiency with which lift can be developed through camber. In Fig. 16 are shown together with previous results for infinite submergence, theoretical two-dimensional foil efficiencies at a submergence of one chord. The optimum ratios of L/D_c are seen to be almost four times higher at this moderately shallow submergence than for deep submergences, but for various reasons these same ratios for practical foils and lift coefficients are reduced to about 1.5. As a caution against any undue optimism that might be generated by this finding, it should be recalled that active load-alleviation devices such as the supercavitating flaps earlier discussed will, it seems safe to predict, inevitably extract their own penalty in terms of increased cavity drag.

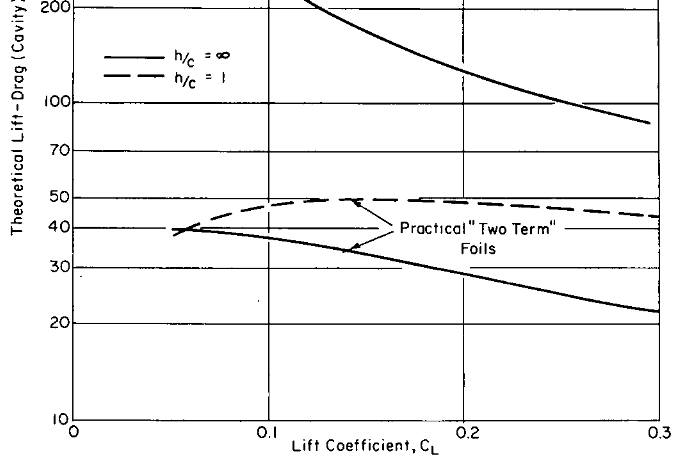

Fig. 16. Theoretical two-dimensional lift-drag (cavity) ratios

CONCLUSION

The subject of the hydrodynamics of high-speed hydrofoil craft has been far from exhaustively discussed here, even with regard to a cataloging of important problems. An effort has been made, however, to provide a little perspective as to the task that faces the designer and, in particular, to emphasize the problem of seaway induced dynamic loads, the related problem of load alleviation, certain problems connected with cavitation suppression—especially in a seaway, and, finally, the problem of the varied effects of near-surface proximity on foil performance. An attempt has also been made to provide some new and useful information relating to these problems; it will be understood that much of this information is based on theoretical developments and calculations carried out by the staff of Hydronautics, Inc., which are themselves the subjects of separate papers, and could not for reasons of space be gone into in any greater detail here; it is a pleasure to acknowledge that a good many of these results that I have just referred to were obtained under a research program sponsored by the U.S. Navy's Bureau of Ships.

Finally, lest some of the conclusions that have been arrived at are interpreted as throwing some doubt on the feasibility of high-speed ocean-going hydrofoil craft, let us affirm our personal conviction that such craft will inevitably be successfully developed and will before too much time passes find their unique place in the transportation scheme of things.

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DISCUSSION

S. F. Hoerner (Gibbs and Cox, Inc., New York)

The Froude number is generally used in the consideration of displacement-type ships. As far as hydrofoil boats are concerned, it is known that such craft will be able to operate efficiently at higher Froude numbers. The size of hydrofoil craft is limited, accordingly, and to mention a number, the limit might be in the order of 500 tons. However, there is also an upper limit to the Froude number as far as hydrofoil craft are concerned. To explain this briefly, consider a craft of 200 tons operating at 50 knots, which is believed to be feasible. We may now put into that craft heavier machinery, propelling it at 100 knots, which is twice the original speed. As a consequence, to support the same weight, we will only need 1/4 the original foil area. The size of the struts supporting the weight of the hull above the foils is, on the other hand, a function of the hull weight and of drag and other forces such as impact which are more or less proportional to that weight. In other words, the struts remain the same size as those of the original craft. Since struts are roughly accountable for half the drag of a foil system, the faster boat will have higher drag. This result can be said to be the consequence of high Froude number. The argument applies to plain configurations of hull plus foil system, while cavitation is not yet taken into account.

Marshall P. Tulin

It is certainly true that all studies of the speed and power of hydrofoil craft have revealed that there is a maximum practical Froude number beyond which hydrofoil craft may not be economically or otherwise feasible. Such studies, of course, include those made by Dr. Hoerner himself—which have proved very valuable to students of hydrofoil craft during the last few years. The actual value of a maximum Froude number depends on structural and power plant weights and its existence is not to be argued, but I would like to suggest that this Froude number may be an increasing function of time and that its estimation is thus not particularly easy. I might further comment on Dr. Hoerner's remark with regard to the drag of struts. In particular, I don't think I can agree that the strut drag is simply about half of the foil system drag; I believe that very much depends upon the configuration of the foil system and that the strut drag may be considerably less than half of the total for certain systems.

S. F. Hoerner

My statement that strut drag is roughly half the foil system drag applies to fully submerged foil systems at maximum speed. Generally, struts in such systems represent approximately 1/2 the *parasitic* drag, which mean approximately 1/4 the total drag, at maximum-range speed.

F. S. Burt (Admiralty Research Laboratory)

I endorse the point Mr. Tulin made that there is a considerable shortage of systematic data of components in association with one another. It is more important that tests on these associated systems should be carried out at the correct cavitation number than at the correct Froude number. In fact you are in the usual difficulty; you want all your numbers right, which can only be achieved at full-scale, and under these conditions it is very difficult to get really systematic measurements under completely controlled conditions. There are very few facilities available which can run at sufficient speed to get the correct cavitation number and a reasonable approximation to the Froude and Reynolds numbers. We have, in fact, been doing some work in the rotating-beam channel at the Admiralty Research Laboratory because we can run at large scale and very high speeds, up to 100 knots. There are available in the world quite a number of seaplane tanks which are going into disuse at the moment and I would suggest that these are ideal facilities for this type of work, particularly as a lot of them have the ability to make tests in simple wave systems, which is a very vital part of the whole problem. I suggest that more use might be made of these facilities by our various governments for hydrofoil craft experiments.

Marshall P. Tulin

I am very happy to hear Mr. Burt's comment on the effects of interactions on inception based upon his own experience and presumably on experimental measurements of cavitation inception. With regard to facilities, he has an admirable point with regard to the utilization of seaplane tanks where they exist. As I mentioned in my talk, the Hydrodynamics Division of the former National Advisory Committee for Aeronautics, now the National Aeronautics and Space Administration (NASA), carried out most valuable research on supercavitating hydrofoils and other related problems very pertinent to the development of hydrofoil craft; we all hope in the United States that those fine facilities which are no longer being used for seaplane research will continue to be put to use for high-speed hydrofoil and other marine testing.

Glen J. Wennagel (Dynamic Developments, Inc., Babylon, New York)

Mr. Burt talked on the further use of existing high-speed towing tanks and certainly these should be used. In fact, with the decrease in interest in high-speed seaplanes in recent years, perhaps hydrofoils have given these tanks a new lease on life. However, it is not always easy to test in the existing towing tank facilities. Sometimes they are far away and scheduling difficulties exist. Also, they are expensive. We went, about a year ago, to facilities like the Whirling tank and the Pendulum in order to have something relatively cheap in our own back yard, where we could use relatively inexpensive small models, make changes quickly and put ourselves in the right ball park on a hydrofoil or strut design. Then we would look forward to using some of the high-speed tanks, such as those at Langley Field, Virginia, after a foil design has been optimized. Let me give you an idea of the dollars and cents involved here. The whirling tank is worth about 100,000 dollars. You can use that amount of money up rather quickly in testing with larger scale models. To get the accuracies we wanted, a single model tested at Langley Field was worth about 12,000 dollars. You do not have to build many of those to use up the cost of a smaller facility.

P. Kaplan (Technical Research Group, Inc., Syosset, New York)

I have some questions as to the validity of the simple gust-load formula for the g loading of a hydrofoil system. The numbers appear to be too pessimistic, at least from my quick judgement of them, and we must remember the fact that the real hydrofoil craft is a coupled system where there is important effect of pitch and you have really two foils at different positions relative to the center, but quite different from a simple aircraft and what I have done was to compute some values of this gust-load factor according to the quasi-steady formula and then compare that with some values obtained from some experiments at the Model Basin. This bore out the fact that the original formulation appears to be quite pessimistic. However, the Model Basin tests were at a rather low Froude number, so perhaps that may cover some of the difference. Also, Mr. Tulin mentioned that he did not cover all of the various problems associated with the hydrodynamics of high-speed craft, and in particular I would like to put forward the fact that in this case of high-speed and supercavitating foils it appears that there may be a rather distinct possibility of the hydroelastic instability, that is, flutter. Some theoretical results carried out about a year ago at Stevens indicated that there is a greater possibility of obtaining a hydroelastic instability, that is, flutter, for supercavitating foils as compared to fully wetted foils. This sort of problem should be looked into very carefully in the design of these craft.

Marshall P. Tulin

With regard to Dr. Kaplan's question about the calculation of g loadings (which were admittedly based on the simplest sort of analysis), there is no question that very much more sophisticated calculations for hydrofoil craft should be carried out. In my paper I refer to several sophisticated calculations carried out for aircraft and I would suggest that these calculations should serve as a model with regard to hydrofoil investigations. To say that coupled motions are involved in such calculations is a gross understatement. In the case of a recent aircraft investigation, five degrees-of-freedom were considered, including torsion and bending of the wing, which are very important for high-speed aircraft and should certainly be as important in the case of the hydrofoil craft with its high wing loadings. It was particularly this aircraft investigation which prompted me to make the remark in my paper that the simplest kind of analysis leads, if anything, to conservative results regarding load estimations. Of course, the damping of hydrofoil craft motions is not necessarily the same as in the case of an aircraft, and for that reason alone we cannot come to any rigorous conclusions from aircraft experience. I hope that the kind of calculations, as I have indicated above, will be carried out; I can say that we plan to make some calculations ourselves.

Problems of hydroelastic phenomena are well-known to be important for high-speed supercavitating foils whether used in hydrofoil craft or in propellers. Such problems, particularly with regard to leading edge flutter, have already been experienced, and some stopgap solutions have been obtained. Certainly research on the subject of flutter and on strut divergence, which may be very important for high-speed craft, should be the subject of future investigations.

Edward V. Lewis (Davidson Laboratory, Stevens Institute of Technology)

Mr. Tulin has pointed out some of the serious problems of hydrofoil craft design for rough sea conditions. He expresses optimism regarding the possibility of solving these problems and suggests possible solutions.

I should like to return to a more basic problem of the hydrofoil boat which pertains to fundamental limitations on this type of craft. For this purpose we may compare a hydrofoil boat with an airplane, in which the boat hull and airplane fuselage are comparable, but the hydrofoil wings are in water instead of air. At any particular speed the increased density of water makes it possible for the wing area to be proportionately reduced for the hydrofoil boat. The total drag and hence overall L/D would be about the same as an airplane for an idealized hydrofoil craft in which resistance of appendages and supports is neglected. However, the increased density of water makes it possible with the proper "wing" area to obtain sufficient dynamic lift for the hydrofoil boat to "fly" at lower speeds than the airplane in air. When the hydrofoil craft is then designed to operate at a speed intermediate between that of an airplane and a ship, there should theoretically be a reduction in hull or fuselage resistance in air which is proportional to the square of the speed. Hence, the initial appeal of the hydrofoil boat was the hope that it could fill the speed gap between ships and airplanes, with a higher L/D or lower P/WV than the airplane. Unfortunately, the strut system required to put the wings in the water adds more to the resistance than is saved by the reduced speed. Hence, even the most enthusiastic hydrofoil man does not expect as good an L/D for the hydrofoil craft as for the airplane.

An important difference remains between the hydrofoil boat and the airplane. At its lower speed, the hydrofoil craft requires much less power, which should be advantageous. But the lower speed is less efficient for propulsion, and the drive system becomes very complex. Hence, no gain in payload from reduced power requirements can be expected in practice. Insofar as fuel is concerned, for the same specific fuel rate the total fuel consumed for equal distances is the same or greater.

Hence, it appears that the goal of the hydrofoil boat designer is simply to equal the performance of aircraft, but at reduced speed. The possibility of doing this in terms of L/D and gross weight (payload) appears remote. In short, a seaplane can outperform a hydrofoil boat, and attain higher speed at the same time. We must recognize therefore that the hydrofoil craft is inherently a special purpose vehicle.

I realize that it is dangerous in this company to appear antihydrofoil, hence, I hasten to add that I am enthusiastic about this development. My reason is simply that it is already stimulating technical progress in naval architecture, bringing advanced hydrodynamics, better structures, and more efficient power plants into the picture. No matter what happens to the hydrofoil itself, naval architecture will never be the same again.

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