VIII
HYDRODYNAMICS OF HIGH-SPEED WATER-BASED AIRCRAFT

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I. ABSTRACT

Post-war trends in aeronautics have brought with them a significant increase in the scope of hydrodynamics research and development for water-based aircraft. Recent contributions include the high length-beam ratio hull and the hydro-ski landing gear, both of which are compatible with the aerodynamic requirements of high-speed flight. The hydro-ski provides a solution for the pantobase airplane, a means of reducing water loads and resistance at high water speeds, an effective ditching aid, and a land-water mode of operation that minimizes or eliminates the need for a prepared runway.

Fundamental problems on which recent progress has been made include that of the planing surface and the low aspect-ratio submerged lifting element near the water surface. The take-off resistance of hulls at high water speeds, the emergence

(unporting) resistance of ski-body combinations, resistance due to spray, and the transition resistance of land-water skis have been investigated.

Other continuing problems include that of separated flows with negative pressure regions ventilated to the atmosphere, the increase in wave impact effects with landing speed and their alleviation, and high aspect-ratio hydrofoil configurations for modern aircraft. The need for higher-speed hydrodynamic test facilities to keep pace with the increasing minimum flight speeds associated with transonic and supersonic airplanes has been recognized.

II. Introduction

The last fifteen years have seen many revolutionary changes in the power plants, performance, and geometry of aircraft, and in their missions and modes of operation. At the same time there has been an almost complete disappearance of the seaplane from the aeronautical scene. History has begun to repeat itself, however, in that some of the original reasons for water-basing are again becoming valid and some cogent new ones are emerging. Without dwelling on these reasons, it may be said that the present military interest in the use of water as a landing and take-off medium lies in its still unexploited potentialities for aerial warfare from advance bases and its unequaled invulnerability to conventional or high-energy bombing.

The term "high-speed" in aeronautics is typical rather than restrictive since the trend has always been toward higher powers in smaller packages and higher useful speeds. The jet engine has greatly accelerated the curve of attainable speed against time so that high speeds are now transonic and even supersonic. It has also brought with it for water-based aircraft a liberation from the propeller-clearance dimension and a true size parity with other aircraft. This fact leads for the first time to water-based airplanes having mission capabilities comparable to those of the best landplanes, and greatly encourages a new utilization of the water-basing concept.

This paper reviews briefly the basic considerations involved in the design of water-based aircraft as influenced by the present era of high-speed flight, the new concepts for water operation that have arisen, and some of the associated hydrodynamic problems that have been investigated or formulated. The contents for the most part represent the activities and views of the author and his associates in the National Advisory Committee for Aeronautics, which, in cooperation with the military services and the aircraft industry, has continued to devote a substantial research effort to this area.

III. Symbols and Definitions

Planing and Submerged Surfaces

C_L	planing lift coefficient, $\frac{L}{qS}$
$C_{m_{t.e.}}$	planing trimming-moment coefficient about trailing edge, $\frac{M}{qSl_m}$
C_{L_L}	lifting-line component of C_L
C_{L_C}	cross-flow component of C_L
A	planing aspect ratio, $\frac{b}{l_m}$
τ	trim or angle of attack with respect to still-water surface.
β	angle of dead rise from keel to chine

l_p distance of center of pressure of total lift forward of trailing edge

l_m mean wetted length from trailing edge to stagnation line

$\frac{l_p}{l_m}$ center-of-pressure ratio for total lift

a_1 center-of-pressure ratio for lifting line component of lift

a_2 center-of-pressure ratio for cross-flow component of lift

b maximum wetted width of planing surface

$\frac{l_m}{b}$ wetted length-beam ratio

R longitudinal radius of curvature of planing surface

Z vertical clearance from trailing edge of planing surface to water bottom

L planing lift

D planing drag

M planing trimming moment about trailing edge

q dynamic pressure $\frac{\rho}{2}V^2$

S wetted area

ρ water mass density

V water speed

α angle of attack of submerged surface with respect to still water level

Submersion distance of highest point of submerged surface below still-water level

Aircraft Configurations

$(R + D)$ total resistance (water resistance plus aerodynamic drag during take-off)

V_G take-off or "getaway" speed

C_Δ Froude load coefficient, $\frac{\Delta}{wb^3}$

C_{Δ_o} Froude load coefficient at rest, $\frac{\Delta_o}{wb^3}$

C_R Froude resistance coefficient, $\frac{R}{wb^3}$

C_V Froude speed coefficient $\frac{V}{\sqrt{gb}}$

Δ_o take-off gross weight

Δ water-borne load during take-off

R water resistance plus hull air drag

b maximum wetted width over forebody chines

w specific weight of water

g acceleration of gravity

IV. Basic Considerations

The obvious and important factors to be considered in the design of a high-speed water-based aircraft in the sense defined are listed in Figure 1. What is not so obvious and depends greatly on current trends is their relative importance with regard to the basic compromises that must be made in procurement specifications and major design decisions.

Flight

In the first place, there can be little or no concession to established aerodynamic principles that provide favorable drag levels near and above the speed of sound in relation to currently available thrust levels. Once the desired speed is achieved, range and payload remain critical so that various factors in the range equation must be carefully balanced to attain useful mission radii. The characteristically low lift-drag ratios at supersonic speeds and the large adverse effects of small weight increases on range demand a great deal of design ingenuity to obtain useful performance, and more than ever before place flight considerations first.

Take-Off and Landing

The wing geometries and areas associated with high-speed flight have led to very high minimum flight speeds and the maximum water speeds with which the hydrodynamicist must deal. Contemporary landplanes are operated at runway speeds approching 250 knots, and unless STOL or VTOL techniques can be applied their water-based counterparts will be required to take-off and land at twice or three times the water speeds of post-war propeller-driven seaplanes. The questions of whether such speeds

A. FLIGHT
- SPEED
- RANGE AND PAYLOAD

B. TAKE-OFF AND LANDING
- SPRAY CLEARANCES
- STABILITY AND CONTROL
- TAKE-OFF PERFORMANCE
- ROUGH-WATER CAPABILITIES

C. MANEUVERING AND HANDLING

Figure 1. Basic considerations.

are practical and less or more so than for land-based operations appear of fundamental importance, and worthy of intensive investigation.

Spray clearances.—High-speed jet-propelled configurations are characterized by high fineness ratios, small frontall areas, high hydrodynamic loadings, and little or no spray clearance for vital components such as the engines themselves, the flaps when extended, and the horizontal tail. This problem in some respects dominates the basic design, although not necessarily adversely. Spray can be tolerated to some extent, and spray damage can be minimized by auxiliary devices and operating techniques. It must, however, be recognized and lived with as far as aerodynamic considerations permit, and in the treatment of mechanical or electrical gear subject to wetting.

Stability and control.—Adequate hydrodynamic stability and control during water operation are relatively difficult to achieve because high-speed aircraft are never too well off aerodynamically in these respects and their marginal characteristics reflect on their water behavior more than is generally appreciated. In the case of new and untried hydrodynamic design solutions, which abound in this era, the configuration must be made operable before other characteristics can be evaluated or optimized. "Runability" must therefore receive a great deal of attention in towing tank investigations, and is the basis for much of the work there with dynamically similar models.

Take-off performance.—Take-off performance is defined in terms of the total time and water distance required and of the ease of acceleration through critical spray or stability regimes. The latter is probably of greatest importance since it determines the adequacy of severly compromised hydrodynamic solutions found desirable from flight considerations. High-speed aircraft are blessed with high thrust-weight ratios for take-off; on the other hand, their high take-off speeds still prolong this phase of the flight. With both thrust and wing loadings determined primarily from mission requirements, the actual take-off performance remains properly a dependent characteristic except as it may be optimized in the detailed hydrodynamic design.

Rough-water capabilities.—The surface of the water in nature is seldom perfectly smooth or, on the other hand, too rough for seaplane operation except in large operating areas with long fetches. It is a moot question what should be demanded of a high-performance water-based airplane in this respect. Even relatively small waves and swells can inflict local damage on light aircraft structures, and at the high water speeds for take-off and landing can impart excessive motions and accelerations to the airplane as a whole. Adequate provision for these contingencies in severe sea states can be made only at the expense of the structural weight-gross weight ratio which is already critical. The alleviation of rough-water effects is recognized as a major goal in hydrodynamic research and some progress had been made, but it is believed strongly that the rough-water capabilities of a transonic or supersonic airplane is a derived rather than a primary specification, subordinate to rigid flight requirements.

Maneuvering and Handling

The maneuvering and taxying problems of high-speed water-based aircraft are at this point probably more severe than those of propeller-driven seaplanes because of the relative inflexibility of jet engines, their lack of reversibility, and generally close-coupled transverse locations. Wing-tip floats may still be required for static transverse stability and safe cross-wind taxying, but may have to be retracted or jettisoned in flight because of their drag penalty at sonic speeds.

While outside the scope of this paper, the subject of basing requirements must be included in any listing of considerations for advanced water-based aircraft. The point of such aircraft is, of course, their ability to operate in unprepared areas and independently of elaborate facilities; nevertheless, they will require bases of some sort where they can be fueled, loaded, and repaired. The airplane's part in these operations must be determined early and provisions made for it, subject, however, to the same flight restrictions that apply to all the factors discussed.

V. New Configuration and Concepts

High-Speed Hulls

The classic hydrodynamic solution for a large water-based airplane remains the flying-boat hull which combines the functions of the fuselage, floatation, and landing gear. Such a hull for a high-speed jet-propelled configuration reflecting several features resulting from post-war research and development is shown in Figure 2.

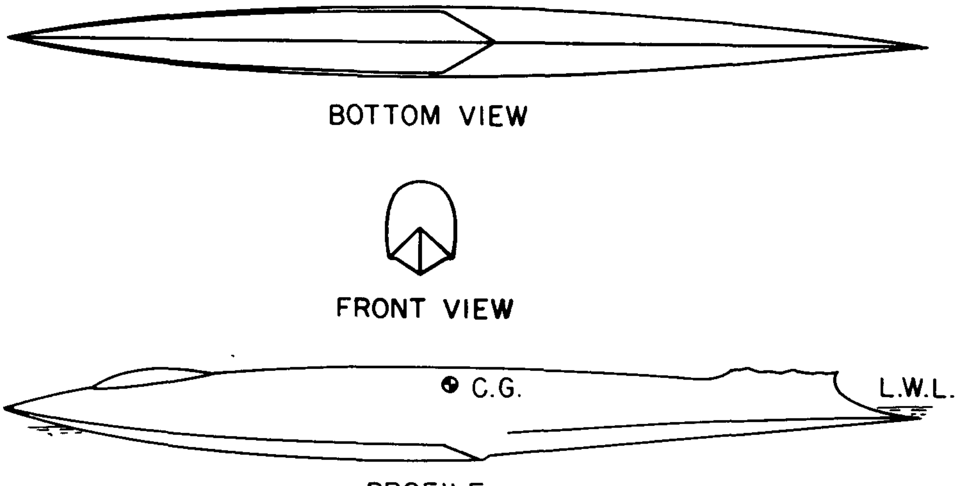

Figure 2. Typical high-speed hull.

Overall proportions.—One of the basic contributions has been an emancipation from arbitrary beam formulas, provided the hydrodynamic lengths are selected to suit. When the beam is reduced to reduce frontal area, the required lengths, particularly the forebody length, increase at a slower rate, resulting in a smaller bottom area without sacrifice of essential hydrodynamic qualities (ref. [1, 2, and 3]). The higher beam loading results in lower wetted aspect ratios and more intense side spray at the hump and planing speeds (ref. [4]); on the other hand, it provides a significant alleviation in water impact loads and motions (refs. [2 and 5]). This beneficial process can be carried to a practical limit from the construction point of view and embraces hydrodynamic length-beam ratios entirely compatible with the high body fineness ratios and low frontal areas mandatory for low drag at supersonic speeds.

Forebody.—With a hull of the type shown, the long streamlined forebody is hydrodynamically necessary for buoyance, cleanness of running, and low water resistance at pre-hump speeds. The relatively high angles of dead rise favorable for absorption of impacts at high water speeds are also advantageous with regard to low-speed spray (ref. [6]). The heavy main spray can be controlled to some extent by horizontal chine flare, or even vertical chine strips or "spray dams," but the close coupling of high-speed configurations still makes high wing and tail positions desirable for seaworthiness.

Step.—The trend in step design as shown is the use of a highly tapered plan form with some form of step fairing. These features minimize the aerodynamic and structural discontinuities and appear hydrodynamically acceptable if not carried too far. The tapered plan form tends to reduce impact loads (ref. [7]) and to improve the landing stability with shallow step depths.

Afterbody.—The long clean afterbody and low angle of afterbody keel are almost mandatory in a high-speed hull for buoyancy and fairing purposes. This type of afterbody improves rough-water loads and motions (ref. [8]), but is detrimental with regard to stability and resistance at high water speeds, as will be discussed later.

Area rule application.—In addition to the features shown, the form may include body indentations and bulges to minimize aerodynamic interference effects at transonic speeds. Such distortions of the form will be located above the chines, and, except near the after end, should not influence the hydrodynamic characteristics. In arriving at the proper distribution of hull volume from area-rule considerations, the graphical line-fairing methods of the naval architect have been employed to advantage to blend the various aerodynamic and hydrodynamic features desired. Trial solutions in the research laboratory for transonic and low supersonic configurations have indicated the continued usefulness of the flying-boat hull for aircraft in this category.

Hydro-Skis

Probably the most significant of the post-war hydrodynamic developments has been the so-called hydro-ski landing gear. This concept in its original form, stimulated by the trend to jet power and the need to approach more closely an optimum aerodynamic configuration, is illustrated in Figure 3.

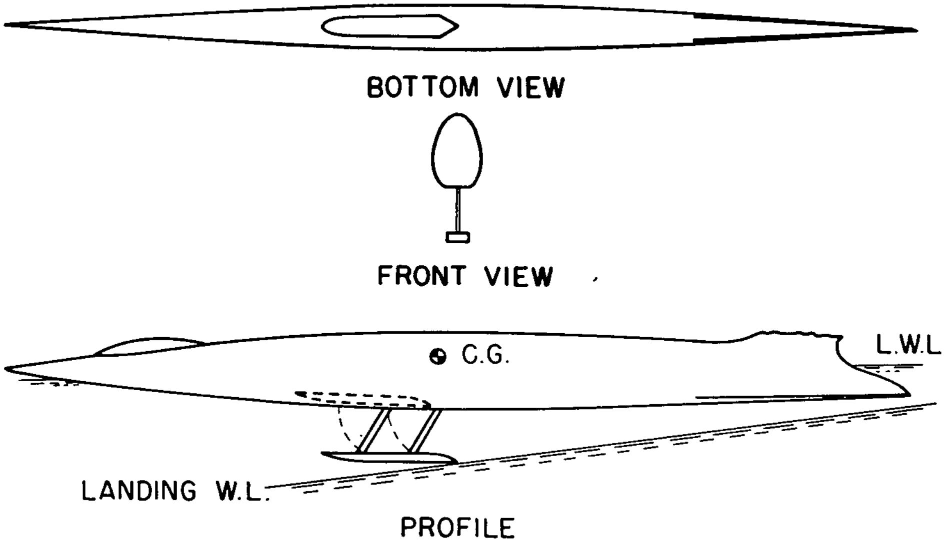

Figure 3. Typical high-speed fuselage with hydro-ski.

General.—Basically the hydro-ski is the hydrodynamic equivalent of the landing wheel rather than the conventional seaplane float. As such, the floatation function is dispensed with and it is deliberately made small enough for complete retraction in flight. It then becomes comparable in weight and complexity with a wheel gear, and localizes the landing loads near the airplane center of gravity.

Stability.—Early investigations with free dynamic models indicated that simple configurations like that shown may be expected to emerge (unport) stably, and to operate under control of the pilot at high water speeds very much like a wheel gear. They likewise may be made to land stably, and as the speed is reduced to the point where the ski gear submerges, they settle gracefully into the water without uncomfortable motions or changes in course (refs. [9 to 11]).

Resistance.—It was accepted at the start that the emergence water resistance would be high, since the fuselage would preferably have a minimum of hydrodynamic form and the necessary ski lift would be generated at a high angle of attack to make up for its small area compared to a hull forebody. At high planing speeds where the ski wake clears the fuselage, the water resistance can approach that of the planing surface alone, depending primarily on wetted aspect ratio and angle of attack.

Spray.—Large amounts of spray are generated by a small ski gear, particularly during emergence when the angle of attack is high and the ski nose is breaking the surface. The spray remains severe at planing speeds because of the high hydrodynamic loading. Most of this spray is relatively harmless, but makes a high degree of waterproofing and corrosion resistance important in the engineering design.

Rough-water qualities.—Highly loaded skis increase the effective stroke during water impacts to a degree dependent on their size and shape, and thus offer a further fundamental improvement in rough-water capabilities. This quality has been observed generally in model experiments as well as full-scale operation, and is substantiated by impact theory. Since the loads are localized in the ski struts, additional alleviation for the airplane can be provided by mechanical shock absorbers (ref. [7]), although this elaboration may be fundamentally redundant if the ski size can be made small enough.

Ski arrangements.—Many ski arrangements are possible for applications of the principle; they may be single or multiple, twin or tandem, retractable into different airplane components, etc., In any event, variations in the system must obviously, as for landplane gears, suit an established operating sequence requiring the minimum of attention and special control from the pilot.

Additional Hydro-Ski Applications

The Convair F2Y-1 Sea Dart represents the only literal application so far of the bold hydro-ski principle as originally conceived. Several additional concepts have, however, appeared from military attempts to evaluate the usefulness of the idea, which are of potential importance. These concepts are summarized in Figure 4.

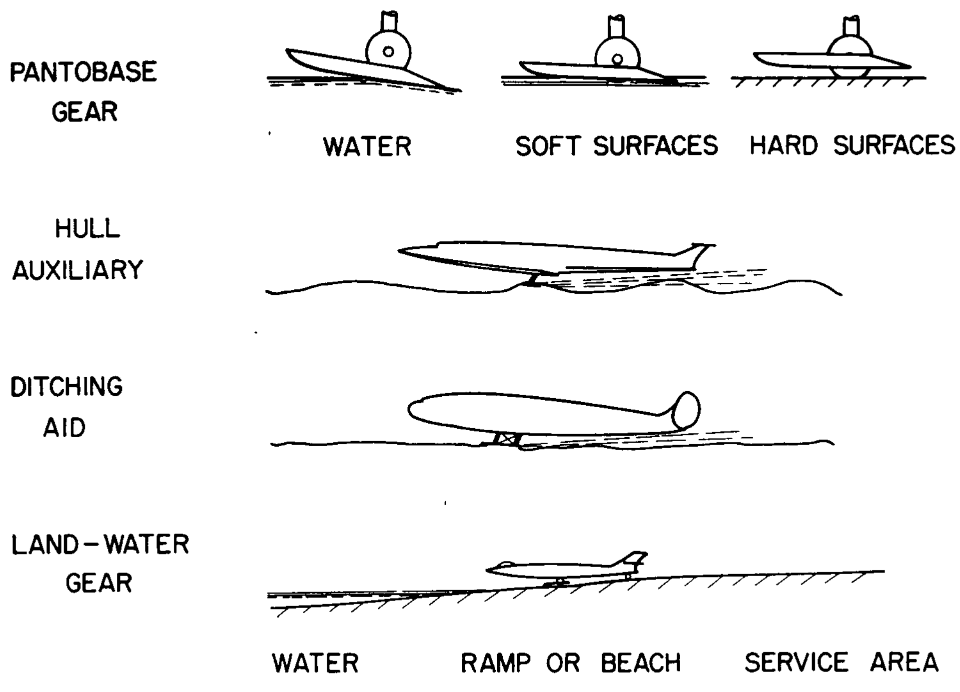

Figure 4. **Additional hydro-ski applications.**

Pantobase gear.—The similarity of water and snow skis leads immediately to arrangements suitable for operation on water, snow, and ice, and even other "wet" surfaces such as mud and sod. Such arrangements, combined with a conventional landing gear for normal runway use, provides the so-called "pantobase" airplane for universal operation in prepared and unprepared areas. These concepts have been investigated by hydro-ski conversions of a JRF-5 amphibian for Arctic service and of a C-123 assault transport for pantobase service (ref. [12]). The conversions of course increase utility rather than performance, but the principles explored are applicable to high-speed aircraft in other categories without the flight penalties so far incurred.

The logical ski-wheel configurations for a pantobase gear are indicated in the figure. For water operation, the skis are locked at a positive trim angle for hydrodynamic lift and stability, while the landing wheels are retracted above the skis to minimize their adverse effect on resistance. For soft surfaces and ice, the skis are free-to-trim as in the case of snow skis to follow surface contours and climb over obstructions. In this case the wheels may or may not be used depending on the nature of the medium. For hard-surface runways, the wheels are extended and the skis retracted above them so that the landing gear can function in a normal fashion.

Hull auxiliaries.—The employment of existing hull-type seaplanes as test beds for hydro-ski evaluations has confirmed their inherent superiority in rough water and the advantages of the large increase in afterbody clearances provided near take-off. This experience and continued model experiments have suggested the possibility of adding auxiliary skis to high-speed hulls to inprove their hydrodynamic performance. If the existing aerodynamic stability and control permit, the ski can be made very small and extended to completely penetrate the surface during wave impacts and thus provide a larger amount of energy absorption. Because even small skis increase water resistance in the early stages of take-off, they preferably remain retracted in these stages and be jacked out at speeds near getaway where water loads and afterbody interferences are most critical.

Ditching aids.—In emergency ditchings of land-based aircraft in rough seas, hazardous motions and extensive structural damage result from wave impacts at high water speeds leading to serious casualties and rapid flooding of the fuselage after the airplane comes to rest. The concept of the hydro-ski landing gear offers a positive means of eliminating these hazards from the ditching operation, and greatly increasing the chances of survival and rescue (ref. [13]). In this case, the gear would be used only once and a manual arrangement for extending it would be sufficient, hence its weight should be small as compared to that of a normal installation. It is conceivable that such a device would permit the fuselage to stay intact during a ditching and thus able to float indefinitely while awaiting rescue of the occupants.

Land-water operation.—Small airplanes have been operated successfully on and off beaches and ramps using snow skis, and several landplanes have been converted to water operation by the addition of small hydro-skis to the wheel gear. This experience leads to an entirely new concept to free high-performance aircraft from present runway limitations, and at the same time eliminate the handling, floatation, and low-speed hydrodynamic problems associated with complete water-based systems.

Essentially the airplane is land-based adjacent to one of the sheltered bodies of water which abound in most parts of the world. To take-off it accelerates down a beach or short prepared ramp to a suitable low planing speed. At this point, it enters the water and completes the high-speed portion of its take-off run on the hydro-skis. Coming back, it reverses the process by landing on the water, decelerating to near the minimum planing speed, and going up the ramp to a convenient point for service and maintenance.

The essential features of a gear for land-water operation are similar to those for a pantobase gear in that the skis must be free-to-trim on land and fixed in trim on the water and the wheels are preferably retracted during the water runs. Both the ski and wheels can be smaller and lighter than for a true water-based version or a land-plane, and the airplane fuselage requires little or no hydrodynamic modification. The minimum planing speeds are low compared to take-off and landing speeds, hence accidents resulting from power failure would be less severe than for the equivalent maneuvers on restricted land runways.

The employment of this mode of operation could be of great military or commercial significance since it embodies the primary advantages of land basing and water basing without the serious disadvantages of either. There are, of course, many design and operational problems which must be solved, but which can best be evaluated by economical conversions of existing high-speed land-based equipment and operation of these conversions under actual service conditions.

VI. Hydrodynamic Research Results and Problems

Planing Surfaces

With trends toward higher landing speeds and the developments described, experimental research on planing by the NACA has been largely directed toward extensions of the ranges of available data to higher speeds, trims, and length-beam ratios. At the same time, the scope of the work has included practical variations in geometric parameters introduced by the new concepts and configurations (refs. [14 to 20]).

Most of the previously determined and extended ranges of experimental pure planing data for the classic flat plate have been satisfactorily correlated by Shuford of the Langely Aeronautical Laboratory (ref. [21]) using the methods of modern low-aspect-ratio airfoil theory. This investigator has recently extended his contribution to include cross-section and plan-form effects as indicated in Figure 5.

Lift.—The hydrodynamic lift coefficient based on wetted area is a simple function of a lifting-line airfoil term and a crossflow lift term. In this equation, A is the hydrodynamic aspect ratio $\frac{b}{l_m}$, where b is the maximum width and l_m is the mean

LIFTING LINE TERM, C_{L_L} CROSS-FLOW TERM, C_{L_C}

$$C_L = \frac{0.5\pi A\tau}{1+A}\cos^2\tau\,(1-\sin\beta) + C_{D_C}\sin^2\tau\cos^3\tau\cos\beta$$

$$\frac{l_p}{l_m} = \frac{a_1 C_{L_L} + a_2 C_{L_C}}{C_L}$$

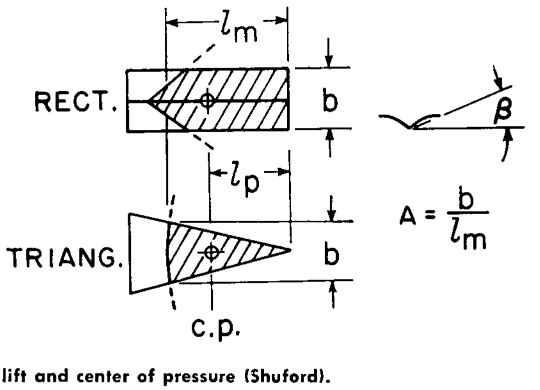

Figure 5. **Pure Planing lift and center of pressure (Shuford).**

wetted length. τ is the trim angle, and β is the effective angle of dead rise from keel to chine. The introduction of a constant crossflow drag coefficient in the second term correlates the experimental data from different sources, and for different cross sections and plan forms over a very wide range of the independent variables; for example, speeds up to 80 feet per second, trims up to 30°, and length-beam ratios up to 8.0.

Center of pressure.—The center-of-pressure ratio derives from corresponding ratios for the lifting-line and crossflow lift terms, a_1 and a_2. These ratios remain constant for either rectangular or triangular plan forms throughout the range of available data. The two equations are therefore generally representative of the recent research on pure planing, and numerical solutions of them provide a convenient summary of the significant results.

Chine rounding.—The variation of lift coefficient and center-of-pressure ratio of a sharp-edged flat plate with trim for a typical wetted length-beam ratio of 3.0 is shown in Figure 6. The curves fit recent experimental data from metal models best

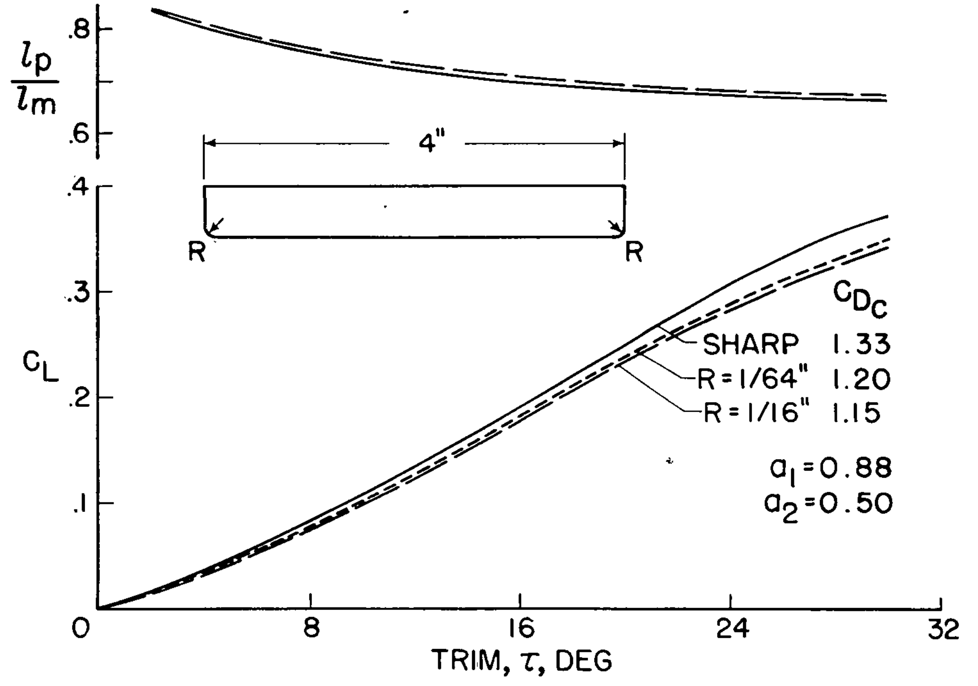

Figure 6. **Effects of chine rounding, deadrise 0°, $l_m/b = 3.0$.**

using a crossflow drag coefficient of 4/3. A small amount of chine rounding (1/64 inch in a 4-inch beam) such as might be found on a sanded wooden model appreciably reduced the lift coefficient and the apparent value of C_{D_c} which might account for some of the observed discrepancies among data from various sources. With a given load, this effect would be expected to increase the wetted area, frictional resistance, and total resistance at low trim angles. At high trims where the frictional resistance is small, the effect on planing efficiency is negligible.

For rectangular-plan-form flat plates, the center of pressure of the lifting-line component of lift apparently remains at 7/8 of the mean wetted length, and of the crossflow component at 1/2 the mean wetted length. The total center-of-pressure ratio moves from approximately 0.80 at low trims to 2/3 at the high trim of 30°. Chine rounding has only a small effect on the position of the center of pressure.

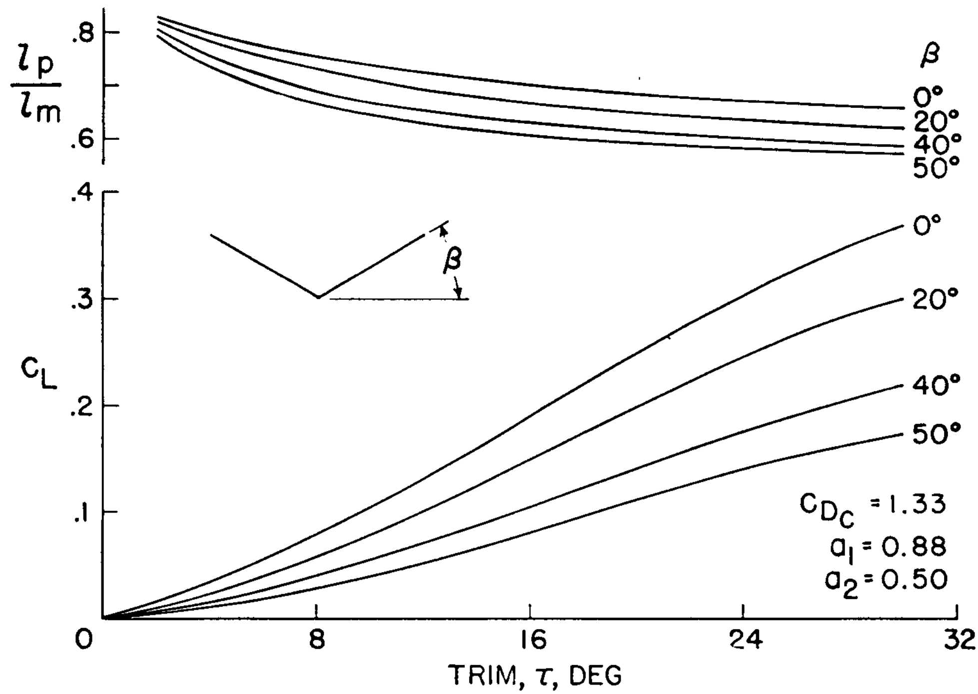

Figure 7. Effects of deadrise, $l_m/b = 3.0$.

Dead rise.—The results for various angles of dead rise are compared in Figure 7. With sharp-edged models, the three coefficients established for the flat plate appear to remain constant for angles of dead rise up to 50°. Variations with dead-rise angle are uniform through the trim range and exhibit the usual nonlinear characteristic associated with theoretical dead-rise functions.

Cross section.—Practical hulls and hydro-skis with dead rise usually require some form of chine flare to control spray, and many model tests have indicated additional benefits from the use of flare on resistance and stability. This experience is substantiated in Figure 8, which shows the progressive increace in lift coefficient obtained with horizontal flare and vertical strips on a rectangular-plan-form surface with a basic angle of dead rise of 20°. The experimental data correlate with the theory entirely on the basis of an increase in the crossflow-drag coefficient as noted. The center-of-pressure coefficients remain constant as before, hence the center-of-pressure ratio is reduced only slightly by the chine modifications.

The corresponding effects for a basic dead rise of 40° are shown in Figure 9. The same trends are obtained to an even greater degree with larger apparent values of the cross-flow-drag coefficient and the same constant center-of-pressure coefficients. These results indicate that the Shuford formulation provides a means of obtaining the planing characteristics of an arbitrary cross section over a wide range of operating parameters with only a brief experiment to determine the constant value of the cross-flow-drag coefficient.

Triangular plan form.—The application of the theory to a flat surface with a pointed plan form such as preferred for hydro-ski trailing edges is shown in Figure 10. Good correlation with unpublished experimental data is obtained with the same sharp-chine crossflow-drag coefficient as for rectangular plan forms. In this case, however, the lifting-line component of lift apparently effectively acts at the leading edge,

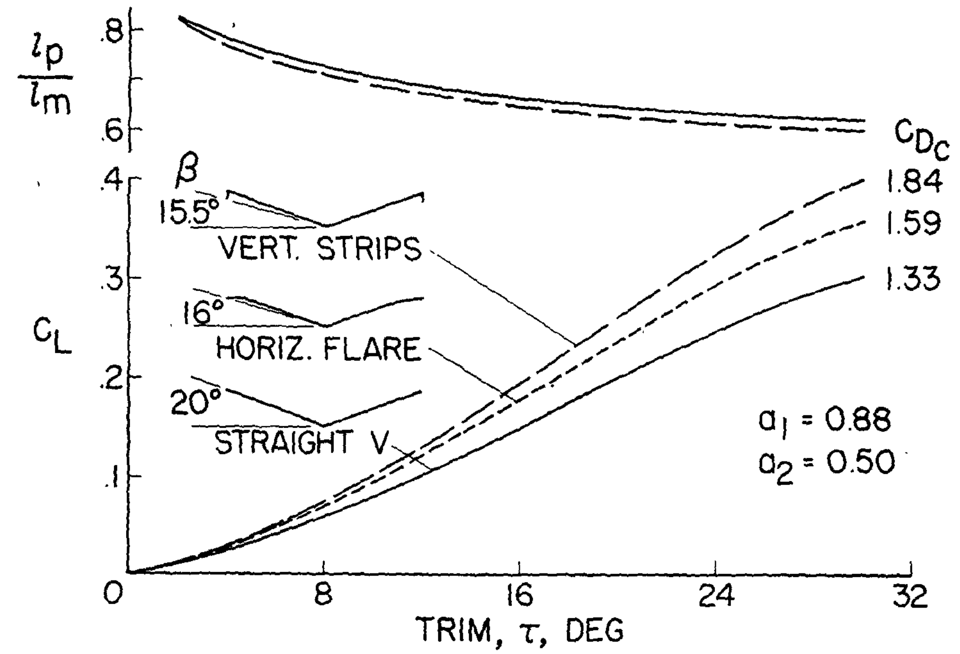

Figure 8. Effects of cross section, basic deadrise 20°, $l_m/b = 3.0$.

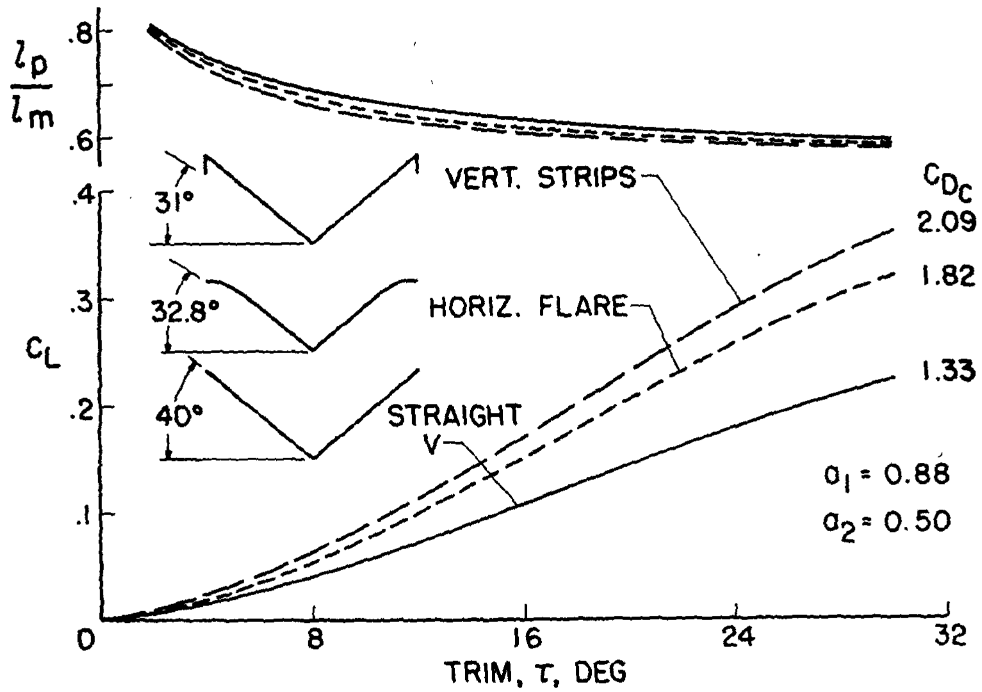

Figure 9. Effects of cross section, basic deadrise 40°, $l_m/b = 3.0$.

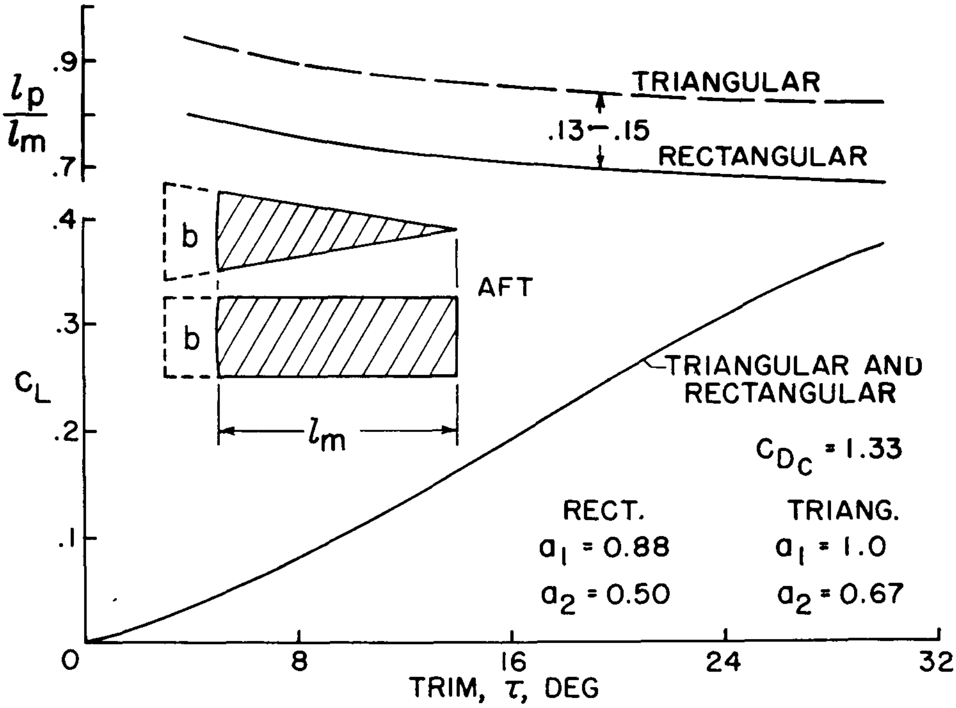

Figure 10. Effects of planform, deadrise 0°, $l_m/b = 3.0$.

and the crossflow component at two-thirds the wetted length. Going to a triangular plan form does not change the lift coefficient appreciably, and shifts the center-of-pressure forward by an approximately constant amount.

Resistance.—The drag associated with planing surfaces is partly skin friction and depends on boundary-layer conditions which are influenced by pressure gradients and Reynolds number. In the case of prismatic surfaces, the induced drag is assumed to be simply the load times the tangent of the trim angle, and the boundary layer to be fully turbulent. Analyses of model measurements have largely substantiated the validity of these assumptions for engineering estimates. It is then preferable to calculate the resistance of full-size elements, using the wetted area-lift coefficient relationship derived from tank model tests rather than extrapolating model resistance values.

The relative planing efficiency for various cross sections (refs. [14 to -8]) is shown in Figure 11. This is the hydrodynamic lift-drag ratio from model data plotted against trim for a mean wetted length-beam ratio of 3.0. The peaks of the curves for various cross sections occur at trims of from 5° to 9° depending on the dead rise. At high trims, the curves tend to approach the cot_τ boundary curve representing the induced lift-drag ratio. It has been noted that at high trims and low length-beam ratios, measured lift-drag ratios for a flat plate actually lie a little above this boundary because of forward flow in the spray root ahead of the stagnation line.

The L/D is reduced as the dead rise is increased throughout the range of trim shown as would be expected. As shown previously the addition of horizontal chine flare or vertical chine strips increases the lift of the dead rise surfaces. These additions also increase the lift-drag ratios by a useful amount in the best trim range in the same manner as a decrease in the effective angle of dead rise. There is little to choose between the two forms of chine with regard to their beneficial effect on the efficiency of either the 20° or 40° surfaces.

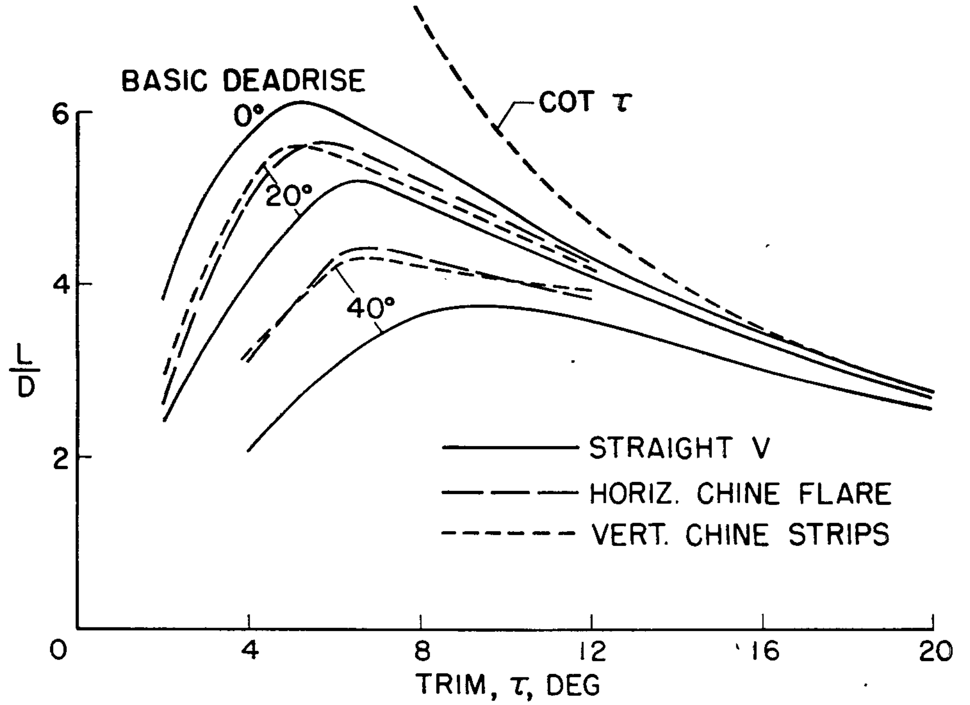

Figure 11. **Planing efficiency for various cross sections, $l_m/b = 3.0$.**

Longitudinal curvature.—In the case of a planing surface with longitudinal curvature, the effective trim and the induced drag are not simply defined. A correlation of model resistance data to indicate curvature effects on planing efficiency is shown in Figure 12. Here the maximum lift-drag ratio obtained at the optimum trim is plotted against length-beam ratio for a rectangular flat plate (ref. [18]) and plates with curvature. The maximum obtainable ratio for the flat plate approaches a value of 8 at low length-beam ratios (high aspect ratios) and falls off to less than 6 at length-beam ratios of practical interest for heavily-loaded skis. Corresponding unpublished data for a longitudinally convex surface, which is commonly found in practice, indicates a large penalty on planing efficiency that increases with length-beam ratio. The brief data of Sottorf (ref. [22]), on the other hand, has indicated an improvement in maximum lift-drag ratio attainable with increasing degrees of longitudinal concavity. Practically, concave surfaces have had adverse stability characteristics which have discouraged their use on seaplane hulls. The available evidence presented, however, indicates not only the marked inferiority of convex planing elements, but the possibility of exceeding the efficiency of the flat plate by introducing camber as for airfoils, particularly for the very high length-beam ratios of current interest.

Shallow-water.—It has been observed many times by service pilots that shallow water seems to improve seaplane take-off performance. As yet, a theoretical solution of this effect has not been made, although it should be possible by available methods. Its magnitude has been evaluated, however, by model tests in a tank with a variable-depth bottom (ref. [23]). This brief investigation indicated that lift, drag, and trimming-moment coefficients about the trailing edge increase with decreasing bottom clearance at clearances less than one beam, and significant changes in the wake occur.

A condition of practical interest is the case of a hydro-ski airplane approaching a constant-slope ramp as shown in Figure 13. Here it may be assumed that the water-

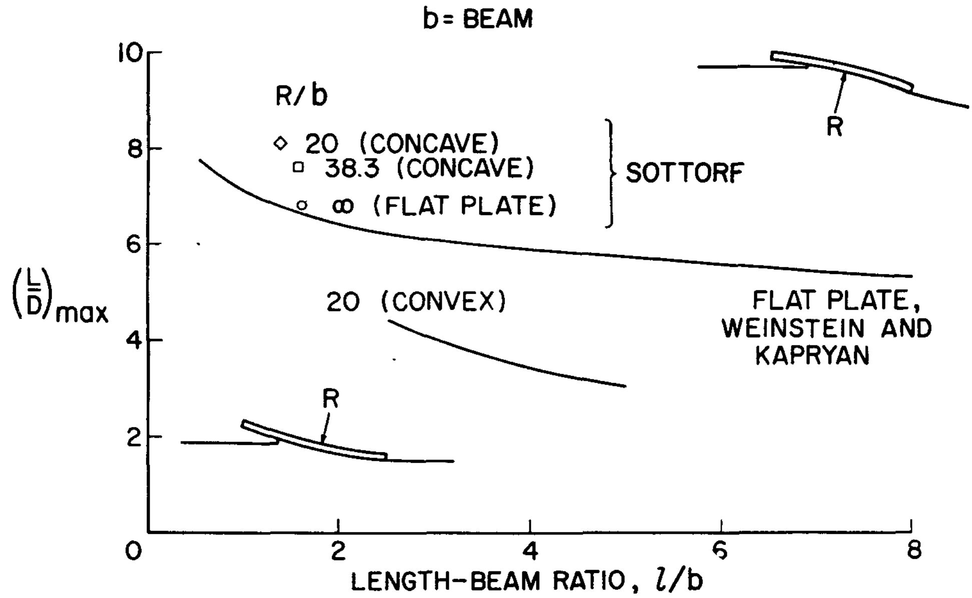

Figure 12. **Effects of longitudinal curvature on planing efficiency.**

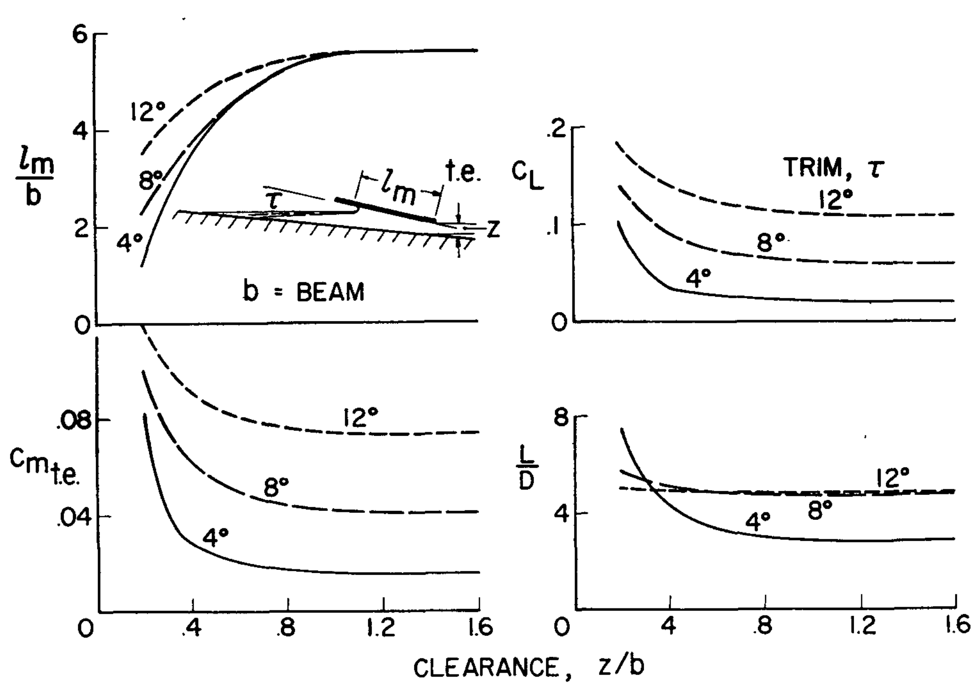

Figure 13. **Effects of shoaling water, constant load, speed, and beam,** $\frac{l_m}{b} \times C_L = K$.

borne load, speed, and trim do not change appreciably for the short interval influenced by the bottom clearance, or that the product of the length-beam ratio times the lift coefficient is constant. The plots against the clearance parameter z/b for various trim angles indicate a large reduction in wetted-length-beam ratio and increase in moment coefficient as the clearance approaches zero. The hydrodynamic center of pressure actually moves aft with the decrease in wetted length. The lift coefficient increases because the hydrodynamic lift is constant. At high angles, the L/D remains the same, but at low trims it increases sharply because of the decreased wetted area and frictional resistance. These effects are relatively unimportant for transition to and from the ramp, as has been demonstrated by operation with light ski airplanes and dynamic model tests of jet airplanes with high ramp speeds, because of the very shallow depths at which they appear.

Self-excited vibration.—A tendency for flat planing surfaces to vibrate in a vertical plane at high speeds and short wetted lengths has been encountered as shown in Figure 14. The oscillations are self-starting in smooth water, have high fundamental frequencies, and can be very violent. The speed for inception is a function of the trim angle and load (wetted length-beam ratio) as indicated, and the inception conditions are the same for both the systems diagrammed. The phenomenon is thus not explainable on the basis of coupling between trim and vertical motions since it occurs without freedom in trim (ref. [24]).

It can be seen that the inception moves to higher speeds with decrease in trim or increase in load, both of which are in the direction to increase wetted length. The vibration can be reduced or eliminated by the use of V plan forms or cross sections, which limit the wetted aspect ratio to low values. It can also be minimized or avoided by stiffening the planing surface itself, or restraining the vertical motion by reduction in overhang or the use of auxiliary struts.

The evidence so far shows that the problem is not inherent and where it exists, may be reproduced in the towing tank with a Froude model. The basic mechanism involved however, is not well understood, and theoretical means to predict its occurrence in practical cases are not yet at hand.

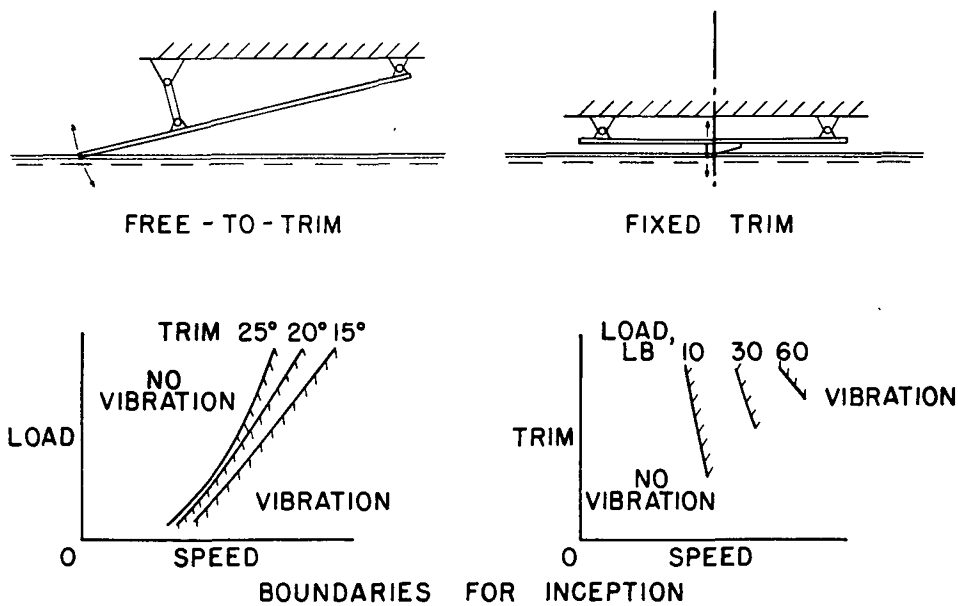

Figure 14. **Self-excited vibration of planing surface.**

Underwater Lifting Surfaces

The problem of low-aspect-ratio flat plates moving under and close to the water surface at high speeds has been investigated experimentally by the NACA, and a theoretical method has been developed to predict the lift for unseparated flow at large depths (ref. [23]). The problem remains of taking into account in the theory the influence of the surface, and this phase of the research is continuing.

In addition to the familiar phenomenon of cavitation at large depths, a dynamic lifting element at shallow depths experiences a type of separated flow brought about by ventilation from the atmosphere as shown in Figure 15. At high angles of attack, air is drawn in through the strong trailing vortices as the speed increases until it reaches the plate and the flow separates from the upper surface. At first the flow reattaches, but which further increase in speed, it completely clears the plate forming the so-called planing bubble. At this point sharp discontinuities in the forces occur as upper surface lift is completely lost (ref. [25]).

At high speeds, the fully ventilated flow occurs suddenly at low angles of attack without the progressive development described for high angles. The form of the angle of attack speed boundaries for inception of the two types of fully-ventilated flow are shown in the figure for two depths of submersion (unpublished data). The inception speed for the high-angle type does not vary appreciably with angle of attack but increases with depth of submersion; the angle for the low-angle type decreases with speed and varies only slightly with depth of submersion. Between the two branches, the boundaries are essentially independent of speed and submersion as indicated.

Since the inception of ventilated flow is generally a function of speed, the question arises as to the effects of scale in model tests of submerged elements. Experiments with two sizes of plate have indicated that the high-angle portion of the boundaries at corresponding depths scale according to Froude's Law, a useful result for configuration tests in a towing tank. The low angle portions of the boundaries

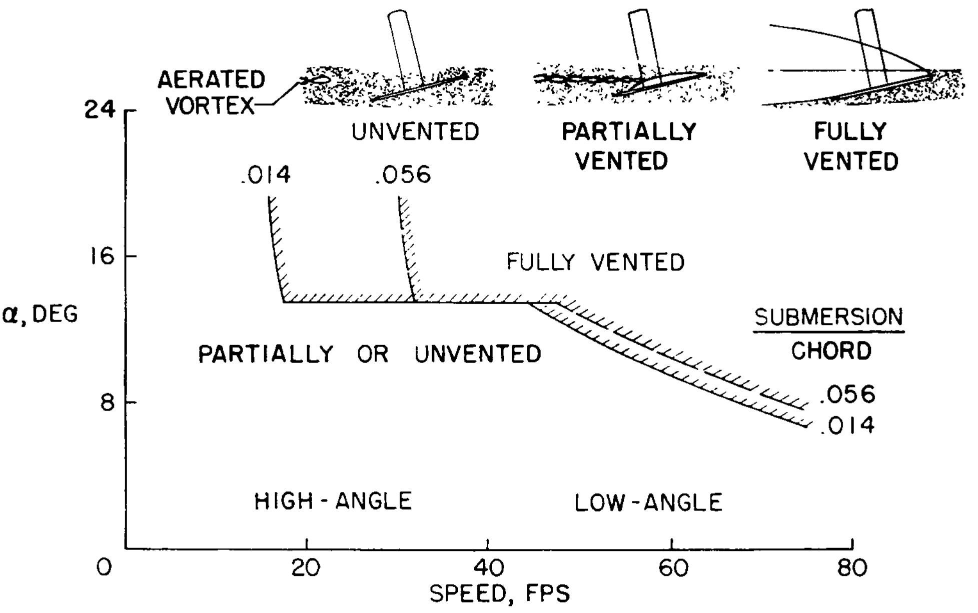

Figure 15. Ventilation of underwater lifting surfaces.

however are relatively independent of scale as for cavitating flows. The whole subject is therefore amenable to a better understanding and theoretical treatment before extrapolations of model data involving ventilated flows can be made with confidence.

Take-Off Resistance

Typical take-off resistance curves for three types of water-based aircraft are shown in Figure 16. In order to make them comparable, the ordinate is the water

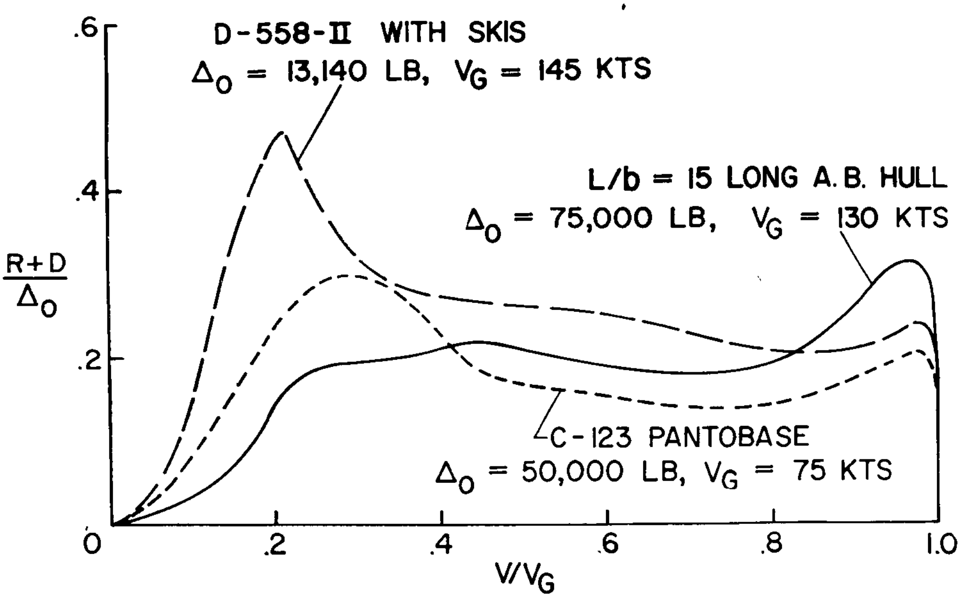

Figure 16. Take-off resistance of water-based aircraft.

resistance plus air drag of the configuration divided by the gross weight, and the abscissa is the ratio of water speed to getaway speed in each case. The curves are for a high length-beam ratio, long-afterbody, hull-type seaplane with a take-off speed corresponding to wing parameters of current interest (unpublished data); the original application of twin hydro-skis to a transonic research airplane (ref. [10]); and the pantobase C-123 assault transport (ref. [12]). None of these curves are necessarily optimum, but they represent operable arrangements for widely different purposes.

The hull configuration has low resistance at low speeds with a hump resistance of 22 percent of the gross weight or an average L/D up to 0.8 V_G of 4.5. The pronounced second hump near take-off rises to over 30 percent of the gross weight. A part of this rise is attributal to the increasing air drag with speed, but it is largely an increase in water resistance due to wetting of the long afterbody by the forebody wake.

The hydro-ski D-558 has a very high resistance, 45 percent of the gross weight, at speeds near ski emergence. As mentioned previously, this low-speed peak is characteristic since it is related to a small ski size and a deliberate disregard of hydrodynamic concessions to take-off resistance that would increase ski size and weight or the drag in flight. Lower peaks have been obtained, but this type of ski application is properly associated with airplane take-off thrust-weight ratios of 0.4 or greater. The high-speed resistance is generally higher than for the hull because of high ski trims and wetting of airframe components; however, there is a significant improvement near take-off where the afterbody clearance is greater than can possibly be achieved with a hull.

The pantobase ski example has the benefits of a large existing fuselage with a flat bottom, large skis with side wings to add planing area, and a relatively low take-off speed. These characteristics add up to favorable resistance levels as compared to the ski D-558 at low speeds and to the hull seaplane near take-off.

Hulls.—The nature of the afterbody interference problem when hulls are applied to high-landing-speed aircraft is illustrated in figure 17. This is a plot of the optimum (best trim) load-resistance ratio of a high length-beam ratio hull (ref. [32]) plotted against the parameter $\sqrt{C_\Delta}/C_V$ which is the square root of the conventional planing lift coefficient based on the square of the beam. When towing tank resistance data at a given trim or at the best trim are reduced to this form, the points for various loads and speeds fall along a singlecurvewhichextrapolates to zero at infinite speed or zero load (ref. [33]). Corresponding data for a prismatic planing surface having the same 20° dead-rise cross section with horizontal chine flare as the forebody of the hull (ref. [14]), and obtained behind a wind screen to eliminate all air drag, show a constant $(\Delta/R)_{max}$ of about 6.0. Adding the air drag of the hull as determined from separate wind tunnel tests (ref. [34]) to the drag of the planing surface gives the intermediate curve, which also goes to zero at zero planing coefficient. Since the hull data include the air drag of the model, the difference represents approximately the decrement due to afterbody wetting. It is because of these two factors that hull efficiency becomes progressively poorer at higher speeds and lighter loads.

The results of a simple calculation of the water resistance plus air drag of the hull alone for a high-speed water-based bomber, based on the tank data curve of Figure 17, are shown in Figure 18. A design beam loading C_{Δ_0}, of 6.0 was assumed, giving a beam of 7.48 feet for a gross weight of 160,000 pounds. With parabolic unloading, the ratio of the water-borne load to the gross weight, $\frac{C_\Delta}{C_{\Delta_0}}$, is shown by the dashed line.

The corresponding ratios of hull resistance to gross load $\frac{C_R}{C_{\Delta_0}}$ for various assumed values of take-off speed are shown by the solid curves. It is seen that for conventional seaplane take-off speeds, the hull resistance near take-off is relatively low, in fact it has not been a serious problem. At take-off speeds of current interest, it is three times as high, while at take-off speeds which may be associated with supersonic aircraft it could become as much as six times as high. It must be remembered that these curves are extrapolations of the data shown, and are of value chiefly as the formulation of a problem requiring further investigation.

Tank data similar to that presented indicate that the resistance due to afterbody interference increases with afterbody length-beam ratio, so that the problem is more severe for high-speed hull applications than for low length-beam ratio hulls with short afterbodies. The situation actually is similar to that of seaplane floats for small personal-type aircraft, which also operate at high water speeds in proportion to their size, that is at high Froude numbers, and whose water resistance is critical near take-off (ref. [33]). The resistance in practice is not as high as indicated by tank data which is not corrected for Reynolds number effects on skin friction, but experience with small underpowered seaplanes has substantiated qualitatively the existence of the effects described.

Tank data for hulls of the planing-tail type having large afterbody clearances (ref. [33]) lie very close to the forebody plus air drag-curve in Figure 17, indicating one solution to the problem if such a hull can be integrated into the overall design in other respects. A second method to increase clearance is the use of auxiliary skis at high-water speeds, extended far enough below the hull for their wakes to clear the afterbody.

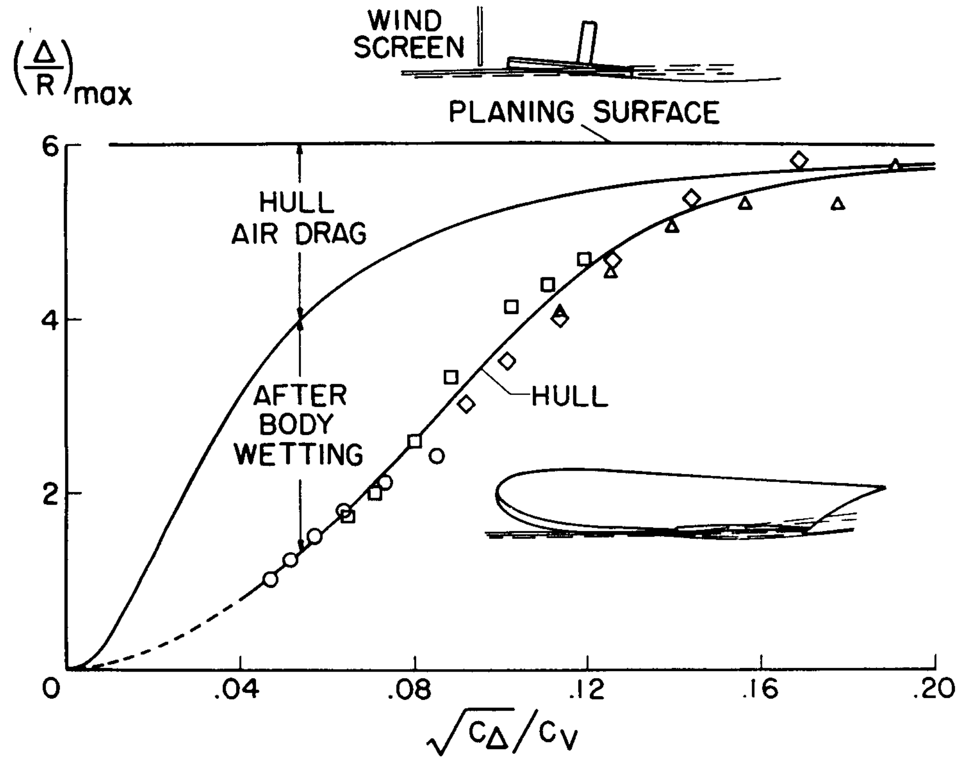

Figure 17. **Variation of hull efficiency with planing coefficient.**

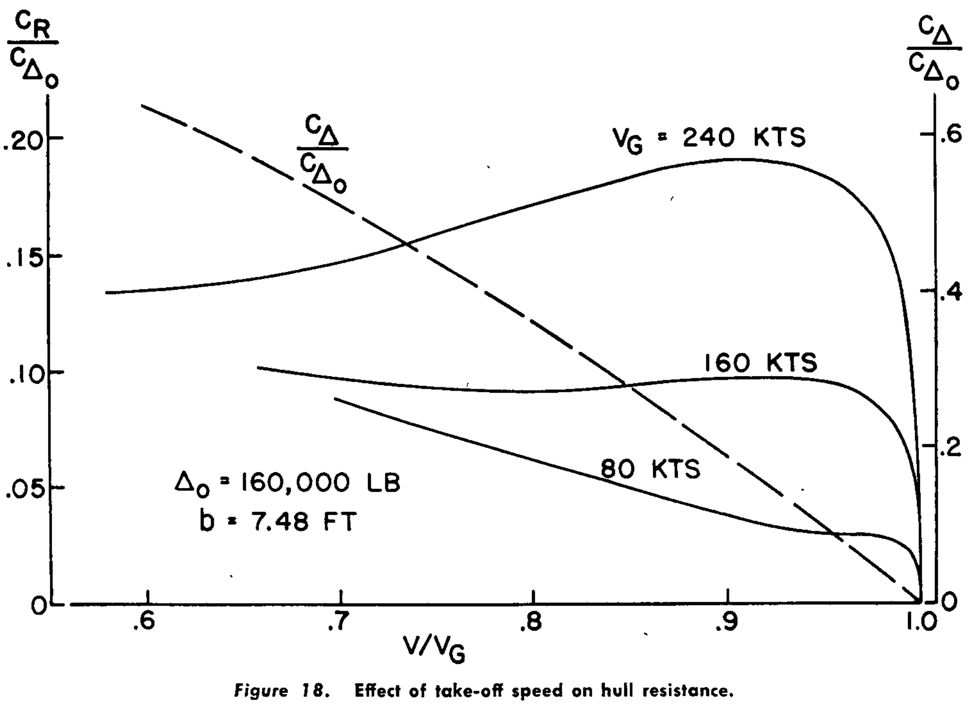

Figure 18. **Effect of take-off speed on hull resistance.**

Ski-body combinations.—The nature of the relatively high hump resistance of an aerodynamically-refined hydro-ski water-based airplane is shown in Figure 19. The hydrodynamic resistance of the aerodynamically-shaped fuselage alone rises rapidly with speed to a prohibitive value (refs. [35 to 38]). The planing resistance of

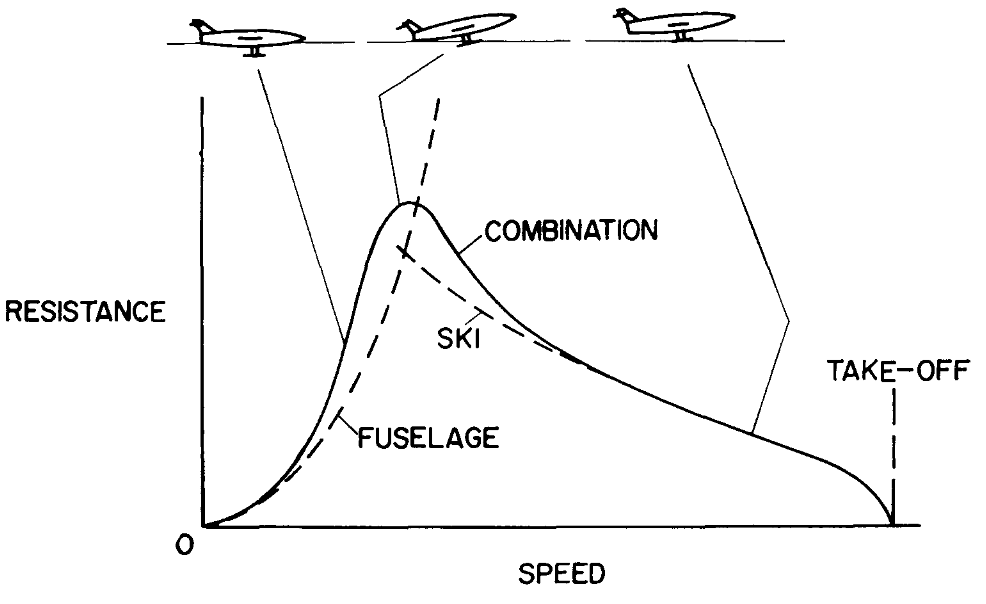

Figure 19. **Take-off resistance of hydro-ski airplane.**

the skis alone intersects that of the fuselage at a speed depending on ski size and angle of attack, and this speed is selected to transfer th water-borne load to the skis before the resistance becomes too high for the available thrust. The resistance of the combination is somewhat higher than the intersection because of spray interferences, the resistance of the ski gear before emergence, and the energy required for the dynamic emergenc maneuver itself. Above emergence, the resistance decreases rapidly with speed until it approaches that of the skis.

The hump resistance can obviously be decreased by designing the skis for earlier emergence, but they then approach the proportions of a hull forebody and become more difficult to retract in flight. It can also be decreased by hydrodynamic treatment of the fuselage, which can be accomplished to some extent without a large departure from an aerodynamically clean body. Even with a complete forebody and afterbody on the body, however, the hump resistance is considerably higher than that of a hull alone.

Because of these considerations, the application of skis to airplanes with low thrust-weight ratios (below 0.3) is not strictly in accord with the concept. The emegence resistance of practical ski-body combinations remains a research problem of some complexity, and means for reducing it to the level of the hump resistance of a hull have not yet been found.

The extensive involvement with spray of the aerodynamic components of a hydro-ski airplane raises the question of how the forces due to spray vary with scale. A preliminary experimental investigation (ref. [39]) has indicated that the lift force generated on a flat plate by impinging spray from a planing surface can be scaled by the conventional Froude methods. The spray drag forces, however, are relatively smaller for a larger model, evidencing a Reynolds number effect similar to that for turbulent skin friction in solid flow.

Land-water gears.—In the case of a land-water airplane, the hump resistance of the hull or emergence resistance of the ski-body combination are by-passed entirely by the use of the ramp and taxiing wheels as shown in Figure 20. Here the governing

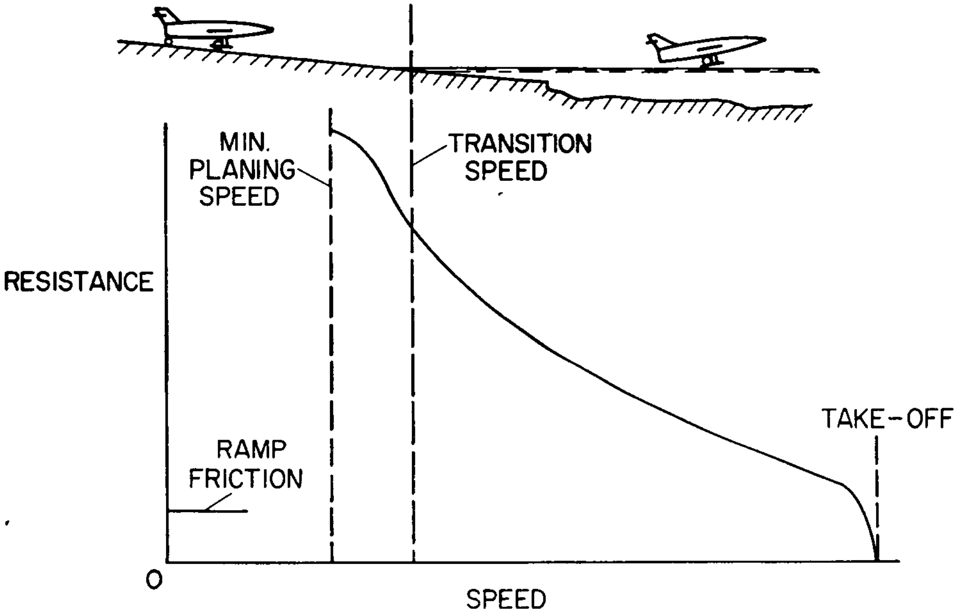

Figure 20. Take-off resistance of land-water airplane.

factor is the minimum planing speed below which "water stall" occurs and the resistance is very high. Above this speed, the resistance decreases rapidly as shown, and the transition speed must be enough higher to keep the resistance to an acceptable value after leaving the ramp. In general the planing resistance will be higher than for the larger skis of a completely water-based combination because of the associated heavier ski-loadings and lower hydrodynamic aspect rations. Thus although the problem is alleviated by the mode of operation, it cannot be neglected entirely, particularly in the choice of design transition speeds and in the need for a hydrodynamically clean configuration in the water-borne part of the operation.

Hydrofoils and Struts

Hydrofoils.—The use of submerged hydrofoils as lifting elements for water-based aircraft has always been an interesting idea because of their potentially high lift-drag ratios and favorable rough-water qualities as compared with flying-boat hulls. The hydro-ski is essentially a low-aspect ratio hydrofoil that can be integrated into airplane design and operation, and avoids the flow problems associated with negative pressures by planing on the surface at high water speeds. Apart from early Italian applications, however, competitive high aspect-ratio hydrofoil systems for aircraft have not yet appeared, although fundamental research on the subject has been continued (ref. [28 to 31]) and applied in fields other than aeronautics.

The incentives for the development of practical hydrofoil configurations remain high, since even with moderate aspect-ratios and separated flows they continue to offer efficiencies somewhat superior to those of hydro-skis, and their rough-water advantages over planing hulls have been further demonstrated by recent surface-craft applications. There is therefore a need for further basic research on high-speed cavitated and ventilated flows, and new design and operational concepts leading to their effective integration into high-speed aircraft configurations.

Struts.—Underwater lifting elements for aircraft must be supported by strut systems extending below the hull or fuselage. When completely submerged, the struts are a source of drag predictable from airfoil data, except when the speeds are high enough for the onset of cavitation. Rake reduces the section drag coefficient and increases the incipient cavitation speed as would be expected because of the reduction in effective thickness ratio (ref. [40]).

When piercing the surface, struts produce wave drag also predictable from theory (ref. [41]), and are subject to ventilation effects. As for the underwater plates, the mechanism of the ventilated flow and the laws of similitude that apply are not completely understood and merit further investigation.

Impact Loads and Motions

The loads and motions resulting from wave encounter increase with forward speed and must continue to be dealt with in the design of high-speed water-based aircraft. Theoretically, the acceleration resulting from an isolated wave impact varies as the square of the vertical velocity, and, with the same flight-path angle as the square of the forward speed. Actually, other things do not remain equal and maximum accelerations increase at a slower rate (unpublished experimental data), but even the first power is prohibitive when landing speeds are being doubled or tripled.

The results cited have shown that rough-water loads and motions of hulls are greatly reduced by increased beam loadings, afterbody lengths and angles of dead rise (ref. [5]). They have also been ameliorated in practice by the use of reversible thrust during landing and thrust augmentation during take-off to reduce the number of critical impacts. Perhaps the greatest improvements are offered by the use of heavily-loaded elements, to achieve high orders of penetration and localization of the loads. The development of auxiliary systems for this purpose constitutes a fruitful field for further investigation in order to hold high-speed water-based aircraft competitive with their land-based equivalents with regard to structural weight while retaining a reasonable degree of seaworthiness.

High-Speed Test Facilities

Along with increases in airplane landing speeds, there is an obvious need for a corresponding increase in the water speeds available for experimental investigations of hydrodynamic elements and configurations. The maximum towing speeds of the NACA seaplane tanks (50 knots) are now regularly employed in fundamental experiments and Froude model evaluations. Full-scale experience has approached 160 knots for seaplanes and 200 knots for racing craft. The latter speeds are still below the runway speeds of current high-speed landplanes.

Planing data has been obtained at the NACA's Langley Aeronautical Laboratory up to 120 knots by the use of a free-water jet propelled by compressed air (ref. [42]) as shown in figure 21. This apparatus has proved useful and capable of further development; it is subject, however, to boundary corrections and free-surface effects not present in a still-water towing tank.

This laboratory has recently placed in operation a high-speed hydrodynamics facility capable of test speeds up to 130 knots. A view of the facility is shown in Figure 22. It consists of a concrete tank 2,000 feet long, 8 feet wide, and 5 feet deep adjacent to an existing track and towing carriage provided for research on wheel landing gears. The hydrodynamic model and its instrumentation are suspended from a temporary boom on the carriage overhanging the water tank, and data are obtained during decelerated runs after the carriage is brought up to speed by a water-jet catapult.

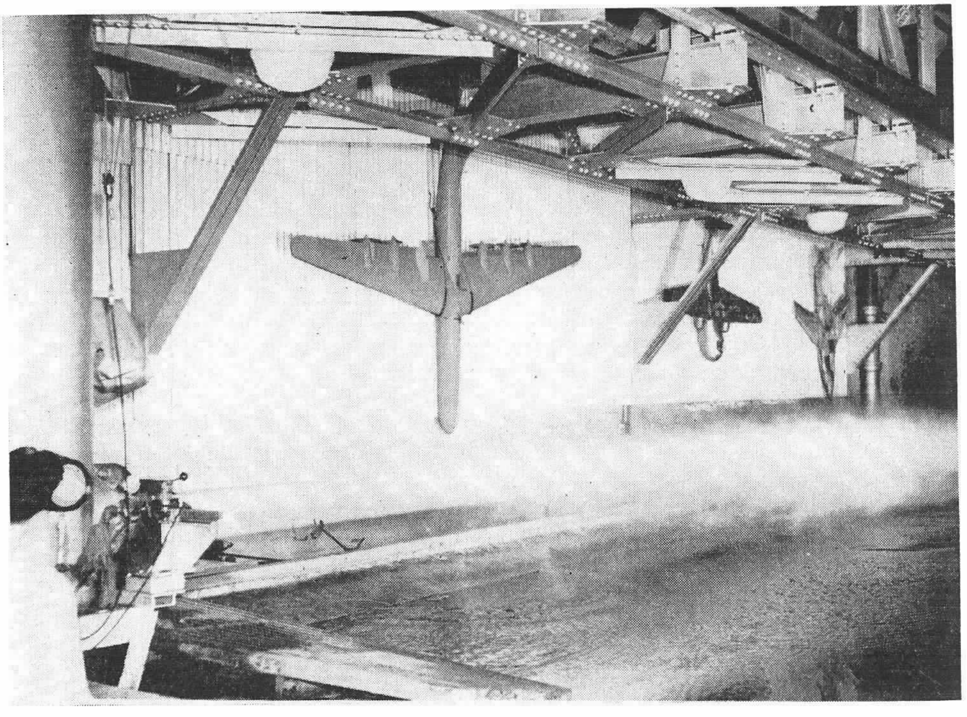

Figure 21. NACA water-jet apparatus.

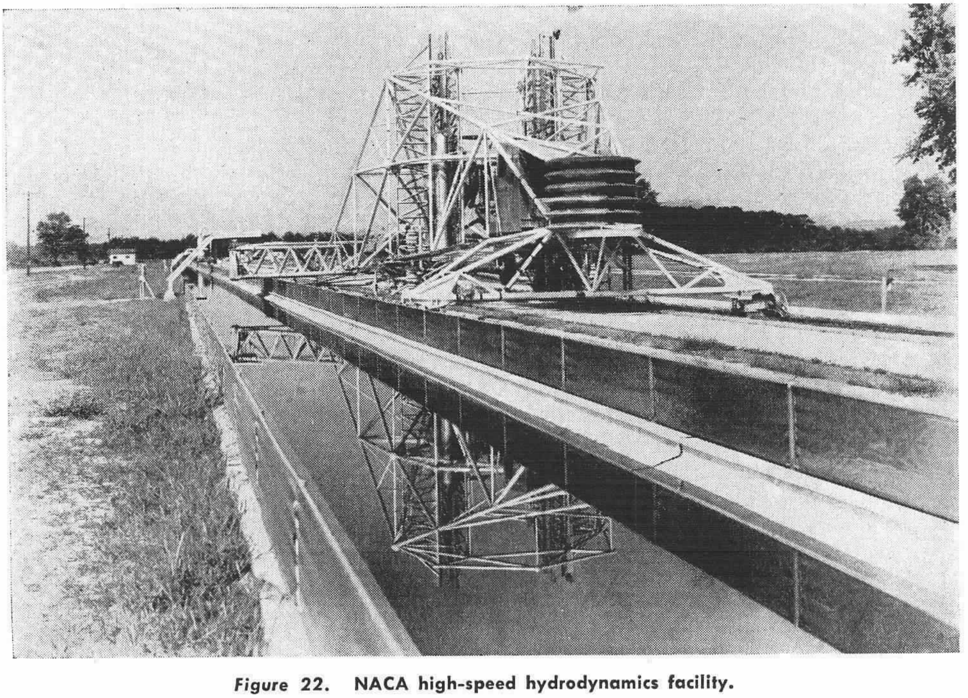

Figure 22. NACA high-speed hydrodynamics facility.

A second lighter carriage is being provided for hydrodynamic testing that will raise the available speeds up to the order of 150 knots, or three times the still-water range hitherto available.

VII. Concluding Remarks

In conclusion, it may be repeated that the present era of high-speed flight has a profound influence on the relative importance of the various considerations and conflicts involved in the design and procurement of water-based aircraft. Aircraft of this era are transonic and supersonic with fantastic speed penalties associated with departures from optimum aerodynamic design. Their water-based counterparts at present may have minimum flight speeds beyond the range of past experience; at the same time, they have take-off thrust-weight ratios that encourage the employment of radically different hydrodynamic configurations and concepts.

The changing picture brings with it new hydrodynamic problems, and new justification for the continued attention of qualified authorities in the field. The opportunity to review the state of the art in this Symposium is therefore appreciated by the author and the agency represented.

REFERENCES

1. Carter, Arthur W., and Haar, Marvin I.: Hydrodynamic Qualities of a Hypothetical Flying Boat With a Low-Drag Hull Having a Length-Beam Ratio of 15. NACA TN No. 1570, 1948.
2. Carter, Arthur W.: Effect of Hull Length-Beam Ratio on the Hydrodynamic Characteristics of Flying Boats in Waves, NACA TN No. 1782, 1949.
3. Carter, Arthur W., and Whitaker, Walter E., Jr.: Effect of an Increase in Hull Length-Beam Ratio From 15 to 20 on the Hydrodynamic Characteristics of Flying Boats. NACA RM L9G05, 1949.
4. Hodges, William W., and Woodward, David R.: Spray Characteristics of Four Flying-Boat Hulls as Affected by Length-Beam Ratio. NACA TN No. 1726, 1948.
5. Parkinson, John B.: NACA Model Investigations of Seaplanes in Waves. NACA TN No. 3419, 1955.
6. Whitaker, Walter E., Jr., and Bryce, Paul W., Jr.: Effect of an Increase in Angle of Dead Rise on the Hydrodynamic Characteristics of a High-Length-Beam-Ratio Hull. NACA TN No. 2297, 1951.
7. Schnitzer, Emanuel: Estimation of Water Landing Loads on Hydro-Ski-Equipped Aircraft. NACA RM L53D29, 1953.
8. Kapryan, Walter J., and Clement, Eugene P.: Effect of Increase in Afterbody Length on the Hydrodynamic Qualities of a Flying-Boat Hull of High Length-Beam Ratio. NACA TN No. 1853, 1949.
9. Dawson, John R., and Wadlin, Kenneth L.: Preliminary Tank Tests of NACA Hydro-Skis for High-Speed Airplanes. NACA RM L7I04, 1947.
10. Ramsen, John A.: The Effect of Rear Chine Strips on the Take-Off Characteristics of a High-Speed Airplane Fitted With NACA Hydro-Skis. NACA RM L9B10a, 1949.
11. Wadlin, Kenneth L., and Ramsen, John A.: Tank Spray Tests of a Jet-Powered Model Fitted With NACA Hydro-Skis. NACA RM L8B18.
12. Thompson, William C., and Fisher, Lloyd J.: Investigation of the Hydrodynamic Characteristics of the Panto-Base Chase C-123 Airplane. NACA RM SL54A28, 1954.
13. Fisher, Lloyd J.: Model Ditching Investigations of Three Airplanes Equipped With Hydro-Skis. NACA RM L9K23, 1950.
14. Kapryan, Walter J., and Weinstein, Irving: The Planning Characteristics of a Surface Having a Basic Angle of Dead Rise of 20° and Horizontal Chine Flare. NACA TN No. 2804, 1952.

15. Blanchard, Ulysse J.: The Planning Characteristics of a Surface Having a Basic Angle of Dead Rise of 40° and Horizontal Chine Flare. NACA TN No. 2842, 1952.
16. Chambliss, Derrill B., and Boyd, George M., Jr.: The Planning Characteristics of Two V-Shaped Prismatic Surfaces Having Angles of Dead Rise of 20° and 40°. NACA TN No. 2876, 1953.
17. Kapryan, Walter J., and Boyd, George M., Jr.: The Effect of Vertical Chine Strips on the Planning Characteristics of V-Shaped Prismatic Surfaces Having Angles of Dead Rise of 20° and 40°. NACA TN No. 3052, 1953.
18. Weinstein, Irving, and Kapryan, Walter J.: The High-Speed Planning Characteristics of a Rectangular Flat Plate Over a Wide Range of Trim and Wetted Length. NACC TN No. 2981, 1953.
19. Kapryan, Walter J., and Boyd, George M., Jr.: Hydrodynamic Pressure Distributions Obtained During a Planing Investigation of Five Related Prismatic Surfaces. NACA TN No. 3477, 1955.
20. Wadlin, Kenneth L., and McGehee, John R.: Planing Characteristics of Three Surfaces Representative of Hydro-Ski Forms. NACA RM L9C03, 1949.
21. Shuford, Charles L., Jr.: A Review of Planing Theory and Experiment With a Theoretical Study of Pure-Planing Lift of Rectangular Flat Plates. NACA TN No. 3233, 1954.
22. Sottorf, W.: Experiments With Planing Surfaces. NACA TM No. 739, 1934.
23. Christopher, Kenneth W.: Effect of Shallow Water on the Hydrodynamic Characteristics of a Flat-Bottom Planing Surface. NACA TN No. 3642, 1956.
24. Mottard, Elmo J.: Preliminary Investigation of Self-Excited Vibrations of Single Planing Surfaces. NACA TN No. 3698, 1956.
25. Wadlin, Kenneth L., Ramsen, John A., and Vaughan, Victor L., Jr.: The Hydrodynamic Characteristics of Modified Rectangular Flat Plates Having Aspect Ratios of 1.00, 0.25, and 0.125 and Operating Near a Free Water Surface. NACA Rept. No. 1246, 1955.
26. Imlay, Frederick H.: Theoretical Motions of Hydrofoil Systems. NACA TR No. 918, 1947.
27. Land, Norman S., Chambliss, Derrill B., and Petynia, William W.: A Preliminary Investigation of the Static and Dynamic Longitudinal Stability of a Grunberg Hydrofoil System. NACA RM L52D15.
28. Wadlin, Kenneth L., Fontana, Rudolph E., and Shuford, Charles L., Jr.: The Effect of Eng Plates, End Struts, and Depth of Submergence on the Characteristics of a Hydrofoil. NACA RM L51B13, 1951.
29. Carter, Arthur W., and Butler, Roger V.: Experimental Investigation of the Flow Field Behind an Aspect-Ratio-10 Hydrofoil Near the Water Surface. NACA RM L52L11, 1953.
30. Wadlin, Kenneth L., Shuford, Charles L., Jr., and McGehee, John R.: A Theoretical and Experimental Investigation of the Lift and Drag Characteristics of Hydrofoils at Subcritical and Supercritical Speeds. NACA Rept. No. 1232, 1955.
31. King, Douglas A., and Land, Norman S.: Effects of Sweepback and Taper on the Force and Cavitation Characteristics of Aspect-Ratio-r Hydrofoils. NACA RM L52J10, 1952.
32. Carter, Arthur W., and Woodward, David R.: Static Properties and Resistance Characteristics of a Family of Seaplane Hulls Having Varying Length-Beam Ratio. NACA TN No. 3119, 1954.
33. Parkinson, John B.: Take-Off Performance of Light Twin-Float Seaplanes. NACA TN No. 1524, 1948.
34. Lowry, John B., and Riebe, John M.: Effect of Length-Beam Ratio on Aerodynamic Characteristics of Flying-Boat Hulls Without Wing Interference. NACA TN No. 1686, 1948.
35. Weinflash, Bernard: The Effect of Air Jets Simulating Chines or Multiple Steps on the Hydrodynamic Characteristics of a Streamline Fuselage. NACA RM L8J21, 1949.

36. Weinflash, Bernard, Christopher, Kenneth W., and Shuford, Charles L., Jr.: The Effect of Air-Jet and Strip Modifications on the Hydrodynamic Characteristics of the Streamline Fuselage of a Transonic Airplane. NACA RM L9D20, 1949.
37. Weinflash, Bernard; Shuford, Charles L., Jr.; and Christopher, Kenneth W.: Hydrodynamic Force Characteristics of a Streamline Fuselage Modified by Either Breaker Strips or Rows of Air Jets Simulating Chines. NACA RM L9L21a, 1950.
38. Weinflash, Bernard, and Shuford, Charles L., Jr.: Investigation of the Hydrodynamic Stability and Resistance of Two Streamline Fuselages. NACA RM L52B11, 1952.
39. McBride, Ellis E.: An Experimental Investigation of the Scale Relations for the Impinging Water Spray Generated by a Planing Surface. NACA TN No. 3615, 1956.
40. Coffee, Claude W., Jr., and McKann, Robert E.: Hydrodynamic Drag of 12- and 21-Percent-Thick Surface-Piercing Struts. NACA TN No. 3092, 1953.
41. Ramsen, John A., and Vaughan, Victor L., Jr.: Hydrodynamic Tares and Interference Effects for a 12-Percent-Thick Surface-Piercing Strut and an Aspect-Ratio-0.25 Lifting Surface. NACA TN No. 3420, 1955.
42. Weinflash, Bernard, and McGehee, John R.: An Investigation of a Method for Obtaining Hydrodynamic Data at Very High Speeds With a Free Water Jet. NACA RM L54D23, 1954.

DISCUSSION

W. A. Schoech

I would like to congratulate Mr. Parkinson for a timely and important contribution to the science of the hydrodynamics of high speed water based aircraft. This field is of great interest to the Bureau of Aeronautics and we have attempted to keep abreast of the art with research vehicles and prototype aircraft. The Navy has now flown and obtained experience with three different flying boats having hull length/beam ratios greater than 12. The excellent hydrodynamic characteristics predicted by the model tests has been generally borne out by the flight tests. As might have been expected, the low speed maneuvering characteristics of these hulls were unsatisfactory and sparked off additional research.

An extensive flight test program has been conducted with a variety of aircraft equipped with hydro-skis. One of these aircraft, the XF2Y-1, was not only the first aircraft designed with hydro-skies as part of the original concept, it was also the first flying boat to exceed the speed of sound. The flight tests of hydro-skis have uncovered new and novel hydrodynamic problems. Mr. Parkinson has been instrumental in solving these problems and providing us with a clear physical understanding of the phenomena so that they can be avoided in the future. The full scale experience with flying boats equipped with hydro-skis has also clearly demonstrated improved ability to operate in rough water. This is of considerable interest to the Navy.

Some years ago All American Engineering Co., in an unsolicited proposal, suggested the application of wheeled hydro-skis to landplanes. This concept has been found to increase greatly the operational flexibility of Marine Corps observation airplanes. Mr. Parkinson's work has done much to put the design of these hydro-skis on a rational and straight forward basis.

Hydrofoils have offered promise of greatly improved rough water characteristics and the Bureau of Aeronautics has actively supported research in this field for at least twenty years. The very great difficulty of providing both stability and control has seriously hampered efforts to incorporate hydrofoils on a man-carrying aircraft. Recent work by Mr. Parkinson has indicated that solutions to these problems may be in sight. If this turns out to be the case, hydrofoils will open the door to much improved performance.

Mr. Parkinson's paper offers much fresh data which will be invaluable to designers of high speed flying boats. Again, I would like to offer my congratulations to Mr. Parkinson for his most interesting and informative contribution to the hydrodynamics of high speed water-based aircraft.

C. L. Fenn

Mr. Parkinson's complete coverage of the high speed hydrodynamic situation has left me with practically nothing to say. I might, however, make one or two points. They are very small.

It might be possible in future development to arrange a hydroski or hydrofoil, but for the moment let us consider a hydroski, of such a nature that it would lift the aircraft out of the water at a speed at which the aerodynamic, but not the hydrodynamic, loads would design the fuselage. This would put the seaplane on an even footing with the land plane. It is something to think about.

The next things that occurs to me is where does the hydrofoil sit in relation to the hydroski, development-wise? It seems to be somewhat further back. At the moment, we have no correlation between the model tests and full scale operation.

It also appears—and I will not say the dangerous thing—the dangerous thing to say is that there has been no successful hydrofoil aircraft. When you say that, someone says "Oh, they had one in Hammondsport in 1908." But, let's put it this way —there has been no hydrofoil aircraft so good that it spawned a family of hydrofoil airplanes.

Such is not true with the hydroski. There have been complete families of hydroski airplanes. I know of one, four in number, which started at 8,000 pounds and which has grown to 55,000 pounds, and they have lent themselves to high-speed operation.

R. M. Hopkins

Mr. Parkinson is to be congratulated on a very interesting and comprehensive paper. While listening to it, however, several thoughts arose which might be of some interest to you. On looking back—particularly over the past year—I can imagine that Jack may well feel that we never meet without complaints on my part over things he hasn't done. It may therefore be appropriate at this point to mention a few of the things he has done.

First, Jack and his group at Langley did the pioneering work on hydro-skis, which in conjunction with the development of the turbojet engine was the initial step toward high speed equality between land-based and water-based aircraft. More recently Jack has combined forces with the aerodynamics people at N.A.C.A. to show that there are no fundamental reasons why the famed "area rule" concept may not be applied equally as well to water-based as to land-based aircraft. This type of leadership has caused many to re-evaluate the future role the seaplane may play.

I should now like to bring to your attention one or two high speed hydrodynamic problems in somewhat more detail. In the slides just presented, you will recall the one showing the very large facility designed to examine the problems involved in a land-plane landing gear when it makes contact with a nice smooth runway. It is suggested that the high speed towing tank auxiliary to that facility which Jack discussed might be used to examine the much more severe problems of high speed seaplane landing gears in contact with a runway that is far from smooth.

These problems are closely allied to the self-excited or hydroelastic vibrations which Jack discussed, and for which some insight may be gained through the brief theoretical treatment of the flow involved contained in Professor Milne-Thomson's book on "Theoretical Hydrodynamics." It is believed, however, that the crux of the matter is best stated as that case for which the unsteady input forces (whether self-excited in character or due to wave impacts) excite the natural or resonant frequency (or frequencies) of the aircraft structure. The serious nature of this problem may be appreciated by a reference to an early incident in Sea Dart development. This seaplane originally incorporated twin skis with rectangular trailing edges for low resistance reasons. We soon became aware of our mistake, however; for soon after the first taxi run, and while taxiing over what may be very roughly described as four to six inch wind waves, about 12 to 15 feet apart, we had a failure of the nose-mounted airspeed boom. The dynamic characteristics of the Sea Dart structure were such that these seeming insignificant waves produced a failure in an airpseed boom designed for in excess of 50 g's. It is believed that the structural and hydrodynamic implications of this incident might well be sufficient justification for test runs of full scale hardware in this new N.A.C.A. facility, particularly in view of the trend toward greater airframe slenderness and flexibility.

It is also believed possible that hull bottom plating fatigue failures may be partially attributed to the higher stresses resulting from resonance effects. It is known that the pressure pulses imposed upon seaplane bottoms during high speed planing over waves may exhibit a pressure-time history so steep as to approach a so-called "step function" in character. Since a step-function theoretically contains all frequencies, it would seem plausible that these very steep pressure pulses might, through resonance effects, produce a plating stress in excess of that which would be produced by the same peak pressure acting statically. It therefore seems that the new facility would lend itself very nicely to an investigation of this type through runs of a segment of actual seaplane bottom structure at high speed over waves and with pressure pick-ups and strain gauges installed.

One other area might be mentioned for which the new facility could supply answers of interest to the high speed seaplane designer. Most of the impact theories presently available are built around the concept of the single, isolated, design landing. They are based on a mental image of a relatively large wave, and the detailed calculations therefore treat an impact on an unlimited expanse of water. The preceding discussion makes it clear that waves which are relatively small compared with the airplane and having relatively steep slopes may be of considerable importance. It is therefore suggested that a theory is needed to account for the finite expanse of the wave—an allowance for breaking through the back side of the impacted wave.

R. W. L. Gawn

We should all be grateful to Mr. Parkinson for an excellent paper with a clear account of many important developments in flying boats. It serves as a reminder that there are some common hydrodynamic problems between the flying boat and the craft known as fast patrol boats or in your country P.T. boats and it is instructive to consider these and ascertain the extent to which experience matches up.

The "Princess" flying boat is much the same all-up weight as the fast patrol boats known as the BOLD Class. There is a notable difference in the hull in that the flying boat is longer and narrower. In fact the length is 8.9 times the beam whereas the ratio is only 5.0 in the fast patrol boat.

An interesting point in common is that the running trim is controlled in both craft. The elevators serve this purpose on the flying boat and operate in air. Transom flaps are the counterpart on fast patrol boats and are noticeably smaller than the aircraft's elevators, one reason being that they operate in water. The purpose is to reduce the running trim primarily to make the fast patrol boat more seaworthy at the hump speed by reducing slamming. It is very satisfactory in this respect and also leads to less hull resistance.

There has been controversy as to the relative merits of hard chine and round bilge hull shapes for fast patrol boats. A boat has been built of each type in recent years and trials carried out at sea and in addition there has been a series of comparative tests on models. The latter indicated that the ship motions including accelerations are very much the same, the hull resistance of the round bilge form is less up to a speed length coefficient approaching 4 but is greater at higher speeds and the only other notable difference is that the hard chine form is drier in a seaway. The comprehensive sea trials are not yet complete but so far the comparative results do not seem to differ significantly from those obtained in model tests.

A matter of great importance is the pressure and acceleration which the hulls of fast patrol boats have to sustain at sea. Pressures have been recorded up to 25 lbs. per square inch with maximum accelerations ranging from about 2g to 3g. The latter are of course well below the figure of 50g mentioned by the last speaker in another connection. The seas to which the fast patrol boats were subject are probably more severe than those for flying boats and in the particular trial for which results are quoted the waves were 3 to 4 feet high and about 70 to 80 feet long. The large pressures build quickly in the fast patrol boats and generally in about a thirtieth of a second. My impression is that impact stresses develop at a slower rate in aircraft.

It would be most useful if Mr. Parkinson could add to the value of his most instructive paper by giving some complementary information from his wide experience with flying boats regarding the various points mentioned.

J. D. Pierson

Mr. Parkinson has presented an excellent, comprehensive review of the trends in seaplane design particularly with regard to high speed aircraft. I have only a few comments to add with regard to the water loads imposed in take-off and landing.

It appears that the trend towards longer and thinner hulls required for high speed flight is consistent with the improvement in seaworthiness in rough water ship designs. Unfortunately, the aircraft trend includes an increasing speed for take-off and landing.

In a more descriptive sense the aircraft speeds on the water are approaching the conditions at the bottom of a great waterfall such as Yosemite Falls. From a height of over 1500 feet the free fall velocity would be over 300 feet per second. It is in such a relative stream that the thin-skinned, lightly built seaplane must be successfully landed. And not only must this be accomplished many times in calm conditions but also in waves.

Many ways of doing this have been noted. On wheeled aircraft the tire and oleo strut provide the energy absorbing stroke. For the hull the deadrise of the bottom effectively provides this stroke, and devices such as skis and hydrofoils may be extended below the keel to extend further the effective stroke.

The actual application of these configurations to seaplane designs requires the detailed calculation of loads for structural design. Because of the trend towards the longer, slimmer hull forms these loads calculations have been made more complex by the interaction of the body flexibility and the dynamic water forces. It has only been in the past few years that the development of the rapid automatic computation systems has made such combined solutions possible.

The water loads problem is treated by dividing the hull into a number of transverse slices which are acted upon by the water forces and react according to the overall motion of the aircraft and the major bending modes. The water forces on each slice are determined on the basis of the local hull shape and water conditions (including waves) and the dynamical motion of the slice. The summation of all slices gives the net effect on the body.

Even for a very limited number of divisions of the hull, manual calculation of this loads problem is well-nigh impossible. However, with the large computers such as the IBM 701 and then the 704 a large number of sections may be handled simultaneously for the required solution.

So far in the computational work, uniform waves of trochoidal form, have been used to represent the sea as a matter of convenience. Other wave shapes and combinations of water conditions are within the capability of the computational machinery, and we look forward to a greater combination of the results of oceanographic studies and practical seaplane design.

D. Savitsky

Mr. Parkinson has presented a fine summary of the "status of the art" of high speed seaplane hydrodynamics—both as regards the special hydrodynamic problems which have been accentuated by the high speed water based aircraft and as regards some of the new hydrodynamic developments which are available and necessary to the designer of high speed seaplanes.

I would like to amplify further Mr. Parkinson's reference to the beneficial potentials which may develop with the application of hydrofoil alighting gear to the aerodynamically refined high length beam ratio hulls. In particular, it appears that a hydrofoil system shows a good deal of promise in improving and extending both the high and low speed rough water capabilities of the seaplane. As pointed out by Mr. Parkinson, high speed hulls, while having a satisfactory lift drag ratio, are subjected to heavy impact loads and motions in a seaway. Small, highly loaded, penetrating hydro-skis alleviate the severe rough water loads and motions but have excessive water resistance during ski emergence. The high aspect ratio hydrofoil, on the other hand, has a lift drag ratio comparable to the hull and can be designed to alleviate the impact loads and motions to a degree comparable to the hydroski. A significant design feature which is inherent in a hydrofoil system is that the hydrodynamic support area of the main foil will probably be distributed vertically rather than longitudinally as in the case of either a hull or hydroski. This would keep the center of pressure essentially in a fixed longitudinal position and hence eliminate generation of excessive pitching moments. Further, the vertical arrangement of support area can be designed to contact the water surface with small areas during the impact process and hence lead to alleviation of the impact forces.

Another advantage of the hydrofoil system which has not been generally discussed, is the effective damping in pitch that a tandem foil system provides at prehump speeds. In these speed ranges, aerodynamic damping is negligible and the high density, low frontal area hulls are subjected to severe pitching and excessive bow spray generation when operating in a seaway at low speeds. In some cases the development of severe wetting of engines and structure may preclude take-off. The tandem hydrofoil system has the capability of providing significant pitch damping which in turn would reduce the pitch motions and the corresponding bow spray development.

To achieve these hydrofoil potentials we must continue our research on the basic hydrodynamic problems attendant with hydrofoils, e.g. cavitation, ventilation, longitudinal and lateral stability of foil systems suitable for seaplane application.

The high landing speeds associated with projected high speed water based aircraft has put a strain on the existing facilities of the Stevens Experimental Towing Tank. It appears that the top speed of our No. 3 Tank will have to be increased to accommodate the increasing landing speed of seaplanes and to handle some of the cavitation problems which exist with the hydrofoil systems. Also, an irregular wave maker has been installed in our No. 3 Tank to provide for more realistic evaluation of the rough water characteristics of seaplane forms. Our present No. 2 rectangular tank facility which is being altered to examine ship behavior in oblique seas, will also be able to accommodate tests of seaplanes at oblique headings to a sea. Combining these new test facilities with the so-called ETT "free-to-surge" towing apparatus, which permits a model to be towed with complete longitudinal freedom, will make for a more realistic evaluation of the new seaplane designs.

M. C. Eames

The writer was most gratified to learn of the progress being made in the study of the mechanics of ventilated flow on submerged lifting surfaces, but was disappointed to discover the relative states of development of the hydro-ski and the hydrofoil for application to water based aircraft.

It is to be hoped that recent work by Tulin and Wu on the theory of hydrofoils operating in a fully cavitated state will provide the additional incentive required to initiate an active research program in this field.

Sufficient evidence must now exist to convince the aircraft designer of the hydrodynamic superiority of the hydrofoil. One's thoughts, therefore, naturally turn to the structural problems involved, and it seems inevitable that these will be very much more severe in the case of the hydrofoil. One thought in this direction appears appropriate to a symposium on hydrodynamics. The writer is treading on dangerous ground, but it is believed that several of the problems met in high speed flight have a counterpart in the design of hydrofoils. (One elementary example that comes to mind is the simple relation that exists between the critical Mach number and the critical cavitation number of a foil section.) It might not, therefore, prove to be beyond feasibility to design a hydrofoil system which, rather than being an awkward encumberance in flight, could perform a useful aerodynamic function—thus obviating the need for retraction. If this were possible the weight normally associated with retraction gear would presumably be the hydrofoil structure, and it is even feasible that an increased payload might result.

J. B. Parkinson

The discussers of this paper have enhanced its value by supporting and amplifying two major points which were made but not developed to any extent. The first is that water loads and their effects on airplane structures are of increasing concern because of current design trends and operating requirements. The second is that there remain valid reasons for further research and development in the area of hydrofoil-supported aircraft. The two are interrelated since the hydrofoil provides an additional promising approach to alleviation of prohibitive loads and motions due to wave impacts. With this clarification of objective, it now should be possible to arrive at practical hydrofoil applications for water-based aircraft that are competitive with or perhaps superior to presently available solutions.

An extended discussion of water loads is beyond the scope of the paper. It may be mentioned that authorities on this subject are reluctant to prescribe upper limits on loads, pressures, and rates of build-up resulting from rough-water operation. Transient pressures up to 50 psi have been measured on a seaplane and up to 100 psi on a large hull model in the Langley impact basin. The effects of local resonances and flexibilities, finite expanse of the waves, etc., are not too well understood, but in general are believed to be small compared to the total loads, statistical variations of the dominating parameters, and the orders of alleviation required for significant improvements in rough-water capabilities.

The author wishes to express his thanks and those of his colleagues in the NACA for the favorable comments on the paper and the stimulating thoughts contributed in its discussion.