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A PRELIMINARY EXPERIMENTAL STUDY OF VERTICAL HYDROFOILS OF LOW ASPECT RATIO PIERCING A WATER SURFACE

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INTRODUCTION

Most types of problems which arise in connection with the use of a hydrofoil operating in water can be solved simply by treating it as an airfoil operating in air. For this purpose, use can be made of the great wealth of theoretical information and experimental data which can be found in the literature. There are, however, regimes of operation of the hydrofoil which are not duplicated by the airfoil excepting possibly under very special conditions. These regimes are identified by one of the following:

(a) cavitation
(b) ventilation
(c) proximity to a free surface

Cavitation is characterized by the presence of water vapor bubbles at regions in the flow where the pressure is less than the vapor pressure correcponding to the existing water temperature. Although most commonly observed on the blades of propellers or on the vanes of axial flow pumps, cavitation can also be present on fins used to stabilize high speed underwater missiles, on hydrofoils used as lifting surfaces, or on support struts of various kinds. Allied to this problem is ventilation, a condition which is like cavitation in that it results in discontinuities in density in the fluid surrounding the hydrofoil, although the initiating mechanism is fundamentally different and the lighter medium is air or gas instead of water vapor. A third type of flow regime which may be very important is that associated with a hydrofoil which approaches or intersects a water-vapor or water-gas interface. In this case the flow must satisfy the constant pressure boundary condition on that interface. The effect of gravity may or may not be important, and the hydrofoil can be oriented in any direction. A lifting hydrofoil would most likely be parallel, or nearly parallel, to the water surface, whereas a support strut or a stabilizing fin would intersect the water surface nearly at right angles. It is this last mentioned type of operation which is investigated in this report, and which, as will be seen later, also implies a study of the effects of air ventilation.

Among the specific fundamental questions which arise in considering a vertical hydrofoil piercing a flat water surface and which is at an angle of attack to the flow, are the following:

(a) How does the presence of the air-water interface affect the apparent aspect ratio of the hydrofoil as compared with its geometrical value?

(b) What is the effect of air ventilation on the value of cross-force developed by the hydrofoil, and what observations can be made regarding the inception of this phenomenon?

Since no previous hydrofoil studies had been performed in the Free-Surface Water Tunnel, it was also of interest to determine the suitability of that facility and its associated equipment for doing work of this kind. On the other hand, the investigation was intended only as a preliminary one and was, therefore, undertaken with limited resources.

APPARATUS AND EXPERIMENTAL PROCEDURE

The Reflection Plane

In this study, the method used to find the effective aspect ratio of a vertical, surface-piercing hydrofoil required knowing the slope of the curve of measured values of lift coefficient plotted against angle of attack. In the case of the vertical hydrofoil the lift force acts horizontally and is perpendicular to the direction of flow at infinity. In practical applications, hydrofoils which pierce a constant pressure surface are most apt to be of small aspect ratio, and since it is in this region that the approximations of lifting line theory are most suspect, experimental methods were used to determine the hydrofoil characteristics in the absence of the free surface. To that end, a piece of existing equipment, which was formerly used as a false bottom in the Free-Surface Water Tunnel, was adapted and made to serve as a surface skimming device. By mounting the skimmer about one-eighth inch below the water surface, a reflection plane was established through which the vertical hydrofoil could project, thereby effectively converting the Free-Surface Water Tunnel into a tunnel of the closed-throat type (Fig. 1). To measure the cross force, the existing three-component force balance, which is described in Ref. 1, was rotated 90° about a vertical axis so that the former drag component now measured the cross (lift) force. The remaining two force component assemblies on the balance were caged to minimize movement of the model assembly, a precaution

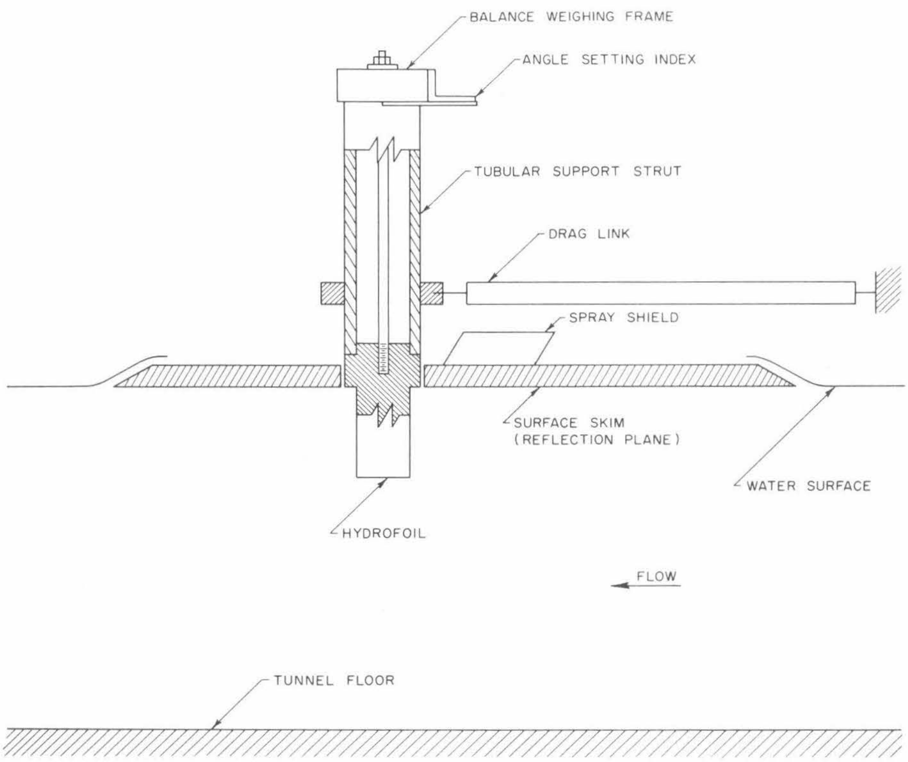

Fig. 1 - Schematic drawing of hydrofoil support assembly and reflection plane installed in the working section of the Free-Surface Water Tunnel.

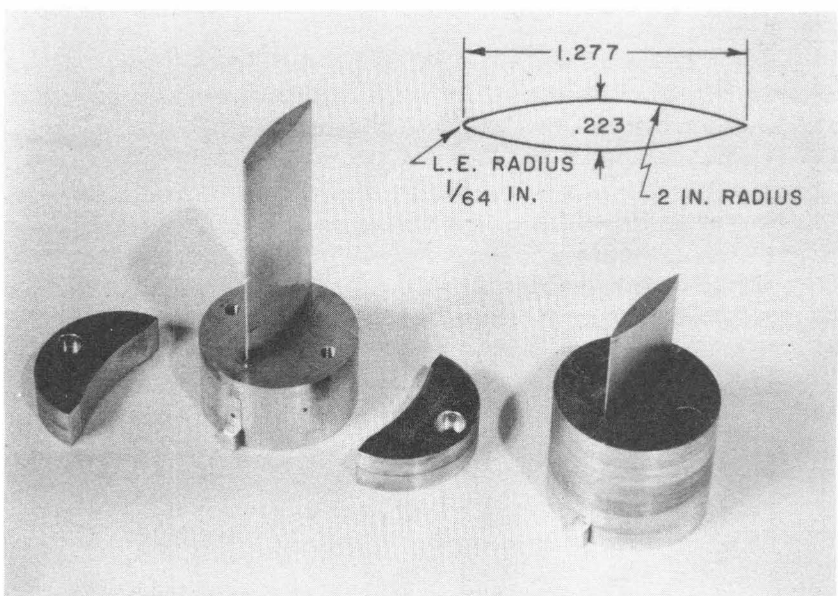

Fig. 2 - 17.5% thick symmetrical lenticular section hydrofoils used in this experiment. The side cheeks have been removed from the larger model to minimize spray interference at the free surface.

which was necessary because of the small clearance gap between the model and the skim plate (reflection plane). In this rotated position there is not sufficient width between the tunnel windows to permit lowering the balance close to the water surface. Therefore, the model was mounted to a cylindrical strut 15 in. long and connected to the balance, which could be rotated to provide adjustment of the angle between the hydrofoil and the oncoming flow. A drag link was added to tie the lower part of the strut to the tunnel working section structure when it was found that elastic deflection of the balance support reduced the gap clearance on the downstream side.

The Models

The hydrofoil models (Fig. 2) were machined from aluminum bars 1-3/4 in. in diameter to facilitate connecting them to the tubular support strut in a way that provides a practical means of bringing the hydrofoil through the image plate. A hole was bored through the plate 0.005 in. larger than the cylindrical base of the model. By using a cylindrical base larger in diameter than the chord of the hydrofoil, it was possible to hold a very small clearance gap which could easily be checked from above the tunnel working section during the course of a run. Because the end of the cylindrical portion of the model was made flush with the bottom surface of the skim plate, it was subjected to skin friction forces, but these forces acted nearly at right angles to the measured lift force and probably did not affect the accuracy of the results. Gap leakage effects were not detected when the gap was deliberately made 100% greater, so they too were considered negligible. In this connection, it is to be noted that no mechanical seal was provided for sealing the gap. It was found that water which did leak through the gap lay in a shallow pool on the top of the plate and served to prevent air from leaking in on the suction side of the hydrofoil at the higher angles of attack. Spray shields and water deflectors were added to the upper surface of the skim plate to keep water from splashing against the strut assembly and to protect the operator from the spray while changing angle settings and adjusting gap clearances during the run. The free surface runs were made simply by removing the skim plate assembly and drag link. In this configuration the cheeks (see Fig. 2) were removed from the hydrofoils so that the same physical span could be used as in the reflection plane series without having too much interference between the cylindrical portion of the models and the water spray sheet. In spite of this precaution, at higher angles of attack a sheet of water did ride up the pressure side of the foil and onto the cylindrical model base.

The Force Balance

The balance used to obtain the force coefficients presented in this report was equipped with a controllable dashpot which permitted critical viscous damping of the lift force oscillations, so that the mean forces could be observed and recorded. In practice, the force reading is obtained by means of sliding weights which are located on a double beam and which are manipulated to return the balance beam to a previously determined null position. A Schaevitz linear differential transformer located at the end of a beam, together with a Hewlett Packard vacuum tube voltmeter measuring the secondary emf, served as an accurate position indicator. A stiff spring had been introduced into the system to reduce the excursion of the weighing system under the influence of the oscillating forces. By connecting the output of the position indicating element to a Brush oscillograph it was possible to record the nature and magnitude of these force oscillations under varying operating conditions of the hydrofoil.

EXPERIMENTAL OBSERVATIONS AND DISCUSSION OF RESULTS

Effective Aspect Ratio: Reflection Plane Runs

As previously indicated, the effect of the free surface on the apparent aspect ratio was determined with the aid of control runs in which no free surface was present. As an alternative, it was possible to select for the hydrofoil an airfoil section with known characteristics, so that only a series of free-surface runs would be necessary. This method was not satisfactory for several reasons. First of all, limitations in the size of allowable loads on the force balance precluded the use of models larger than about 0.03 square feet in area. The cost of fabricating such small models to an acceptable tolerance would be prohibitive unless the surfaces could be generated by simple machine operations. Hence it was decided to use a lenticular section formed by two equal and intersecting circular arcs, with some hand filing to produce a finite radius at the leading edge

(Fig. 2). Secondly, it had been anticipated that viscosity effects might prove troublesome at such low values of Reynolds number. These considerations, plus any effects which might result from the high turbulence level of the Free-Surface Water Tunnel, would have made theoretical prediction of the hydrofoil performance extremely difficult. Without a control standard it is very likely that the influence of the free surface would have been entirely masked by these other effects.

The control runs were made on hydrofoils of three different aspect ratios: 1.95, 2.72 and 3.92. For these runs made, using the reflection plane, the aspect ratio was taken as

$$AR = \frac{2\ell}{C}$$

where ℓ = distance from the reflection plane to the wing tip

and C = chord length.

The plotted curves (Fig. 3) show the expected systematic decrease in slope of the lift coefficient curve with decrease in geometrical aspect ratio. The slopes were carefully measured in the region where $C_L = 0$ and are in good agreement with the findings of Winter[2], Zimmerman[3], and Jones[4], each of whom has investigated airfoils of low aspect ratio with rectangular plan form. The measured values are shown in Table 1.

Because the tunnel working section has finite dimensions (20 in. x 20 in. in cross section), a correction is required to compensate for the presence of the tunnel walls and floor on the measured value of effective aspect ratio. The magnitude of this correction is determined by assuming the existence of a series of hypothetical image hydrofoils which will satisfy the condition that there be no flow through the boundary, and then computing the upwash at the hydrofoil induced by these images. For purposes of analysis the hydrofoil and its images are replaced by arrays of vortices with an assumed distribution of circulation. Pankhurst and Holder[5] have plotted the correction for two alternative loading distributions, uniform and elliptical. In neither case does the induced upwash ever amount to more than 0.05 degrees, even at the greatest attack angles and for the wings of greatest area (.208 ft^2). The high ratio of tunnel cross-section area to wing area is the primary reason for the correction being negligible. In

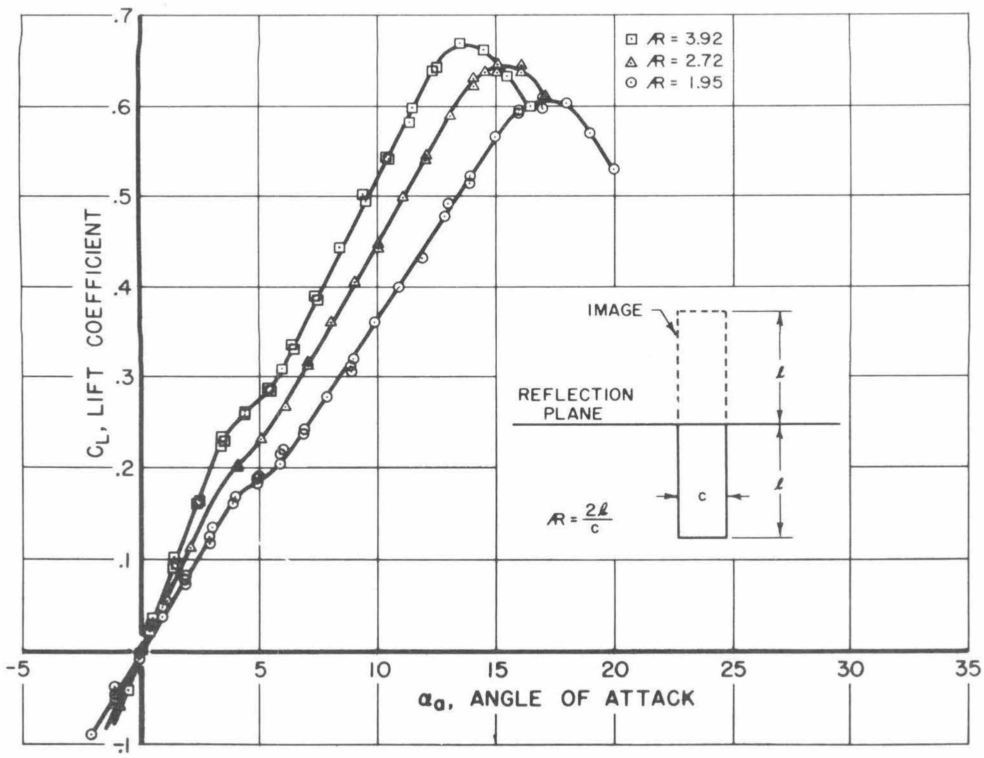

Fig. 3 - The effect of changes in aspect ratio on the lift coefficient curves of a 17.5% thick symmetrical lenticular airfoil using a reflection plane. Water velocity head = 4 ft (16 fps).

Table 1 - Table of measured values of $(dC_L/d\alpha_a)$ at $C_L = 0$ for hydrofoils of various aspect ratio piercing a water surface or projecting from a reflection plane. The span used to define geometric aspect ratio is the distance from the free surface to the wing tip for the free-surface runs and twice the distance from the reflection plane to the wing tip in the reflection plane runs.

Geometric Aspect Ratio, AR	$\frac{V^2}{2g}$	Nominal Velocity	Reflection Plane or Free Surface	$\left(\frac{dC_L}{d\alpha_a}\right)_{C_L=0}$	Estimated Slope Accuracy
1.96	2 ft	11.4 fps	Reflection Plane	0.051/deg	± 5%
1.96	4 ft	16.0 fps	Reflection Plane	0.042/deg	± 2%
2.74	4 ft	16.0 fps	Reflection Plane	0.056/deg	± 2%
3.93	4 ft	16.0 fps	Reflection Plane	0.067/deg	± 2%
0.98	4 ft	16.0 fps	Free Surface	0.027/deg	± 2%
1.96	2 ft	11.4 fps	Free Surface	0.048/deg	± 3%
1.96	4 ft	16.0 fps	Free Surface	0.049/deg	± 3%
1.96	8 ft	22.7 fps	Free Surface	0.037/deg	± 2%

the free surface configuration where the load distribution is unknown and is, in fact, an implied object of this investigation, the correction factor due to tunnel blockage was assumed to be of the same order of magnitude.

Other investigators[6] have shown that insofar as induction effects are concerned, the presence of a thin boundary layer along the reflection plane can be neglected. In the present study, where the displacement thickness of the boundary layer was computed to be on the order of 5% of the chord length, it may be that this no longer holds true. In any case, the spanwise loading was assumed to be unaffected by the presence of the boundary layer, in the curves and tables presented herein.

To determine if any important scale effects were present, a run was made at half the velocity head for one selected value of aspect ratio. The results, shown in Table 1 and in Fig. 4, indicate a somewhat greater slope

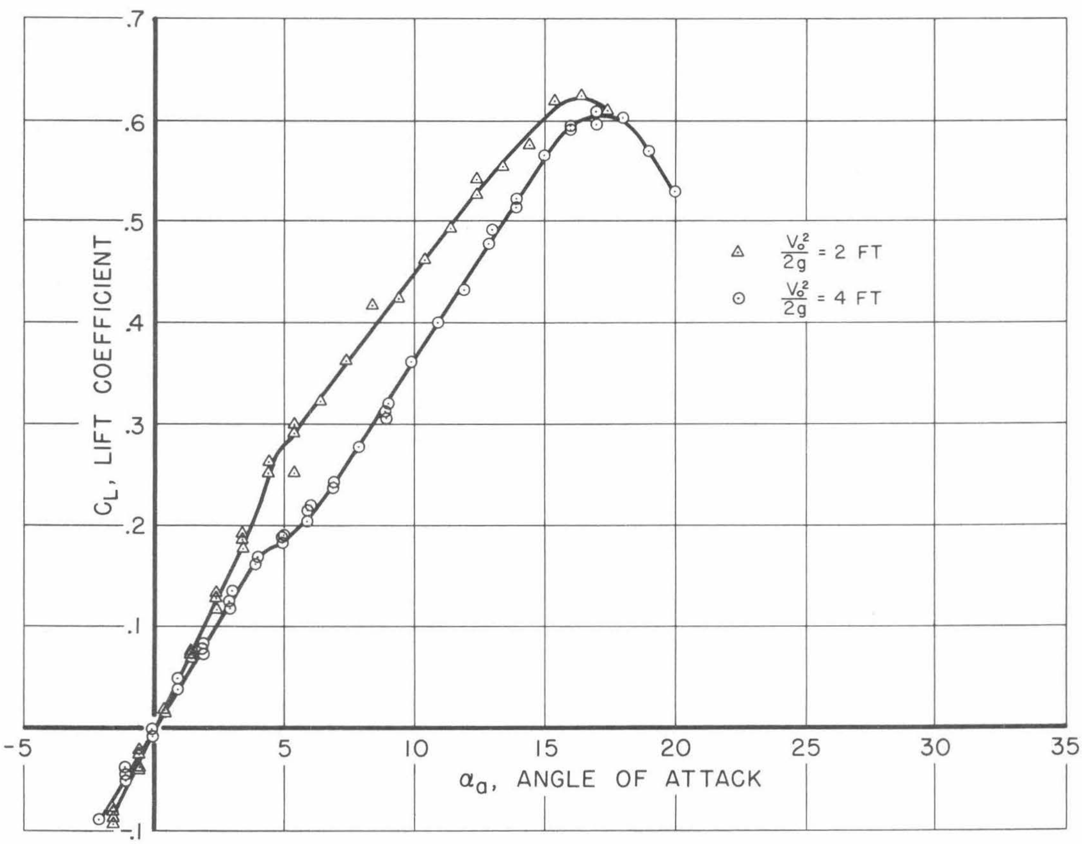

Fig. 4 - The effect of changes in velocity head on the lift coefficient curves of a 17.5% thick symmetrical lenticular airfoil using a reflection plane. Aspect ratio = 1.96.

of the C_L curve at the lower velocity. Even more obvious is the difference in the nature of the curves in the middle range of angles of attack. At this point in the investigation it was not known whether the "dog leg" in the curve was due to two-dimensional phenomena or whether it was due to some other effect. It was considered not unlikely that premature separation could occur behind the rather sharp leading edge in the boundary layer of the reflection plane at moderate angles of attack, progressing spanwise as the angle of attack was increased and giving rise to the observed jog. The jog remained at virtually the same region of the curve even after the skim plate was removed, suggesting that it is primarily a characteristic of the model section under the conditions of velocity and scale employed in this experiment. Subsequent search of the literature[7, 8, 9] revealed that this type of behavior is due to flow separation at the leading edge, followed by reattachment downstream, and that it is primarily a two-dimensional one arising from the use of sharp-edged sections. To demonstrate this effect, the leading edge of one of the models was filled in with tape and wax so as to produce a leading edge radius three times as large as the original. The break in the curve vanished completely, but the value of the lift curve slope was only about one-half that of the original model.

A characteristic which is associated with the jog in the curve was noticed while making the force measurements when it became obvious that the model oscillated less at that point than it did at other angle settings. This effect was so pronounced that at first the runs were discontinued in the belief that the support strut was interfering with the skim plate. To verify the observations, the setup described on page 5 was used and an oscillograph trace of the residual force oscillations was made. The trace disclosed that the force fluctuations were greatest just prior to the break in the curve and smallest immediately after, for all angle settings less than that corresponding to the maximum lift coefficient. The range of fluctuations was between $\pm$ 10% of the force reading just before the "dog leg" and $\pm$2% immediately after. After the stall point was reached the fluctuations became extremely severe, with the mechanical stops on the balance acting to limit the excursion of the weighing frame.

How many of these peculiar section characteristics can be attributed to the low value of Reynolds number and how many to the turbulent flow of the Free-Surface Water Tunnel is not known. The highest value of Reynolds number employed in these tests was 250,000, which is very low compared to the usual range encountered in aerodynamic investigations and which accounts for the relative scarcity of useful published information.

Higher velocities were not attempted because of the likelihood of structural failure of the reflection plane supports. The serious consequences of this limitation were not to be realized until later, when the high-speed free-surface run was analyzed.

Effective Aspect Ratio: Free-Surface Runs

The curves plotted in Fig. 5a show that up to the angle of attack corresponding to $C_{L\ max}$ there is little difference between the behavior of the surface piercing hydrofoil as compared to the one projecting from the reflection plane. At this velocity then, the three-dimensional effects of the hydrofoil-free surface intersection are equivalent to those of a wing tip terminating in the fluid, insofar as the induced downwash effects are concerned. It should be remembered that the aspect ratio of the surface-piercing hydrofoil is different from that described on page 6, in that the span of the reflection plane model takes into account the image, whereas the span for the free-surface model is the distance from the undisturbed water surface to the free tip.

The good agreement shown in Fig. 5a indicates a fortuitous choice of model Froude number. If the Froude number were decreased, say by lowering the velocity, the relative influence of gravity in affecting the flow pattern would become greater, and in the limiting case the free surface would act like a solid boundary. At this vanishingly small Froude number the slope of the C_L curve for the free-surface run should correspond to an aspect ratio twice that of the reflection plane run for models of equal geometric aspect ratio, as defined above. Conversely, an increase in Froude number should produce a relative decrease in the measured slope at $C_L = 0$ for the surface-piercing hydrofoil. This conclusion follows from an extension of the method of Glauert[10] and others who solved the similar open-jet wind tunnel interference problem by assuming the existence of image vortices outside the jet which are of the same sign as those representing the airfoil under test. This choice of signs is made to secure, as a linearized approximation, a surface of constant pressure. The approximation breaks

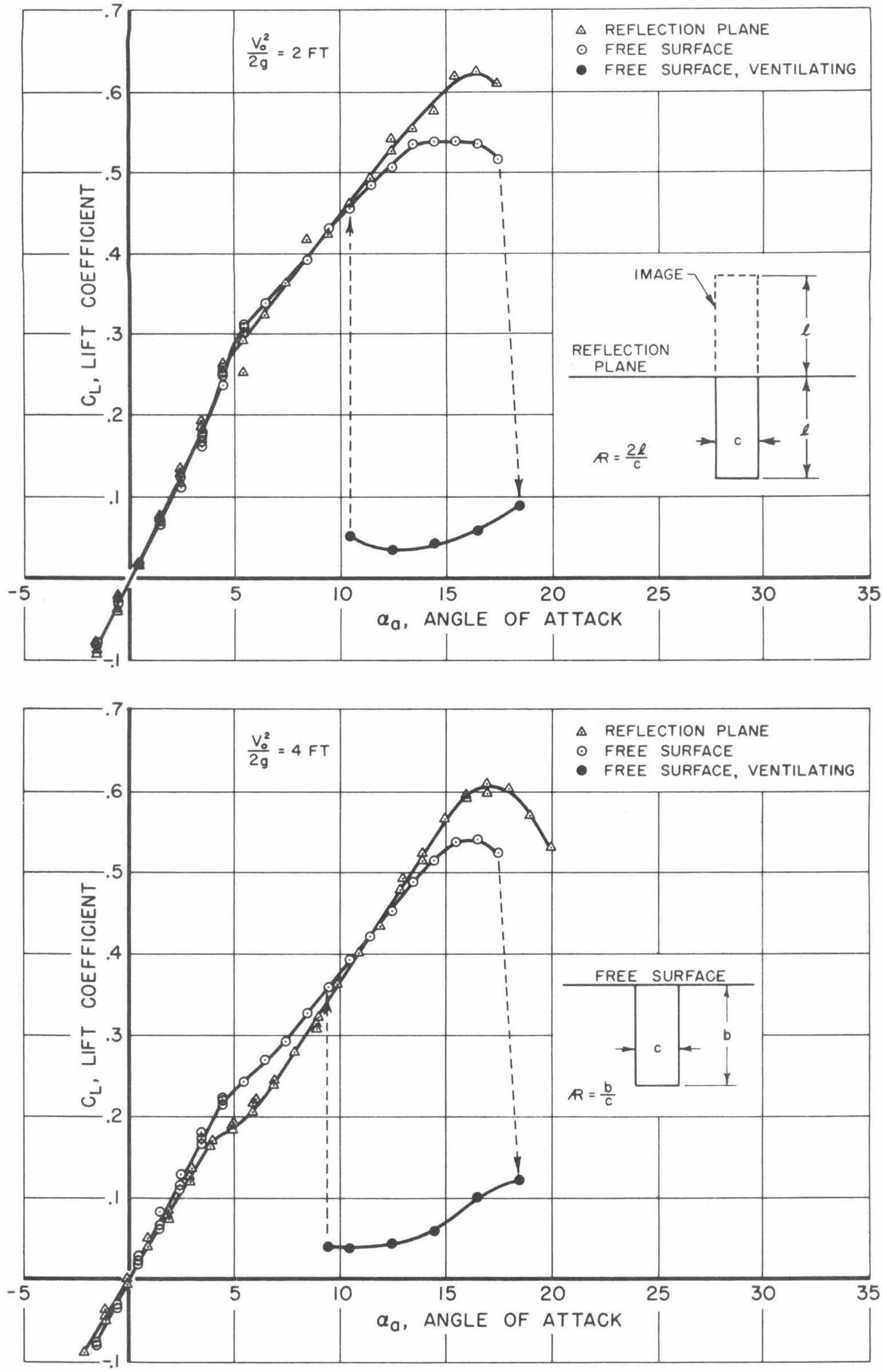

Fig. 5 - The effect of the presence of a free surface upon the lift curve for a 17.5% thick symmetrical lenticular airfoil. Aspect ratio = 1.96.

down in the immediate vicinity of the intersection of the wing with the constant pressure surface, especially when using the small aspect ratios considered in this study. One should suspect however, that the direction of change be accounted for by the theory. That this was not so can be seen in Fig. 5b, where the free surface is seen to act more like a fixed boundary at this higher velocity (and Froude number) than in the previous case shown in Fig. 5a. Equally important, Figs. 4 and 5 show that scale effects resulting from velocity changes are larger than those due to the presence of the free surface, so that final conclusions regarding the effective aspect ratio of a surface-piercing hydrofoil must be withheld until the various scale effects can be isolated.

A single run was made at a velocity head $V^2/2g = 8$ ft with the hydrofoil piercing the free water surface and which exhibited a smaller value for the slope of the lift curve (see Table 1) than was found at the lower velocities, but in the absence of a reflection plane run at this same velocity it is not possible to isolate or evaluate the free-surface effects.

Ventilation

The flow in the neighborhood of a slender body which intersects a water surface can be one of two greatly differing types, depending upon existing operating conditions. On the one hand the flow can close behind the body in what might be called the fully wetted case, or it can spring clear of the body, producing the fully ventilated configuration. Some body shapes can exhibit either flow picture, depending upon past history, while others are restricted to one or the other at the given conditions of operation. The effects of these alternative regimes of operation are of interest in any application where the use of a surface-piercing hydrofoil is contemplated.

When the hydrofoil used in these tests was set at small angles of attack (Fig. 6) at a velocity of 16 ft per second, the flow is seen to have closed behind it, and the only visible disturbance is the "trough" formed in the water surface on the suction side of the wing, and the "wall" or sheet on the pressure side. As the angle of attack was increased beyond the stall point the suction side began to ventilate intermittently. This action is so rapid that to the naked eye it appears only as an occasional frothing of the water, which is accompanied by severe fluctuations in force reading. This

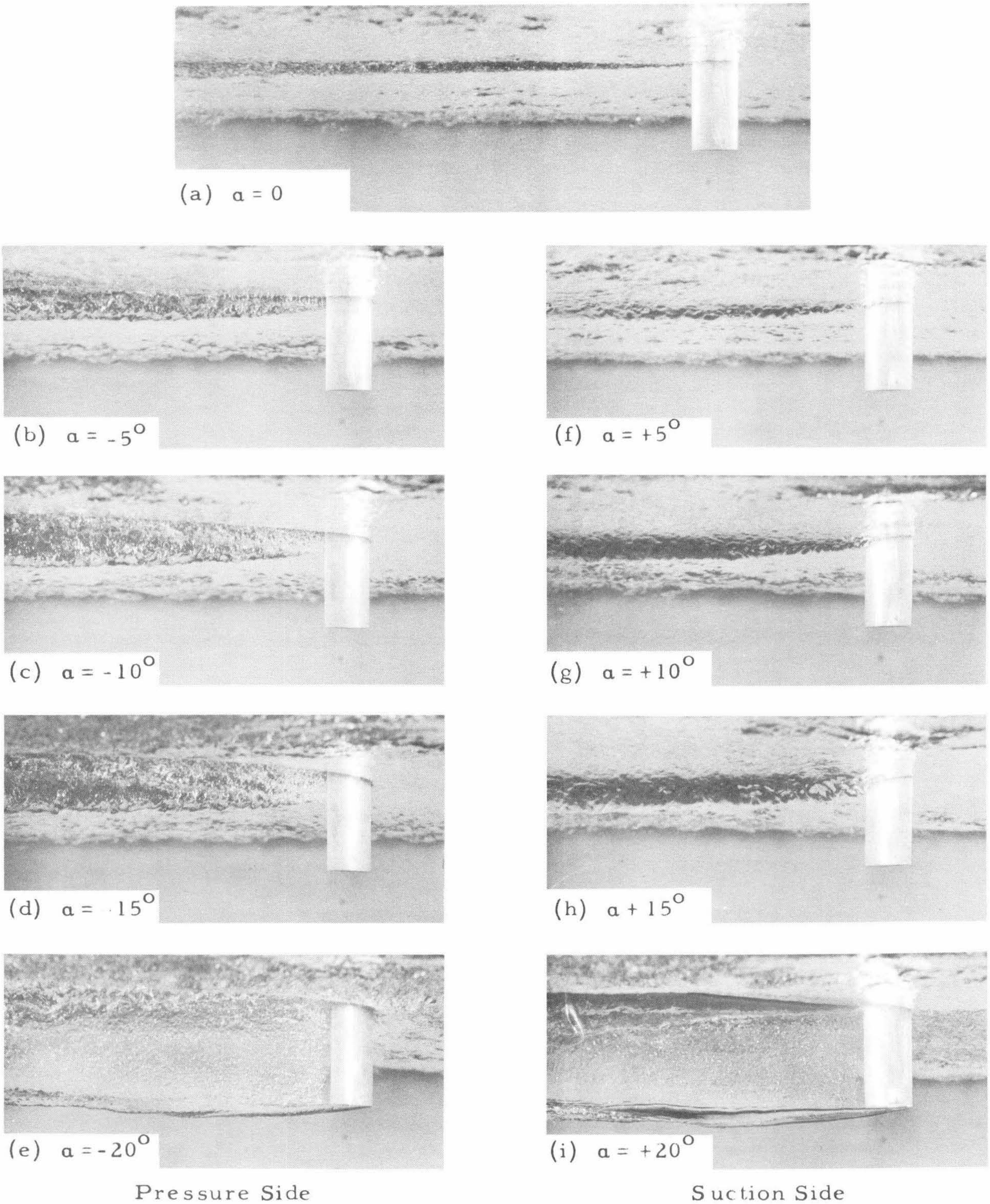

Fig. 6 - Symmetrical surface-piercing hydrofoil at varying angles of attack seen obliquely from below the water surface. Water velocity 16 ft per sec. Aspect ratio 1.96. Parts (e) and (i) show the fully ventilating type of flow.

behavior may continue indefinitely or some chance occurrence can trigger off the fully ventilating configuration. Figure 7 shows the hydrofoil at the same velocity (16 fps) and angle of attack (18^o) but with two different flow types. In part (a) the intermittent ventilation or "puffing" is taking place. The high speed electronic flash photograph shows air-filled vortices which have been swept downstream from the model. In part (b) the ventilation pocket is fully developed. Unlike the fully wetted case at these higher angles of attack, the fully ventilating case is a stable one, and it is almost impossible for the operator to remove the ventilation cavity by interfering with or disturbing the flow. Once secured by having increased the angle of attack beyond the stall point, it will remain more or less fully ventilated for a large range of angles, depending upon the operating velocity. The hysteresis effect is clearly shown in Fig. 5, as is the severe effect of ventilation on the lift coefficient values. At higher velocities it is possible to maintain ventilation (once achieved by passing beyond the stall point) at an attack angle of zero, but the cavity is easily lost as the angle of attack is decreased, and the hydrofoil usually becomes fully wetted again.

The line of separation on the model does not necessarily occur at the trailing edge, as might at first be expected. Figure 6e reveals, upon close inspection, that ventilation can also take place on the trailing edge of the pressure side of the hydrofoil, an effect which is greatly increased by lessening the angle of attack. With so uncertain a line of demarcation between the wetted and dry zones on the hydrofoil, it is fairly certain that viscosity and/or surface tension scale effects can play an important part in describing the flow pattern and in determining the magnitude of the hydrodynamic forces acting on it.

CONCLUSIONS AND RECOMMENDATIONS

When a moving hydrofoil intersects a constant pressure surface, the effective aspect ratio of the hydrofoil, which is determined by the slope of the lift curve, should be different from the geometric value because the wing tip which is in effect formed at the intersection is not the same as the actual tip terminating within an infinite field of fluid. Contrary to this supposition, the results of these experiments indicate that no large difference can be detected within the range of operating conditions used. On the other

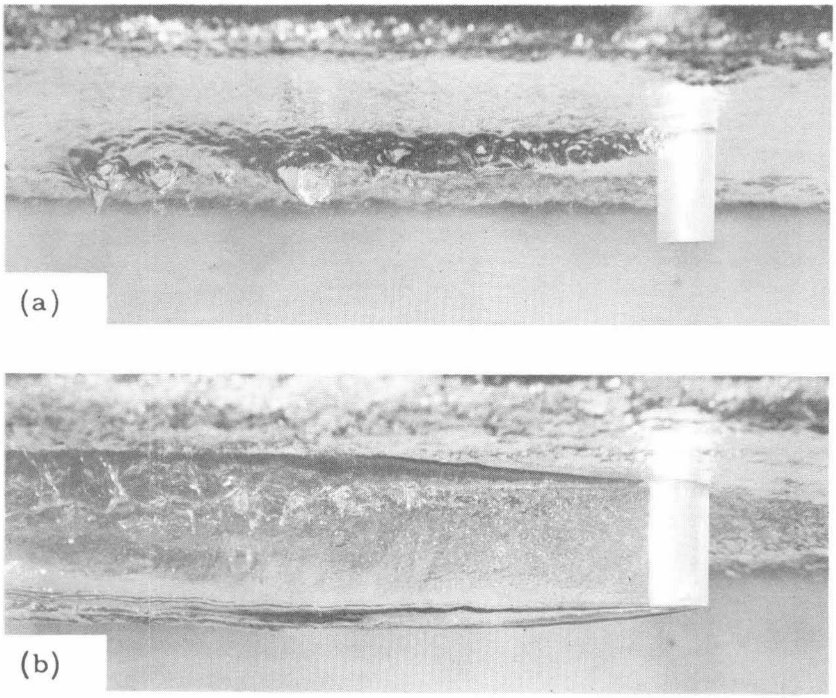

Fig. 7 - The surface-piercing hydrofoil at 18° angle of attack and 16 fps ($V^2/2g = 4$ ft) shows intermittent ventilation above (a), and fully developed ventilation below (b).

hand, two-dimensional Reynolds number scale effects are very large under these conditions and tend to mask the behavior being sought. Subject to these qualifications and pending further investigation, the effective aspect ratio of a surface-piercing hydrofoil should be taken as being equal to its geometric value.

The problem of air ventilation of a lifting, surface-piercing hydrofoil is found to be very important because of the great loss in lift which can result. Ventilation was observed to arise spontaneously only when the lifting hydrofoil was at or beyond the stall point, although once established it could maintain itself over a large range of attack angles. Scale effect seems to play an important role in defining the line of separation, and possibly on the forces measured, when the hydrofoil ventilates.

The Free-Surface Water Tunnel proved well-suited for this type of investigation, but the following shortcomings and suggested corrections are noted:

(a) The flow is too turbulent to permit the easy, accurate measurement of the forces that would otherwise be possible, or to permit separation of possible unsteady flow phenomena intrinsic to the flow regime from those due to water velocity fluctuations. A honeycomb installation in the tunnel should help greatly in solving this problem.

(b) The force balance, having been designed to measure small forces, was not rugged enough to permit the use of larger models which have at least two advantages: easier, more accurate construction, and a more useful and interesting range of Reynolds numbers.

(c) The reflection plane, which was an adaptation of existing equipment, was too large and too weak structurally to permit high-speed runs. For future investigations of this type, the reflection plane should extend upstream of the model only far enough to prevent perceptible distortion of the water surface. By observing this precaution, the boundary layer thickness along the plate can be kept very small, and the question of the effects of boundary layer on the effective aspect ratio of a wing projecting from a reflection plane can be avoided.

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