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A Study of a Small Hydrofoil Boat with Airplane Type Controls

Allyn B. Hazard

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HAZARD — A SMALL HYDROFOIL BOAT

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A STUDY OF A SMALL HYDROFOIL BOAT WITH AIRPLANE TYPE CONTROLS

By

Allyn B. Hazard

A Thesis
In partial fulfillment of the
Requirements for the Degree of
Master of Science in Mechanical
Engineering

The University of New Mexico
1950

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

E F Castetter
DEAN

May 26, 1950
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Thesis committee

A. D. Ford
CHAIRMAN

Charles Truman Grace

Edward C. Rightley

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CHAPTER I

INTRODUCTION

Types of boats. Boats may be classified in the following way:

1. The displacement boat.
2. The planing boat.
3. The hydrofoil boat.

All boats when at rest or traveling at slow speeds are displacement boats. As a boat's speed is increased its bow rises, and eventually, if enough power is available, a speed is reached where the boat levels off and planes on the surface. The hydrofoil boat operates with its hull supported above the surface of the water by lift forces generated by wings running under water. These wings, which are called hydrofoils, are airfoils which have been especially designed for underwater operation.

Besides being able to attain high speeds, hydrofoil boats have very smooth riding characteristics in choppy weather because the hull is supported high enough above the waves to pass completely over them.

Unlike the airplane which is able to travel an almost unlimited distance vertically, a flying boat of this type is limited in the distance it can move in a vertical direction to somewhat less than the length of the hydrofoil sup-

port struts. Obviously a hydrofoil boat must be inherently stable or there must be some means to control the vertical motion, or the boat would perform very erratically, first climbing until the hydrofoils broke the surface, and then falling back and repeating the process.

Early hydrofoil boats. In Figure 1 and Figure 2 hydrofoil boats are pictured which have the hydrofoils arranged in such a manner that the boat will travel in an approximately smooth horizontal direction. In the ladder arrangement the faster the boat goes the more lift is generated and the higher the boat climbs, but the higher the boat climbs the greater the number of wings that is lifted out of water. Eventually so much wing area is out of water that the lift is exactly equal to the weight of the boat and it climbs no higher. The high dihedral hydrofoil arrangement achieves vertical stability in approximately the same manner, only the change in lift with elevation is less abrupt than with the ladder system.

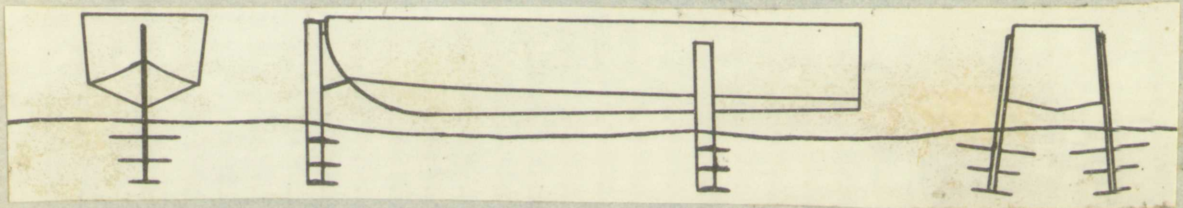

Figure 1. Ladder system of hydrofoil arrangement.

Either of these systems is subject to the unsteady-

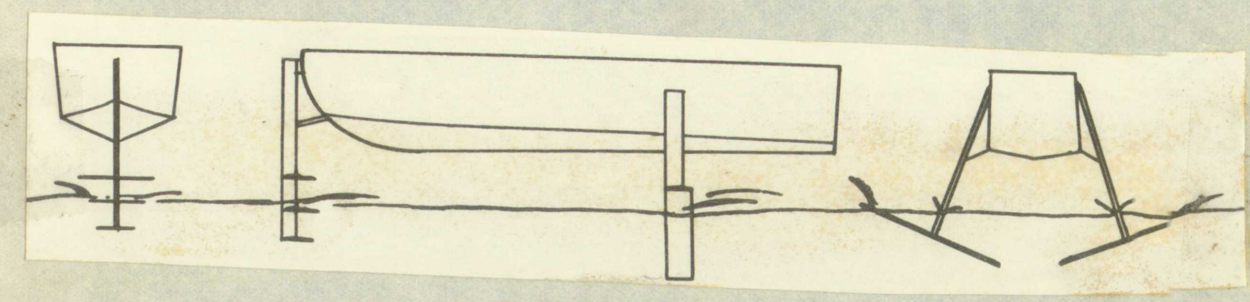

Figure 2. Ladder and high dihedral system of hydrofoil arrangement combined.

ing influence of wave action. The ladder system is also subject to interference drag losses caused by the close arrangement of many hydrofoils, while in the high dihedral system air ventilates the upper surface of the hydrofoil for a considerable distance below the water surface with a consequent increase in drag.[1]

In 1920 the HD-4, a hydrofoil boat of the ladder type developed by Doctor Alexander Graham Bell, set the world's speed record for boats by going 71 MPH. His boat weighed 9,900 pounds, and was powered by two 300 HP low compression Liberty Aircraft engines. At 60 MPH the boat was supported by only four square feet of hydrofoil area.[2]

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[1] James M. Benson and Douglas A. King, Preliminary Tests to Determine the Dynamic Stability Characteristics Of Various Hydrofoil Systems, N.A.C.A. WARTIME REPORT L-756, p. 2.

[2] William Washburn Nutting, A 70-Miler with Remarkable Possibilities, Annual Report of Smithsonian Institute, 1919.

Controllable hydrofoil systems. Early experimenters with hydrofoil boats made no attempt to obtain control by varying the angle of attack of the hydrofoils when the boat was in motion. Only recently have experiments been made with controllable hydrofoil systems. Currently an Englishman, Christopher Hook, is developing a controllable hydrofoil system which he calls Hydrofin. On either side and ahead of the boat there is a jockey float which follows the shape of the waves and causes its respective hydrofoil to change angle of attack in such a manner as to always remain below the surface. In choppy weather the jockeys are restrained from dropping into the wave troughs too quickly by hydraulic dampers, so instead of following the waves sharply up and down they and the boat follow an almost smooth horizontal course. It should be mentioned that the only controls the operator has to be concerned with are the throttle and the rudder.[3]

Review of literature. Both the United States Patent Office and the National Advisory Committee for Aeronautics were important sources of information relevant to this problem. A patent search disclosed that many inventors have given much thought to the problems connected with hydrofoil

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[3] Marion P. Courtney, "Boat With Legs", Science and Mechanics, XXI: 84-85, April, 1950

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[5] Marion F. [illegible], "Boat with Legs", Science and Mechanics, XXI: 84-85, April, 1950.

boats. As far as could be determined, however, none have applied for a patent on the idea tested on this project. The NACA reports listed in the Bibliography provided valuable information without which this project could never have been completed so successfully.

Summation.

1. Hydrofoil boats are able to reach high speeds and maintain these high speeds in rough water by passing above the pounding action of the waves.

2. Though hydrofoil boats have been built with both fixed and controllable hydrofoils, instability or other factors have prevented their more widespread use.

CHAPTER II

THE PROBLEM

Controls. A review of pertinent literature has revealed that no hydrofoil boat has been constructed in which the operator would have sufficient control of the hydrofoils to insure positive control of the craft about the three major orthogonal axes.

The primary purpose of this study was to determine if the application of airplane type controls to the hydrofoil boat would produce a stable craft that would be safe to operate. The secondary purpose of this study was to determine if a human operator could respond to changes in the boat's attitude brought on by wave action or other factors in time to keep the craft running in a desirable operating condition. Finally, the commercial possibilities were to be determined by the performance of the prototype.

A hydrofoil boat equipped with such controls would differ greatly from existing hydrofoil boats in that stability would not be achieved by some mechanical means that functioned in response to variations in depth of the hydrofoils, but rather, the stability would be obtained in response to the desires of the operator.

Paths of research. The three major directions along

which research effort on this project could be directed were:

I. Small self-propelled radio controlled models.

II. Water flume or tow tank tests of small models.

III. Construction of a full scale man-carrying prototype.

The first two courses would have required much expensive equipment incidental to the operation and testing of the hydrofoil controls. Because of this and because the first two paths would eventually require the construction of a full size boat it was decided that choice number three was the most desirable course to follow.

CHAPTER III

DESIGN AND CONSTRUCTION DETAILS OF WATER HAZARD II

Figure 3 indicates the relative size and the location of the important members of WATER HAZARD II. (The first boat to be named WATER HAZARD was an outboard planing boat owned by the experimenter.) It can be seen from these illustrations that this boat is somewhat unconventional in appearance. An attempt was made to compromise the shape necessary for low air resistance with that which it was believed would result in low water resistance. The result is the sea-sled type hull which approximates an airfoil in longitudinal cross-section. It can be seen from the front view that the sides flare in such a manner that the hull has more beam at the bottom than at the top. This uncommon method of flaring the sides was chosen so that the lateral hydrofoils would be separated by a great enough distance to increase the boat's stability in roll about the longitudinal axis.

Hull construction. The materials used in the hull's construction and the manner in which they were assembled were, with few exception, representative of contemporary small boat construction. The frame was made of select grade white oak while the sides and bottom were covered with fir

Figure 3. WATER HAZARD II

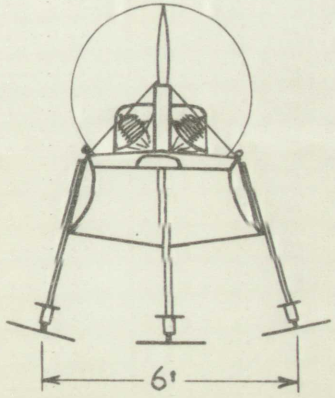
Gross Weight	650 LBS.
Hull	200 "
Engine & Mount	120 "
Gas, Oil, and Tanks	60 "
Battery, and Propeller	50 "
Struts, Foils, and Rudder	60 "
Operator	160 "

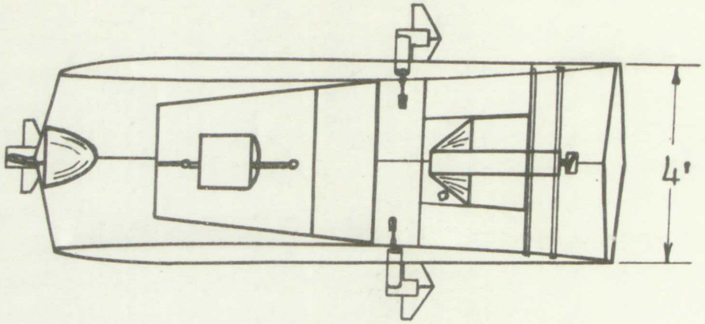
Hull: Original Design
Oak Frame
Fir Marine Plywood Skin
1/4 IN. Deck and Sides
3/8 IN. Bottom

Engine: Harley Davidson 23 BHP
45 CU. IN. Displacement
Air-cooled

Propeller: 45 IN. Diameter, Wood,
Fixed Pitch, Chain Drive

Hydrofoil Area: 1.5 SQ. FT.





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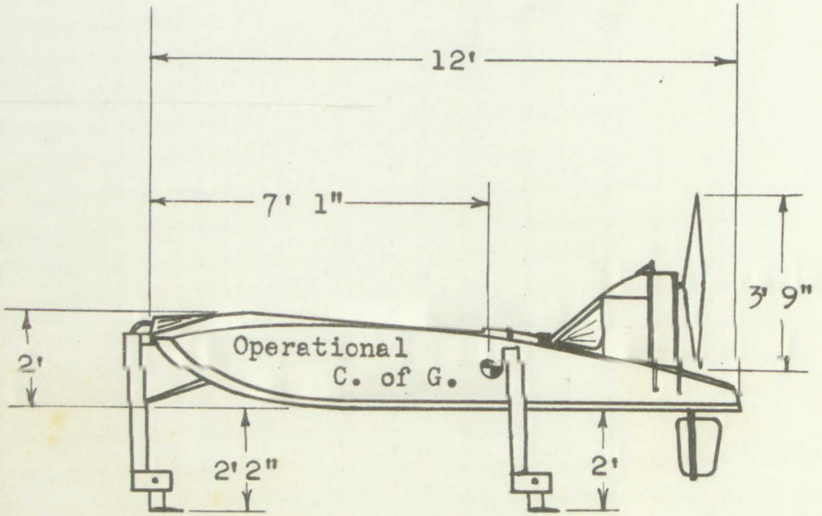

marine plywood.[4] Imstead of using quarter inch plywood on the bottom as om the sides it was decided that, due to the unusually high stresses that might be imposed upon the bottom, three eighths inch plywood would be more satisfactory. To make certain that all seams would remain watertight an elastic rubber base marine glue was used instead of the more commonly used Weldwood glue which it was felt might have had a tendency to crack and leak. That this innovation was successful is evidenced by the fact that the seams never developed a leak in the seven weeks that the boat was in the water.

Steering. It should be noted in Figure 3 that the boat was designed with two rudders. The front strut was pivoted in such a manner that it would function as a rudder when the boat was flying. The water rudder at the stern would be used when the three hydrofoil struts were folded up on the deck while the boat was passing over shoals or through seaweed.

Power plant. The choice of an engine was difficult. An air-cooled 23 BHP Harley Davidson motorcycle engine was available for $150, and a water-cooled Crosley Cobra automobile engine was available, complete with starter and ring gear for $165. Each merited serious consideration. Finally

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[4] How to Build 20 Boats, 9, Fawcett Publications, Inc., Greenwich, Connecticut.

it was decided that the problem of feeding cooling water to the Crosley through a hollow strut would present more difficulties that those which would be encountered in adding a starter ring gear assembly to the Harley Davidson. In retrospect the validity of this decision seems questionable, since the starter and the ring gear were the source of much trouble. It might be mentioned, now that these difficulties have been corrected, that the entire power transmission system is trouble-free and vibrationless in operation. Standard motorcycle sprockets and chain were used to transmit power from the engine, which sits low in the hull, to the propeller drive shaft at the top of the propeller pylon.

Fuel system. Some difficulties were experienced in getting the fuel system to function properly. The carburetor on a Harley Davidson is designed to operate a few inches under a gravity feed fuel tank. However, in this particular installation the bottom of the gasolene tank was more than 24 inches below the carburetor and it was necessary to install a Stewart-Warner 110 Series electric fuel pump. This pump develops enough pressure to deliver 15 gallons an hour through a vertical distance of 24 inches. It can be imagined what happened when this pump was first connected to a carburetor whose float system was designed to control the feeding of two gallons an hour under a low gravity head. When the fuel pump was turned on gasolene im-

mediately gushed out of the air intake. This condition was remedied by installing a by-pass on the outlet side of the fuel pump to return most of the fuel to the gas tank.

Propeller. It was not considered practical to attempt the construction of a propeller so one was purchased from a manufacturer who specializes in propellers for ice sleds and small air drive boats. No attempt was made to calculate the variation in blade pitch from the axis to the tip. Instead the manufacturer was given information about the HP, RPM, and the boat's maximum velocity to enable him to do so. The figure for velocity was deliberately made high, for a fixed pitch propeller is definitely limited in the velocity that it can advance upwind. Therefore the pitch must be based on a higher velocity than the boat will travel through the water.[5]

Center of gravity. During very preliminary design calculations it was determined that the center of gravity would be located five feet back from the bow. This would permit an approximately equal lift load distribution with

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[5] In the Appendix the maximum velocity is calculated to be 34 MPH, approximately. If the boat's propeller were designed for this maximum velocity and the boat attempted to move upwind in a 30 MPH wind, the boat might manage to make 5 to 10 MPH which is much less than the calculated takeoff velocity of 16 MPH. Considering this a figure of 45 MPH for the maximum velocity was sent to the manufacturer.

the hydrofoils placed as shown in Figure 3. However, as construction progressed the center of gravity shifted rearward until it was finally 7.85 feet back from the bow. Considering the effect of the propeller thrust and the strut and hydrofoil drag when the boat is in operation the center of gravity is in effect moved forward to 7 feet, 1 inch. The front hydrofoil then carries 78 pounds, while each of the rear hydrofoils carry 286 pounds. The most important effect of this uneven foil loading was a higher takeoff speed. Additional effects of this center of gravity shift are discussed in Chapter IV.

Struts and hydrofoils. The struts and hydrofoils presented the most difficult design problems encountered on this project, mostly because there was no way to determine in advance what unusual stresses might develop in operation. It was decided that the design of the struts should be based on a large factor of safety. The struts were made of S.A.E. 4130 high yield point steel.

Figure 4 illustrates most of the important design details of a typical strut and hydrofoil combination. It can be seen that if the control cable is pulled up it will result in a clockwise rotation of the hydrofoil about the pitch pin, which results in increased lift. It can be seen that the pitch pin is so located that the moments produced by the lift and drag forces will tend to keep the control

Figure 4. Details of struts and hydrofoils.

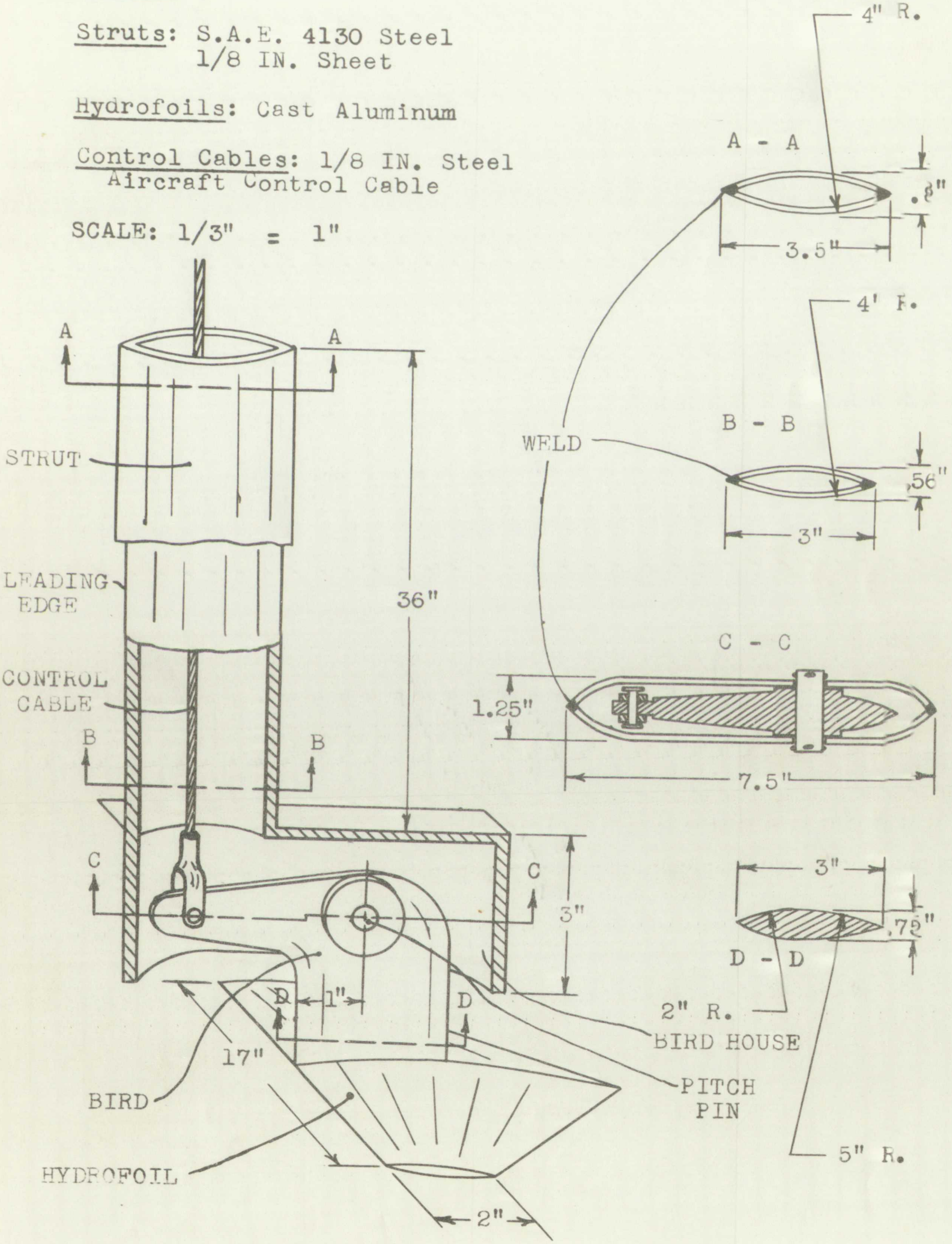
Materials:

Struts: S.A.E. 4130 Steel
1/8 IN. Sheet

Hydrofoils: Cast Aluminum

Control Cables: 1/8 IN. Steel
Aircraft Control Cable

SCALE: 1/3" = 1"



cable in tension. By locating the pitch pin thus with repect to the hydrofoil it is possible to achieve fairly positive pitch control without the necessity of resorting to a two-cable system. The single cable system has obvious advantages with regard to mechanical simplicity and to strut size.

Finishing the hydrofoils. The hydrofoils and the birds (see Figure 4) were cast seperately in the University foundry and then welded together in a local welding shop. The hydrofoil castings had a tendency to shrink excessively at the thin tip sections and in this condition they were unusable. However, it was possible to save them by building up the depressions with aluminium cold solder. No attempt was made to finish the hydrofoils to the accuracy which the NACA finished their hydrofoil test sections. After polishing, the hydrofoils were given two coats of aluminum paint for protection.

Cockpit controls. The boat is equipped with dual controls to simplify the instruction of others. The control column, which was removed from a wrecked Cub airplane, was modified slightly for this installation. The rudder pedals were made from T hinges with cable cranks welded on. Provisions were made for varying the lever ratios of all three control systems (elevator, aileron, and rudder) so that the controls could be made to approximate airplane cable in tension. By locating the pitch pin thus with respect to the hydrofoil it is possible to achieve fairly positive pitch control without the necessity of resorting to a two-cable system. The single cable system has obvious advantages with regard to mechanical simplicity and to strut size.

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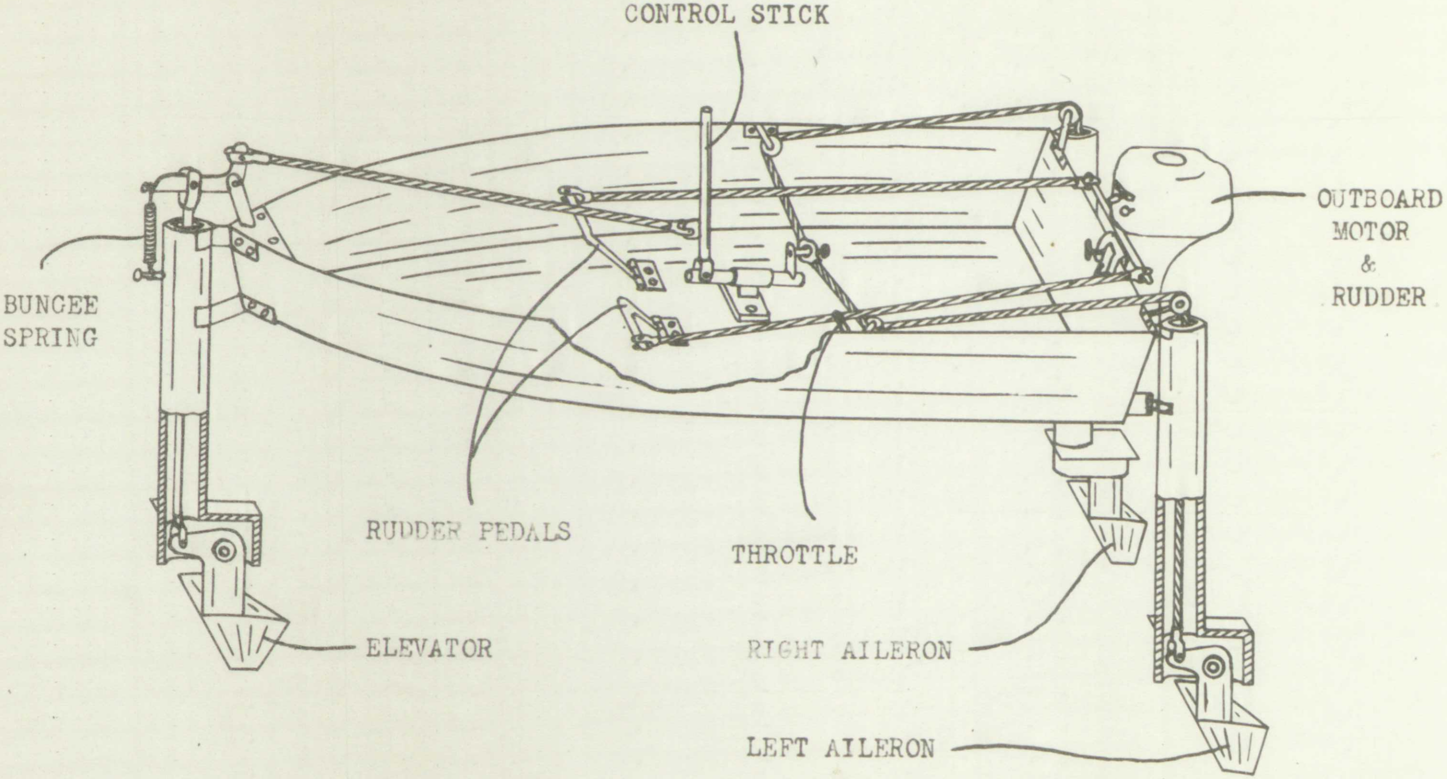
Cockpit controls. The boat is equipped with dual controls to simplify the instruction of others. The control column, which was removed from a wrecked Cub airplane, was modified slightly for this installation. The rudder pedals were made from T hinges with cable guards welded on. Provisions were made for varying the lever ratios of all three control systems (elevator, aileron, and rudder) so that the controls could be made to approximate airplane controls both in "feel" and response. Figure 5 is a schematic drawing illustrating the arrangement of the cockpit controls and all members important to the proper functioning of controls in a hydrofoil boat of this type.

Figure 5. Schematic illustration of a hydrofoil boat equipped with airplane type controls.



CHAPTER IV

THE TESTING OF WATER HAZARD II

Tests without hydrofoils. Three runs were made with the boat in various stages of completion. When launched the boat sat well in the water and its water line was in the predicted location. The hull was so stable that it could not be capsized even when two adults leaned over the same gunwale. Much of this static stability can be attributed to the reverse flair of the sides.

Some difficulties were experienced during the first run with the drive system. For one thing, since the engine had not yet been completely broken in it was necessary to restrict the boat to part throttle operation. This resulted in some difficulty in steering, especially when trying to turn upwind for there was not enough forward velocity for the rudder to be very effective. However, it was easy to control the boat on a straight course or on large radius turns.

The boat had been in operation for less than five minutes when two welds holding a flange to the extension drive shaft failed allowing the propeller to slow to about 20% of direct drive speed. The drive system had to be dis-

assembled and the defective part taken to Hot Springs where temporary welding repairs were hurriedly made. After reassembly a short test run was made with the throttle open for short periods only. Even with the throttle wide open the boat did not perform too well but this was believed to be caused by the fact that the throttle was never left open for more than several seconds at a time which was hardly long enough to permit high speed to be developed. It was later discovered that the high speed carburetor needle had been improperly adjusted. For these two reasons the experimenter was convinced that with the engine properly broken in and with the carburetor properly adjusted there would be no difficulty in getting up to takeoff speed.

Additional runs were made without hydrofoils to test the carburetor and to break the engine in further. After completion of these runs the experimenter finally realized that the poor speed performance evidenced by the boat on the first test had not resulted from the short period of time the throttle was allowed to remain open, nor from the improper adjustment of the carburetor, for the boat seemed to perform just as poorly after these conditions were remedied.

Tests with hydrofoils. Before testing the boat with all hydrofoils in place one run was made with only the bow assembled and the defective part taken to Hot Springs where temporary welding repairs were hurriedly made. After reassembly a short test run was made with the throttle open for short periods only. Even with the throttle wide open the boat did not perform too well but this was believed to be caused by the fact that the throttle was never left open for more than several seconds at a time which was hardly long enough to permit high speed to be developed. It was later discovered that the high speed carburetor needle had been improperly adjusted. For these two reasons the experimenter was convinced that with the engine properly broken in and with the carburetor properly adjusted there would be no difficulty in getting up to takeoff speed.

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Tests with hydrofoils. Before testing the boat with all hydrofoils in place one run was made with only the bow hydrofoil. Under these conditions there was definite response to movement of the control stick in a fore and aft direction. There seemed to be no appreciable speed advantage however. Apparently the possibility of attaining increased velocity with the bow riding higher off the water was offset by the increased drag of the strut and hydrofoil.[6]

On the day chosen to test the boat with all three hydrofoils in place the wind was blowing about 30 MPH and the waves were running about a foot high. These were thought to be ideal conditions for the test because the wave action would help to break the bottom of the boat free from the water surface when taking off. Furthermore, if too much wind resistance was encountered going upwind then it seemed that it would only be necessary to turn the boat around and make an easy takeoff downwind.

The boat was towed through a weedbed into the middle of the lake where there was rough water. With the towline cast off the engine was started with the boat heading down-

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[6] It still seemed to the experimenter that with three hydrofoils in place generating lift the boat would ride higher in the water, the drag would be decreased and the speed could be increased which would in turn generate more lift causing the boat to ride still higher, until finally the boat would be running with the hull completely off the water.

wind. A turn was made to head the boat upwind and as the bow came around into the wind the waves started breaking on the sloping sides and throwing enough spray into the engine cooling passages to cause the engine to stop with a drowned out ignition system. In trying to restart, the battery ran down and WATER HAZARD II had to be towed back to shore. In considering the poor overall performance of the boat it became evident to the experimenter that the boat could not be made to operate properly unless radical changes were made. Clearly the boat was underpowered, overweight, and operating at too high a foil loading. The most expedient solution to these difficulties would have been to increase the total hydrofoil area to six square feet, or four times the area tested. This would reduce the takeoff velocity by one half to an easily obtainable 12 feet per second. Since shop facilities and finances were limited at that time even this simple modification was impossible. The only remaining alternative was to have the boat towed by a speedboat having enough power to reach takeoff speed.

Tow test. On this, the final run, a 22 foot Chris Craft powered by a 140 HP engine was used as the towboat. It is estimated that the maximum speed obtained while being towed was around 14 to 15 MPH, or just below the calculated

takeoff speed. This speed was so near takeoff speed that it was possible to jump the front hydrofoil out completely and lift the hull off for a fraction of a second.

During the course of the run it was possible to learn much about how a successful hydrofoil boat with airplane type controls would perform. So little of the hull remained on the water that it was possible to test the response of the controls in sideslips, banked turns and other maneuvers. The boat seemed steady but it was not known for certain how much of this stability could be attributed to the probable steadying influence of the towrope.

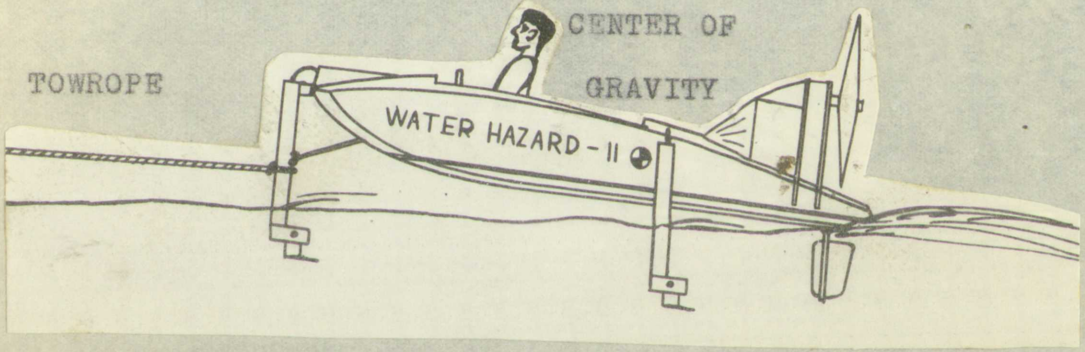


Figure 6. Tow test, steady state conditions.

Figure 6 shows that the center of gravity is almost directly over the rear set of hydrofoils. Had the rear set of hydrofoils been fastened at the stern, the lift distribution among the hydrofoils would probably have been so nearly equalized that the boat would have been able to takeoff and stay off during the tow test.

Figure 7 on the next page shows WATER HAZARD II with

struts and hydrofoils in place.

Figure 7. Profile view of WATER HAZARD II.

Fig 9

CHAPTER V

CONCLUSIONS ABOUT WATER HAZARD II

Certainly it cannot be said that this boat came anywhere near equalling its calculated performance. This seems somewhat strange for eventually every individual mechanical and electrical system on the boat performed as intended. The factors which caused this poor performance were known and appropriate measures were taken in the design and construction of WATER HAZARD III to correct these difficulties. It might be well to list these factors in the approximate order of importance.

1. Center of gravity shift causing unequal foil loading and increased takeoff speed.
2. The boat was so underpowered and overweight that it was even unable to perform as a planing boat as intended for comparison tests between planing and hydrofoil operation.

<u>WATER HAZARD III?</u> It was decided as a result of the inadequate performance of WATER HAZARD II to build an entirely new boat. Some question may be raised as to why this decision was made instead of deciding to rebuild the first model until it worked successfully. For one thing, the many changes that were needed to make WATER HAZARD II operate as desired would have required

nearly as much time and money as would be required in the construction of an entirely new boat propelled by an outboard motor.

If further reason is needed for abandoning WATER HAZARD II an accurate account of man hours expended in its construction shows that 48% of the time was required on the engine and drive system alone. An air drive was chosen originally because it was not known if the operator could achieve sufficiently good control to keep an underwater propeller immersed for an adequate portion of the time. After the tow test it was felt that an outboard power plant would be satisfactory for a boat of this type. If an outboard-propelled hydrofoil boat of this type could be made to work it would be possible to convert some of the many existing outboard-powered boats to hydrofoil operation with a minimum of effort and expense. This would greatly aid the hydrofoil boat in achieving popularity.

CHAPTER VI

DESIGN AND CONSTRUCTION DETAILS OF WATER HAZARD III

Hull. By staying as near as possible to modern boat construction methods much time was saved in the construction of this boat. From information available on several brands of precut, plywood outboard boat kits, an Ozarka Model 12B kit, which is designed to take outboards up to 16HP, was ordered since it seemed to have the most satisfactory features. This hull was constructed in less than half the time required for the hull of WATER HAZARD II. In fact, the boat was tested without hydrofoils four weeks after construction started, and two weeks later it was tested with hydrofoils.

Power plant. The motor chosen was a Mercury KE-7 which is rated at 10HP at 4000 RPM. Instead of being mounted directly on the transom the engine is attached to an auxiliary motor mount board fastened to the transom. This lowers the propeller seven inches, allowing the boat to climb higher.

Controls. Rudder control is achieved on this boat by having the rudder pedals turn the outboard. The hydrofoil and strut system is much the same as on the first boat; in fact the struts and hydrofoils were taken from

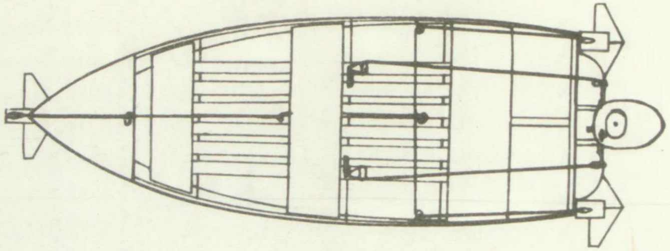
Figure 8 . WATER HAZARD III

Gross Weight:	455 LBS.
Hull	170 "
Outboard Motor and Fuel . .	70 "
Struts, Foils, and Controls	55 "
Operator	160 "

Hull: Commercial Boat Kit
Ozarka, Model 12B
Laminated Oak Ribs
1/4 IN. Marine Plywood Skin

Engine: Mercury KE-7, 10 BHP

Hydrofoil Area:	
Controllable	1.5 SQ. FT.
Boosters	1.0 " "



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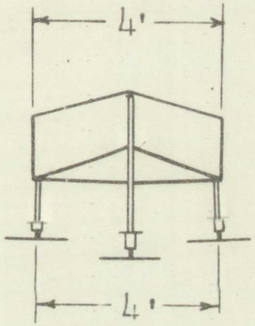

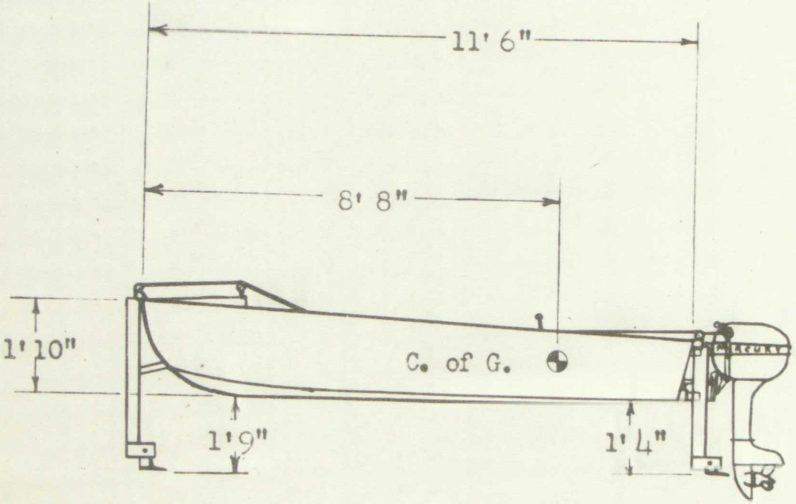

ATER HAZARD II. The front strut is fixed and acts as he pivot during turns while the rear struts are free o trail in response to the water forces so that they o not interfere with the rudder action of the outboard. n this boat the center of gravity is located in a po- tion which comes near to distributing the lift load enly among the hydrofoils.

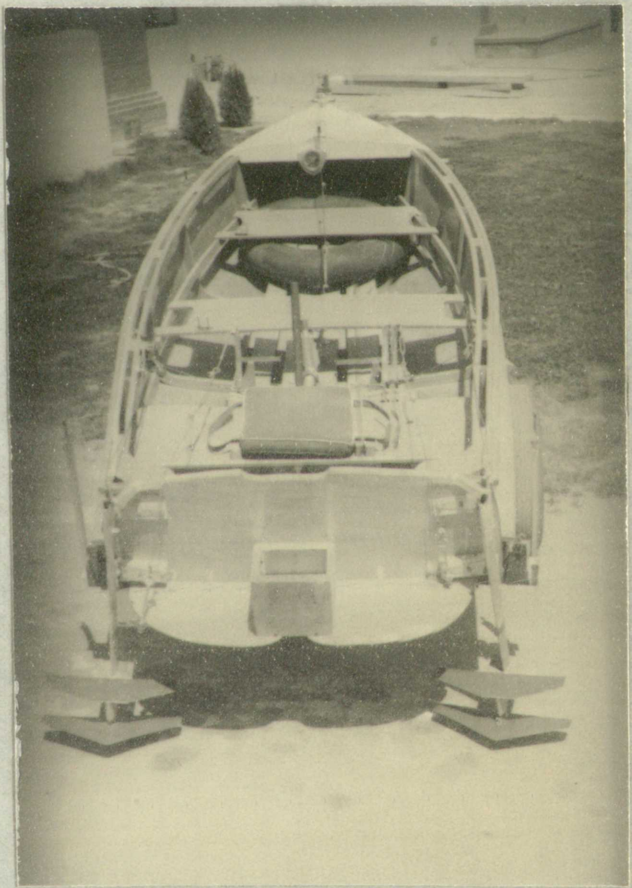

Figure 9. WATER HAZARD III, (Controls, Stern Struts and Hydrofoils, Auxiliary Motor Mount Board

In the above photograph two hydrofoils can be seen

Fig 12

on each strut. The lower one is the ontrollable and the upper one is the booster. When th control stick is moved to the right the control cabl leading to the left hydrofoil is pulled, which increaes the pitch and lift of that hydrofoil. At the same tme the control cable to the right hydrofoil is slackend somewhat, decreasing its pitch and lift. This causs the boat to roll to the right. Opposite movement of the stick produces the opposite effect. When the cotrol stick is pulled back the control cable leading trough the pulley above the speedometer to the front hyirfoil is pulled, increasing the pitch and lift of the frnt hydrofoil which causes the boat to climb.

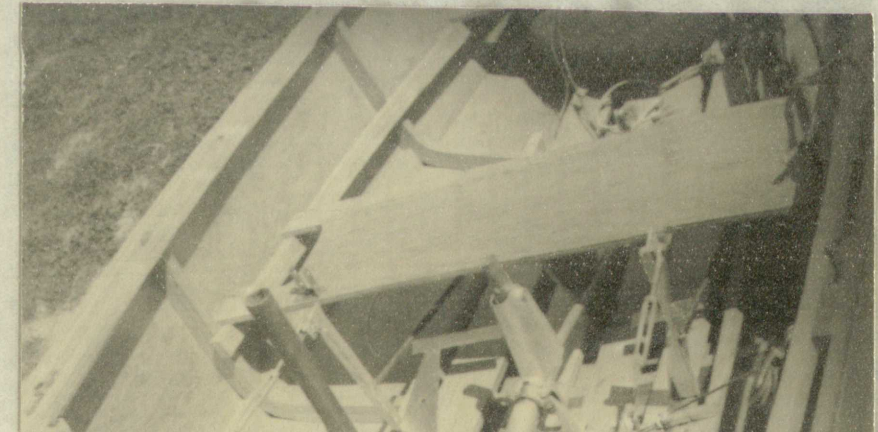

Figure 10. Details of cockpit controls o WATER HAZARD III

Figure 9 also shows the auxiliary motor mount board. The flat plywood piece extending aft from the bottom of the hull, which is called the planing board, serves the double purpose of keeping spray from reaching the motor and of adding increased planing area aft of the transom to keep the bow from tending to rise too high when starting. The rudder pedals can also be seen this side of the middle seat.

CHAPTER VII

THE TESTING OF WATER HAZARD III

Tests with hydrofoils.[7] Before the boat can be launched, nearly an hour of preparation is required. Adjustments must be made on the hydrofoil controls the engine must be installed and the throttle and steering cables must be connected. The controllable hydrofoils are initially adjusted to about four degrees positive angle of attack with respect to the keel although they need readjustment later when the boat is in the water.[8]

During the first run some difficulty was experienced keeping the bow down. The natural tendency of a hull is to point the bow high into the air during the transition from displacement to planing operation. For some reason, when the bow was in this nose-high attitude

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[7] Prior to these tests with hydrofoils attached one run was made to determine whether the boat had any important undesirable performance characteristics. None were discovered. The motor and hull seemed to be well matched, for little fuel was used, although the boat was fast and accelerated quickly.

[8] It must be remembered when considering the operation of a hydrofoil boat that all hydrofoils change pitch when the hull of the boat changes pitch. The boats tested on this project were so rigged that when the control stick was pulled back the increased lift resulting from the increased angle of attack of the front hydrofoil would result in a moment that would cause the bow of the boat to rise. As the bow of the boat rises the pitch of the boat and all the hydrofoils is increased and the resulting increased lift causes the boat to climb.

with the front hydrofoil near the surface the lift and drag moments about the pitch pin (see Figure 4) were not sufficient to reduce the pitch of the hydrofoil when the control stick was moved forward. Since the bow could not be dropped by conventional methods of control, a process of trial and error determined that it was necessary to perform the maneuver that would correspond to a sideslip in an airplane. This would drop the bow sharply, throwing a sheet of water to each side of the bow. In later runs the single cable to the front hydrofoil was replaced by a push rod and tension spring arrangement, making control of the front hydrofoil positive.

Takeoff procedure. The takeoff is a fairly simple maneuver once the operator has enough experience to realize when the hull has left the water. When the throttle is opened wide the control stick is moved so that the hull assumes a slightly nose-down attitude and is in a level attitude in roll. Next the control stick is eased back very, very slowly, causing a gradual increase in the lift generated by the front hydrofoil. Eventually a point is reached where the increased lift resulting from this backward movement of the control stick will have lifted the boat high enough in the water that a very noticeable acceleration can be felt. If the boat has

enough hydrofoil area the speed built up during this acceleration will equal takeoff speed and the boat wil lift off the water. During the first run there was no enough hydrofoil area available to enable the boat to

Figure 11. Steady state conditions without booster foils.

Figure 12. Jump takeoff without booster foils.

stay off. By jerking back on the control stick when the boat reached maximum speed, it was possible to lift the hydrofoils out of water momentarily. As shown in Figure 11 only the last two and a half feet of the keel remain in the water under steady state conditions without boosters.

Figure 13. Sharp turn without booster foils

Figure 13 shows a sharp turn such as is possible with this boat. The rear port hydrofoil can be seen protruding from the water. The boat is actually banked so far to the inside of the turn that it is necessary to use the elevator for rudder control and to turn the outboard by actuating the rudder controls to govern the height of the bow. The large amounts of spray produced when the hydrofoils approach the surface absorb so much of the boat's kinetic energy that, after a turn like

this, the operator has to perform the takeoff operation again.

So many changes were necessary after this first run with hydrofoils that it might be well to list them in the approximate order of their importance:

1. Fabricate booster foils to increase the lift so that the boat will be able to stay off the surface.
2. Replace the control cable going through the hollow front strut with a control rod and spring combination making elevator control positive.
3. Rearrange the control stick and move the operator's seat forward so that more load can be carried by the front hydrofoil.
4. Connect the speedometer to the pitot tube at the bottom of the front strut.
5. Put blocks around the seat cushion to keep the operator from sliding around during violent maneuvers.[9]
6. Rearrange the control pulleys at the rear struts so that sharper turns can be made.
7. Replace pitch pins with shorter ones having less

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[9] Since the boat was capable of performing violent maneuvers a safety belt for the operator was considered. It was finally decided that it would be a good idea not to use a safety belt since if the boat were to tip over there might be more danger from being unable to unfasten the belt than from being thrown out of the boat. With the seat cushion steadied by blocks and with the operator gripping the gunwale tightly with his throttle hand no further difficulty was experienced sliding around.

drag.

8. Minor changes in throttle and control systems.

Performance with boosters. With the modifications suggested by the first hydrofoil run, the boat was tried again, this time on a rough and windy day, to see what unsatisfactory conditions might be disclosed by this type of weather. It is estimated that the offshore wind was blowing from 25 to 40 MPH. With an offshore wind it was possible to obtain any desired conditions of surface roughness by going farther out from shore for more roughness.

The additional area of the booster foils made a very noticeable difference in the way the boat handled. For the first five minutes the boat seemed very light, especially the bow where the front booster kept breaking through the surface and throwing spray. Adjustments were made to the turnbuckles leading to the rear hydrofoils to remedy this condition. While these adjustments were being made the front booster was being twisted by the water forces into a shape which was the cause of a large amount of drag. This twisting action was unknown to the operator. The operator attributed the speed reduction resulting from this twisting action to his adjustments on the rear hydrofoil control turnbuckles, and nearly an hour was wasted attemp· to regain lost speed by readjusting them. The real cause of

the reduced speed was not discovered until the operator had a chance to talk with people witnessing the test from the shore, who were of the unanimous opinion that something was wrong at the front strut. Inspection disclosed the correctness of their opinions. The condition of th

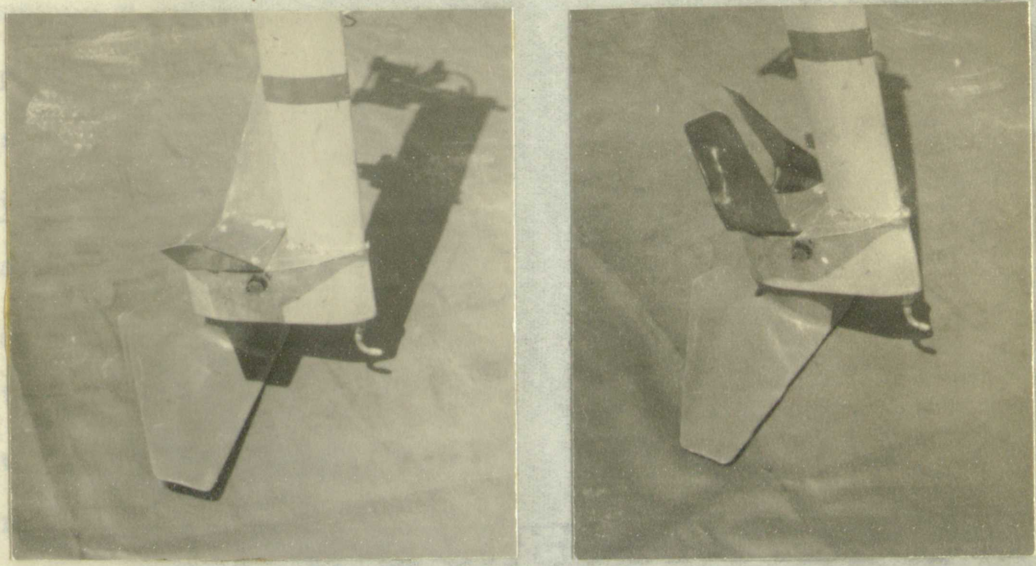

Figure 14. Original front booster foil, before and afte twisting by water forces.

front booster after being twisted is shown in Figure 14. In Figure 14 the small tube curving down and forward fro the bottom of the strut is the speedometer pitot tube. The bottom edge of the one inch wide band painted on the strut is six inches above the bird house (see Figure 14) roof. By having these bands painted on the struts accurate measurements can be made from photographs to determine how near the hydrofoils are to the surface.

Rough water performance. The change in performance with the misshapen front booster removed was almost unbelieveable. Tests were made for about an hour in high wind and rough water. The takeoff was performed in much the same manner as during the first day's tests except that with positive elevator control it was no longer necessary to sideslip to get the bow down. When the control stick was very, very, slowly eased back the boat would pick up speed and rise until eventually only the planing board was dragging on the water. Because of the bouncing action given to the boat as it skimmed over the wave tops the operator was unable to tell whether the boat had taken off because of reaching takeoff velocity or by being bounced and so he was

Figure 15. Rough water steady state conditions with boosters.

Fig 18

unable to get off and stay off. As the oerator became more experiemced in operating the boat takeofs from rough water became no more difficult than smooth watr takeoffs. Figure 15 shows that no spray is produced by th struts under certain conditions of operation.

Tests in moderately high winds an rough water were continued only long enough to determine hat there were no unsatisfactory conditions resulting from these factors. Figure 16 shows a jump takeoff being made Water can be seen dripping off the keel and also the rer starboard booster can be seen protruding from the waer. At the stern the keel is eleven inches out of water andat the bow it is sixteen inches out. The center of gravity s just ahead of

Figure 16. Rough water jump takeoff with rar boosters in place.

Fig 19

where the operator's left arm intersects with the side of of the boat.

As was expected the boat seemed to go faster downwind due to lessened air resistance. On the other hand there seemed to be more aerodynamic lift produced by the hull when headed up wind, which aided the boat in taking off. The overall effect of moderately high winds and rough water was negligible and deserves no further consideration.

Smooth water performance. Not until the hull was tested in smooth water was the operator really able to get the "feel" of the controls. Takeoff occurs about four seconds after the throttle is opened wide. The experienced operator can tell when the hull leaves the water because the ride becomes indescribeably smooth. Once the hull is off the water the operator pushes forward on the control stick to level the boat off so that it won't continue to climb until the foils pop out.

The maximum speed indicated by the speedometer when the hull was off the water was 21 MPH. An interesting phenomenon was noticed during these tests. If the boat was allowed to climb until the boosters popped out, after the foils dropped back into the water the speedometer reading would not exceed 15 MPH. The only way the boat could be made to go faster was to first cut the throttle and allow the hull to settle onto the water. Then when the throttle

was opened the boat would again be able to go 21 MPH. This speed reduction was probably caused by the drag produced by bubbles formed along the trailing edge of the hydrofoils when near the surface.

Performance in turns. During this series of tests on WATER HAZARD III attempts were made to determine any unsafe characteristics it might have by deliberately doing every conceivable maneuver which might cause it to capsize. On one day in particular the operator experimented with sharp turns of all kinds. It was determined, surprisingly enough, that the boat made the sharpest flying turns when the control stick was not moved so as to cause the boat to bank. Even with the control stick held fixed sideways there was no great tendency for the boat to roll outward. As time passed and the operator felt more at ease with the boat he began making turns in which the control stick was moved to cause the boat to bank outward about halfway through the turn. Once the boat started to roll it would sideslip down to the water surface and complete the turn by skidding around on its bottom. Figure 17 shows the boat about halfway through a turn and just the instant before the operator moved the control stick to cause the boat to bank outward. On the turn pictured the boat capsized about one second later. The reason it capsized is shown in Figure 17 where it was opened the boat would again be able to go 21 mph. This speed reduction was probably caused by the drag produced by bubbles formed along the trailing edge of the hydrofoils when near the surface.

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Figure 17. One second before capsizing.

Figure 18. Bottoms up.

Fig 20

Fig. 21

can be determined from the height of the bands painted on the rear struts that the boat has more than the usual amount of elevation. In addition to making a larger amount of potential energy available to tip the boat over, the additional elevation allowed the boat more time in which to roll further before hitting the water.

The boat flipped over so fast that an amount of air sufficient to float twice the weight of the boat was entrapped within the hull. No major damage was incurred by the boat as a result of this incident.

It must be emphasized that the boat capsized, not as a result of any uncontrollable instability characteristics inherent in its design, but as a direct result of deliberate attempts to determine if it was possible to tip the boat over. It is hard to conceive of a situation where such an occurence could be caused accidentally.

CHAPTER VIII

THE CONCLUSIONS

Power plant. An outboard motor is recommended as the most suitable power plant for a small hydrofoil boat of this type. Outboards are lightweight, dependable, and easily adapted to this application. It is possible to save much time in the construction of a completely new boat if an outboard is used instead of the more complicated air drive. If the outboard does not have an extra length drive shaft it is necessary to fasten the motor to an auxilary motor mount to lower the propeller axis to the recommended minimum depth of 18 inches below the static water line, or 12 inches below the keel.

Struts. No positive statement can be made at this time as to the optimum size and shape of the struts if speed, safety and strength are considered together. It is hoped that in the future more definite information can be obtained from further tests to make possible, calculations of the necessary size and shape with regard to strength. It is estimated that the struts used on these boats had an overall factor of safety of 10 to 15.

Hydrofoils. In making the cast aluminum controllable hydrofoils attempts were made to finish them to a definite

contour. Much more time was consumed in their fabrication than in the fabrication of the booster foils, which were hammered out of one-sixteenth inch steel sheet to no particular contour. Since the hammered foils require only about one percent of the time required to finish the cast one, they are recommended for use on experimental boats of this nature where it is often necessary to change the hydrofoils. If hydrofoil boats are ever placed in production zinc die castings would make very suitable hydrofoils and would require very little hand finishing.

Foil loading. With regard to foil loading there are some contradictory requirements. If high speed is desired, high foil loading is required, but high foil loading results in high takeoff speed just as with an airplane. Here, though, the hydrofoil boat has an advantage. The hydrofoils can be arranged ladder-like on the struts with the lower most strut the controllable one. The smaller hydrofoils would be lower on the strut. The boat would perform just like the ladder type illustrated in Figure 1 except that bottom hydrofoils would be controllable as in an airplane. Much area would be immersed before takeoff, but as the speed increases more hydrofoils can be lifted out, reducing drag and increasing lift. It is recommended that enough hydrofoil area be available to limit the takeoff foil

loading to not more than 150 pounds per square foot. At high speeds the NACA has tested hydrofoils with a foil loading of 2300 pounds per square foot.

Controls. It must be admitted that the operator of a this hydrofoil boat would have to concentrate more and wouldbe more susceptible to fatigue than an operator of other tpes of hydrofoil boats or surface boats. While that is true he would be better able to control the boat in conditions of unusually high winds and rough water because he would be able to exert positive control about two more axes than can be done on other types of boats.

Because of the similarity of the controls to thos of an airplane a person with previous flying experience can master the controls on this boat in 10 or 15 minutes. Seeral people with no previous piloting experience have bee able to operate the boat with reasonable success after short periods of instruction. The training process of thse several individuals has consisted of two to three minute briefings on the operation of the controls, and on what to do and what NOT to do; then they are sent out solo to "fel" out the controls. The greatest initial difficulty experienced by pilot and novice alike is not realizing that the bat has taken off.

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Because of the similarity of the controls to those of an airplane a person with previous flying experience can master the controls on this boat in 10 or 15 minutes. Several people with no previous piloting experience have been able to operate the boat with reasonable success after short periods of instruction. The training process of these several individuals has consisted of two to three minute briefings on the operation of the controls, and on what to do and what NOT to do; then they are sent out solo to feel out the controls. The greatest initial difficulty experienced by pilot and novice alike is not realizing that the boat has taken off.

did not reach the maximum speed that was hoped for, it is expected that with planned modifications it will eventually be able to go 30 MPH. The only noticeable instability is about the pitch axis and it is easy to control. The aileron and rudder controls have been held fixed for periods up to 20 seconds with no trouble developing.

Since this hydrofoil boat with airplane type controls is stable and easy to operate it is felt by the experimenter that further research is justified. Some of the possible paths along which this research could be directed are discussed in further detail in Chapter IX.

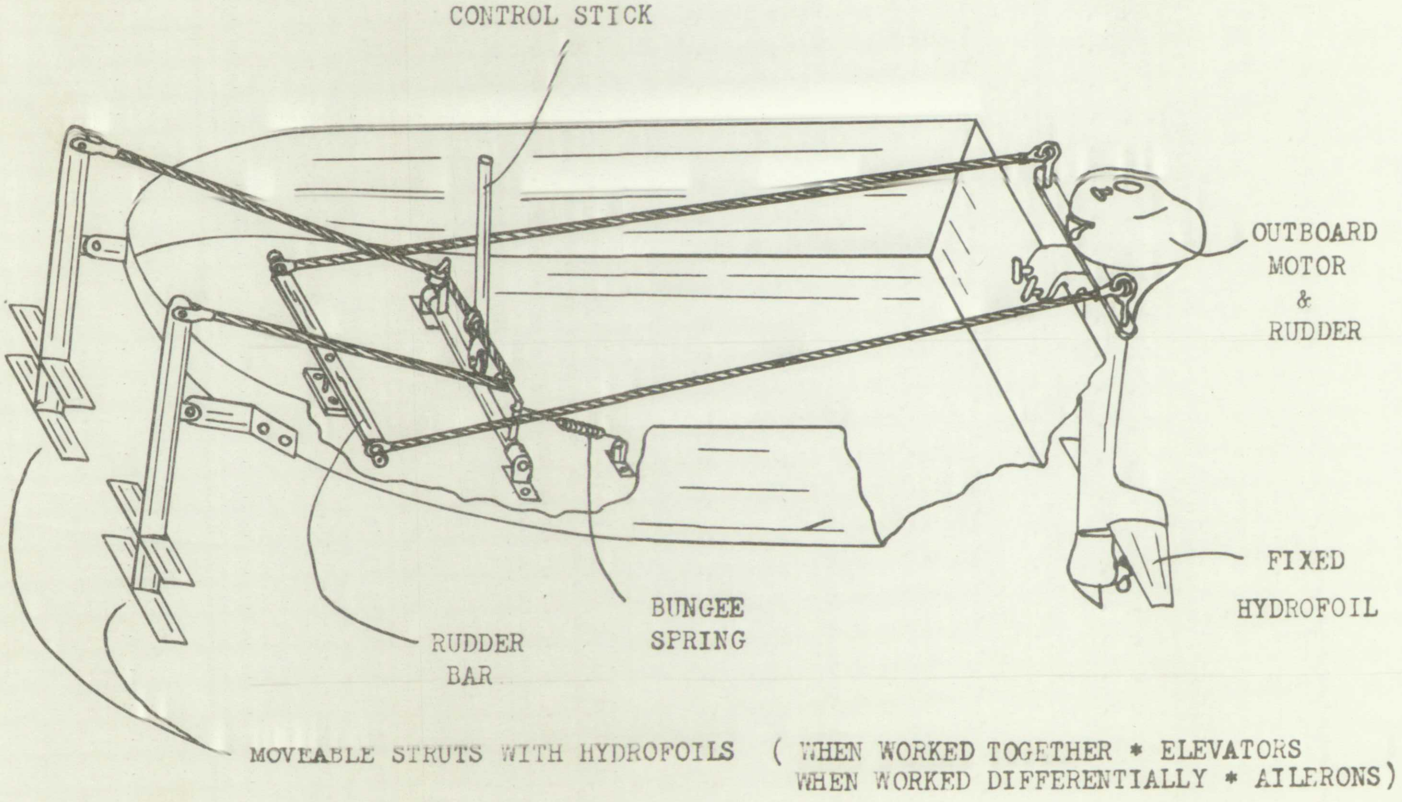
CHAPTER IX

FUTURE RESEARCH

Racing boat. Figure 19 shows the most likely fom form for the prototype of a new class of racing boats. It should be noted in particular that this boat has only two hydrofoil struts and that the outboard motor has fixed hydrofoils fastened to its lower unit and that it substitutes for the third strut. This should reduce drag about one quarter. It can also be seen that instead of having a hollow strut with a moveable hydrofoil at the bottom the entire front struts are tilted when the control stick is moved thus changing the pitch of all hydrofoils fastened to the struts. The controls are so arranged that when the operator moves the control stick in a fore and aft direction both struts will change pitch by the same amount. This gives elevator control. When the control stick is moved from side to side, however, the struts change pitch in an opposite sense producing aileron action. It is the belief of the experimenter that such a combination should be capable of a speed of 40 MPH when powered by an engine of the same size as the one used on WATER HAZARD III.

Pilot trainer. Airplane pilots have had little difficulty learning how to operate this type of boat because

Figure 19. Proposed racing hydrofoil boat.



of the similarity of its controls to those on an airplane. This would indicate that persons who had first received instruction in a boat of this kind would find it easier to learn airplane piloting. Certainly they could become oriented to the "feel" of the controls and the response of the controls in this boat as easily as in the more expensive airplane. A small outboard powered hydrofoil boat would cost no more than 25% of the operating cost of a small trainer airplane when depreciation, insurance and maintainance costs are considered. In times of National emergency when many pilots are trained this might make for important savings in petroleum resources and in airframe materials.

Because the boat seems to be inherently stable it is probable that most of the initial hours of training could be conducted with the student operating solo. If the student becomes confused he can cut the throttle and even let go of the controls and the boat will settle safely to the surface one or two feet below.

Of course the hydrofoil boat with airplane type controls does not simulate the maneuvers of an airplane exactly in all respects. With regard to maneuvers in which accelerations in a vertical direction are involved there is a similarity for only an instant until either the hydro-

foils pop out or the hull hits the water. This type of hydrofoil boat would come closer to duplicating an airplane's flight attitudes than would a Link trainer. Some diffi- might develop if the student were afraid of water.

PT boats. One of the reasons the NACA tested hydrofoils was in hope that they might be applied to high speed PT boats.[10] They tested 1/27th scale models of a hypothetical 75-foot PT boat having a displacement of 80 tons. The results of these tests on fixed hydrofoil models showed them to possess insufficient stability in roll and yaw. It seems likely that if a PT hydrofoil boat having airplane type controls were equipped with a modified version of an airplane auto-pilot it might be able to give satisfactory performance under typical PT operating conditions. It would certainly make a steadier platform for gunfire, or rocket and torpedo launching than do present day surface boats. In addition to the control gyros in the auto-pilot some sort of pitot tube arrangement at the bow of the boat would probably be necessary to detect an impending change in hydrofoil operating depth due to wave action.

Quite likely there are many additional applications to which a hydrofoil boat with airplane type controls could

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[10] James M. Benson and Douglas A. King, Preliminary Tests to Determine the Dynamic Stability Characteristics of Various Hydrofoil Systems, NACA WARTIME REPORT L-756 p. 2

be placed. Though the reason there has been little widespread acceptance of the hydrofoil is not known it is hoped that this boat may do much to remedy this condition.

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APPENDIX I

HYDROFOIL BOAT PERFORMANCE CALCULATIONS

The Performance Chart, Figure 20, simplifies the determination of velocities and horsepower requirements for hydrofoil boats of any size equipped with NACA 66, S-209 hydrofoils. It was decided at an early date to use an NACA 66, S-209 hydrofoil section since complete information was available on its characteristics in an NACA report.[11] Figure 20 was constructed on the basis of information given in this report.

In the figure the Velocity and the Lift coefficients are represented respectively by the X-axis and the Y-axis. The wing-loading or foil-loading is represented by the diagonal W/S lines sloping downward to the right. These three parameters were obtained directly from NACA tow tank tests and should be extremely reliable. However the other parameters indicated on the figure are derived from calculations or graphical plotting based on V, W/S, or C_L so their accuracy is subject to question. It was necessary to plot data concerned with Lift and Horsepower in terms of Lift and Horsepower per unit hydrofoil area

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[11] Norman S. Land, *Characteristics of an NACA 66, S-209 Section Hydrofoil at Various Depths*, NACA WARTIME REPORT, L-757

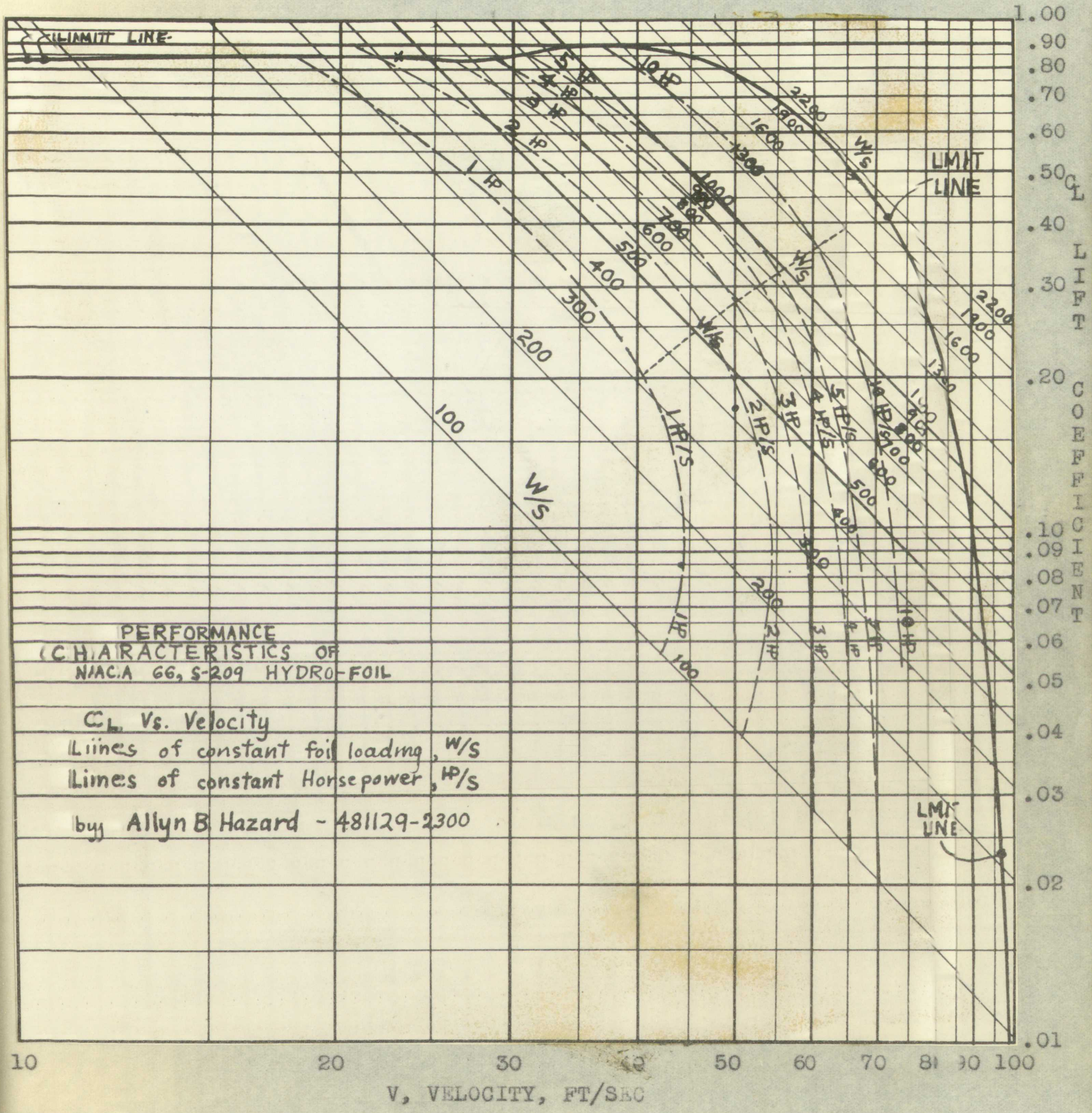

Figure 20. Performance characteristics of NACA 66, S-209 section hydrofoil.

in order to have a chart that would be valid for hydrofoils of any area. Of course it is necessary when calculating the total Lift or Horsepower to multiply the Lif and Horsepower data obtained from the chart by the tota hydrofoil area, S.

Example. An example problem would help to illustrate the use of this figure and give some indication of the other information that is available from the chart. The specifications given are for WATER HAZARD II.

Gross Weight	W	650 LBS
Total hydrofoil area	S	1.5 SQ FT
Foil loading	W/S	433 LBS/SQ FT
Horsepower (75% Propeller Efff.)	HP	17.2 HP
HP/S		11.5 HP/S

The takeoff speed is determined by finding the location of the line W/S equals 433 and then following this in an upper left direction until the limit line is reached. This intersection is indicated by an X. From this intersection go vertically and read a value of the Velocity from the horizontal scale. The velocity found, approximately 3 feet per second in this case, is the takeoff velocity.

In regard to the Limit Line the region to the lef of and below the Limit Line represents the most desirable conditions of operation for the NACA 66, S-209 hydrofoil section. When the angle of attack and C_L become large in order to have a chart that would be valid for hydrofoils of any area. Of course it is necessary when calculating the total lift or horsepower to multiply the lift and Horsepower data obtained from the chart by the total hydrofoil area, S.

Example. An example problem would help to illustrate the use of this figure and give some indication of the other information that is available from the chart. The specifications given are for WATER HAZARD II.

Gross Weight	W	650 lbs
Total hydrofoil area	S	4.3 sq ft
Foil loading	W/S	153 lbs/sq ft
Horsepower (75% Propeller Eff.)	H	15.2 H
HP/S		11.6 H/S

The takeoff speed is determined by finding the location of the line W/S equals 153 and then following this in an upper left direction until the limit line is reached. This intersection is indicated by an X. From this intersection go vertically and read a value of the velocity from the horizontal scale. The velocity found, approximately 23 feet per second in this case, is the takeoff velocity.

In regard to the limit line the region to the left of and below the limit line represents the most desirable conditions of operation for the NACA 65, S-209 hydrofoil section. When the angle of attack and C_L become larger enough or when the necessary high velocity is reached the hydrofoils will be operating in the region above or to the right of the Limit Line and cavitation will occur. The Limit Line then, represents the maximum values of the Lift Coefficient or Velocity that are practical of attainment without the expenditure of abnormal amounts of power.

Since cavitation is an important limiting factor in the performance of a hydrofoil boat it might be well to discuss cavitation further. It is well known that the pressure on an upper surface of an airfoil or wing section is negative with respect to the free-stream conditions in the fluid. The faster the wing travels through the water the greater is this negative pressure or the less is the absolute pressure. Now if the Lift Coefficient or Velocity of a hydrofoil becomes sufficiently great a point will be reached where the absolute pressure becomes less than the vapor pressure of the water and bubbles of water vapor and dissolved air will be formed. This condition is known as cavitation and it causes the undesirable conditions of increased drag and reduced lift. When the hydrofoils are operating in a region near where cavitation first occurs these bubbles will alternately form and collapse. So violently do these bubbles collapse that the upper surfaces will shortly present a

pocked appearance as the metal is worn away. Cavitation is less likely to occur upon hydrofoils operating deep in the water since the absolute pressure increases with depth.

Maximum speed. Unfortunately Figure 19 does not give any information as to how much horsepower will be required to overcome air resistance and strut drag, and this information is necessary before the maximum velocity can be determined. Strut drag and wind resistance could be determined from tests of scale models, but since the results of such tests are not available it is necessary to make assumptions. The struts built for WATER HAZARD II were thick and rough in comparison to the hydrofoils. It is probably not too far wrong to estimate that the hydrofoils required one sixth of the power available, that the struts required one third, and that the air resistance of the hull would absorb the balance. The value of HP/S to enter on the graph would be the share of available HP required by the hydrofoils, or one sixth of 11.5 HP_{avail}/S, 1.9 HP/S. The intersection of HP/S = 1.9 with W/S = 433 is indicated by a dot. The velocity corresponding to this dot is 50 ft/sec or 34 MPH which represents a pretty good, although probably high guess of the maximum velocity.

It is not possible to make accurate predictions of

the performance of a hydrofoil boat without benefit of tank tests on the struts and wind tunnel tests on the hull. It was not considered practical to make any attempt to predict the maneuverability of this type of boat, for there are too many variables to be considered, all of which must be given an assumed value. Besides, one of the functions of this project was to determine the extent of the maneuverability of this type of hydrofoil boat by actual tests on the prototype.

D.T.