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PRELIMINARY TESTS TO DETERMINE THE DYNAMIC STABILITY CHARACTERISTICS OF VARIOUS HYDROFOIL SYSTEMS FOR SEAPLANES AND SURFACE BOATS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESTRICTED BULLETIN

PRELIMINARY TESTS TO DETERMINE THE DYNAMIC STABILITY CHARACTERISTICS OF VARIOUS HYDROFOIL SYSTEMS FOR SEAPLANES AND SURFACE BOATS

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SUMMARY

Preliminary tests were made with dynamically similar models to survey the stability characteristics of several arrangements of hydrofoils that have been proposed for use on seaplanes and high-speed surface boats of the PT class. The results, although obtained under conditions in which cavitation did not occur, indicated that one of the most important effects involved is the erratic change in lift and drag that occurs as a hydrofoil approaches the free surface of the water. This effect is much more severe for a flat horizontal hydrofoil than for one having dihedral. The effect is also much more severe for monoplane hydrofoils than for multiplane hydrofoils.

A ladder-like arrangement of several hydrofoils, inclined at an angle of about 20° from the horizontal and arranged in a tripodal system on a self-propelled model, was found to be relatively free from the severe types of instability exhibited by the monoplane systems. An arrangement of two ladder-like systems in tandem (similar to an arrangement used by Guidoni) on a stream-line spindle, which represented the hull of a flying boat was found to be stable throughout a wide range of speeds. No dynamic instability was observed when this model was lifted out of the water to simulate a take-off.

INTRODUCTION

Numerous arrangements of hydrofoils have been proposed for use on seaplanes and high-speed surface boats. The ladder-like arrangements used by Guidoni for seaplanes (reference 1) and by Baldwin for surface boats (reference 2) have appeared to be satisfactorily stable but have presented the problem of avoiding excessive drag caused by the struts and by interference between strut and hydrofoil. Simpler arrangements of monoplane hydrofoils, which were intended to minimize the induced drag and the drag of the struts and junctures, have been proposed by Tietjens and others (reference 3). From the results of towing monoplane hydrofoils in NACA tank No. 1 (reference 4), it appeared that the stability of monoplane hydrofoil systems even with dihedral might be unsatisfactory because, as a hydrofoil approaches the free surface of the water, a sudden breakdown in flow over the upper surface of the hydrofoil will occur, which will result in a very large abrupt loss in lift.

The present investigation was carried out in the NACA tanks to survey briefly the stability characteristics of several arrangements of hydrofoils described in references 1, 2, and 3. A series of models, each representing a hypothetical surface boat of the PT class fitted with hydrofoils, was tested and the dynamic behavior of each arrangement was observed. One additional model, which had the form of a streamline spindle resembling the fuselage of an airplane, was fitted with hydrofoils and towed over a range of speeds to simulate a take-off.

The methods used included towing the model with restraint in roll by means of a towing staff and towing the model with no restraint in roll from a line. Some of the models of surface craft were also tested with self-propulsion and with remote control of the rudder.

The results of the tests indicate qualitatively the differences in stability of monoplane and multiplane hydrofoil systems. The effect of dihedral on the stability of hydrofoil systems was also investigated and observations were made of the severity of some types of instability that may be expected, particularly with monoplane systems.

MODELS

All the models tested were sufficiently light in weight to permit approximate dynamic similarity between the model and the full-size craft. The gross weight of each model was 8.3 pounds. With the exception of the Guidoni S.V.A.-type hydrofoils, which were mounted on a streamline spindle, all hydrofoils were mounted on a $\frac{1}{27}$-

full-size model of a hypothetical 75-foot PT boat having a displacement of 160,000 pounds. The hydrofoils and struts were either plano-convex or double-convex circular-arc sections. The configurations that were tested are illustrated in figures 1 and 2; the dimensions and other descriptive data are included in table I.

Towed Models

The hydrofoil arrangements tested on the towed models are as follows:

The arrangement of two flat hydrofoils in tandem (fig. 1(a)) consists of two flat hydrofoils of equal area mounted on the hypothetical PT boat previously described.

The arrangement of two V-hydrofoils in tandem (fig. 1(b)) consists of two hydrofoils of equal area, with dihedral angles of 20°, mounted on the same model of a PT boat.

The arrangement of two curved hydrofoils in tandem (fig. 1(c)) consists of two curved hydrofoils of equal area. The curvature of the hydrofoils is about the same as that of one of the arrangements proposed by Tietjens (reference 3), except that the outer portions of the hydrofoils are vertical instead of being curved inward to meet the sides of the hull.

The arrangement of a monoplane hydrofoil with tail plane, designated the Tietjens hydrofoil system herein, is similar to a system proposed and used by Tietjens in reference 3. Figure 1(d) shows the arrangement mounted on the model of the hypothetical PT boat.

The flat-hydrofoil ladder system (fig. 1(e)) comprises two sets of flat hydrofoils forward of the center of gravity and one set of V-shaped hydrofoils at the stern. The forward sets may be rotated about a longitudinal axis at the chine to vary the dihedral of the hydrofoils.

The arrangement of hydrofoils shown in figure 1(f) is similar to that used by Guidoni on the S.V.A. seaplane (reference 1). The hull is a $\frac{1}{18}$-full size model of the hull of a hypothetical flying boat of 50,000 pounds gross weight with a gross load coefficient $C_{\Delta_0} = 1.0$, where

C_{Δ_0} is defined as the gross weight divided by the product of the weight density of water and the cube of the maximum diameter of the hull. The form of the hull is the basic streamline body used previously for NACA models 74 and 75 (reference 5).

Self-Propelled Models

The hull used in the series of tests on self-propelled surface boats was the model of the hypothetical PT boat. The model, which was propelled by a $\frac{1}{5}$-horsepower electric motor driving a water propeller, could be steered by means of an electric control attached to the rear hydrofoil assembly. The model was free from the towing carriage and was under the control of an operator on the carriage.

The hydrofoil arrangements tested in this series were comprised of the forward hydrofoil sets of the following arrangements in conjunction with two rear hydrofoils of small area: Tietjens hydrofoil system, figure 2(a); 20° V-hydrofoil system, figure 2(b); 20° V-hydrofoil ladder system, figure 2(c); flat-hydrofoil ladder system with the dihedral angle kept constant at 20°, figure 2(d).

TEST PROCEDURE

Several of the hydrofoil systems were towed by using a staff that restrained the model in roll and yaw but allowed the model to rise and to pitch freely about the center of gravity. In each case the towing staff was attached at the center of gravity. The angles of incidence of the hydrofoils and the position of the center of gravity were varied. For different combinations of the variables, the dynamic behavior of the model was observed at a series of constant speeds.

The model of the Tietjens hydrofoil system (fig. 1(d)) was towed from a line. The towing point, the location of the center of gravity, the angles of incidence of the forward and rear hydrofoils, and the gross weight of the model were varied. For different combinations of the variables, the dynamic behavior of the model was observed at a series of constant speeds.

The combination of longitudinal, lateral, and directional stability was observed by testing various hydrofoil arrangements as free self-propelled bodies. The dynamic behavior was observed for various settings of angle of incidence of the forward and rear hydrofoils, both at a series of constant speeds and at speeds in which the model was accelerated from rest to top speed.

RESULTS OF TESTS WITH TOWED MODELS

Tests with Restraint in Roll and Yaw

Flat-hydrofoil tandem system.- In the tests of the towed models restrained in roll and yaw, the system of two hydrofoils in tandem lifted the hull out of the water at about 13 feet per second (40 knots, full size). The boat when undisturbed rode steadily on the hydrofoils at speeds up to about 17 feet per second (52 knots, full size) but porpoised when disturbed. The amplitude of porpoising increased during successive cycles until the bottom of the hull hit the water, then the model appeared to run momentarily as a displacement boat. The hydrofoils then lifted the hull out of the water again and the process was repeated with sufficient violence to swamp the model. Moving the center of gravity forward 2 inches from the position indicated in figure 1(a) did not affect the stability characteristics appreciably.

20° V-hydrofoil tandem system.- The 20° V-hydrofoil tandem system was stable at most speeds although a porpoising motion occurred at a speed of 19 feet per second (58 knots, full size). At this speed the intersection of the hydrofoil and the outboard struts was about at the water level. The amplitude of porpoising was about 1° in trim and about $\frac{1}{2}$-inch in rise.

Curved-hydrofoil tandem system.- In the tests of the curved-hydrofoil tandem system, a porpoising motion occurred at speeds in the region of 10 to 14 feet per second (31 to 43 knots, full size). The porpoising seemed to be caused by periodic ventilation of the hydrofoils.

Flat-hydrofoil ladder system.- The flat-hydrofoil ladder system was stable under a wide range of conditions except for some tendency to oscillate when the model was free in both rise and trim. The magnitude of the oscillations was of the same order as the vertical spacing of the hydrofoils. The oscillatory movement was less marked with the larger angles of dihedral. When the model was locked in trim, the oscillation became more violent and could probably be described as a "jumping" oscillation.

Guidoni S.V.A.-type hydrofoils on streamline spindle.- The arrangement of figure 1(f), when towed free to rise and trim but restrained in roll and yaw, was stable at all speeds from rest up to 30 feet per second, a speed that is a scale value typical of the take-off speed of seaplanes in current use. When the model was lifted out of the water to simulate a take-off, no dynamic instability was evident. There may have been some tendency to oscillate in rise and trim but the motions were not sufficiently violent to be observed in the qualitative type of tests that were made.

Tow-Line Tests of Tietjens Hydrofoil System

The Tietjens hydrofoil system was tested by towing the model from a line attached at various points on the model. When the tow line was attached to the bow at the level of the deck, the boat rolled and yawed at low speeds. At speeds greater than about 10 feet per second (31 knots, full size), porpoising occurred. When the tow line was attached to the bow at about the static water line, the rolling was eliminated at low speeds but rolling and porpoising occurred at high speeds. When the tow line was attached to the central strut of the forward hydrofoil, the model rolled and yawed considerably at low speeds. At high speeds the hydrofoils supported the hull above the water and a combined rolling and porpoising motion occurred. When the area of the rear hydrofoil set was reduced by one-half, the stability was improved and the model towed stably at speeds from 13 to 17 feet per second (40 to 52 knots, full size) at which the tips of the rear hydrofoil were nearly at the water surface. At speeds greater than 17 feet per second, the forward hydrofoil approached the water surface too closely and vertical instability developed because of periodic ventilation and breakdown of the flow over the upper surface.

RESULTS OF TESTS WITH SELF-PROPELLED MODELS

Tietjens hydrofoil system.- When the self-propelled model with the Tietjens hydrofoil system was run at speeds sufficiently great to raise the hull out of the water, a combined rolling and porpoising motion occurred. The rolling component of this motion was usually dynamically unstable. Increasing the gross weight and moving the center of gravity did not appreciably affect the stability characteristics. A forward hydrofoil with the area increased by one-third and with a 10-percent-thick lenticular section of 1.33-inch chord was installed and tested with no apparent improvement in stability. The extent to which the relatively large area of the fairing around the propeller shaft contributed to this instability is not known.

20° V-hydrofoil system.- The self-propelled arrangement equipped with a 20° V-hydrofoil system (fig. 2(b)) near the center of gravity rode stably on the hydrofoils until the intersection of the outboard struts and the hydrofoil rose to the water surface, when a rolling and yawing motion occurred. No porpoising was evident.

20° V-hydrofoil ladder system.- The V-hydrofoil ladder arrangement on the self-propelled model was more stable than the two preceding arrangements. No porpoising or severe rolling occurred. When the rudder was moved, the model responded and rolled noticeably to the outside of the turn.

Flat-hydrofoil ladder system.- The flat-hydrofoil ladder system was tested with a dihedral angle of 20°. No porpoising or rolling occurred and the model appeared to be stable. Some tendency was noted for the model to oscillate in roll and pitch as the flow over the uppermost hydrofoils changed intermittently. At the beginning of a turn, the model rolled very slightly toward the outside.

DISCUSSION

General Results

Instability in both roll and yaw.- The most violent form of instability that was observed in any of the tests was one that involved simultaneously yaw, roll, trim, and rise. This instability appeared to be the result mainly of an instability in rise, which occurred whenever a hydrofoil approached the free surface of the water sufficiently close for the flow to separate abruptly from the upper surface of the hydrofoil. In general, the breakdown of the flow would be unsymmetrical and would result in yawing and rolling moments. This resulting instability was much more severe with the monoplane systems than with the multiplane systems, probably because the fraction of the total area of the hydrofoils affected by the change in flow was greater for the monoplane systems than for the multiplane systems.

Spray.- All the hydrofoil systems threw considerable spray from the points at which either a strut or a hydrofoil intersected the water surface. Especially strong jets of spray issued from beneath hydrofoils of the multiplane systems whenever a juncture of hydrofoil and strut emerged from the water. With the monoplane systems, spray was thrown from the central struts onto the hull. With the multiplane systems, some spray hit the hull but most of it was thrown clear. In general, the spray had very small lateral velocities.

Monoplane Systems

The system of flat hydrofoils in tandem was longitudinally unstable after a disturbance; whereas both the 20° V-hydrofoil tandem system and the curved-hydrofoil tandem system appeared to be stable under similar conditions.

As a flat hydrofoil approaches the free surface of the water, there is a definite and gradual loss of lift that may continue smoothly until a point is reached where the flow suddenly breaks down and infiltrating air covers a part or all of the upper surface (reference 4). This gradual loss of lift as a hydrofoil approaches the water surface is evidently not enough of a stabilizing factor to insure longitudinal stability. A hydrofoil with dihedral and operating with the tips out of the water has a change in lift accompanying a change in immersed area. This condition makes the V-hydrofoil and curved-hydrofoil tandem systems more stable than the flat monoplane system. The dynamic behavior of the systems having the area of the forward hydrofoil set equal to that of the rear set was not greatly different from that of systems having unequal areas, provided that the center of gravity was located suitably in each case.

Multiplane Systems

The oscillation in rise and trim noted in the tests of the multiplane systems appeared to result from a periodic breakdown and recovery of the flow over the upper surface of the part of the hydrofoil system that was near the free surface of the water. The oscillatory movement was less marked with the larger angles of dihedral.

The tests of the self-propelled multiplane systems indicated that a pair of ladder-like systems near the center of gravity provided much better lateral stability than did the monoplane hydrofoil systems. Of the two ladder-like systems, the flat-hydrofoil system with a dihedral of 20° appeared to have less tendency to oscillate in roll and appeared to roll less to the outside of a turn than did the 20° V-hydrofoil system.

CONCLUSIONS

The results of the tests of several widely different arrangements of hydrofoils indicate some of the important types of instability that must be considered in applications of hydrofoils to seaplanes or to surface craft. The following conclusions, drawn from these tests, apply only to configurations without horizontal control surfaces operating under water:

1. Multiplane hydrofoil systems in general offer wider margins of stability than do monoplane systems.

2. Dihedral contributes greatly to the stability of hydrofoil systems, principally because a hydrofoil with dihedral will have much less severe discontinuities in lift and drag as it approaches and breaks through the water surface than will a flat hydrofoil.

These conclusions are to be considered tentative until further tests can be carried out to include quantitative investigations under conditions more nearly approximating conditions for full-size models, in which cavitation is probably a very important consideration.

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TABLE I

DIMENSIONS AND DATA OF HYDROFOIL SYSTEMS

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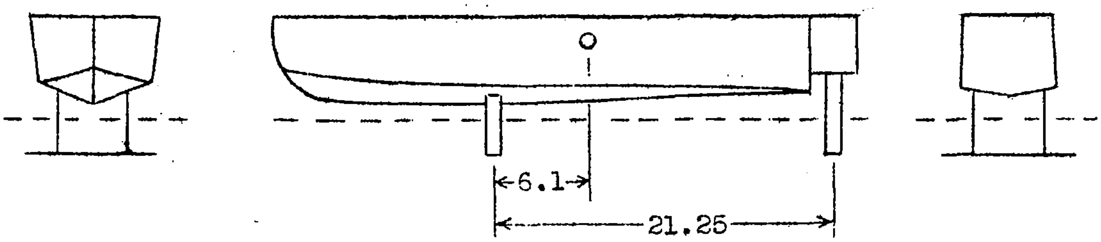
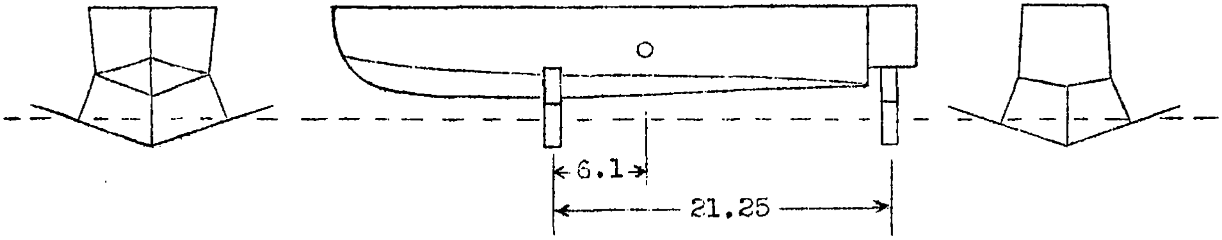
System	Hydrofoil set		Chord (in.)	Area (sq in.)	Maximum thickness (percent chord)	Incidence of hydrofoil to lowest hydrofoil (deg)	Incidence of lowermost hydrofoil to base line (deg)
Towed Models							
Flat hydrofoil tandem system	Front		1.50	13.50	6.67	0	0,3,5,6
	Rear		1.50	13.50	6.67	0	-3,0
20° V-hydrofoil tandem system	Front		1.00	16.00	6.67	0	5
	Rear		1.00	16.00	6.67	0	2
Curved-hydrofoil tandem system	Front		1.00	12.00	6.67	0	0,3,5
	Rear		1.00	12.00	6.67	0	0,2
Tietjens hydrofoil system	Front		1.00	12.00	6.67	0	0,1,2
	Rear		1.00	6.00	6.67	0	-2,-1,0,1,2
[a]Flat-hydrofoil ladder system	Front	Uppermost	.60	3.04	6.67	6	0
		2nd	.60	3.04	6.67	3	
		3rd	.60	3.04	6.67	0	
		4th	.60	3.04	6.67	0	
		Lowermost	.60	3.04	6.67	0	
		Total		15.20			
	Rear	Uppermost	.60	1.52	6.67	6	-4,-2,0
		2nd	.60	1.52	6.67	3	
		3rd	.60	1.52	6.67	0	
		Lowermost	.60	1.52	6.67	0	
		Total		6.08			
Guidoni S.V.A.-type hydrofoils on streamline spindle	Front	Uppermost	.69	2.86	5	0	0,5
		2nd	.69	2.86	5	0	
		Lowermost	.55	.41	8	0	
		Total		6.13			
	Rear	Uppermost	.98	5.74	5	0	0,1
		2nd	.98	5.74	5	0	
		Lowermost	.98	.78	8	0	
		Total		12.26			
Self-Propelled Models							
Tietjens hydrofoil system	Front		1.00	12.00	6.67	0	0,2
	Rear		1.00	6.00	6.67	0	-2,0,2
20° V-hydrofoil system	Front		1.00	16.00	6.67	0	2
	Rear		1.00	6.00	6.67	0	-2,0,2
20° V-hydrofoil ladder system	Front	Uppermost	.60	3.04	6.67	6	5
		2nd	.60	3.04	6.67	3	
		3rd	.60	3.04	6.67	0	
		4th	.60	3.04	6.67	0	
		Lowermost	.60	3.04	6.67	0	
		Total		15.20			
	Rear		1.00	6.00	6.67	0	-1,0,1
[a]Flat-hydrofoil ladder system	Front	Uppermost	.60	3.04	6.67	6	0,5
		2nd	.60	3.04	6.67	3	
		3rd	.60	3.04	6.67	0	
		4th	.60	3.04	6.67	0	
		Lowermost	.60	3.04	6.67	0	
		Total		15.20			
	Rear		1.00	6.00	6.67	0	0,1,2

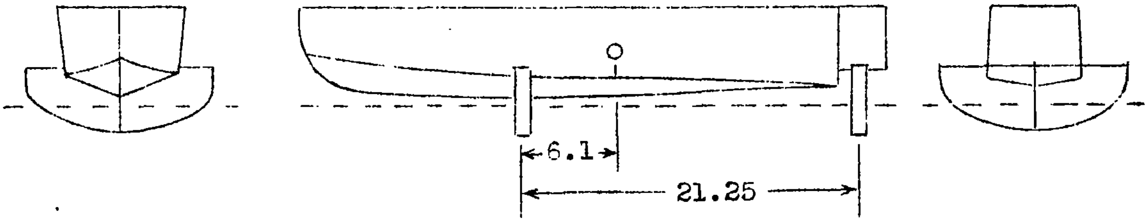
[a] Areas are given for the projected area with an angle of dihedral of 20°.



(a) Flat-hydrofoil tandem system.

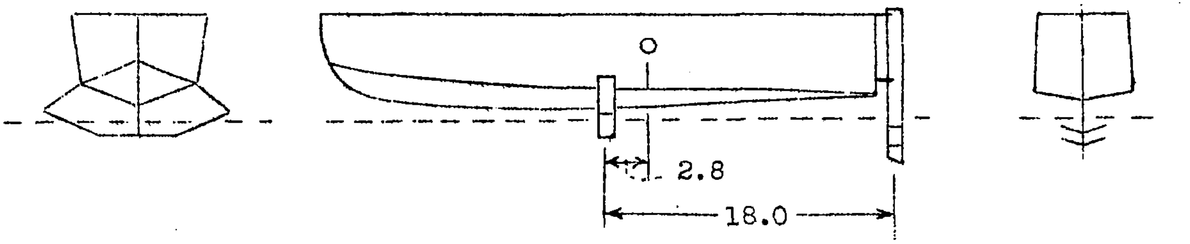


(b) 20° V-hydrofoil tandem system.

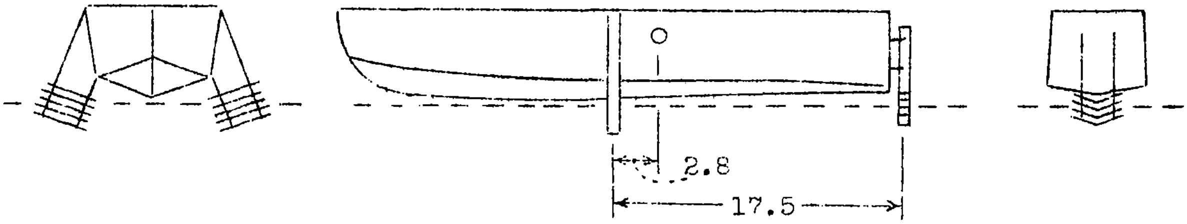


(c) Curved-hydrofoil tandem system.

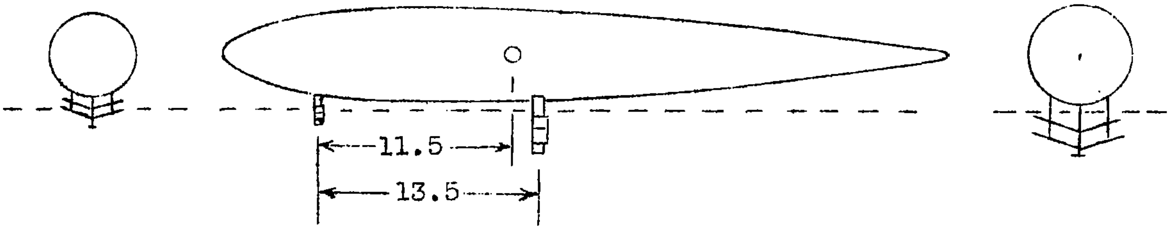
Figure 1.- Hydrofoil systems tested on towed model in the NACA tanks.



(d) Tietjens hydrofoil system.



(e) Flat-hydrofoil ladder system.



(f) Guidoni S.V.A.-type hydrofoils on streamline spindle.

Scale

1 foot

– – – – – – – High-speed water line

Figure 1.- Concluded.

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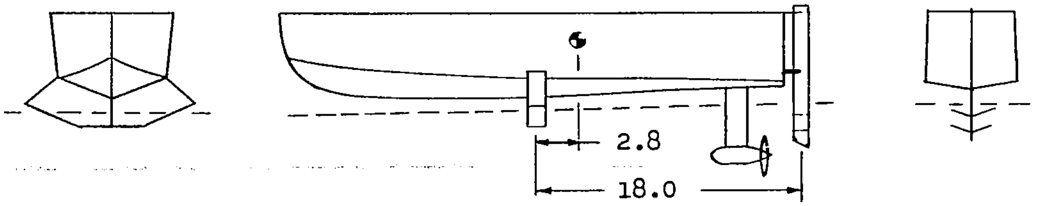
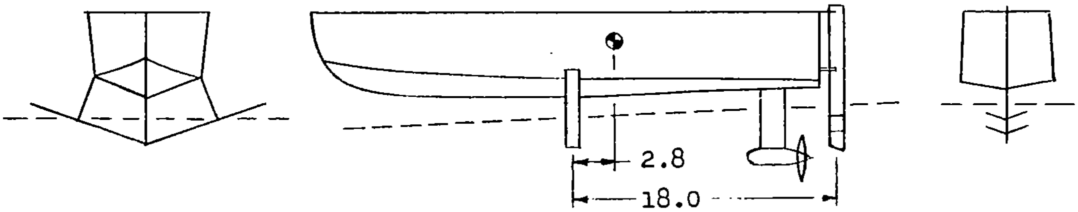
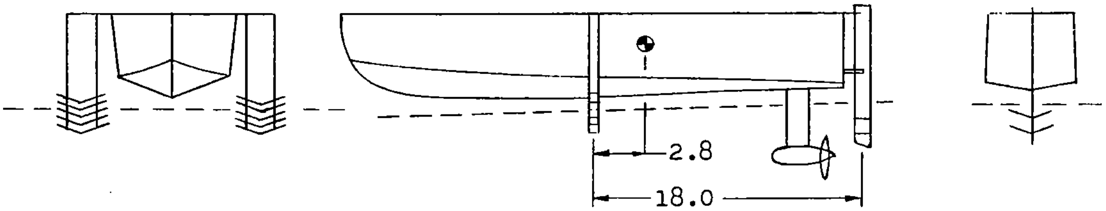


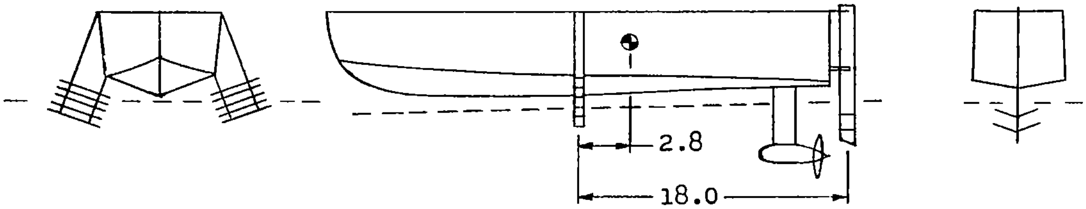
(a) Tietjens hydrofoil system.



(b) 20° V-hydrofoil system.



(c) 20° V-hydrofoil ladder system.



(d) Flat-hydrofoil ladder system.

Scale 1 foot — — — — — — High-speed water line

Figure 2.- Hydrofoil systems tested on self-propelled model in the NACA tank.