NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 470

THE N.A.C.A. TANK
A HIGH-SPEED TOWING BASIN FOR TESTING MODELS OF SEAPLANE FLOATS

By STARR TRUSCOTT

1933

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AERONAUTICAL SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Symbol	Unit	Symbol
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	kg/m/s		horsepower	hp.
Speed		km/h	k.p.h.	mi./hr.	m.p.h.
		m/s	m.p.s.	ft./sec.	f.p.s.

2. GENERAL SYMBOLS, ETC.

W, Weight $=mg$

g, Standard acceleration of gravity $=9.80665$ m/s$^2=32.1740$ ft./sec.^{2}

m, Mass $=\frac{W}{g}$

ρ, Density (mass per unit volume).

Standard density of dry air, 0.12497 (kg-m^{-4} s^2) at 15° C. and 760 mm $=0.002378$ (lb.-ft.$^{-4}$ sec.^{2}).

Specific weight of "standard" air, 1.2255 kg/m$^3=0.07651$ lb./ft.^{3}.

mk^2, Moment of inertia (indicate axis of the radius of gyration k, by proper subscript).

S, Area.

S_w, Wing area, etc.

G, Gap.

b, Span.

c, Chord.

$\frac{b^2}{S}$, Aspect ratio.

μ, Coefficient of viscosity.

3. AERODYNAMICAL SYMBOLS

V, True air speed

q, Dynamic (or impact) pressure $=\frac{1}{2}\rho V^2$.

L, Lift, absolute coefficient $C_L=\frac{L}{qS}$

D, Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o}=\frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

R, Resultant force.

i_w, Angle of setting of wings (relative to thrust line).

i_t, Angle of stabilizer setting (relative to thrust line).

Q, Resultant moment.

Ω, Resultant angular velocity.

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension.

e. g., for a model airfoil 3 in. chord, 100 mi./hr. normal pressure, at 15° C., the corresponding number is 234,000;

or for a model of 10 cm chord 40 m/s, the corresponding number is 274,000.

C_p, Center of pressure coefficient (ratio of distance of c. p. from leading edge to chord length).

α, Angle of attack.

ϵ, Angle of downwash.

α_o, Angle of attack, infinite aspect ratio.

α_i, Angle of attack, induced.

α_o, Angle of attack, absolute. (Measured from zero lift position.)

γ Flight path angle.

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Langley Memorial Aeronautical Laboratory

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

NAVY BUILDING, WASHINGTON, D.C.

(An independent Government establishment, created by act of Congress approved March 3, 1915, for the supervision and direction of the scientific study of the problems of flight. Its membership was increased to 15 by act approved March 2, 1929 (Public, No. 908, 70th Congress). It consists of members who are appointed by the President, all of whom serve as such without compensation.)

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SUMMARY

This report describes the high-speed model towing basin of the National Advisory Committee for Aeronautics, usually referred to as the N.A.C.A. tank. The purpose of this piece of equipment is to enable the Committee to provide information and data regarding the performance of seaplanes on the water analogous to the information furnished concerning the performance of airplanes in the air.

The tank and its equipment, together with the method of operation, are described, and the type of work done in it is illustrated by data from two typical tests. The one was to determine the effect on the take-off performance of a model of the hull of a flying boat of fitting the step with "hooks" of three different heights, and the second to determine the effect on the take-off performance of the same model of fitting the bottom just forward of the main step successively with two and three flutes of two different depths. In each case the performance with the alterations is compared with the performance of the model with a plain bottom. The distinctive discontinuities found in the speed-resistance curves at hump speed are a notable feature of the results of these tests.

INTRODUCTION

HISTORICAL—GENERAL CONSIDERATIONS

A survey of the information available regarding the application of the results of tests of models in towing basins to the design of floats for seaplanes was made by the National Advisory Committee for Aeronautics in 1929. It was found that the development of flying boats and seaplanes had been assisted very much in the United States, and possibly more in other countries, by tests of models in towing basins or tanks (references 1 and 2). Some tanks already existed which were designed especially for testing models of seaplane floats and the construction of other tanks for this special purpose was projected (references 3 and 4). There was no such tank in the United States; in fact, there were only two tanks, both constructed before the appearance of the seaplane and designed originally to test models of ships. The construction in the United States of a special towing basin that could be devoted to tests of models of seaplane floats and hulls might reasonably be expected to be of great assistance in the further development of this type of aircraft, the importance of which appeared to be increasing.

In considering the construction of such a piece of equipment it was necessary to evaluate many features, and in the case of the N.A.C.A. tank the decisions arrived at led to the incorporation of certain novel features which appeared to be more suitable for their respective purposes than the constructions used in other tanks. The reasons for these decisions are of general interest and discussions of them will be found later in the report.

CHARACTERISTICS OF SEAPLANE FLOATS

The desirable characteristics of the float supporting a seaplane are many, but among them may safely be included the following:

1. Low resistance to propulsion on the water.
2. Freedom from tendencies to trim or pitch violently while being propelled on the water.
3. Freedom from excessive moments, about the center of gravity of the whole craft, of the hydrodynamic forces arising from propulsion on the water.
4. Freedom from excessive spray or from throwing solid water upward or outward to excessive distances while being propelled on the water.
5. As great stability as is compatible with other properties.
6. Low drag in the air.

The combination of these characteristics, with others which have not been mentioned, in a single form presents a problem which has been solved in widely different ways by different designers. The forms adopted have changed as experience dictated and with the demands of the respective users until they have taken the distinctive shapes now associated with certain designers, and even with certain nations. This process has been influenced also by the results of tests made in model towing basins to determine the hydrodynamic properties of models of the various forms proposed or adopted.

TESTS OF MODELS IN MODEL BASINS

When the development of the seaplane began, model towing basins had been in regular use for about forty years for the purpose of obtaining information as to the performance of surface vessels of all types, and it was only natural to turn to the towing basins for assistance in designing seaplane floats. Although much valuable information was obtained from the ship-model towing basins, it was soon perceived that tests of models of seaplane floats in such model basins suffered from serious disadvantages because of the relatively low speeds of the towing carriages (reference 1). These disadvantages become apparent from a consideration of the method of applying the results from such tests, which generally is as follows:

The total resistance of the model, and of the ship, is assumed to be made up of two parts: frictional or viscous resistance, and wave-making resistance. The former is computed for the model by the use of generally accepted formulas and coefficients, and is deducted from the total measured resistance. The remainder, the wave-making resistance, is assumed to follow that particular one of the Laws of Mechanical Similitude, usually called Froude's Law, which may be expressed as follows: If V and v are corresponding speeds of ship and model, of lengths L and l, respectively, and R_w and r_w are the respective wave-making resistances at those speeds, then at the corresponding speeds of ship and model

$$\frac{V}{\sqrt{L}}=\frac{v}{\sqrt{l}}$$

and

$$\frac{R_w}{r_w}=\left(\frac{L}{l}\right)^3$$

or

$$R_w=r_w\left(\frac{L}{l}\right)^3$$

The total resistance of the ship is then obtained for each corresponding speed by adding to the wave-making resistance determined from the tests of the model the frictional resistance computed anew from the dimensions of the ship and its speed.

SIZES OF MODEL AND EFFECTS OF SCALE

The expression for corresponding speeds shows that no matter how large the tank may be the maximum size of the model that can be towed at the speed corresponding to a given speed of the full-size craft is fixed by the maximum speed of the towing carriage. If the get-away speed V of a full-size seaplane is 60 miles per hour, the full-size length L 64 feet, and the maximum speed of the towing carriage v 15 miles per hour, then

$$\frac{60}{\sqrt{64}}=\frac{15}{\sqrt{l}}$$

and the length of the longest model of the seaplane that can be towed at a speed corresponding to get-away speed will be 4 feet. As the get-away speed of the craft increases for a given length of hull, or as the length of the hull decreases for a given get-away speed, the length of the model that may be towed to get-away speed decreases.

It must also be remembered that, in contrast with the smooth fair form found in a ship, the form of the hull of a seaplane or flying boat includes definite discontinuities, as the chines and steps. At high speeds, irregularities and inaccuracies in a model may be expected to produce serious disturbances in the results of tests. If the models of the hulls of seaplanes must be made to very small scale, the accuracy of the models to dimensions must be most carefully maintained, otherwise doubt may be thrown on the conclusions.

Difficulties of even more serious character appear with the demonstration that there is a scale effect on the resistance and other quantities measured that increases as the size of the model is reduced (references 5 and 6), and that the difference between the waves and spray produced by a model and those of the full size at the corresponding speed increases as the size of the model decreases (reference 6). As it has been the general practice to consider the observed resistance of models of seaplane floats as all wave-making resistance, and to obtain the resistance of the full-size craft by converting the whole according to Froude's method, these scale effects may explain some of the observed discrepancies.

ADVANTAGES OF A LARGE TANK

In view of the disadvantages found in the use of small models at low speeds, a new tank, to be of the greatest service, should be equipped to tow large models at high speeds so that the similarity of phenomena between full size and model might be greater, the accuracy of construction of the models need not be so great, and the conclusions drawn should therefore be more trustworthy. The nearer the approach to full-scale size and speed the more accurate and satisfactory would be the conclusions drawn from the tests. However, it had to be remembered that excessively large models meant a correspondingly large tank and high speed of the towing carriage. The cost of such equipment would be more than correspondingly high.

The circumstances just outlined were given careful consideration by the National Advisory Committee for Aeronautics, and it was decided to construct a tank which should represent an attempt to balance the various factors involved against one another.

The construction of the tank was approved in 1929, and plans and specifications were prepared by the Committee in that year. Construction began in 1930 and was completed in 1931. The new tank was officially dedicated at the time of the Sixth Annual Aircraft Engineering Conference, May 27, 1931, by Dr. D. W. Taylor, Vice Chairman of the Committee, who supervised the construction of the first modern experimental model basin in this country, at the Washington Navy Yard, and whose work in that basin is known the world over.

DESCRIPTION

Type.—The N.A.C.A. tank is of the Froude type; that is, the model which is being tested is towed through still water at successive constant speeds from a carriage spanning the tank. At each constant speed the towing pull is measured, the trim and the rise, or change of draft, are recorded and, if the model is being towed at a fixed trim, the moment required to hold it there is measured and recorded.

Location.—The N.A.C.A. tank is located at Langley Field, Va., and extends about north and south along the west bank of the Southwest Branch of Back River, the distance from the shore varying from about 75 to 150 feet. (See fig. 1.)

Dimensions.—The reinforced concrete basin containing the water has the following dimensions:

	Feet
(1) Length on water, extreme	2, 020
(2) Normal width of water surface	24
(3) Normal depth of water	12
(4) Length of 12-foot depth	1, 980

The sides of the tank are coved in above the water line in order to bring the rails closer together and thus reduce the width of the car, and also to assist in suppressing the waves which are produced by the models. The appearance of the empty tank is shown in figure 2.

The salt water with which the tank is filled is supplied from Back River by a centrifugal pump driven by an electric motor. The tank contains approximately 4,000,000 gallons of water which can be pumped in or out in about 40 hours.

At the south end of the basin there is an annex containing the shop and offices, together with the pumping plant and the electrical equipment, including motor generator set, switchboards, etc., for the supply of current to the carriage.

Shelter.—The whole tank is covered by a shelter intended more to protect the surface of the water from the effect of wind and weather than to maintain a temperature within the building. This shelter consists of a simple building 2,060 feet long and 28 feet wide having a steel frame of ordinary construction covered with corrugated sheets of an asbestos-cement composition. The trusses and columns supporting the roof are spaced at 20-foot centers, and a small window is placed in the middle of each 20-foot bay on each side and as high up as is feasible. These windows are glazed with light-diffusing glass to reduce the amount of direct sunlight falling on the water of the tank. The general arrangement of the tank may be seen in figure 3.

Rails.—The rails on which the towing carriage runs are heavy H-beams set with the web vertical. They are supported on cross ties, or chairs, made of short lengths of steel tie section. The rails are laid in 60-foot lengths with staggered joints. The joints are not welded or scarfed, but are simply butted with sufficient clearance to permit the ends to come together at a temperature of about 80° F.

The rails are leveled to the same height above the water surface and the east rail is alined with extreme care. Leveling of the top surfaces of the rails is done by measuring from the surface of the water in the tank while it is perfectly still, using an electrical contact point on the extended spindle of a micrometer head. In this manner the rails are made to follow the curvature of the earth taken by the surface of the water. Careful checking of the measurements indicates that the rails are within ± 0.015 inch of parallel to the water surface. The alinement of the east rail is done by means of a special transit and reference points placed in the concrete of the tank. This rail is used to hold the car on the rails and in a straight line by means of guide wheels which bear on both sides of the web. There are no guide wheels on the west rail.

Towing carriage.—The structure of the towing carriage is of carbon-steel tube, with all joints welded. In order to insure accuracy of alinement in the girders forming the car structure, the ends of all the tubes meeting at a joint were milled to fit snugly before welding and all welding was done with the structure in a massive jig. The gear cases also are of welded construction.

The structure of the car may be divided into a center-line girder, two side girders, and two transverse girders. The center-line girder is of sufficient depth to carry the dynamometer and to permit persons to stand within it. The other girders are shallower and are proportioned solely by the strength requirements and the necessity for securing other parts of the carriage, such as the electric motors and the reduction gears between the motors and the wheels. A general view of the towing carriage is shown in figure 4.

Wheels and tires.—The carriage runs on four wheels fitted with pneumatic tires. These wheels are mounted on stub axles, and are not connected by cross axles. They are each driven by an independent electric motor through a single-reduction herringbone pinion and gear. The pneumatic tires are high-speed bus or truck tires, with smooth treads. The guide wheels which hold the carriage in alinement on the east rail have grooved solid rubber tires of a medium soft composition. It is planned to try small pneumatic tires later, although the present tires are very satisfactory.

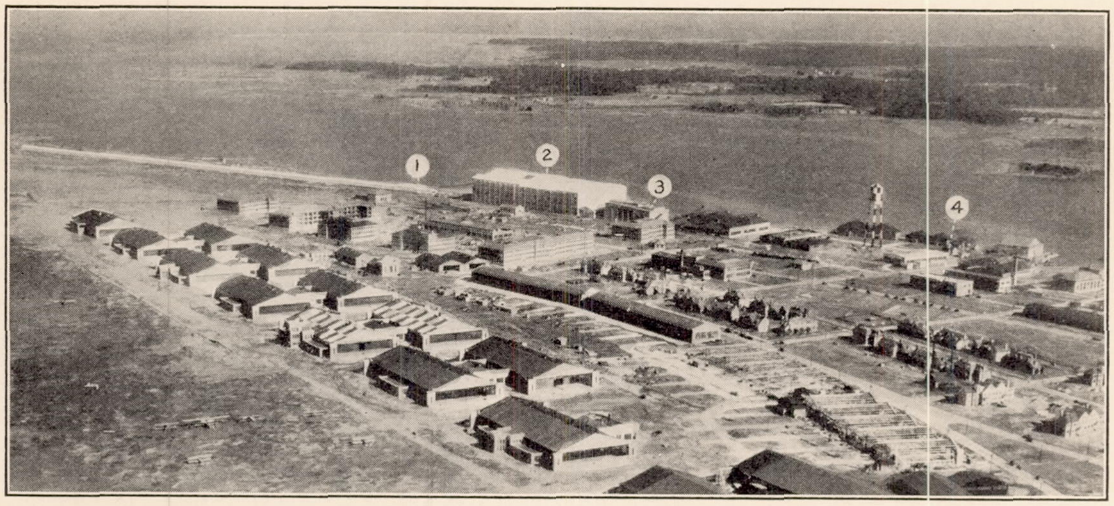
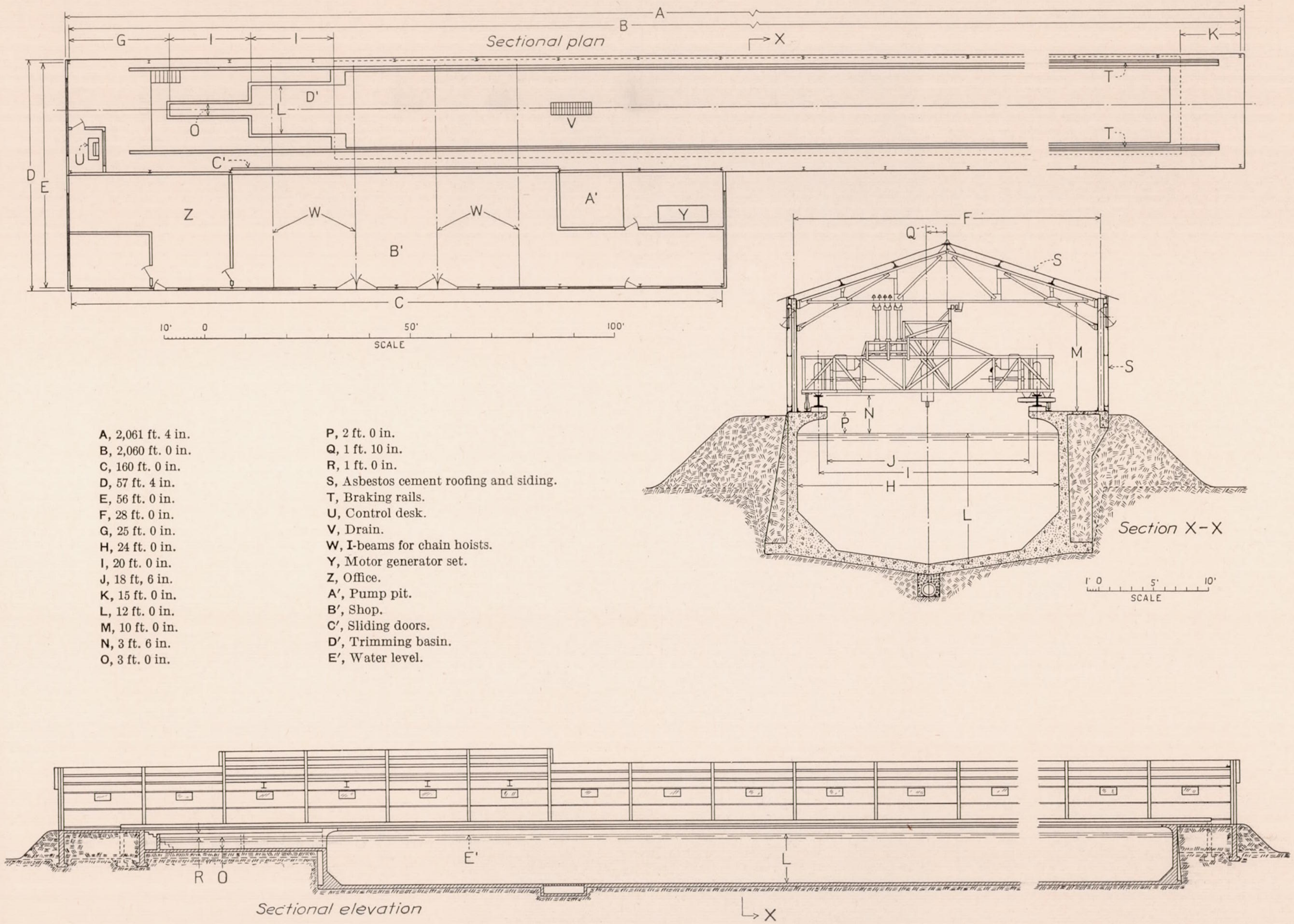


FIGURE 1.—Airplane view showing the location of the N.A.C.A. tank with respect to other equipment of the Committee at Langley Field, Va. 1. The tank. 2. The full-scale tunnel. 3. The propeller-research tunnel. 4. The administration building.

FIGURE 2.—Looking north in the empty basin of the N.A.C.A. tank.



A, 2,061 ft. 4 in.
B, 2,060 ft. 0 in.
C, 160 ft. 0 in.
D, 57 ft. 4 in.
E, 56 ft. 0 in.
F, 28 ft. 0 in.
G, 25 ft. 0 in.
H, 24 ft. 0 in.
I, 20 ft. 0 in.
J, 18 ft, 6 in.
K, 15 ft. 0 in.
L, 12 ft. 0 in.
M, 10 ft. 0 in.
N, 3 ft. 6 in.
O, 3 ft. 0 in.
P, 2 ft. 0 in.
Q, 1 ft. 10 in.
R, 1 ft. 0 in.
S, Asbestos cement roofing and siding.
T, Braking rails.
U, Control desk.
V, Drain.
W, I-beams for chain hoists.
Y, Motor generator set.
Z, Office.
A′, Pump pit.
B′, Shop.
C′, Sliding doors.
D′, Trimming basin.
E′, Water level.

FIGURE 3.—Plan and section of the N.A.C.A. tank.

Propelling motors.—The four electric motors propelling the car are each nominally of 75 horsepower, but for short periods they may be safely called upon to deliver 220 horsepower each. They are direct-current motors having two field windings. One of the fields is excited separately, and the other is excited by the armature current from one of the other motors. The wiring is so arranged that the armature current from the front pair of motors passes through the field windings of the rear pair of motors, and vice versa. The shunt field current is held at a constant voltage and the speed of the car is varied by varying the voltage of the armature current. The increase of the armature current during acceleration is controlled automatically to suit the rate of acceleration desired; the change to constant speed conditions is also made automatically.

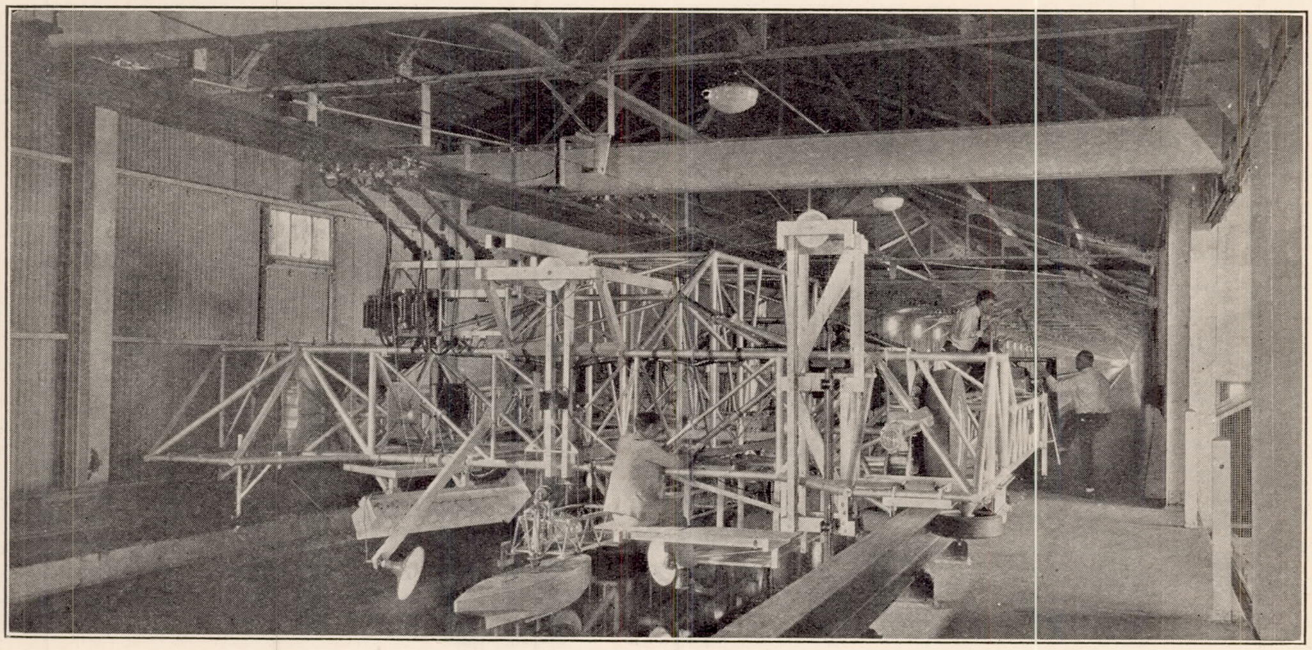


FIGURE 4.—The towing carriage of the N.A.C.A. tank.

Electrical braking.—Current for propulsion is supplied to the car by four overhead trolley wires on which travel two armature trolleys and two field trolleys. In addition there are two trolley wires and trolleys providing two circuits for the control of the electrical braking of the carriage. Opening one of these circuits sets into operation automatically controlled regenerative braking, opening the other dynamic braking. By means of a switch located at the control desk the operator can select either of two points along the tank at which the circuit controlling the regenerative braking will be opened and braking produced. If the incoming line voltage fails the braking automatically changes to dynamic.

The electrical braking can also be applied at will by either the operator at the control desk or the personnel on the towing carriage. A hand-operated brake is also provided to assist in the final stop and to make spotting the carriage at definite positions easier. This brake is of the automotive type with internal-expanding shoes which are carried in brake drums fitted on the wheels.

If the other braking systems should all fail the carriage would be stopped by the emergency brakes at the end of the tank. These are continuous rail friction brakes consisting of two heavy T-bars securely anchored to the concrete, one just outside each running rail. The stem of each projects vertically upward and forcibly sandwiches itself between two spring brake plates secured to the carriage. Four pairs of these brake plates are fitted on each side of the carriage. Instead of using coil springs to control the grip of the brake plates, the plates themselves are designed as flat-plate springs and the intensity of the braking action is controlled by the width of the initial opening between them.

All the braking systems have been thoroughly tested and found to operate satisfactorily in service. The emergency brakes have been used but once. The carriage was moving at less than 5 miles per hour and was stopped in less than 3 inches. The deceleration was violent but without shock.

Control of operation.—The control of the whole propelling system is concentrated at a control desk located at the south end of the tank. Here are the rheostats controlling the acceleration and determining the constant speed at which the carriage is to be propelled. Switches control the field and armature currents, and a selector switch controls the points at which the electrical braking is to be applied. A voltmeter and an ammeter are fitted to indicate the voltage and current in the armature circuit. The whole is mounted on a metal desk with the rheostats concealed within it.

The personnel carried on the car have no control of the speed of the car other than the ability to stop it at any time. They are free to give all their attention to taking the readings and to watching the behavior of the model being towed.

Time and distance gear.—The speed at which the carriage has been propelled on any run is determined from the time and distance traveled. A special clock is mounted on the carriage and so arranged as to send an electrical impulse to the dynamometer every second. The distance traveled is given by an indication in the dynamometer corresponding to every 5 feet of travel. A steel tape extends the entire length of the tank, and is supported by brackets projecting down from the bottom chords of the roof trusses. This tape has an accurately located hole through it every 5 feet. As the carriage moves along the length of the tank the tape is picked up by a set of rollers on the carriage and passes through a slot in a box placed between the rollers which contains a source of light and a photoelectric cell. The path of the light to the cell is interrupted by the solid tape, but when one of the holes in the tape passes through the box the light beam slips through and falls on the cell. The electrical impulse which this produces is amplified by a radio-type amplifier and is sent to the recording device of the dynamometer as a relatively powerful impulse.

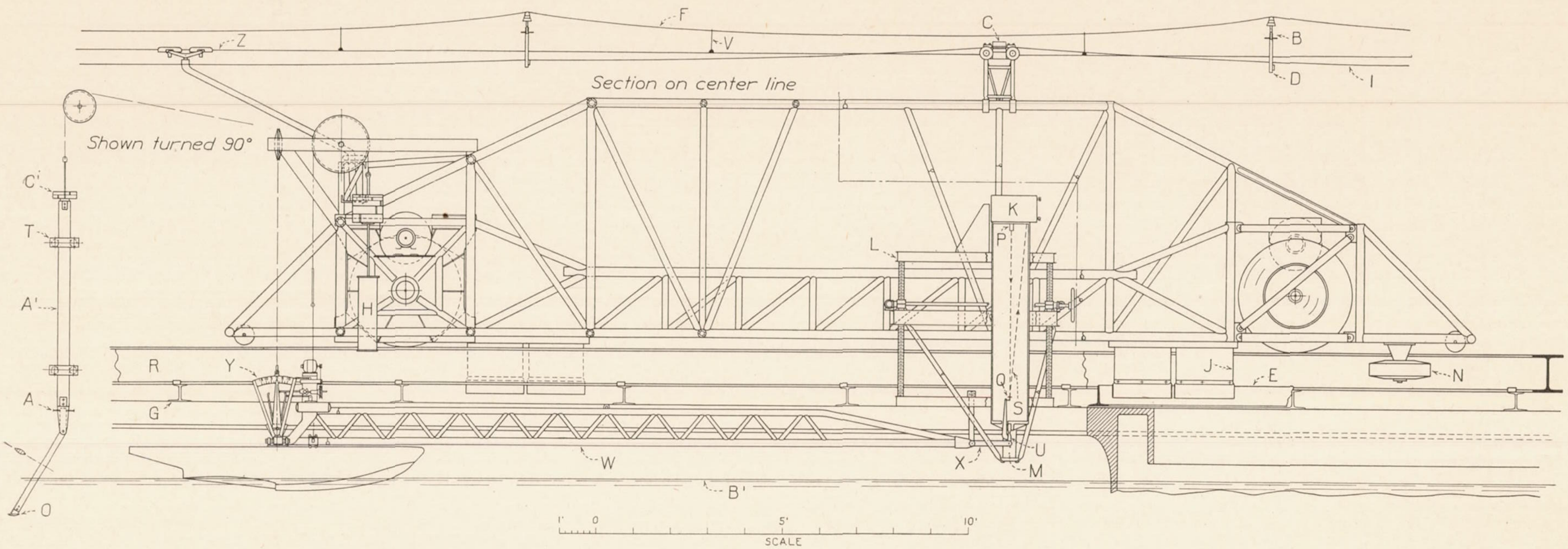
Motor-generator set.—The direct current for operating the carriage is obtained from a motor-generator set located in the shop section of the building. This set consists of a 350-horsepower alternating-current motor, taking current at 2,200 volts, driving a 300-kilowatt direct-current generator and two direct-current exciters. One exciter provides current for the shunt fields of the motors on the car; the other provides exciting current for the alternating-current motor and the fields of the direct-current generator.

The towing gear.—The arrangement of the towing gear is shown on figure 5. The model being towed is attached to the after end of a stiff latticed girder, or "towing gate." The forward end of this girder is attached to the dynamometer proper which weighs and records the pull of the model as it passes through the water. The length of the towing girder is as great as is feasible in order to reduce the obliquity of the pull as the model rises or sinks. The towing pull is applied to the model at a point corresponding to the center of gravity of the full-size craft and about this point the model can swing freely, when tests are made free to trim, or it can be held at any desired trim, and the moment required to hold it thus can be measured. A pointer moving with the model swings over a graduated scale and indicates the trim, while the deflection of a spring through which the constraining force is applied indicates the magnitude of the force and the moment which must be applied to constrain the trim.

Two sizes of towing gates are available, each with its own gear for measuring the trim and moments. The lighter and smaller one is made of duralumin structural sections and is used with models up to about 10 feet in length; the "heavy" one, used with models up to 16 feet in length, is made of steel tubing and has exceptionally heavy gear for measuring the trim and moments. The weight of the gate is counterbalanced by weights on the end of a flexible wire rope suspended over a sheave. A large damping cylinder, fitted on the lower end of the rod carrying the weights, reduces any tendency to vibrate vertically.

Through the point of suspension of the model is applied a vertical lift to simulate the lift derived from the wings of the full-sized craft. This lift is obtained from a flexible wire rope which passes over two sheaves to the upper end of a steel bar that is free to move vertically in roller guides. The upper end of the bar is fitted to receive weights to counterbalance any overweight of the model. At the lower end of the bar there is fitted a bronze blade that projects downward into the water. The immersed end of the blade is fitted to receive any one of several bronze hydrofoils, or hydrovanes, which can be firmly secured to it. The size of the hydrovane is selected to suit the model that is being tested and the angle of attack may be adjusted by changing the angle of the blade. The selection and adjustment of the hydrovane are so made that at the speed corresponding to the get-away speed of the full-sized craft the downward pull exerted by the hydrovane will equal the weight corresponding to the gross weight of the full size and, if the model is balanced to that weight, it will be just lifted from the water. At any other speed the lift produced by the hydrovane will be to the lift at get-away as the square of the speed is to the square of the get-away speed and will correspond to the lift of the wings at that speed. The blade and the hydrovane are placed as far to one side of the model as is feasible to avoid any interference with the flow around the model.

This method of supplying the lift corresponding to the wing lift implies that the lift coefficient of the wings does not change during the take-off. This assumption is contrary to the fact, but devices intended to provide a lift that will be varied automatically to correspond with the variation in angle of attack due to change in trim introduce complications and do not seem to be sufficiently trustworthy to warrant their use at present. Devices similar to the present one have been used for years with reasonably good results. It should also be remembered that if a large range of trim angles is involved the get-away speed can be varied to suit the change in angle of attack of the wings. In general, the difference in the values of Δ/R obtained is not great. The provision of a suitable device providing automatic variation of the lift with



A, Adjustment of hydrovane.
B, Bottom chord of roof truss.
C, Box containing light source and photoelectric cell.
D, Bracket for distance tape.
E, Braking rail.
F, Catenary.
G, Chair.
H, Damping cylinder.
I, Distance tape
J, Emergency brake.
K, Film box.
L, Frame for adjusting height of towing point.
M, Guide.
N, Guide wheel.
O, Hydrovane.
P, Light source.
Q, Mirror.
R, Rail.
S, Reflecting ray.
T, Rollers.
U, Spring.
V, Suspender.
W, Towing gate.
X, Towing link.
Y, Trim and moment indicator.
Z. Trolley wire.
A', Vertical bar.
B', Water level.
C', Weights to counterbalance model.

FIGURE 5.—Elevation and sections of the carriage and towing gear of the N.A.C.A. tank.

the trim is contemplated but its development has not begun.

The rise of the model is indicated by a pointer, attached to the wire providing the lift, which traverses a vertical scale attached to the carriage.

At the forward end of the towing gate are two vertical suspension links which support a part of the weight of the gate and any reaction from the trimming moments. There are thus no vertical forces applied to the weighing device of the dynamometer. A single horizontal link connects the beam to the weighing device, which consists of a stiff spring in the form of a single flat plate of steel. The magnitude of the pull exerted by the model is obtained by measuring the deflection of the spring.

The upper end of the spring is rigidly attached to a massive tube supported in the center girder of the carriage and is presumed to have no deflection. The deflection of the lower end of the spring is magnified by an arm attached to it and extending up into the tube. The upper end of this arm carries a stylus, the point of which bears against a vertical plate mounted on a horizontal staff that also carries a horizontal mirror. The plate on the mirror staff is held against the stylus by a small hairspring.

A beam of light projected against the mirror from a light source at the top of the tube is reflected back against a slit in the top plate of the tube. When a sheet of sensitized paper is moved at constant speed across the slit the reflected spot of light traces a curve that becomes visible on development. In addition to the curve from the movable mirror, a series of parallel straight lines are ruled on the record by light rays from six fixed mirrors. These are so adjusted as to provide a convenient series of reference lines.

In order that the operator may be informed as to the magnitude of the pull exerted by the model during the run, a second beam of light is projected against the measuring mirror at such an angle that as it returns to the top of the tube it may be intercepted by a horizontal mirror set to reflect the beam against a translucent screen. This screen is suitably graduated and the gross pull exerted by the model may be read from the position of the spot of light coming from the measuring mirror.

The speed of the car is determined from the records of time and distance traveled. The time is indicated by successive dots produced by flashes of a lamp lighted every second by the timing clock. The distance is indicated by the breaks in a line traced on the sensitive paper by the light reflected from a galvanometer mirror mounted inside the tube. The deflection of this galvanometer is produced by the amplified impulse coming from the photoelectric tube which is illuminated every 5 feet as the car progresses along the track.

The record thus obtained includes a curve showing the pull exerted by the model, a series of dots which indicate the time in seconds, and a broken line the deflections from which indicate 5-foot intervals of progress. The speed may be computed from the time required to cover a given distance, or the distance covered in a given time.

The recording part of the dynamometer is mounted on a frame that can be moved vertically to bring the point at which the pull is applied to the spring to any desired height from the water. The movable frame is carried on four lead screws in a fixed frame, but two vertical guides on the fixed frame relieve the lead screws of any side load.

PRELIMINARY TESTS

The first task, after the work of construction was finished, was to assemble and test the equipment to demonstrate the accuracy of operation and the ability to reproduce results on successive runs. A number of novel features, referred to in the introduction, required especial attention.

The designed maximum speed of the towing carriage had been set at 60 miles per hour for three reasons: First, to be sure that there would be ample acceleration for any speeds that might ordinarily be required (40 miles per hour as the get-away speed of a ¼-size model of a seaplane having an 80-mile get-away was easily foreseen); second, to make it possible to determine the properties of details of bottons, or of planing surfaces, at speeds at or near actual get-away speeds; and third, to make it possible to study the phenomena of fluid friction on surfaces moving at high speeds and the effects of roughnesses such as rivet heads and plate butts. High speeds meant high accelerations of the carriage and great length of run so that conditions might settle down before readings were taken, at a constant speed.

The towing carriages of all previous tanks had run on wheels with iron or steel tires, usually of hardened steel carefully ground to perfectly circular form. These were used with steel rails which had been carefully machined to give the greatest practicable smoothness and straightness to the surfaces. Such an arrangement appeared certain to be extremely costly if used on the very long tank that was contemplated. It also appeared to include a promise of trouble. At the high accelerations, which were necessary if the already long tank were not to be longer, the torques transmitted to the wheels in starting the carriage might cause them to slip. Furthermore, in braking at the end of the testing run the brakes might lock and slide the wheels. Either event would spoil the truly circular form of the tires and might also spoil the smooth surface of the rails. At the high speeds which were contemplated the slightest irregularities in the rail or in the wheel, no matter how produced, would surely produce violent shocks and erratic motion of the carriage. One method of avoiding the high starting and braking tractions was to provide a catapult for accelerating and a reversed one for braking. These meant considerable increases in the cost and unknown difficulties in operation.

A simple solution was to abandon the steel tires and substitute pneumatic rubber tires running on wide flat surfaces. Such tires could be made and kept very close to truly circular at no great expense. They would have much greater adhesion than steel tires and accelerating and braking torques could be correspondingly increased. There would also be less necessity for a fine finish on the rails for the tires would absorb slight irregularities and even provide damping for any vertical vibrations.

Coupled with these advantages was a possible disadvantage in that a pneumatic tire always has a flat surface in contact with the rail and the loaded radius, or axle height, is not the radius of the unloaded tire. Variations in this height might produce tramping or magnify vertical motions.

The advantages appeared to outweigh the possible disadvantages and it was decided to use the pneumatic tires. It was realized that this was a radical departure from well-established practice and the testing and breaking in of the new equipment was carefully watched to determine exactly how the tires affected the operation of the towing carriage.

During the trial period the carriage was operated through a wide range of speeds and accelerations. The maximum speed attained was 58½ miles per hour. A still higher speed can be reached if required, probably more than the designed 60 miles per hour, but it was thought unwise to attempt it with equipment that was still new and not completely broken in. The carriage has since been operated at speeds of about 50 miles per hour several times in connection with actual tests and the operation is even smoother than it was during the trial period.

The tests during the trial period showed very plainly that the pneumatic tires did not produce tramping, that they did damp out threatened vibrations and absorb the effects of slight irregularities, and also that for a given air pressure in the tires the axle height remained constant as nearly as could be determined.

Because of the use of the pneumatic tires it had been decided to omit the planing of the top surface of the H-beams that were used as rails, and to install them as they came from the mill, depending on the tires to absorb any irregularities. The rails were laid with plain butt joints and no special arrangements were fitted to avoid shocks as the wheels crossed the rail joints. Steel tires would have hammered the open butt joints into violently distorted forms; pneumatic tires promised to leave then unharmed. The tests demonstrated that these anticipations were fulfilled.

However, the heavy H-beam rails were of surprising rigidity, and leveling and alining them so that the two top surfaces should be parallel to the water surface and the web of one should be straight from end to end proved a time-consuming operation. About 2,000 feet of rail had to be leveled on each side of the tank. Weather conditions sometimes produced surges in the water which stopped measurements for days. Some of these could be explained only by the theory that the barometric pressures at the ends of the tank sometimes differed by amounts sufficient to depress bodily the whole mass of water at one end and to permit it to rise correspondingly at the other. The change in level would be small but it would exceed the allowable error in leveling the rails.

METHODS OF TESTING

Tests of models of hulls or floats may be made in either of two ways. The earlier method was originally developed to obtain information regarding an aircraft for which most of the essential data are known. A second, or general, method does not require this information, and at the same time gives much more complete information than the earlier method. Both methods are susceptible of some modification, and may even be partially combined.

Earlier, or specific, method.—The model is presumed to be of a hull or float for a specific aircraft of which the gross weight, initial trim, position of center of gravity, and get-away speed are known. If the dimensions of the model are $\frac{1}{\lambda}$ times those of the full size, then according to Froude's Law,

L, length of full size.

$l=\frac{1}{\lambda}L$, length of model.

W, gross weight of full size.

$w=\frac{1}{\lambda^3}W$, gross weight of model.

V_g, get-away speed of full size.

$v_g=\sqrt{\frac{1}{\lambda}}V_g$, get-away speed of model.

M, trimming moment of full size.

$m=\frac{1}{\lambda^4}M$, trimming moment of model.

The initial trim of the model will be the same as that of the full size and the position of the center of gravity of the model, which is the point at which the towing pull is applied, will be the same as that of the full size to scale.

The weight of the model as constructed will rarely be that determined from the relations given above; usually it will be considerably heavier. Accordingly, counterweights are fitted on the top of the vertical bar carrying the hydrovane until the weight of the model which remains waterborne is exactly that corresponding to the gross weight of the full size.

The setting of the hydrovane device is then adjusted to give a downward pull, and an upward lift at the model, of w at speed v_g. This is obtained approximately from curves previously prepared and is checked and adjusted to the proper setting by trial runs. There is also prepared a curve showing the air drag produced by windage on the parts of the towing gear exposed to the air stream.

The model is towed at a succession of constant speeds. Usually the first runs are made with the model free to trim. These are followed by other series of runs at various fixed trims. If no fixed trims have been specified these usually are 4°, 6°, and 8°. The speeds used vary with the size and type of model. The free-to-trim runs usually begin at about 5 feet per second and extend by intervals of 1 foot per second to about 75 percent of the get-away speed. At this speed the trim usually is back close to the initial trim and there would be danger of putting the bow of the model into the water if the speeds were carried higher with the model free to trim, which might result in the wreck of the gear and the breaking of the model. At such speeds the aerodynamic control of the full size should be sufficiently effective to control the attitude, which will be a considerably larger trim, and usually there seems no need to investigate a condition which does not ordinarily occur. It is possible, however, to carry the free-to-trim runs further if necessary, but in such runs substantial stops must be fitted to the model to keep it from suddenly trimming too far down by the bow, with possibly disastrous consequences.

The aerodynamic controls have little effect at speeds much below 50 percent of get-away speed, so the fixed-trim runs usually begin at about 35 percent get-away speed and are carried up to, or very near to, get-away speed. Usually speeds are selected at somewhat larger intervals for these runs than for the free-to-trim runs. In most cases the trend of the curve governs the speeds selected and the range covered, and additional runs are made at critical points in the curves.

During the runs the resistance, time, and distance are recorded automatically, while the trim angle and rise, for free-to-trim runs, or trimming moment and rise for fixed-trim runs, must be read by an observer stationed at the rear of the carriage. For fixed-trim runs it is also his task to operate the control of the electric motor that drives the device to apply the proper moment to hold the trim at the constant value which has been previously selected.

Photographs of the model are taken at each speed at which the wave system or spray will be of interest. Two cameras are used and are located to give a record of those features of the wave system which show the properties of the model most plainly. Two typical and simultaneous pictures are shown as figures 6 and 7.

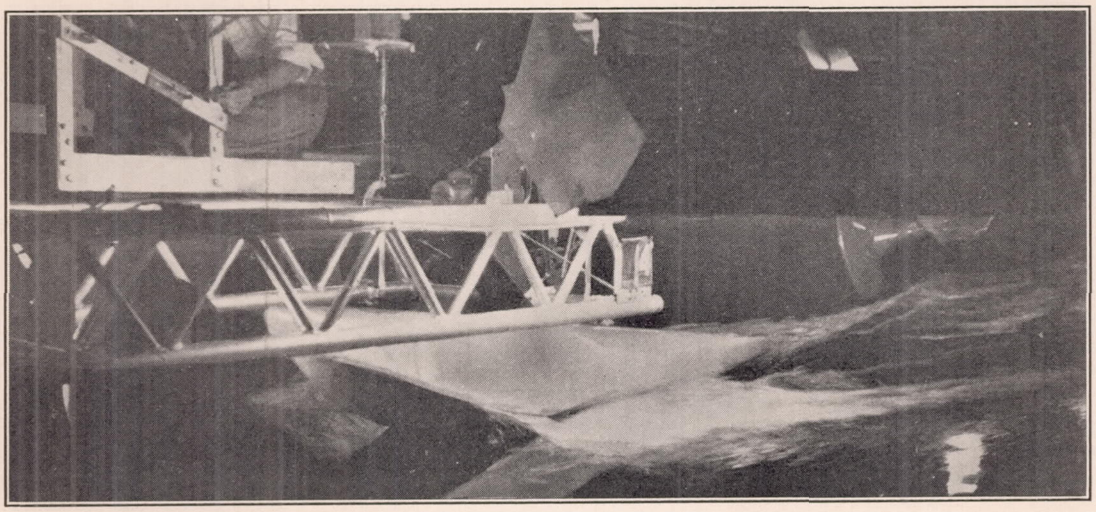


FIGURE 6.—Bow view of model of *PH-1* flying-boat hull at 14 f.p.s., free to trim.

After the runs have been completed the sensitized paper on which the various points of light have been projected is developed and dried. Points giving a curve of gross resistance against speed have been made on a rough plot from readings of the repeater made by an observer, but the accurate readings of resistance and speed can be obtained only after the record has been developed.

The resistance record appears as a wavy line through which a mean line can be drawn by eye, using a straightedge. Experience in drawing this mean line soon makes it possible to draw it so accurately that usually only one attempt is necessary. The height of the mean line above the line representing zero resistance is multiplied by the instrument constant and gives the gross resistance in pounds. The true speed of the run is determined by the distance traveled in a given number of seconds, as recorded by the time and distance indicators.

Corrections.—The gross resistance is corrected for the error introduced by the obliquity of the towing gear, which is determined from the rise of the model as read by the observer, and for the windage drag at the true speed. Both are obtained from curves previously prepared. If the trimming moment has been observed it is corrected to take account of the fact that the vertical position of the center of gravity of the model is not at the towing point, where it was assumed to be, and that the weight of the model is not the true weight corresponding to that of the aircraft. These figures are obtained by weighing the model and determining the gravity moments it exerts about the point of suspension.

No correction is made for windage on the model itself. This part of the resistance probably varies as the wave-making resistance, or so nearly so as to cause an insignificant error in the conversion to full scale. No correction is made for interference between model and gear. This is believed to be of relatively small importance, and there appears to be no reasonably simple method of determining the actual amount in each case.

It has been found that testing can be done without serious difficulty at any temperature ordinarily met with, although the tank is unheated and consequently the air temperature varies with the outside conditions. However, extremely low temperatures last for such short periods that no serious delay has been noted from stopping work when operation becomes uncomfortable to those on the carriage.

The change in temperature of the water in the tank is very slow and the maximum range so far has been from 44° F. in mid March to 63° F. in mid October. No attempt is made, at least for the present, to take account of the effect of variations in the temperature of the water on the viscosity.

The mean specific gravity of the water in the tank is very nearly that of normal sea water. If correction of the results of tests is desired it may be made on the basis of a mean specific gravity of 1.018.

After the computations have been completed there remain for entering in a table of values for each speed the weight on the water (Δ), the resistance (R), the weight on water divided by the resistance (Δ/R), the trim, the trimming moment if recorded, and the rise. The plots of these respective values as they vary with the speed provide the curves that indicate the behavior and properties of a design.

General, or "complete", method.—This method gives more general information than the specific method, and is especially useful if no data are at hand as to the complete airplane with which the float is to be used. It is the same as the method of testing described by P. Schröder in reference 7. In this method the model is towed at a number of fixed weights on the water with fixed trims and at various constant speeds, and the resistance, trimming moment, and rise are determined for each of these as in the earlier method. This method requires more runs but gives information which can be applied to more widely varying conditions of load, get-away speed, position of center of gravity, etc. The data obtained from the individual test runs are the same and the methods of deriving them are identical. In view of the more complete information obtained, this is usually referred to as the "complete" method. A full description of this method, with an example of its application, will form a later report.

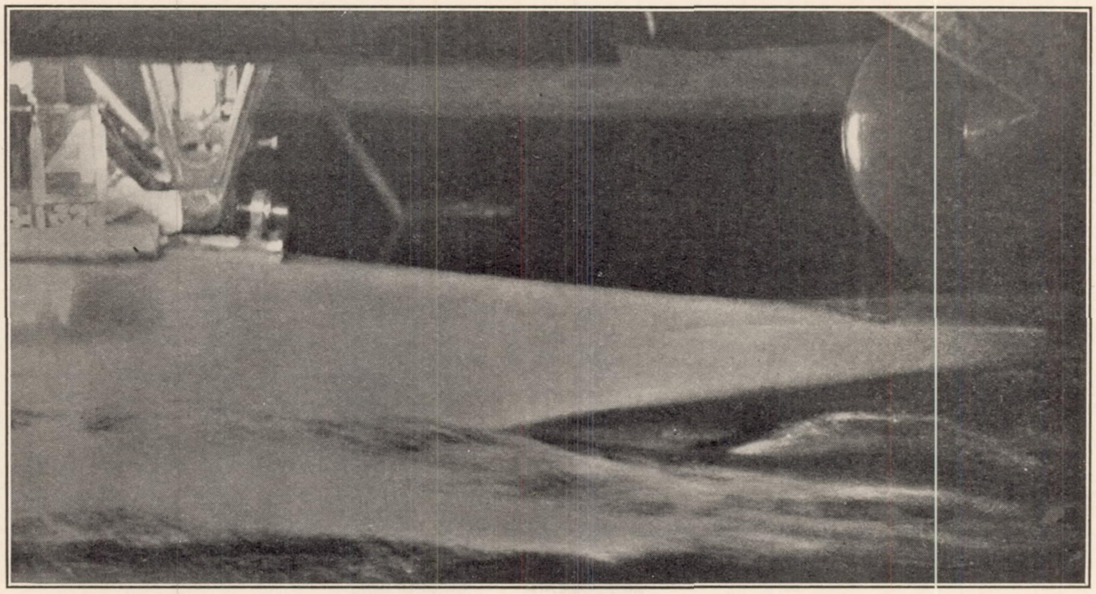


FIGURE 7.—Beam view of model of *PH-1* flying-boat hull at 14 f.p.s., free to trim.

ACCURACY

The accuracy of the readings from the various parts of the dynamometer and towing gear has been checked by frequent calibration and it is believed that the values used in preparing the curves are correct within the following limits:

Speed	±0.1 ft. per sec.
Resistance	±0.1 lb.
Rise	±0.10 in.
Trim	±0° 6′.
Trimming moment	±1.0 lb.-ft.

While the possible errors may seem large, particularly the 1.0 lb.-ft. in the trimming moment, it will be seen by reference to the curves which appear later that they are relatively small percentages of the magnitudes involved.

TYPICAL TEST DATA

COMPARISON OF TAKE-OFF OF LANDPLANE AND SEAPLANE

The special importance of reductions in the resistance to motion on the water of a flying-boat hull or a seaplane float becomes apparent from an examination of the contrast found in the curves of figure 8. This figure presents the curves of resistance on the water and land and in the air which might be expected of a large amphibian flying boat. On land this machine runs up to take-off speed on wheels like any landplane. On water it runs to get-away like any flying boat. For simplicity it is assumed that the aerodynamic resistance is the same in both cases.

The total resistance of the machine as a landplane before it leaves the ground consists of the sum of the aerodynamic resistance and the resistances due to friction and rolling along the ground. The sum of the last two is a maximum at the moment of beginning to move and becomes steadily less until it becomes zero at take-off. Compared to the resistance at take-off the initial value of the total resistance is not very large and at no time before take-off does it exceed that at take-off.

The case is far otherwise when operating as a seaplane. Here the total resistance before the craft leaves the water is the sum of the aerodynamic resistance and the hydrodynamic resistance. The course of the former is the same as for the landplane but the hydrodynamic resistance shows a violent difference. From zero at the start it rises rapidly until at "hump" speed it may be double the total resistance at get-away. It then decreases, first sharply and then more slowly, until it becomes zero at get-away. The total resistance at hump speed often comes surprisingly close to equaling the thrust at that speed. Should there be any decrease in thrust or increase in resistance at this speed the margin of thrust available for acceleration might easily disappear and the craft would not be able to reach a speed above the hump speed and could not leave the water.

That hump of resistance menacing the propeller thrust stands out as a most obvious point to be attacked if we desire to improve the performance of seaplanes. Every reduction in its height and extent will be repaid by a decrease in the time and distance run to get-away and the margin for contingencies between the thrust and resistance will be correspondingly increased.

In the case of the landplane very little can be done to reduce the already low rolling and frictional resistance while on the ground and it is mainly the aerodynamic qualities that determine the time and length of take-off run. In the seaplane the hydrodynamic resistance is preponderant throughout almost the whole run on the water and reductions in the time and length of run to get-away must come almost solely from reductions in that resistance.

The effect of small changes in the form or dimensions of the hull of a seaplane on the hydrodynamic resistance may be surprisingly large. On small models the effects of almost microscopic changes are correspondingly difficult to perceive and interpret. When larger models can be used, as in the N.A.C.A. tank, the changes themselves may be of a substantial nature; their effects are much more apparent and relatively easier to interpret. As illustrating this, we may consider the two following cases:

THE EFFECT OF A "HOOK" ON THE STEP

Designers sometimes introduce a hook, or sharp downward drop of the bottom, at the step of a flying-boat hull. Usually the depth of the addition is small and it is of very small extent fore and aft. On a small model the addition is hardly perceptible.

Test of Navy "PH-1" with hook.—In order to obtain information as to the effect of such hooks on the performance on the water of a typical flying boat, the step of a ⅙ full-size model of the hull of a Navy *PH-1* flying boat that was known to have a good performance on the water and in the air was fitted successively with hooks of three different sizes. A general plan of this model with the principal dimensions appears in figure 9. The model was made of pine and finished with several coats of enamel. The model was carefully checked on a surface plate for closeness to dimensions and it was found that the underwater body was within ±0.01 inch of the designed dimensions.

The dimensions of the hooks appear on figure 10. As fitted on the model these dimensions were held to within ±0.002 inch. A photograph of the model with the various pieces which were inserted at the step to form the hooks is reproduced as figure 11.

The model was tested with no hook on the step and with the three hooks as shown. Test runs were made both free to trim and at fixed trims of 4°, 6°, and 8°. For each run the resistance and speed were recorded and the rise and trim, or trimming moment at fixed trim, were observed and recorded. After the proper corrections had been made for windage and rise of towing gear the results were set forth as the curves forming figures 12 (*a*) to (*e*).

Discussion of results.—A conspicuous feature of these curves is that the speed-resistance curve, free to trim, shows a sharp break, or discontinuity at the hump speed, 10 to 12 feet per second. This discontinuity was faired out in some of the earlier plots and led to curves in which the irregularities were so great as to cast doubt on the tests. Careful checking and additional points confirmed the original points and showed that there existed a real discontinuity which appeared in all four curves, but to a degree which was much influenced by the depth of the hook. A search was made of the published results of tests of boat and float models and it was found that such a discontinuity had been mentioned in reference 8 and shown in figure 4 of that paper. This peculiarity has been found in curves from other models tested in the N.A.C.A tank and is now regularly looked for. The speed-resistance

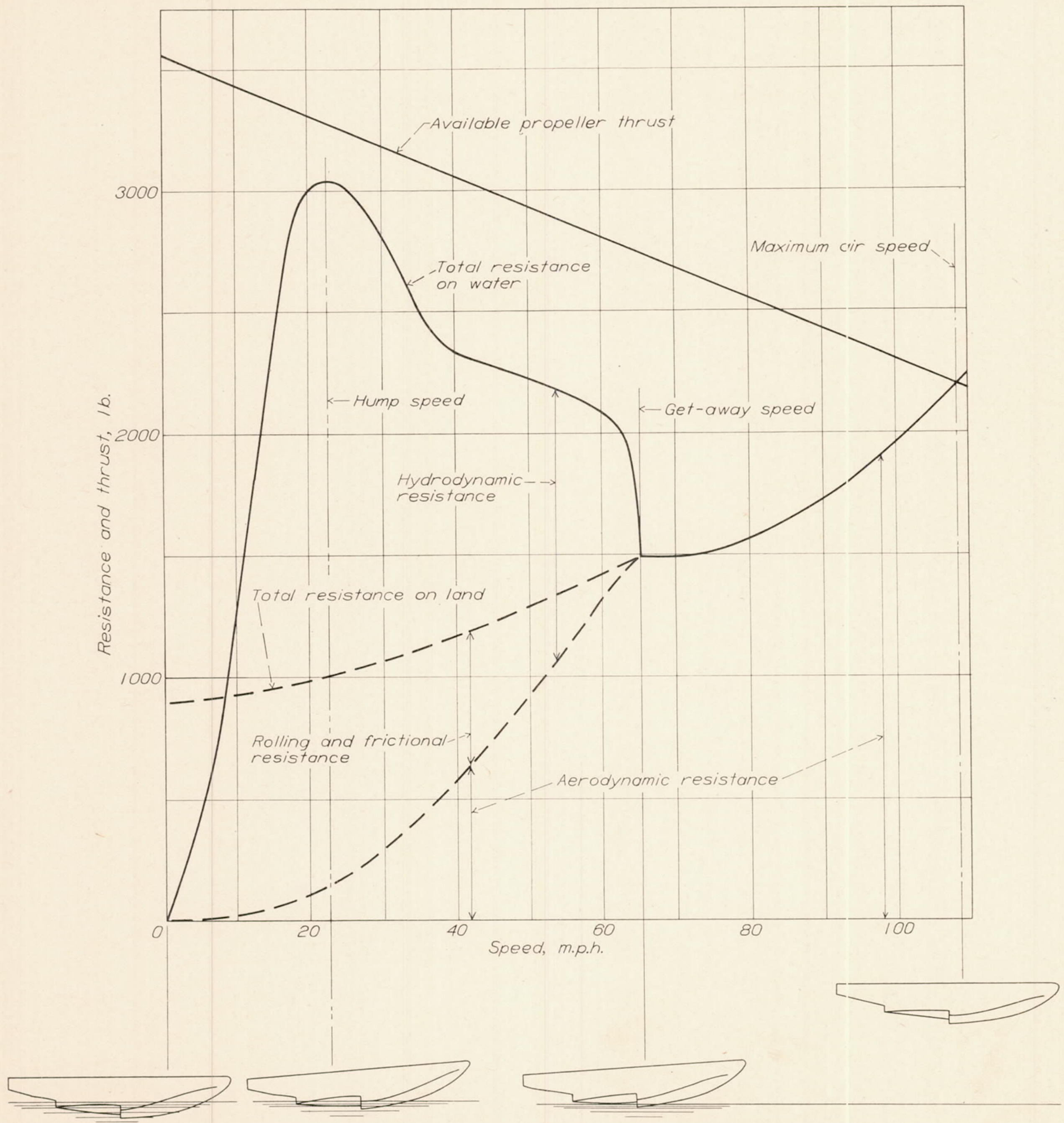


FIGURE 8.—Comparison of the resistances of an amphibian flying boat taking off from water and from land.

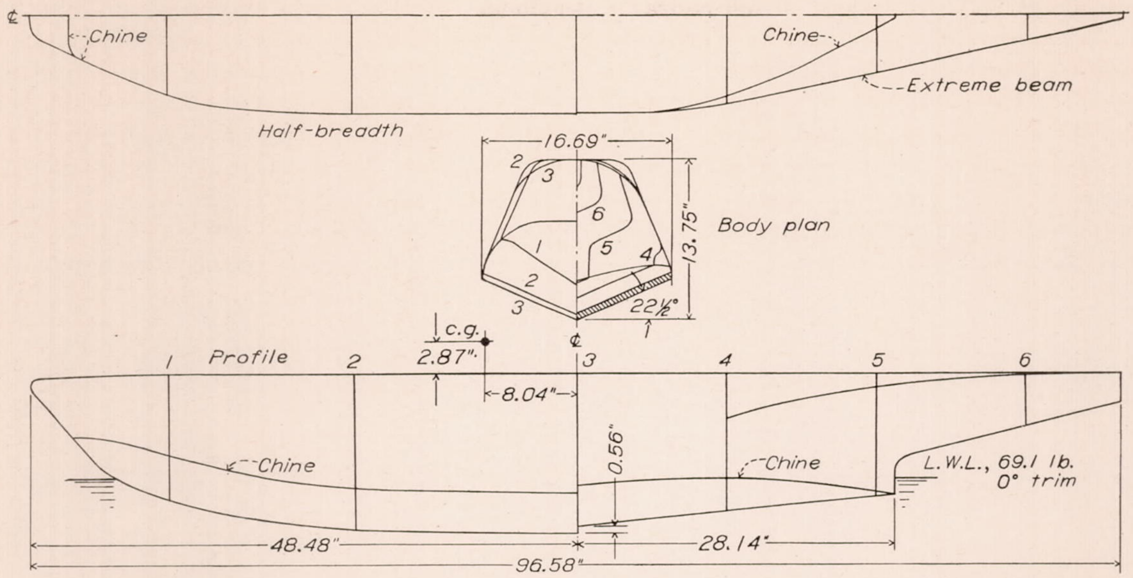


FIGURE 9.—Principal dimensions of the model of the hull of the *PH-1* flying boat used in tests in the N.A.C.A. tank.

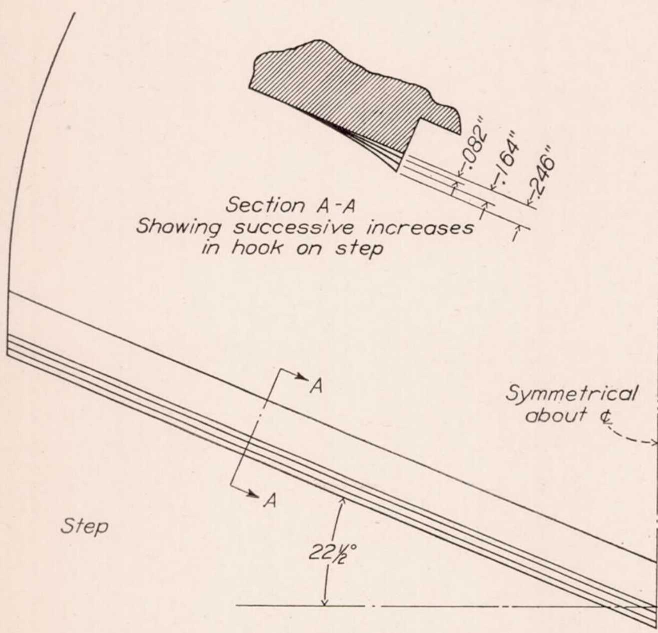


FIGURE 10.—Dimensions of the hooks fitted on the step of the model of the *PH-1*.

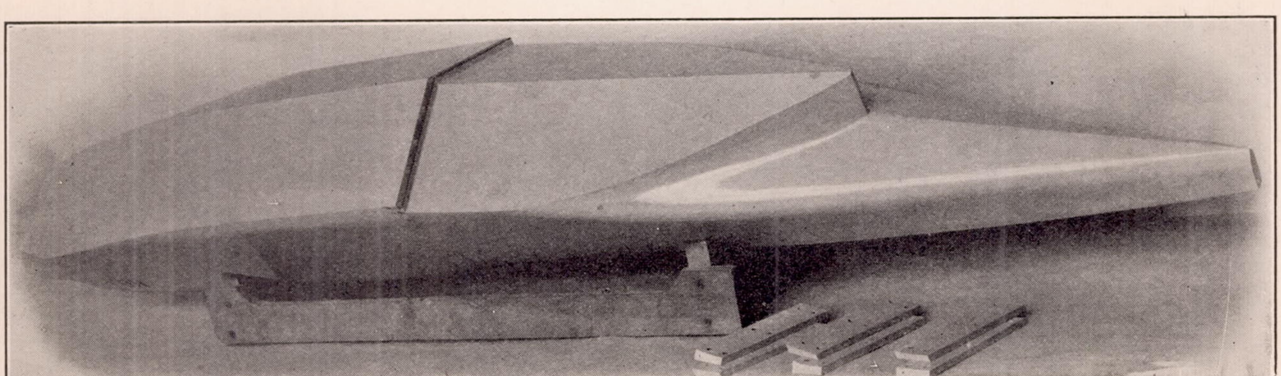
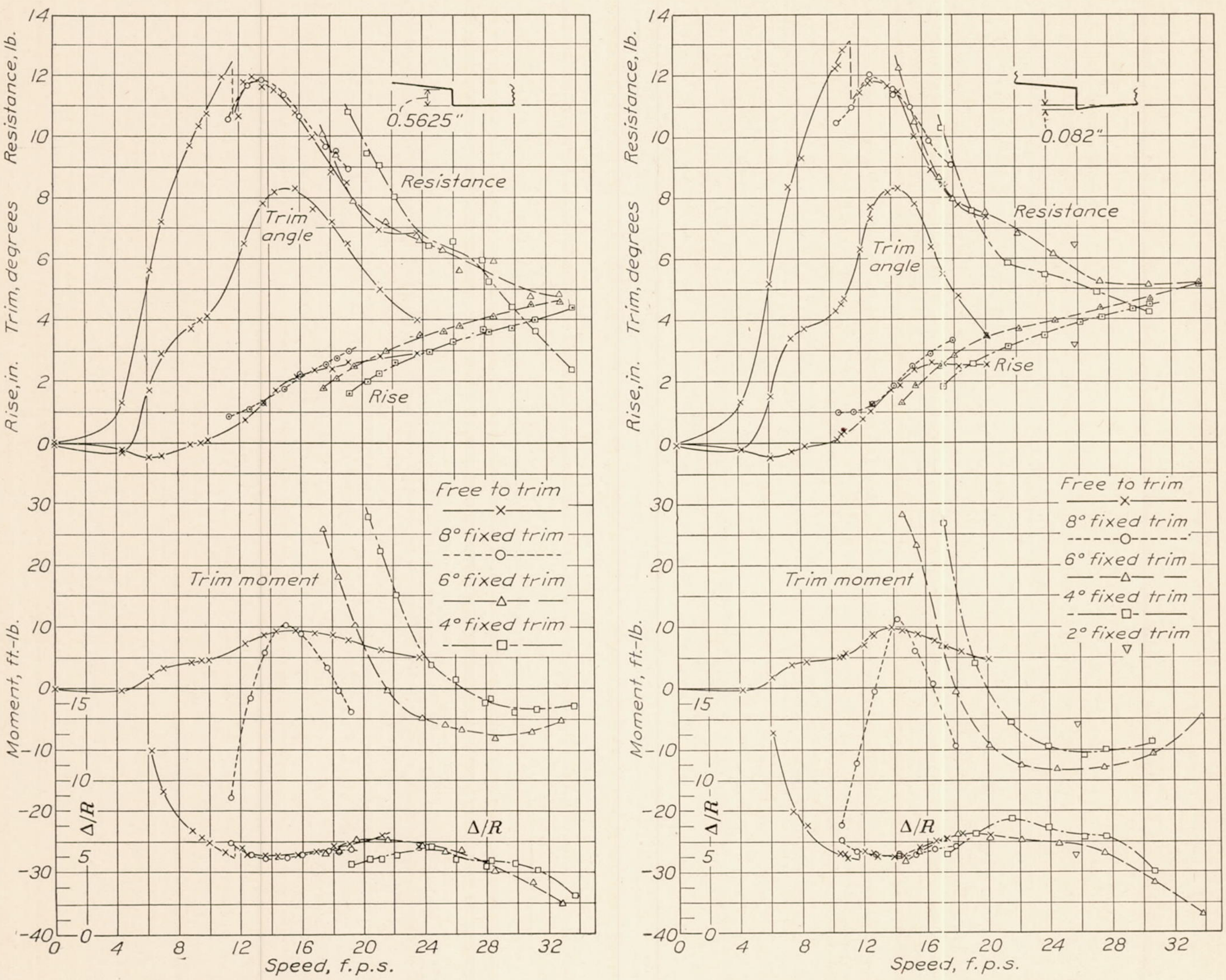


FIGURE 11.—The model of the *PH-1* showing the blocks for fitting the hooks on the step.

curve for a model with a stepped bottom is drawn as a smooth curve only after check tests have shown that the expected discontinuity does not exist.

The discontinuity appears at about the speed where the model changes from a condition where buoyant support predominates to one where hydrodynamic support becomes predominant. The change can be seen in the waves and spray thrown by the model, where it appears as the point where the flow from the step model are extended to meet and this point is indicated by a circle. The manner in which this point travels toward a lower speed and a higher resistance as the depth of the hook increases suggests the possibility of a systematic connection between depth of step, depth of hook, and resistance. This possibility has been noted for future investigation.

From the present curves we may draw the conclusion that the second hook, 0.164 inch high, is somewhat



(a) Performance curves of model with no hook.

(b) Performance curves of model with 0.082-inch hook.

FIGURE 12.—The effect of fitting hooks on the step of the model of the *PH-1* flying-boat hull.

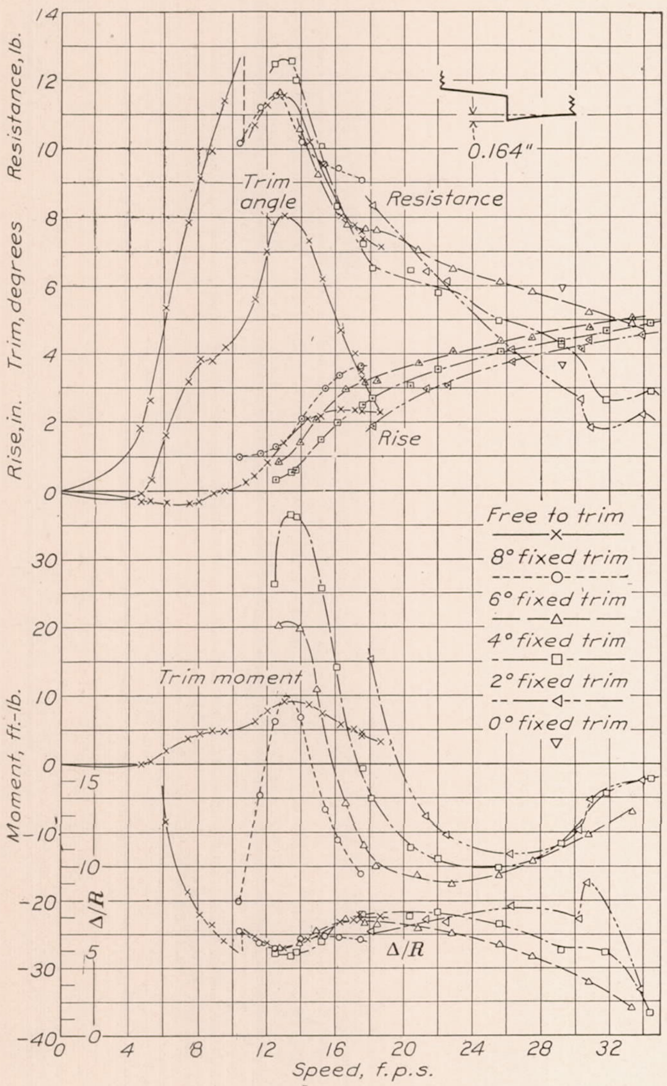
cleans up and the step ventilates properly. At that point the character of the resistance probably changes from predominantly wave making to predominantly viscous.

It is believed that the use of large models in the N.A.C.A. tank makes it possible to detect this discontinuity; it probably does not appear as plainly with small models.

In figure 12 (*e*) the comparison of the curves of resistance free to trim and at 4° fixed trim is facilitated by plotting them together. The two curves for each the better. It gave a slight reduction in maximum resistance, made the maximum resistance come at a lower speed, and caused a general lowering of resistance from maximum resistance on.

The highest hook was most unfavorable for it produced an increase in resistance at the hump of more than 20 percent above that for the model with no hook. In all probability this would exceed the thrust at that speed and if allowed to run along freely the craft with this hook on the step probably would fail to accelerate and could not get off.

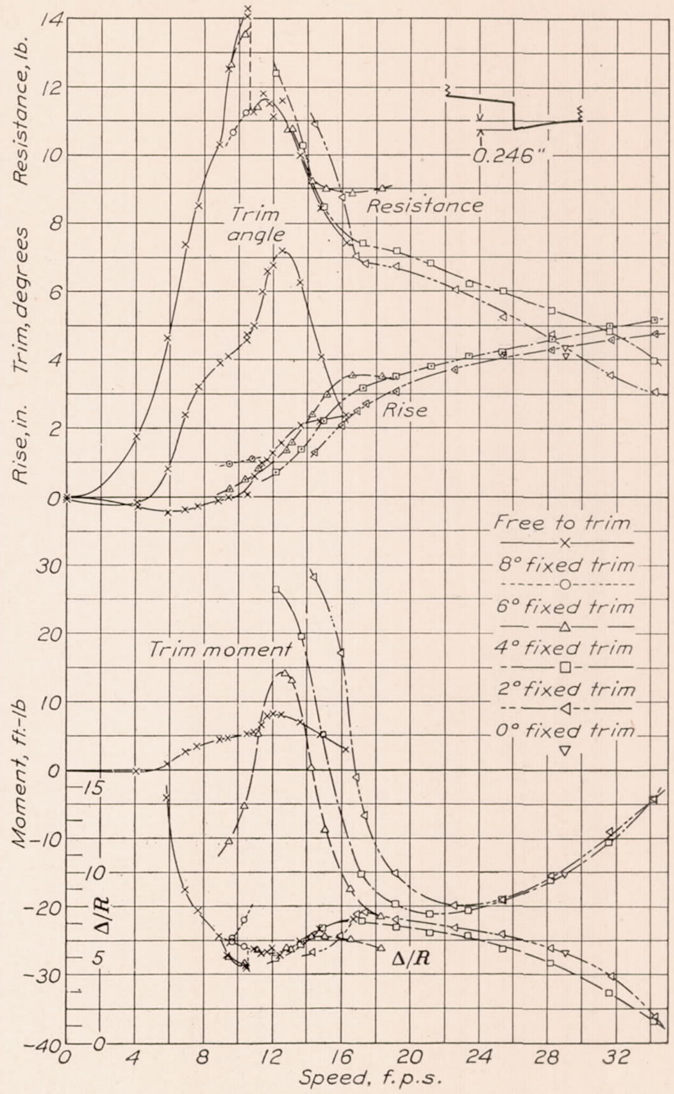
From these curves it can be seen why "rocking" a flying boat sometimes helps it to get off. If by rocking back and forth a regime can be found which will even momentarily have a lower resistance, the speed may be increased enough to pass through the narrow peak of the discontinuity and permit further running to be done on the rapidly decreasing second part of the curve. It would appear that the real purpose of the rocking,



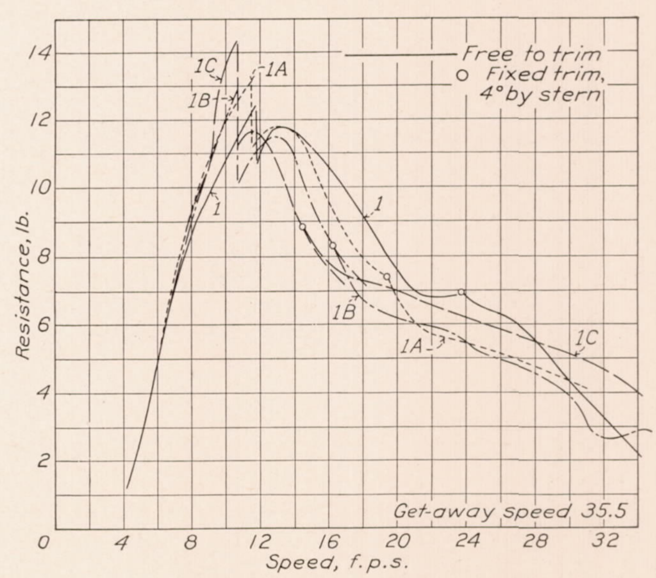
(c) Performance curves of model with 0.164-inch hook.

which frequently proves effective, is to find by trial the regime which momentarily permits the jumping from one part of the resistance curve to the other. This change in regime of course involves a change in many elements, not in the resistance alone.

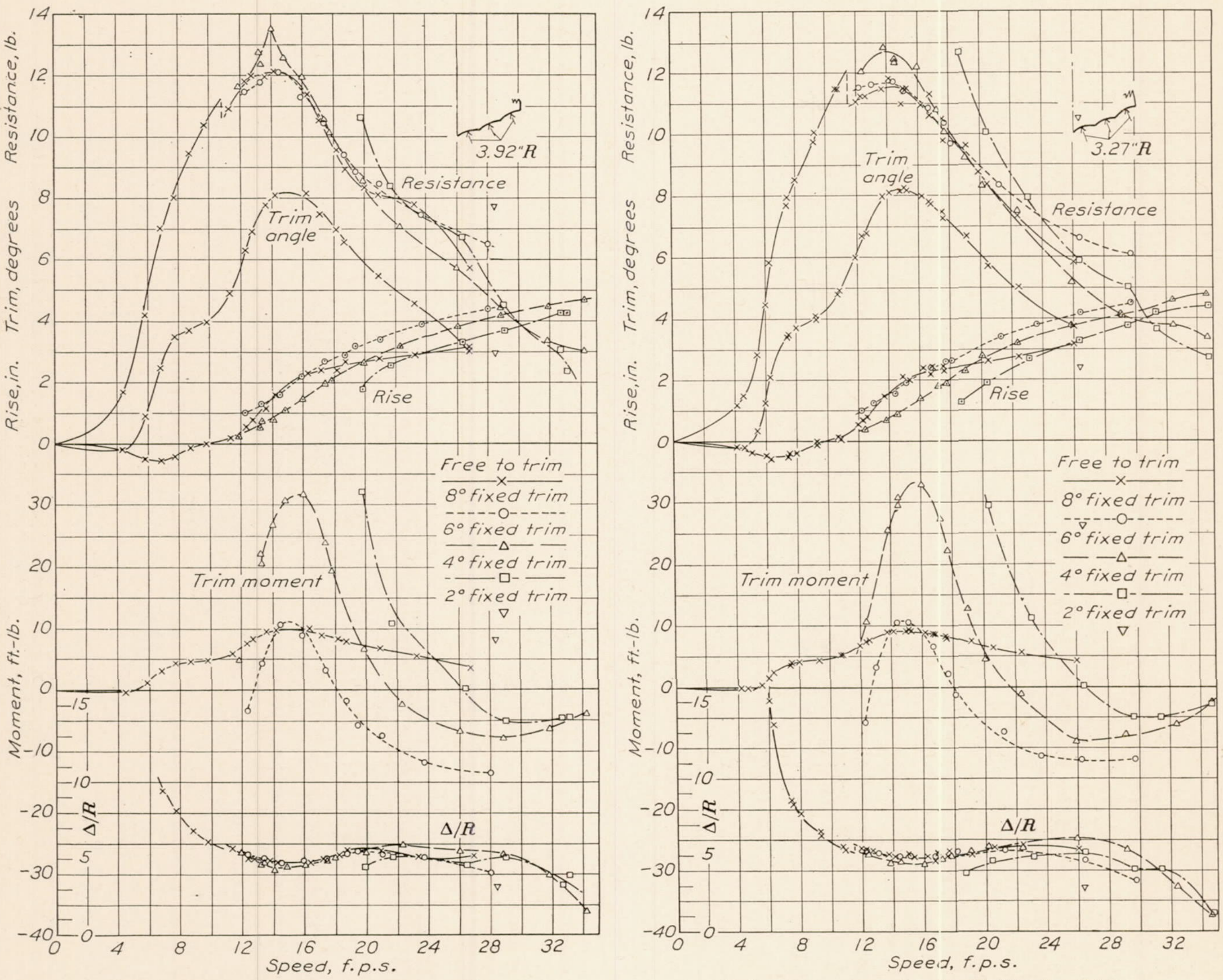
A further general conclusion is that a moderate hook on the step is an advantage. The present data are insufficient to formulate a rule. However, the proportions which gave the best result in these tests should hold for generally similar forms and applications.



(d) Performance curves of model with 0.246-inch hook.



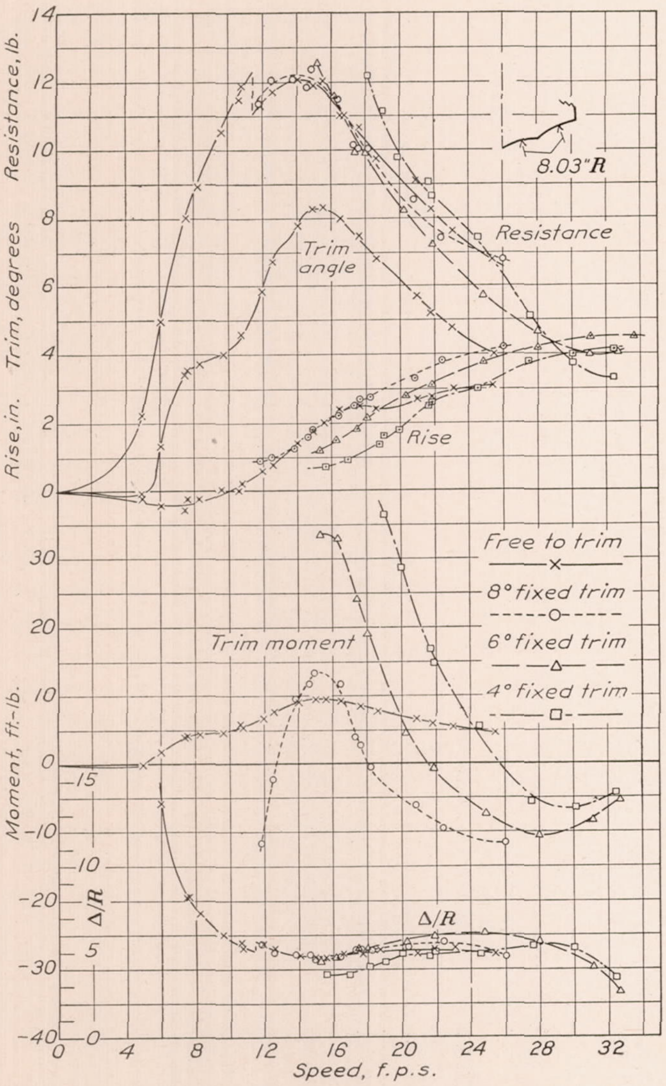
(e) Comparison of four speed-resistance curves.



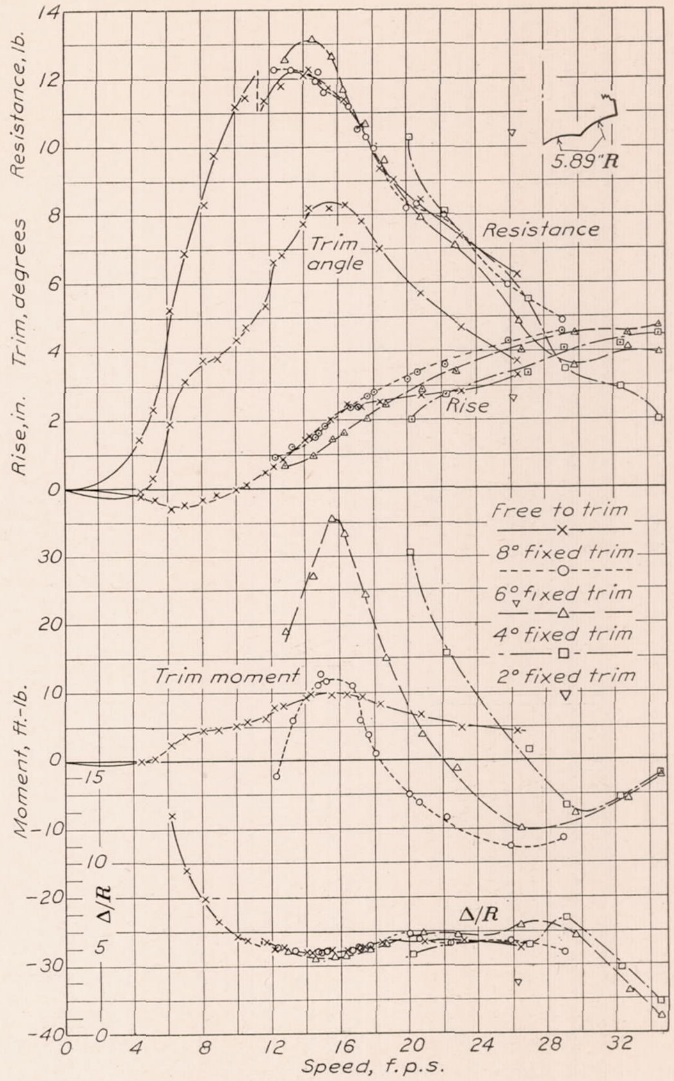
(a) Performance curves of model with three shallow flutes.

(b) Performance curves of model with three deep flutes.

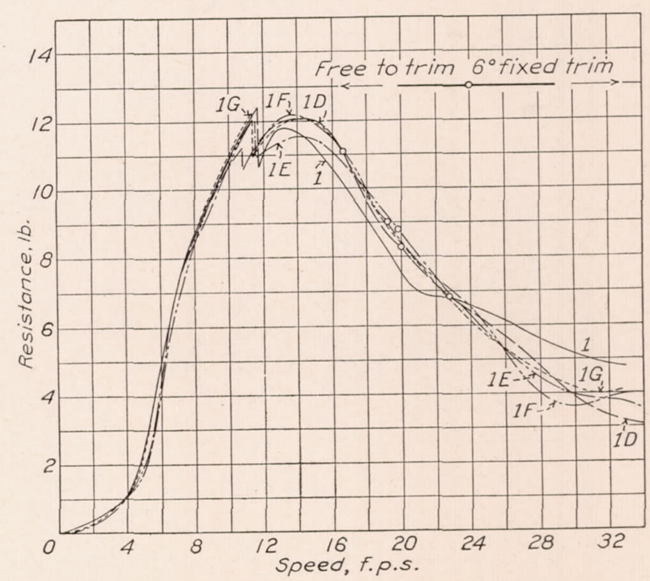
FIGURE 15.—The effect of fitting flutes in the forward bottom of the model of the *PH-1* flying-boat hull.



(c) Performance curves of model with two shallow flutes.



(d) Performance curves of model with two deep flutes.



(e) Comparison of four speed-resistance curves with that of original model.

THE EFFECT OF FLUTED BOTTOMS

Longitudinal flutes have been fitted in the planing bottom of a float by several designers. The flutes usually produce a reduction in the spray thrown and as the craft rises on the step it would appear that they should give a reduction in the area of bottom wetted by the rising sheet of water and thus reduce the frictional resistance.

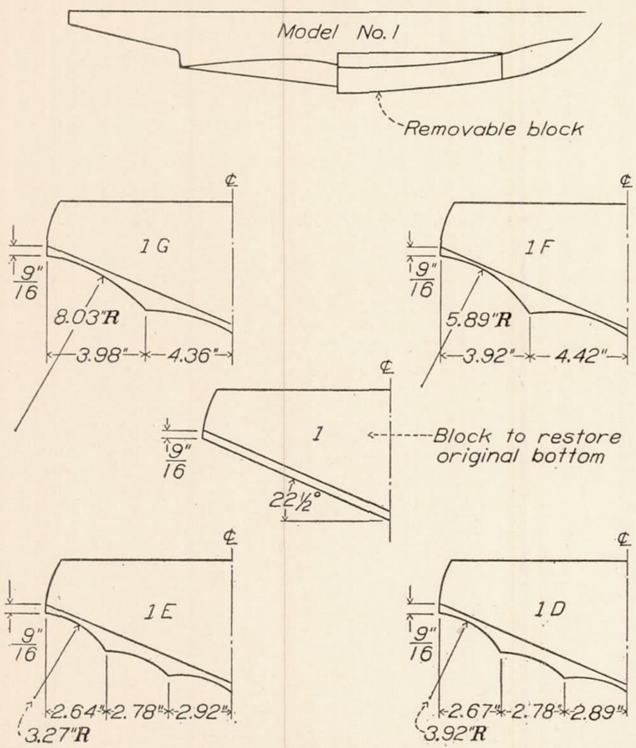


FIGURE 13.—Cross sections at the step of the model of the *PH-1* flying-boat hull showing the original and the fluted forward bottoms.

Test of Navy "PH-1" with flutes.—In order to obtain an idea of the effect of a relatively simple set of flutes in the bottom of a flying-boat hull the model of the *PH-1* which was used in the tests just described was modified, by fitting portable blocks in the bottom, to have successively four different types of flutes. The original cross section at the step and those produced by the four modifications are shown in figure 13. It will be seen that there are two shallow and two deep and three shallow and three deep flutes. The extent of the block containing the flutes is shown on the same figure. The appearance of the original model and the fluted blocks can be seen in figure 14.

The model was tested with the four modifications both free to trim and at fixed trims. During each test run the resistance and speed were recorded and the rise and trim, or trimming moment if at fixed trim, were observed and recorded. After the proper corrections had been made for windage and rise of towing gear the results were set forth as the curves forming figure 15 (*a*) to (*e*). The curves obtained from tests in the original form, with no hook on the step, are included for comparison.

Discussion of results.—In figure 15 (*e*) are shown the assembled curves for the resistance free to trim and at 6° fixed trim. The curves for the two conditions have been extended until they intersect and this point of intersection is indicated by a circle.

An examination of the curves shows that the fitting of the fluted bottom has had little effect on the resistances. All the curves have the same general character with a discontinuity at a speed of about 11 feet per second. Before this discontinuity appears the model is running as a displacement craft and the change produced by the flutes is small. After the discontinuity has been passed the model is more nearly a planing craft but the resistance is held up by the interference in the flows from the respective flutes. When the model has risen to where it is running on a single flute on each side the flow cleans up and the area of bottom wetted is sharply reduced below that wetted with the plain bottom. From this point the resistance of the fluted bottoms lies below that of the plain bottom.

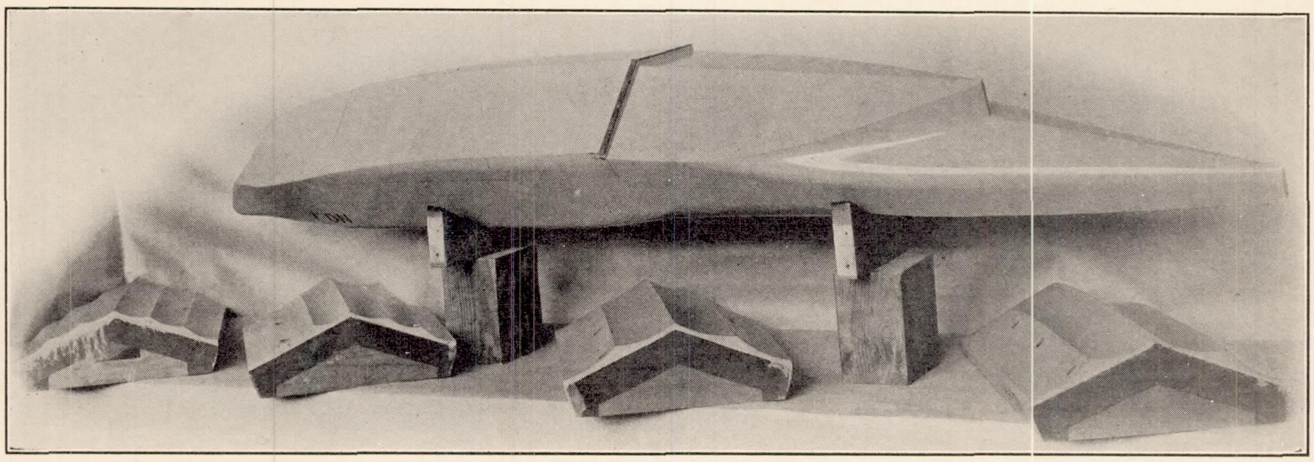


FIGURE 14.—Model of the *PH-1* flying-boat hull showing the original form and the blocks to be inserted to give the four fluted forward bottoms.

As is usually the case, observation of the flow around the bottom gave many interesting hints. At the hump and at certain stages after the hump was passed the number of flutes in the bottom could be told by the number of clearly marked separate jets in which the water issued from under the bottom.

In general, the fluted bottoms threw less spray than the plain bottom. However, a spray strip at the chine on the original model made the spray from the plain bottom as little as from the fluted bottom. A report on the effect of spray strips on the performance of this model is in preparation.

From the results of this test it may be concluded that fluting the bottom of a flying-boat hull of a good design, such as was used in this case, will probably give no very large changes in performance. Any improvement in spray thrown can probably be equaled by a proper spray strip on the original model.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *June 9, 1933.*

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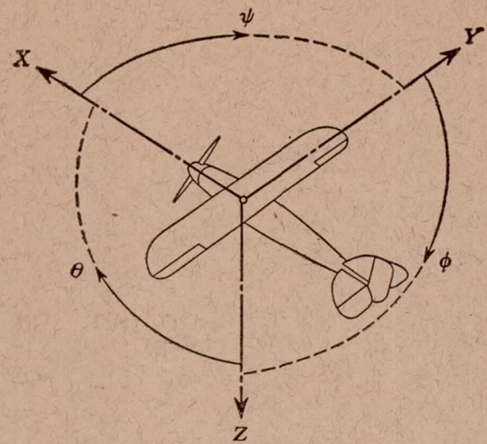

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	rolling	L	$Y \longrightarrow Z$	roll	ϕ	u	p
Lateral	Y	Y	pitching	M	$Z \longrightarrow X$	pitch	θ	v	q
Normal	Z	Z	yawing	N	$X \longrightarrow Y$	yaw	ψ	w	r

Absolute coefficients of moment

$$C_l = \frac{L}{qbS} \qquad C_m = \frac{M}{qcS} \qquad C_n = \frac{N}{qbS}$$

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter.
p, Geometric pitch.
p/D, Pitch ratio.
V', Inflow velocity.
V_s, Slipstream velocity.
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$.
C_s, Speed power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$.
η, Efficiency.
n, Revolutions per second, r. p. s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg/m/s = 550 lb./ft./sec.
1 kg/m/s = 0.01315 hp.
1 mi./hr. = 0.44704 m/s
1 m/s = 2.23693 mi./hr.

1 lb. = 0.4535924277 kg
1 kg = 2.2046224 lb.
1 mi. = 1609.35 m = 5280 ft.
1 m = 3.2808333 ft.