NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 753

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METHODS USED IN THE NACA TANK FOR THE INVESTIGATION OF THE LONGITUDINAL-STABILITY CHARACTERISTICS OF MODELS OF FLYING BOATS

By ROLAND E. OLSON and NORMAN S. LAND

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
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	horsepower (metric)	----------	horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s^2 or 32.1740 ft/sec^2

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

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

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

V True air speed

q Dynamic 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_0 Profile drag, absolute coefficient $C_{D0}=\frac{D_0}{qS}$

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

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

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

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

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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METHODS USED IN THE NACA TANK FOR THE INVESTIGATION OF THE LONGITUDINAL-STABILITY CHARACTERISTICS OF MODELS OF FLYING BOATS

By Roland E. Olson and Norman S. Land

SUMMARY

Recent trends in the design of flying boats, such as high wing loadings (high get-away speeds) and high load coefficients (relatively narrow hulls) have made the problems associated with longitudinal stability of primary importance. The need for additional research on longitudinal stability or porpoising is recognized and the stability characteristics of models of several flying boats have been determined in NACA Tank No. 1. These investigations were made for the purpose of (1) determining suitable methods for evaluating the stability characteristics of models of flying boats, and (2) determining the design parameters which have an important effect on the porpoising. This report is mainly concerned with the construction of suitable models, the apparatus, and the methods used in the tests. The effect of changes in some design parameters is discussed.

The models were dynamically similar to the full-size airplane. Dynamic similarity required the use of a complete model with wings, tail, and hull built to scale dimensions, the weight of the model being so disposed as to result in scale weight, balance, and pitching moment of inertia. The use of such models results in forces and motions similar to those of the full-size flying boat. A description of the construction of a typical model and the ballasting procedure used is presented.

For the purpose of investigating the stability characteristics of a model during take-off, two general methods are usually followed: (1) the range of trims at which the model is stable is determined for a series of constant speeds covering a practical range of operation, and (2) the variation in attitude and behavior of the model is noted during accelerated runs. It is found that, in general, there are two primary limits of stability: an upper limit of trim above which porpoising occurs, and a lower limit of trim below which porpoising occurs. Between these limits lies a range of stable trims which is the operating range for stable take-off. This stable range of trims forms the limitation on center-of-gravity locations and aerodynamic control-surface settings for stable take-offs. The upper trim limit has two branches. The higher branch defines the trims at which porpoising starts as the trim is increased, and the lower branch defines the trims at which stability is again reached as the trim is decreased.

An increase in model gross load is found to move the trim limits of stability to higher trims. An increase in the depth of step has no appreciable effect on the lower trim limit of stability but raises the upper trim limits to higher trims and reduces the violence of the porpoising.

INTRODUCTION

The problem of the longitudinal stability of flying boats while in motion on the water has become of major importance in the design of such boats because of the present trends in the construction of that type of craft. Flying boats are being designed with high wing loadings (increased get-away speeds), greater load coefficients (relatively narrow hulls), and high centers of gravity. These characteristics, not found in older designs, cause the flying boats to operate under conditions that, in general, have not been previously encountered. With these and other changes, the flying boat is apparently becoming more unstable while on the water and at the same time, in view of the increased get-away and landing speeds, a condition of stability is more essential now than previously. The resistance characteristics have become of secondary importance because of the increased power available in present engine designs.

The need for additional research on the problem of longitudinal stability, or porpoising, is recognized and models of several flying boats have already been tested at the NACA tank. Many of the forms have had poor characteristics of longitudinal stability, and changes in form have been suggested for the purpose of either correcting or reducing the porpoising tendencies. Models of new designs have been tested to determine under what conditions they are unstable, and changes in form have been made in an effort to insure stability for the full-size flying boat.

The present paper is devoted to the discussion of certain methods of testing dynamic models that have been found helpful in the determination of the longitudinal-stability characteristics on the water of a number of specific flying boats. It should be noted that these methods are still in the process of improvement and no method as yet gives a perfect or final answer. Consequently, both specific and general research must be continued for the purpose of improving knowledge of the problems associated with the appearance of dynamic instability.

The effects of similar modifications on the longitudinal-stability characteristics of these models will be compared and general conclusions may be drawn as to the importance of these modifications. These results should be of assistance in evaluating the effects of possible variations in the planing bottom of any particular model.

Research should not be confined to the investigation of definite forms but should be extended to include the determination, insofar as possible, of the necessary conditions that must exist in the design of the flying boat to provide stability on the water and the order of the importance of these conditions. The technique used in testing should be developed, with emphasis placed on duplicating full-size maneuvers. Additional information should also be obtained concerning the application of tank data and observations to the full-size airplane.

METHODS USED IN PREDICTING STABILITY CHARACTERISTICS

Theoretical.—Mathematical theories for determining the condition of stability of a flying boat while on the water have been suggested. Perring and Glauert (reference 1) were among the first to publish an approximate solution to the equations of motion for a flying boat. Klemin, Pierson, and Storer (reference 2) have presented a slightly different treatment of the same general method given in the British paper.

The amount of work necessary to determine the condition of stability by use of the method of reference 1 or reference 2 is extremely large. Aerodynamic and hydrodynamic data for the airplane must be available, and the actual computations are tedious. Until a more simple, less laborious, and more accurate method for determining the condition of stability by means of theoretical computations is developed, the need for tests of dynamic models in the towing tank will remain.

Observations made during the usual tank tests.—Predicting the stability characteristics of the model on the basis of observations made during the usual tank tests may lead to erroneous conclusions. The procedure followed in this type of test (reference 3) requires only that a model be geometrically similar to the full-size hull; the correct gross weight is obtained by counterbalancing the weight of the model and the weight of the towing gear. The mass that is moving vertically is thus greatly in excess of the weight corresponding to the gross weight of the aircraft. With the present type of towing gear, it would be impossible to obtain the correct mass moving vertically. The lift of the wings is simulated by a hydrofoil lifting device or dead weights, and no effort is made to duplicate the change in lift with change in trim, the damping effect, or the control moments of the aerodynamic surfaces. The models are generally constructed of pine or mahogany and no attempt is made to obtain the correct moment of inertia.

The porpoising characteristics observed during this type of test are only a very rough approximation of those for the full-size flying boat.

Research using dynamically similar models.—References 4, 5, and 6 report research conducted by the British in the Vickers and R.A.E. tanks with dynamic models, models with the proper geometric form and also the correct moment of inertia and mass moving vertically. These reports discuss the methods used and a few of the conclusions drawn from the results of the tests.

Research has been conducted at the NACA tank to investigate the stability characteristics of flying boats by use of dynamically similar models. The aerodynamic surfaces, wing and tail group, are a part of the model.

The remainder of this report will be devoted mainly to a discussion of the problems involved in the construction of the model, the apparatus for making the tests, and the methods of testing. In this discussion, data from the construction and tests of a model of a typical flying boat will be used for illustration and from the data some conclusions will be drawn as to changes in the form of the hull that will improve the stability characteristics.

MODEL

Selection of size of model.—In tank tests the results of model tests are converted to full size by applying Froude's law of comparison. According to this law, the hydrodynamic forces vary as the cube of the scale at a given value of the Froude number V^2/bg (where V is the speed; b, the beam of the model; and g, the gravity constant). It can also be shown that, neglecting scale effect, the aerodynamic forces vary in the same way with scale. Neglecting scale effect, the aerodynamic forces are a function of $\rho l^2 V^2$ (where ρ is the density of the air; l, a characteristic length; and V, the speed). At the same Froude number, V^2 varies as the first power of the scale and l^2 varies as the square of the scale; hence the aerodynamic forces vary as the cube of the scale.

If the model is built with a form similar to the full size and the gross weight is proportional to the cube of the scale, the hydrodynamic and aerodynamic forces on the model will simulate those on the full size, if scale effect is neglected. In order to reduce the error due to scale effect, the models are built as large as possible, the limiting condition being the width of the tank. (See fig. 1.)

Particulars of model.—The model used for illustration represents a hypothetical design for a modern flying boat of 133,000 pounds gross weight and is designated NACA model 101. The form of the hull was chosen from a series of streamline hulls originated at the NACA tank. Part of the series has been tested, but the results have not been published. A later extension of the series was made to include variation in the length-beam ratio, and it was from this last-mentioned family that the hull for model 101 was chosen.

The heights of the bow and stern were selected on the basis of the results obtained during tests of the original streamline hulls. The length-beam ratio is 6.54. The lines of the hull are given in figure 2; the typical sections, in figure 3; and the offsets, in tables I and II. The general arrangement of the complete model is shown in figure 4.

Important dimensions of the model are as follows:

	Full-size (feet)	*One-twelfth-size model (inches)*
Dimensions of hull:		
Beam, maximum	14. 25	14. 25
Beam, at step	13. 84	13. 84
Length of forebody	56. 02	56. 02
Length of afterbody	37. 15	37. 15
Length of tail extension	35. 24	35. 24
Length, over-all	128. 41	128. 41
Depth of step:		
Model 101BA, 2.8 percent beam	. 40	. 40
Model 101BB, 4.9 percent beam	. 70	. 70
Model 101BC, 7.0 percent beam	1. 00	1. 00
Angle of dead rise at step:		
Excluding chine flare	20°	
Including chine flare	18.5°	
Angle between keel lines at step	6.8°	

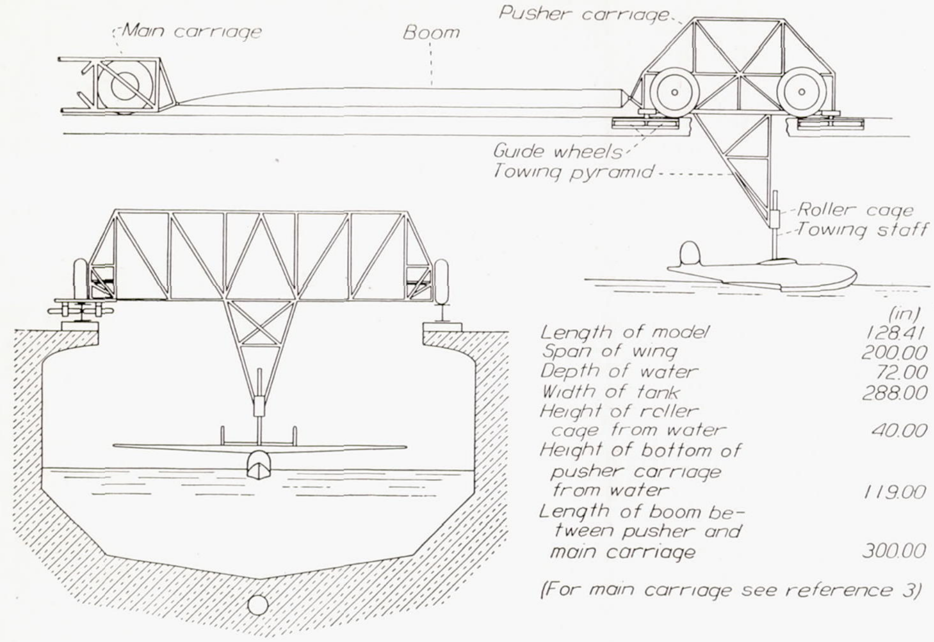

FIGURE 1.—General arrangement of pusher carriage for towing dynamic models.

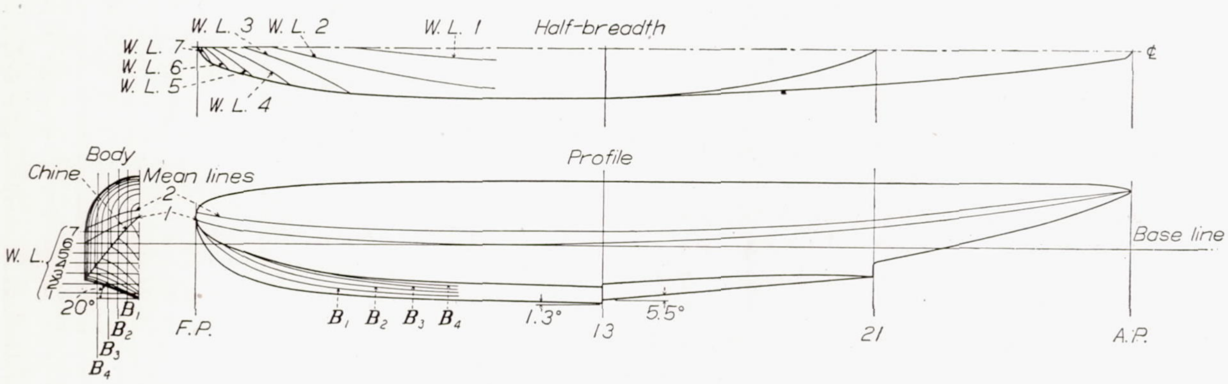

FIGURE 2.—Lines of model 101BA.

	Full-size	One-twelfth-seze model
Dimensions of wing:	*Square feet*	*Square inches*
Area	3, 700	3, 700
	Feet	*Inches*
Span	200	200
Root chord	28	28
Root chord, section	NACA 23021	
Tip chord	9. 33	9. 33
Tip chord, section	NACA 23012	
Angle of wing setting, to base line	5.5°	
Leading edge at root, aft of bow	41. 03	41. 03
Length M. A. C	20. 12	20. 12
Leading edge M. A. C. aft of bow	43. 79	43. 79
Leading edge M. A. C. forward of step	12. 23	12. 23
Taper ratio	3:1	
Aspect ratio	10.7	

Upper-surface ordinates at 35-percent chord lie on line perpendicular to center line of model. No twist.

Dimensions of horizontal tail surface:	*Square feet*	*Square inches*
Area	504	504
	Feet	*Inches*
Span	42. 0	42. 0
Chord, total	12. 0	12. 0

Dimensions of horizontal tail surface—Continued	*Full-size*	*One-twelfth-size model*
Chord, elevator	6. 0	6. 0
Section	NACA 0015	
Aspect ratio	3.5	
Loading conditions:	*Feet*	*Inches*
c. g. forward of step	7. 20	7. 20
c. g. above keel	13. 11	13. 11
c. g., percent M. A. C	25	
Gross loads:	*Pounds*	*Pounds*
All models (normal $C_{\Delta_0}=0.72$)	133, 000	76. 5
Also on model 101BC:		
$C_{\Delta_0}=0.62$	107, 800	65. 8
$C_{\Delta_0}=0.82$	142, 500	87. 1
Pitching moment of inertia about *c. g.*:	*Slug-feet* [2]	*Slug-feet* [2]
All models (normal)	149, 000	5. 97
Also on model 101BC (25-percent increase)	186, 000	7. 46
Mass moving vertically:	*Pounds*	*Pounds*
All models (normal)	133, 000	76. 5
Also on model 101BC		87. 1 95. 6 114. 7

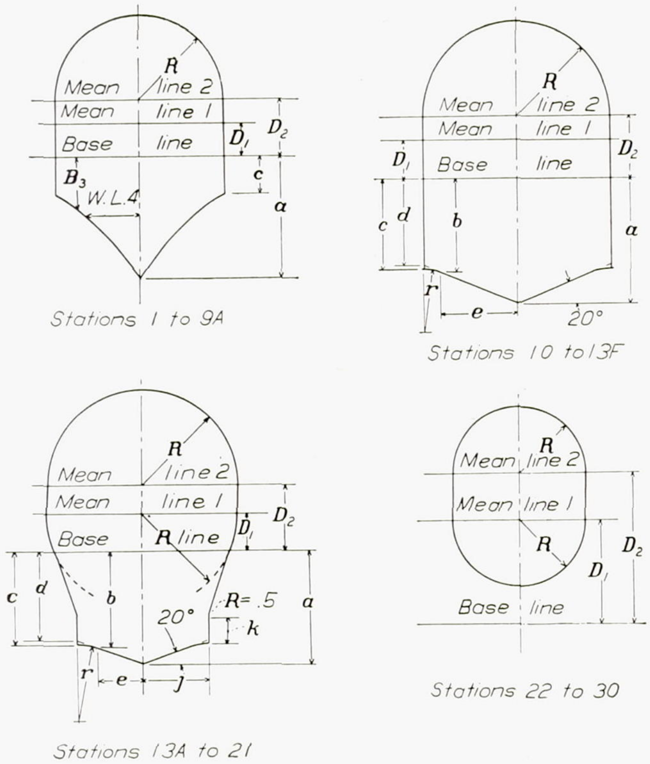

FIGURE 3.—Typical hull sections.

Figure 5 shows model 101BA assembled and ready for testing.

Construction of model.—In order that modifications may be easily made, the hull of this particular model is constructed in three sections. The bow section forms the portion of the hull forward of station 10. The main section extends from station 10 to the after perpendicular and is recessed to receive the third, or afterbody, section. Three afterbody sections were available for these tests giving three depths of main step. The wing and tail group are attached to the main section of the hull.

Figure 6 shows the type of construction used throughout the hull. Transverse frames with lightening holes are cut from 1/16-inch and 1/8-inch spruce plywood. A mean-line stringer of 1/16-inch plywood extends on each side from bow to stern. Other stringers are 1/4- by 1/4-inch balsa. Two relatively heavy bulkheads (1/8-inch plywood with no lightening holes) and a heavy horizontal platform (1/2-inch mahogany) are located at the position of attachment of wing and towing fitting. The bottom is planked with 1/8-inch balsa and the sides and deck are planked with 1/16-inch balsa. The hull is covered with profilm to prevent absorption of water by the balsa planking. The bottom and lower portion of the sides have two coats of gray pigmented varnish in addition to the profilm. The profilm is applied to the balsa skin in small sheets, or strips, with overlapping edges.

The same type of construction (fig. 7) is used in the wing. Ribs are plywood and stringers are balsa. A hollowed balsa leading edge forms the main spar. The skin is 1/16-inch

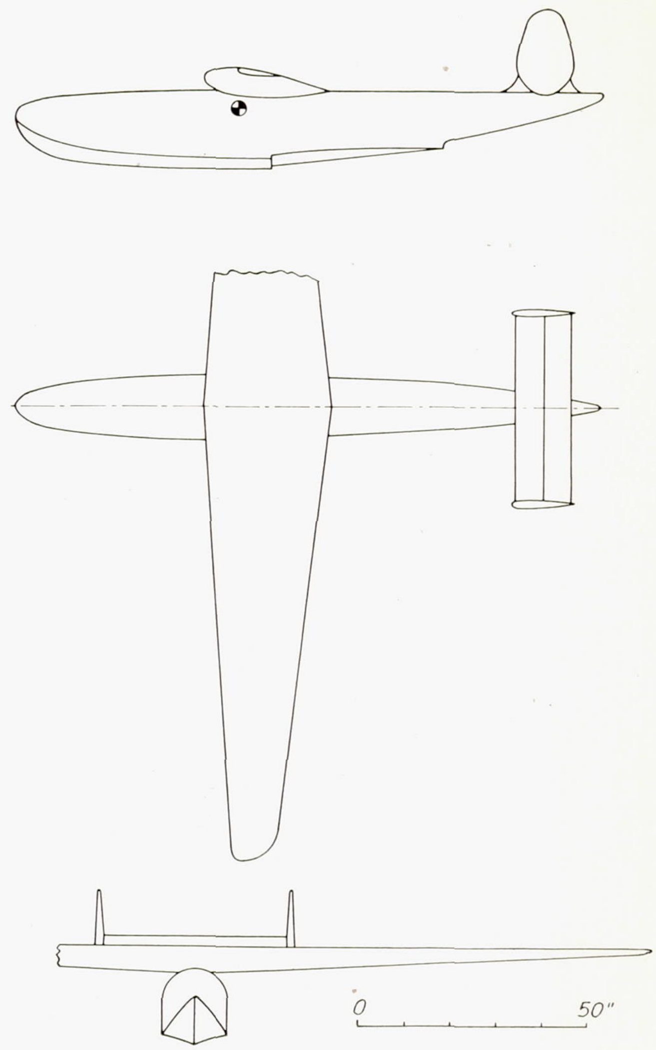

FIGURE 4.—General arrangement of NACA model 101.

balsa applied in diagonal strips. Like the hull, the wing is entirely covered with profilm and its undersurface was given two coats of gray pigmented varnish. The wing is bolted to the hull at a fixed location and with a fixed angle of incidence of 5½°.

The tail group is made up of four subassemblies: two vertical surfaces, a stabilizer, and an elevator. Construction of these surfaces is similar to that of the hull and the wing. Inasmuch as the lateral stability was not being investigated, the two vertical surfaces do not have movable rudders; instead, each is a single fixed surface of proper area to simulate rudder and vertical stabilizer. The settings of both elevator and stabilizer are independently and remotely controllable from the carriage by means of Bowden type cables.

Two duralumin rails are mounted in the forebody of the model to carry the ballast weights. The ballast can be moved fore and aft along the rails and adjusted vertically by means of spacers. The center of gravity is made to coincide with the pivot by adjusting the position of the ballast.

The moment of inertia is determined by swinging the model. Methods for swinging are described in the appendix.

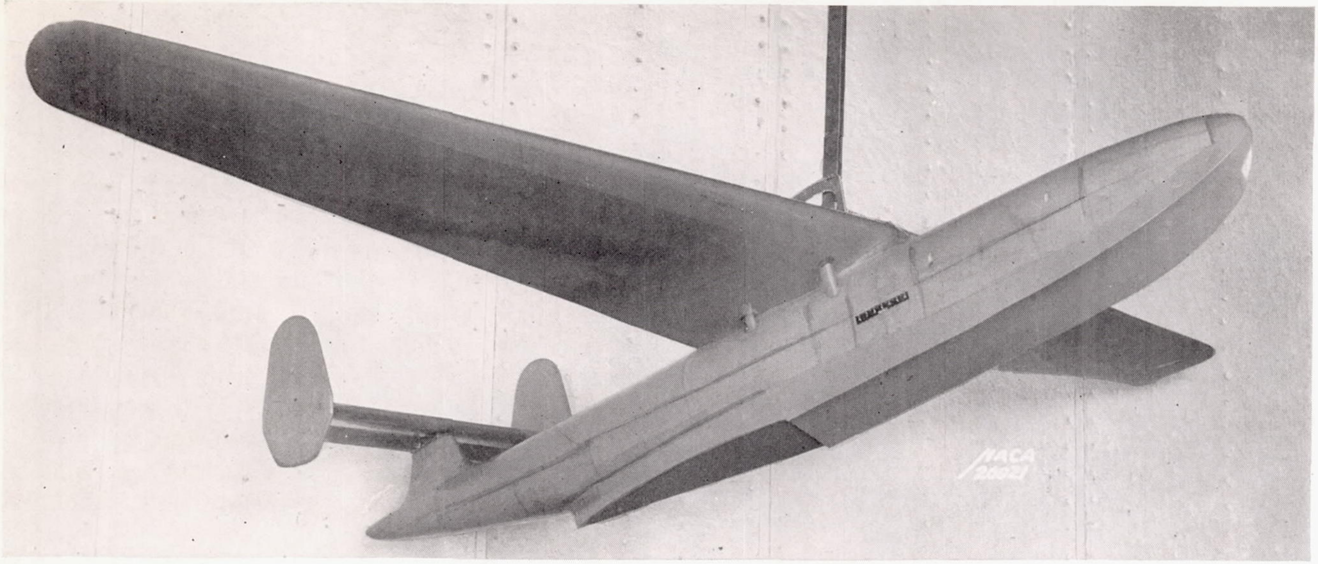

FIGURE 5.— Model 101BA assembled for testing.

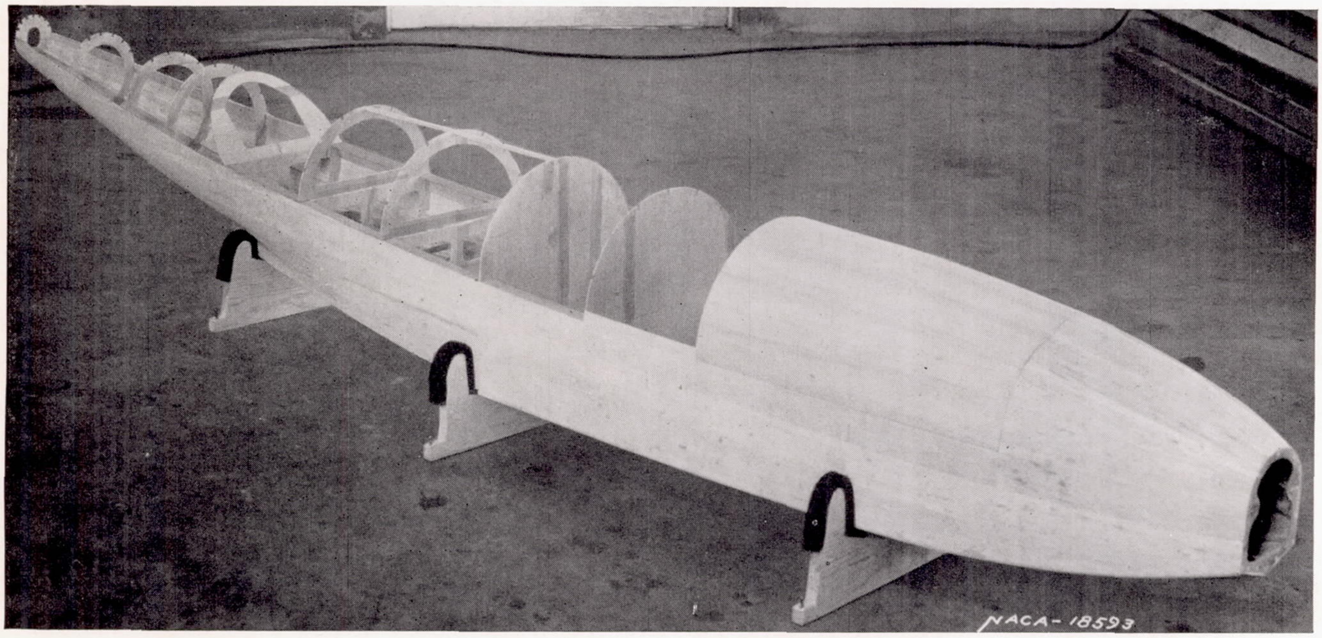

FIGURE 6.—Model 101. Construction of hull.

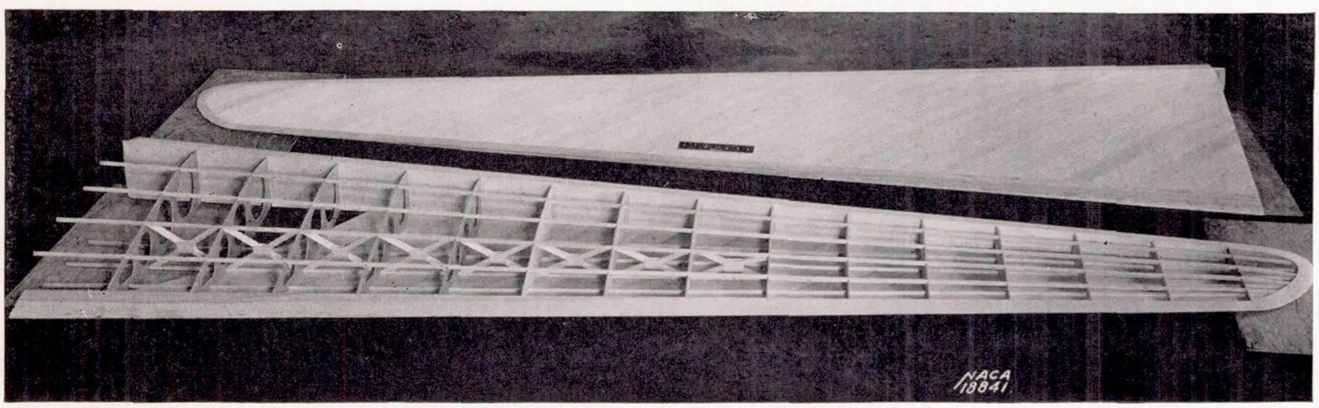

FIGURE 7.—Model 101. Construction of wing.

Relative contribution of parts of model to the total moment of inertia.—As a guide in the construction of future dynamic models, the main subassemblies of NACA model 101 were swung individually to determine the relative importance of each in the total moment of inertia of the whole model. All moments of inertia are in slug-feet^2. The data are assembled as follows:

Item	I_o about own *c. g.*	MR^2 transfer inertia to test *c. g.*	I about test *c. g.*	I about test *c. g.*, percent of total
Hull	2.32	0.11	2.43	40.7
Wing	.11	.12	.23	3.8
Horizontal tail	----------	1.25	1.25	21.0
Vertical tails		.43	.43	7.2
Ballast	----------	1.63	1.63	27.3
Totals	2.43	3.54	5.97	100.0

Note that the I_o of the tail surfaces was too small to measure, but the final contribution of the tail surfaces to the required test moment of inertia of the complete model is slightly greater than that of the ballast. Light construction of the tail surfaces and the after portion of the hull is therefore essential.

Departures from full-size form that permit more exact simulation of full-size behavior.—The model previously described may be considered a dimensionally and dynamically correct reproduction of a hypothetical flying boat. It has been found that such a model is primarily useful for comparing the relative stability of any forms tested. Nevertheless, the stability of any form tested on such a model may not reproduce exactly that of a similar full-size flying boat.

In order that a more accurate indication of full-size behavior may be obtained from the behavior of the model, certain modifications must be made to the true, scaled-down aerodynamic surfaces. These changes are necessitated by the low Reynolds number at which the models are tested. The low Reynolds number is due to: (1) practical limitations on size and speed, and (2) the necessity of running the hull at the proper Froude number. The result of these requirements is to reduce the angle of attack at which the surfaces stall and also the maximum lift coefficient.

An additional difficulty arises from the fact that the airspeed over the model is reduced to a value slightly below the water speed, because the air is dragged along by the towing carriage. A reduction in the total lift at any angle and speed is therefore inherent.

The low stalling angle and low maximum lift coefficient can be compensated for by adding leading-edge slats to the wing of the model. The data given in reference 7 have been used in designing such slats.

The low total lift may be compensated for by adding area to the scale-size wing, usually by extending the tips. Additional area may also be necessary on elevators to obtain the correct control moments.

The aerodynamic characteristics are determined by towing the model just clear of the water and measuring the total lift and trimming moment. Adjustments of slats, areas, and so forth may then be made on the basis of these results.

APPARATUS

In order to reduce the aerodynamic interference between the towing carriage and a dynamic model, the water level is reduced from that given in reference 3 resulting in a clearance between the model and the bottom of the carriage of approximately 10 feet. In these tests the model was towed from a small auxiliary carriage which was pushed by the main carriage. The relative positions of the model, the main and auxiliary carriages, and the tank are shown in figure 1. Figure 8 shows the model being towed under the carriage. With the model supported beneath the auxiliary carriage, the airspeed in the vicinity of the wing of the model is slightly lower than the carriage speed. With the model supported beneath the main carriage at this same low-water level, the airspeed is slightly higher than the carriage speed. In neither case is there any appreciable distortion of the direction of the air stream.

The auxiliary carriage, shown in figure 1, is of welded-steel-tube construction with four supporting wheels and two pairs of guide wheels. All wheels have pneumatic tires. An inverted pyramid made of steel tubing and extending below the carriage supports a roller cage. The roller cage consists of two sets of ball-bearing rollers, located about a foot apart vertically. Each of these sets of rollers is made up of eight rollers located two on each side of a 2- by 1-inch rectangle. A vertical towing staff of rectangular section, and of the above dimensions, is guided by the roller cage. The model to be tested is pivoted at the lower end of the towing staff, the pivot being located at the center of gravity of the ballasted model. The model is thus free to pitch about its center of gravity, at the lower end of the staff, and rise vertically with the staff. Restraint in yaw and roll is provided by the roller cage.

For the usual stability tests, trim is read from an indicator located on the model.

PROCEDURE

For the purpose of investigating the stability characteristics of flying boats in the NACA tank, two general types of test procedure are usually followed: (1) The range of trims at which the model is stable is determined for a series of constant speeds covering a practical range of operation; and (2) the variation in attitude and behavior of the model is noted during accelerated runs.

Constant-speed runs.—In general, there are two primary limits of stability: an upper limit consisting of two parts (the upper limit, increasing trim; and the upper limit, decreasing trim) and a lower limit. Changes in trim beyond the upper limit, increasing trim, or the lower limit result in porpoising.

During the early investigations, the tail was set at fixed angles and the trim and condition of stability were noted at a series of tail settings and constant speeds. The model assumed free-to-trim attitudes, and the condition of stability was noted after a small initial pitching motion had been applied. If the model was violently unstable, the trim was determined by restraining the model in pitch with two opposite vertical forces applied to the tail and by gradually reducing

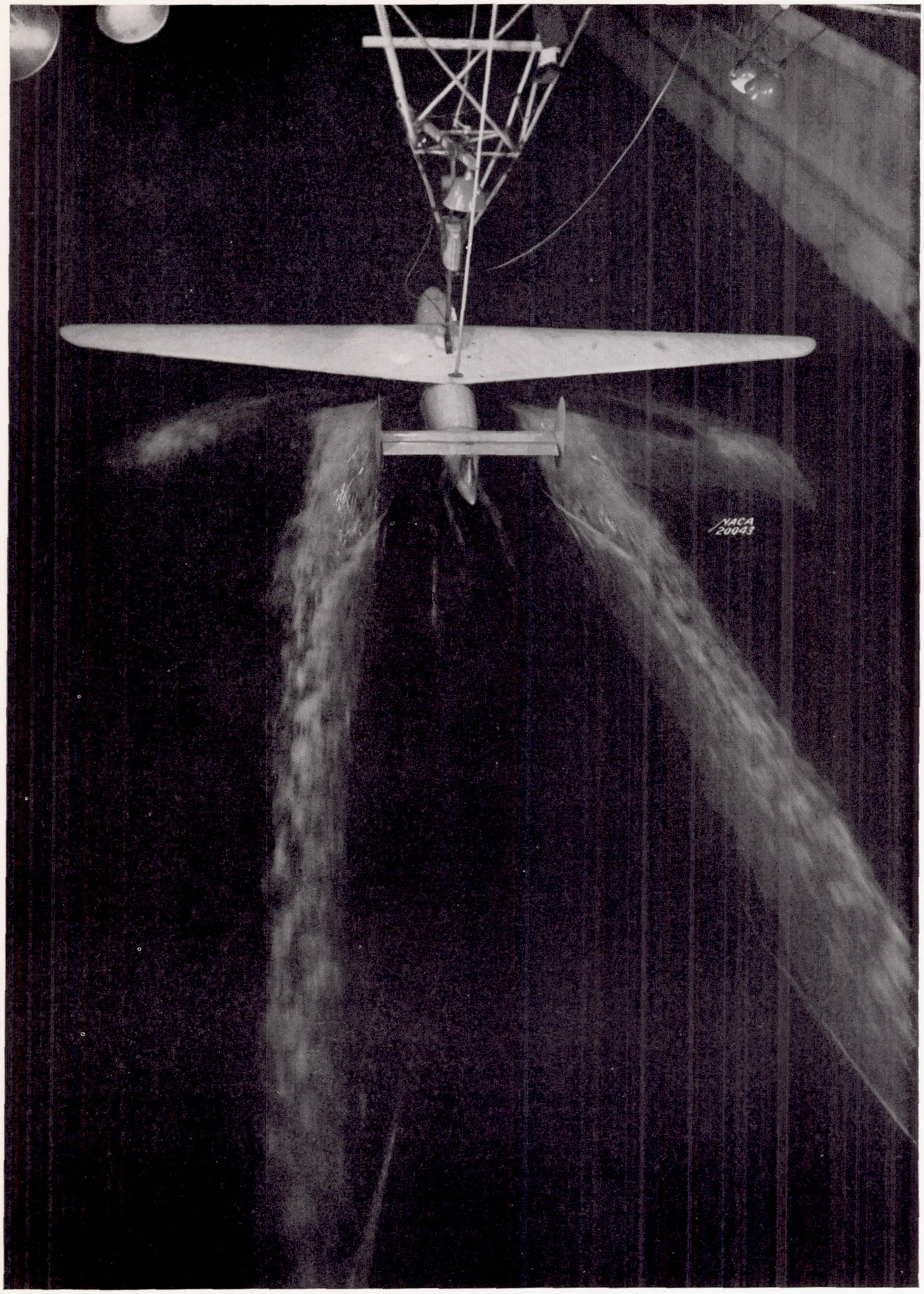

FIGURE 8.—Model 101 being towed under auxiliary carriage.

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these forces until, at the instant of release, the forces were approximately zero. The trim was read at the instant of release before an appreciable amplitude of porpoising developed.

By the investigation of the condition of stability for a number of settings of the tail, the trims at which the model will be stable can be determined.

The model is likewise run at a series of constant speeds with the position of the tail group controlled by an operator on the carriage. At each speed the trim of the hull is changed by adjusting the elevator and stabilizer positions until the available maximum or minimum trims are obtained or until porpoising motion is noted. The trim at which porpoising motion is first observed is designated a limit of stability. Typical curves are shown in figure 9.

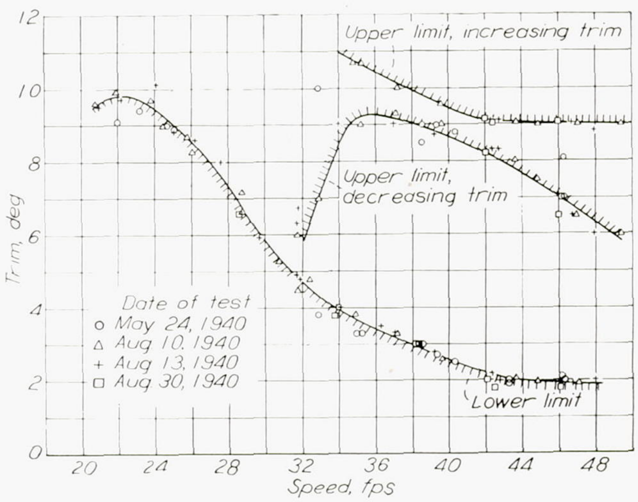


FIGURE 9.—Model 101BC. Scatter of points obtained during tests of model 101BC.

The lower limit of stability is obtained by decreasing the trim and usually appears just over the hump speed as the afterbody comes clear of the water. This limit is present over the remainder of the take-off.

The upper limit of stability (increasing trim) generally appears at intermediate planing speeds and is reached by increasing the trim until porpoising occurs. Because the trim of the hull is high, this porpoising is often referred to as "high-angle porpoising."

After the upper limit of stability (increasing trim) has been exceeded and porpoising is started, the elevators are moved to produce a lower trim and stop the motion. The model does not become stable as the upper limit (increasing trim) is again reached. Often the trim must be decreased by several degrees below this limit, before stability is established. When the model becomes stable, there is generally a sudden decrease in trim indicating that an excess of control moment had to be applied to stop the porpoising. The trim is noted just before this sudden decrease and is designated the upper limit, decreasing trim.

If the elevator control is insufficient to reach the upper limit, the model is jumped to a high trim by a sudden change in the angle of attack of the elevators. This maneuver sometimes starts porpoising that continues until the trim is decreased to the upper limit, decreasing trim.

Accelerated runs.—Accelerated runs are used for determining the stable positions of the center of gravity and for locating the best position of the step. These tests are made with the tail group at fixed angles of attack. At prearranged speeds (intervals of 5 fps) during the acceleration, the trim of the model is read and the behavior noted. This procedure is repeated at several settings of the tail group. The acceleration is continued to get-away speed unless the porpoising becomes too violent, in which case the model is taken out of the water. For this type of test the get-away speed of the model should logically be attained in a time equal to that for the full-size multiplied by the square root of the scale. If too rapid an acceleration were used, the time available for making readings would be insufficient. A lower rate of acceleration is therefore applied, and emphasis is placed on the reproducing of the rate of acceleration in successive runs. Get-away speed generally is reached in 30 or 40 seconds. The effect of changing the rate of acceleration will be discussed later.

If a specific design is being investigated, the control moment produced by the tail should correspond to that of the full size. This control moment is checked by making an aerodynamic test in which the model is towed just clear of the water, and the lift and the control moments are read from dynamometers located in the supporting cables.

A variation of the accelerated-run method of testing is used in investigating take-off and landing characteristics. The rate of acceleration of the carriage is increased and the model is flown off and landed at different attitudes. Motion pictures permit a more detailed study of the behavior.

RESULTS AND DISCUSSION

Constant-speed tests.—Inasmuch as most of the investigations were made using model 101BC (1.00 inch, depth of step), the results obtained with this model will be discussed in detail.

The data plotted in figure 9, representing the limits of stability for model 101BC, show a considerable scatter of points, especially between tests made on different dates. This scatter may be partially explained by the fact that the planing bottom near the step could not be maintained as smooth as would be desirable. Because of the severe porpoising to which the model had been subjected during these tests, it was necessary to repair the covering on the forebody bottom near the main step on several occasions. Each time the wood was found to be water-soaked. For one test, this planing bottom was deliberately roughened by fitting strips of profilm, which were attached just forward of the main step and loose at the trailing end. The scatter of points was increased and the lower limit of stability was substantially decreased. These results emphasize the necessity of maintaining the same condition of smoothness throughout the tests if the results obtained with different modifications are to be compared.

The porpoising motion that appears on departures in trim below the lower limit is mainly motion in pitch and generally damps rapidly as the trim is increased. The accuracy of the determination of this limit is about $\pm\frac{1}{4}°$ for these tests.

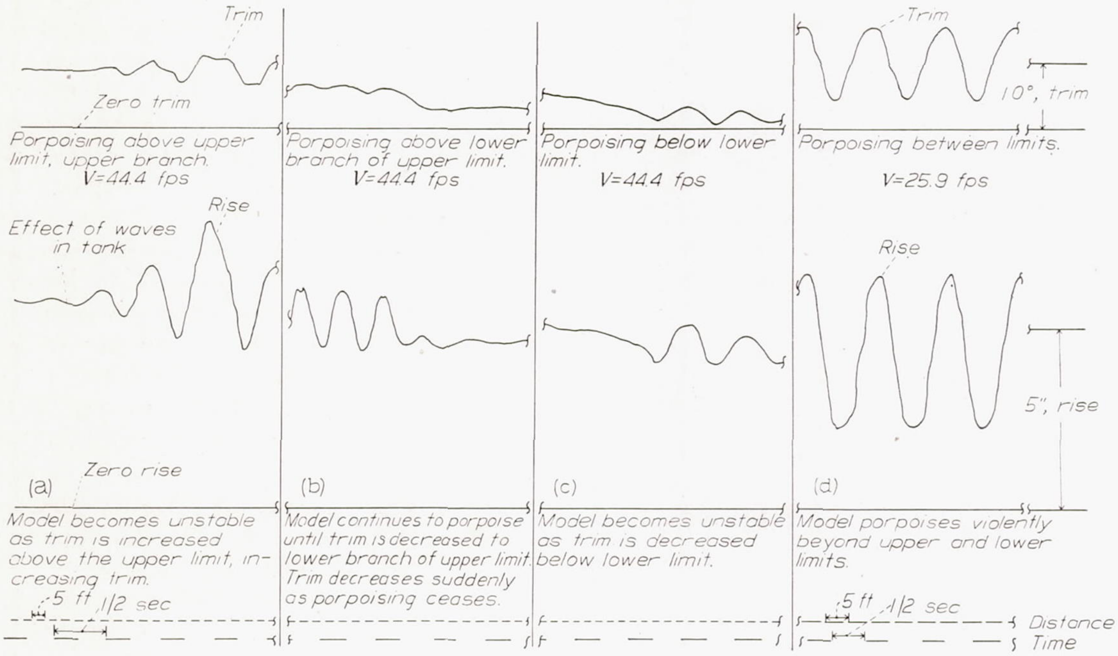


FIGURE 10.—Model 101BC. Trim and rise records of porpoising at upper limits, lower limit, between limits.

The porpoising just beyond the hump speed is not particularly violent and the amplitude of the motion increases slowly. The reverse is also true; the amplitude decreases slowly when the trim is again increased, indicating that the damping forces are small. This characteristic was particularly evident for all the modifications of model 101.

Porpoising at the upper limit is generally violent. After a very slight departure in trim above the upper limit, the porpoising motion increases rapidly and appears to be almost independent of the amount of the departure in trim above the limit. The motion is mainly in rise, and the model appears to bounce on the main step with relatively little vertical motion at the second step. The variation of the trim and rise during this porpoising is shown in figure 10(a). The large variation in rise is evident from these records. The accuracy of determination of the upper limit (increasing trim) is about $\pm\frac{1}{4}°$ for these tests.

If the elevators are returned to the setting at which the model was stable just before the porpoising began, the motion will not stop. Further decrease in trim is necessary to recover stability. The trim at which porpoising ceases (upper limit, decreasing trim) is determined in these tests to an accuracy of about $\pm\frac{1}{2}°$. At 48 feet per second (fig. 9) the model did not start porpoising until a trim of 9° was exceeded, but a recovery from this instability could not be made until the trim was decreased to almost 6°. With a stable condition at 48 feet per second there is a range of trims of about 7° in which the model does not porpoise. When porpoising at high angles is started, however, this range of stable trims is reduced to about 4°.

A record of the trim and rise during a recovery from this type of porpoising is shown in figure 10(b). This record illustrates the sudden decrease in trim as porpoising stops.

The presence of the upper limit, decreasing trim, may account for the violent porpoising that occurs in making stalled landings with some flying boats which, at the same time, apparently have no porpoising tendencies during the take-off.

At high speeds the lower limit is very definite and the amplitude of the porpoising rapidly increases with departure in trim below the limit. Most of the dynamic models tested in the tank show this characteristic. A record of the trim and rise during this porpoising is shown in figure 10(c).

At low speeds, approximately 26 to 31 feet per second, another variation in the porpoising was observed. If the trim is very suddenly increased to a high value, either by changing the elevator angle or by starting violent porpoising because of a large decrease in trim below the lower limit, a porpoising motion that is entirely uncontrollable may be established. The amplitude in several cases was greater than 10°. The lower extreme of the trim lies below the lower limit. The upper extreme is a higher trim than can be obtained with the available control moment and probably lies above an upper limit. A recovery by use of the elevators was impossible; the model was usually removed from the water to prevent its being damaged. Figure 10(d) shows the variation in trim and rise during this porpoising.

The condition of stability obtained with fixed settings of the tail may be compared with the limits of stability obtained by changing the angle of incidence of the tail surfaces

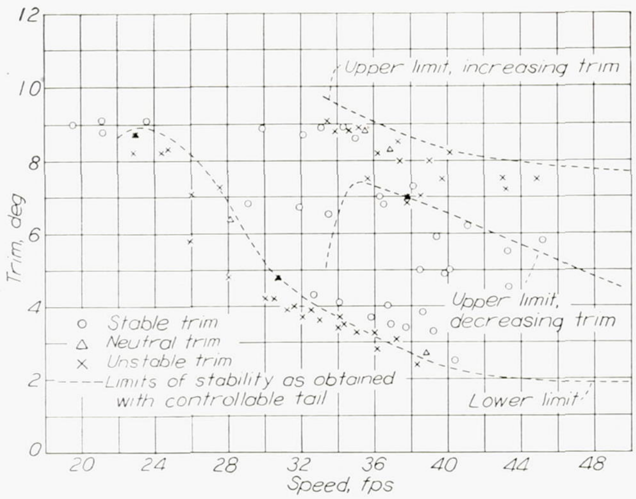


FIGURE 11.—Model 101BA. Illustration of condition of stability as obtained by tests with fixed tail settings and varied tail settings.

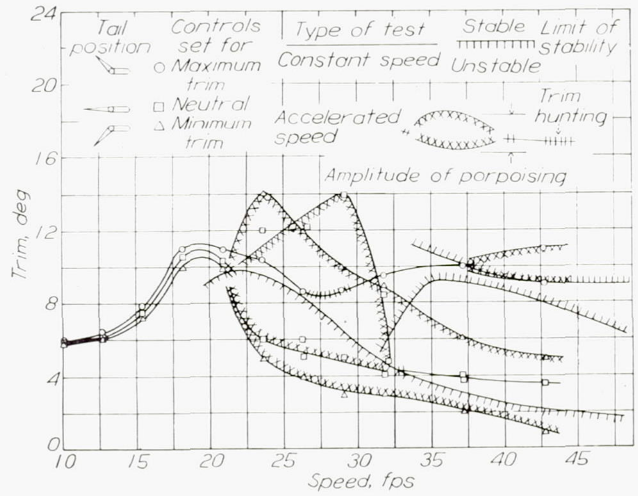


FIGURE 12.—Model 101BC. Stability characteristics obtained during accelerated and constant-speed runs. Load at rest, Δ_0=76.5 pounds; mass moving vertically, 76.5 pounds.

until porpoising occurs. Such a comparison is shown in figure 11. The results obtained by either procedure are substantially the same. This agreement indicates that any small moments that may be introduced by the presence of the Bowden cable are negligible.

As a rule, when tests are made at constant speeds, the stability characteristics are determined for only one position of the center of gravity. Modifications of the model are then tested in an effort to determine the changes that will increase the range of stable trims. Available information indicates that the principal effect of moving the center of gravity is the change in pitching moment that results in a change in the trim.

An increase in the range of stable trims would be expected to increase the range of stable positions for the center of gravity unless the modification produces a comparable change in hydrodynamic moment. In order to determine the range of stable positions for the center of gravity, tests are ordinarily made at accelerated speeds.

Accelerated runs.—Results obtained by making tests at accelerated speeds are plotted in figure 12. The limits of stability obtained at constant speeds are also shown in figure 12. As the trim during the accelerated runs crosses the limit of stability, the model begins to porpoise and continues porpoising until the trim is again in a stable region. In this respect the two methods give fairly consistent results.

If the control moment and lift of the full-size flying boat are simulated on the model, this method gives a rapid indication of the stability. Only settings of the elevator used in actual flight need to be investigated. This method has been used to determine the range of positions for the center of gravity at which the model is stable.

If the acceleration is small, the amplitude of porpoising may become large because the trim of the model is in an unstable region for a long period of time. With a more rapid acceleration the model passes through an unstable region without developing an appreciable amplitude of porpoising. This effect has been noted in tests of several models. The acceleration must therefore be reproduced as nearly as possible for tests of all modifications of a model if the results are to be comparable.

The results obtained by either method of testing are influenced by waves. With accelerated runs, however, the presence of the waves will have a greater effect on the results. Each reading is a part of the time history of the variation of the trim, and the readings at any particular speed are not independent of previous readings. If the trim is suddenly increased as the model passes through a wave, porpoising may be started and the readings taken immediately thereafter are changed by this initial porpoising. For this reason all runs are made with about the same time interval between runs and about the same degree of roughness of the water.

In the case of tests at accelerated speeds the condition of the waves in the tank, the variations in rate of acceleration, and the general difficulty of reading trim during propoising cause considerable scatter of the points when the results are plotted. If the stability characteristics of the model are particularly poor, it is very difficult to obtain data showing a systematic variation that tests of other models (by the same method) indicate is present.

Effect of variations in moment of inertia.—The effect on the porpoising characteristics of a change in moment of inertia is of interest because it is often necessary or desirable to make tests at other than the design values. If the construction of the model is not sufficiently light, the moment of inertia of the unballasted model may be such that it is impossible to obtain balance about the center of gravity without exceeding the design value for the moment of inertia. When several loads are being investigated, it is usually sufficient and most convenient to use one value of the moment of inertia for all the loads.

In order to determine the effect of variation in the moment of inertia on the limits of stability, model 101BC was run with a 25-percent excess moment of inertia, the gross load and mass moving vertically being kept constant.

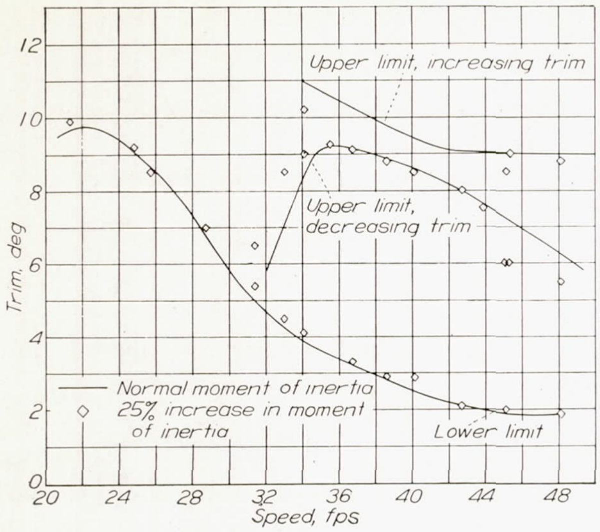


FIGURE 13.—Model 101BC. Effect of increasing moment of inertia. Constant-speed runs.

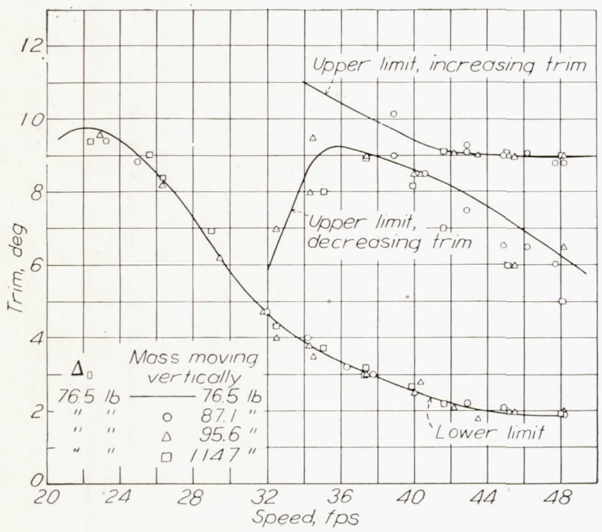
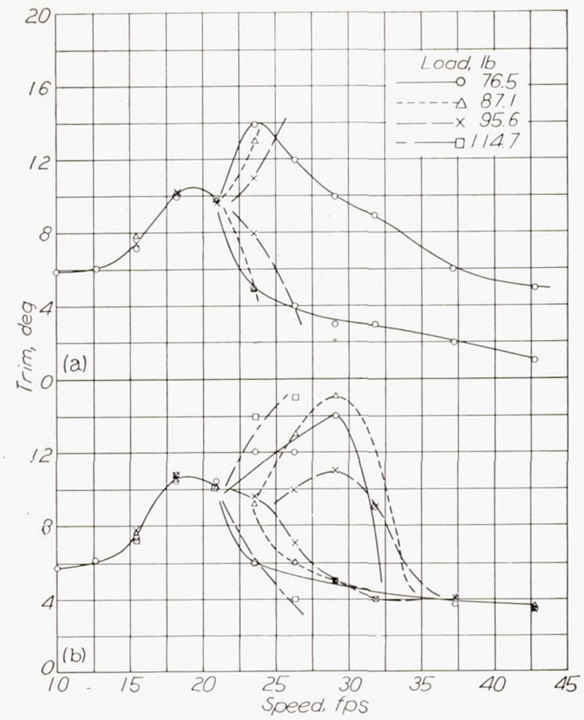


FIGURE 14.—Model 101BC. Effect of increasing mass moving vertically. Constant-speed runs.

The limits of stability for the normal condition (5.97 slug-ft ^{2}) and for a 25-percent excess (7.46 slug-ft ^{2}) are shown in figure 13. The excess moment of inertia has little effect on the limits of stability within the accuracy of the tests, the only measurable difference being at the upper limit, decreasing trim. Since this limit is determined by a recovery from an existing unstable condition, some change would be expected with a change in the moment of inertia. A precise adjustment of the moment of inertia of a model to the design value is, therefore, not critical if the limits of stability are to be determined from constant-speed runs. If several conditions of loading are being investigated, an average value of the moment of inertia may be used for all the loads.

Unfortunately, comparable data were not obtained at accelerated speeds. Tests of other models indicate, however, that very large departures from the design value of the moment of inertia do influence the results.



(a) Elevator full down (minimum trim).
(b) Elevator neutral (neutral trim).

FIGURE 15.—Model 101BC. Effect of varying the mass moving vertically on the amplitudes of porpoising.

Effect of variations in mass moving vertically.—The effect of varying the mass moving vertically (model 101BC) on the limits of stability is shown in figure 14. The mass moving vertically was increased by adding a weight to the towing staff and an equal counterweight, thus keeping a constant load on the water. The normal mass moving vertically (76.5 pounds) was increased by 14 percent, 25 percent, and 50 percent.

The lower limit and the upper limit, increasing trim, are unaffected by the variations in mass moving vertically, within the limits of accuracy of the tests. The upper limit, decreasing trim, is shifted to lower trims as the mass moving vertically is increased. Such a change is expected because this limit represents the trim of recovery from an already existing porpoising condition.

Figure 15 shows similar data obtained by accelerated runs for two settings of the tail group. In general, an increase in mass moving vertically tends to delay the increase in amplitude of porpoising. With neutral elevators and 95.6 pounds moving vertically, the amplitude apparently did not have time to develop. With 114.7 pounds moving vertically, the porpoising became unmanageable at a lower speed. This behavior is probably due to the presence of waves in the tank. With the tail set for minimum trim, the increase in amplitude of porpoising was definitely delayed as the mass moving vertically was increased. With this setting of the tail and excess mass moving vertically, the model was removed from the water soon after porpoising began, to prevent its being damaged.

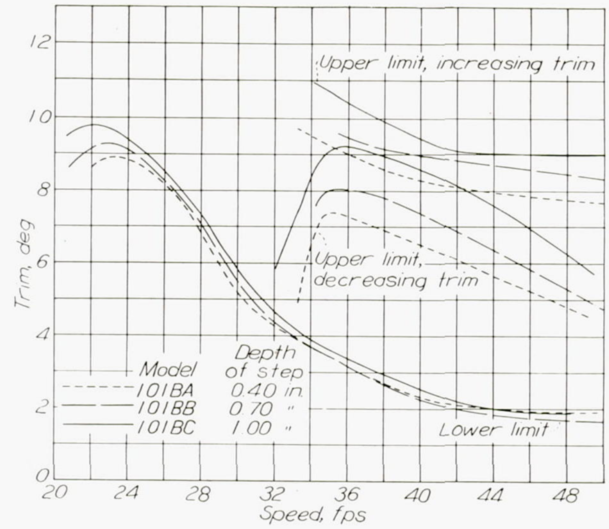


FIGURE 16.—Model 101. Effect of depth of step on limits of stability.

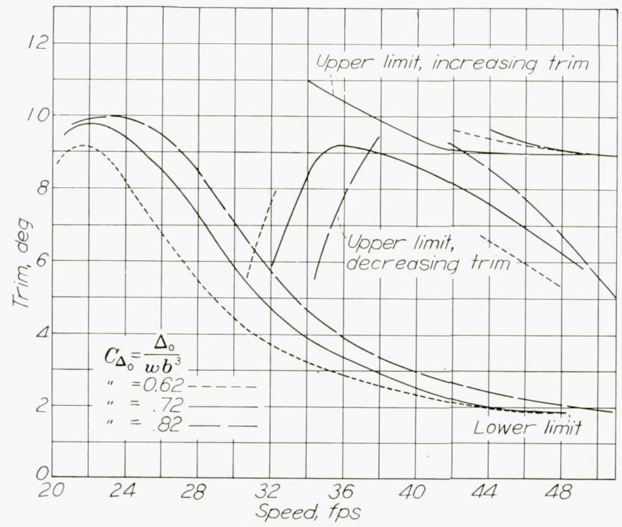


FIGURE 17.—Model 101BC. Effect of load coefficient on limits of stability.

Effect of variations of depth of step.—The limits of stability, with three depths of step, are shown in figure 16. The change in the lower limit is very small and is probably caused by changes in the condition of the planing bottom rather than by the increase in depth of step. No appreciable change is expected because the model is planing on the forebody alone, and the only water striking the afterbody is the spray from under the forebody, which occurs at high speeds.

The upper limit of stability, increasing trim, is raised as the depth of step increases. This raising of the limit may be caused by increased afterbody clearance, better ventilation behind the step, or a combination of the two.

With the shallow step (model 101BA) excessive negative pressures were present during porpoising at high angles and high speeds; and both sides of the afterbody planing surface behind the step were torn out of the model during the tests. Pressure measurements made on another model indicate that the negative pressures may become quite large during high-angle porpoising. In this last-mentioned case either ventilation of the step by the installation of air ducts or an increase in the depth of step improved the performance.

The upper limit, decreasing trim, is also raised as the depth of step is increased. The violence of the motion, as the trim is decreased to approach this limit, is also reduced. The model is more controllable and generally easier to handle with a deep step.

Effect of variations of gross load coefficient C_{Δ_0}.—Gross load coefficient is defined by

$$C_{\Delta_0}=\Delta_0/wb^3$$

where

Δ_0 gross load, pounds
w specific weight of water, pounds per cubic foot.
b beam of hull, feet

The effects of variations in load coefficient on the limits of stability are shown in figure 17. For these tests the moment of inertia and the mass moving vertically were kept constant. The previous tests indicate that the effects of variations of these quantities are small and for convenience they were not varied.

Over the hump and at intermediate planing speeds, the lower limit of stability is raised as the load coefficient is increased. There is an increase in damping at speeds just over the hump with the higher load coefficients, the model with the smallest load coefficient ($C_{\Delta_0}=0.62$) having almost no damping at all in this speed range. At high speeds the lower limits of stability with the three values of the load coefficient tend to approach the same trims.

The variation in the upper limit of stability, increasing trim, is small and is not so consistent as the variation in the lower limit. The limit is raised as the load is increased and, with the same available tr mming moment, the limit first appears at a higher speed.

The effect on the lower branch of the upper limit is quite large. As the load coefficient is increased, this limit is raised and the speed at which it first appears is increased.

CONCLUDING REMARKS

Two methods for investigating the stability characteristics of dynamic models have been suggested:

(1) **Tests at constant speed.**—The attitude of the model is varied by means of the tail group, and the trim at which porpoising begins or stops is noted. This type of test defines the range of trims at which the model is stable.

Although an accurate simulation of full-size control moment is not essential, sufficient control should be available to attain the limiting trims. A shift of the center of gravity may be necessary to obtain this control moment.

Small variations in the moment of inertia and in the mass moving vertically have a negligible effect on the limits of stability. With an excess of either, a slight shift of the upper limit, decreasing trim, is made toward lower trims.

The porpoising characteristics are generally determined for only one position of the center of gravity by this method. In order to determine the range of stable positions for the center of gravity, the following method requires less time and is consequently preferable.

(2) Tests at accelerated speed.—The trim and amplitude of porpoising are noted at predetermined speeds during an accelerated run. Data are taken for two or three settings of the tail. This type of test determines the amplitudes of porpoising of the model over the range of available control moment.

Control moments, corresponding to the full size, must be simulated if these results are to be used in predicting full-size behavior.

Maintaining correct moment of inertia and mass moving vertically is more important if this procedure is used than if tests are of the constant-speed type.

Different amplitudes of porpoising can be obtained for the same model by varying the rate of acceleration. With the present method for controlling the towing carriage, an accurate reproduction of accelerated runs is difficult.

A combination of the two methods for testing would probably give the most reliable results with the least amount of testing. The limits of stability would be first determined by making constant-speed runs. Modifications would be made on the basis of these tests and the merit of any alteration in form would, in general, be measured in terms of changes of the stability limits. The modification showing the most desirable stability characteristics would then be tested by accelerated runs, and the range of stable positions for the center of gravity would be determined. These last-mentioned tests would indicate any further changes necessary to make this range of positions correspond to those necessary for aerodynamic stability.

Increasing the depth of step has no appreciable effect on the lower limit of stability. The upper limits are raised with an increase in depth of step, and the violence of high-angle porpoising is greatly reduced.

Increasing the load coefficient raises the lower limit of stability. The effect is greatest at intermediate planing speeds. The upper limit, increasing trim, is raised as the load is increased and the speed at which this limit is first determined is also increased. The upper limit, decreasing trim, is moved to higher trims and speeds with an increase in load coefficient.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *September 9, 1942.*

APPENDIX

DETERMINATION OF THE PITCHING MOMENT OF INERTIA OF A DYNAMIC MODEL

In an experimental study of the longitudinal stability of a flying boat by the use of a model, it is desirable that the motions of the model correctly reproduce those of the full-size craft. It is therefore necessary to measure the pitching moment of inertia of the model. This measurement may be accomplished by swinging the model as a compound pendulum.

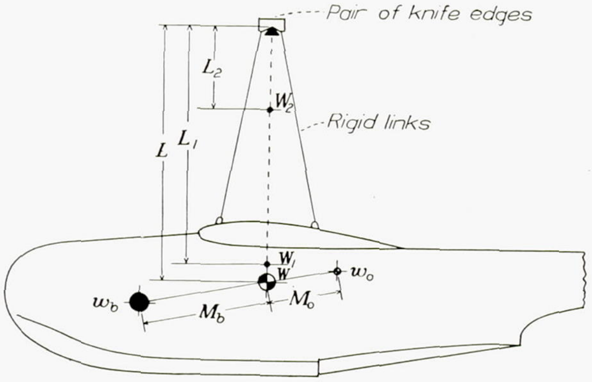


FIGURE 18.—Knife-edge pendulum for determination of moment of inertia.

Knife-edge pendulum.—An elementary form of the pendulum is that shown in figure 18. The model is suspended by means of rigid links from a pair of knife edges. A detailed discussion of the method is given in reference 8. The virtual moment of inertia of the model about a lateral axis through its center of gravity may be expressed as follows:

$$I=\frac{T_1^2W_1L_1}{4\pi^2}-\frac{T_2^2W_2L_2}{4\pi^2}-I_A-\left(\frac{W}{g}+V\rho+M_A\right)L^2$$

where

- I true moment of inertia of structure of model about a lateral axis through its center of gravity, slug-ft ^{2}
- T_1 period of oscillation of complete pendulum, sec
- W_1 weight of complete pendulum, lb
- L_1 distance from axis of rotation (knife edges) to center of gravity of complete pendulum, ft
- T_2 period of swinging gear alone, sec
- W_2 weight of swinging gear alone, lb
- L_2 distance from knife edges to center of gravity of swinging gear, ft
- W weight of model, lb
- g acceleration due to gravity, ft/sec ^{2}
- V volume of model, cu ft
- ρ mass density of air, slugs/cu ft
- M_A additional mass effect due to momentum imparted to surrounding air, slugs
- L distance from knife edges to center of gravity of model, ft
- I_A additional moment of inertia of air disturbed by model about knife edges, slug-ft ^{2}

The first two terms of the equation represent, respectively, the moments of inertia about the knife-edge axis of the complete pendulum and of the swinging gear alone. The last term transfers the remaining moment of inertia (that of the model itself) to a parallel axis through the center of gravity of the model. The factor $\left(\frac{W}{g}+V\rho+M_A\right)$ is the true mass of the model as swung. This factor is the sum of the mass determined from the weight of the model in air $\frac{W}{g}$; the mass of air entrapped in the model $V\rho$; and the additional mass effect due to the motion imparted to the surrounding air M_A. Under ordinary conditions, the last two effects may be safely neglected. The third term of the equation I_A is the moment of inertia (about the axis of oscillation) of the air set in motion by the model.

In the design of a full-scale flying boat, the moment of inertia is usually computed for the structure alone. This value, when reduced in proportion to the fifth power of the scale of the model, is that to which the moment of inertia of the structure of the model should correspond. The neglect of the I_A term in swinging the model causes an appreciable error. For example (if the results obtained with NACA model 101 are used), the value of I_A computed by the method of reference 8 is 0.32 slug-feet^2 or 5.4 percent of the true moment of inertia desired for the structure alone, 5.97 slug-feet^2.

The pendulum should be kept short in order that the moment of inertia of the model about its own center of gravity be a large part of the moment of inertia of the total pendulum about the axis of oscillation.

The error in measuring a moment of inertia that may be expected in any given case may be easily determined from the fundamental formula and the probable errors in measuring time, length, and weight. In the case of the subject model, this error amounts to approximately 1 percent.

Care must also be taken that the model is swinging in an arc about the knife-edge axis and that no other freedom is possible.

Added-weight method of swinging.—A somewhat more convenient adaptation of the compound pendulum is at present used at the NACA tank. Figure 19 shows the arrangement. In this method the model is suspended from the towing staff actually used in testing. The ball-bearing pivot is located at the desired center of gravity to be tested and an additional weight is suspended rigidly below the model to give the pendulum stability. A compound pendulum is thus formed with its center of gravity somewhat below the pivot. The following equation may be derived:

$$I=wl\left(\frac{T^2}{4\pi^2}-\frac{l}{g}\right)-I_w$$

where

I moment of inertia of model about a lateral axis through its center of gravity, slug-ft²

w added weight, lb

l distance from pivot to center of gravity of added weight, ft

T period of oscillation, sec

I_w moment of inertia of added weight about its own center of gravity, slug-ft²

The moment of inertia of the added weight about its own center of gravity may in most cases be neglected. Ambient-air effects have not been considered in the above equation, and their omission results in an error exactly the same as that due to their omission from the formula for the knife-edge system. The possible error due to errors in measurement is, of course, the same as that in a knife-edge pendulum.

The chief advantages in the use of an added-weight pendulum lie in the ease of setting up and balancing the model. One disadvantage is that the friction of the ball-bearing pivot is higher than that of a set of knife edges, making it more difficult to get a sufficient number of oscillations.

Ballasting procedure.—The usual procedure followed at the NACA tank is to suspend the model at the desired location of the center of gravity and to balance the model about the pivot by trial location of ballast. The added weight is then attached to the model and a trial moment of inertia obtained. Computations then indicate the proper location and amount of ballast to give the correct location of the center of gravity and the correct moment of inertia. From the trial ballast and its location, the center of gravity of the unballasted model and its moment of inertia may be determined. The following relations may then be worked out (see fig. 18).

$$r_b=\frac{I_r-I_o-w_or_o^2-I_b}{w_or_o}$$

and

$$w_b=\frac{w_or_o}{r_b}$$

where

r_b moment arm of ballast required, ft

I_r required moment of inertia about pivot, slug-ft²

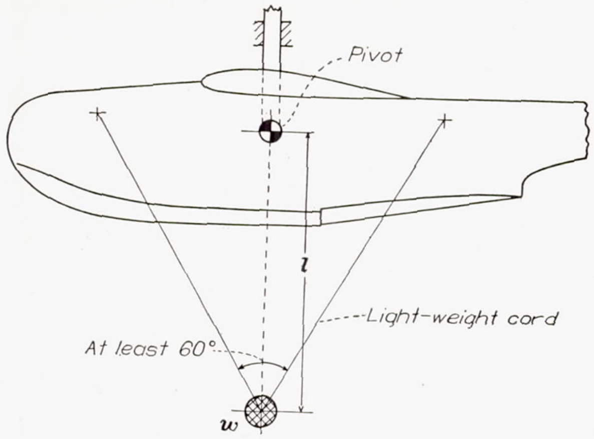


FIGURE 19.—Added-weight method of swinging model to determine moment of inertia.

I_o moment of inertia of unballasted model about its own center of gravity, slug-ft²

w_o weight of unballasted model, lb

r_o moment arm of unballasted model, ft.

I_b moment of inertia of ballast weight about its own center of gravity, slug-ft². Neglect, at least, for first approximation of r_b.

w_b required ballast weight, lb

A check determination of the moment of inertia is usually made after setting the proper ballast at the computed location.

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TABLE I.—OFFSETS OF MODEL 101BA

[Dimensions in inches]

Station	Distance from F. P.	k	r	D1	D2	Distance below base line: a	b	c	d	B1 [a] 1.40	B2 2.80	B3 4.20	B4 5.60	R	Half-breadth: e	j	WL1 [b] 7.00	WL2 5.60	WL3 4.20	WL4 2.80	WL5 1.40	WL6 0	WL7 −1.40
F. P.	0			3.26	4.42	−3.26		−3.26						0									
1	.67			3.08	4.28	−.68		−2.36						1.11									0.34
2	3.19			2.44	3.84	2.54		−.64		0.36				2.72							0.62	1.75	
3	5.70			1.93	3.45	4.12		.61		2.27	1.08			3.72						0.95	2.35		
4	10.73			1.23	2.85	5.83		2.36		4.42	3.35	2.62		5.07				0.20	1.65	3.80			
5	15.77			.78	2.45	6.61		3.48		5.53	4.64	3.96	3.53	5.93				1.29	3.65				
6	20.80			.49	2.20	6.98		4.20		6.17	5.42	4.77	4.34	6.50				2.44					
7	25.83			.29	1.98	7.24		4.69		6.59	5.94	5.31	4.86	6.81			0.50	3.53					
8	30.86			.18	1.87	7.38		4.97		6.81	6.24	5.66	5.21	6.99			.92	4.36					
9	35.89			.10	1.82	7.49		5.15		6.97	6.45	5.94	5.44	7.09			1.30	5.06					
9A	36.60			.09	1.80	7.52		5.17		6.99	6.48	5.97	5.47	7.10			1.40	5.11					
10	40.92		4.17	.07	1.78	7.60	5.52	5.27	4.99					7.12	5.70								
11	45.95		↑	.06	1.80	7.72	5.63	5.38	5.11					7.10	5.70								
12	50.99			.11	1.86	7.83	5.74	5.49	5.24					7.04	5.70								
13F	56.02			.22	1.97	7.94	5.86	5.61	5.40					6.93	5.70								
13A		0				7.54	5.46	5.21	5.00						5.70								
14	61.05	.13		.44	2.12	7.06	5.05	4.80	4.59					6.78	5.49	6.73							
15	66.08	.22		.72	2.31	6.58	4.69	4.44	4.24					6.59	5.15	6.39							
16	71.11	.34		1.05	2.54	6.09	4.41	4.15	3.95					6.36	4.61	5.84							
17	76.14	.48		1.42	2.82	5.61	4.22	3.97	3.76					6.08	3.82	5.05							
18	81.17	.63		1.83	3.13	5.13	4.12	3.87	3.66					5.77	2.78	4.02							
19	86.21	.76	↓	2.29	3.49	4.64	4.13	3.88	3.67					5.41	1.42	2.65							
20	91.24	1.23	4.17	2.78	3.88	4.15	4.15	3.90	3.82					5.02	0	.91							
21	93.17	1.64		2.98	4.04	3.97		3.97	3.97					4.86		.18 rad							
22	96.27			3.32	4.32									4.58									
23	101.30			3.89	4.79									4.11									
24	106.33			4.50	5.31									3.59									
25	111.36			5.15	5.87									3.03									
26	116.39			5.84	6.46									2.44									
27	121.43			6.58	7.08									1.82									
27A	122.16			6.69	7.18									1.72									
28	126.12			7.39	7.71									1.10									
29	127.46			7.69	7.92									.78									
30	128.13			7.88	8.02									.46									
A. P.	128.41			7.98	7.98									0									

[a] Distance from center line to buttock.
[b] Distance from base line to water line.

TABLE II.—AFTERBODY OFFSETS FOR MODELS 101BB AND 101BC

[Dimensions in inches. Offsets not given are same as 101BA]

Station	Distance from F. P.	Both models: Half-breadth e	j	r	Model 101BB, 0.70 step depth: Distance below base line a	b	c	k	Model 101BC, 1.0 step depth: Distance below base line a	b	c	k
13A	56.02	5.70	6.93	4.17	7.24	5.16	4.91	([a])	6.94	4.86	4.61	([a])
14	61.05	5.49	6.73	4.17	6.76	5.75	4.50	0.04	6.46	5.45	4.20	([a])
15	66.08	5.15	6.39	4.17	6.28	4.39	4.14	.12	5.98	4.09	3.84	([a])
16	71.11	4.61	5.84	4.17	5.79	4.11	3.85	.24	5.49	3.81	3.55	([a])
17	76.14	3.82	5.05	4.17	5.31	3.92	3.67	.39	5.01	3.62	3.37	0.09
18	81.17	2.78	4.02	4.17	4.83	3.82	3.57	.54	4.53	3.52	3.27	.24
19	86.21	1.42	2.65	4.17	4.34	3.83	3.58	.67	4.04	3.53	3.28	.37
20	91.24	0	.91	4.17	3.85	3.85	3.60	1.01	3.55	3.85	3.30	.71
21	93.17		.18 rad	4.17	3.67		3.67	1.34	3.37		3.37	1.04

[a] No radius; draw to chine.

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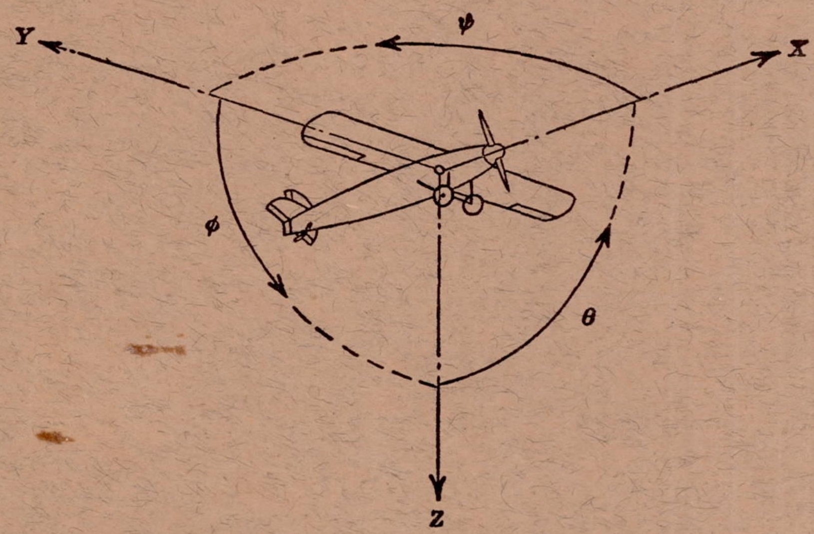

Positive directions of axes and angles (forces and moments) are shown by arrows

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

$C_l=\frac{L}{qbS}$ (rolling) $C_m=\frac{M}{qcS}$ (pitching) $C_n=\frac{N}{qbS}$ (yawing)

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 $C_T=\frac{T}{\rho n^2D^4}$
Q	Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2D^5}$
P	Power, absolute coefficient $C_P=\frac{P}{\rho n^3D^5}$
C_s	Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η	Efficiency
n	Revolutions per second, rps
Φ	Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph

1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft