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A METHOD FOR STUDYING THE LONGITUDINAL DYNAMIC STABILITY OF FLYING-BOAT-HULL MODELS AT HIGH PLANING SPEEDS AND DURING LANDING

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WASHINGTON

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A METHOD FOR STUDYING THE LONGITUDINAL DYNAMIC STABILITY OF FLYING-BOAT-HULL MODELS AT HIGH PLANING SPEEDS AND DURING LANDING

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SUMMARY

The investigation which forms the subject of this report originated with the concept that the various types of instability sometimes encountered in the motion of a flying boat on the water at high speeds and high trim angles, particularly upper-limit porpoising and skipping, might have the same basic source and therefore be susceptible of investigation by the same test procedures.

A method is described for carrying out generalized experimental studies of the longitudinal dynamic stability of flying-boat-hull models. Predetermined disturbances of the motion at constant speed are introduced at an initial instant of time, simulating disturbances which might occur in actual landing or take-off maneuvers, and the effects on the subsequent motion are recorded graphically. Direct comparisons between different models, on a quantitative basis, are thus provided for.

Data on three related models are presented, which cover wide variations of initial disturbances within a limited range of equilibrium conditions of motion. Although not extensive enough to justify sweeping conclusions, these data show:

1. That initial disturbances will bring out unstable characteristics in a model, within regions consistent in extent with those defined in special tests for particular characteristics such as the "upper limit, decreasing trim"

2. That the magnitudes of the initial disturbances are more important in this connection than their character, even when their character is so altered that in one case the model is deeper in the water at the initial instant of time, while in another case it is clear out of the water - so that it must then land

3. That, within bounds, increasing the magnitudes of the initial disturbances tends to cause progressively wider trim ranges of instability in a given model. Beyond certain more or less well defined bounds, however, increasing the magnitudes of the disturbances seems to have almost no effect

It is concluded that the method could be used, if desired, for the study of normal service landings as such, though no particular effort to do this was made in the present instance.

The main thesis, that upper-limit porpoising and skipping have the same basic source, is not definitely proved. The work is believed, however, to contribute to the growing body of circumstantial evidence in support of it, and there does not appear to be pressing need for attempting a rigorous proof at this time. The matter is thought to have been reduced from practical to academic importance.

INTRODUCTION

The need for improved landing and take-off characteristics of flying-boat hulls has been accentuated in recent years because of progressive increases of size, gross weight, and get-away speed.

The region of high speeds and high trim angles is a particularly important one in connection with these maneuvers, and especially so in view of the various types of longitudinal dynamic instability peculiar to this region. These instabilities are always undesirable and have sometimes reached catastrophic proportions; they are known by such names as

(a) High-angle or upper-limit porpoising, associated with the "upper limit, increasing trim" or the "primary upper limit," which will originate at constant speeds on the water less than the landing or take-off speed

(b) High-angle "hysteresis" porpoising, associated with the upper limit, decreasing trim or the "secondary upper limit," which is an extension of the basic high-angle type of porpoising into regions of lower trim angle

(c) Skipping, which is recognized as being connected with the actual process of making or breaking contact with the water in either landing or take-off ("jump" take-off), though somewhat more prominently associated with landing, and which tosses the flying boat into the air at speeds below flying speed, and

(d) Bouncing, which is apparently more or less similar to skipping but is as yet not very accurately defined

The last two types of longitudinal dynamic instability can occur at low trim angles as well as at high trim angles. In this report, however, only trim angles above 4° were investigated. See diagram facing page 9.

It has been recognized for some time that all of these are manifestations, in one way or another, of hydrodynamic instability: although they involve periodic oscillatory motions, they do not depend for their occurrence upon the presence of any external system of periodic disturbing forces - such, for instance, as might be provided by waves on the water surface. Nor does it require much stretch of the imagination to conceive the possibility of their being directly related to each other, and attributable jointly to the influence of common initiating circumstances. It was this possibility which first suggested the present investigation.

In extending the thought it was argued that if, at an initial instant in time, a flying boat found itself in a given situation with respect to the water surface, representing either or both of the following: (1) given differences of attitude (in heave or trim) from the equilibrium attitude, and/or (2) given states of secondary motion (vertical or angular), then a given behavior might be expected to follow, regardless of the train of events which brought about the given situation.

If this could be shown to be the case, it obviously would constitute a considerable simplification, both in fact and in the designer's mind, since any change of design which helped with respect to any one type of

instability could be counted on to help with respect to the other types. Furthermore, it was reasoned that the relative merits of different designs could then be evaluated from the point of view of all the types of instability at once, by a single series of tests conducted under prescribed equilibrium conditions of speed, load, trim, and moment, and involving systematic initial disturbances from the equilibrium conditions. Such a procedure, if successful, would avoid the uncertainties inherent in attempts to interpret the results of actual landings and take-offs, and would substitute strictly comparable quantitative data.

To proceed along these lines it obviously would be necessary (1) to devise a suitable test method, and (2) to establish its reliability by comparing its indications with the best information available from other sources, in several test cases.

This report deals primarily with the development of a test method. It bears upon the second requirement by presenting and discussing tests on three models differing only in the height of the main step, a design feature which has come to be recognized from both model and full-scale experience as having an important influence on stability in landing and take-off. The tests do not cover a wide range of equilibrium conditions, since it was considered preferable at the start to emphasize breadth in the ranges of initial disturbances covered rather than breadth in the equilibrium conditions; the test indications are, however, consistent with other information on the effect of step height.

The investigation, conducted at the Experimental Towing Tank, Stevens Institute of Technology, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

APPARATUS

For the present investigation, the apparatus regularly employed at the Experimental Towing Tank for studies of dynamic stability, and described in reference 1, was provided with two auxiliary devices:

1. A clamping bar, by means of which the model could be clamped at predetermined attitudes in trim and in elevation of the center of gravity prior to starting a test run, and then be released after being brought up to constant speed, and

2. A spring, by means of which the model could be given, when desired, an initial downward thrust upon being released from above the water surface

These additions to the apparatus are shown in figures 1 and 2.

Details of the usual test procedure employed with the basic apparatus (without the additions) are given in reference 1. It has been found in a particular instance that determinations of the upper limit, increasing trim, and of the lower limit, by this procedure, are in good agreement with corresponding determinations at the NACA tank for the same flying-boat design. This case is shown in figure 3, which gives data from both tanks for the parent design used in the present investigation. (The NACA data used in preparing this particular chart are from unpublished information.)

The clamping bar referred to in item (1) was developed when it became clear that the usual procedure did not define the upper limit, decreasing trim. Its purpose was to introduce initial disturbances of the sort employed here, with the thought that these might be the means of bringing out hysteresis porpoising and the upper limit, decreasing trim. Preliminary tests with this end in view, described in an unpublished report, were promising. The present investigation is, in a sense, an extension of the earlier work but rests upon a somewhat broader background.

The spring was developed for the present investigation, as a means of imparting higher downward velocities to the model than could be obtained by dropping the model from the maximum height available within the limitations imposed by the design of the rail and towing carriage of the tank.

GENERAL PROCEDURE

In principle, disturbances from an equilibrium condition occurring at an initial instant of time $t = 0$ might be of four different types:

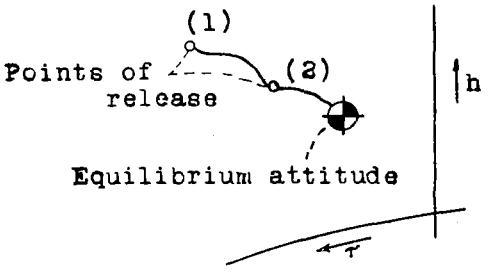
1. Δh, a difference of heave, or elevation of the center of gravity, with respect to the equilibrium value

2. $\Delta\tau$, a difference of trim, with respect to the equilibrium value

3. $dh/dt = w$, a vertical velocity of the center of gravity

4. $d\tau/dt = q$, an angular velocity about the center of gravity

It seems clear enough, however, that in planning model tests it is unnecessary to deal with all four types of initial disturbance. Referring to the following sketch:



assuming that at some hypothetical point of release of the model (2) it is desired that all four types of disturbance have finite values, then it may be supposed that there is some other point of release (1) where, for instance, dh/dt and $d\tau/dt$ are zero, and Δh and $\Delta\tau$ can be given values which alone will produce the desired values of the four types of disturbance when the model passes, after release, through the point (2). It follows from this reasoning that the effects of any possible combination of the four types of disturbance can be duplicated by taking any two of the types equal to zero and assigning appropriate values to the other two - which means, in effect, that two of the types can be disregarded, provided sufficiently wide ranges of values and combinations of the other two are covered. This point of view was adopted in laying out the tests in the present instance.

Other things being equal, it would have been desirable to select two types of disturbance and use them for all the tests. This could not be done, for the reason that tests were desired both with the model in the water at the instant of release and with the model above the water surface at the instant of release. For these two kinds of tests, the logical choices appeared to be

1. Δh and $\Delta\tau$, when the model was in the water

2. dh/dt and $\Delta\tau$, when the model was above the water surface, both values to be measured at an arbitrary elevation of the center of gravity, preferably close to the elevation at which contact was normally established between the model and the water

The shift from Δh to dh/dt in the second kind of test was dictated by the fact that Δh ceases to have definite meaning when the model is above the water surface.

In practice, Δh and $\Delta\tau$ proved entirely satisfactory for the first kind of test. For the second kind of test, however, it proved cumbersome to use dh/dt, which had to be derived from the test data and was not, therefore, an independent variable like Δh. Hence, the potential energy at release, in excess of the potential energy at the arbitrary elevation of the center of gravity mentioned above, was substituted. Also, for convenience, $\Delta\tau$ was defined in the second kind of test by the point of release rather than by the arbitrary elevation of the center of gravity.

The excess potential energy at release from a position above the water surface is evidently

$$\Delta \text{ P.E.} = WH + \frac{kH^2}{2}$$

where

W = gross weight

H = vertical distance dropped through from point of release to arbitrary height of the center of gravity, used as reference (roughly the distance from keel to free water surface)

k = constant (force per unit stretch) of the spring used to impart initial downward thrust ($k = 0$ when the spring is not used)

This potential energy difference is related to the kinetic energy at the arbitrary height of the center of gravity used as reference, and hence to the value of dh/dt at this height, but the relationship is not direct because energy is lost in forcing the hydrofoil downward, and the amount of the lost energy depends upon the angle of attack of the hydrofoil. Use of the potential energy at release avoided the necessity of calculating the lost energy in each test and thus simplified the work.

TEST PROCEDURE

Except for the use of the clamping bar and the spring, the detailed test procedures followed during this investigation were the same as those used in making the porpoising tests discussed in reference 1.

Runs were made at two steady speeds near get-away with various values of applied moments selected to produce equilibrium trim angles extending from well below, to somewhat above, the trim for the primary upper limit of stability as determined in earlier tests.

At each combination of speed and applied moment, an initial run was made without using the clamping bar or spring, in order to determine the equilibrium trim, using heavy pitch damping when necessary to avoid porpoising.

Tests were then made with normal damping, in which the model was released successively from a number of attitudes differing from the equilibrium attitude, and corresponding to prescribed initial disturbances.

The tests were divided into two groups, one group in which the model was released in the water, the other, in which the model was released from above the water surface. When the model was released in the water, the clamping bar alone was used. When the model was released above the water surface, the spring was used in addition to the bar whenever it was desired to impart an additional downward thrust.

The behavior of the model after the instant of release was recorded in each test on a smoked-glass slide by a scriber mounted on the model, 6 inches above the center of gravity at zero trim. On each record were marked, for reference:

(a) A vertical line and a horizontal line corresponding, respectively, to zero trim and zero heave at static floatation

(b) Two lines indicating the combinations of heave and trim of the model at which either the forebody or the afterbody would touch the water. These lines provided references to determine, after the test, how the model had made contact with the water and whether it subsequently left the water if porpoising occurred.

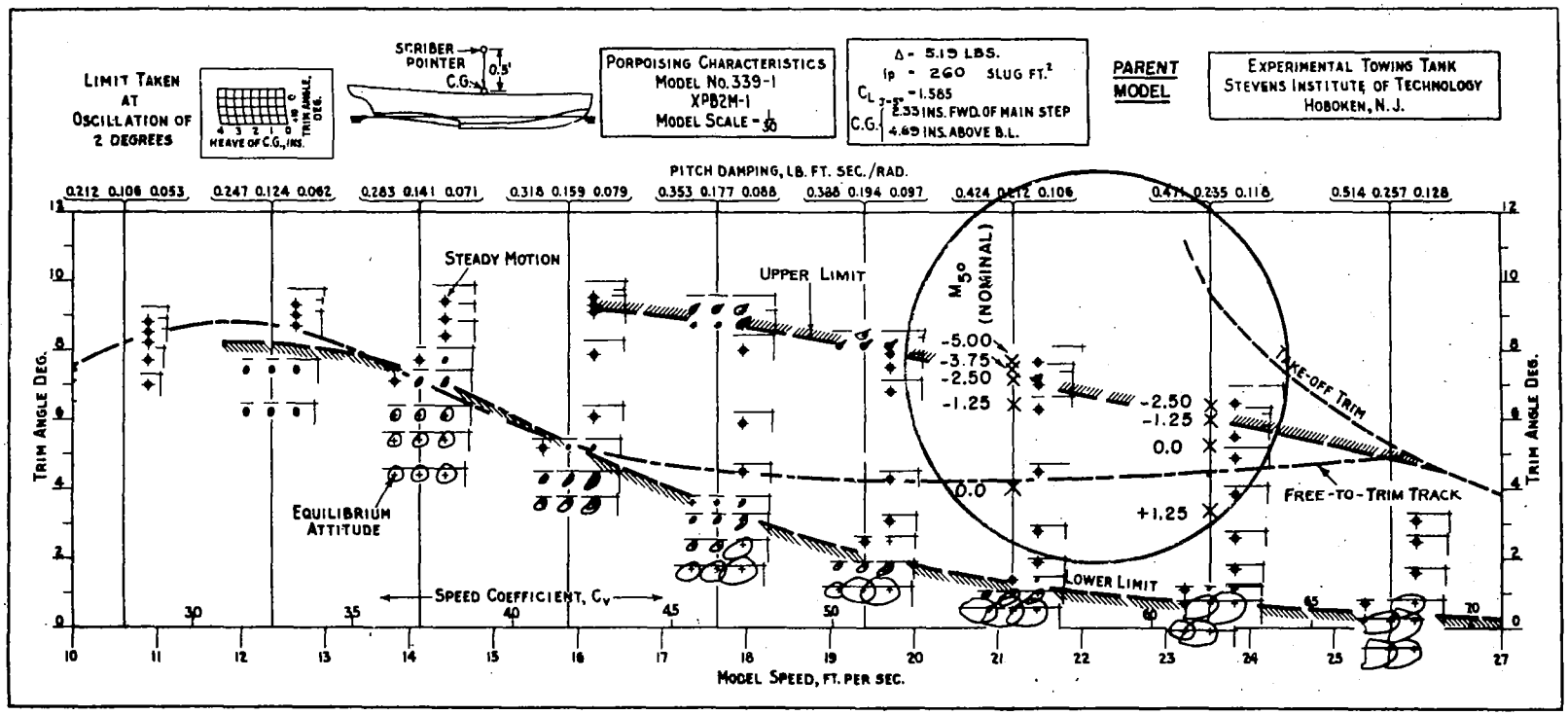
MODELS

Tests were made on three related models. The parent of the family was Model No. 339-1, which is a 1/30-scale model of the XPB2M-1, with a step height of 5 percent of the beam. The other two models, Nos. 339-27 and 339-26, were modifications of the parent model, to provide step heights of 1 and 9 percent of the beam, respectively. The changes of step height were accomplished by rotating the afterbody about the intersection of the afterbody keel and the sternpost. Thus, the sternpost angle was held constant when the step height was changed.

Body plans of the parent model are shown in figure 4.

The particulars, specifications and aerodynamic characteristics used for all three models were those of the parent XPB2M-1 flying boat, reduced to the model scale of 1/30 (except, of course, for the difference in step heights). They are shown on page 21.

LOCATION OF EQUILIBRIUM TEST CONDITIONS IN RELATION TO TOTAL TEST RANGE



TEST RANGES

Equilibrium Test Conditions

The diagram on the facing page shows the location of the equilibrium test conditions, as listed below, with respect to the take-off trim track, the free-to-trim track, the ordinary stability limits, and so forth, in the case of the parent model.

Speeds: The tests were made at two speeds,

Starts in the water		
Speed in feet per second	21.18	X
C_V	5.57	X
Starts above the water surface		
Speed in feet per second	21.18	23.53
C_V	5.57	6.19

Tests with starts in the water were omitted at the higher speed when it became evident from the tests at the lower speed, which were run first, that both types of test were unnecessary (see discussion on p. 15).

Moments: The moments used at the respective test speeds (for both kinds of starts, when made) were

(Speed)	21.18		23.53
Nominal moment = M_{5o} inch-pounds	-5.00		
	-3.75		
	-2.50	——	-2.50
	-1.25	——	-1.25
	0	——	0
			+1.25

corresponding to equilibrium trim angles of the parent model of

Equilibrium trim angle, degrees			
	7.6°		
	7.4°		
	7.1°	——	6.5°
	6.6°	——	6.1°
	4.2°	——	5.5°
			3.5°

The "nominal" moment, as used throughout this report, is defined as the moment measured at an arbitrary trim angle of 5°. In general, it differs slightly from the actual moment occurring at the equilibrium trim angle. The signs refer to hydrodynamic moments; a negative hydrodynamic moment tends to depress the bow and requires a nosing-up moment applied by the elevators to produce equilibrium.

Ranges of Disturbances

A. Starts in the Water

At each combination of speed and moment covered (one speed in this case), tests were made with combinations of initial disturbances, as defined by

1. Δh, a difference of heave or elevation of the center of gravity with respect to the equilibrium value, ranging from +0.3 to -0.3 inch in intervals of 0.1 inch

2. $\Delta\tau$, a difference of trim with respect to the equilibrium value, ranging from +8.0° to -6.0° in intervals of 2°

B. Starts above the Water Surface

At each combination of speed and moment covered (both speeds in this case) tests were made with combinations of initial disturbances, as defined by

1. Δ P.E., an excess of potential energy at the instant of release, with respect to the potential energy at an arbitrary height at the center of gravity close to that at which contact was normally made. Three values of Δ P.E., listed below, were selected to give approximately the indicated values of dh/dt, the vertical velocity of the center of gravity at the arbitrary height, and the indicated values of the glide-path angle.

Δ P.E. (lb/ft)	dh/dt (ft/sec)	Glide path (deg)
0.3	0.7	2
.6	1.4	4
.9	2.1	6

The values of Δ P.E. are those actually used. The values of dh/dt and of the glide-path angle are approximations, covering roughly the whole range of the experiments. The glide-path angles are seen to cover reasonably well conditions likely to be encountered even in violent full-scale landings.

RESULTS

The test results are summarized in tables I to VI and show, respectively,

Table	Model	Speed (ft/sec)
I, II	1 percent step (No. 339-27)	21.18, 23.53
III, IV	5 percent step (No. 339-1)	21.18, 23.53
V, VI	9 percent step (No. 339-26)	21.18, 23.53

Each of these tables shows, in separate boxes, the results obtained with each of the several values of moment used. Each box shows all the conditions covered with the moment in question, including starts both in the water and above the water surface. The result shown is in each case the worst obtained in a series of repeat test runs.

Figure 5 is an enlarged view of one of the boxes in table III, which shows the actual graphical records of the motion for the tests in point; its purpose is to give a visual impression of the tabulations and to illustrate the basis on which the interpretation of the data was made.

The interpretation is illustrated in greater detail by the graphical records on figure 6 for certain of the tests shown in table I, especially selected to bring out the characteristics of the four types of motion which were fairly readily recognizable throughout the whole range of the investigation, and which were adopted as criteria in preparing the summary tables. It happens that all the tests selected for this chart were made with starts above the water surface, but this is incidental and has no particular significance; for present purposes the point is simply that all the tests were made with initial disturbances. The four types of motion are:

S - Stable. The model proceeds from the attitude of release to the equilibrium attitude in a reasonably orderly manner, sometimes overshooting the mark but returning quietly.

D - Damped Upper-Limit Porpoising. The model proceeds in a very disorderly manner, passing through one or more irregular porpoising cycles, and then steadying at the equilibrium attitude. In cases where there is more than one cycle, succeeding cycles may or may not duplicate each other.

P - Self-Sustaining Upper-Limit Porpoising. The model proceeds as before, but enters very quickly a regime of self-sustaining porpoising with consistently uniform successive cycles, and would apparently continue indefinitely in the same way. Sometimes the first 1 or 2 cycles are a little larger than the others.

B - Incipient Lower-Limit Porpoising. The model passes through a partial cycle of what has the appearance of ordinary lower-limit-type porpoising, and is then flung into the air. Upon reentering the water, any of the three preceding types of motion may occur, though stable motion is the most probable. This type of motion usually occurred following starts above the water surface, with low trim angles at contact.

DISCUSSION

Determination of Secondary Upper Limit

The summary tables, I to VI, together with data for certain intermediate test conditions not shown thereon, provide a means of determining the secondary upper limits within the narrow speed range covered by the tests. If the secondary upper limit is defined as the trim angle below which self-sustaining upper-limit porpoising (indicated by "P") failed to occur under the most extreme combinations of initial disturbances considered in the investigation, with starts either in or above the water, the secondary upper limit for the parent model is found to be at about

$\tau = 6^{\circ}$ for the lower test speed, 21.18 feet per second

$\tau = 4\frac{1}{2}^{\circ}$ for the higher test speed, 23.53 feet per second

These values are compared in the chart on figure 7 with values of the upper limit, decreasing trim of unpublished NACA information for the same design. This chart is in the same nondimensional form as figure 3, and the same mean curves are shown on both charts for the primary upper limit of stability and the lower limit of stability. The NACA tests covered five gross loads and various speeds.

It will be seen that the secondary upper limit, as defined in the foregoing paragraph, and the upper limit, decreasing trim, as defined by the NACA, are in reasonably good agreement. This is important, because it indicates that the two limits are in fact much the same thing or, conversely, that a single, definable limit can be determined by two quite different methods.

Figure 8 provides additional, though somewhat less direct, evidence along the same lines. It shows the secondary upper limits determined from the summary tables in the same way, for all three models of the series. It will be seen that increasing the step height raises the secondary upper limit, and this is consistent with the evidence in references 2 and 3 that increasing the step height raises the upper limit, decreasing trim, as determined by the NACA.

Magnitudes of Initial Disturbances

The summary tables, I to VI, show clearly that progressively greater initial disturbances are required to induce self-sustaining porpoising when the nosing-up moment, and hence the equilibrium trim, is progressively reduced below that corresponding to the primary upper limit. Thus it might easily have been supposed, in advance, that sufficiently large initial disturbances might induce self-sustaining porpoising at equilibrium trim angles below the upper limit, decreasing trim, determined by the NACA. This possibility cannot be said to have been completely ruled out, of course, for the simple reason that the initial disturbances covered by the present investigation may not have been sufficiently extreme. On the other hand, the disturbances are believed to have been at least as great as any likely to be encountered in actual landing or take-off maneuvers, even under very rough conditions, and there is nothing in the summary charts to suggest that larger disturbances would have altered the picture appreciably.

In effect, the NACA procedure may be said to use an already-established porpoising motion to introduce disturbance; whereas the procedure under consideration uses initial disturbances of predetermined magnitudes. Evidently an established porpoising motion is as effective insofar as fixing the position of the secondary upper limit is concerned, as are the largest of the initial disturbances here considered.

From the point of view of design, the fact that progressively greater initial disturbances are required to produce self-sustaining porpoising, as the equilibrium trim angle progresses downwardly from the primary to the secondary upper limit, is probably of less importance than the fact that the whole region between the two limits is one of inherent instability. Nevertheless, the progression in the necessary magnitudes of the initial disturbances alters the likelihood of porpoising within the region - the more violent the disturbance the more likely the porpoising - and this appears to have practical significance, as will be seen presently. Also, it implies a certain sensitiveness, which was, in fact, evident in carrying out the tests. For instance, a few ripples on the water surface seemed sufficient in a number of cases to start porpoising which would not occur with the same initial disturbances in glassy calm water. Considerable care should be taken in the actual conduct of the tests to eliminate, as far as possible, irregularities in the results attributable to this sort of thing.

Types of Initial Disturbance

The preceding section refers to magnitudes of initial disturbances without differentiating as to their types. Questions naturally arise regarding the relative influence of the different types; whether it is easier, for instance, to induce porpoising in tests started in the water by disturbances in heave Δh than by disturbances in trim $\Delta\tau$, or vice versa. The available information does not permit precise answers to such questions. But the questions are probably of secondary importance in any case, for it appears to be the magnitude rather than the type of the disturbance that counts most heavily.

Starts in the Water and above the Water Surface

An over-all view of the relative influences of different types of initial disturbances, along somewhat broader and more directly useful lines, is afforded by comparing the results for starts in the water and above the water surface.

Direct comparison is difficult from the summary tables of test results; there are no simple means of cross-reference by which equivalent initial disturbances can be readily visualized for the two kinds of test, because of the differing definitions of the initial disturbances necessarily used. For this reason, an over-all comparison on a statistical basis has been resorted to in the bar chart. (See fig. 9.)

The upper half of this chart refers to starts in the water, and the lower half to starts above the water surface. Each bar represents the results of all the tests made under the stated conditions, including those listed in the summary tables and all repeat tests (a total of some 60 tests in each case), and shows the relative frequency of occurrence of the four types of motion described on page 12. The three models, and the various equilibrium conditions covered by the investigation, are shown separately. The chart is naturally limited to the lower of the two test speeds, where both kinds of test were carried out.

The chart confirms the indications already referred to that porpoising is more likely with higher equilibrium-trim angles and that increase of step height is beneficial. But its importance for the purpose in hand is the evidence it presents that approximately the same frequencies of occurrence can be expected, under otherwise identical conditions, regardless of whether the model is started in or above the water. Bars directly above or below each other on the chart are strikingly similar in all cases, and it is obvious that essentially the same conclusions would be drawn on the basis of either kind of test.

The actual percentages shown by the chart for each of the four types of motion would be expected, from the point of view of earlier discussion, to depend to some extent upon the distribution of the tests represented according to the magnitudes of the initial disturbances used. This distribution was, however, fairly uniform in all cases.

Evidently, then, even such large distinctions in the types of initial disturbances as those corresponding to the definitions used for starts in and above the water, respectively, have little influence on the resulting behavior.

Landing

The bar chart (fig. 9) gives forceful evidence that the main factor influencing the behavior of a given model after release is the equilibrium-trim-angle setting, and not the character of the initial disturbances or even the distinction of whether the model was released in the water or above the water surface.

The implication is clear that there is nothing in landing, per se, which basically alters matters. It may well be that in actual practice the landing maneuver is especially likely to involve large disturbances from an equilibrium attitude but, if so, this seems to be its only unique feature.

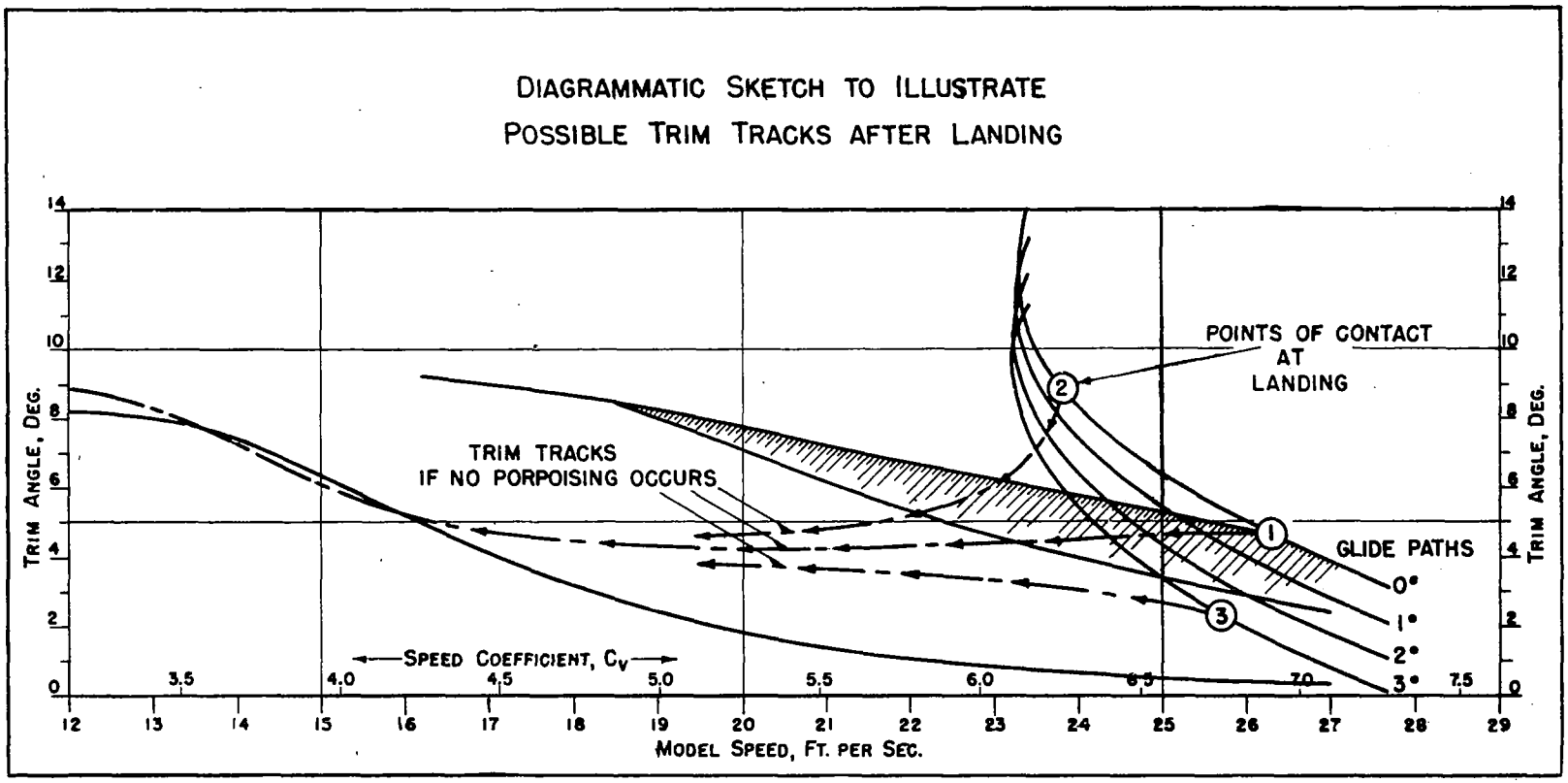
All the tests here reported, in which the model was released from above the water surface, represent theoretically possible landings. Most of them, however, represent much more extreme landings than are at all probable under service conditions. If the definition be adopted that a "normal" service landing is one in which

(a) A fixed elevator setting is maintained throughout

(b) The glide-path angle is reasonably small, and constant for an appreciable time interval prior to contact (that is, there is no vertical acceleration just prior to contact), and

(c) There is no angular velocity or acceleration just prior to contact

then the "initial disturbances" which can occur are restricted to much smaller magnitudes than were embraced in the present series of tests.


DIAGRAMMATIC SKETCH TO ILLUSTRATE
POSSIBLE TRIM TRACKS AFTER LANDING
POINTS OF CONTACT
AT
LANDING
TRIM TRACKS
IF NO PORPOISING OCCURS
GLIDE PATHS
0°
1°
2°
3°
SPEED COEFFICIENT, C_V
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
TRIM ANGLE, DEG.
MODEL SPEED, FT. PER SEC.
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
0
2
4
6
8
10
12
14
1
2
3

In a normal landing, as defined in the foregoing paragraph, contact with the water evidently may be established at any combination of speed, trim, and glide-path angle which provides equilibrium between the gross load and the lift, with the further restriction that the glide-path angle shall be reasonably small. The diagram on the facing page shows possible combinations of speed and trim for several glide-path angles, in a typical case, and indicates the region in which normal landings will occur if 3° is taken as about the maximum glide-path angle which, with any justice, can be referred to as "reasonably small." The two upper limits are shown also, and the region between them is shaded to indicate the greater likelihood of porpoising as the primary upper limit is approached from below. It should be emphasized that it is proper to think of the region between the two upper limits as defining the range in trim angle within which upper-limit porpoising can occur, for when the primary upper limit is approached from above, the trim angle has to be lowered to very nearly the value corresponding to the primary upper limit before the forebody touches the water and upper-limit porpoising becomes possible.

The probable progression of events in normal landings with fixed elevators can be traced on a diagram of this sort.* Referring to the diagram:

Landing (1). Contact is made with 0° glide-path angle, hence with no appreciable shock or "initial disturbance," and at the zero-moment trim for water operation. Instability following contact is very likely to develop, however, because the trim path during deceleration crosses the entire region of instability relatively slowly, giving time for porpoising to develop.

Landing (2). Contact is made with 0° glide-path angle as before, but at a trim angle considerably greater than the zero-moment trim, and in a region of stability. The afterbody makes contact first, and the trim is reduced very rapidly after contact. Stability is perhaps better assured here than in Landing (1), because the region of worst instability is crossed more quickly, leaving less time for porpoising to develop.

Landing (3). Contact is made with a 3° glide-path angle, and hence with a considerable shock or initial disturbance. But the trim angle at contact is low and in a region of stability, so that the initial disturbance cannot easily initiate porpoising, and the trim path during deceleration may never enter the region between the limits where porpoising is likely to occur. Stability is thus reasonably well assured.

*A diagram along the same general lines was suggested by Mr. Ernest Stout.

Other examples could be cited. The underlying concept, however, is illustrated by these three: namely, that it is not landing as such, or even necessarily the shocks (or disturbances) incident to landing, which determine the subsequent behavior, but rather

1. The upper-limit porpoising characteristics as a whole, as determined in tests at constant speed,

2. The position of the equilibrium trim track in relation to the region of instability, and

3. Possibly the time factor involved in the speed and trim changes which occur after contact is first established.

This concept leads naturally to the point of view that upper-limit porpoising and skipping have the same origin and are, in fact, much the same thing, the distinction in terminology probably being accounted for by the differing circumstances under which they have been observed. The term "upper-limit porpoising" has come to be associated with steady speeds on the water, often well below possible landing speeds; the term "skipping" has come to be associated with the actual landing maneuver. If the speeds are high and the water-borne loads are small, the hull usually will leave the water for some part of each cycle of motion during ordinary upper-limit porpoising. But there is no particular reason for associating the leaving of the water with upper-limit porpoising in general, because it does not occur at lower speeds with heavier loads. In landing, however, the combination of high speeds and light loads is the usual one and the leaving of the water is therefore usual, and naturally associated with it. There would be nothing inconsistent with existing evidence in the statement that skipping is upper-limit porpoising in which the hull leaves the water during a part of each cycle, and in reality this is the most obvious feature of the motion. The tendency for the cyclic motion to involve changes of heave primarily and changes of trim only secondarily has often been commented on in connection with both upper-limit porpoising and skipping.

The point of view discussed in the foregoing paragraph appears to be entirely consistent with the views expressed by Parkinson in reference 4, which has been published since the present investigation was undertaken. Reference 4 relates directly to skipping as encountered in the course of normal landings of models in the NACA tank, but in its explanation of the physical mechanism which is responsible, skipping and upper-limit porpoising are clearly linked together. A generally similar explanation was, in fact, attempted in reference 5 but, in that case, in connection with upper-limit porpoising as such. As Parkinson puts it, the explanation hinges upon the fact that when the trim angle is high enough to make the afterbody keel roughly horizontal, the free flow of air to the space behind the step may be cut off, with the result that entrainment of the trapped air by the water flowing aft from the forebody bottom causes a powerful suction. This depresses the hull, producing excess forebody lift which, in turn, lifts the hull and breaks the suction. Evidently the same train of events might occur whether the hull previously had been in the air, or on the water surface at a lower trim angle.

The more extreme landings in the present series of tests were produced by disregarding the restrictions imposed by the definitions for normal landings on page 15. In these landings, the model was released from above the water surface both at a lower speed (21.18 ft/sec) and with larger initial disturbances than were considered likely to occur in practice. This was done purposely, to exaggerate matters for the purpose in hand.

The use of relatively large nosing-up applied moments in the tests, corresponding to more extreme up-elevator settings than would be likely to be needed in normal landings, may be thought of as falling into the same category of exaggeration. This is partially true, but a high nosing-up applied moment also may be thought of as simulating in some measure the combination of a normal elevator moment with an aftward shift of the center of gravity. The tests suggest, therefore, that shifts of the center of gravity probably have little or no direct effect on landing stability, but influence it mainly through their effect on the normal trim tracks.

No emphasis was placed on reproducing normal landings in the present investigation. It will be seen, however, that apart from the fact that no provision was made for controlled deceleration of the model during the course of a test run, the test method could be employed to simulate many aspects of normal landings, if this were desired. The choice of suitable combinations of speeds and glide-path angles would be the principal requirement.

CONCLUDING REMARKS

The tests reported indicate

1. That initial disturbances, with respect to the equilibrium attitude at steady speed, will cause porpoising of the upper-limit type in the region between primary upper limit and a definable secondary upper limit which agrees well, in the case investigated, with the upper limit, decreasing trim, defined at the NACA tank.

2. That progressively larger disturbances are required to initiate porpoising as the equilibrium trim angle is progressively lowered within this region, although, when the secondary upper limit is reached, further increases of initial disturbance have practically no effect.

It is suggested that skipping at high trim angles and upper-limit porpoising are physically one and the same, and that the skipping tendency in normal landings is governed to a large extent by the range in trim angle between the primary and secondary upper limits (upper limit, increasing trim, and upper limit, decreasing trim, respectively).

Experimental Towing Tank,
Stevens Institute of Technology,
Hoboken, N. J., May 19, 1944.

REFERENCES

1. Davidson, Kenneth S. M., and Locke, F. W. S., Jr.: Some Systematic Model Experiments on the Porpoising Characteristics of Flying-Boat Hulls. NACA ARR No. 3F12, 1943.

2. Olson, Roland E., and Land, Norman S.: The Longitudinal Stability of Flying Boats as Determined by Tests of Models in the NACA Tank: I - Methods Used for the Investigation of Longitudinal-Stability Characteristics. NACA ARR, Nov. 1942.

3. Truscott, Starr, and Olson, Roland E.: The Longitudinal Stability of Flying Boats as Determined by Tests of Models in the NACA Tank: II - Effect of Variations in Form of Hull on Longitudinal Stability. NACA ARR, Nov. 1942.

4. Parkinson, John B.: Notes on the Skipping of Seaplanes. NACA RB No. 3I27, 1943.

5. Davidson, Kenneth S. M., and Locke, F. W. S., Jr.: Some Analyses of Systematic Experiments on the Resistance and Porpoising Characteristics of Flying-Boat Hulls. NACA ARR No. 3I06, 1943.

PARTICULARS AND SPECIFICATIONS (Normal)	Full size		Model
Navy Designation	XPB2M-1		
Martin Model No.	170		
Martin Drawing No.	R240078		
Stevens Model No.			339-1
Scale	1		1/30
Dimensions			
Beam at main step, in.	162		5.40
[a]Angle between forebody keel and base line, deg	2.0		2.0
Angle between afterbody keel and base line, deg	5.0		5.0
Height of main step at keel, in.	8.1		0.27
Center of gravity forward of main step (26.58 percent M.A.C.), in.	70		2.33
Center of gravity above base line, in.	146.7		4.89
Gross weight, Δ, lb	140,000		5.19 f.w.
Load coefficient, C_Δ (sea water)	0.89		
Moment of inertia in pitch, slug-ft^2	1.366×10^6		
lb-in.^{2}	6.328×10^9		260
Wing span, ft	200		6.67
Wing area, S, sq ft	3683		4.092
Mean aerodynamic chord, M.A.C., in.	249		8.30
Aspect ratio (geometric)	10.87		10.87
Horizontal tail area, sq ft	508		0.565
Elevator area, sq ft	143.7		0.160
Distance, center of gravity to 35 percent M.A.C. horizontal tail (tail length), ft	63.6		2.12
Thrust line, above base line at main step, in.	230.3		7.68
Thrust line, inclined upward to base line, deg	5.5		5.5
Ratios $\frac{\text{Full-size}}{\text{Model}}$			
Of speed, $\lambda^{1/2}$		5.477	
Of length, λ		3.0×10	
Of area, λ^2		9.0×10^2	
Of volume, λ^3		27.0×10^3	
Of moment, λ^4		81.0×10^4	
Of moment of inertia, λ^5		243.0×10^5	
Aerodynamic characteristics			
C_L at $\tau = 5^\circ$ (relative to base line, flaps, 30°)	1.585		1.585
L at $\tau = 5^\circ$	$6.95\ v^2$		$7.72 \times 10^{-3}\ v^2$
$dC_L/d\tau$	0.1045		0.1045
$dL/d\tau$ ($dZ/d\theta$), lb/deg	$0.458\ v^2$		$0.509 \times 10^{-3}\ v$
dL/dw (dZ/dw), lb-sec/ft $\left(\frac{dL}{d\tau}\frac{1}{v}\right)$	$0.458\ v$		$0.509 \times 10^{-3}\ v$
$dC_{M_{CG}}/d\alpha_{BL} = dC_{M_{CG}}/d\tau$ (av.)	0.0150		0.0150
$dM_{CG}/d\tau$ ($dM/d\theta$), lb ft/deg (av.)	$1.365\ v^2$		$5.05 \times 10^{-5}\ v^2$
[b]dM/dq, lb ft sec/radian	$8020 \times v$		$9.90 \times 10^{-3}\ v$
dM/dw, lb sec (av.)	$78.3 \times v$		$2.90 \times 10^{-3}\ v$
$\frac{dM/dq}{dM/dw}$, ft/radian	102.5		3.41
$\frac{dM/dq}{dM/dw}$ / Tail length, 1/radian	1.61		1.61
Get-away speed, fps	130		23.74
Get-away C_L	1.890		1.890
Get-away τ, deg	8.8		8.8

[a]All trim angles measured relative to the base line.
[b]Contribution of horizontal tail surface only.

STARTS IN WATER

STARTS ABOVE WATER SURFACE

(NOMINAL)

TEST RESULTS

TABLE I

STEP HEIGHT = 1.0% b

MODEL 339-27

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 21.18 FT./SEC.

$M_{5°} = -5.00$

h_{equil} = 2.00 in. J_{equil} = 7.4 deg. M_{equil} = -4.28 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0								(4.8) 7.0P	(4.2) 6.5P	(4.8) 6.8P
+6.0								(2.0) 6.2P	(1.0) 6.3P	(0.0) 7.0P
+4.0			6.2P	6.5P	6.1P			(6.0) 6.4P	(9.0) 6.8P	(10.0) 6.3P
+2.0			6.5P	6.8P	6.1P			(7.0) 6.7P	(11.0) 6.5P	(14.0) 6.4P
0			6.7P	6.8P	6.7P			(10.0) 6.0P	(8.0) 6.2P	(8.0) 7.0P
-2.0			6.7P	6.7P	6.8P			(7.0) 6.3P	(8.0) 6.2P	(6.0) 6.6P
-4.0			6.8P	6.8P	6.7P			(6.0) 6.4P	(6.1) 6.7P	(6.0) 6.0P
-6.0										

$M_{5°} = -3.75$

h_{equil} = 1.99 in. J_{equil} = 7.4 deg. M_{equil} = -3.21 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0								(8.0) 5.2P	(7.2) 4.3D	(8.2) 6.3D
+6.0								(7.0) 7.3P	(8.1) 3.4P	(11.0) 5.7P
+4.0			5.7P	5.7P	6.2P			(8.2) 4.8P	(11.0) 4.7P	(14.0) 4.9P
+2.0			6.5P	6.0P	6.0P			(7.0) 4.3P	(9.0) 6.4P	(9.0) 3.9P
0			5.6P	4.6P	5.8P	5.8P		(7.0) 3.9P	(8.7) 5.9P	(10.0) 6.3P
-2.0			6.0P	6.0P	5.7P	5.9P		(6.0) 3.4P	(7.0) 6.9P	(6.0) 6.0P
-4.0			5.5P	5.5P	2.7P	5.7P		(5.1) 6.2P	(6.0) 6.0P	(4.0) 4.7P
-6.0										

$M_{5°} = -2.50$

h_{equil} = 1.98 in. J_{equil} = 7.1 deg. M_{equil} = -2.11 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0				5.2P					(7.0) 5.3P	(8.0) 5.0P
+6.0				4.9P				(4.0) 5.0P	(7.0) 5.9P	(10.0) 5.5P
+4.0			6.7P	5.0P	5.4P			(8.7) 5.8P	(10.0) 5.9P	(10.0) 6.0P
+2.0			4.3P	5.0P	5.0P			(8.0) 5.4P	(7.0) 5.5P	(7.0) 5.4P
0			4.6P	6.3P	5.2P	4.7P	4.8P	(7.0) 6.5P	(6.0) 5.7P	(6.0) 5.4P
-2.0			5.5P	4.5P	5.5P	5.3P	5.3P	(6.0) 6.0P	(6.0) 6.0P	(6.0) 5.0P
-4.0			6.8P	4.5P	5.5P	5.5P	4.3P	(6.0) 5.7P	(5.0) 5.0P	(5.0) 5.8P
-6.0										

$M_{5°} = -1.25$

h_{equil} = 1.97 in. J_{equil} = 6.7 deg. M_{equil} = -1.00 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0		5.9P	5.7P	5.5D		4.8D	5.0D	(3.0) 5.3P	(4.0) S	(7.0) 6.0P
+6.0		6.0P	5.4P	5.0D	5.0P	5.1D	6.0D	(9.0) 4.0P	(11.0) 6.2D	(12.0) 5.0P
+4.0	5.0P	5.6P	5.4P	5.0D	6.0D	4.5D	4.5D	(6.0) 6.0D	(10.0) 6.3D	(9.0) 6.3P
+2.0	6.0P	3.4D	4.0P	4.0D	5.0D	6.0D		(7.0) 5.0P	(7.0) 6.0D	(7.0) 5.6P
0	5.3P	3.5D	5.0D	S	4.5D	4.2D	2.7D	(8.0) 5.4P	(8.4) 5.0D	(8.0) 6.0P
-2.0	5.4D	4.9D	5.5D	4.7D	5.4D	5.8D	5.0D	(4.0) 5.5P	(4.1) 2.8P	(4.1) 6.0P
-4.0	5.5D	S	6.0D	5.0D	5.4D	2.1D	3.2D	(9.0) 6.1D	(2.0) 6.0D	(3.0) 5.4B
-6.0				5.2D						

$M_{5°} = 0.0$

h_{equil} = 1.80 in. J_{equil} = 4.5 deg. M_{equil} = +0.10 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0		6.0P	S	S	5.3P	8.0D	7.5D	(4.0) S	(1.0) S	(0.0) S
+6.0		S	S	S	S	5.8D	6.8D	(4.4) S	(0.5) S	(2.0) S
+4.0	5.7P	S	S	S	S	S	S	(0.5) S	(1.0) S	(1.0) S
+2.0	S	S	S	S	S	S	S	(1.5) S	(6.0) S	(6.1) S
0	5.5P	S	S	S	S	1.4P	S	(8.0) S	(4.4) S	(5.5) 5.0B
-2.0	S	S	S	S	S	6.0D	S	(4.0) S	(6.7) 7.0B	(3.7) 8.1B
-4.0	S	S	S	S	5.4D	5.5P	5.4D	(1.5) 6.9B	(1.6) 9.1B	(0.2) 12.8B
-6.0								(-0.5) 12.0B	(-0.5) 12.5B	

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

TEST RESULTS

TABLE II

STEP HEIGHT = 1.0% b

MODEL 339-27

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 23.53 FT./SEC.

STARTS IN WATER

STARTS ABOVE WATER SURFACE (NOMINAL)

h_{equil} = 2.00 in. J_{equil} = 7.3 deg. M_{equil} = -1.43 in.lb. $M_{5°}$ = -2.50

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0										
+4.0									(1.0) S	(1.0) S
+2.0									(3.2) 4.5P	(8.0) 4.3P
0									(8.0) 4.3P	(8.0) 5.0P
-2.0								L.W.	(7.0) 4.6P	(6.0) 5.2P
-4.0								(5.0) 4.3P	(5.0) 4.8P	(9.0) 4.5P
-6.0								(3.0) 4.7P		

h_{equil} = 1.98 in. J_{equil} = 6.8 deg. M_{equil} = -0.76 in.lb. $M_{5°}$ = -1.25

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0									(1.5) S	(2.0) 4.3P
+4.0									(5.0) 4.0P	(6.0) 4.5P
+2.0									(9.0) 4.2P	(8.0) 4.0P
0								L.W.	(8.0) 4.5P	(7.0) 5.0P
-2.0								(6.0) 4.0P	(6.7) 7.3D	(5.7) 4.0P
-4.0								(4.0) 4.0P	(5.7) 4.5D	(3.5) 4.5P
-6.0										

h_{equil} = 1.90 in. J_{equil} = 5.5 deg. M_{equil} = -0.15 in.lb. $M_{5°}$ = 0.0

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0									(1.5) S	(1.0) S
+4.0									(0.5) S	(6.0) 2.1D
+2.0								L.W.	(6.0) S	(7.0) S
0								(6.7) S	(5.0) S	(9.0) 7.3D
-2.0								(5.0) S	(4.0) 5.9D	(5.0) 3.1D
-4.0								L.W.	(2.7) S	(1.5) S
-6.0										

h_{equil} = 1.65 in. J_{equil} = 3.5 deg. M_{equil} = +0.35 in.lb. $M_{5°}$ = +1.25

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0								(5.0) S	(6.7) S	(7.0) 3.7D
+4.0								(8.1) S	(6.0) 1.9D	(5.0) 3.7D
+2.0								(4.7) S	(4.0) S	(1.0) S
0								(4.3) S	(3.0) S	(5.0) 4.0D
-2.0								(5.0) 4.0D	(5.0) S	(1.0) 7.1B
-4.0								(0.1) 3.2D	(1.0) 11.3B	(1.7) 13.5B
-6.0										

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

L.W. = LEAVES WATER

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

TEST RESULTS

TABLE III

STEP HEIGHT = 5.0% b

MODEL 339-1

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 21.18 FT./SEC.

STARTS IN WATER — **STARTS ABOVE WATER SURFACE**

(NOMINAL) $M_{5°} = -5.00$

h_{equil} = 2.14 in. τ_{equil} = 7.6 deg. M_{equil} = -425 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0							
+6.0							
+4.0							
+2.0				5.2P	5.3P		
0			5.0P	S	S	5.0P	
-2.0				5.3P	5.0P	5.2P	
-4.0							
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(8.0) 5.5P	(6.6) 5.0D	(6.8) 4.9P
(7.2) 6.1P	(9.0) 6.2P	(7.0) 7.0P
(6.7) 5.3P	(11.0) 5.3P	(7.2) 6.8P
(7.2) 5.5P	(7.0) 6.1P	(8.2) 7.0P
(8.5) 6.0P	(8.7) 6.0P	(6.8) 6.8P
(6.5) 5.1P	(7.1) 5.6P	(5.0) 7.2P
(5.0) 6.2P	(5.4) 5.0P	(9.0) 7.2P
		(0.8) 7.3P

$M_{5°} = -3.75$

h_{equil} = 2.05 in. τ_{equil} = 7.4 deg. M_{equil} = -3.10 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0			4.0P	4.5P	4.8P	4.0P	
+6.0			5.2P	5.5P	5.0P	4.6P	
+4.0		4.8P	5.8P	5.4P	4.8P	4.7P	4.3P
+2.0		4.6P	5.5P	S	3.8P	4.2P	3.5P
0		5.5P	5.9P	S	4.9P	4.4P	3.4P
-2.0		5.8P	5.3P	5.9P	4.5P	4.5P	5.2P
-4.0		4.1P	4.2P	4.6P	4.4P	4.8P	4.4P
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(6.0) 5.2P	(7.2) 4.3D	(6.3) 6.3D
(7.0) 7.3P	(8.3) 3.4P	(11.5) 5.7P
(6.8) 4.8P	(11.0) 4.7P	(10.0) 4.9P
(7.8) 4.3P	(9.8) 5.4P	(9.6) 3.9P
(7.0) 3.9P	(8.7) 5.9P	(7.8) 6.3P
(5.5) 5.4P	(7.0) 6.9P	(6.8) 6.0P
(4.7) 6.2P	(4.2) 6.8P	(6.2) 4.7P

$M_{5°} = -2.50$

h_{equil} = 2.02 in. τ_{equil} = 7.1 deg. M_{equil} = -1.92 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0		5.4P	5.2P	4.9P	5.3P		
+6.0		5.2P	5.2P	5.0D	4.9P		4.2P
+4.0	5.2P	4.6P	4.2D	3.8D	5.6P	5.9P	4.3P
+2.0	4.8P	4.5P	2.5D	S	5.2D	5.9P	S
0	5.4P	4.0D	S	S	5.2D	4.0P	4.4P
-2.0	6.0P	S	3.0D	S	4.8D	S	S
-4.0	5.1P	4.6P	5.2P	4.5P	4.6P	4.6P	5.3P
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(4.0) 5.7P	(6.0) 5.4P	(3.4) 3.0D
(4.2) 4.7P	(3.2) 2.5D	(3.0) S
(3.3) 2.9D	(7.8) 5.4P	(7.0) 5.9P
(7.6) 5.1P	(7.1) 5.4P	(7.0) 2.2D
(7.5) 5.2P	(7.5) 3.5P	(3.0) S
(4.8) 6.2P	(5.0) 5.3D	(3.1) S
(4.4) 6.2P	(2.7) 7.0P	(1.8) 9.1B
	(6.0) 5.0D	(0.1) 13.7B

$M_{5°} = -1.25$

h_{equil} = 1.98 in. τ_{equil} = 6.6 deg. M_{equil} = -0.96 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0		S	5.4D	S	5.4P	3.7P	
+6.0		S	S	S	5.0D	7.2D	
+4.0		S	S	S	S	S	
+2.0		S	S	S	S	S	
0		S	S	S	S	5.0P	
-2.0		S	S	S	2.8D	5.0D	
-4.0		S	S	S	4.5P	5.2P	
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(2.8) S	(4.0) S	(3.0) 4.8P
(5.0) S	(7.8) 4.9D	(6.0) S
(5.0) S	(10.6) S	(3.2) S
(6.0) S	(7.0) S	(7.2) S
(7.0) S	(3.3) S	(3.2) S
(4.8) S	(3.2) S	(3.0) 7.8B
(5.0) 4.1P	(2.0) 8.4B	(1.2) 11.1B
(1.0) 9.0B	(-0.4) 9.5B	(-2.7) 13.0B

$M_{5°} = 0.0$

h_{equil} = 1.82 in. τ_{equil} = 4.2 deg. M_{equil} = +0.10 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0			S	S	S	7.3D	8.4D
+6.0			S	S	S	S	8.0D
+4.0			S	S	S	S	7.0D
+2.0			S	S	S	S	S
0			S	S	S	S	S
-2.0			S	S	S	S	S
-4.0			S	S	S	S	S
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(1.0) S	(4.8) S	(6.0) S
(2.5) S	(9.0) S	(11.0) S
(8.5) S	(6.5) S	(6.8) S
(6.2) S	(5.0) S	(4.0) S
(4.8) S	(9.6) S	(2.7) 7.0D
(2.0) 4.8B	(1.8) 8.7B	(0.8) 9.2B
(0.8) 8.2B	(-0.1) 11.3B	(-0.9) 12.9B
(-1.0) 12.5B	(-1.8) 14.8B	(-3.2) 13.5B

THESE RESULTS PRESENTED GRAPHICALLY IN FIG. 5

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

TEST RESULTS

TABLE IV

STEP HEIGHT = 5.0% b

MODEL 339-1

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 23.53 FT./SEC.

STARTS IN WATER

STARTS ABOVE WATER SURFACE (NOMINAL)

h_{equil} = 2.05 in. τ_{equil} = 6.8 deg. M_{equil} = -2.01 in.lb. $M_{5°}$ = -2.50

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0										
+4.0										(2.8) S
+2.0									(0.7) S	(7.0) 6.0P
0								L.W.	(7.1) S	(6.8) 7.0P
-2.0								(6.6) 4.0D	(4.8) S	(4.2) S
-4.0								(4.3) 3.0D	(3.7) S	(1.8) 8.0B
-6.0								(2.8) 5.0D	(1.8) 4.0D	(-0.8) 9.0B

h_{equil} = 2.02 in. τ_{equil} = 6.1 deg. M_{equil} = -0.82 in.lb. $M_{5°}$ = -1.25

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0										
+4.0									(9.1) S	(6.8) S
+2.0								L.W.	(7.7) S	(6.8) S
0								(7.2) 2.0D	(5.8) S	(4.7) S
-2.0								(5.0) 2.0D	(4.1) S	(2.7) 5.0P
-4.0								(2.7) S	(2.0) 3.8D	(1.3) 5.0P
-6.0								(1.5) 4.7D	(-0.3) 4.0D	(-1.1) 13.0B

h_{equil} = 1.95 in. τ_{equil} = 5.5 deg. M_{equil} = -0.20 in.lb. $M_{5°}$ = 0.0

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										(4.4) S
+6.0								(7.0) 5.2P	(6.2) S	(12.8) 4.0D
+4.0								(6.0) 4.0P	(6.2) S	(10.7) S
+2.0								(6.6) 4.2P	(6.0) S	(4.4) S
0								(5.0) 3.8D	(3.1) S	(3.2) S
-2.0								(3.4) 4.8P	(1.2) S	(1.9) S
-4.0								(-1.) 4.7P	(2.8) S	(0.8) S
-6.0								(-4.2) 9.8B	(-3.0) 14.0B	(-4.9) 17.0B

h_{equil} = 1.75 in. τ_{equil} = 3.5 deg. M_{equil} = +0.33 in.lb. $M_{5°}$ = +1.25

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0								(5.8) S	(4.8) S	(2.8) S
+4.0								(5.0) 5.0D	(4.0) S	(4.7) S
+2.0								(4.8) 4.8D	(3.8) S	(3.8) S
0								(3.9) 4.2D	(1.9) S	(1.0) S
-2.0								(2.1) S	(+0.8) S	(1.0) S
-4.0								(0.1) 8.5B	(-2.3) 12.0B	(-2.8) 14.5B
-6.0								(-2.0) 12.5B	(-3.7) 14.0B	(-3.4) 12.5B

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

L.W. = LEAVES WATER

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

TEST RESULTS

TABLE V

STEP HEIGHT = 9.0% b

MODEL 339-26

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 21.18 FT./SEC.

STARTS IN WATER — **STARTS ABOVE WATER SURFACE**

(NOMINAL)

$M_{5°} = -5.00$

h_{equil} = 2.15 in. J_{equil} = 7.6 deg. M_{equil} = -4.22 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0							
+6.0							
+4.0							
+2.0				4.5P			
0			3.8P	S	4.7P		
-2.0				4.5P			
-4.0							
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(7.0) 4.6P	(12.8) 4.5P	(11.0) 4.5P
(8.0) 4.0P	(8.4) 4.3P	(10.0) 4.5P
(7.5) 3.8P	(6.8) 4.1P	(8.3) 4.6P
(6.3) 3.8P	(4.9) 3.7P	(4.2) 4.5P
(5.0) 4.1P	(2.4) 4.0P	(1.0) 5.0P
(2.5) 4.2P	(1.5) 4.5P	(1.0) 4.5P

$M_{5°} = -3.75$

h_{equil} = 2.14 in. J_{equil} = 7.4 deg. M_{equil} = -3.03 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0							
+6.0							
+4.0			3.8P	4.0P	3.9P		
+2.0			5.5P	3.9P	5.5P		
0			3.8P	S	3.4P		
-2.0			3.3P	3.0P	3.9P		
-4.0			4.0P	4.0P	4.8P		
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
	(6.5) 5.0D	(5.1) 5.5P
(6.0) 4.0P	(9.3) S	(12.0) 5.0P
(8.0) 3.3P	(8.0) 5.5D	(8.2) 4.2P
(7.5) 3.0P	(6.0) 5.3P	(6.0) 4.0P
(5.0) 4.5P	(4.3) 3.9P	(4.2) 4.7P
(4.1) 4.0P	(2.4) 7.0P	(1.3) 3.8P
(2.5) 4.9P	(0.4) 7.0P	(0) 4.0P

$M_{5°} = -2.50$

h_{equil} = 2.13 in. J_{equil} = 7.1 deg. M_{equil} = -1.81 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0				4.4P	4.8D	3.8D	4.5D
+6.0				4.5P	4.5P	5.8D	6.0D
+4.0		3.5P	4.2P	2.8D	3.5D	2.9D	S
+2.0		5.0P	4.5D	S	3.5D	S	S
0		3.1D	S	S	S	S	S
-2.0		S	3.3D	2.3D	3.0D	S	S
-4.0		3.2D	3.5D	3.5D	3.3D	3.3D	4.2D
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
	(4.9) 5.5P	
(3.5) 4.1D	(5.5) 4.5P	(5.5) 4.5D
(4.4) S	(11.0) 3.5P	(13.0) 4.0D
(7.8) 2.5D	(8.1) 4.5P	(9.0) 3.1D
(7.7) 3.0D	(6.4) 3.0D	(5.7) S
(6.5) 4.5D	(4.0) S	(7.2) 3.0D
(1.0) S	(3.2) 5.0D	(1.7) 11.0B
(2.0) 4.0D	(6.1) 6.0D	(0.7) 15.0B

$M_{5°} = -1.25$

h_{equil} = 2.08 in. J_{equil} = 6.5 deg. M_{equil} = -0.84 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0		S	S	S	S	S	S
+6.0		S	S	S	S	S	S
+4.0	S	S	S	S	S	S	S
+2.0	S	S	S	S	S	S	S
0	S	S	S	S	S	S	S
-2.0	S	S	S	S	S	S	S
-4.0	S	S	S	S	S	S	S
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(14.0) S	(6.5) S	(7.2) S
(17.0) S	(9.0) S	(6.0) S
(6.8) S	(8.4) S	(10.0) S
(5.0) S	(6.0) S	(7.3) S
(9.0) S	(4.0) S	(5.8) S
(4.2) S	(2.8) S	(3.8) 9.8B
(3.2) 6.5B	(4.0) 6.0B	(1.0) 15.0B
(6.4) 10.0B	(-0.8) 6.5B	(-1.7) 18.0B

$M_{5°} = 0.0$

h_{equil} = 1.85 in. J_{equil} = 4.0 deg. M_{equil} = +0.10 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3
	Change from Equil. Heave, in.						
+8.0		S	S	S	S	S	S
+6.0		S	S	S	S	S	S
+4.0		S	S	S	S	S	S
+2.0		S	S	S	S	S	S
0		S	S	S	S	S	S
-2.0		S	S	S	S	S	S
-4.0		S	S	S	S	S	S
-6.0							

0.3	0.6	0.9
Δ P.E., lb. ft.		
(13.0) S	(8.0) S	(11.0) S
(10.0) S	(7.0) S	(8.9) S
(4.3) S	(4.9) S	(6.7) S
(4.3) S	(5.0) S	(5.9) S
(5.8) S	(1.9) 8.5B	(3.0) 8.0B
(0.4) 9.7B	(0.0) 10.0B	(-1.8) 9.8B
(-1.0) 13.5B	(-2.2) 15.0B	(0) 12.0B
(-0.5) 9.0B	(-3.4) 17.0B	

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

STARTS IN WATER

STARTS ABOVE WATER SURFACE

(NOMINAL)

TEST RESULTS

TABLE VI

STEP HEIGHT = 9.0% b

MODEL 339-26

C.G. = 2.33 IN. FWD. OF STEP
4.89 IN. ABOVE B.L.

SPEED 23.53 FT./SEC.

$M_{5°} = -2.50$

h_{equil} = 2.10 in. J_{equil} = 6.5 deg. M_{equil} = -2.07 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0										
+4.0									(18.0) S	(10.0) S
+2.0									(7.1) S	(8.0) S
0								(7.5) S	(6.2) S	(8.0) S
-2.0								(7.0) S	(4.0) S	(5.0) S
-4.0								(6.0) S	(3.3) S	(6.0) S
-6.0								(2.0) S	(4.9) S	(-1.0) S

$M_{5°} = -1.25$

h_{equil} = 2.08 in. J_{equil} = 6.1 deg. M_{equil} = -0.92 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0										
+4.0									(9.0) 2.3D	(11.0) S
+2.0								(7.7) L.W.	(7.0) S	(5.5) S
0								(4.7) S	(5.1) S	(4.1) 4.0D
-2.0								(3.9) S	(3.3) 3.1D	(2.7) S
-4.0								(2.2) S	(0.0) 6.5D	(0.0) 11.0B
-6.0										

$M_{5°} = 0.0$

h_{equil} = 2.05 in. J_{equil} = 5.5 deg. M_{equil} = -0.20 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0									(6.3) S	(12.0) S
+4.0									(4.1) S	(9.0) S
+2.0								(7.7) S	(7.2) S	(3.5) S
0								(4.7) S	(2.5) S	(3.3) 3.0D
-2.0								(3.9) S	(2.3) S	(1.0) 9.0B
-4.0								(2.2) S	(0.2) 9.0B	(0) 12.0B
-6.0								(0) S	(-1.0) 12.0B	

$M_{5°} = +1.25$

h_{equil} = 1.80 in. J_{equil} = 3.5 deg. M_{equil} = +0.35 in.lb.

Change from Equil. Trim, deg.	-0.3	-0.2	-0.1	0	+0.1	+0.2	+0.3	0.3	0.6	0.9
	Change from Equil. Heave, in.							Δ P.E., lb. ft.		
+8.0										
+6.0								(9.0) S	(1.0) S	(5.7) S
+4.0								(4.0) S	(3.7) S	(2.9) 3.0D
+2.0								(3.4) S	(2.9) S	(2.2) 1.4D
0								(2.2) S	(1.0) S	(0.2) 11.0B
-2.0								(0.9) S	(-1.0) 11.5B	(-1.0) 14.0B
-4.0								(-1.9) 11.5B		(-4.0) 17.0B
-6.0										

S = STABLE

D = DAMPED UPPER LIMIT PORPOISE

P = SELF-SUSTAINING UPPER LIMIT PORPOISE

B = INCIPIENT LOWER LIMIT PORPOISE

L.W. = LEAVES WATER

NOTES: FIGURES WHICH PRECEDE THESE LETTERS INDICATE THE MAGNITUDE OF THE TRIM SWEEP IN DEGREES.

FIGURES IN PARENTHESES INDICATE ACTUAL TRIM AT WHICH HULL FIRST MADE CONTACT WITH WATER.

SCHEMATIC SKETCH OF APPARATUS FOR LANDING TESTS

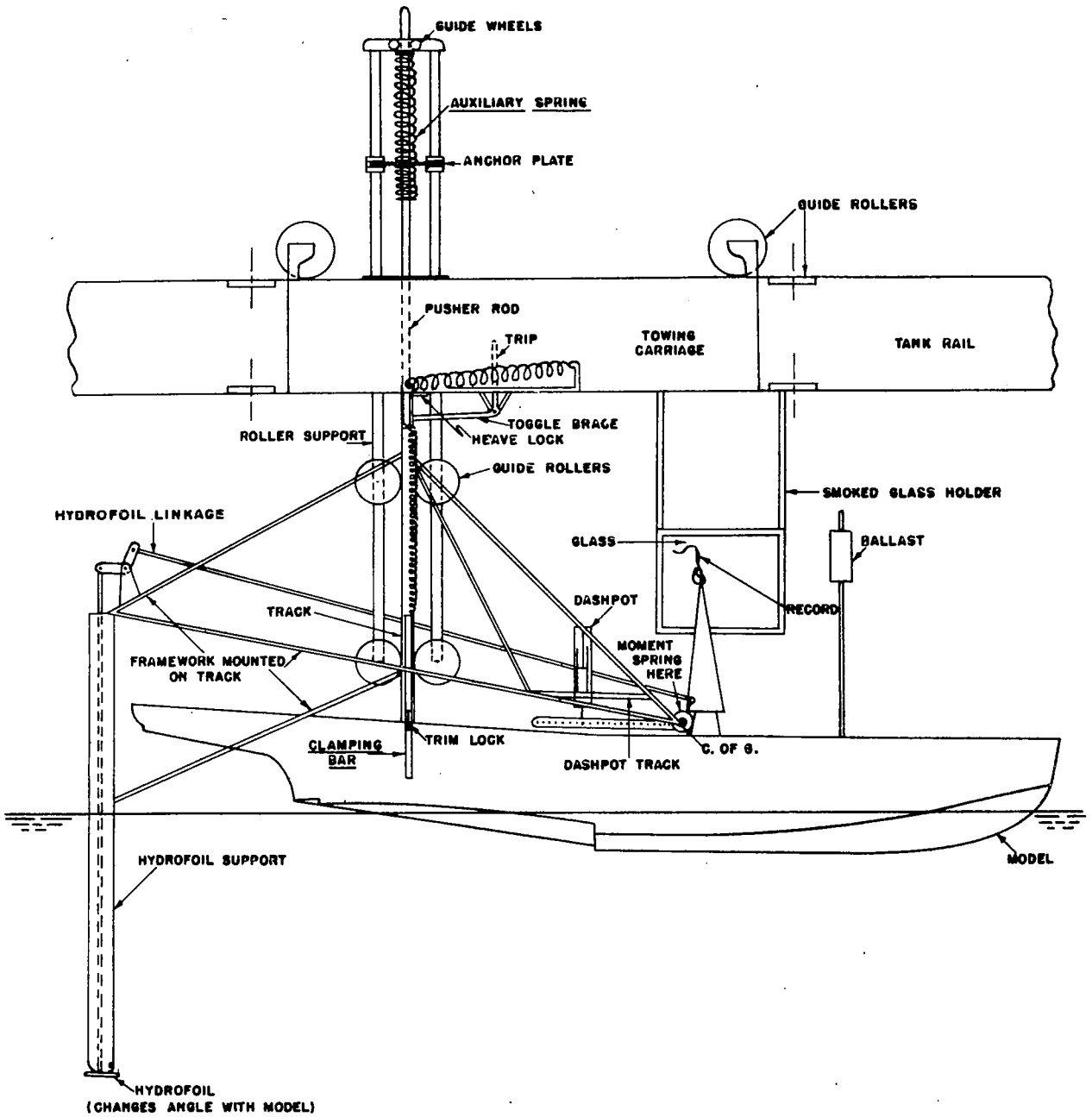
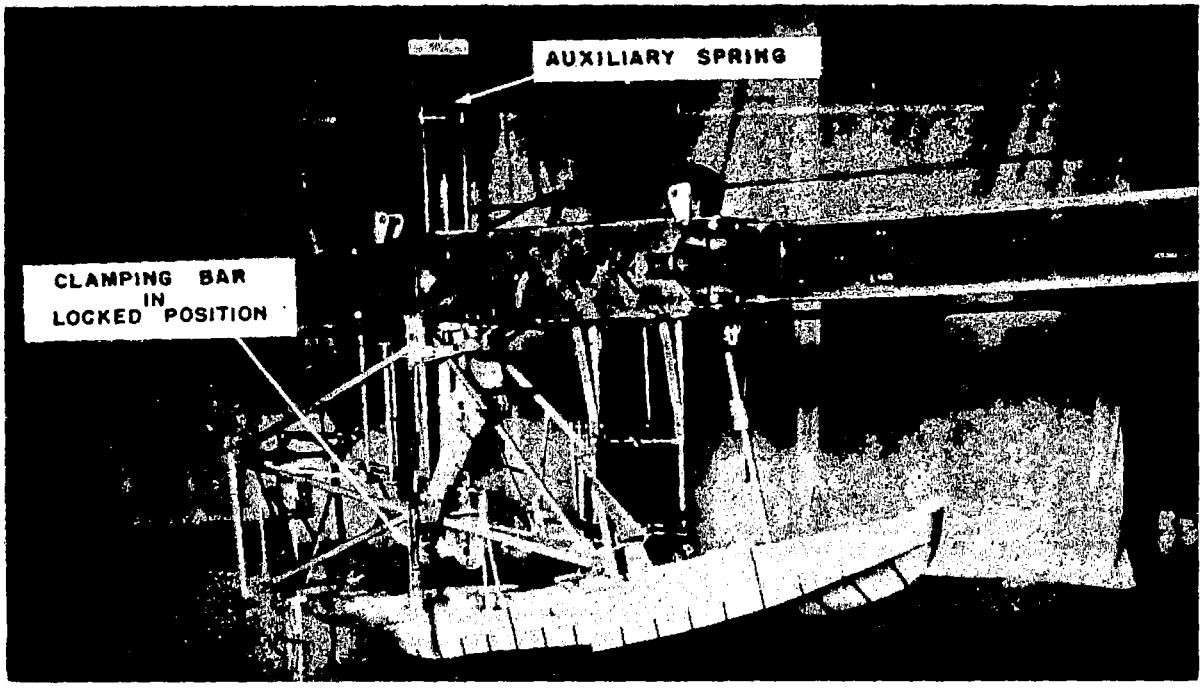
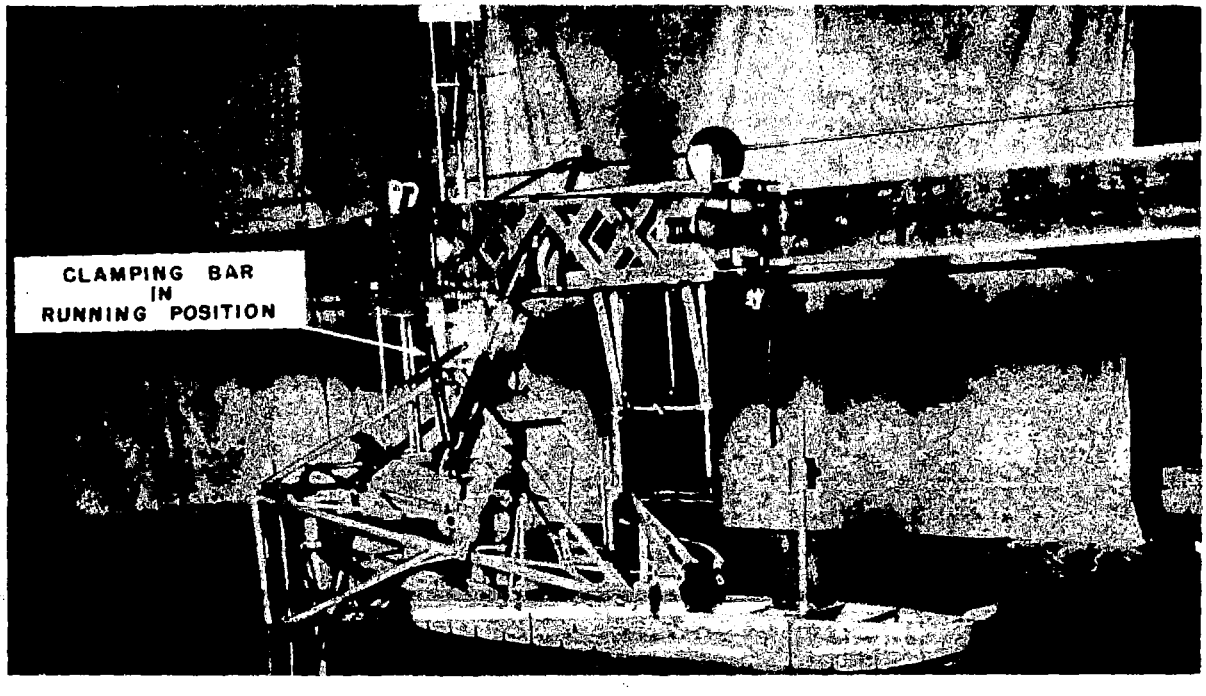


Fig. 1



(a)



(b)

Figure 2.- Auxiliary devices.

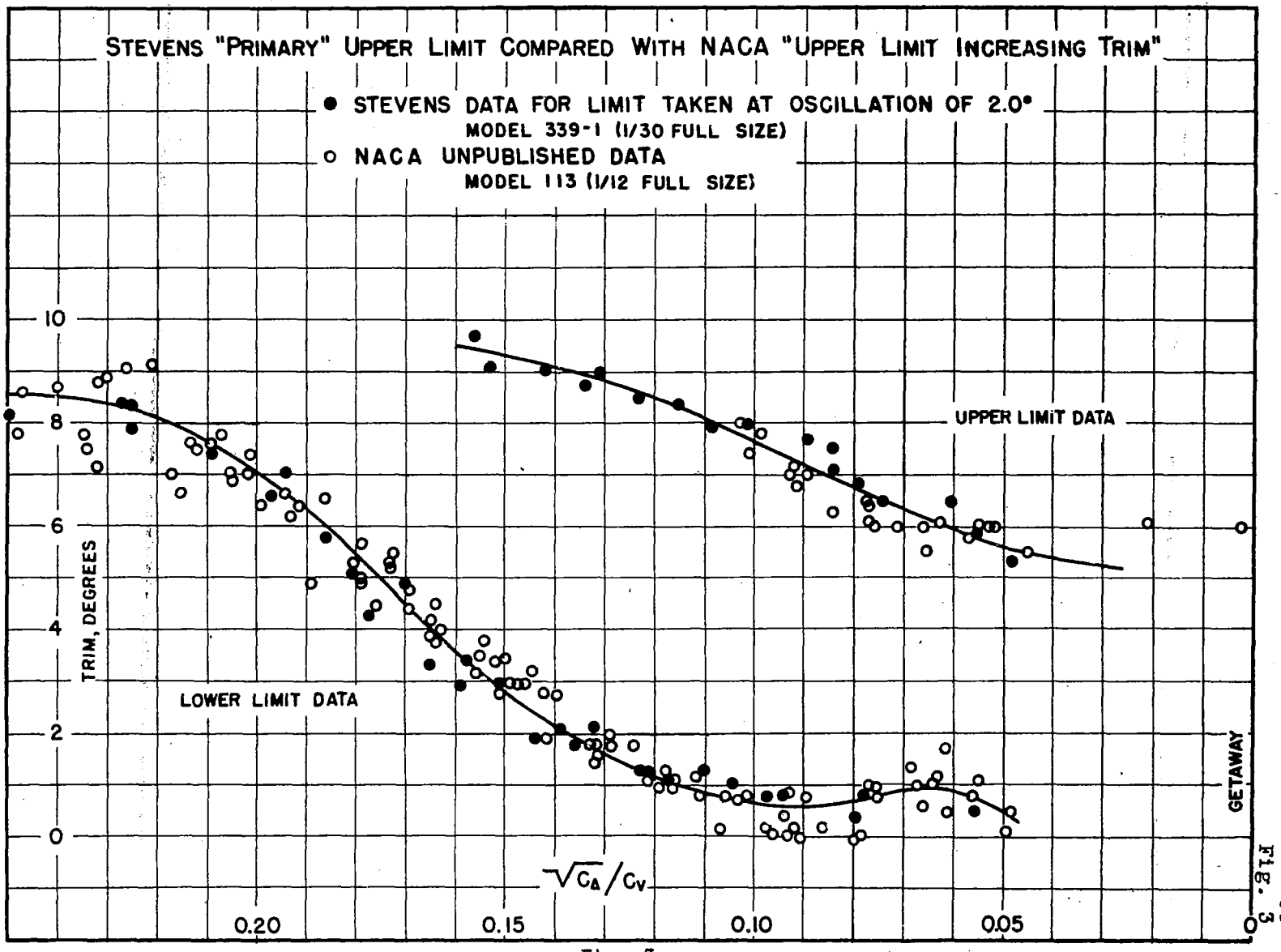
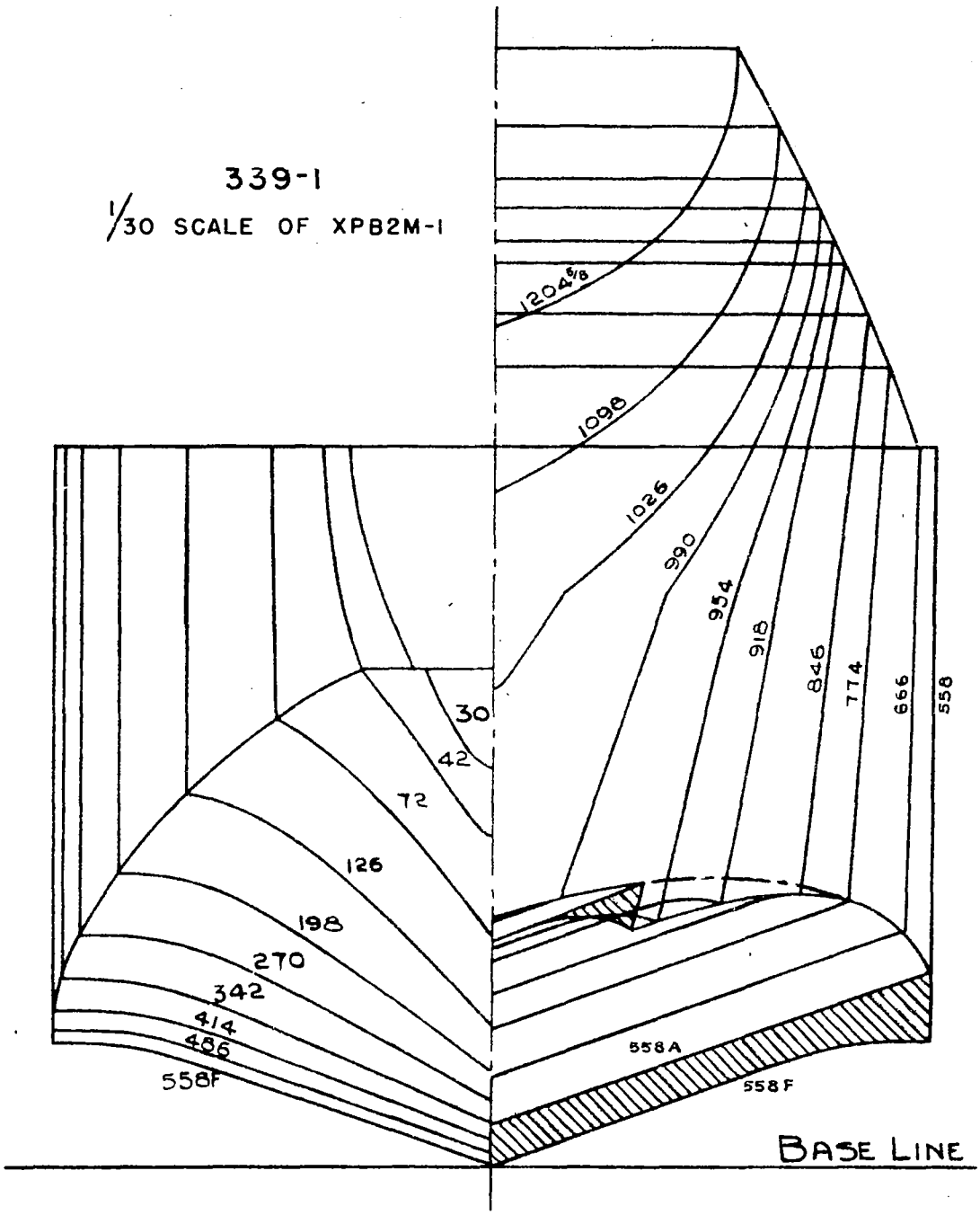

STEVENS "PRIMARY" UPPER LIMIT COMPARED WITH NACA "UPPER LIMIT INCREASING TRIM"
● STEVENS DATA FOR LIMIT TAKEN AT OSCILLATION OF 2.0°
MODEL 339-1 (1/30 FULL SIZE)
○ NACA UNPUBLISHED DATA
MODEL 113 (1/12 FULL SIZE)
UPPER LIMIT DATA
LOWER LIMIT DATA
TRIM, DEGREES
10
8
6
4
2
0
$\sqrt{C_\Delta}/C_V$
0.20
0.15
0.10
0.05
0
GETAWAY

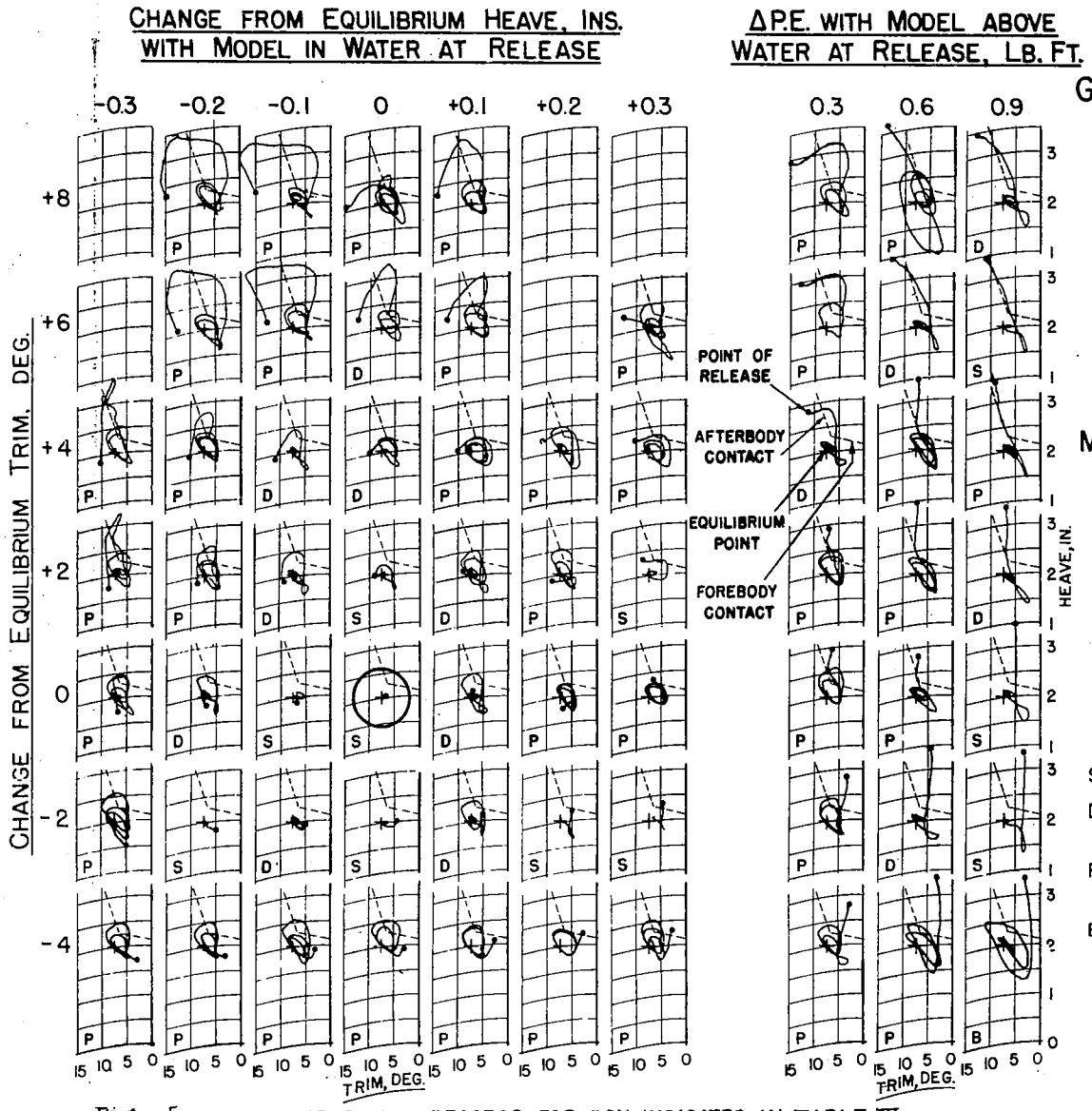
Fig. 3

BODY PLAN OF PARENT MODEL



Station Numbers are Inches Aft of Forepoint on Full Size.

Fig. 4



GRAPHICAL RECORDS OF TEST RESULTS FOR MODEL 339-1

STEP HEIGHT = 5.0%b

C.G. = 2.33 IN. FWD. OF STEP, 4.89 IN. ABOVE B.L.

SPEED 21.18 FT./SEC.

$M_{5°}$ = -2.50 IN.LB. (NOMINAL) FROM TABLE III

S=STABLE

D=DAMPED UPPER LIMIT PORPOISE

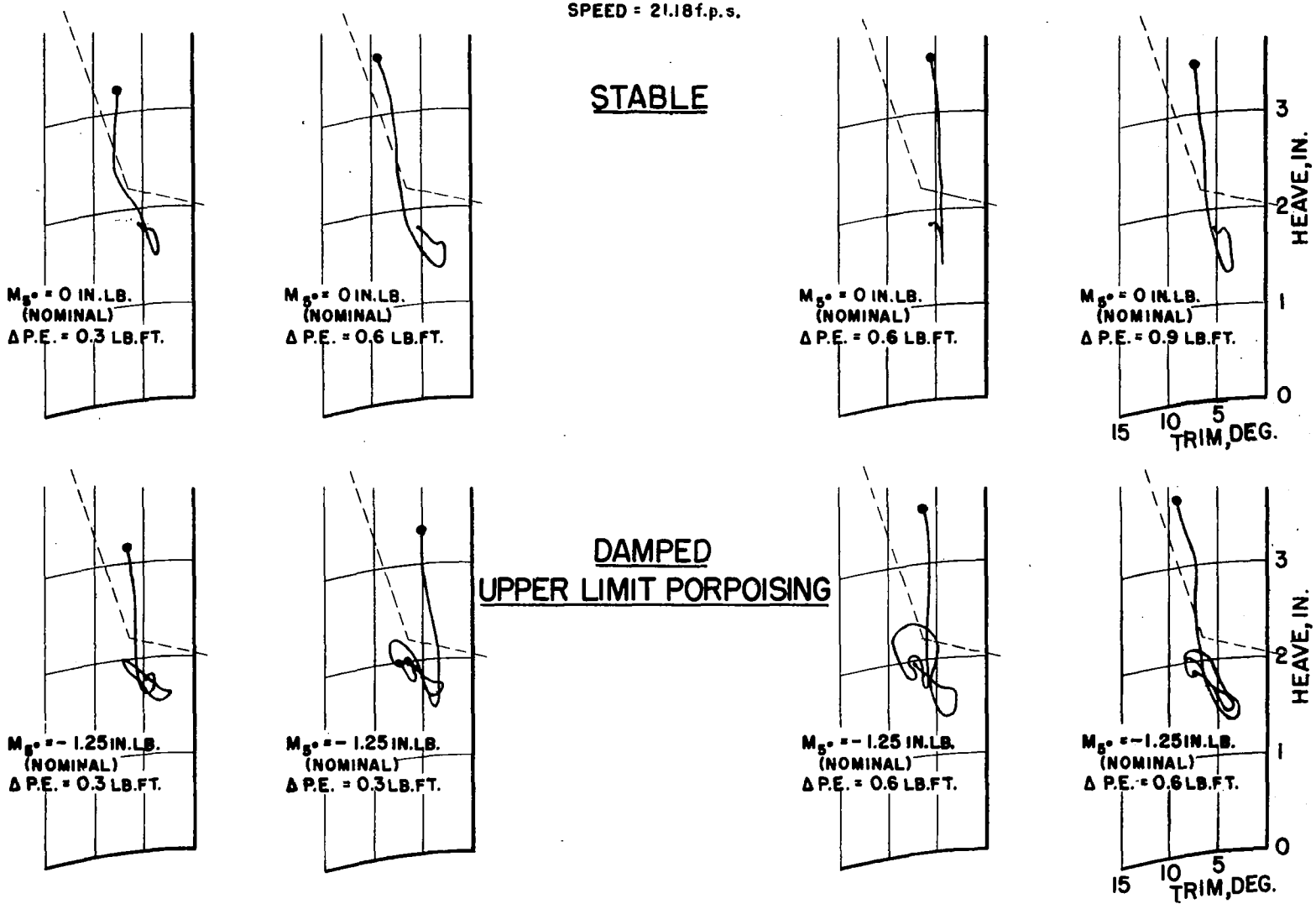
P=SELF-SUSTAINING UPPER LIMIT PORPOISE

B=INCIPIENT LOWER LIMIT PORPOISE

Fig. 5 GRAPHICAL RECORDS FOR BOX INDICATED IN TABLE III

SELECTED RECORDS ILLUSTRATING THE FOUR TYPES OF MOTION FOUND THROUGHOUT TESTS

STEP HEIGHT = 1%b
SPEED = 21.18 f.p.s.



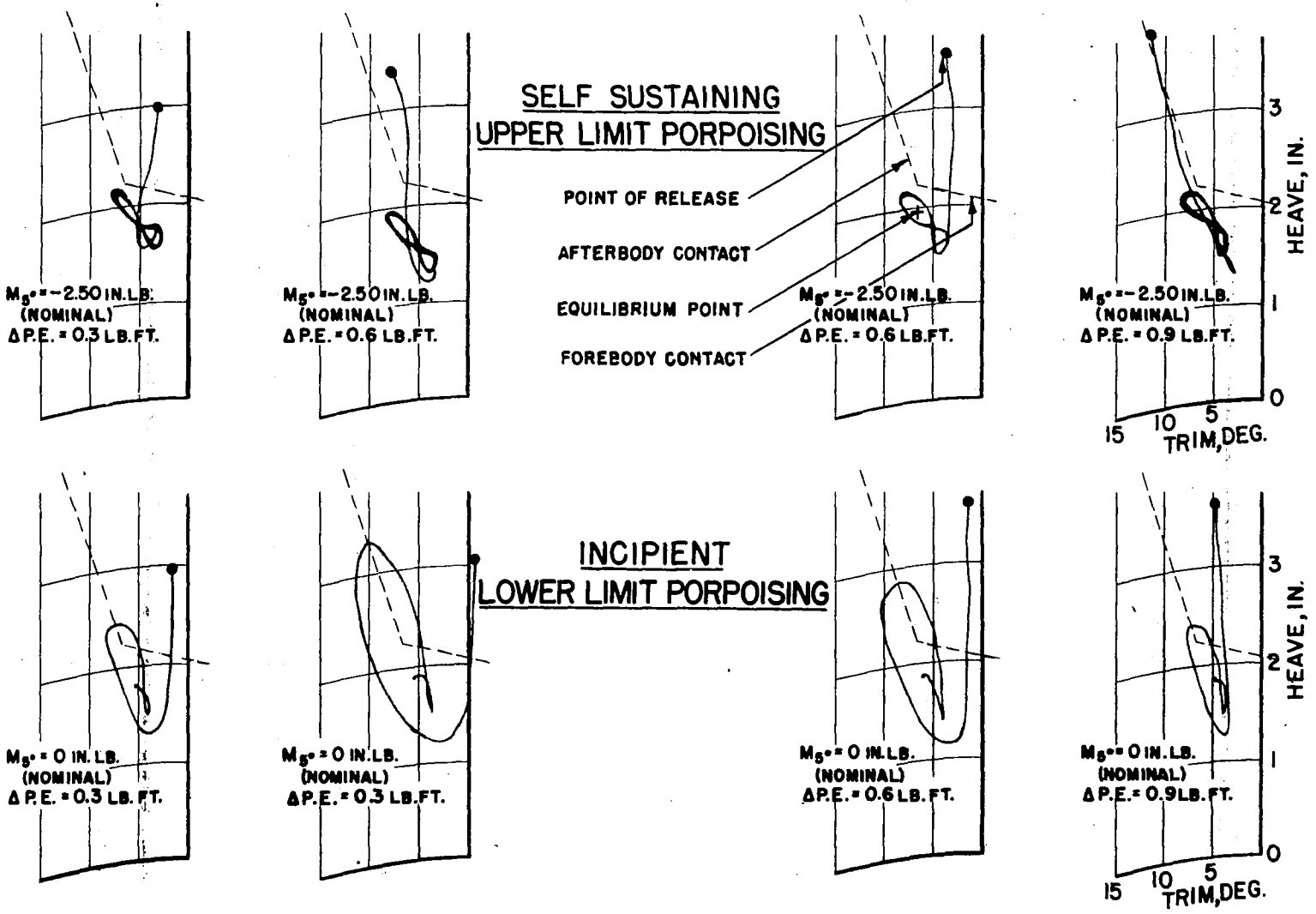

SELF SUSTAINING
UPPER LIMIT PORPOISING
POINT OF RELEASE
AFTERBODY CONTACT
EQUILIBRIUM POINT
FOREBODY CONTACT
M_{S^*} = -2.50 IN.LB. (NOMINAL) ΔP.E. = 0.3 LB.FT.
M_{S^*} = -2.50 IN.LB. (NOMINAL) ΔP.E. = 0.6 LB.FT.
M_{S^*} = -2.50 IN.LB. (NOMINAL) ΔP.E. = 0.6 LB.FT.
M_{S^*} = -2.50 IN.LB. (NOMINAL) ΔP.E. = 0.9 LB.FT.
INCIPIENT
LOWER LIMIT PORPOISING
M_{S^*} = 0 IN.LB. (NOMINAL) ΔP.E. = 0.3 LB.FT.
M_{S^*} = 0 IN.LB. (NOMINAL) ΔP.E. = 0.3 LB.FT.
M_{S^*} = 0 IN.LB. (NOMINAL) ΔP.E. = 0.6 LB.FT.
M_{S^*} = 0 IN.LB. (NOMINAL) ΔP.E. = 0.9 LB.FT.
HEAVE, IN.
0
1
2
3
15
10
5
TRIM, DEG.

Fig. 6

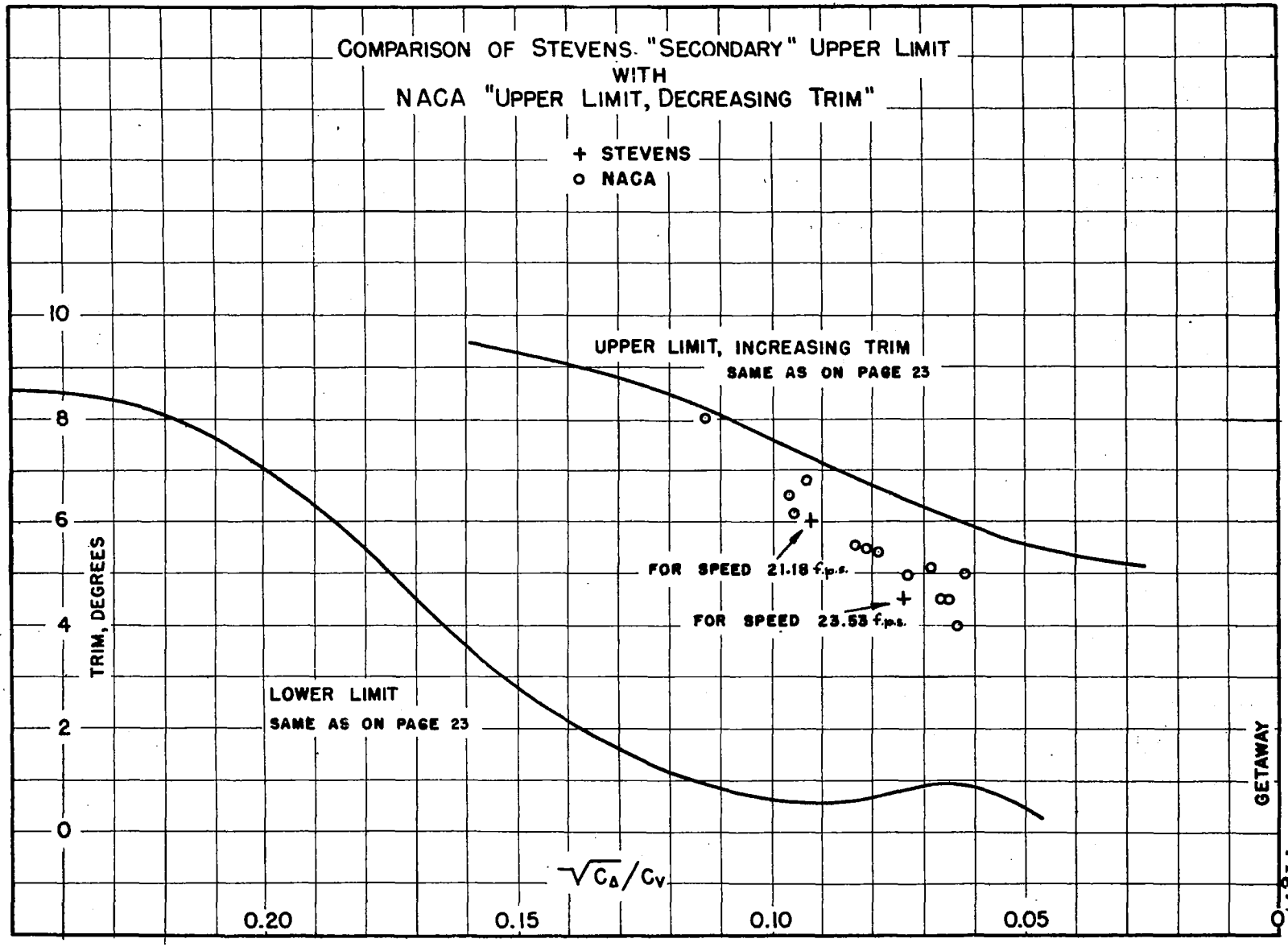

COMPARISON OF STEVENS "SECONDARY" UPPER LIMIT
WITH
NACA "UPPER LIMIT, DECREASING TRIM"
+ STEVENS
o NACA
UPPER LIMIT, INCREASING TRIM
SAME AS ON PAGE 23
FOR SPEED 21.18 f.p.s.
FOR SPEED 23.53 f.p.s.
LOWER LIMIT
SAME AS ON PAGE 23
TRIM, DEGREES
10
8
6
4
2
0
0.20
0.15
0.10
0.05
0
$\sqrt{C_\Delta}/C_V$
GETAWAY

Fig. 7

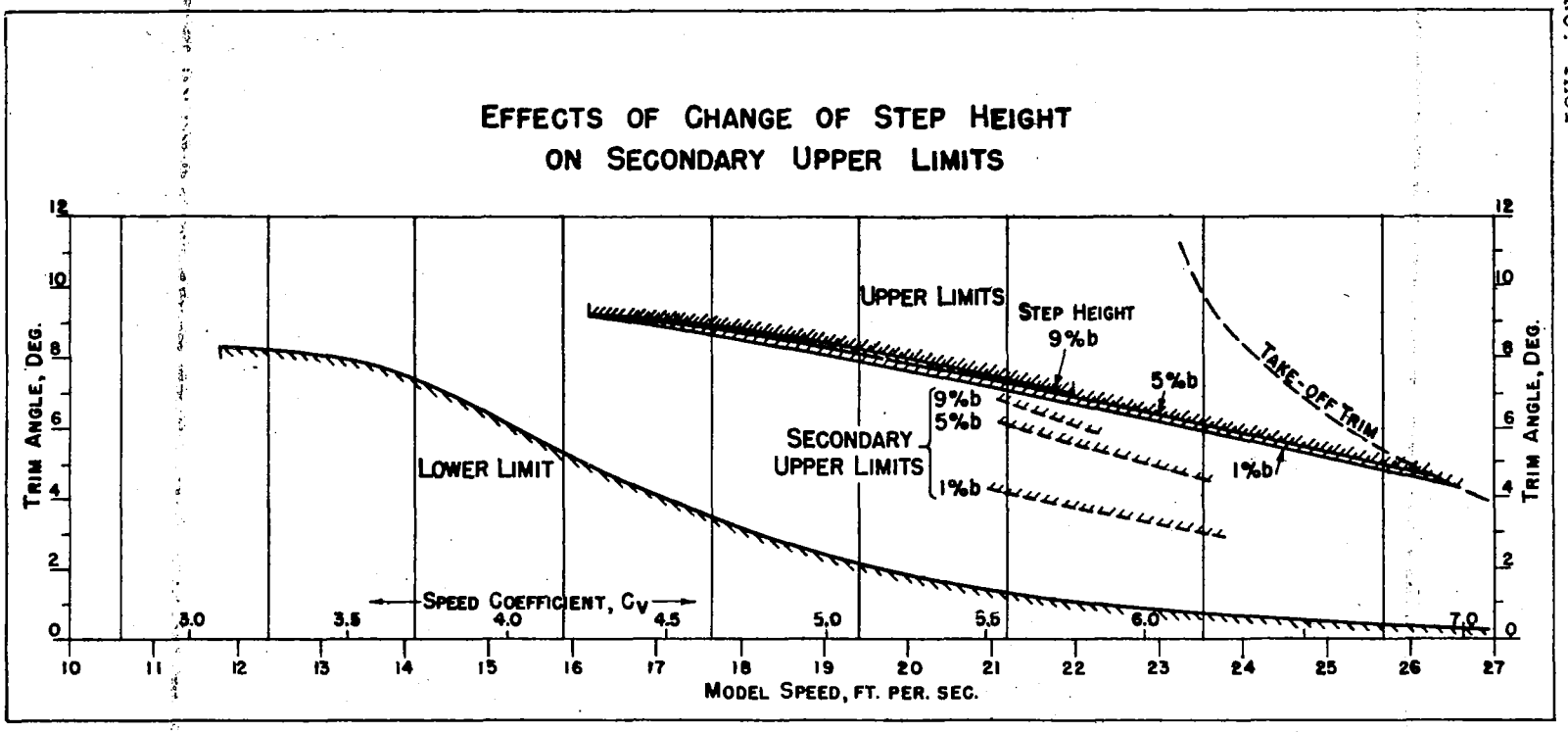

EFFECTS OF CHANGE OF STEP HEIGHT
ON SECONDARY UPPER LIMITS
UPPER LIMITS
STEP HEIGHT
9%b
5%b
1%b
TAKE-OFF TRIM
SECONDARY
UPPER LIMITS
9%b
5%b
1%b
LOWER LIMIT
SPEED COEFFICIENT, Cv
3.0
3.5
4.0
4.5
5.0
5.5
6.0
7.0
TRIM ANGLE, DEG.
MODEL SPEED, FT. PER. SEC.

Fig. 8

BAR CHART FOR THE THREE MODELS SHOWING RELATIVE FREQUENCY OF THE FOUR TYPES OF MOTION
(STARTS IN AND ABOVE THE WATER SURFACE)
(SPEED 21.18 FT./SEC.)

C.G. = 2.33 INS. FWD. OF STEP
4.89 INS. ABOVE B.L.

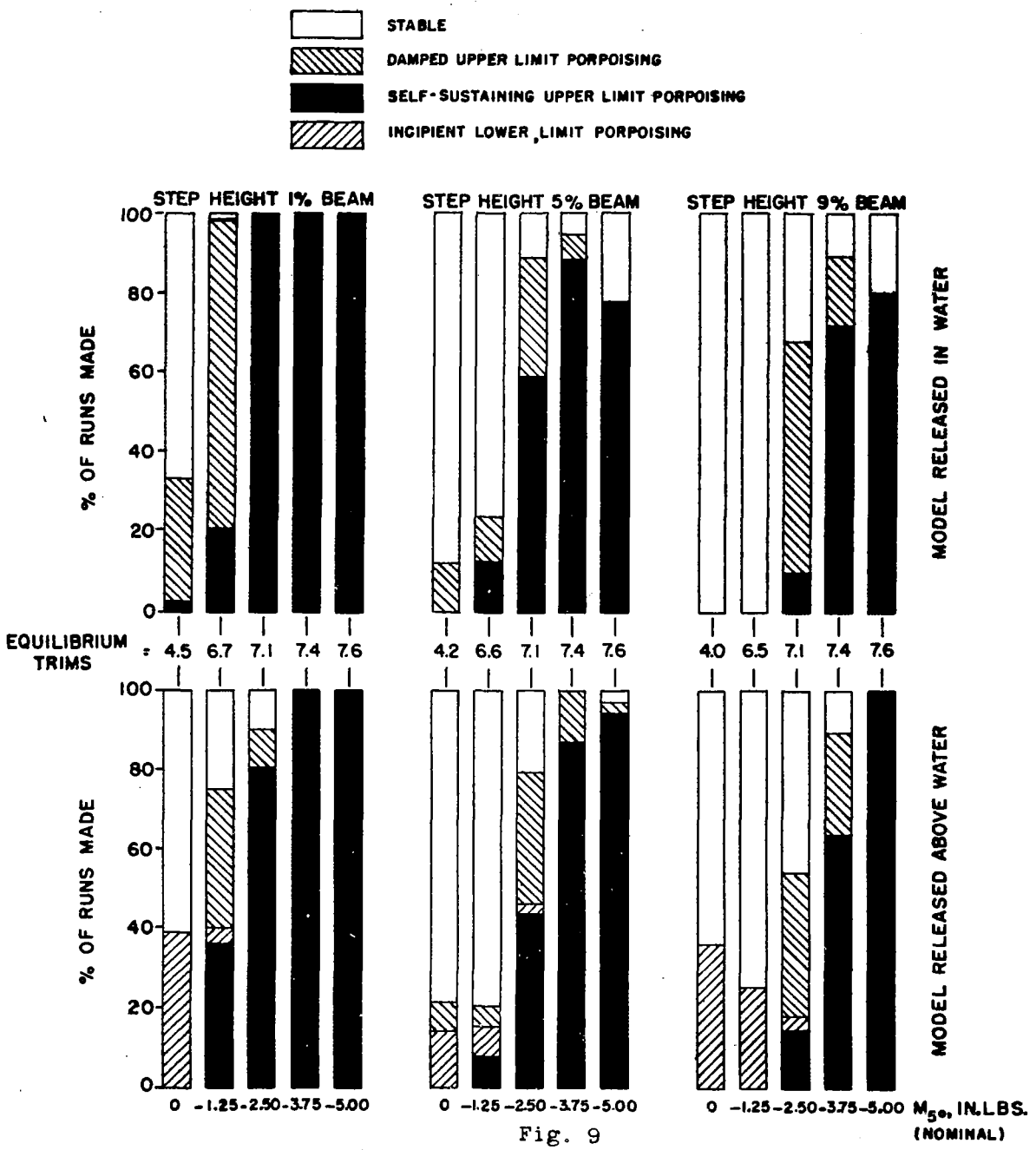


Fig. 9