Report No. 54EFS12

May 1954

TESTS OF THE SEAWORTHINESS OF SEAPLANE HULLS HAVING A HIGH LENGTH TO BEAM RATIO

By

E. F. Schulz

Department of Civil Engineering

Colorado Agricultural and Mechanical College

Fort Collins, Colorado

Tests of the Seaworthiness of Seaplane Hulls Having a High Length to Beam Ratio

by

E. F. Schulz
Civil Engineering Section
Colorado A & M College
Fort Collins, Colorado

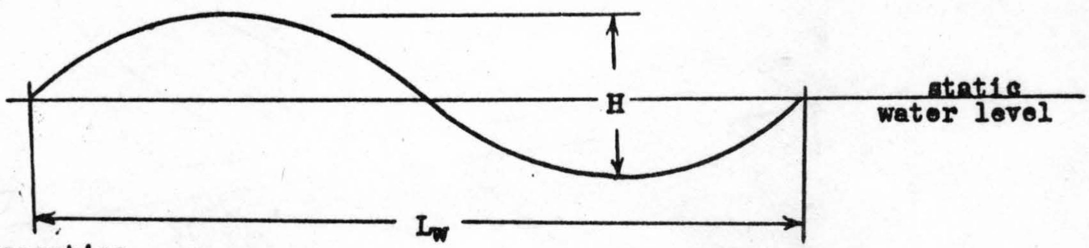
prepared for
Bureau of Aeronautics
Navy Department
under Contract No. NOas 52-1077-c
through the
Colorado A & M Research Foundation

TABLE OF CONTENTS

LIST OF TABLES

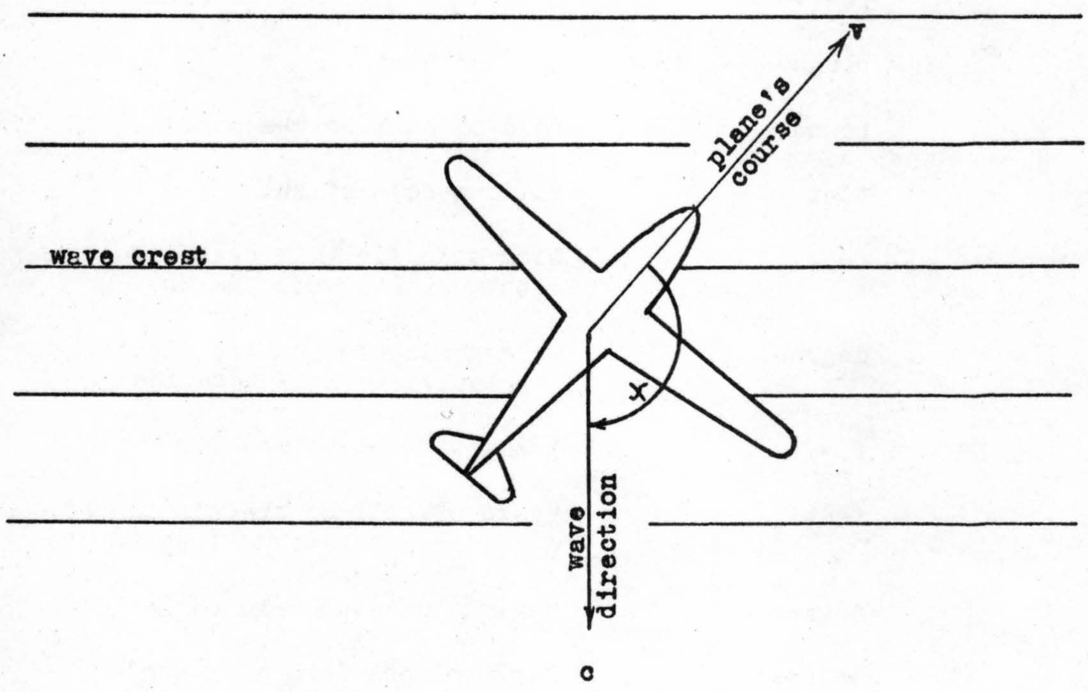
LIST OF FIGURES

STANDARD NOTATION AND DEFINITIONS

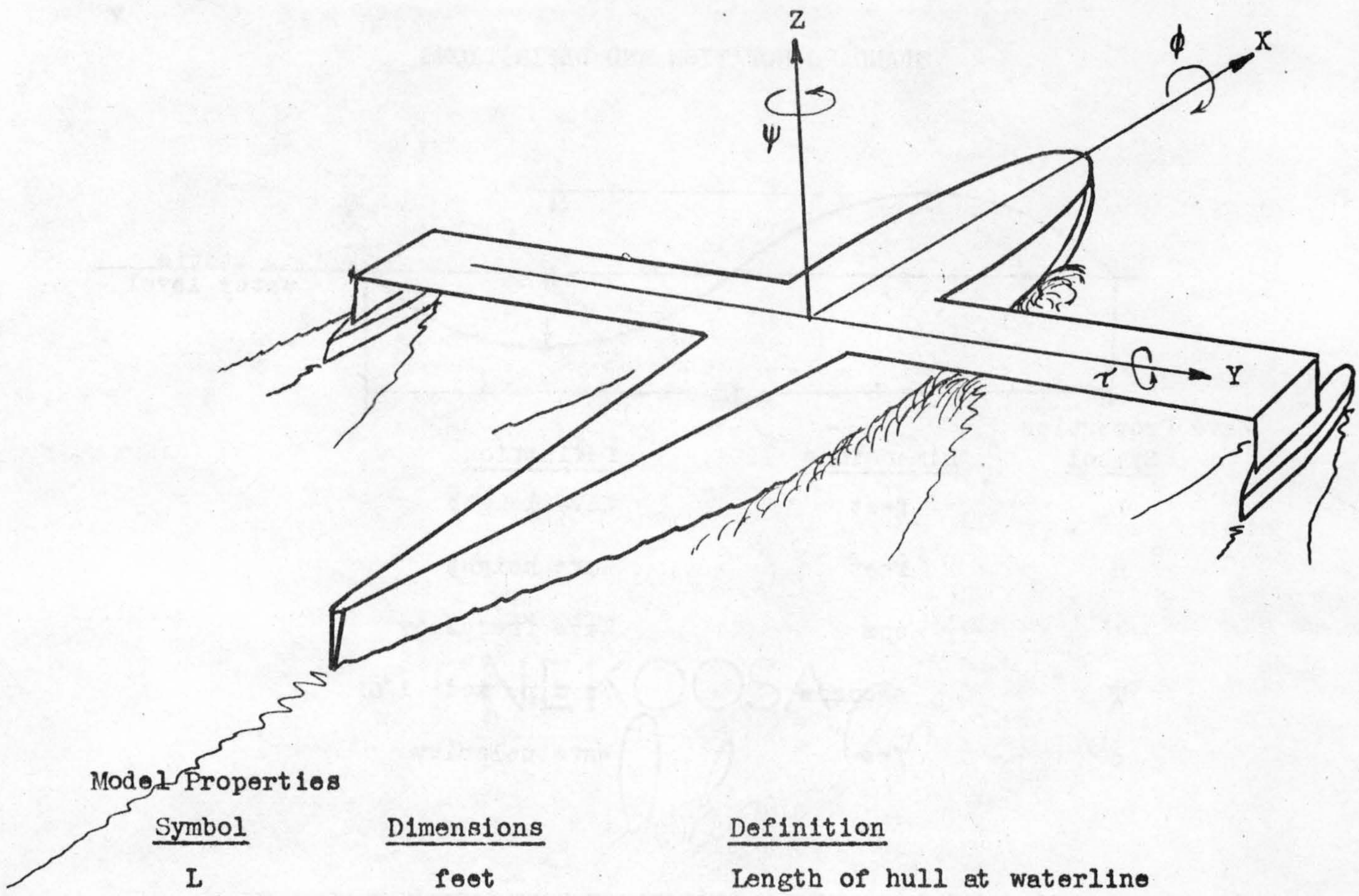


Wave Properties

Symbol	Dimensions	Definition
L_w	feet	Wave length
H	feet	Wave height
ω	cps	Wave frequency
T	seconds	Wave period $1/\omega$
c	fps	Wave celerity



χ	degrees	Angle between the heading of the plane and the direction of wave travel.



Model Properties

Symbol	Dimensions	Definition
L	feet	Length of hull at waterline
M	slugs	Mass of hull
Δ	pounds	Load of hull on the water
b	feet	Maximum beam of hull
s	feet	Wing span (in this case also span between wing tip floats)
τ_t	degrees	Trim angle of wing tip floats relative to hull baseline
v	fps	Average speed of model
h	feet	Heave of hull or translation of center of gravity along z-axis
τ_u	degrees	Maximum nose-up trim angle
τ_d	degrees	Maximum nose-down trim angle
$\Delta\tau$	degrees	Maximum change in trim angle
ϕ_r	degrees	Maximum angle of roll to right
ϕ_l	degrees	Maximum angle of roll to left
$\Delta\phi$	degrees	Maximum change of angle of roll
ψ_r	degrees	Maximum angle of yaw to right

ACKNOWLEDGEMENT

The author wishes to thank Messrs. F. W. S. Locke, Jr. and Charles J. Daniels of the Bureau of Aeronautics, Navy Department, for valuable suggestions in the analysis of the data. The writer also wishes to acknowledge the valuable assistance of Mr. A. D. Farmanfarma under whose direction this work was started; Mr. J. B. Parkinson and members of his staff at the NACA Towing Tank at Langley Field, Virginia; and Dr. K. S. M. Davidson and members of the staff at the Experimental Towing Tank at Stevens Institute of Technology.

Dr. D. F. Peterson, Head of the Department of Civil Engineering at the College, offered valuable comments during the analysis of the data and preparation of this report.

The work is indebted to Robert Davis, Director of the Colorado A & M Athletic Department for the loan of two motion picture cameras and to Messrs. Gene Rouse and Richard Stauffer of Fishback's Studio, Fort Collins for their technical assistance in the preparation of the movies and to Prof. J. R. Barton and Richard Shen who assisted as camera operators.

Appreciation is also due to Messrs. P. V. Djanjigian, Rolland Moore, Eugene Bachman, and R. M. Ryan, students, who spend many hours in the reduction and preparation of the data.

Dr. M. L. Albertson is Head of Fluid Mechanics Research under whose leadership the work was conducted and Prof. T. H. Evans is Dean of the School of Engineering wherein the work was done.

ABSTRACT

The performance of model seaplane hulls having length-to-beam ratios of 8 and 12 was estimated by observing the motions of heave, pitch and roll while towing the model at various angles and at various speeds into a simple seaway. The models were each towed at three different speeds on five different courses. Two different wave lengths and two different model loadings were used.

The data were recorded on 16-mm movie film taken from two cameras one showing a front view and the other showing a side view.

The results were somewhat inconclusive since all parameters were not varied through a complete range. Results indicate that increasing the length to beam ratio from 8 to 12 for the same planform area results in a slight improvement of the seaworthiness of the seaplane. The tests also indicate that greater magnitudes of pitching, rolling and heaving exist on courses of 120° to 150° than on courses of 90° and 180° relative to wave travel.

Introduction

"A quantitative investigation of the rough-water qualities of a seaplane are not always feasible or even safe." This statement taken from reference (10) points out the most important reason for this investigation. It is of utmost importance to develop procedures for testing the seaworthiness of seaplanes using small relatively inexpensive models. The seaworthiness of a seaplane generally refers to its ability to remain operational and reliable under two situations:

1. Survive as a surface vessel in a moderate sea without severe damage from wind or waves.

2. Be able to take off and land safely on the water under all the loading conditions. This requirement means the seaplane must have good spray characteristics, adequate controllability and good stability.

This means that the seaplane operates both as a planing and a displacement vessel. For this investigation the experiments were arbitrarily limited to the range of speeds below the "hump", i.e. point where the seaplane behaves as a true planing ship. Thus it is seen that during the test the model always derives a good deal of its support by virtue of buoyant forces.

At the present time the seaworthiness of a seaplane is determined from some rather indefinite predictions from the behavior of the model hull when it is being towed into a train of uniform waves. These predictions are then finally correlated with actual experience with flight tests on the prototype. The results of the model testing could be more complete if the testing could be carried out in a seaway which is more "true to life" and if the model motions were unrestrained so that they could be studied in their true intercoupled state.

A seaplane is free to move in six possible ways. Three of these motions are linear along the three orthogonal axes through the center of gravity and three are rotational about these axes. Table 1 shows motions and axes with which they are identified.

Table 1

Model Motions

Axis	Linear Motion	Rotational Motion
Longitudinal, x	Surge	Roll, ϕ
Lateral, y	Sway	Pitch, τ
Vertical, z	Heave, H	Yaw, ψ

The damping of these motions results from:

1. Changes in displacement distribution of the hull.

2. Changes in net hydrodynamic forces on the hull.

For a seaplane in the displacement range of speed the interrelation of heave, pitch and roll is important because the damping results from changes in displacement. Damping of the motions of surge, sway, and yaw is mobilized hydrodynamically. In the displacement range the hydrodynamic forces are small. As the speed increases, the seaplane moves gradually from the displacement range to the planing range, the relative magnitude of the displacement forces is reduced and hydrodynamic forces predominate. Any complete study of the seaworthiness of a seaplane must consider the hull first as a displacement vessel and then as a planing vessel.

During this investigation the model was towed on different headings to the seaway when the waves were simple waves of a rather steep profile. In this manner the more important intercoupled motions of heave, pitch and roll were studied and the possibility that more severe accelerations are experienced may occur at some other heading than directly into the seaway. At some future date similar experiments can be conducted in a complex or a confused seaway.

The current trend in seaplane design is toward a higher length to beam ration. The effects of increasing the length to beam ratio on the aerodynamic and hydrodynamic qualities of a seaplane were systematically determined previously in a series of experiments. The performance of the hulls having the higher length to beam ratios is generally superior to more conventional types. During this investigation two hulls having length to beam ratios of 8 and 12 were tested.

Present Procedure and Investigations

Tests of model seaplane hulls are usually conducted to determine:

1. Drag resistance.

2. Longitudinal and directional stability in both calm water and waves.

3. Spray characteristics in both calm water and waves.

The seaworthiness of the seaplane is predicted from stability and spray characteristics parts of the experiments. In this country both dynamic models and models of the hull only have been used for these tests. Complete descriptions of these tests appear in references (2) and (3). The British technique is to use different models for the directional and longitudinal stability tests. The longitudinal stability experiments are conducted using a model which is free to trim and heave only.

The spray characteristics are determined from photographs taken during the runs both in calm water and waves. The tests usually consist of:

1. Runs in calm water to give information in taxiing speed range,

2. Accelerated runs to simulate take-off,

3. Decelerated runs to simulate landing.

The great shortcoming of these testing procedures is the restriction placed on the intercoupled motions and the fact the models operate on a single heading -- into the sea.

Model testing in waves is usually carried out in a seaway composed of simple waves of a single wave height and a single wave length. The wave height to length ratio usually being from 1:20 to 1:40. Actually the surface of the sea is very complex. The waves consist of superimposed wave trains varying greatly in length, height and direction of travel. Furthermore, many times it is necessary that seaplanes operate in choppy seas caused by winds, where the wave height to length ratio is as steep as 1:10. The sea virtually never repeats itself. This makes any analysis of wave records largely a statistical procedure. This complexity of the sea has made a simple mathematical solution of the sea difficult. A mathematical model of the sea has been proposed in reference (14). This mathematical representation consists of a Lebesque energy intergral for the Gaussian case. This integral can only be solved by an approximation; however, it will be a valuable tool in future theoretical studies of seaplane and ship motions.

Procedures Used in Testing

Models:- The two models used during these experiments were previously used during a systematic investigation of the effect of increasing the length to beam ratio of a series of seaplane hull forms. The models were constructed from pine. The model particulars are given in Table 2.

Table 2

Model Particulars

	Model 1067-01	Model 1068-01
Beam, maximum, in.	6.15	5.02
Overall length to beam ratio	8	12

Table 2 Cont.

	Model 1067-01	Model 1068-01
Forebody length, in.	24.6	30.12
Afterbody length, in.	24.6	30.12
Total hull length, in.	49.2	60.24
Step depth (at keel), in.	0.37	0.30
Sternpost angle, degrees	8.0	8.0
Center of Gravity		
Distance forward from main step apex, in.	4.12	3.60
above baseline, in.	3.50	3.50
Gross load coefficient, C_{Δ_0}	1.0 & 1.5	1.8 & 2.7

Length to beam ratio:- The length to beam ratio can be changed by a change in either the length or the beam. For a systematic investigation the ratio must be changed in an orderly and logical manner. Three possible ways to increase the ratio are:

1. Retain the same beam and increase the length,

2. Retain the same length and reduce the beam,

3. Increase the length and reduce the beam but retain the same value of Lb. This is called the constant planform area.

It has been pointed out in reference (2) that the constant planform area is the best way to systematically vary the length to beam ratio because this is the only way that the size is held constant for all the models. If two hulls of different length to beam ratio are to be compared, then the effects of different size, load, and speed must be properly accounted for in the analysis of the data. In order to make the comparison of the performance of the two hulls simple and direct, the two models used during these investigations were tested at the same loads, same speeds, and the models had the same planform area; i.e. size.

Model loading:- The lightest load attainable in a practical testing configuration was 8.68 lb. This corresponds to a load coefficient, C_{Δ_0} = 1.0 for the short hull and C_{Δ_0}=1.8 for the longer hull. Actually the unit planform area loading was the same for the models. The difference in the load coefficient resulted from the fact that the beam only is used in the definition of the load coefficient. Possibly the characteristic length in the load coefficient should be $\sqrt{Lb}$.

The models were also tested at 150% of this load or at a test gross weight of 13.02 lb. This corresponds to a load coefficient of 1.5 and 2.7 for the short and the long hull, respectively. Lead ballast was added fore and aft to the hull so that the center of gravity was maintained at the same position.

Wing and wing tip floats:- Since the hulls were first used in tests of the hulls only and not as dynamic models, a wing, wing tip floats and a hull cover had to be provided. No attempt was made to produce the air drag or lift or the slipstream effects because for these tests the models were considered primarily as displacement vessels. For this reason it was not necessary to model the engine, the wing as an airfoil or the empennage. The wing was simply a spar to support the wing tip floats. It consisted of a 2-inch extruded aluminum channel. The wing span (distance between wing-tip floats) was arbitrarily made equal to the length of the hull.

The wing tip floats were based on the design of the wing tip floats of the XP5Y-1 floats. The required tip float displacement was based on computations outlined in reference (1). The float volume for the short hull was 9.2 cu. in. and 12.5 cu. in. for the long hull. The length of the wing tip float was arbitrarily fixed at 1/7 of length of the hull. The beam of the tip float was then adjusted until the proper float volume was obtained. The length of the tip float was altered for the longer hull by applying a constant multiplier to the station spacing of the lines published in reference

The wing-tip float for the shorter hull was carved from a solid block of mahogany. The chine-lines were made as sharp as possible. Because weight was a critical factor in the longer hull the tip floats were carved from balsa wood. The chine was made as sharp as possible; however, because of the weakness of the wood, the chines are more rounded than the mahogany floats. A brass strip should undoubtedly be inserted along the chine line of the balsa float as described in reference (8).

The wing-tip floats were attached to the wing-tip in such a manner that the angle of trim relative to the forebody keel line could be adjusted. The float displacement relative to the hull displacement could also be adjusted. The floats were given a 3° nose-up trim relative to the forebody keel at the step. The float displacement was adjusted so that the model could roll 3° to the right or left before the displacement of the respective float became effective. These adjustments were made at the light loading (C_{Δ_0} = 1.0 and 1.8 for the short and the long hull respectively).

The hull was covered with a clear pliofilm sheet to prevent swamping the hull. A longitudinal rib made from pine was glued to the hull. This supported the plastic sheeting so that any spray promptly drained off the hull. The plastic sheeting was tightly stretched and fastened around the edge of the hull with plastic electrical tape. The hull was manufactured in a forward and an after part. The joint was at the step. Provision had been made to adjust the depth of step at this joint. The hull was thus divided into two compartments. An access panel was made in each compartment by covering an opening in the pliofilm cover with clear cellulose acetate. The purpose of the access panel was to provide an opening for drying out the air in the compartment and for inserting the lead ballast. The lead ballast in the form of body solder was securely attached to the longitudinal rib, installed to support the plastic hull cover. Fig. 1 shows the two hulls in their testing configuration and Fig. 2 shows the short hull with the access covers open and ready for insertion of the lead ballast.

Towing bridle:- It is desirable to apply the thrust required for moving the model in the same manner and along the same line as in the prototype. Since models were towed at relatively low speeds, the hydrodynamic forces resulting in directional stability were low and it was necessary to use a towing bridle to give a satisfactory degree of directional stability. In the prototype the pilot would have available a number of methods of steering control such as a water rudder, hydroflaps or differential power in the case of a multi-engine craft. The point of attachment for the bridle was on the wing at one-third the distance from hull to the tip. An aluminum bracket was attached to the wing at these points. The bridle was attached to the bracket so that the towing thrust was applied along a lateral axis through the center of gravity. In this manner the towing did not influence the pitching moments of the model. This method of towing may have influenced the motions of the model in yaw, surge and sway; however, the motions of heave, pitch and roll were unrestricted.

A length of 108-lb fishing line was attached to each bracket. These two lines were fastened to a single line at a point about one span ahead of the wing. This single line was attached to the endless towing line at a point about 8 ft ahead of the center of gravity of the model. The line of thrust was inclined at a slope of about 1 to 5.

A stern line was used to stop the model at the end of the run. This stern line was attached to a cleat fastened to the longitudinal rib near the stern. The other end of the line was attached to the endless towing line at a point slightly astern of the end of the model when all of the slack is taken out of the bridle. There was enough slack in the stern line so that there was no interference of the line with the normal motions of the model. The stern line was necessary to stop the model at the end of the run and to return the model to the starting point.

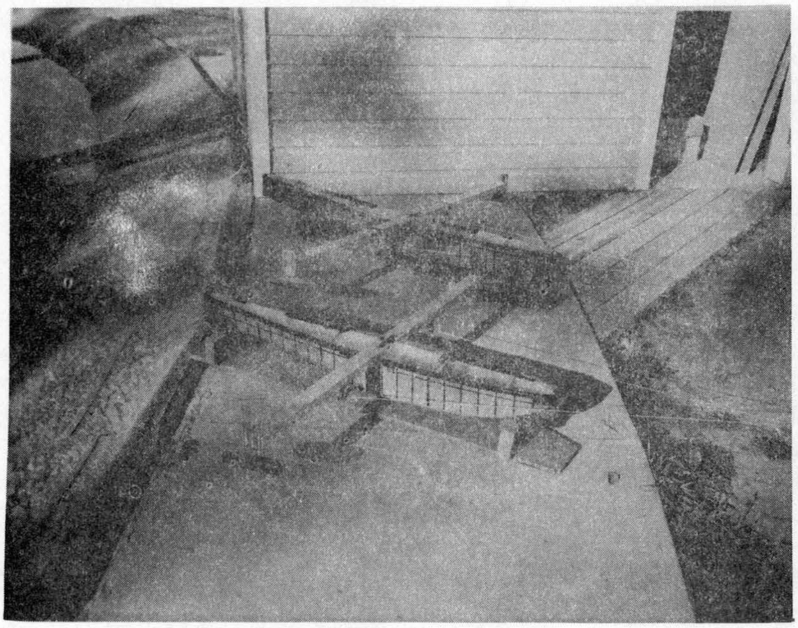


Fig. 1 Photograph of Models showing Testing Configuration

Fig. 2 Photograph showing Access Panels Open

Motion Picture Records

The history of the model motions was recorded on 16 mm motion picture film. The model was photographed from the front and side with Cine Special 16 mm motion picture cameras equipped with telephoto lenses. The camera-to-model distance varied from 68 to 45 ft for the camera taking the side view and from 85 to 30 ft for the camera taking the front view. The camera taking the front view was set about 4 ft above the water surface. The lateral axis of the camera was carefully levelled and then either the edge of the tank or the top of the frame of the exposure was used as a reference for measuring angles of roll of the model.

A 1/4-in. wire cable which had been painted a contrasting yellow, was used as a horizontal reference for measuring angles of trim and heave. This wire cable was stretched tightly across the pond in a position parallel to the model's expected course and about 2 ft above the static water level. The cable was always in the photograph. A baseline and grid system had been painted on the side of the hull (see Fig.1). The angles of trim were determined from a projected image of the movie film by measuring the inclination of the baseline with respect to the wire cable. Measurements of heave were made by scaling the distance between the reference cable and a mark on the top surface of the wing which indicated the position of the center of gravity. The grid painted on the side of the model was used as the scale.

During the first day of testing, the wire cable used for reference was not available. The measurements during these runs were made relative to the top edge of the wave guides or the edge of the tank.

The two series of movies taken during each run were synchronized by firing a Sylvania Type FP-26 short persistence flash bulb near the model at the start of the run. This marked one and sometimes two exposures during each run on each of the two series of movie film. This synchronizing signal was also placed on the oscillograph record.

Records of Wave Profile

Records of wave profile were obtained from the oscillograph records of the change of resistance of the wave profile probe with respect to time. The wave height was determined from distance between crest and trough. The wave period was determined from the length of time between crests. The wave length was determined from the period and from other measurements of the wave celerity.

The calibration of the wave profile has proved to be unreliable; therefore, the wave height was checked, where possible, from the movie film. The first eleven feet of the wave guide had been painted white with a 12-in. square grid painted in black. A reasonably clear picture of the wave profile against this painted grid was obtained at some-time during most of the runs. This picture was obtained from the film taken by the side camera. Unfortunately, these pictures were obtained in the area where the wave filter was producing some modification of the wave profile. The painted grid has now been extended throughout the entire length of the wave guide along the north side of the seaway.

Model Tests

The two models were each tested in a seaway composed of two different wave lengths, on five different headings from straight into the seaway to parallel to the wave crests and at two different loadings and at three different speeds. This is not by any means a complete range of variation of all the parameters. The range of variation of the different variables is given in Table 3.

Table 3

Range of Variables

Model Speed, fps, V	2.3,	6.0,	15.5
Speed Coefficient, C_s			
Short Hull - L/b = 8	0.56,	1.47,	3.67
Long Hull - L/b = 12	0.62,	1.62,	4.05
Model Heading (relative to direction of sea) degrees χ	180, 150, 135, 120, 90		
Model Loading, lbs.	8.68, 13.02		
Load Coefficient $C_{\Delta o}$			
Short Hull - L/b = 8	1.0,	1.5	
Long Hull - L/b = 12	1.8,	2.7	
Wave Length, feet, Lw	4.6, 9.4		
Wave Height, feet, H	for L_w = 4.6, 0.375; for L_w = 9.4, 0.333		
Wave Height-Length Ratio	for L_w = 4.6, 0.0815; for L_w = 9.4, 0.036		
Wave Length-Model Length Ratio			
Short Hull - L/b = 8	1.12,	2.29	
Long Hull - L/b = 12	0.92	1.87	

Natural Frequency of Models

The natural frequency of the models in water at the test loadings was determined by measuring the average period of oscillation of the model after being disturbed while floating in the center of the tank of calm water. The dimensions of the tank were 8 ft wide, 12 ft long and 8 ft deep.

No attempt was made to correct the observations for the small surface waves which resulted from the model bobbing on the water surface. The values of natural frequency finally used resulted from the average of three different observations. The average values of the natural frequency about the lateral and longitudinal axis is given in Table 4.

Table 4

Natural Frequency of the Models

Axis	Frequency, cps: Short Hull 1067-01	Frequency, cps: Long Hull 1068-01
for light loading (8.68 lbs)	$C_{\Delta o} = 1.0$	$C_{\Delta o} = 1.8$
Pitching axis	1.998	2.067
Rolling axis	0.60	0.80
for heavy loading (13.02 lbs)	$C_{\Delta o} = 1.5$	$C_{\Delta o} = 2.7$
Pitching axis	1.71	2.00
Rolling axis	0.87	1.24

Frequency of Encounter

The force which disturbs the normal equilibrium of the seaplane is the waves. If the seaplane encounters the waves at the proper frequency, large scale amplitudes can be expected. This is to say, if the exciting frequency and the natural frequency are equal, then resonance occurs and the amplitude of the oscillation is limited only by frictional forces mobilized by the motion. The frequency of encounter for a seaplane traveling in a regular seaway is dependent upon the the celerity of the waves, c , the heading of the seaplane relative to the direction of wave travel, χ , and the speed of the seaplane , v . Before proceeding further in the derivation of an equation for the frequency of encounter, a number of well known equations will be listed. These equations have been derived in a number of text books and references and can be found in references (4), (12), or (14). The validity of these equations holds only for surface waves in infinitely deep water. For most practical purposes these equations can be considered applicable for water deeper than one-half of a wave length.

$$c = \frac{L_w}{T} = \frac{g}{\omega} = \sqrt{\frac{g\,L_w}{2\pi}} = \frac{gT}{2\pi} \tag{1}$$

$$L_w = cT = \frac{2\pi c^2}{g} = \frac{2\pi g}{\omega^2} = \frac{g\,T^2}{2\pi} \tag{2}$$

$$T = \frac{2\pi c}{g} = \frac{L_w}{c} = \sqrt{\frac{2\pi L_w}{g}} \tag{3}$$

$$\omega = \frac{g}{c} = \sqrt{\frac{2\pi g}{L_w}} \tag{4}$$

Eq. 4 can be rearranged:

$$\omega = \frac{2\pi c}{L_w} \tag{5}$$

Eq. 5 is the basic relationship for the frequency of encounter. If the seaplane is moving in any direction, the effective celerity of waves then becomes the vector addition of the wave celerity and the velocity of the seaplane as expressed by:

$$c_e = c - v \cos \chi . \tag{6}$$

Substituting Eq. 6 in Eq. 5:

$$\omega_e = \frac{2\pi(c - v \cos \chi)}{L_w} . \tag{7}$$

Substituting the third relationship of Eq 2 in Eq 7 and simplifying:

$$\omega_e = \omega\left(1 - \frac{v \cos \chi}{g}\right) = \left(1 - \frac{v \cos \chi}{c}\right)\omega \tag{8}$$

Eq 8 is an equation giving the frequency of encounter in terms of the wave frequency, wave celerity, heading of seaplane and the speed of the seaplane. This equation is equivalent to the relationship derived in reference (14).

Results

The results obtained in this experiment are both quantitative and qualitative. The quantitative results are obtained from measurements made from both the oscillograph records and the movies of the model made from two different directions.

Oscillograph records:- The oscillograph records contain four basic elements which were obtained from three galvanometers:

1. Model velocity,

2. wave height,

3. wave frequency,

4. film synchronization.

Each time the oscillograph is started, the oscillograph record is automatically numbered. This number is also recorded in the experimental testing log together with an adequate description of the run. Since the oscillograph records tend to be bulky and hard to handle, they were processed in one step taking all the data at one time. The oscillograph paper speed used during this investigation was 1.5 inch per second. Timing lines appear on the record at 0.1 second intervals.

Each time the towing line travelled a distance of 2.58 feet, a mark was made on the velocity trace in the oscillograph records. The average model speed was determined by this equation:

$$v = \frac{2.58 \times \text{number of marks}}{\text{length of time between start and end}} .$$

The start of the run was considered to be at the point where the model attained a uniform speed and ended where model began decelerating.

The wave height is proportional to the resistance between the two wires mounted on the wave profile probe. The wave height was the vertical distance between the wave crests and troughs. In the cases where slight nonuniformity of the individual wave heights during a particular run existed, the average wave height was used as measured wave heights during the run. The wave height was also determined from measurements made from the wave profile along the wave guide appearing in the background in some of the movies. Thus two independent sources of wave height measurement were available. Often the two measurements of the wave height did not agree. In these cases, the measurements taken from the movies were used.

The wave frequency was the length of time between the wave crests as recorded in the oscillograph records. Comparison of the values of the wave frequency determined from the oscillograph records indicates that very little variation of the wave frequency exists for a particular setting of the wave generator.

The wave length was determined from the first relationship of Eq 2. The wave celerity was determined by measuring the time interval required for a wave crest to travel a distance of 41.5 feet in the seaway at a uniform depth to bottom.

The oscillograph records were marked with the time of the synchronizing. The current required to fire the flash bulbs was also utilized to operate the galvanometer. During this investigation no attempt was made to determine instantaneous values acceleration; therefore, the synchronization of the two movie films and the galvanometer records was not seriously attempted. Possibly at some future date when more data are available, the opportunity to use these synchronizing points will occur.

Film analysis: - Quantitative measurements taken from the movie film consist of:

1. Measurements of heave taken from the side view,

2. measurements of maximum nose-up trim angle and maximum nose-down trim angle taken from the side view,

3. measurements of maximum roll to the right and to the left taken from the front view.

All the films were carefully scanned using a 16 mm silent Keystone projector. The film could be stopped at any point for careful examination of single exposures. If the film was stopped for more than about 10 seconds at any one exposure the heat from the light produced a "projector burn" which ruined the exposure. In order to make the necessary measurements, it was necessary to use projectors having lower intensity in order to avoid "burning" the film. Two different projectors were used during the analysis of the film. One is a standard 16 mm Recordak Projector designed for reading microfilm. The other projector was a Craig Senior 16 mm movie film editor. The regular projection screen was replaced by a glass covered with a thin plastic overlay on which a convenient grid had been ruled.

The Recordak Projector was not entirely satisfactory because the light intensity was too low to see through a sheet of vellum graph paper and still recognize the necessary markings on the image of the hull. Since the Recordak projector is rental equipment, the projection screen itself could not be ruled.

The Craig projector produced a brighter image. The projection screen of the Craig projector was 3 x 3 in.

compared to approx. 14 x 14 in. for the Recordak. Most of the film was analyzed in the Craig projector.

Measurements of angle of trim:- Angles of trim were measured as the seaplane went over the crest. The greatest angular acceleration occurs as the plane goes over the crest. The movie film viewing the plane from the side was used for determining the heave and angles of trim. Since the camera taking the side view was situated at a fixed location opposite the center of the run, the line of sight of the camera is most nearly normal to the path of the model at the center of the run and the distortion of the actual angles is least at this point. All measurements of heave and angles of trim were made at the wave encounter nearest this point. The film was slowly threaded through the projector noting the inclination of the baseline painted on the hull. When the exposure having the maximum baseline inclination was found, the actual angle of nose-up trim was measured. The procedure was repeated for the nose-down trim. In all cases the measured angles of nose-up trim and nose-down trim were determined for the same wave encounter. Thus the difference between the nose-up and nose-down trim angle represents the total change in trim for the particular wave encountered. Since the waves were reasonably uniform, this change in trim represents the magnitude of the model motion in pitch.

No attempt was made to determine the time between the maximum nose-up and the maximum nose-down position. This time is necessary if the average angular accelerations were to be determined. This time period could be determined by counting the number of exposures occurring between the pictures from which these two angles were determined.

Measurements of heave:- Measurements in heave were taken from the side view of the test. All measurements were made normal to the horizontal reference cable or to the edge of the pond or the wave guide. The distance between the reference cable and a point on the top surface of the wing was measured with a pair of dividers and scaled off along the grid painted on the side of the hull. The difference between the distance to the reference when the seaplane was at the crest and the distance when the hull was in the trough was the heave. At times the minimum distance between the reference cable and the center of gravity of the seaplane occurred a short time after the wave crest passed the point under the center of gravity of the hull. This time lag seems to be dependent upon the speed of the plane and the speed of the plane relative to the wave celerity.

Measurements of angle of roll:- Angles of roll were measured from the front view of the tests. No attempt was made to measure the angles of roll at the same relative time as the angles of trim were measured. While it is possible to measure instantaneous values of the motions of heave, pitch and roll, the procedure would be involved and time consuming and for these reasons has been temporarily disregarded. The data obtained from the film and from the oscillograph records has been tabulated in Table 5.

The procedure would be to determine the number of frames or exposures between the synchronizing point and the center of the run or the position in the approximate vicinity where most of the data are located. The values of trim, angle of roll, and heave must then be measured frame by frame for a complete wave encounter preceding and following the center point. Since the frames are not numbered or otherwise individually identified, the identification becomes involved because there are from 10 to 30 frames per wave encounter on each roll for each run.

Spray:- The spray comparisons were difficult because complete dynamic models were not available. The hull used represented those parts of the seaplane which are affected hydrodynamically. The complete dynamic model would have the wings attached to the hull at a higher position, windshield, tail surfaces, engine nacelles, propeller disks and flaps to be considered. Since the models had only the bare rudiments of the seaplane, no quantitative measurements of the main blister or of the bow spray were attempted. Comparative information was obtained by going through the movies several times at very slow speed in a motion picture projector.

Discussion

The data in Table 5 can be used to obtain a large number of graphs which would yield some comparative information regarding the two hulls, but would lead to few if any general conclusions. Before any further attempt is made to discuss the data further, the variables will be organized into orderly dimensionless parameters using the principles of the Buckingham π -Theorem.

Dimensional analysis:- All the fundamental variables which affect the motion of the seaplane on the water are tabulated, together with their dimensions.

L_W - wave length - feet (L)

H - wave height - feet (L)

c - wave celerity - ft.sec (L/T)

ω - frequency of waves - cps (1/T)

TABLE 5

EXPERIMENTAL DATA

Run No.	V (1) (fps)	C_v (2)	λ (3) (deg)	ω_{e_h} (4) (cps)	ω_{n_h} (5) (cps)	ω_e/ω_{n_h} [2] (6)	h (7) (ft)	h/H (8)	$\Delta\tau$ (9) (deg)	$\Delta\tau/H/L_w$ (10)	$\omega_{e\phi}$ (11) (cps)	$\omega_{n\phi}$ (12) (cps)	$\omega_e/\omega_{n\phi}$ (13)	$\Delta\phi$ (14)	$\Delta\phi/H/L_w$ [3] (15)
$L/b = 8$, $C = 1.0$	$c = 4.85$ fps,	$L_w = 4.60$ ft.	$H/L_w = .0815$,	$L_w = 1.15$											
180.1	2.3(1	0.58	180	1.134	1.998	.568	.20	.533	6.9	85	1.057	0.60	1.760	1.5	--
150.1	2.15	0.58	150	1.118	1.998	.560	.208	.556	9.5	117	1.092	0.60	1.882	2.3	28
135.1	2.26	0.58	135	1.110	1.998	.556	.292	.778	5.0	61	1.108	0.60	1.846	4.5	--
120.1	2.26	0.58	120	1.095	1.998	.549	.142	.378	11.1	136	1.121	0.60	1.871	15.0	--
90.1	2.26	0.58	90	1.057	1.998	.530	.183	.489	2.3	28	1.131	0.60	1.888	1.8	22
180.2	6.01	1.45	180	1.252	1.998	.628	.167	.445	9.8	120	1.057	0.60	1.760	1.5	--
150.2	6.03	1.45	150	1.230	1.998	.616	.183	.489	12.7	156	1.156	0.60	1.928	0.8	10
135.2	6.03	1.45	135	1.198	1.998	.600	.050	.133	15.5	190	1.198	0.60	1.999	2.6	32
120.2	6.02	1.45	120	1.158	1.998	.580	.167	.445	6.2	76	1.228	0.60	2.045	4.5	55
90.2	6.03	1.45	90	1.057	1.998	.530	.358	.956	0.4	5	1.253	0.60	2.090	0	0
180.3	15.56	3.62	180	1.57	1.998	.787	.175	.467	3.5	43	1.057	0.60	1.760	0.5	6
150.3	15.52	3.62	150	1.498	1.998	.750	.150	.400	5.0	61	1.312	0.60	2.190	2.1	26
135.3	15.40	3.62	135	1.423	1.998	.713	.275	.734	15.0	184	1.413	0.60	2.360	6.2	76
120.3	15.50	3.62	120	1.313	1.998	.658	.241	.645	7.5	92	1.497	0.60	2.498	5.2	64
90.3	15.60	3.62	90	1.057	1.998	.530	.192	.512	0.7	11	1.569	0.60	2.615	11.5	141
$L/b = 8$, $C = 1.0$	$c = 6.73$ fps,	$L_w = 9.39$ ft.	$H/L_w = .036$	$L_w/L = 2.34$											
180.4	2.3(1	0.58	180	.766	1.998	.384	.433	1.30	4.6	128	0.717	0.60	1.193	4.6	--
150.4	2.24	0.58	150	.759	1.998	.380	.192	.58	6.0	167	0.740	0.60	1.232	2.5	--
135.4	2.26	0.58	135	.750	1.998	.375	.192	.58	5.4	150	0.750	0.60	1.25	0.9	--
120.4	2.3(1	0.58	120	.741	1.998	.371	.183	.55	6.0	167	0.761	0.60	1.27	0.9	25
90.4	2.26	0.58	90	.717	1.998	.359	.266	.80	4.0	111	0.767	0.60	1.278	2.4	67
180.5	6.0(1	1.45	180	.849	1.998	.425	.183	.55	7.8	217	0.717	0.60	1.193	4.0	111
150.5	6.05	1.45	150	.832	1.998	.416	.416	1.25	7.9	219	0.785	0.60	1.309	0.7	20
135.5	6.04	1.45	135	.810	1.998	.405	.183	.55	3.2	89	0.812	0.60	1.351	1.1	31
120.5	6.0(1	1.45	120	.782	1.998	.391	.233	.70	3.8	105	0.832	0.60	1.385	1.4	39
90.5	6.02	1.45	90	.717	1.998	.359	.167	.50	2.3	64	0.850	0.60	1.417	1.0	28
180.6	15.5(1	3.62	180	1.061	1.998	.532	.225	.68	13.8	384	0.717	0.60	1.193	4.8	133
150.6	15.52	3.62	150	1.013	1.998	.508	.517	1.55	11.1	309	0.890	0.60	1.484	2.0	--
135.6	15.64	3.62	135	.962	1.998	.482	.117	.35	14.0	389	.963	0.60	1.603	2.5	69
120.6	15.5	3.62	120	.889	1.998	.445	.433	1.30	9.9	275	1.015	0.60	1.693	1.0	--
90.6	15.58	3.62	90	.717	1.998	.359	.083	.25	1.0	28	1.063	0.60	1.774	2.5	69

(1 Assumed values (2 Also used for ω_e/ω_{n_τ} (3 Data omitted because of unreliable values of $\Delta\phi$

TABLE 9

CON'T EXPERIMENTAL DATA

Run No.	V	C_V	χ	ω_{e_h}	ω_{n_h}	ω_e/ω_{n_h} (2	h	h/H	$\Delta\tau$	$\Delta\tau/H/L_w$	$\omega_{e\phi}$	$\omega_{n\phi}$	$\omega_e/\omega_{n\phi}$	$\Delta\phi$	$\Delta\phi/H/L_w$ (3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	(fps)		(deg)	(cps)	(cps)		(ft)		(deg)		(cps)	(cps)			
L/b = 8 , C = 1.5	c = 4.85 fps , L_W = 4.60 ft	H/L_W = .0815 , L_W/L = 1.15													
180.7	2.25	0.58	180	1.130	1.716	.659	.266	.711	6.6	81	1.057	0.87	1.218	1.1	--
150.7	2.28	0.58	150	1.121	1.716	.655	.208	.555	16.8	206	1.093	0.87	1.258	3.8	--
135.7	2.28	0.58	135	1.110	1.716	.648	.217	.578	6.4	79	1.110	0.87	1.277	0.2	2
120.7	2.28	0.58	120	1.093	1.716	.638	.284	.755	8.5	104	1.123	0.87	1.294	0.3	4
90.7	2.28	0.58	90	1.057	1.716	.616	.275	.733	7.8	96	1.132	0.87	1.303	12.7	--
180.8	6.00	1.45	180	1.251	1.716	.730	.083	.222	13.6	167	1.057	0.87	1.218	0.4	--
150.8	6.01	1.45	150	1.229	1.716	.717	.150	.400	14.2	174	1.156	0.87	1.330	1.4	17
135.8	6.03	1.45	135	1.196	1.716	.697	.242	.645	10.7	131	1.198	0.87	1.378	7.0	86
120.8	6.02	1.45	120	1.155	1.716	.673	.342	.911	15.9	195	1.230	0.87	1.415	5.2	64
90.8	6.02	1.45	90	1.057	1.716	.616	.508	1.355	3.0	37	1.252	0.87	1.441	4.5	55
180.9	15.10	3.62	180	1.551	1.716	.905	.175	.467	4.6	57	1.057	0.87	1.218	0.9	11
150.9	15.00	3.62	150	1.483	1.716	.865	.058	.156	4.0	49	1.303	0.87	1.500	2.3	28
135.9	15.01	3.62	135	1.403	1.716	.819	.108	.289	0.6	7	1.409	0.87	1.620	1.4	17
120.9	14.31	3.62	120	1.291	1.716	.754	.225	.600	7.0	86	1.464	0.87	1.684	1.3	16
90.9	15.25	3.62	90	1.057	1.716	.616	.208	.555	4.5	55	1.560	0.87	1.794	4.5	55
L/b 8 , C = 1.5	c = 6.73 fps , L_W = 9.39 ft	H/L_W = .036 , L_W/L = 2.34													
180.10	2.3(1	0.58	180	.767	1.716	.447	.266	.800	3.0	83	.717	0.87	.825	0.5	14
150.10	2.26	0.58	150	.759	1.716	.442	.208	.625	10.4	289	.739	0.87	.848	2.0	56
135.10	2.26	0.58	135	.750	1.716	.437	.216	.650	5.8	161	.750	0.87	.861	4.7	130
120.10	2.27	0.58	120	.741	1.716	.432	.375	1.125	8.9	247	.760	0.87	.873	2.0	56
90.10	2.27	0.58	90	.717	1.716	.418	.316	.950	4.5	125	.765	0.87	.878	0.6	17
180.11	6.03	1.45	180	.850	1.716	.495	.200	.600	7.0	194	.717	0.87	.825	1.6	44
150.11	6.02	1.45	150	.839	1.716	.489	.283	.850	10.9	303	.783	0.87	.899	0.6	17
135.11	6.02	1.45	135	.811	1.716	.473	.142	.425	4.8	133	.810	0.87	.930	4.2	117
120.11	6.06	1.45	120	.784	1.716	.457	.157	.475	6.4	178	.833	0.87	.957	2.6	72
90.11	6.03	1.45	90	.717	1.716	.418	.175	.525	0.3	8	.849	0.87	.975	3.6	100
180.12	15.20	3.62	180	1.055	1.716	.615	.083	.250	11.0	306	.717	0.87	.825	5.6	--
150.12	13.95	3.62	150	.985	1.716	.574	.500	1.500	14.5	403	.870	0.87	1.000	0.7	19
135.12	15.00	3.62	135	.952	1.716	.555	.433	1.300	17.0	473	.952	0.87	1.093	4.6	--
120.12	15.20	3.62	120	.885	1.716	.516	.566	1.700	20.5	570	1.009	0.87	1.160	8.1	225
90.12	15.30	3.62	90	.717	1.716	.418	.083	.250	2.7	75	1.056	0.87	1.213	3.3	92

Run No.	V	C_v	χ	ω_{e_h}	ω_{n_h}	ω_e/ω_{n_h} (2	h	h/H	$\Delta\tau$	$\Delta\tau/H/L_w$	$\omega_{e\phi}$	$\omega_{n\phi}$	$\omega_e/\omega_{n\phi}$	$\Delta\phi$	$\Delta\phi/H/L_w$ (3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	(fps)		(deg)	(cps)	(cps)		(ft)		(deg)		(cps)	(cps)			
$L/b = 12$, $C = 1.8$	$c = 4.85$ fps, $L_w = 4.60$ft	$H/L_w = .0815$	$L_w/L = 0.920$												
180.13	2.26	0.62	180	1.132	2.067	.549	.158	.422	9.6	118	0.920	0.80	1.320	1.3	--
150.13	2.26	0.62	150	1.121	2.067	.543	.183	.489	10.2	125	1.093	0.80	1.369	2.2	27
135.13	2.26	0.62	135	1.108	2.067	.535	.317	.845	3.1	38	1.109	0.80	1.386	1.4	--
120.13	2.26	0.62	120	1.093	2.067	.529	.250	.667	5.0	61	1.121	0.80	1.403	6.0	--
90.13	2.26	0.62	90	1.057	2.067	.511	.175	.467	5.5	68	1.131	0.80	1.418	5.7	--
180.14	6.02	1.62	180	1.253	2.067	.606	.150	.400	7.2	88	1.057	0.80	1.320	1.8	22
150.14	6.03	1.62	150	1.230	2.067	.595	.167	.445	11.6	142	1.156	0.80	1.446	0.5	6
135.14	6.01	1.62	135	1.198	2.067	.580	.267	.711	11.4	140	1.198	0.80	1.498	0.1	1
120.14	6.01	1.62	120	1.158	2.067	.560	.292	.778	9.7	119	1.23	0.80	1.538	6.5	80
90.14	6.03	1.62	90	1.057	2.067	.511	.275	.734	1.4	17	1.255	0.80	1.570	7.3	90
180.15	15.40	4.05	180	1.562	2.067	.756	.050	.133	2.3	28	1.057	0.80	1.320	2.6	32
150.15	15.30	4.05	150	1.493	2.067	.722	.083	.223	2.8	34	1.309	0.80	1.638	0.4	5
135.15	15.37	4.05	135	1.413	2.067	.684	.183	.489	3.6	44	1.412	0.80	1.768	2.4	29
120.15	15.31	4.05	120	1.308	2.067	.633	.242	.645	6.2	76	1.493	0.80	1.870	3.3	40
90.15	15.45	4.05	90	1.057	2.067	.511	.450	1.200	6.4	79	1.567	0.80	1.960	12.8	--
$L/b = 12$, $C = 1.8$	$c = 4.85$ fps, $L_w = 4.60$ ft	$H/L_w = .0815$	$L_w/L = 1.88$												
180.16	2.3)1	0.62	180	.766	2.067	.370	.233	.700	6.8	189	.717	0.80	.897	5.4	--
150.16	2.34	0.62	150	.761	2.067	.368	.233	.750	7.9	220	.742	0.80	.927	2.7	75
135.16	2.26	0.62	135	.750	2.067	.363	.308	.93	3.9	108	.750	0.80	.938	0.1	3
120.16	2.26	0.62	120	.740	2.067	.358	.316	.95	6.5	180	.760	0.80	.950	2.2	61
90.16	2.15	0.62	90	.717	2.067	.347	.083	.25	8.0	222	.764	0.80	.955	1.5	42
180.17	6.0(1	1.62	180	.849	2.067	.410	.300	.90	8.6	239	.717	0.80	.897	4.7	130
150.17	6.04	1.62	150	.831	2.067	.403	.308	.95	6.3	175	.784	0.80	.981	1.0	28
135.17	6.05	1.62	135	.811	2.067	.392	.150	.45	5.2	144	.812	0.80	1.014	2.5	69
120.17	6.02	1.62	120	.783	2.067	.379	.417	1.25	3.0	83	.833	0.80	1.041	0.5	14
90.17	6.02	1.62	90	.717	2.067	.347	.283	.85	8.1	225	.850	0.80	1.061	1.4	39
180.18	15.5(1	4.05	180	1.061	2.067	.513	.308	.93	7.9	219	.717	0.80	.897	3.2	89
150.18	15.31	4.05	150	1.011	2.067	.490	.200	.60	9.7	269	.885	0.80	1.105	2.5	69
135.18	15.4	4.05	135	.956	2.067	.453	.700	2.10	13.5	375	.958	0.80	1.198	3.1	86
120.18	15.5	4.05	120	.889	2.067	.430	.616	1.85	11.7	325	1.015	0.80	1.269	0.8	22
90.18	15.5	4.05	90	.717	2.067	.347	.0	.0	11.4	3.7	1.062	0.80	1.329	2.8	78

(2 (3

Run No.	V	C_V	χ	ω_{e_h}	ω_{n_h}	ω_e/ω_{n_h}	h	h/H	$\Delta\tau$	$\Delta\tau/H/L_w$	ω_{e_ϕ}	ω_{n_ϕ}	ω_e/ω_{n_ϕ}	$\Delta\phi$	$\Delta\phi/H/L_w$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	(fps)		(deg)	(cps)	(cps)		(ft)		(deg)		(cps)	(cps)			
L/b = 12 , C = 2.7 , c = 4.85 fps, L_W = 4.60 ft H/L_W = .0815 , L_W/L = 0.92															
180.19	2.28	0.62	180	1.130	2.00	.565	.083	.222	9.2	113	1.057	1.24	.852	0.6	7
150.19	2.28	0.62	150	1.121	2.00	.560	.150	.400	11.5	141	1.094	1.24	.883	0.2	--
135.19	2.28	0.62	135	1.110	2.00	.555	.183	.490	9.1	112	1.110	1.24	.895	2.5	--
120.19	2.27	0.62	120	1.092	2.00	.546	.242	.645	9.2	113	1.122	1.24	.905	2.8	--
90.19	2.26	0.62	90	1.057	2.00	.529	.242	.645	2.0	25	1.132	1.24	.914	10.0	--
180.20	6.03	1.62	180	1.254	2.00	.627	.042	.111	9.2	113	1.057	1.24	.852	0.2	--
150.20	6.02	1.62	150	1.228	2.00	.614	.083	.222	15.5	190	1.155	1.24	.932	3.9	47
135.20	6.02	1.62	135	1.195	2.00	.598	.242	.645	14.5	178	1.198	1.24	.967	0.1	1
120.20	6.01	1.62	120	1.155	2.00	.578	.208	.555	14.4	177	1.228	1.24	.990	2.7	33
90.20	6.04	1.62	90	1.057	2.00	.529	.250	.667	0.8	10	1.252	1.24	1.010	4.5	--
180.21	14.31	4.05	180	1.526	2.00	.763	.042	.111	2.1	26	1.057	1.24	.852	2.9	36
150.21	14.31	4.05	150	1.463	2.00	.732	.042	.111	3.2	39	1.293	1.24	1.043	0.9	--
135.21	14.46	4.05	135	1.392	2.00	.696	.075	.200	6.8	84	1.391	1.24	1.122	0.8	10
120.21	12.04	4.05	120	1.252	2.00	.626	.292	.778	16.1	198	1.400	1.24	1.130	3.0	37
90.21	11.59	4.05	90	1.057	2.00	.529	.100	.267	4.1	50	1.438	1.24	1.158	5.1	63
L/b = 12, C = 2.7 , c = 6.73 fps , L_W = 9.39 ft , H/L_W = .036 , L_W/L = 1.88															
180.22	2.26	0.62	180	.766	2.00	.383	.258	.775	4.9	136	.717	1.24	.578	2.6	72
150.22	2.26	0.62	150	.759	2.00	.380	.250	.750	6.5	181	.742	1.24	.599	0.5	14
135.22	2.26	0.62	135	.750	2.00	.375	.157	.475	5.2	144	.750	1.24	.605	8.1	225
120.22	2.26	0.62	120	.741	2.00	.371	.250	.750	3.5	97	.760	1.24	.613	0.5	14
90.22	2.26	0.62	90	.717	2.00	.359	.275	.825	3.2	89	.767	1.24	.620	0.4	--
180.23	6.01	1.62	180	.850	2.00	.425	.250	.750	7.2	200	.717	1.24	.578	0.8	22
150.23	6.03	1.62	150	.833	2.00	.417	.100	.300	8.7	242	.783	1.24	.633	2.3	64
135.23	6.00	1.62	135	.811	2.00	.406	.233	.700	6.7	.86	.811	1.24	.655	1.4	39
120.23	6.02	1.62	120	.783	2.00	.392	.192	.575	4.3	119	.832	1.24	.672	6.9	192
90.23	6.03	1.62	90	.717	2.00	.359	.125	.375	1.4	39	.850	1.24	.686	1.5	42
180.24	14.75	4.05	180	1.043	2.00	.522	.167	.500	12.8	356	.717	1.24	.578	4.4	--
150.24	15.10	4.05	150	1.008	2.00	.504	.375	1.125	20.0	556	.885	1.24	.715	0.6	--
135.24	15.30	4.05	135	.956	2.00	.478	.366	1.100	19.3	536	.956	1.24	.773	1.0	28
120.24	15.20	4.05	120	.885	2.00	.443	.258	.775	16.2	450	1.010	1.24	.815	6.0	167
90.24	15.20	4.05	90	.717	2.00	.359	.683	1.750	1.9	53	1.055	1.24	.852	1.9	53

χ - relative heading - degrees (L/L)

L - length of hull - feet (L)

b - beam of hull - feet (L)

Δ - load on water - pounds (F)

v - speed of model - ft/sec (L/T)

h - heave - feet (L)

$\Delta\tau$ - change in trim - degrees (L/L)

$\Delta\phi$ - change in roll - degrees (L/L)

ω_n - natural frequency of hull - cps (1/T)

w - unit weight of water - lb/cu ft (F/L^3)

From this tabulation L_w , H , c , ω and w represent properties of the waves; χ , and g represent properties of the seaway; L , b , Δ , v , h , $\Delta\tau$, $\Delta\phi$, ω_n represent properties of the seaplane. These variables can be expressed in the following functional equation:

$$\phi_1 (L_w , H , c , \omega , \chi , L , b , \Delta , v , h , \Delta\tau , \Delta\phi , \omega_n , w) = 0 . \qquad (11)$$

The large number of variables considered illustrates the complexity of the problem. The number of the variables can be reduced if interpedendence of some can be shown. Previously Eq 10 has been derived for the frequency of encounter. In Eq 10, c , ω , x , and v are shown to be interrelated; hence Eq 11 can be rewritten as follows:

$$\phi_2 (L_w , H , \omega_e , L , b , \Delta , h , \Delta\tau , \Delta\phi , \omega_n , w) = 0. \qquad (12)$$

The variables of Eq 12 can be combined into an equation of dimensionless parameters thus reducing the number of factors which must be considered. In addition, the research project can be conducted in a systematic manner which yields generalized solutions. An example of the simplification and generalization is given in reference (5).

$$\phi_3 \left[H/L_w , \omega_e/\omega_n , L_w/L , L/b , \frac{\Delta}{wb^3} , h/H , \frac{\Delta\tau}{H/L_w} , \frac{\Delta\phi}{H/L_w} \right] = 0. \qquad (13)$$

The parameters of Eq 13 are further described as follows:

H/L_w - wave height to length ratio is the well known measure of wave steepness.

ω_e/ω_n - ratio of frequency of encounter to the natural frequency of the seaplane.

L_w/L - ratio of seaplane length to wave length. This has been shown to be a significant parameter in reference (13).

L/b - planform fineness ratio.

$\frac{\Delta}{wb^3}$ - also known as the load coefficient, C_Δ.

h/H - the heave magnification or heave parameter.

$\frac{\Delta\tau}{H/L_w}$ - the trim parameter.

$\frac{\Delta\phi}{H/L_w}$ - the roll parameter.

The wave height to length ratio appears in the trim and roll parameters and for this reason the H/L_w parameter will be eliminated for further consideration for the present time.

If the reasoning employed in reference 13 is correct, then Eq 13 can be rearranged and separated into three equations with the heave parameter, h/H, the trim parameter, $\frac{\Delta\tau}{H/L_w}$, and the roll parameter $\frac{\Delta\phi}{H/L_w}$ each as the dependent variables:

$$h/H = \phi_4 \left(\omega_e/\omega_n , L_w/L , L/b , C_\Delta \right), \quad (14)$$

$$\frac{\Delta\tau}{H/L_w} = \phi_5 \left(\omega_e/\omega_n , L_w/L , L/b , C_\Delta \right), \quad (15)$$

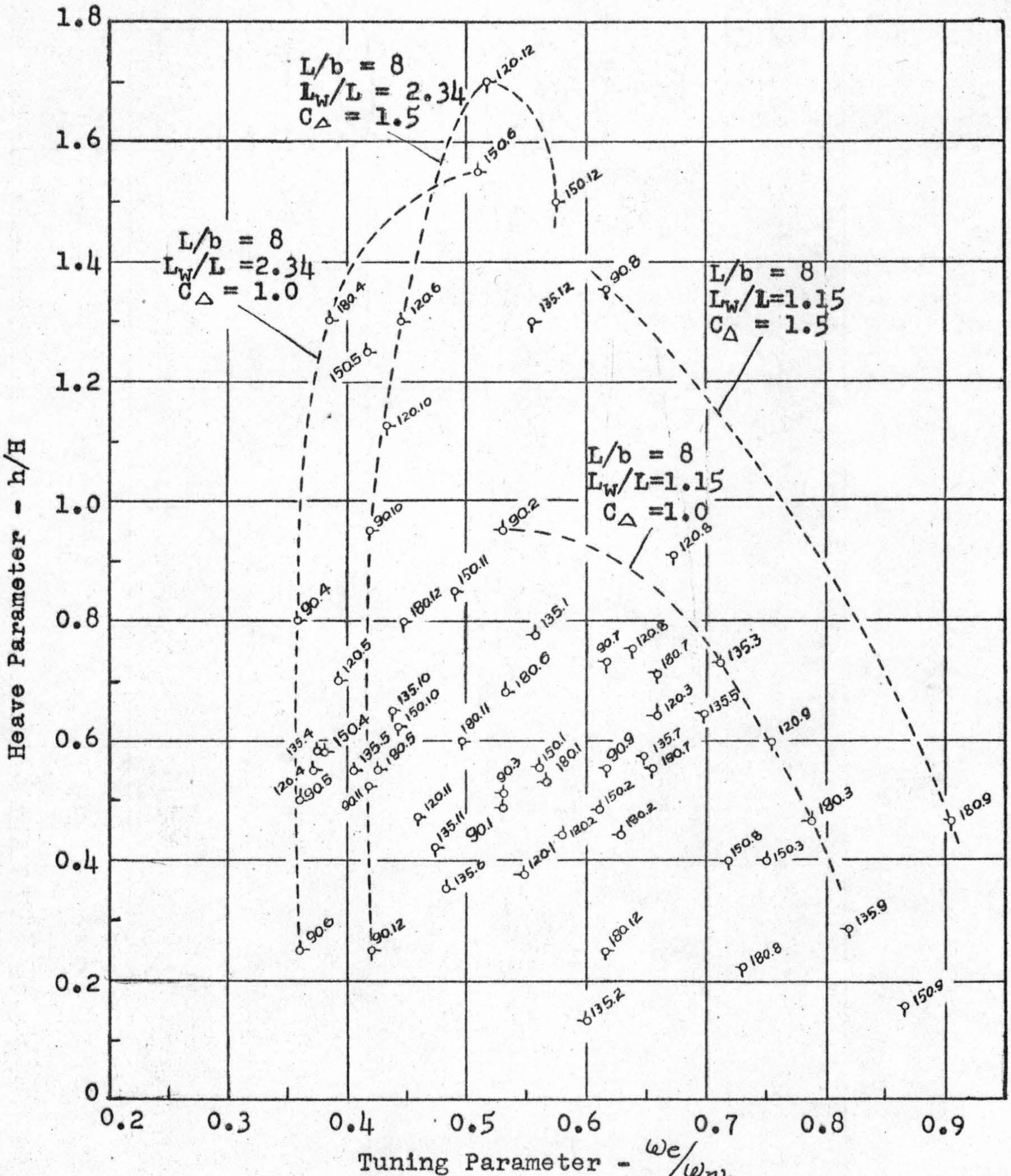
$$\frac{\Delta\phi}{H/L_w} = \phi_6 \left(\omega_e/\omega_n , L_w/L , L/b , C_\Delta \right). \quad (16)$$

These three equations form the basis for the analysis of the experimental data. The complete experimental program should obtain data for a complete range of variation of each of these parameters. The results obtained to date are limited in scope; however, they represent variation of each parameter listed in Eqs 14, 15 and 16. The dimensionless parameters are also listed in Table 5, together with variables from which they were derived.

The Heave Parameter:- The heave parameter has been plotted as a function of the ratio of the frequency of encounter to the natural frequency in parameters of length to beam ratio, wave length to hull ratio and load coefficient. The data were plotted on two graphs. The data for the short hull (L/b = 8) is shown on Fig. 3. Lines enveloping the test data for a particular L^w/L ratio and a particular load coefficient are shown. Each point is marked with a number comprising two elements. That part of the number to the left of the decimal point refers to the heading of the model and the part of the number to the right of the decimal refers to the run series number. A run is referred to as a group of tests at a single speed, wave length and loading and varying throughout the five different headings. A series of runs consisted of three runs wherein the speed was the second variable. The data for the long hull (L/b = 12) is shown on Fig. 4. The envelope lines resemble to some extent the predictions for a tanker based on a theoretical analysis reported in reference (13).

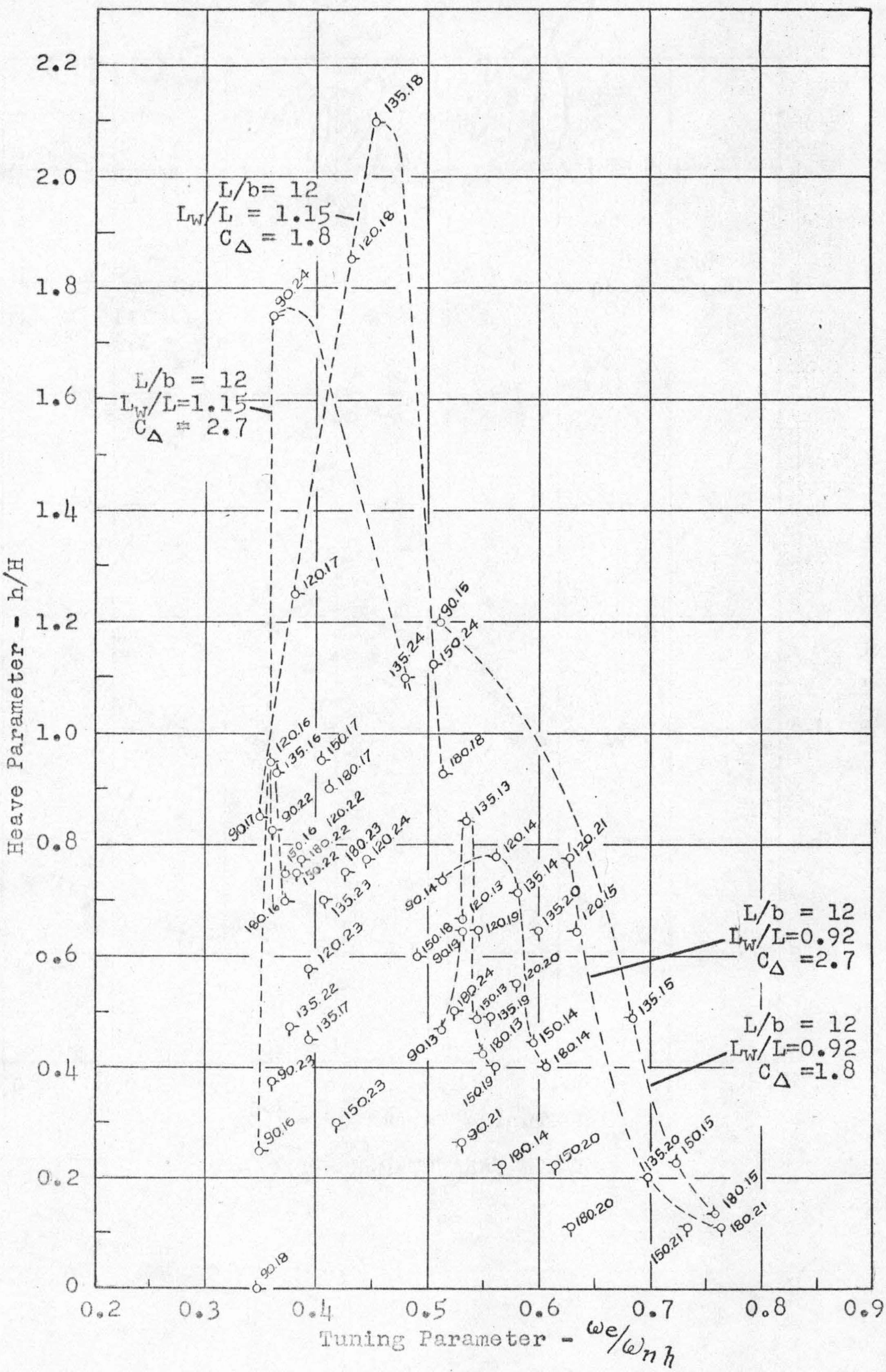
Increasing the Lw/L ratio results in a shift of the envelope lines upward and to the left for both hulls. This is in agreement with the predictions for the tanker previously cited. The envelope lines shift to the right as the load coefficient is increased. This shift to the right is less pronounced in the long hull (L/b= 12). The peak values of the heave parameter occur when the frequency of encounter is approximately one-half the natural frequency of the hull. This is contrary to the predictions given in reference (13). The heave parameter has a peak value because of a resonance which should logically occur when the ω_e/ω_n ratio is equal to 1.0. A possible explanation of this anomaly is that the determination of the natural frequency was incorrect.

The envelope lines from Figs 3 and 4 have been plotted on Fig. 5. The actual data have not been plotted on Fig. 5 to avoid confusion. The conclusions drawn from Fig. 5 indicate that the long hull L/b = 12)exhibits higher values of the heave parameter which probably results in greater linear accelerations along the vertical axis. The curves also indicate that the long hull was tested over a narrower range of the ω_e/ω_n parameter. More conclusive comparisons will be reserved until the tests on the two models can be conducted over a wider range of the various parameters. The solution of the damping coefficients was not attempted since more data is desired before the curves are finally drawn.



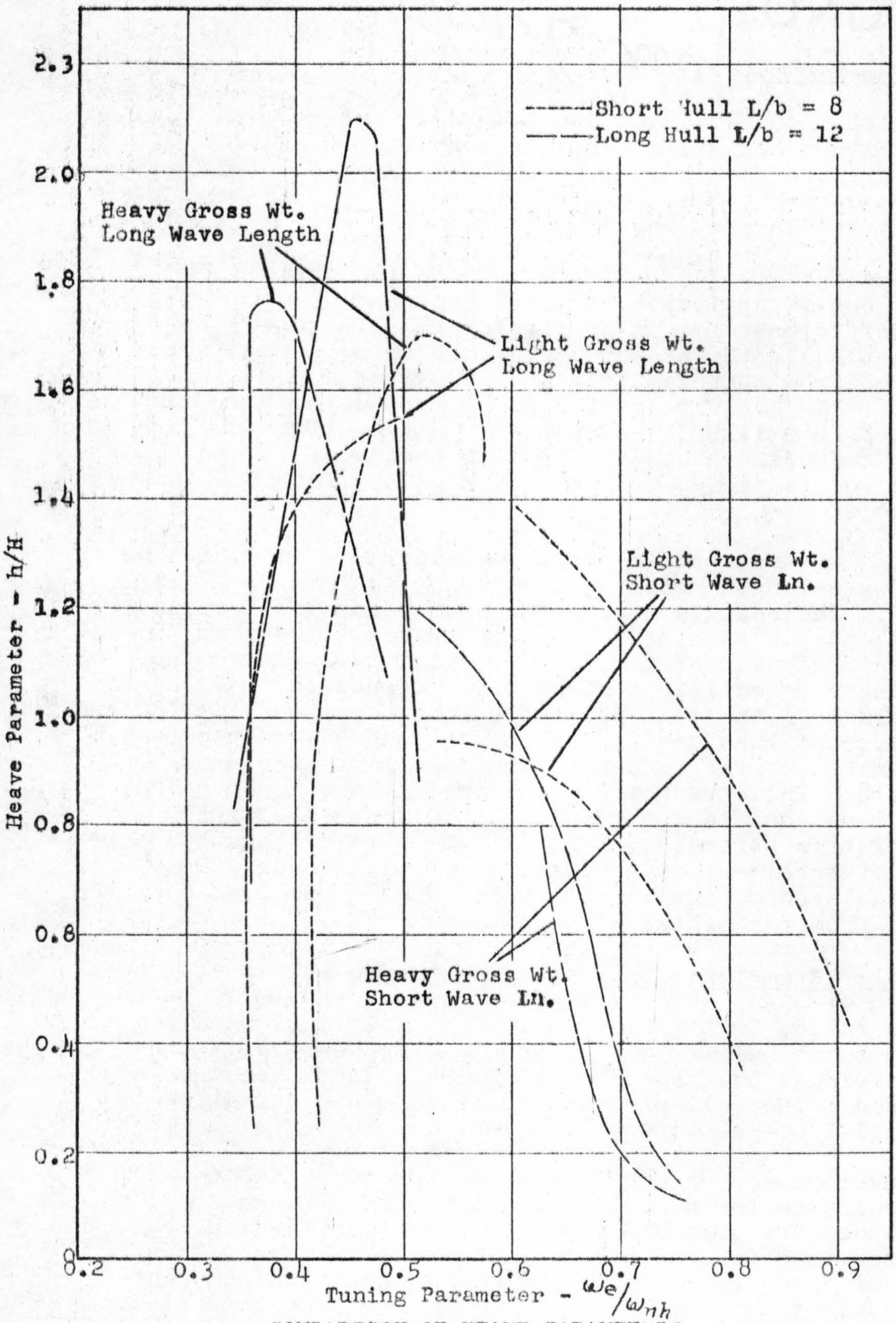
HEAVE PARAMETER FOR L/b = 8

Fig.3



HEAVE PARAMETER FOR L/b = 12

Fig.4



COMPARISON OF HEAVE PARAMETERS

Fig.5

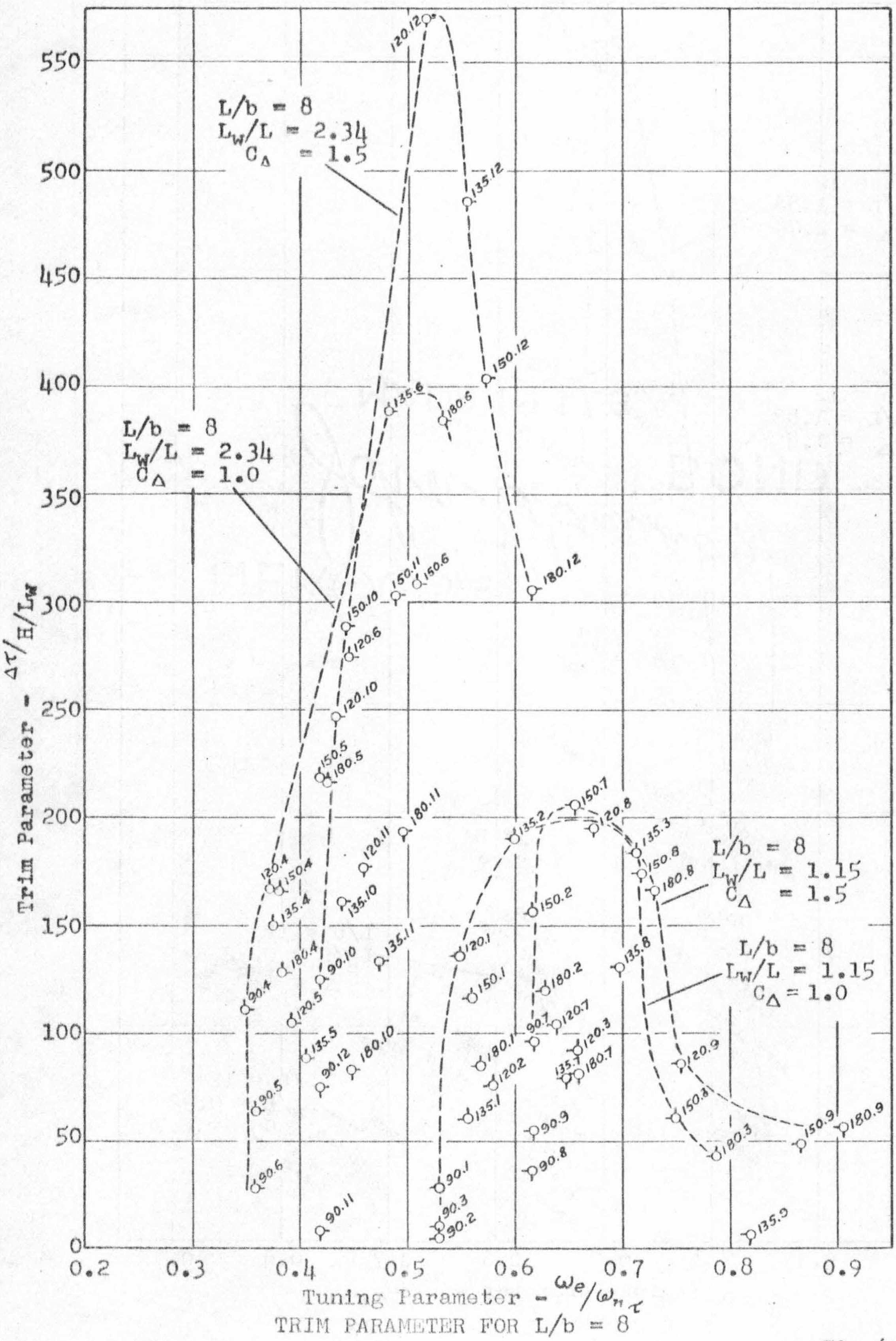
Trim Parameter:- The values of the trim parameter as a function of ω_e/ω_n were plotted on Fig. 6 and 7 in terms of the L/b ratio, L_w/L ratio and the load coefficient. All values for the short hull (L/b = 8) were plotted on Fig. 6 and the values for the long hull (L/b = 12) were plotted on Fig. 7. Each point is marked with a code number described in the previous section.

Envelope curves were drawn through the data on Figs. 6 and 7 for a particular value of Lw/L and C_Δ . As the load coefficient C_Δ , is increased from 1.0 to 1.5 for the short hull, the peak value of the trim parameter increased from approximately 400 to 570 at ω_e/ω_n = .525 for Lw/L = 2.34. For the series of runs using the short hull at Lw/L = 1.15 there was very little difference between the peak values of the trim parameter as the load coefficient is increased from 1.0 to 1.5. The peak values occurred at ω_e/ω_n = 0.65.

Similar tests on the long hull resulted in variation of the wave length relative to the hull length from 0.92 to 1.88. The peak values of the trim parameter increased from 370 to 560 at ω_e/ω_n = 0.45 for Lw/L = 1.88 when the load coefficient was increased from 1.8 to 2.7. As the wave length to hull length ratio was decreased to 0.92, the peak values of the trim parameter were approximately 150 and 200 for values of load coefficient of 1.8 and 2.7 respectively. A comparison of the values of the trim parameter is shown on Fig. 8. This graph indicates that at the lower values of the load coefficeint the longer hull has a slightly lower value of trim parameter. This may be interpreted as lower values of acceleration. Certainly it would mean a more comfortable condition for the pilot located at some distance forward from the center of gravity.

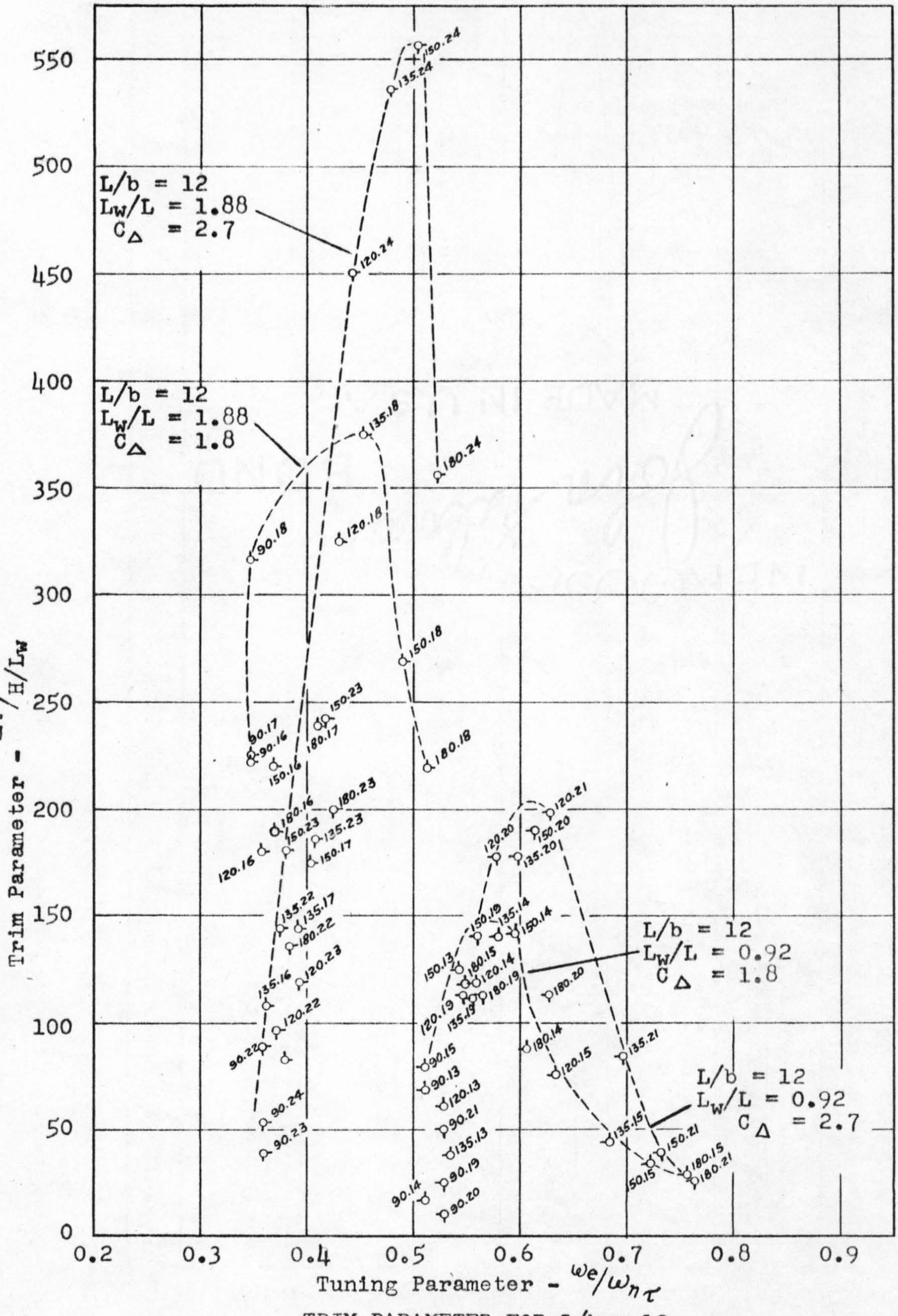
Roll Parameter:- The values of the roll parameter as a function of ω_e/ω_n were plotted on Figs. 9 and 10 in terms of the L/b ratio, Lw/L ratio and load coefficient. All values for the short hull (L/b = 8) were plotted on Fig. 9 and the individual points marked with the code number previously described. The roll parameter data obtained using the long hull L/b = 12 were plotted on Fig. 10.

Envelope curves were drawn through the data on Figs. 9 and 10 for a particular value of L_W/L and C_Δ . The trends were more difficult to establish for the roll parameter than for the heave and trim parameters. In a number of cases the model's freedom to roll was somewhat restricted by the manner in which the test was conducted. The restraint was caused when the stern line was too taut and the model was traveling on headings of from 90° to 135° to the seaway. Under these circumstances the plane would be carried along with the crest of the waves until all the



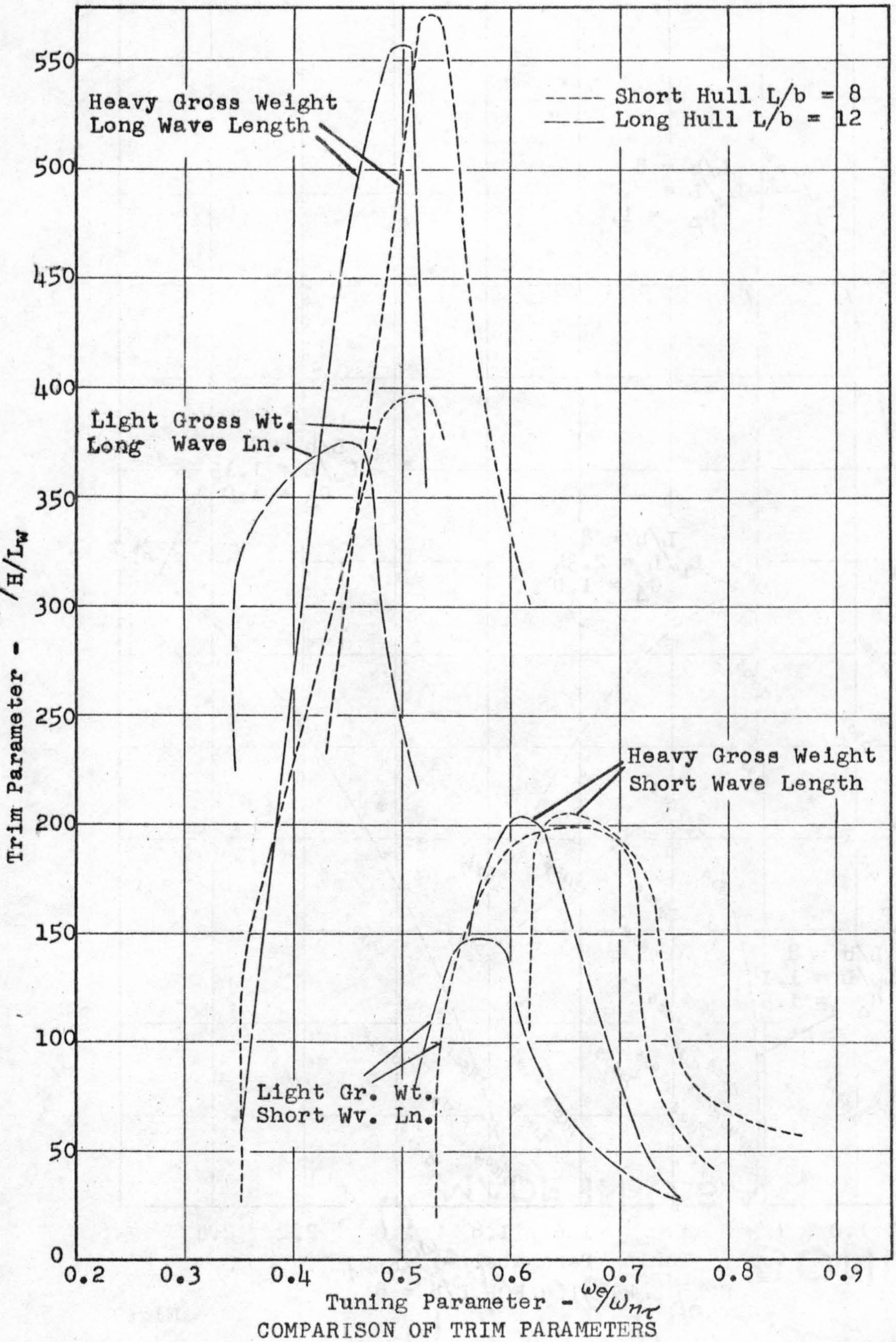
TRIM PARAMETER FOR L/b = 8

Fig.6



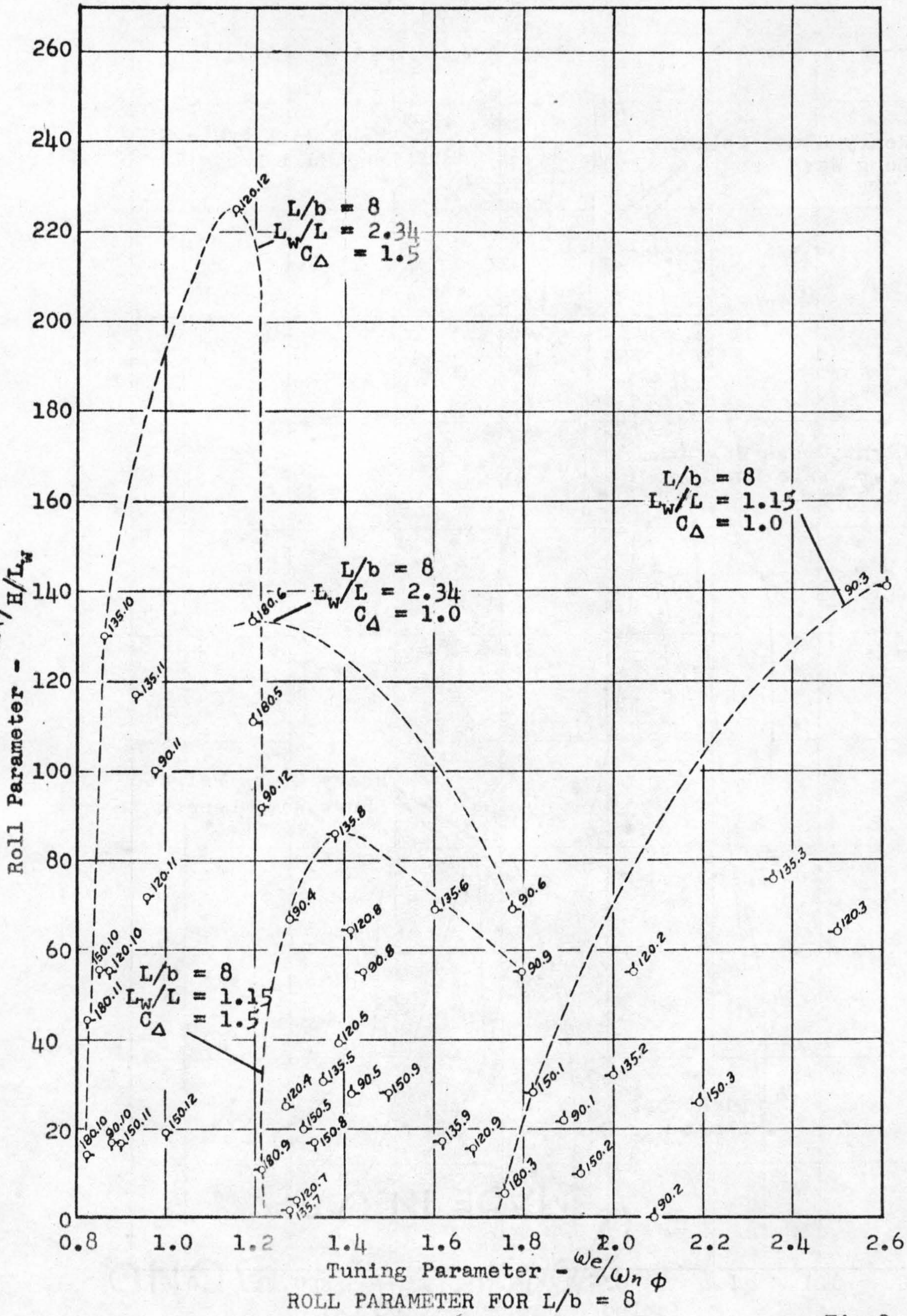
TRIM PARAMETER FOR L/b = 12

Fig.7



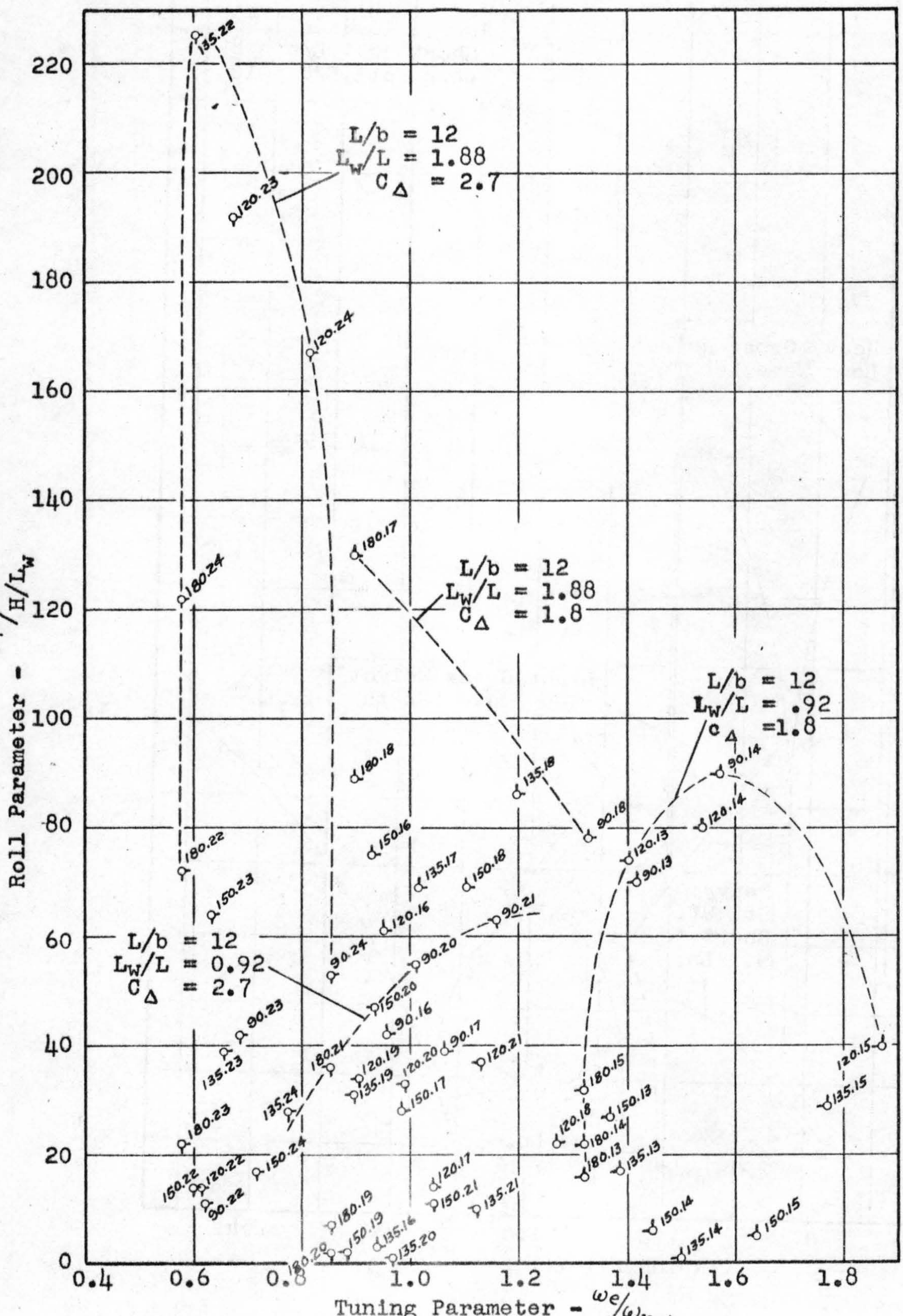
COMPARISON OF TRIM PARAMETERS

Fig.8



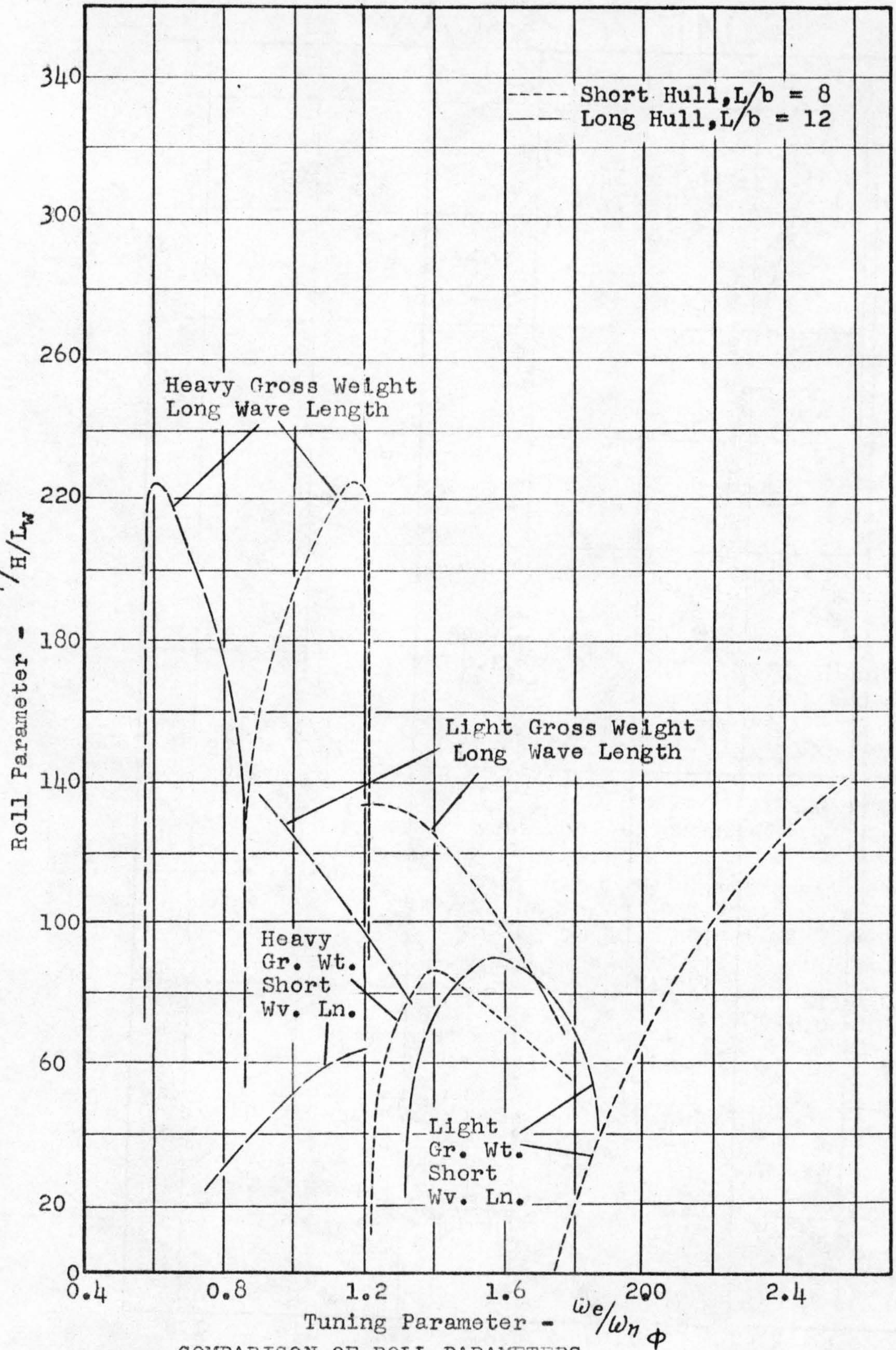
ROLL PARAMETER FOR L/b = 8

Fig.9



ROLL PARAMETER FOR L/b = 12

Fig.10



COMPARISON OF ROLL PARAMETERS

Fig.11

slack in the towing line was taken up. Succeeding wave encounters would provide a rolling moment to the left until left wing tip float was well submerged and the right wing tip float would ride clear of the water. When these conditions existed the data providing the angles of roll were discarded.

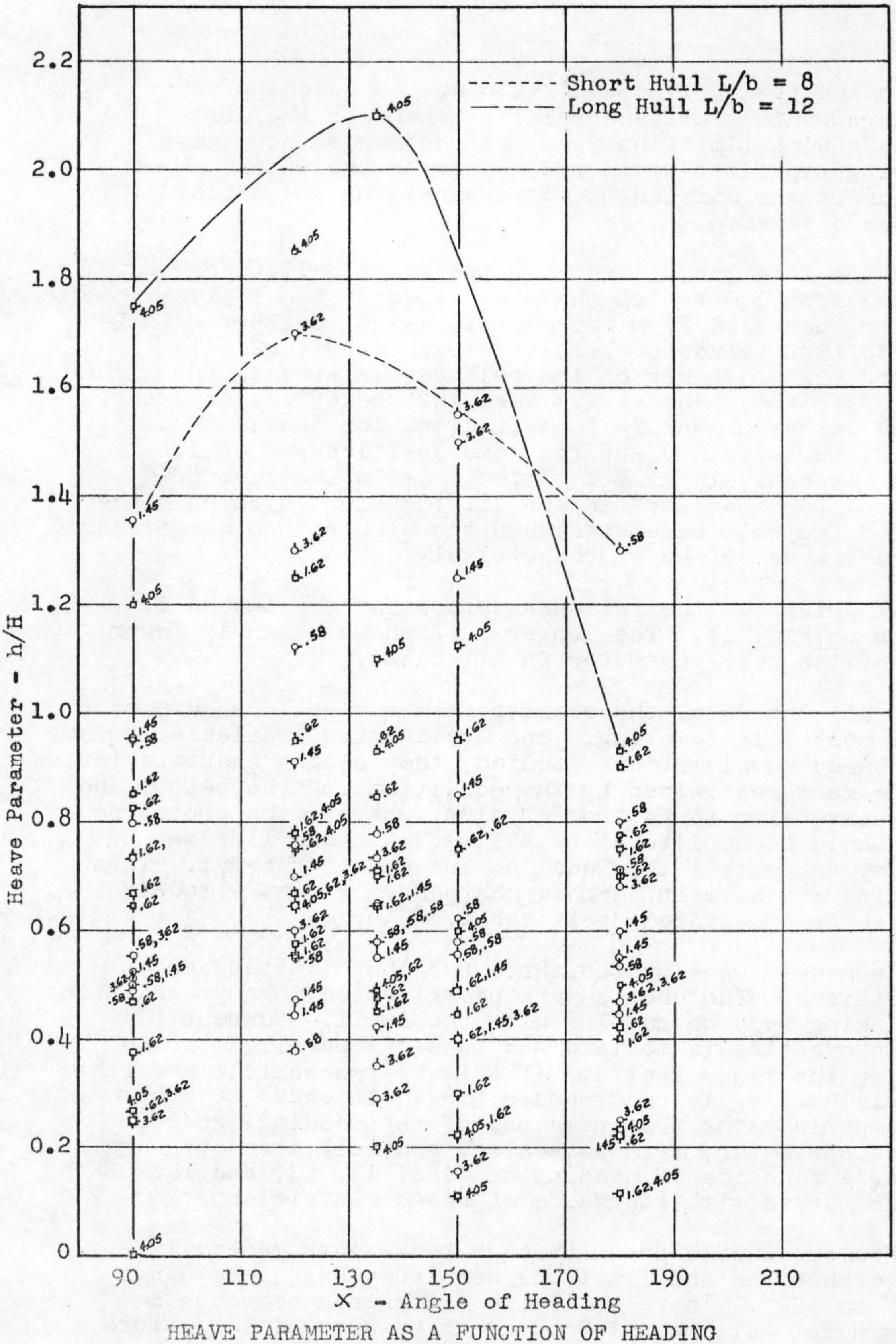
As the load coefficient for the short hull (L/b = 8) increased from 1.0 to 1.5 the peak value of the roll parameter increased from approximately 140 to 225 for Lw/L= 2.34. At Lw/L values of 1.15 the lower load coefficient indicated higher values of the roll parameter than the higher load coefficient. The values were 140 and 85 respectively. The peak values of the roll coefficient for the long hull (L/b =12) were 130 and 225 for load coefficients of 1.8 and 2.7 respectively at Lw/L = 1.88. At Lw/L values of 0.92 the lower load coefficient (1.8) again indicated higher values of the roll parameter than the higher load coefficient. The values were 90 and 65 respectively.

Comparison of the roll parameters for the two hulls is shown on Fig. 11. The longer hull shows slightly lower values of the roll parameter in all cases.

Of all the data, the results from the roll measurements are the most disappointing. One explanation available is that of the three model motions studied, the rolling characteristics were the most restrained by the conditions of the test. The models were being towed from a point, whereas the prototype thrust would be applied along a line. A stern line was necessary to control the model at the end of the run. This stern line may have influenced the behavior of the models more than is immediately noticeable.

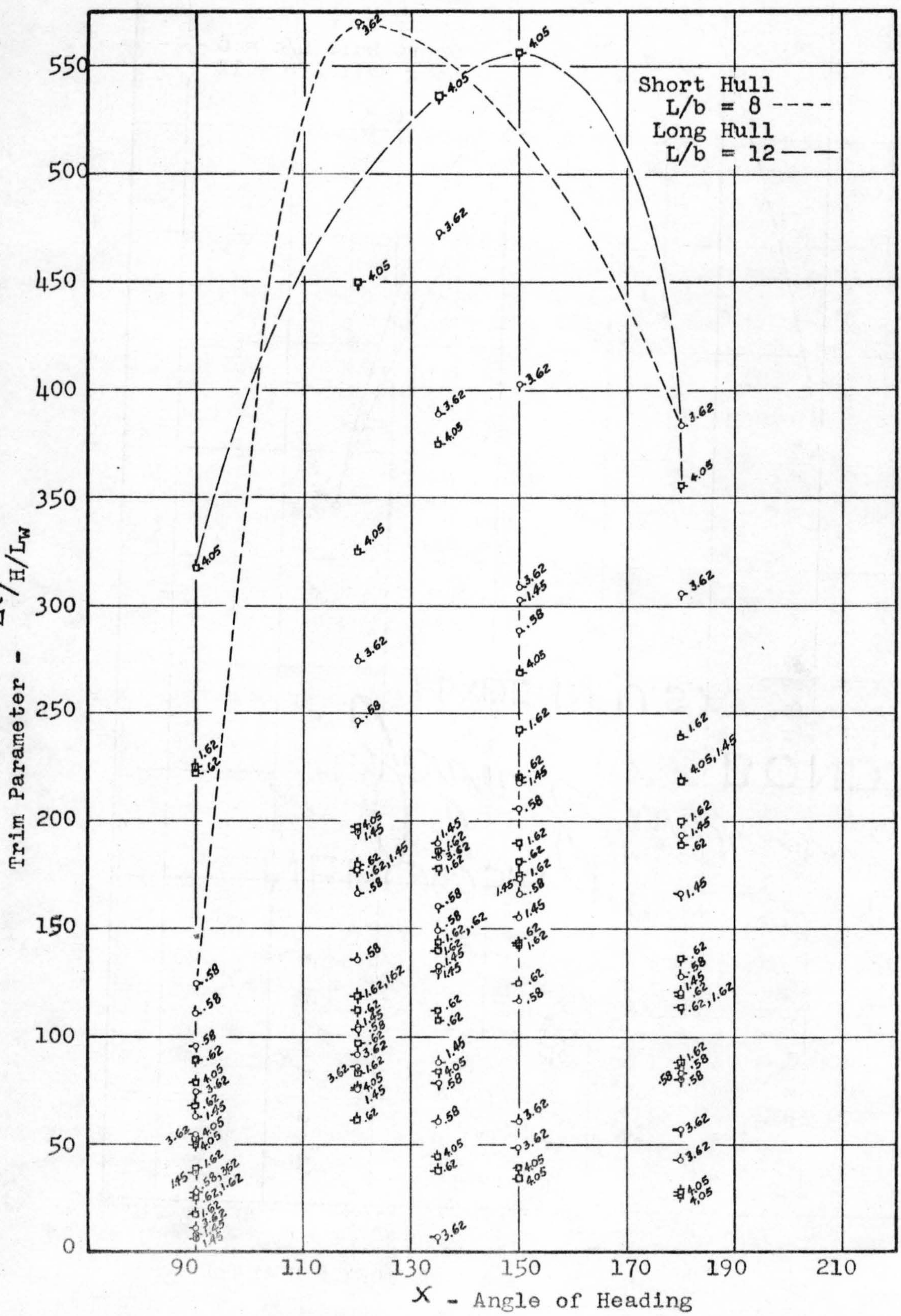
The models were tested through rather limited range of conditions. The models were never tested in any condition of following seas or running with the swell. Current seaplane practice is to land and take-off parallel to the crests of the major swells. If this is impractical a slight downswell heading is recommended (16). In order to draw some comparisons of the influence of the heading, graphs of heave parameter, trim parameter, and roll parameter are shown as a function of heading on Figs. 12, 13, and 14. Each point is marked with its value of speed coefficient.

Envelope curves drawn through these data generally indicate that the model motions were greatest on headings of 120° to 150°. There is little difference between the maximum model motions which occur at heading of 180° (into waves) and 90° (parallel to waves). This is not in accordance with a logical analysis of the model motions. It would seem as if the motions in pitch and heave should reach



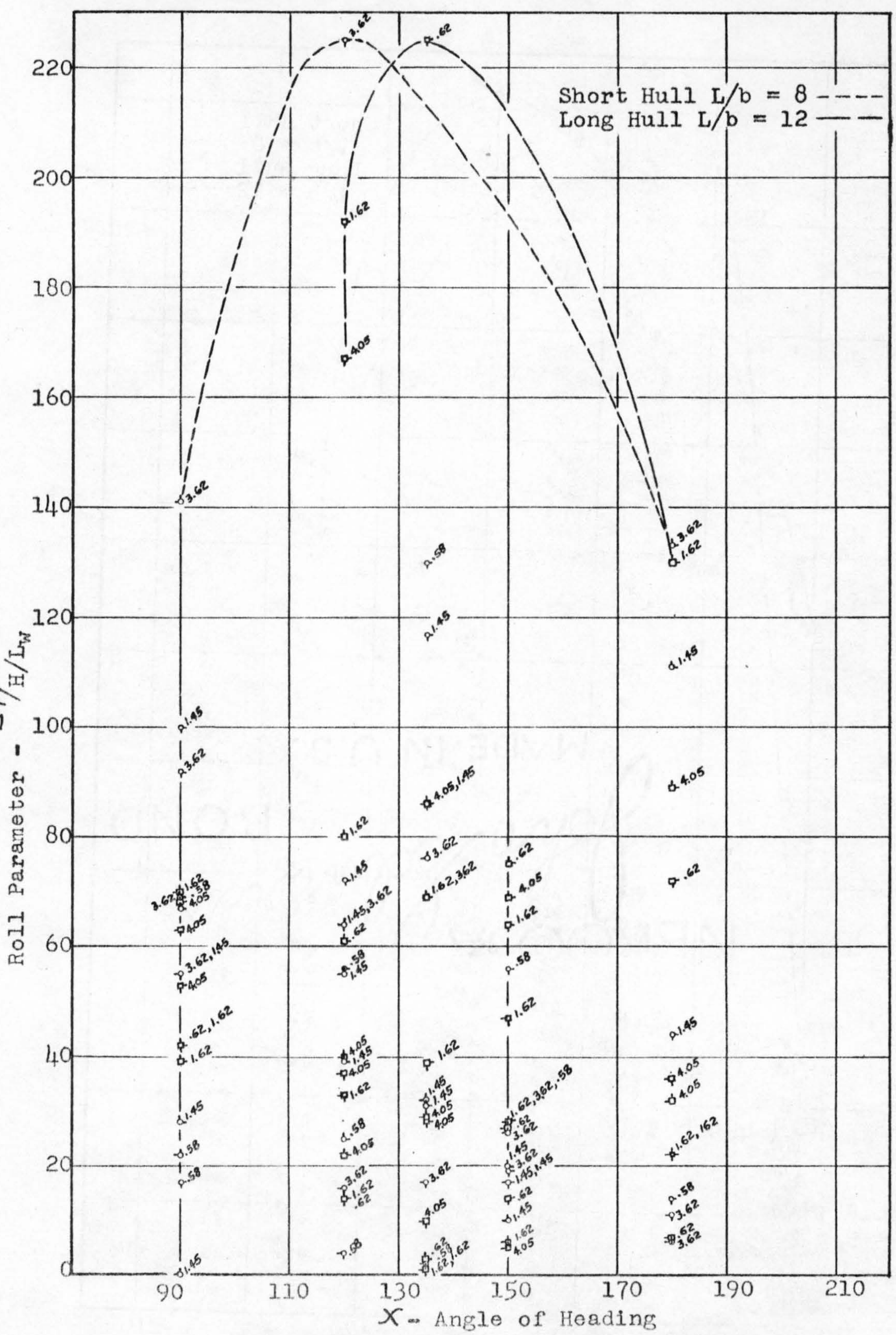
HEAVE PARAMETER AS A FUNCTION OF HEADING

Fig.12



TRIM PARAMETER AS A FUNCTION OF HEADING

Fig.13



ROLL PARAMETER AS A FUNCTION OF HEADING

Fig.14

a maximum at a heading is somewhere between 150° and 180° and the motions in roll should reach a maximum at a heading of 90° and should be a minimum at 180°.

The use of the envelope curve may be questionable since there may be some doubt regarding the measurements in some instances, and none of the runs were repeated. Unfortunately, the testing season was terminated with stormy weather. In addition, it was considerable time before all of the data were completely analyzed and any serious deficiencies discovered. It would be well to repeat all of the runs which have determined the position of these envelop curves. There is some indication that there may be a critical synchronization of all of the factors involved. If this is true, then more data are certainly necessary. Some method for quickly analyzing the data must be devised. Other methods of analysis have been discussed in Colorado A & M College report No. 54EFS11, entitled, "Development of a Basin for Investigation of the Seaworthiness of Model Seaplane Hulls".

Conclusions

The results of these investigations are summarized as follows:

1. Results from the model studies on the model of a long length to beam ratio hull indicate that increasing the length to beam ratio from 8 to 12 for the same planform area results in a slight improvement of the seaworthiness of the seaplane.

2. The tests also indicate agreement with current seaplane doctrine that the preferred headings for landing of seaplanes are

   (a) parallel to wave crests or

   (b) into wave crests.

3. The scope of the investigations was too limited to draw final conclusions.

4. More severe conditions seem to exist at headings of 120° to 150° as compared to 180°. Current tests of resistance and stability in towing basins are limited to a heading of 180°.

5. Additional information is necessary before final conclusions should be drawn.

6. A method of taking the data should result in improved methods of data analysis.

If the results obtained from these experiments would mean the saving of the life of some pilot and his seaplane then the work would be rewarding indeed.

REFERENCES

1. Anon. Specification for transverse stability of seaplanes. Displacement and location of auxiliary floats. NAVAER SR 59c, Bu. Aero., Feb. 20, 1942.

2. Davidson, K. S. M. and Locke, F. W. S., Jr. General tank tests on the hydrodynamic characteristics of four flying-boat hull models of differing length-beam ratio. NACA ARR No. 4F15.

3. Carter, A. W. and Haar, M. I. Hydrodynamic qualities of a hypothetical flying boat with a low-drag hull having a length-beam ratio of 15. NACA TN No. 1570.

4. Johnson, J. W. and Wiegel, R. L. Elements of wave theory. Proc. 1st Conference on Coastal Engineering, Berkeley, Oct. 1950.

5. Locke, F. W. S., Jr. General resistance tests on flying boat hull models. NACA ARR No. 2B19, 1944.

6. Locke, F. W. S., Jr. Tests of a flat bottom planing surface to determine the inception of planing. NAVAER DR Report 1096, Dec. 1948.

7. Murray, A. B. The hydrodynamics of planing hulls. Proc. Society of Naval Architects and Marine Engineers, 1950.

8. Owen, T. B., Kurn, A. G. and Smith, A. G. Model testing technique employed in the R.A.E. seaplane tank. Report No. AERO 2505.

9. Parkinson, J. B. The design of the optimum hull for a large long-range flying boat. NACA ARR No. L4112, 1944.

10. Parkinson, J. B. Appreciation and determination of the hydrodynamic qualities of seaplanes. NACA TN No. 1290, 1947.

11. Sverdrup, H. U. and Munk, W. H. Wind, sea and swell: Theory of relations for forecasting. Hydrographic Office Publication 601 (1947).

12. Sverdrup, H. U., Johnson, M. W. and Fleming, R. H. The oceans. New York, Prentice Hall, Inc., 1942. 1087 p.

13. St. Denis, M. On sustained sea speed. Proc. Society of Naval Architects and Marine Engineers. New York, Nov. 15 & 16, 1951.

14. St. Denis, M. and Pierson, W. J. On the motions of ships in confused seas. Proc. Society of Naval Architects and Marine Engineers, New York. Nov. 12 & 13, 1953.

15. Taylor, J. W. R. America is developing flying-boats. Air Pictorial and Air Reserve Gazette. Vol. XIV, No. 9 pp. 261-63, Sept. 1952.

16. U. S. Naval Aviation Safety Activity. Open sea seaplane operations. NASA A64-P1-953, 1943.

17. Weinblum, G. and St. Denis, M. On the motions of ships at sea. Proc. Society of Naval Architects and Marine Engineers, New York, Nov. 9, 1950.

18. Marcinek, Jack. Dynamic lift characteristics of six wing-tip floats. Stevens Institute of Technology Report No. 371, Hoboken, N. J., Sept. 1951.