R-1437

DAVIDSON LABORATORY

Report SIT-DL-69-1437

December 1969

ENGINEERING APPROXIMATION OF MAXIMUM ACCELERATIONS EXPERIENCED BY PLANING CRAFT IN ROUGH WATER

by

John K. Roper

This research was sponsored by the
Naval Ship Systems Command
Exploratory Development Research Program
SF 35421009 and prepared under
Office of Naval Research
Contract N00014-67-A-0202-0014,
NR062-419/9-18-68 (Code 438)

This document has been approved for public release and sale; its distribution is unlimited. Application for copies may be made to the Defense Documentation Center, Cameron Station, 5010 Duke St., Alexandria, Va., 22314. Reproduction of the document in whole or in part is permitted for any purpose of the United States Government.

STEVENS INSTITUTE OF TECHNOLOGY
CASTLE POINT STATION
HOBOKEN, NEW JERSEY

D D C
RECEIVED
MAY 4 1970
B

R-1437

37

DAVIDSON LABORATORY

Stevens Institute of Technology
Castle Point Station
Hoboken, New Jersey 07030

Report SIT-DL-69-1437

December 1969

ENGINEERING APPROXIMATION OF MAXIMUM ACCELERATIONS EXPERIENCED BY PLANING CRAFT IN ROUGH WATER

by

John K. Roper

This research was sponsored by the
Naval Ship Systems Command
Exploratory Development Research Program SF 35421009
and prepared under Office of Naval Research
Contract N00014-67-A-0202-0014
NR062-419/9-18-68 (Code 438)

(DL Project 103, File No. 3529)

Approved

Daniel Savitsky

Daniel Savitsky
Assistant Director

13 + viii pages
plus 4 tables, 10 figures

ABSTRACT

An engineering procedure is presented for estimating the maximum impact accelerations experienced by planing craft in irregular head seas. General agreement between calculated and model test results indicates that the proposed method is realistic. The procedure should be particularly useful during preliminary design.

Keywords

Planing Hulls
Impact Accelerations

CONTENTS

NOMENCLATURE

a	Horizontal distance from LCG
b	Beam
$C\ell_o$	Total lift coefficient, zero deadrise $= f(C\ell_\beta,\beta)$
$C\ell_{o_D}$	Dynamic lift coefficient, zero deadrise $= .012\tau_o^{1.1}\lambda_o^{1/2}$
$C\ell_\beta$	Total lift coefficient, deadrise surface $= \Delta/qb^2$
$C\ell_{\beta_D}$	Dynamic lift coefficient, deadrise surface $= f(C\ell_{o_D}, \beta)$
C_V	Speed coefficient $= \dot{x}/\sqrt{gb}$
g	Acceleration due to gravity
H_w	Wave height
$\dot{h}$	Wave particle velocity, vertical, at surface
I	Mass moment of inertia
L	Total lift
L_B	Buoyant lift
L_D	Dynamic lift
LCF	Centroid of chine planform area forward of transom
LCG	Center of gravity location forward of transom
ℓ	Effective wetted length
ℓ_c	Projected chine length
ℓ_w	Wave length
M	Applied moment
n	Incremental load factor
q	Dynamic pressure $= \dot{x}^2(\rho/2)$
T_w	Wave period
V	Speed, knots
$\dot{x}$	Horizontal velocity
$\dot{y}$	Vertical velocity

$\ddot{y}$	Vertical acceleration
$\dot{z}$	Velocity, relative to adjacent fluid, of planing body normal to its keel
β	Deadrise angle
Δ	Gross weight
$\ddot{\theta}$	Angular acceleration
λ	Effective wetted length to beam ratio
ρ	Mass density
τ	Trim angle
ϕ	Wave slope (maximum)

Subscripts

o	Denotes smooth water operation
max	Denotes rough water operation
CG	Denotes center of gravity
θ	Denotes angular motion

INTRODUCTION

Research in the area of hydrodynamic impact has been carried out mainly by the aerodynamicist in his studies of landings of water-based aircraft and recently by the hydrodynamicist in his studies of ship slamming. Numerous theoretical developments have been published and a great deal of experimental data on hydrodynamic impact exists in the various publications associated with these two technological disciplines. A brief study was undertaken to review the existing information on hydrodynamic impact and to exact therefrom those results particularly applicable to the design of high speed planing craft. In the course of this review, an empirical procedure was formulated which allowed for reliable engineering estimates of the maximum impact accelerations experienced by planing craft in rough water. It was believed that this procedure would be of immediate direct benefit to the small craft designer and, consequently, the emphasis of the present report is on a description of this engineering procedure and includes a comparison of computed and measured rough water accelerations obtained in model tests at the Davidson Laboratory.

The present study was carried out under sponsorship of the Naval Ship Systems Command Exploratory Development Research Program SF 35421009 and prepared under Office of Naval Research Contract N00014-67-A-0202-0014 NRC62-419/9-18-68 (Code 438).

BACKGROUND

Some of the earliest studies of the phenomenon of hydrodynamic impact were initiated by aircraft designers concerned with the determinations of hull impact loads for seaplanes alighting upon a smooth water surface. Analytical and experimental investigations of hydrodynamic impact were continuously pursued during the period when seaplanes were a viable component of aviation. As a consequence, an extensive technical literature was developed which is generally available in NACA (now NASA) reports.

For the most part, seaplane impact theories deal mainly with the case of constant deadrise surfaces alighting upon a smooth water surface at a fixed trim angle such that the initial contact between hull and water is at the transom-keel intersection and the maximum impact load occurs prior to chine immersion. These conditions are typically representative of most seaplane landings. Well-documented reviews of seaplane impact theory have been prepared by Mayo[1] and Monoghan[2]. In essence, these papers describe the impact process as the transfer of momentum from an impacting hull to an "added mass" of water which is directly associated with the hull during its contact with the water and to the "added mass" shed into the wake as the hull moves forward. The expression for the time rate of change of momentum between hull and added mass components then describes the differential equation of motion governing the impact. It is apparent then that this impact theory is dependent upon a proper definition of the form of added mass and, as a result, a substantial research effort has been directed to this end (von Karman[3], Wagner[4], Pabst[5], Milwitzky[6] among others). The added mass is defined for two-dimensional sections normal to the keel which are then integrated over the wetted length of the hull and corrected by an aspect-ratio correction developed by Pabst[5] to provide for a three-dimensional estimate of the total added mass in contact with the hull. This is the usual procedure used in seaplane impact theory and must be limited to the chines-dry impact of a constant deadrise hull.

More comprehensive impact theories dealing with heavily loaded, high length-beam ratio warped hulls were being developed for both smooth and rough water impact conditions when water-based aircraft research was essentially terminated. This new approach, which consists in exploiting the fact that planing is a particular case of impact, would have been of particular advantage to the planing hull. It can be applied to any hull shape for which planing data are available whether or not the chines are immersed and is not limited to prismatic surfaces. Steiner[7] used this approach to obtain a correlation between planing data and one of the empirico-theoretical virtual mass expressions using limited data mostly confined to the chines dry condition. Brown[8] and Smiley[9,10,11,12] exploit, to varying degrees, the concept that impact characteristics may be predicted from planing data. In both cases, the basic equations of motion governing the smooth water impact of a hull are formulated, integrated, and adapted to the prediction of smooth water impact loads and motions from planing equations. Since this work was carried out prior to the development of modern high speed computers, the analytical solutions are dependent upon the application of special tabulated mathematical functions which make the use of the computational procedure extremely tedious. This method for impact calculations should be reactivated and extended to the case of planing hull operation in waves. This extension was not possible within the limited scope of the present study.

Analytical studies of the impact process establish the form of relation between the impact force; the mass of the planing hull and its geometry; and the relative approach conditions between hull and wave; i.e., hull trim, hull velocity (horizontal and vertical components), position in wave. These approach conditions are statistically related and can only be determined from analysis of operational experiences. At the present time, there is insufficient information to describe realistic combinations of approach parameters to be used with impact theory. These operational conditions require much further study.

ENGINEERING APPROXIMATION OF MAXIMUM ACCELERATIONS

The actual case of a planing craft operating in an irregular sea state is a most difficult problem for precise analysis. As previously noted, the basic impact theory requires further development; and among the unknown, moreover, are the hull trim and velocities at the time of impact and the geometry and relative position of the local wave surface against which the hull impacts. In recent years, however, a moderate amount of experimental data has been collected on the behavior of planing hulls in waves. One of the more complete works is a report by Chey[13] on model tests of a series of six patrol boats in smooth and rough water. In that report, numerous plots of angular and center-of-gravity accelerations are presented for round and hard chine hulls in several irregular seas. It was believed that, by a combination of present understanding of the fundamentals of impact theory, full scale and model test observations of planing hulls in waves, and a judicious set of approximations, an engineering procedure for estimating maximum accelerations on planing hulls could be established to at least be applicable within the range of available experimental data. Accordingly, the following assumptions and approximations have been made to represent the impact process and the hull-wave contact conditions at the time of maximum hull acceleration.

A) Hydrodynamic Representation of the Impact Process

1) The planing hull is subjected to both dynamic and buoyant pressures during the planing and impact process. In steady planing, the dynamic lift (L_D) and the buoyant lift (L_B) can be obtained from planing lift equations such as given by Savitsky[14].

2) For a given trim angle, the dynamic pressures are taken to be proportional to the square of the velocity, $\dot{z}$, normal to the keel of the body relative to the adjacent fluid. This assumption is similar to that made by Smiley[9] and Brown[8] where hydrodynamic impact and planing are shown to be related. Then, $\dot{z}$ is equal to the sum of the normal component of the hull's vertical velocity ($\dot{z}$), the normal component of the hull's horizontal velocity $\dot{x}$, and the normal component of the vertical velocity of the wave ($\dot{h}$). This relationship can be written as:

$$\dot{z} = \dot{x}\,\sin\tau + \dot{y}\,\cos\tau + \dot{h}\,\cos\tau$$

where τ is the hull trim relative to level water.

3) All other conditions being equal, the hydrodynamic lift (L_D) is equal to the product of the average bottom pressure and the wetted bottom area. The wetted area is proportional to the mean wetted length (ℓ). Actually, as can be seen from Figure 10 of Ref. 14, a linear relation between planing lift and mean wetted length-beam ratio is realistic for the range of speed coefficients ($2.0 \leq C_V \leq 6.0$) and mean wetted length-beam ratios ($1.5 \leq \lambda \leq 4.0$) typical for planing hulls. Thus

$$L_D \approx (\dot{z})^2(\ell)$$

4) For pure planing in smooth water (subscript o), the vertical velocity of the craft ($\dot{y}_o$) and the velocity of the water ($\dot{h}_o$) are both zero. The trim (τ_o) and corresponding effective wetted length (ℓ_o) are functions of the basic characteristics of the craft (beam, weight, center of gravity location, deadrise, and speed). Thus

$$\dot{z}_o = \dot{x}\,\sin\tau_o$$

$$\tau_o = f(b,\Delta,LCG,\beta,\dot{x})$$

$$\ell_o = f(b,\Delta,LCG,\beta,\dot{x})$$

The smooth water equilibrium condition shown in Figure 1 can be evolved by applying the procedures of Ref. 14.

B) Relative Hull-Wave Contact Conditions at Time of Maximum Hull Acceleration (Figure 2)

1) In rough water (subscript max.) the maximum hydrodynamic lift ($L_{D_{max}}$) occurs in head seas at the time of maximum chine immersion (ℓ_{max}) and at the time when the vertical velocity ($\dot{y}_{max}$) of the hull is essentially zero.

2) Observations of full-scale and model planing craft in waves indicate that, at maximum acceleration, the mid-length of the craft encounters the mid-flank of an oncoming wave and there is an increase in the trim of the craft (τ_{max}) to equal the maximum slope (φ_{max}) of the wave.

3) The length of the wave in contact with the hull is assumed to move vertically with maximum wave orbital velocity, that is:

$$\dot{h}_{max} = \frac{\pi H_w}{T_w}$$

where T_w = wave period
H_w = wave height

Combining conditions (1), (2) and (3) above, the maximum velocity normal to the hull keel and the time of maximum acceleration in a wave is given by

$$\dot{z}_{max} = \dot{x}\,\sin\tau_{max} + \dot{h}_{max}\,\cos\tau_{max}$$

where

$$\tau_{max} = \varphi_{max} \text{ or } \tau_o \text{ (whichever is larger)}$$

$$\tan\varphi_{max} = \frac{\pi H_w}{\ell w}$$

$$\dot{h}_{max} = \frac{\pi H_w}{T_w}$$

and

$$\cos\tau_{max} \approx 1$$

In these expressions, ℓ_w, H_w, and φ_{max} are the wave length, height and maximum slope respectively. For irregular head seas, Table I can be used to define these quantities as a function of wind speed or sea state.

4) Relative to the magnitude of the hull wetted length and the time of maximum acceleration, it is assumed that for the case when (ℓ_w) is large relative to the hull length, the maximum effective wetted hull length (ℓ_{max}) is equal to the projected chine length (ℓ_c) as shown in Figure 2. In relatively shorter waves, the forebody of the craft extends beyond the wave crest and the maximum effective length is reduced to ($\ell_c/2 + \ell_w/8$) or $3\ell_w/8$. Thus:

$$\ell_{max} = \ell_c \text{ or } \left(\frac{\ell_c}{2} + \frac{\ell_w}{8}\right) \text{ or } \frac{3}{8}\,\ell_w \text{ (whichever is smallest)}$$

C) Maximum Accelerations During Hull Impact in Waves

1) The ratio of maximum dynamic lift in rough water to the hydrodynamic lift during smooth water planing can be expressed

$$\frac{L_{D_{max}}}{L_{D_o}} = \left(\frac{\dot{z}_{max}}{\dot{z}_o}\right)^2 \left(\frac{\ell_{max}}{\ell_o}\right) = \left(\frac{\dot{x}\sin\tau_{max} + \dot{h}_{max}}{\dot{x}\sin\tau_o}\right)^2 \left(\frac{\ell_{max}}{\ell_o}\right)$$

2) The ratio of maximum buoyant lift in rough water impact to buoyant lift during smooth water planing is taken to be

$$\frac{L_{B_{max}}}{L_{B_o}} = \frac{\ell_{max}}{\ell_o}$$

3) Using the basic characteristics of the craft (beam, weight, center of gravity location, deadrise, and speed), Ref. 14 can be used to calculate the dynamic lift (L_{D_o}) and the buoyant lift (L_{B_o}) during smooth water planing. Then

$$L_{D_o} = f(b,\Delta,LCG,\beta,\dot{x})$$

$$L_{B_o} = \Delta - L_{D_o}$$

4) Applying conditions (1), (2) and (3) above, the maximum total lift in rough water (L_{max}) can be computed:

$$L_{max} = L_{D_o}\left(\frac{L_{D_{max}}}{L_{D_o}}\right) + L_{B_o}\left(\frac{L_{B_{max}}}{L_{B_o}}\right)$$

and the maximum center of gravity acceleration ($\ddot{y}_{CG_{max}}$) is

$$\ddot{y}_{CG_{max}} = \frac{L_{max}}{\Delta} g$$

The corresponding load factor is

$$n_{CG_{max}} = \frac{\ddot{y}_{CG_{max}}}{g} - 1$$

5) In rough water, it is assumed that the maximum total lift (L_{max}) acts at the centroid (LCF) of the chine planform area. Thus, the maximum applied pitching moment about the center of gravity can be written

$$M_{max} = L_{max}(LCF - LCG)$$

6) The mass moment of inertia (I) of the craft about its center of gravity is approximately

$$I = (.25\ \ell_c)^2 \frac{\Delta}{g}$$

Thus, the maximum angular acceleration ($\ddot{\theta}_{max}$) is

$$\ddot{\theta}_{max} = \frac{M_{max}}{I}$$

and the associated linear acceleration ($\ddot{y}_\theta$) at any distance (a) from the center of gravity is

$$\ddot{y}_\theta = \ddot{\theta}_{max} a$$

and the corresponding incremental load factor at any distance, a, from the center of gravity is then

$$n_{max} = \frac{\ddot{y}_\theta}{g} + \frac{\ddot{y}_{CG_{max}}}{g} - 1$$

D) Summary of Engineering Procedure for Estimating Maximum Accelerations

1) Given:

Planing craft characteristics

$\Delta, b, \ell_c, LCG, LCF, \beta, \dot{x}, I$

Wave characteristics

H_w, ℓ_w, T_w

2) Objective:

Estimate maximum center of gravity and angular accelerations.

3) Procedure:

$L_{D_o} = f_1(\Delta, b, LCG, \beta, \dot{x})$ from Ref. 14

$L_{B_o} = \Delta - L_{D_o}$

$\tau_o = f_2(\Delta, b, LCG, \beta, \dot{x})$ from Ref. 14

$\ell_o = f_3(\Delta, b, LCG, \beta, \dot{x})$ from Ref. 14

$\tan \varphi_{max} = \frac{\pi H_w}{\ell_w}$

$\dot{h}_{max} = \frac{\pi H_w}{T_w}$

$\ell_{max} = \ell_c$ or $\left(\frac{\ell_c}{2} + \frac{\ell_w}{8}\right)$ or $\frac{3\ell_w}{8}$ whichever is smallest

$\tau_{max} = \varphi_{max}$ or τ_o whichever is largest

$$L_{D_{max}} = L_{D_o}\left[\frac{\dot{x}\sin\tau_{max} + \dot{h}_{max}}{\dot{x}\sin\tau_o}\right]^2\left[\frac{\ell_{max}}{\ell_o}\right]$$

$$L_{B_{max}} = L_{B_o}\left[\frac{\ell_{max}}{\ell_o}\right]$$

$$L_{max} = L_{D_{max}} + L_{B_{max}}$$

$$\ddot{y}_{CG_{max}} = \frac{L_{max}}{(\Delta/g)}$$

Also:

$$\ddot{M}_{max} = (LCF - LCG)L_{max}$$

$$I = (.25\ell_c)^2/C\Delta/g)$$

$$\ddot{\theta}_{max} = \frac{M_{max}}{I}$$

It may be that some of the previous assumptions which comprise this engineering procedure can be individually questioned. Nonetheless, it will be demonstrated that the synthesis of these elemental approximations does indeed compose a satisfactory engineering computational procedure which provides values of maximum accelerations that are in good agreement with model test results. This will be demonstrated in the following section of the report entitled "Verification". It is recommended that further study of the impact problem be pursued to establish a vigorously forward design procedure applicable for a wide range of impact conditions.

VERIFICATION

The proposed method has been employed to predict the center of gravity and angular accelerations of three hard chine hulls in a variety of irregular sea conditions. The calculated accelerations are compared with experimental model data reported by Chey[15].

Detailed calculations for the average and 1/10 highest accelerations at the center of gravity and bow are illustrated in Tables 2, 3 and 4 as a function of speed for head sea operation in sea state 3 and 5. The calculations are for Model 4928 and for sea state characteristics as described in Ref. 15. In particular, the hull and sea state properties are as follows:

Hull Characteristics (Model 4928, Ref. 15)

$\Delta = 55{,}000$ lbs. (Full scale values)

$\ell_c = 42$ ft.

$b = 14$ ft.

$LCG/b = 1.29$

$\beta_{av} = 17.5^o$

$C_v = V/ gb = V/21.2$

$LCG = 18.05$ ft.

$LCF = 19.05$ ft.

$I = 200{,}000$ ft.-lbs.-sec.^{2}

$a = 13.45$ ft. (from LCG to bow accelerometer)

Sea State 5 Characteristics (as reported in Ref. 15)

$H_{av} = 5.5$ ft. (Full scale values)

$T_{av} = 6.0$ sec.

$$\dot{h}_{av} = \frac{\pi H_{av}}{T_{av}} = 2.88 \text{ ft.-sec.}^{-1}$$

$$\ell w_{av} = \frac{gT^2_{av}}{2\pi} = 184.5 \text{ ft.}$$

$$\varphi_{av} = \tan^{-1} \frac{H_{av}\pi}{\ell_{w_{av}}} = 5.4^o$$

$H_{1/10} = 9.4$ ft.

$\dot{h}_{1/10} = 4.92$ ft.-sec.$^{-1}$

$\varphi_{1/10} = 9.1$ degrees

Sea State 3 Characteristics (as reported in Ref. 15)

$H_{av} = 2.47$ ft. (Full scale values)

$T_{av} = 4.5$ sec.

$\dot{h}_{av} = 1.72$ ft.-sec.$^{-1}$

$\ell_w = 104$ ft.

$\varphi_{av} = 4.14^\circ$

$H_{1/10} = 4.42$ ft.

$\dot{h}_{1/10} = 3.09$ ft.-sec.$^{-1}$

$\varphi_{1/10} = 7.63$ degrees

Table 2 presents the results of calculations for the smooth water performance as a function of speed from 15 to 45 ft/sec. Presented in Table 2 are the equilibrium trim angle (τ_o); the equilibrium mean wetted length-beam ratio (λ_o) and the dynamic (L_{D_o}) and buoyant (L_{B_o}) components of planing lift force. Table 3 presents the details of the computations and results for the center-of-gravity acceleration (both average and 1/10 highest) as a function of speed for sea states 3 and 5. Table 4 considers the bow accelerations for similar test conditions.

Comparisons between computed and measured accelerations are given in Figures 3 through 10. It can be seen that the agreement between computed and measured accelerations is reasonably good--at least for engineering design purposes. In general, the computed accelerations appear to be somewhat higher than measured values, especially at speeds in excess of approximately 35 knots. Similar calculations and comparisons have been made for hull forms 4929 ($\beta_{av} = 19^\circ$) and 2387 ($\beta_{av} = 19^\circ$) described in Ref. 15. The agreement between computed and measured results is equally favorable; detailed comparisons are therefore not presented in this report.

A brief study was made of the effects of trim change and loading change on the average center-of-gravity acceleration for Model 4928 planing at 30 knots in a sea state 5. It was found that a 50% increase in trim resulted in a 90% increase in acceleration while a 50% increase in loading resulted in a 25% decrease in acceleration. These results are qualitatively in agreement with the conclusions of Savitsky[16] and Fridsma[17], thus further confirming the applicability of the proposed engineering computational procedure.

CONCLUSIONS

General agreement between calculated and experimental results indicates that the proposed method for computing maximum accelerations of planing craft during rough water operation is realistic. Since the method is easy to apply and requires no knowledge of the detailed craft characteristics, this procedure should be particularly useful during preliminary design.

REFERENCES

1. Mayo, W.L.: "Analysis and Modification of Theory for Impact of Seaplanes on Water," NACA TN 1008, December 1945

2. Monaghan, R.J.: "A Review of the Essentials of Impact Force Theories for Seaplanes and Suggestions for Approximate Design Formulae," RAE Rep. Aero 2230, November 1947

3. von Karman, T.: "The Impact of Seaplane Floats During Landing," NACA TN 321, 1929

4. Wagner, H.: "Landing of Seaplanes," NACA TM No. 622, 1931

5. Pabst, W.: "Theory of Landing Impact of Seaplanes," NACA TM No. 850, 1930

6. Milwitzky, B.: "A Generalized Theoretical and Experimental Investigation of the Motions and Loads Experienced by V-Bottom Seaplanes During Step Landings," NACA TN No. 1516, February 1948

7. Steiner, M.F.: "Analysis of Planing Data for Use in Predicting Hydrodynamic Impact Loads," NACA TN 1694, August 1948

8. Brown, P. Ward: "Seaplane Impact Theory," Shorts HN 46, Belfast, August 1954

9. Smiley, R.F.: "The Application of Planing Characteristics to the Calculation of the Water-Landing Loads and Motions of Seaplanes of Arbitrary Constant Cross Section," NACA TN 2814

10. Smiley, R.F.: "Water Pressure Distributions During Landings of a Prismatic Model Having an Angle of Deadrise of 22-1/2°," NACA TN 2816, November 1952

11. Smiley, R.F.: "An Experimental Study of Water Pressure Distributions During Landings and Planing of a Heavily Loaded Rectangular Flat-Plate Model," NACA TN 2453, September 1951

12. Smiley, R.F.: "A Theoretical and Experimental Investigation of the Effects of Yaw on Pressures, Forces, and Moments During Seaplane Landings and Planing," NACA TN 2817, November 1952

13. Chey, Y.: "Model Tests of a Series of Six Patrol Boats in Smooth and Rough Water," Davidson Laboratory, Stevens Institute of Technology R-985, October 1963

14. Savitsky, Daniel: "Hydrodynamic Design of Planing Hulls," Marine Technology, Vol. 1, October 1964

15. Chey, Y.: "Model Tests of a Series of Six Patrol Boats in Smooth and Rough Water," Davidson Laboratory, Stevens Institute of Technology R-985, October 1963

16. Savitsky, Daniel: "On the Seakeeping of Planing Hulls," Marine Technology, Vol. No. 2, April 1968

17. Fridsma, G.: "A Systematic Study of the Rough Water Performance of Planing Boats," Davidson Laboratory, Stevens Institute of Technology, R-1275, December 1969

TABLE 1

WIND AND SEA SCALE FOR FULLY ARISEN SEA

SEA-GENERAL		WIND 3)				SEA 3)								
						WAVE HEIGHT FEET								
SEA STATE 1)	DESCRIPTION 2)	(BEAUFORT) WIND FORCE	DESCRIPTION	RANGE (KNOTS)	WIND VELOCITY (KNOTS)	AVERAGE	SIGNIFICANT	AVERAGE 1/10 HIGHEST	SIGNIFICANT RANGE OF PERIODS (SECONDS)	T_{max} PERIOD OF MAXIMUM ENERGY OF SPECTRUM	$\bar{T}$ (AVERAGE PERIOD)	$\bar{L}$ (AVERAGE WAVE LENGTH)	MINIMUM FETCH (NAUTICAL MILES)	MINIMUM DURATION (HOURS)
0	Sea like a mirror.	0	Calm	Less than 1	a) 0	0	0	0	-	-	-	-	-	-
	Ripples with the appearance of scales are formed, but without foam crests.	1	Light Airs	1 - 3	2	0.05	0.08	0.10	up to 1.2 sec	0.7	0.5	10 in.	5	18 min
1	Small wavelets, still short but more pronounced; crests have a glassy appearance, but do not break.	2	Light Breeze	4 - 6	5	0.18	0.29	0.37	0.4-2.8	2.0	1.4	6.7 ft	8	39 min
	Large wavelets, crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.	3	Gentle Breeze	7 - 10	8.5	0.6	1.0	1.2	0.8-5.0	3.4	2.4	20	9.8	1.7 hrs
					10	0.88	1.4	1.8	1.0-6.0	4	2.9	27	10	2.4
2	Small waves, becoming larger; fairly frequent white horses.	4	Moderate Breeze	11-16	12	1.4	2.2	2.8	1.0-7.0	4.8	3.4	40	18	3.8
					13.5	1.8	2.9	3.7	1.4-7.6	5.4	3.9	52	24	4.8
3					14	2.0	3.3	4.2	1.5-7.8	5.6	4.0	59	28	5.2
					16	2.9	4.6	5.8	2.0-8.8	6.5	4.6	71	40	6.6
4	Moderate waves, taking a more pronounced long form; many white horses are formed. (Chance of some spray).	5	Fresh Breeze	17-21	18	3.8	6.1	7.8	2.5-10.0	7.2	5.1	90	55	8.3
					19	4.3	6.9	8.7	2.8-10.6	7.7	5.4	99	65	9.2
					20	5.0	8.0	10	3.0-11.1	8.1	5.7	111	75	10
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	22-27	22	6.4	10	13	3.4-12.2	8.9	6.3	134	100	12
					24	7.9	12	16	3.7-13.5	9.7	6.8	160	130	14
6					24.5	8.2	13	17	3.8-13.6	9.9	7.0	164	140	15
6					26	9.6	15	20	4.0-14.5	10.5	7.4	188	180	17
	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind. (Spindrift begins to be seen).	7	Moderate Gale	28-33	28	11	18	23	4.5-15.5	11.3	7.9	212	230	20
					30	14	22	28	4.7-16.7	12.1	8.6	250	280	23
					30.5	14	23	29	4.8-17.0	12.4	8.7	258	290	24
					32	16	26	33	5.0-17.5	12.9	9.1	285	340	27
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	34-40	34	19	30	38	5.5-18.5	13.6	9.7	322	420	30
					36	21	35	44	5.8-19.7	14.5	10.3	363	500	34
					37	23	37	46.7	6-20.5	14.9	10.5	376	530	37
					38	25	40	50	6.2-20.8	15.4	10.7	392	600	38
					40	28	45	58	6.5-21.7	16.1	11.4	444	710	42
8	High waves. Dense streaks of foam along the direction of the wind. Sea begins to roll. Visibility affected.	9	Strong Gale	41-47	42	31	50	64	7-23	17.0	12.0	492	830	47
					44	36	58	73	7-24.2	17.7	12.5	534	960	52
					46	40	64	81	7-25	18.6	13.1	590	1110	57
	Very high waves with long overhanging crests. The resulting foam is in great patches and is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes a white appearance. The rolling of the sea becomes heavy and shocklike. Visibility is affected.	10	Whole Gale*	48-55	48	44	71	90	7.5-26	19.4	13.8	650	1250	63
					50	49	78	99	7.5-27	20.2	14.3	700	1420	69
					51.5	52	83	106	8-28.2	20.8	14.7	736	1560	73
9					52	54	87	110	8-28.5	21.0	14.8	750	1610	75
					54	59	95	121	8-29.5	21.8	15.4	810	1800	81
	Exceptionally high waves (Small and medium-sized ships might for a long time be lost to view behind the waves.) The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.	11	Storm*	56-63	56	64	103	130	8.5-31	22.6	16.3	910	2100	88
					59.5	73	116	148	10-32	24	17.0	985	2500	101
	Air filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.	12	Hurricane*	64-71	> 64	> 80 b)	> 128 b)	> 164 b)	10-(35)	(26)	(18)	~	~	~

*For hurricane winds (and often whole gale and storm winds) required durations and fetches are rarely attained. Seas are therefore not fully arisen.

a) A heavy box around this value means that the values tabulated are at the center of the Beaufort range.

b) For such high winds, the seas are confused. The wave crests blow off, and the water and the air mix.

1) Encyclopedia of Nautical Knowledge, W.A. McEwen and A.H. Lewis, Cornell Maritime Press, Cambridge, Maryland, 1953, p. 483

2) Manual of Seamanship, Volume II, Admiralty, London, H.M. Stationery Office, 1952, pp. 717-718

3) Practical Methods for observing and forecasting Ocean Waves, Pierson, Neumann, James, N.Y. Univ. College of Engin. 1953.

This table compiled by Wilbur Marks,
David Taylor Model Basin

TABLE II. CALCULATIONS FOR SMOOTH-WATER PERFORMANCE

(Model 4928, Ref. 15)

Δ	b	V	$\dot{x}$	q	C_{l_β}	$\frac{LCG}{b}$	C_v	λ_o	$\frac{C_{l_o}}{\tau_o^{1.1}}$	β	C_{l_o}	$\tau_o^{1.1}$	τ_o	$C_{l_{o_D}}$	$C_{l_{\beta_D}}$	L_{D_o}	L_{R_o}
55,000	14	15	25.4	645	0.435	1.29	1.2	2.9	0.075	17.5	0.51	6.8	5.7	0.139	0.105	13,300	41,700
		20	33.8	1,140	0.245		1.59	2.4	0.038		0.30	7.9	6.55	0.147	0.11	24,600	30,400
		25	42.25	1,785	0.157		1.98	2.15	0.027		0.20	7.41	6.2	0.13	0.10	35,000	20,000
		30	50.7	2,570	0.109		2.39	1.95	0.022		0.14	6.36	5.36	0.1065	0.08	40,300	14,700
		35	59.2	3,500	0.08		2.79	1.90	0.02		0.11	5.5	4.71	0.091	0.064	43,900	11,100
		40	67.6	4,570	0.0613		3.19	1.85	0.019		0.087	4.57	3.98	0.0737	0.049	44,000	11,000
		45	76	5,780	0.0486		3.59	1.80	0.018		0.074	4.11	3.61	0.0664	0.042	47,500	7,500
		15	25.4													13,300	41,700
		20	33.8													24,600	30,400
		25	42.25													35,000	20,000
		30	50.7													40,300	14,700
		35	59.2													43,900	11,100
		40	67.6													44,000	11,000
		45	76													47,500	7,500
		15	25.4													13,300	41,700
		20	33.8													24,600	30,400
		25	42.25													35,000	20,000
		30	50.7													40,300	14,700
		35	59.2													43,900	11,100
		40	67.6													44,000	11,000
		45	76													47,500	7,500
		15	25.4													13,300	41,700
		20	33.8													24,600	30,400
		25	42.25													35,000	20,000
		30	50.7													40,300	14,700
		35	59.2													43,900	11,100
		40	67.6													44,000	11,000
		45	76													47,500	7,500

TABLE III. CALCULATIONS FOR CG ACCELERATIONS

(Model 4928, Ref. 15)

V	$\dot{X} \sin \tau_o$	φ_{max}	$\tau_{max} = \tau_o$ or φ_{max}	$\dot{X} \sin \tau_{max}$	h_{max}	$\dot{X} \sin \tau_{max} + \dot{h}_{max}$	$\frac{\dot{X} \sin \tau_{max} + \dot{h}_{max}}{\dot{X} \sin \tau_o}$	$\left(\frac{\dot{X} \sin \tau_{max} + \dot{h}_{max}}{\dot{X} \sin \tau_o}\right)^2 = K_1$	ℓ_{max}	$\frac{\ell_{max}}{\lambda_o b} = K_2$	$K_1 K_2 L_{D_o} = L_{D_{max}}$	$K_2 L_{B_o} = L_{B_{max}}$	$L_{D_{max}} + L_{B_{max}} = L_{max}$	$\frac{L_{max}}{\Delta} = \frac{\ddot{Y}_{CG_{max}}}{g}$	$\frac{\ddot{Y}_{CG_{max}}}{g} - 1$	
15	2.52	5.4	5.7	2.52	2.88	5.4	2.14	4.58	42	1.035	63,000	44,200	107,200	1.95	0.95	Sea State 5 Head Seas Average
20	3.85		6.55	3.85		6.73	1.75	3.06		1.25	94,000	38,000	132,000	2.40	1.40	
25	4.56		6.2	4.56		7.44	1.63	2.66		1.395	130,000	27,900	157,900	2.87	1.87	
30	4.74		5.4	4.76		7.64	1.61	2.59		1.54	161,000	22,600	183,600	3.34	2.37	
35	4.85		5.4	5.56		8.44	1.74	3.02		1.58	210,000	17,500	227,500	4.14	3.14	
40	4.69		5.4	6.35		9.23	1.97	3.80		1.62	27,600	17,800	293,800	5.34	4.34	
45	4.78		5.4	7.14		10.02	2.09	4.37		1.67	346,000	12,500	358,500	6.52	5.52	
15	2.52	9.1	9.1	4.00	4.92	8.92	3.54	12.5	42	1.035	172,000	44,200	216,200	3.94	2.94	Sea State 5 Head Seas Avg. 1/10 Highest
20	3.85			5.35		10.27	2.66	7.08		1.25	217,000	38,000	255,000	4.64	3.64	
25	4.56			6.68		11.60	2.54	6.45		1.395	315,000	27,900	342,900	6.24	5.24	
30	4.74			8.00		12.92	2.73	7.45		1.54	462,000	22,600	484,600	8.80	7.80	
35	4.85			9.35		14.27	2.94	8.65		1.58	600,000	17,500	617,500	11.25	10.25	
40	4.69			10.7		15.62	3.33	11.1		1.62	790,000	17,800	807,800	14.70	13.70	
45	4.78			12		16.92	3.54	12.5		1.67	992,000	12,500	1,004,500	18.25	17.25	
15	2.52	4.14	5.7	2.52	1.72	4.24	1.68	2.82	34	0.838	31,400	34,900	66,300	1.205	0.205	Sea State 3 Head Seas Average
20	3.85		6.55	3.85		5.57	1.45	2.10		1.01	52,100	30,700	82,800	1.505	0.505	
25	4.56		6.2	4.56		6.28	1.38	1.90		1.13	75,200	22,600	97,800	1.78	0.78	
30	4.74		5.36	4.74		6.46	1.36	1.65		1.245	92,800	18,300	111,100	2.02	1.02	
35	4.85		4.71	4.85		6.57	1.35	1.82		1.28	102,500	14,200	116,700	2.12	1.12	
40	4.69		4.14	4.88		6.60	1.41	1.99		1.31	115,000	14,400	129,400	2.35	1.35	
45	4.78		4.14	5.48		7.20	1.505	2.26		1.35	145,000	10,000	155,100	2.82	1.82	
15	2.52	7.63	7.63	3.38	3.09	6.47	2.57	6.60	34	0.838	73,500	34,900	108,400	1.97	0.97	Sea State 3 Head Seas Avg. 1/10 Highest
20	3.85			4.50		7.59	1.97	3.88		1.01	96,500	30,700	127,200	2.31	1.31	
25	4.56			5.62		8.71	1.91	3.54		1.13	140,000	22,600	162,600	2.96	1.96	
30	4.74			6.75		9.84	2.07	4.28		1.245	215,000	18,300	233,300	4.24	3.24	
35	4.85			7.86		10.95	2.26	5.1		1.28	286,000	14,200	300,200	5.46	4.46	
40	4.69			9.00		12.09	2.58	6.65		1.31	383,000	14,400	397,400	7.22	6.22	
45	4.78			10.1		13.19	2.76	7.62		1.35	489,000	10,100	499,100	9.09	8.09	

TABLE IV. CALCULATIONS FOR BOW ACCELERATIONS

(Model 4928, Ref. 15)

V	LCF	LCG	LCF-LCG	L_{max}	$(LCF-LCG)\,L_{max} = M_{max}$	I	$\ddot{\theta}_{max}$	a	$\frac{\ddot{\theta}_{max}(a)}{g} = \frac{\ddot{y}_\theta}{g}$	$\frac{\ddot{y}_{cg}}{g} - 1$	$\frac{\ddot{y}_\theta}{g} + \frac{\ddot{y}_{cg}}{g} - 1$	
15	19.05	18.05	1.00	107,200	107,200	200,000	0.536	13.45	0.224	0.95	1.174	
20				132,000	132,000		0.66		0.276	1.40	1.676	
25				157,900	157,900		0.79		0.33	1.87	2.20	Sea State 5
30				183,600	183,600		0.916		0.383	2.37	2.753	Head Seas
35				227,500	227,500		1.14		0.475	3.14	3.615	Average
40				293,800	293,800		1.47		0.613	4.34	4.953	
45				358,500	358,500		1.79		0.748	5.52	6.268	
15			1.00	216,200	216,200	200,000	1.08	13.45	0.451	2.94	3.391	
20				255,000	255,000		1.275		0.533	3.64	4.173	
25				324,900	324,900		1.625		0.679	5.24	5.919	Sea State 5
30				484,600	484,600		2.42		1.02	7.80	8.82	Head Seas
35				617,500	617,500		3.065		1.29	10.25	11.54	Avg. 1/10 Highest
40				807,800	807,800		4.04		1.69	13.70	15.39	
45				1,004,500	1,004,500		5.02		2.10	17.25	19.35	
15			1.00	66,300	66,300	200,000	0.332	13.45	0.138	0.205	0.343	
20				82,800	82,800		0.414		0.173	0.505	0.678	
25				97,800	97,800		0.489		0.204	0.78	0.984	Sea State 3
30				111,100	111,100		0.555		0.232	1.02	1 252	Head Seas
35				116,700	116,700		0.583		0.244	1.12	1.364	Average
40				129,400	129.400		0.647		0.270	1.35	1.62	
45				155,100	155,100		0.775		0.324	1.82	2.144	
15			1.00	108,400	108,400	200,000	0.542	13.45	0.226	0.97	1.196	
20				127,200	127,200		0.636		0.266	1.31	1 576	
25				162,600	162,600		0.813		0.339	1.96	2.299	Sea State 3
30				233,300	233,300		1.166		0.486	3.24	3.726	Head Seas
35				300,200	300,200		1.50		0.626	4.46	5.086	Avg. 1/10 Highest
40				397,400	397,400		1.985		0.83	6.22	7.05	
45				499,100	499,100		2.50		1.04	8.09	9.13	

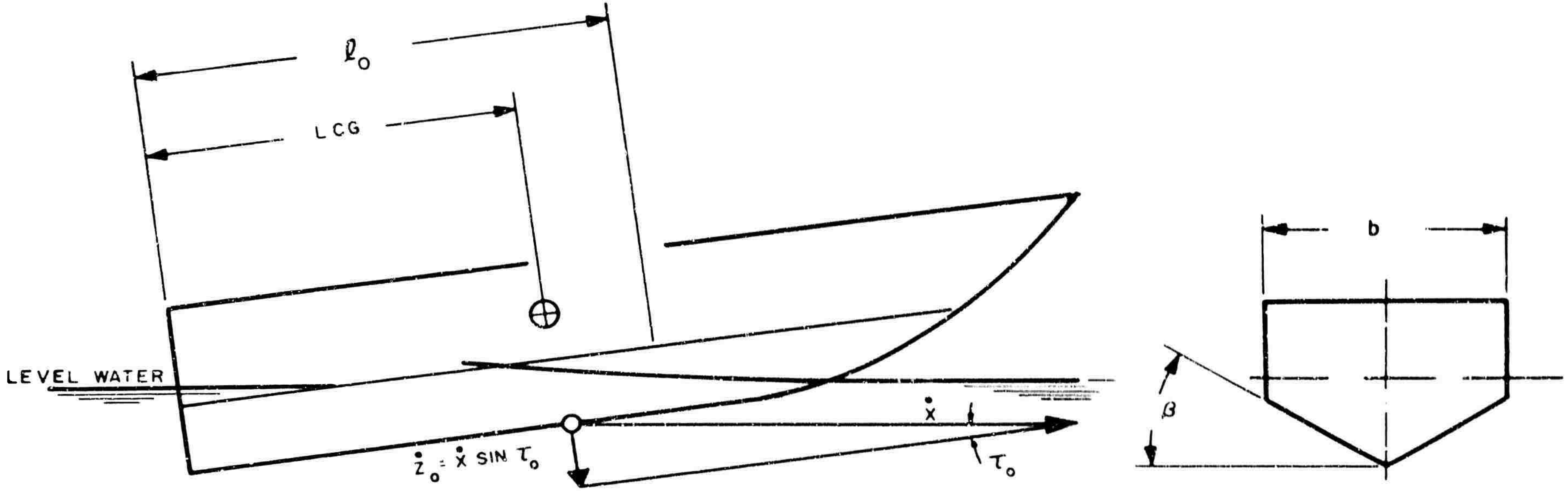

FIG.1 SMOOTH WATER PURE PLANING

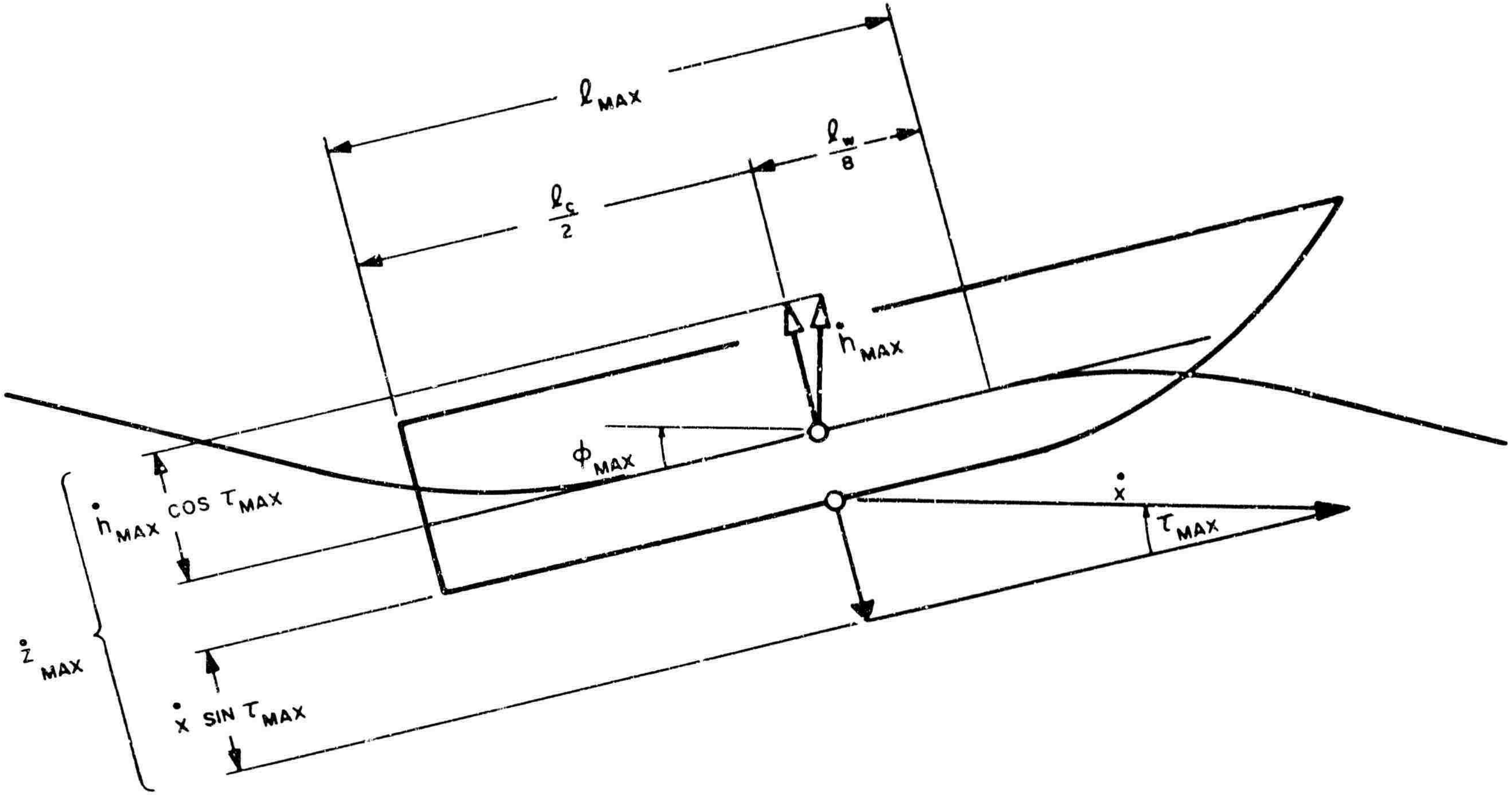

FIG. 2 ROUGH WATER MAXIMUM LOAD CONDITION

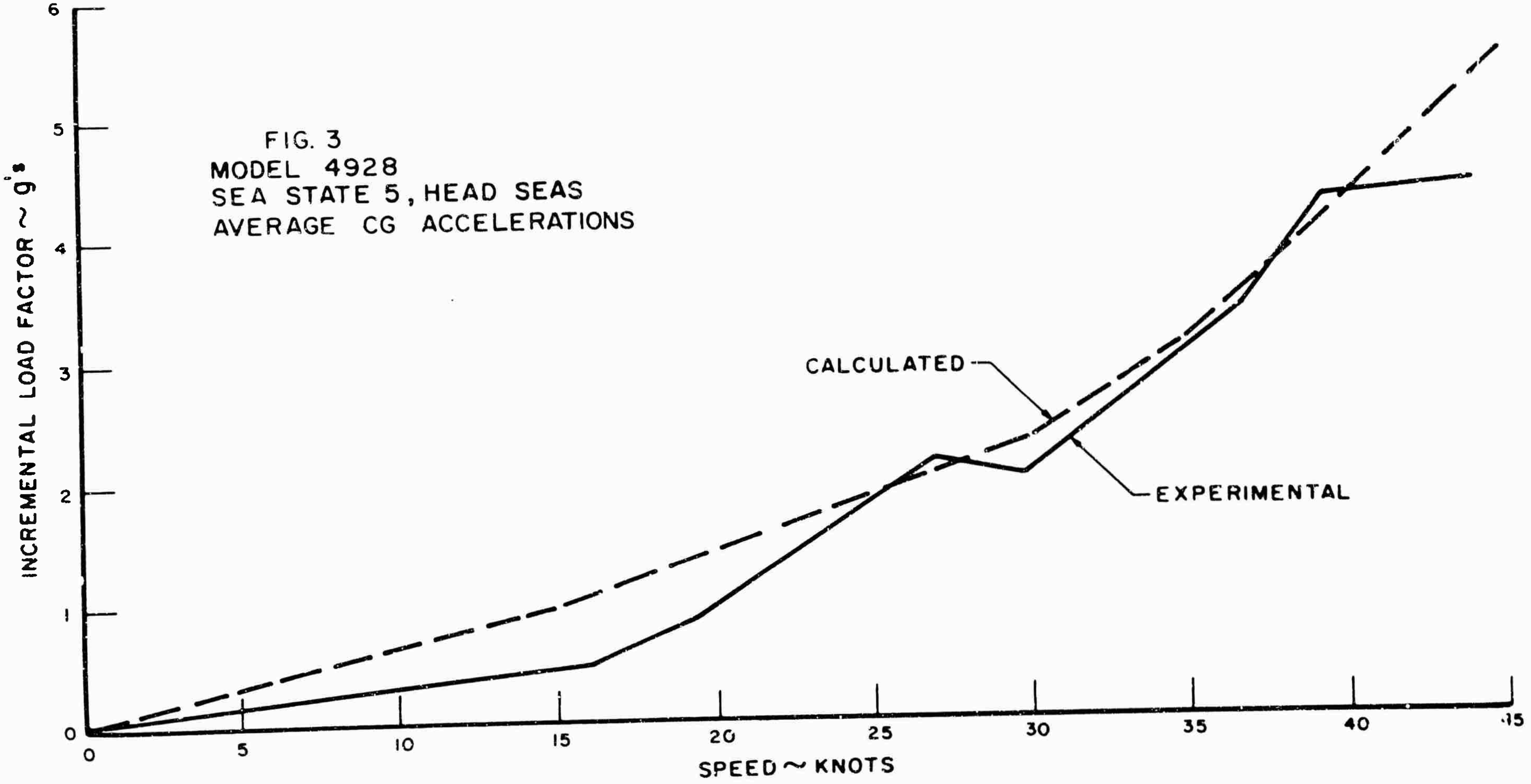

FIG. 3
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE CG ACCELERATIONS

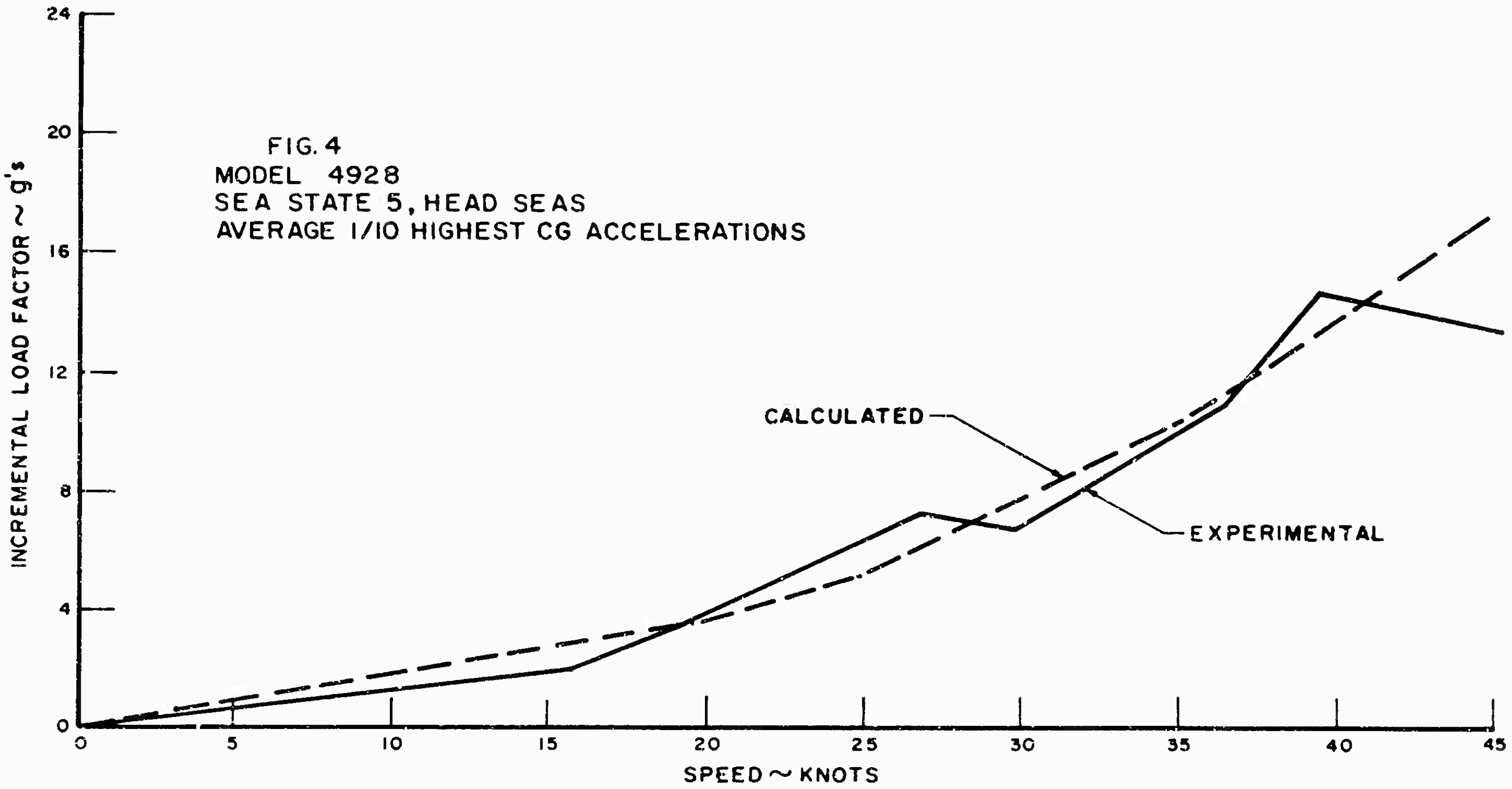

FIG. 4
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

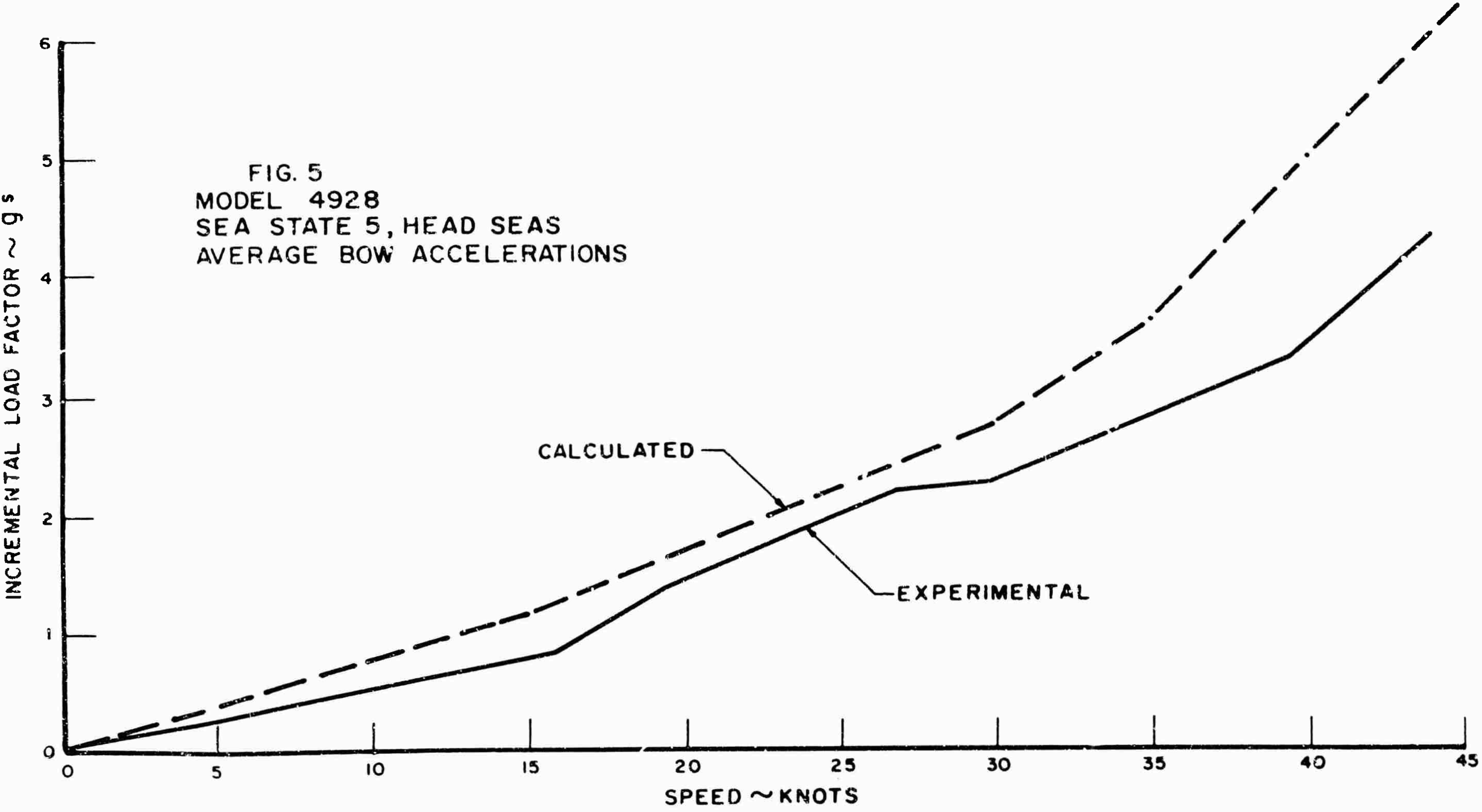

FIG. 5
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE BOW ACCELERATIONS

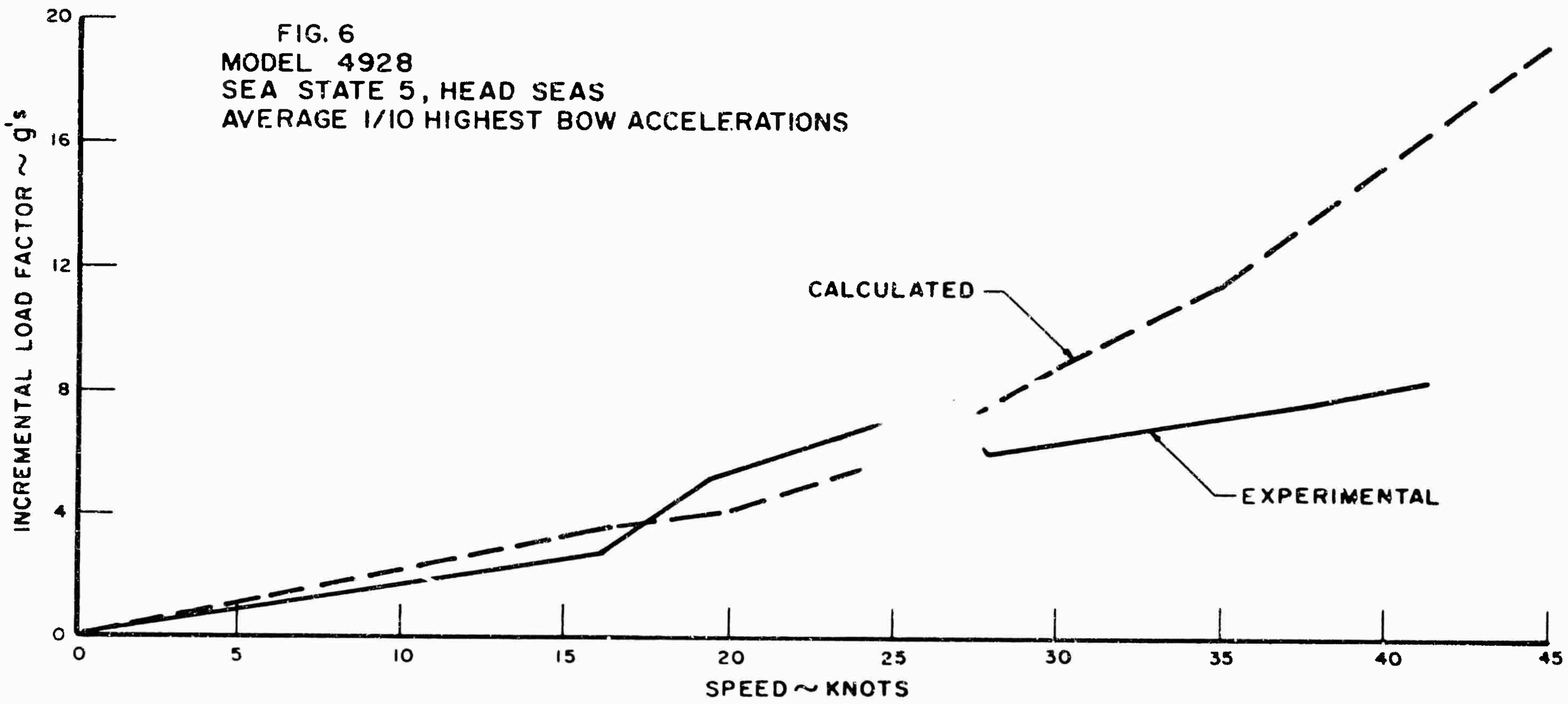

FIG. 6
MODEL 4928
SEA STATE 5, HEAD SEAS
AVERAGE 1/10 HIGHEST BOW ACCELERATIONS

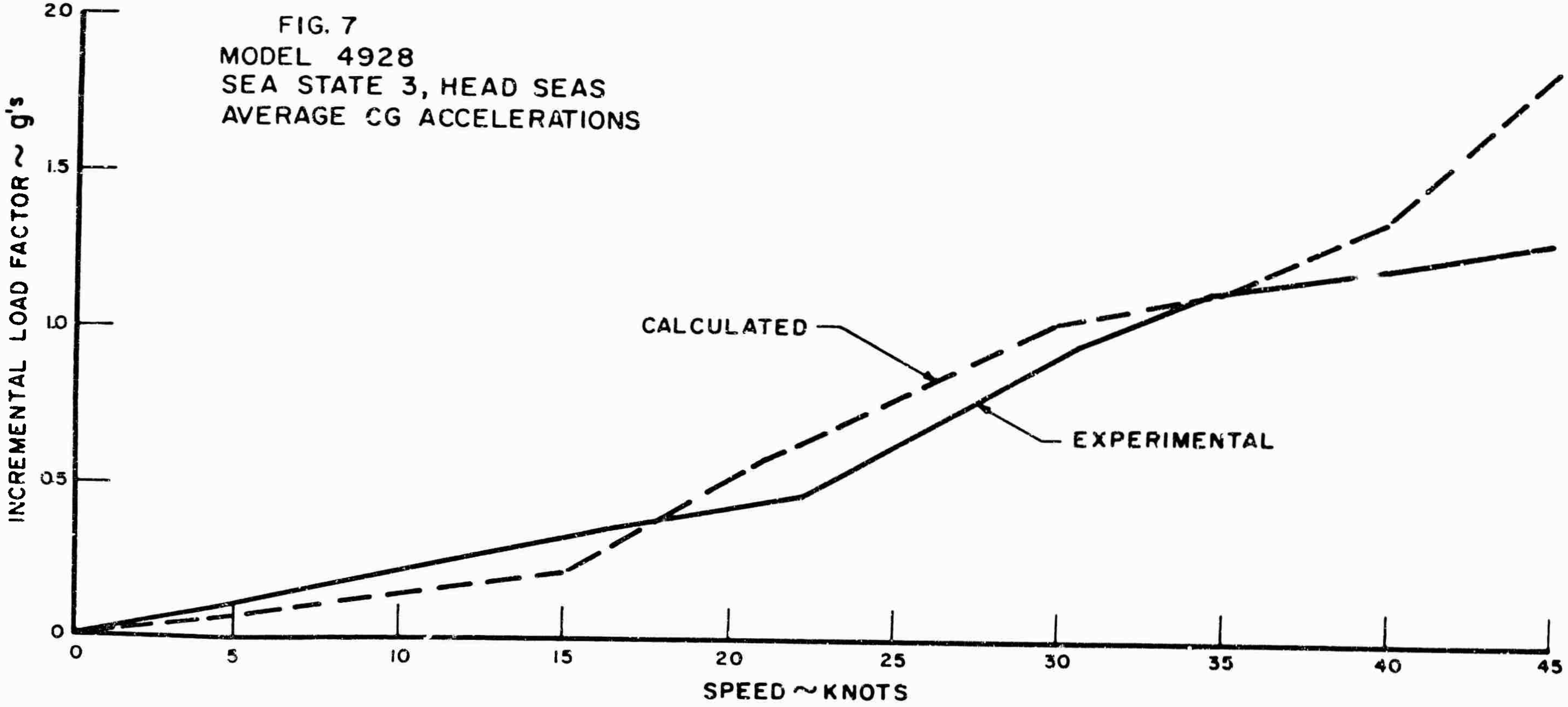

FIG. 7
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE CG ACCELERATIONS

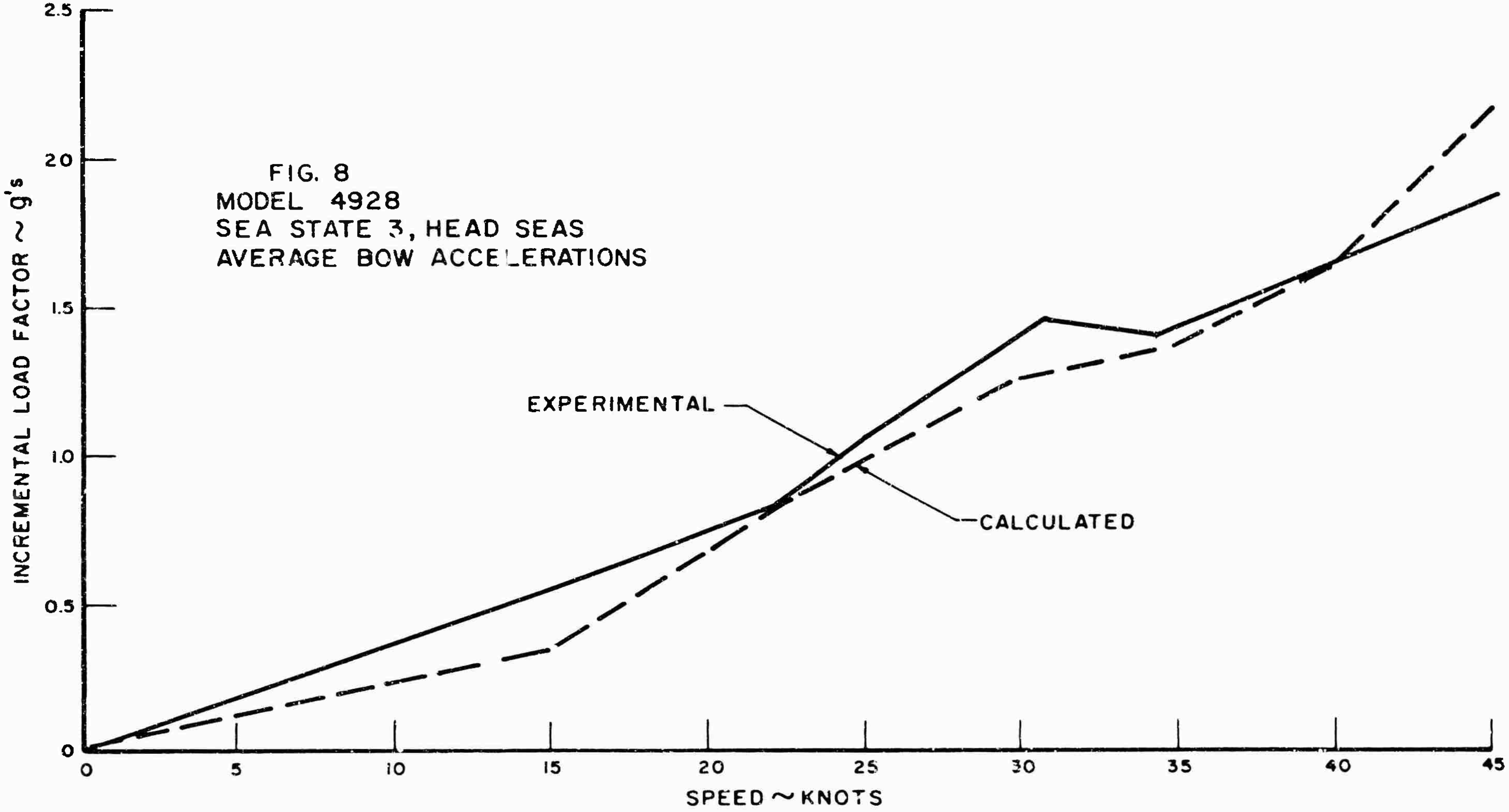

FIG. 8
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE BOW ACCELERATIONS

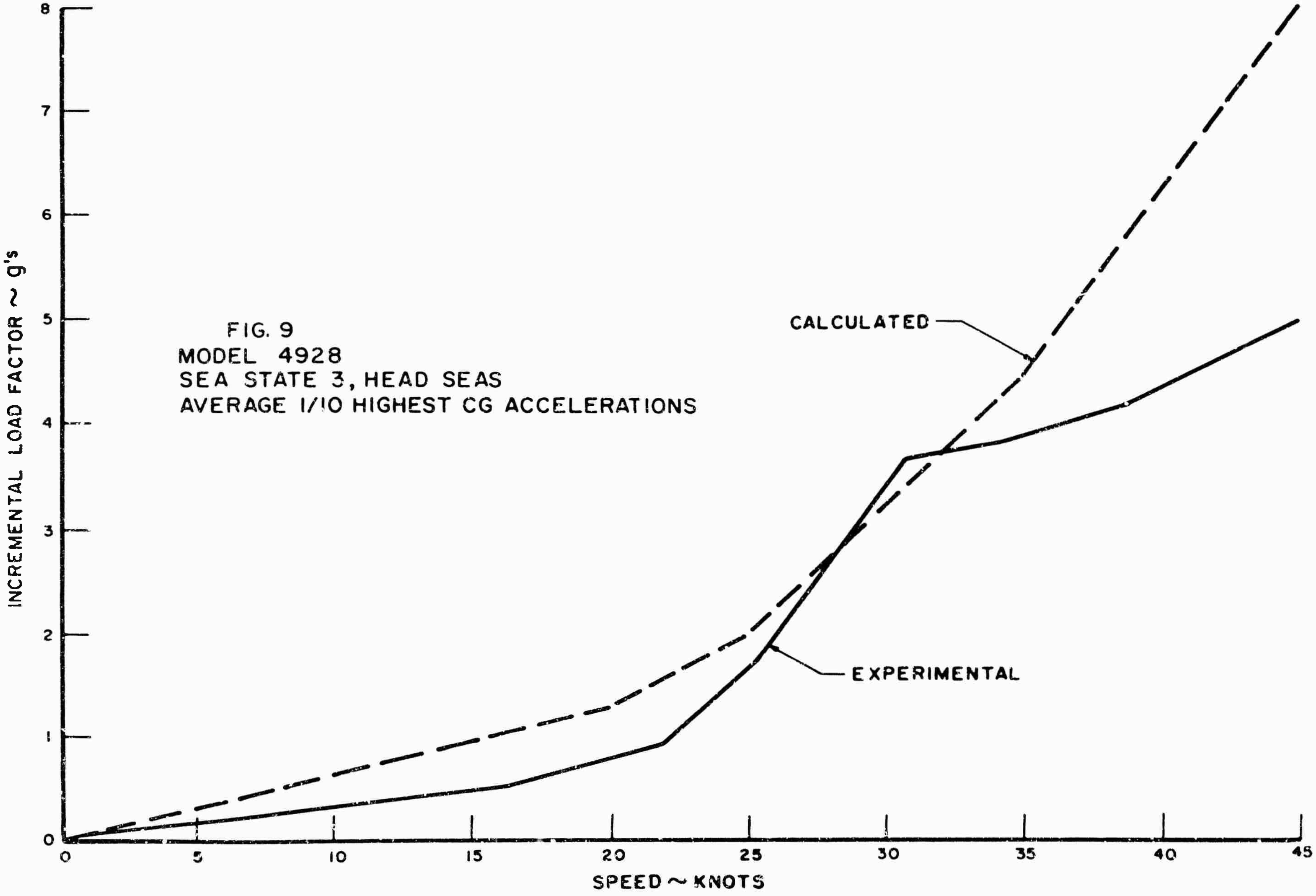

FIG. 9
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

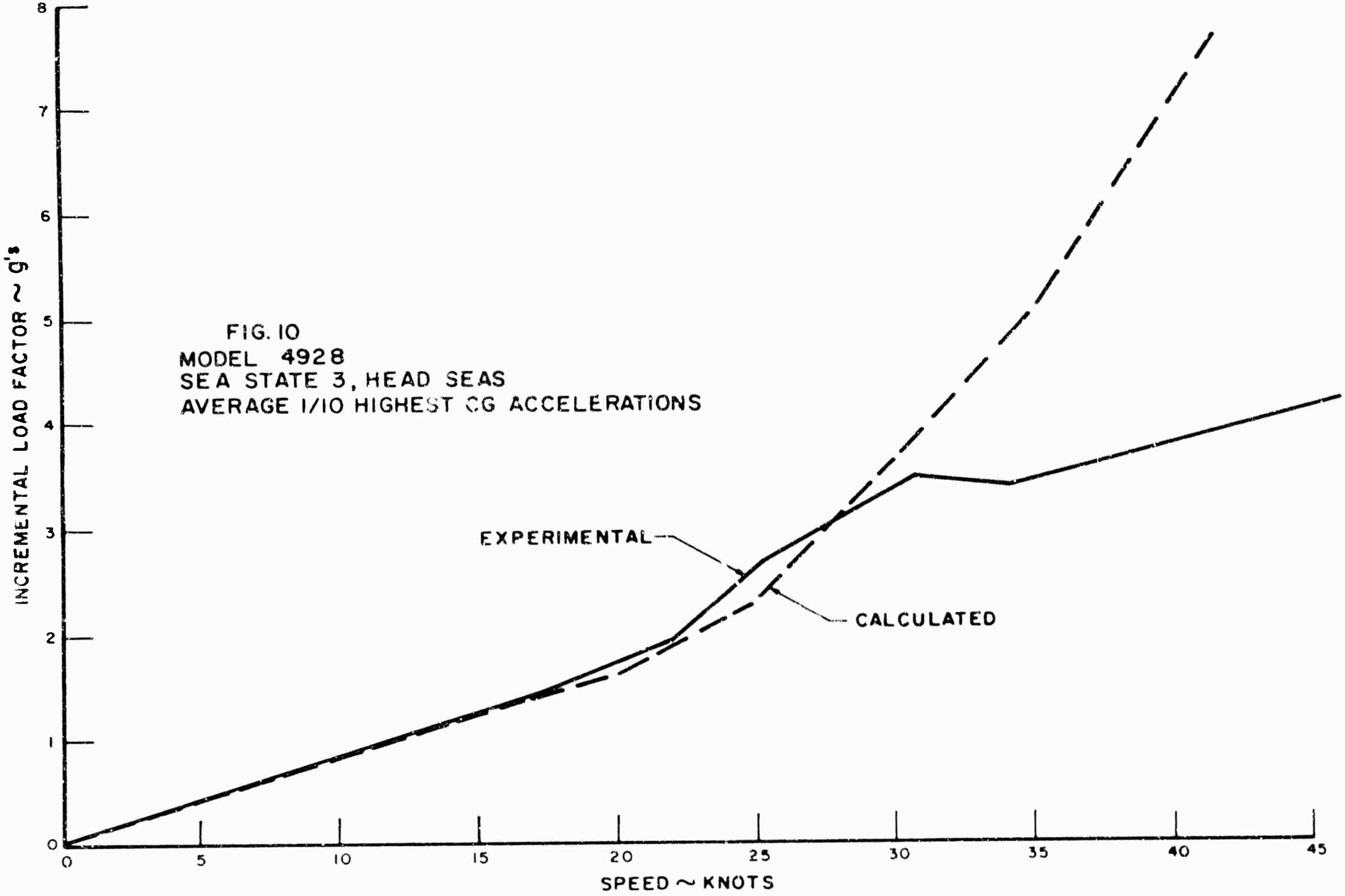

FIG. 10
MODEL 4928
SEA STATE 3, HEAD SEAS
AVERAGE 1/10 HIGHEST CG ACCELERATIONS

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Davidson Laboratory
Stevens Institute of Technology, Hoboken, N. J.

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
Engineering Approximation of Maximum Accelerations Experienced by Planing Craft in Rough Water

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*
John K. Roper

6. REPORT DATE
December 1969

7a. TOTAL NO. OF PAGES
13 + viii pages

7b. NO. OF REFS

8a. CONTRACT OR GRANT NO. N00014-67-A-0202-0014
NR062-419/9-18-68 (Code 438)

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
R-1437

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT This document has been approved for public release and sale; its distribution is unlimited. Application for copies may be made to the Defense Documentation Center, 5010 Duke Street, Alexandria, Va. 22314. Reproduction of the document in whole or in part is permitted for any purpose of the U. S. Government.

11. SUPPLEMENTARY NOTES
Sponsored by Naval Ship Systems Command
Exploratory Development Research Program
SF 35421009.

12. SPONSORING MILITARY ACTIVITY
Office of Naval Research
Department of the Navy
Washington, D. C. 20360

13. ABSTRACT

An engineering procedure is presented for estimating the maximum impact accelerations experienced by planing craft in irregular head seas. General agreement between calculated and model test results indicates that the proposed method is realistic. The procedure should be particularly useful during preliminary design.

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Planing Hulls						
Impact Accelerations						

DD FORM 1 NOV 65 1473 (BACK)
S/N 0101-807-6821

UNCLASSIFIED
Security Classification

A-31409