UNITED STATES

EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

AN INVESTIGATION OF SOME OF THE FACTORS AFFECTING THE ROLLING OF SHIPS

BY M. E. SERAT AND J. G. THEWS

EXPERIMENTAL MODEL BASIN
ERECTED 1898
BUREAU OF
CONSTRUCTION AND REPAIR
NAVY DEPARTMENT

REPORT NO. 348 FEBRUARY 1933

AN INVESTIGATION of SOME of the FACTORS AFFECTING the ROLLING of SHIPS

By M.E. Serat and J.G. Thews

U.S. EXPERIMENTAL MODEL BASIN
NAVY YARD, WASHINGTON, D.C.

February, 1933 Report No. 348

NOTATION

B center of buoyancy
G center of gravity
M transverse metacenter
BM distance from B to M
GM metacentric height
b beam of model, inches
l length of model, inches
H draft of model, inches, and wave height
L length of wave (crest to crest)
t time, seconds
T_m period of roll, port to starboard to port, of model, seconds
T_s period of roll, port to starboard to port, of ship, seconds
T_w period of wave, crest to crest, seconds
γ_s maximum wave slope, degrees
W.L. water line
μ height of M above W.L., inches
ϕ midship-section coefficient; that is, midship section area divided by water line beam times draft
θ angle of roll of model or ship, degrees
g acceleration of gravity, ft.sec.^{2}
K radius of gyration of model or ship, inches or feet
S surface area of model, square inches
V linear velocity
w density of water, pounds per cubic foot
E energy, inch-pounds
GZ horizontal component of distance between B and G
W displacement of model or ship
d depth below water level, feet
h distance below axis of roll, feet
ω angular velocity

INDEX

AN INVESTIGATION of SOME of the FACTORS
AFFECTING the ROLLING of SHIPS

Abstract

This report describes experiments made to investigate the rolling of ships and in particular to determine the effect on rolling of changes in certain characteristics, which depend upon the form or loading of a ship. In particular, the experiments were intended to indicate the effect on roll of:—

1. Variation in vertical position of the center of gravity.
2. Variation in the rolling period.
3. Variation in height of the metacenter above the water plane.
4. Variation in midship-section coefficient.

The first section of the report is devoted to a general discussion of the subject of rolling. The second section describes the experiments performed, discussing fully the methods used and the manner of analyzing the data. Recommendations for further investigation of factors pertinent to rolling are made, together with suggestions for determining the rolling characteristics of a new design from its model.

The following is a brief summary of the conclusions:—

A.

1. When the center of gravity is raised, damping is increased.
2. When the period is increased, damping is decreased.
3. When the metacenter is raised, damping is increased.
4. When the midship section coefficient is increased, damping is increased. When this coefficient exceeds unity, damping is greatly increased.

B.

The amplitude of roll of a ship in synchronous waves may be predicted from its model by the use of methods described.

INTRODUCTION

Any ship among waves will roll. The degree of rolling, that is, the amplitude of roll, of a given ship with a given condition of loading depends upon:—

(1) The relation between the natural period of the ship and the apparent period of the waves,

(2) The wave slope,

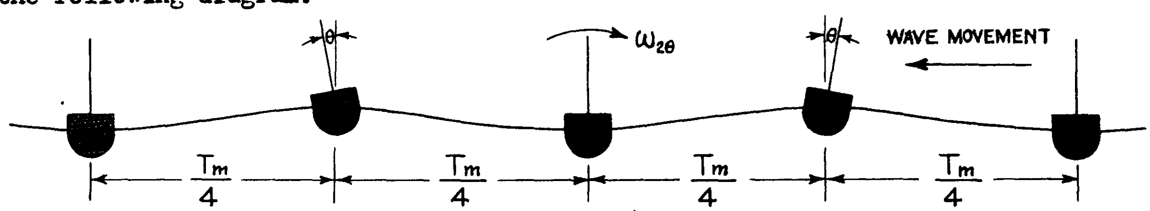
(3) The damping of roll of the ship.

Most waves encountered at sea are irregular. Frequently several series of waves travelling in different directions exist simultaneously. In such a sea a ship rolls with an irregular period and amplitude. The rolling generally builds up to a maximum over a period of several rolls and then diminishes. The successive maxima attained are not equal nor are the number of rolls the same in the successive cycles from maximum to maximum. This rolling is forced; and except for deep lurches caused by occasional waves of great height no dangerous amplitudes of roll are produced.

Sometimes, however, when there has been a wind of long duration from one direction, a fairly uniform train of waves is established. The length and period of these waves depends upon the velocity of the wind and the "fetch" or sweep of open water over which it has blown. A ship in such a train of waves will roll in the apparent period of the waves. By "apparent period" is meant the interval between the passage of two successive wave crests past a fixed point on the ship. If the ship's course is parallel to the wave crests the apparent wave period will be the true period of the waves. If the ship's course is 30° to the crest line of the waves, in the direction of travel of the waves, and the ship's speed is equal to the velocity of travel of the waves, the apparent period will be two times the true period of the waves. Many observations of models rolling in waves have led to the conclusion that when a ship rolls in a uniform wave train, it will roll in the apparent period of the waves. When the natural period of the ship is greater or less than the apparent period of the waves, the rolling will be forced.

No large amplitudes will be attained in forced rolling except when the ship's period is nearly equal to the apparent wave period; that is, when they are nearly synchronous. As a general rule, the roll may be expected to reach large amplitudes only when the period of the ship differs from that of the wave by less than 10 per cent. The amplitude attained under these conditions depends upon the wave slope and the damping of the ship. A discussion of the probability of synchronism between ship and wave will be found in Appendix I.

Some have believed that a ship in waves of apparent period equal to half the ship's period would roll in its own natural period and might attain large amplitudes. Many careful observations of models in waves of period equal to half the model period showed that under these conditions the model would behave as in the following diagram:—



Assuming the model upright and at rest in the hollow, the front of wave 1 will list it to an angle θ , in time 1/4 T_m, where T_m is the period of the model. It will roll down the back of wave 1, reaching the upright position in the hollow with a velocity, $\omega_{2\theta}$, a velocity which it would have in the upright position if it were heeled to an angle 2θ and released in still water. The model now. with velocity $\omega_{2\theta}$, rolls into the front of wave 2. This slope opposes the roll and the model reaches the second crest with a heel of θ in the opposite direction. The back of wave 2 opposes the roll of the model and it reaches the upright position in the hollow with velocity zero.

To a casual observer the model appears to be rolling in its natural period. However, the model starts from rest in the upright position and returns to the same position at rest after the passage of each successive pair of waves. The motion is cyclic, starting from rest and returning to rest in each natural period of the model.

Since there is no cumulative effect of amplitude from passing waves, there is no likelihood of dangerous rolling. Waves of period equal to half that of a ship would be short and, if high, would be steep. The angle of inclination θ of a ship caused by the passage of such a wave might be considerable. A wave 30 feet high and 400 feet long would cause a heel of about 15°. Dangerous amplitudes would be caused only by waves of extreme height such as tidal waves.

The slope of a wave depends upon its length and height which, in turn, depend upon the duration, velocity, and fetch of the wind, and the depth of the water. There is very little information extant correlating wave lengths and heights with the wind. Wave heights are especially difficult to measure or estimate from a ship, so much so that most observers greatly over-estimate the height of waves. Reports are frequently made of waves 50 and 60 feet high. Undoubtedly such waves do occur but they are rare. Storm waves 30 feet high might be encountered on occasion but there would be no established train of waves of this height. The large ones would occur at intervals with smaller waves between and with considerable variation of period. Probably the large waves, certainly those over 30 feet high, are produced by the superposition of two or more smaller waves. There is a saying among seagoing people that in a storm every seventh wave is a big one. There is no basis for the belief that large waves occur at intervals of seven, but the statement does indicate the irregularity of storm waves and the occasional production of a large wave by superposition of smaller ones.

Stereoscopic pictures of waves might provide a valuable means of determining their heights and lengths, but this method is at present in an undeveloped state.

The third consideration affecting the amplitude of roll of a ship among waves is the damping of the ship. The damping action of a ship may be explained more clearly by comparison to a pendulum. Suppose a pendulum having a period T, whose bob is a thin metal disc, is forced to oscillate in air in the plane of the disc by the periodic application of a synchronous force. A certain amplitude.

Θ_2, will be attained by the pendulum and it will oscillate at that amplitude in in period T as long as the periodic force is applied. Now suppose that the disc forming the bob is turned through 90 degrees with respect to the pendulum and the same periodic force is applied in the same period T. The air resistance of the disc swinging broadside will be much greater than it was when the disc was moving edgewise and the amplitude attained, Θ_1 , will be smaller than Θ_2. The resistance offered by the air to the swinging of the pendulum is the damping force.

In each case, when equilibrium is reached, the pendulum swings out to an angle such that the work done by the damping force in resisting the swing during a complete oscillation in time T is equal to the work done by the periodic force. The energy absorbed by the damping force per oscillation may be referred to as the energy damping per oscillation.

Now consider the case of a ship rolling in synchronous waves. Each passing wave applies a force to roll the ship. These forces will build up the amplitude of roll to a limiting angle Θ , at which angle the work done by the damping force resisting the roll is equal to the work done by the wave in causing the roll. Here again, as in the case of the pendulum, the energy damping per roll is the energy absorbed by damping during each roll.

When comparing the damping of ships and the effects of various factors on damping, it is this energy damping that must be used as a basis of comparison. An analogy between a ship and a pendulum will again be drawn to explain why this is so.

Suppose two pendulums of the same length but having bobs of different masses swing through the same arc in the same time when released from a common angle of displacement Θ_0 . The angle attained by the pendulums on the other side of the vertical will be designated $\Theta_{1,2}$. At the starting angle, Θ_0, the pendulums had potential energies measured by the integrals of the moments about the point of suspension:

$$\int_0^{\theta_0} W_1 \; l \sin \theta \, d \theta \qquad \text{and} \qquad \int_0^{\theta_0} W_2 \; l \sin \theta \, d \theta$$

where W_1 and W_2 are the weights of the bobs and l is the length of the pendulums.

In swinging through the arc $\Theta_0 + \Theta_{1,2}$ some of the energy is consumed in damping. This loss of energy is measured by the difference of potential energy of the pendulum at $\theta_{1,2}$ from that at θ_0. The potential energies at $\Theta_{1,2}$ are:

$$\int_0^{\theta_{1,2}} W_1 \; l \sin \theta_{1,2} \, d \theta \qquad \text{and} \qquad \int_0^{\theta_{1,2}} W_2 \; l \sin \theta_{1,2} \, d \theta$$

The loss of energy or the energy damping of pendulum 1 is:

$$\int_{-\theta_{1,2}}^{\theta_0} W_1 \, l \sin \theta \, d\theta$$

that of pendulum 2 is:

$$\int_{-\theta_{1,2}}^{\theta_0} W_2 \, l \sin \theta \, d\theta$$

Taking pendulum 2 as the heavier one:

$$\int_{-\theta_{1,2}}^{\theta_0} W_2 \, l \sin \theta \, d\theta \quad \text{is greater than} \int_{-\theta_{1,2}}^{\theta_0} W_1 \, l \sin \theta \, d\theta$$

that is to say, the energy damping of pendulum 2 is greater than that of pendulum 1. Although the loss of angle in each case is $(\theta_0 - \theta_{1,2})$, the forces resisting the swing are greater in the case of pendulum 2.

If the energy damping were equal in both pendulums, they would attain angles θ_1 and θ_2 respectively. In this case the energy losses are:

$$\int_{-\theta_1}^{\theta_0} W_1 \, l \sin \theta \, d\theta \quad \text{and} \quad \int_{-\theta_2}^{\theta_0} W_2 \, l \sin \theta \, d\theta$$

Since the energy damping is assumed to be the same for both pendulums

$$\int_{-\theta_1}^{\theta_0} W_1 \, l \sin \theta \, d\theta = \int_{-\theta_2}^{\theta_0} W_2 \, l \sin \theta \, d\theta$$

W_2 is greater than W_1 hence from the integrals

$$\cos \theta_1 - \cos \theta_0 > \cos \theta_2 - \cos \theta_0$$

or

$$\theta_1 < \theta_2$$

The pendulum with the heavier bob swings through a greater arc than the other. The loss of angle $(\theta_0 - \theta_2)$ is less than $(\theta_0 - \theta_1)$.

It is seen that when the arcs of swing of the pendulums are equal, the energy damping of the heavier one is the greater. When the energy damping is equal, the loss of angle of the lighter pendulum is greater. The loss of angle is called the angular damping and unless otherwise stated angular damping hereafter will mean loss of angle per cycle (port to starboard to port.).

Since the angular damping of two similar pendulums may be different, due to different masses in the bobs, when the energy damping is the same, it is apparent that angular damping can not be taken as a measure of the forces or moments of damping when comparing the pendulums. Energy damping is the true measure and should be used in comparisons.

In applying this to ships, two identical ships are assumed to be ballasted to have different GM's but the same period and displacement. Here the different GM's correspond to the different weights of bobs in the case of the pendulums.

If these ships are listed to a common angle θ_0 their potential energies at this angle are:

$$\int_0^{\theta_0} W\, GZ_1\, d\theta \quad \text{and} \quad \int_0^{\theta_0} W\, GZ_2\, d\theta$$

GZ_1 and GZ_2 being the values of the righting arms corresponding to GM_1 and GM_2.

If when released the ships roll through the same arc to $\theta_{1,2}$ in the same period T, the loss of energy in each case is:

$$\int_{-\theta_{1,2}}^{\theta_0} W\, GZ_1\, d\theta \quad \text{and} \quad \int_{-\theta_{1,2}}^{\theta_0} W\, GZ_2\, d\theta$$

If GM_2 is greater than GM_1, GZ_2 will be greater than GZ_1 since the ships are identical, and the loss of energy is greater for the greater GM. If the energy damping were equal the ship with GM_1 would roll through a smaller arc, that is, the angular damping is greater for the smaller GM. For this reason, as in the pendulums, the energy damping must be used for a basis of comparison.

Of course in a single ship with GM constant, the angular damping could be used as a measure of damping but only because the GM remains constant.

It must be clearly understood that the ideas of energy damping and angular damping are both of great importance and each has its own field of usefulness where the other does not apply. The idea of energy damping was used to furnish a means of comparing the actual forces or moments resisting the rolling. The angular damping of a ship determines the amplitude of roll.

If a ship is rolling under the impulses of synchronous waves, each passing trough and crest will add a constant increment to the angle of roll. The amplitude will build up until an angle is reached where the angular damping per half oscillation is equal to the increment added. The ship will then roll steadily at this angle. The greater the angular damping the less will be the angle of roll for a given set of conditions. Once the form of a ship has been determined, the angular damping is affected more by the GM than any other factor. As GM is increased, the angular damping decreases. A ship with a large GM will roll to greater angles than a similar ship with smaller GM.

The idea of energy damping as distinguished from angular damping is not new. Wm.Froude used it in his original paper on rolling. Energy damping is described at length because it is the basis of the analysis of this report.

Since Froude published the results of his investigations in 1861, a large amount of work, both theoretical and experimental, has been done to clarify the subject of the rolling of ships. The greater part of it has resulted in verifying Froude's theories. Most of the gain in knowledge has been in the field of reducing the roll by means of various devices for increasing damping. The purpose of this experiment was to determine the effect on rolling of variations in the form and loading of a ship. Investigations were made of the effect of variations of:

1. The vertical position of G.
2. The period.
3. The height of the metacenter above W.L.
4. The midship-section coefficient.

APPARATUS and METHOD of INVESTIGATION

Four series of models with parallel middle bodies were used, without bow or stern. Series I, II, and III had elliptical, rectangular, and tumble home underwater forms respectively, with midship-section coefficients of 0.785, 0.96, and 1.10. The beam draft ratio was held between 2 and 4 in all series. The forms of the models were varied to provide changes in the height of metacenter above the water line in 2/3 inch increments. These restrictions resulted in four models in Series I, four in II, and three in III. Series IV comprised four models with wall sides and vee bottoms with midship-section coefficients 0.80, 0.90, 1.00, and 1.10. The height of metacenter above W.L. was 0.53 inches in all models of Series IV. This series was intended to avoid the radical change in form between Series II and III and to provide a check on the results obtained by comparing corresponding models in Series I, II, and III. (See Table 1 and Fig. 1.)

To determine the effect on rolling of the variations in the location of G and the variations of T, μ , and ϕ , each was varied in turn, keeping the others constant. The effect in each case was measured by the variations in damping of the models. Changes in damping were derived from declining angle curves.

The experiment was carried out in a small basin 30' x 4' and 2-1/2 feet deep with a beach at one end and a wave maker at the other. The model was secured to an aluminum frame weighing 5 ounces which allowed freedom of motion to the model in all directions except drift down the basin. The period of the frame was kept well above that of the model. No measurable restriction of roll was placed on the model by the frame. (See Figs. 2 and 3.) The model was ballasted with lead bars so arranged that they could be raised or lowered and spread or contracted, to provide desired changes in the location of G and control of T by variation of the moment of inertia. (See Fig. 4.)

Declining angle curves were taken of each model with constant T and varying GM and also with constant GM and varying T. Each model was rolled in synchronous waves with a constant GM, and a period of 1.18 seconds. This period was about the mean of the most favorable range of wave periods as determined by calibrating the wave maker. (Fig. 5). The period of the model, and of the wave maker when used, was electrically recorded on a chronograph.

The effect of variation of the location of G was determined by comparing the damping of each model with varying GM's and constant T.

The influence of T was similarly determined by varying T and holding GM constant.

The effect of varying μ was obtained by comparing the damping of the models within each series with GM and T constant.

The influence of ϕ was determined by comparing the damping of the models having the same value of μ across Series I, II, and III where GM and T were constant. A check determination was obtained by comparing the damping of the models in Series IV.

The GM was measured by the method of moving a small weight in the model and noting the angle of heel. The angle of roll, θ, was obtained by reading the travel of a pointer secured to the model over a scale secured to the aluminum frame.

ANALYSIS of DATA

When a ship not fitted with gyros, tanks, or other auxiliary stabilizing devices, is rolling the damping is produced solely by the action of the hull on the water, neglecting air resistance, which is small. The amount of damping of a ship with no way on depends on the underwater form, the wetted surface, the velocity in roll of the surface relative to the water, and the manner of motion through the water. The wetted surface depends on the form and displacement. The velocity depends on the angle and period of roll. The manner of motion depends on the axis of roll. The effect of headway on damping will not be considered in this report.

To obtain the still water rolling characteristics every model was listed 25° to port and released. As it rolled down, each maximum angle on the starboard side was read and recorded. The period of each roll was recorded electrically.

Trials of several methods of plotting the data proved that the most accurate was to first plot θ against time t on log paper. From this curve a declining angle curve was plotted on regular co-ordinate paper. The $d\theta/dt$ curve obtained graphically from the declining angle curve was plotted on log paper. From this $d\theta/dt$ curve and the GZ curve for the model (Figs. 6, 7, 8, 9), the dE/dt curve was computed and plotted on log paper.

$$\frac{dE}{dt} = \frac{d\theta}{dt} \times GZ \times W$$

where $\frac{dE}{dt}$ is the rate of energy damping.

The rate of energy damping was plotted, rather than energy damping per roll, because with the declining angle curves plotted with θ against t their derivative curves were $d\theta/dt$ plotted against t, $d\theta/dt$ being the loss of angle per second rather than the loss of angle per roll. The energy damping curves derived from the $d\theta/dt$ curves therefore gave energy loss per second or rate of energy damping. Since the period of each roll was obtained the energy damping per roll at any amplitude is obtained by multiplying the rate of energy damping and the period at that angle. In comparing the damping of models of equal periods the dE/dt curves are used directly.

The θ's in these curves and this discussion are, of course, successive maximum heels on one side in rolling down the declining angle curve. θ was plotted against t because the rolling of some of the models was not isochronous at large angles (see Figs. 10, 11, 12).

For each model the angle of roll in synchronous waves was computed, assuming a wave height obtained from the calibration of the wave maker. In making this computation the increment of roll added per wave was obtained from Froude's formula $\Delta\theta = (\pi\gamma/2)$ where γ is the maximum wave slope. Assuming a sine wave of height H and length L, $\gamma = \pi H/L$. The $\Delta\theta$ so obtained was divided by the average T_m and the $d\theta/dt$ curve (see Figs. 13, 14, 15) entered. The θ corresponding to this $\Delta\theta/T$ was the computed angle of roll in the synchronous waves.

The amplitude of roll attained by the models rolling in synchronous waves of the heights used in computation checked the computed values closely, except in a few instances where either synchronism had manifestly not been obtained in the rolling or where the computed θ was obtained by extrapolation far beyond the controlled region of the $d\theta/dt$ curve (See Table 2).

Table 3 shows the GM's and T's used in comparing the models.

RESULTS

1. EFFECT of VARYING the VERTICAL POSITION of G.

In every model as GM was increased, other factors remaining constant, the energy damping was decreased. (See Figs. 16, 17, 18). This was probably due to the fact that a vertical movement of G caused a change in the axis of roll.

It is important to note, however, that as GM is increased the angular damping is decreased since with a large GM the damping energy is absorbed with a smaller angular decrement. Increasing GM not only reduces the angular damping, thereby entailing heavier angles of roll, but also actually reduces the energy damping thus augmenting the angle of roll still more.

2. EFFECT of VARYING T.

In every model as T was increased, other factors being constant, the energy damping was decreased (See Figs. 19 and 20). This was to be expected as an increase in T reduced the velocity through the water. With the periods used the frictional resistance was well within the laminar region and varied as V. The wave-making resistance to roll probably, as Froude assumed, varied as V. Some eddy-making resistance probably occurred in the wider models. This resistance varied as V^2.

For the narrow models I-1, I-2, II-1, and II-2, the energy damping varied nearly as 1/T. In the wider models I-3, I-4, II-3, and II-4, the energy damping varied somewhere between 1/T and $1/T^2$. Due to the form of the models of Series III, it was not possible to obtain an appreciable variation of T with a constant GM.

It might again be pointed out here that although an increase of T entails a reduction of energy damping, on the other hand, as T increases, the probability of encountering synchronous waves diminishes. Other things being equal a large T is generally desirable. (Appendix I).

3. EFFECT of VARIATION of MIDSHIP-SECTION COEFFICIENT.

In all groups of corresponding models such as I-1, II-1, and III-1, as the midship-section coefficient, ϕ, was increased, other factors remaining constant, the energy damping was increased (see Fig. 21). As ϕ was increased the angle of the bilge became sharper and the damping at the bilges became to some extent of the same kind as that due to bilge keels. This view was strengthened by the fact that the curves (Fig. 21) converged at low angles where V was small. Series IV furnished a check on the other groups. The trends of the curves are similar. Models IV-1 and IV-2 fall on the same line. IV-2 might have been expected to fall slightly above IV-1 at large angles because of its sharper bilges.

It was striking in all groups and in Series IV that as ϕ became 1 or greater (that is, as soon as a portion of the underwater body extended beyond the water line beam) the damping energy was greatly increased. For this reason the installation of blisters might permit the removal or reduction of bilge keels.

4. EFFECT of HEIGHT of M ABOVE W.L., μ

In all series as μ was increased the damping energy was increased (see Fig. 22). This was due to at least four factors. First, as μ was increased the model became wider and the bilges more acute. Second, the increased beam increased the wave-making resistance. Third, as μ was increased, with GM constant, G was raised and the axis of roll changed. Fourth, in the wider models the wetted surface was increased, thus augmenting the frictional resistance.

5. EFFECT of BILGE KEELS.

Model II-2 fitted with bilge keels showed the effects of varying GM and T to be in the same direction as when without bilge keels. The variations, however, had greater effect. See Fig. 23. The predictions of model roll in synchronous waves when fitted with bilge keels were close to the observed values. (See Table 2). Since the greater part of the damping when bilge keels were fitted was due to eddy-making the rate of energy damping varied nearly as $1/T^2$. Model II-2 fitted with bilge keels showed much less energy damping than did III-2 without bilge keels at the same GM and T. The sharp angles at the bilges of III-2 in effect constitute large bilge keels. The energy damping of II-2 with bilge keels was about the same as that of IV-3 with the same GM and T. The latter form is similar to that of a ship with blisters.

6.

Although no accurate data are at hand to prove that a ship has the same rolling characteristics as its model with a corresponding period, it is believed that predictions, accurate to 10 per cent, can be made of the rolling of a ship in synchronous waves from the declining angle curve of the model.

It is appreciated that the frictional resistance to roll of ship and model are in the ratio of $\lambda^{2.5}$ instead of λ^3 . Usually however, the frictional resistance is a small part of the total damping resistance and this error should be negligible. (See Appendix II).

The fact that most of the predictions of roll are somewhat in excess of actual roll, shows that the ship receives its impulses for rolling from a wave of lesser slope than the surface maximum. Froude assumed the slope of the wave at the depth of the center of buoyancy of the ship. The only data available on the rolling of model and ship are those of the 10,000 ton cruisers, and they are incomplete. As an example and to illustrate the method the rolling of a ship as reported is compared with the values computed for the same conditions from model data in Appendix III.

CONCLUSIONS

A.

With all other factors remaining unchanged:

1. When the center of gravity is lowered, the rate of energy damping is decreased.
2. When the period is increased, the rate of energy damping is decreased. However, to avoid synchronism with waves the period should be

made as large as possible.

3. When the height of the metacenter above the water line is increased, the rate of energy damping is increased.

4. When the midship-section coefficient is increased, the rate of energy damping is increased. When the midship-section coefficient becomes greater than unity the rate of energy damping is greatly increased.

5. The effect of variation of GM on the rate of energy damping is due to the change in location of the center of gravity and through it the axis of roll. An increase of GM decreases the rate of angular damping. For the latter reason GM should be no greater than required by considerations of safety.

6. The form of a ship influences its rolling only through its effect on damping. Two ships having the same period and identical declining angle curves would roll to the same angles in given waves regardless of their forms.

B.

1. The amplitude of roll of a model in synchronous waves can be closely predicted from its declining angle curve. The amplitude of roll of a ship in synchronous waves can be predicted with sufficient accuracy from the declining angle curve of the model.

RECOMMENDATIONS

1. The rolling behavior of ships at sea should be observed at all opportunities so that eventually an accurate comparison of the behavior of the ship and model in rolling may be obtained. Angles of roll should be measured by observations on the horizon with battens or directors. Periods may be measured with a stop watch. Observations should be taken over periods of about 15 minutes, the amplitude of each angle of heel and the total stop watch time being recorded for the duration of each period of observation. The time divided by the number of rolls gives a fairly accurate mean period. If a roll and pitch recorder is available, it should be used in preference to other methods. Clinometer readings of angles are apt to contain large errors (see Appendix IV). Reports of rolling should include ship's course and speed, direction and speed of apparent wind, estimated height and length of waves, and direction of travel of waves.

2. Whenever a model of a new design is tested in the basin, part of the data obtained should be a declining angle curve from 30°. From this curve predictions of roll in waves can be made for the ship at corresponding T, GM, etc.

3. Whenever opportunity offers, work should be done to develop and perfect the method of measuring waves by stereoscopic photographs.

Table 1

MODEL DATA

Series No.	Mid-Sect. Coef. ϕ	Model No.	μ inches	BM inches	H inches	b inches	b/H	Wetted Surface sq. inches
I	0.7854	1	0.00	1.27	3.00	6.00	2.00	188.5
		2	0.67	1.80	2.68	6.74	2.52	190.6
		3	1.33	2.37	2.44	7.38	3.03	194.6
		4	2.00	2.96	2.27	7.95	3.51	199.6
II	0.96	1	0.00	1.24	2.56	5.75	2.24	197.6
		2*	0.67	1.76	2.25	6.54	2.91	201.6
		3	1.33	2.32	2.04	7.23	3.55	206.4
		4	2.00	2.91	1.88	7.83	4.16	212.0
III	1.10	1	0.00	1.13	2.23	5.77	2.59	222.0
		2	0.67	1.66	1.96	6.56	3.35	232.0
		3	1.33	2.24	1.78	7.24	4.08	242.0
IV	0.80	1	0.53	1.64	2.71	6.53	2.41	197.6
	0.90	2	0.53	1.60	2.43	6.47	2.66	201.6
	1.00	3	0.53	1.56	2.21	6.41	2.90	220.8
	1.10	4	0.53	1.51	2.02	6.36	3.15	229.0

All models:	Length	20.0 inches
	Displacement	10.21 pounds
	Midship-section area	14.14 square inches

* The bilge keels when fitted on this model were 3/16 inches wide for the length of the model.

TABLE 3

TABULATED SUMMARY OF RUNS

			μ	GM	T	FIG.
I - 1 —	II - 1 —	III - 1 →	0.00	0.350	1.18	21
I - 2 —	II - 2 —	III - 2 →	0.67	0.496	1.18	21
I - 3 —	II - 3 —	III - 3 →	1.33	0.705	1.18	21
I - 4	II - 4					
↓	↓	↓				

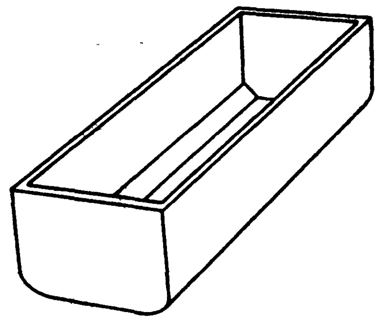
ϕ	0.785	0.96	1.10
GM	0.350	0.496	0.705
T	1.18	1.18	1.18
FIG.	22	22	22

Table 2

Model No.	GM Inches	Eccentric No.	Synchronous Wave Period Seconds	Wave Height Inches	Wave Length Inches	+ dθ/dt Deg./Sec.	Predicted Roll Degrees	Experimental Roll Degrees
I - 1	0.294	6	1.10	1.11	81	7.05	38	34
I - 2	0.294	6	1.10	1.11	81	7.05	36	39
I - 3	0.294	6	1.27	0.98	102	4.28	17.5	17.5
I - 3	0.373	6	1.21	1.03	95	5.07	25	23
I - 3	0.547	6	1.25	1.00	100	4.53	—	35
I - 3	0.705	6	1.27	0.98	102	4.28	—	40
II -1	0.496	6	1.08	1.13	79	7.50	—	37
II -1	0.496	7	1.14	0.60	86	3.46	29	26
II -2	0.496	6	1.04	1.17	74	8.60	—	32.5
II -2	0.496	7	1.11	0.60	83	3.68	27	23
II -3	0.496	6	1.17	1.06	90	5.70	22	18
II -3	0.496	7	1.14	0.60	86	3.47	16	14
II -4	0.496	6	1.20	1.04	94	5.22	14	13.7
II -4	0.496	7	1.12	0.60	84	3.62	11	10.0
III-1	0.705	6	1.20	1.04	94	5.22	18	15.5
III-1	0.705	7	1.21	0.58	95	2.86	14	12.0
III-2	0.705	6	1.22	1.03	96	4.98	11	9
III-2	0.705	7	1.18	0.60	91	3.16	9	5.5
III-3	0.705	6	1.23	1.02	97	4.84	6	6
IV - 1	0.491	6	1.06	1.15	77	7.98	30	31.5
IV - 2	0.491	6	1.09	1.13	80	7.34	29	28.5
IV - 3	0.491	6	1.08	1.13	79	7.50	18	15
IV - 4	0.491	6	1.20	1.04	94	5.22	13	5.3
II-2*	0.496	5	1.20	1.39	94	6.98	16	14.7
		6	1.21	1.03	95	5.07	13	12.0
		7	1.23	0.57	97	2.71	8	7.7
II-2*	0.467	4	1.08	2.39	79	15.85	17	13.5
		5	1.08	1.54	79	10.21	13	10.5
		6	1.00	1.22	69	10.02	13	9
		7	1.00	0.68	69	5.58	9	7.5
II-2*	0.518	4	1.01	2.52	70	20.2	22	16
		5	1.02	1.63	72	12.56	17	13.7
		6	0.99	1.23	68	10.35	15	12
		7	1.00	0.68	69	5.58	10	5
II-2*	0.666	4	0.99	2.57	68	21.6	—	22.5
		5	0.99	1.69	68	14.2	23	18
		6	0.99	1.23	68	10.35	19	16
		7	1.01	0.66	70	5.28	13	12
II-2*	0.814	4	0.97	2.63	66	23.3	—	32.5
		5	1.00	1.67	69	13.7	29	25
		6	1.00	1.22	69	10.0	24	21.5
		7	1.01	0.66	70	5.28	16	16

* With bilge keels.

GENERAL FORM OF MODELS



SECTIONS OF THE MODELS

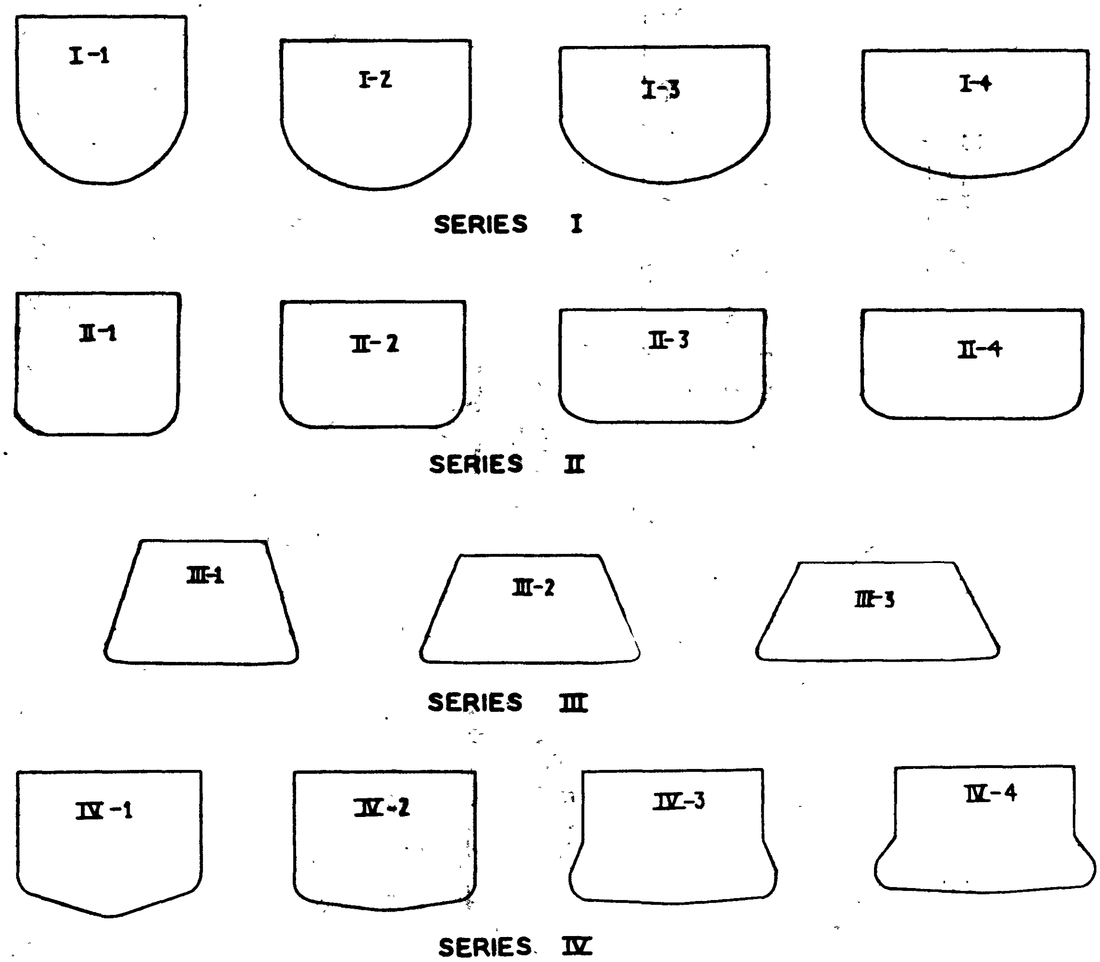


FIG. 1.

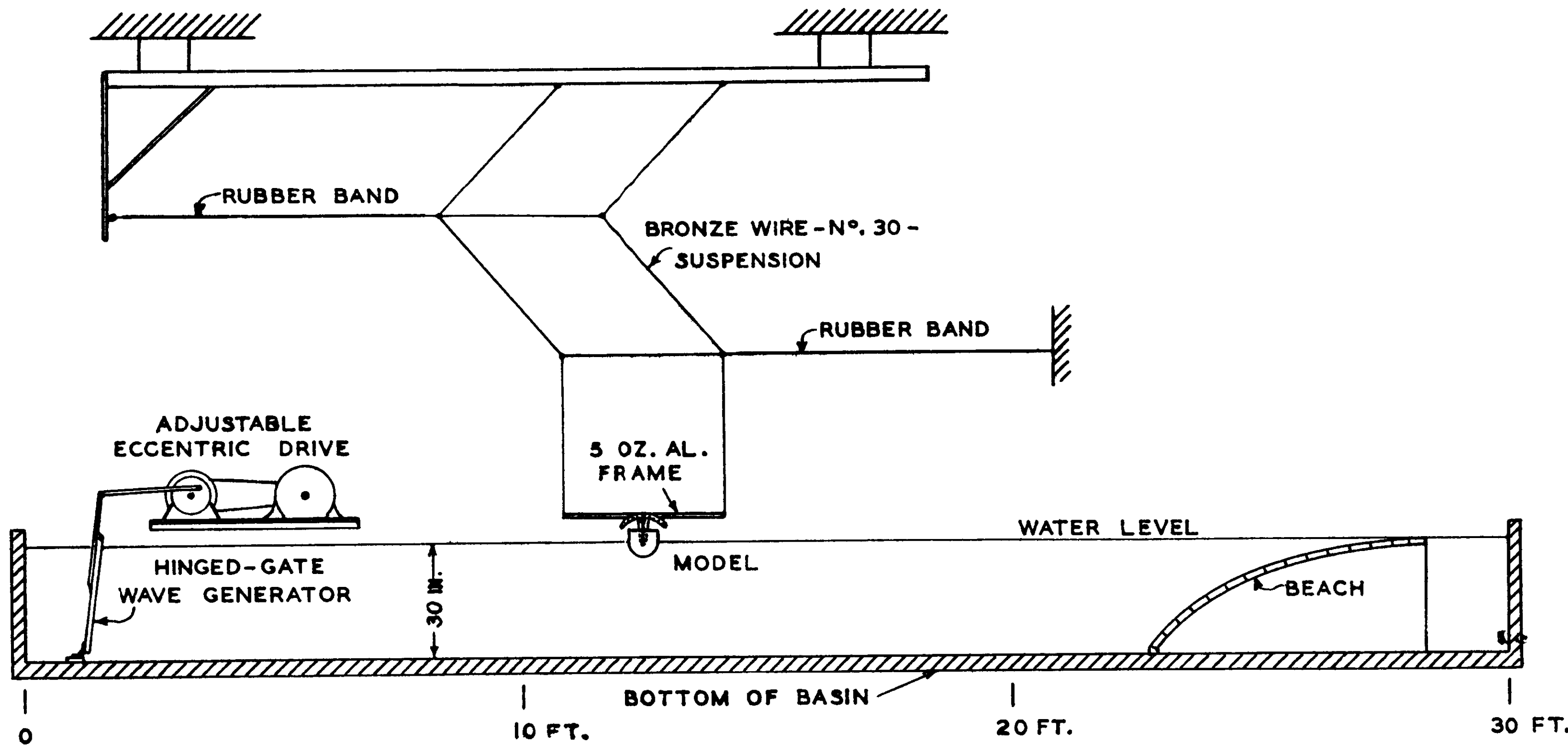


FIG. 2. DIAGRAM OF APPARATUS IN THE 30-FOOT MODEL BASIN

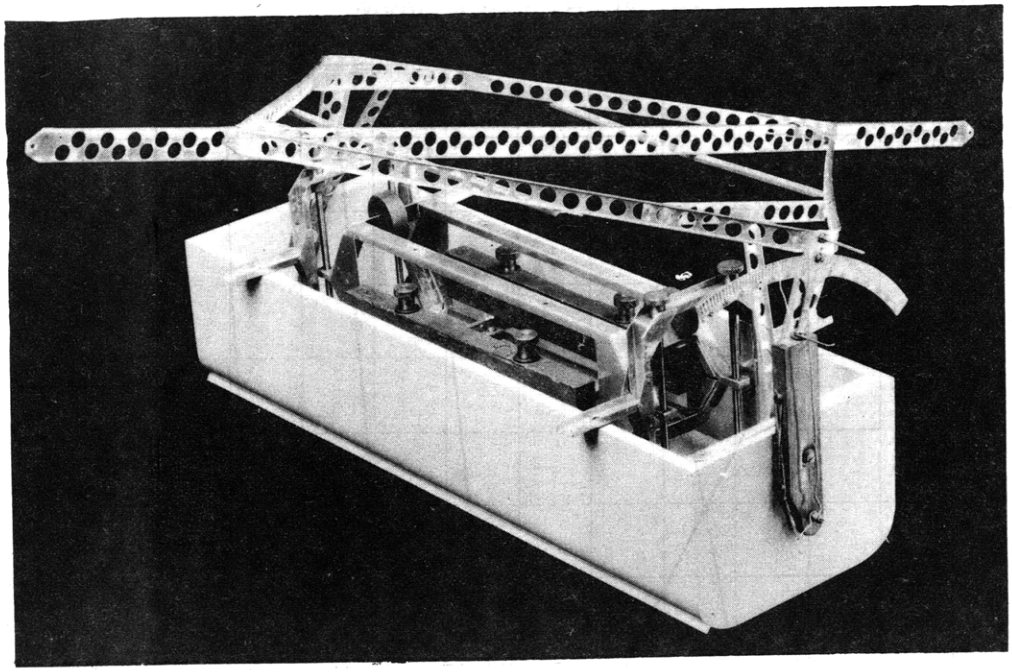


FIGURE 3

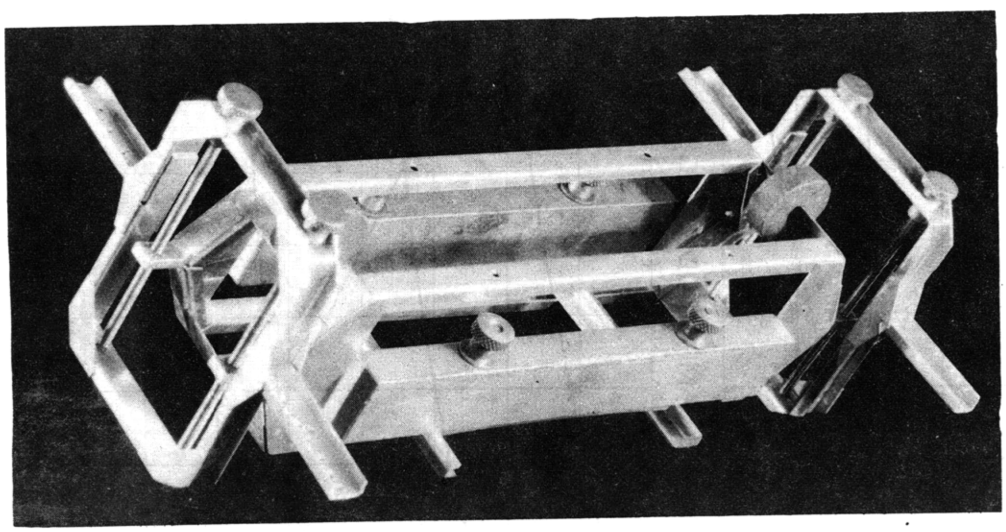


FIGURE 4

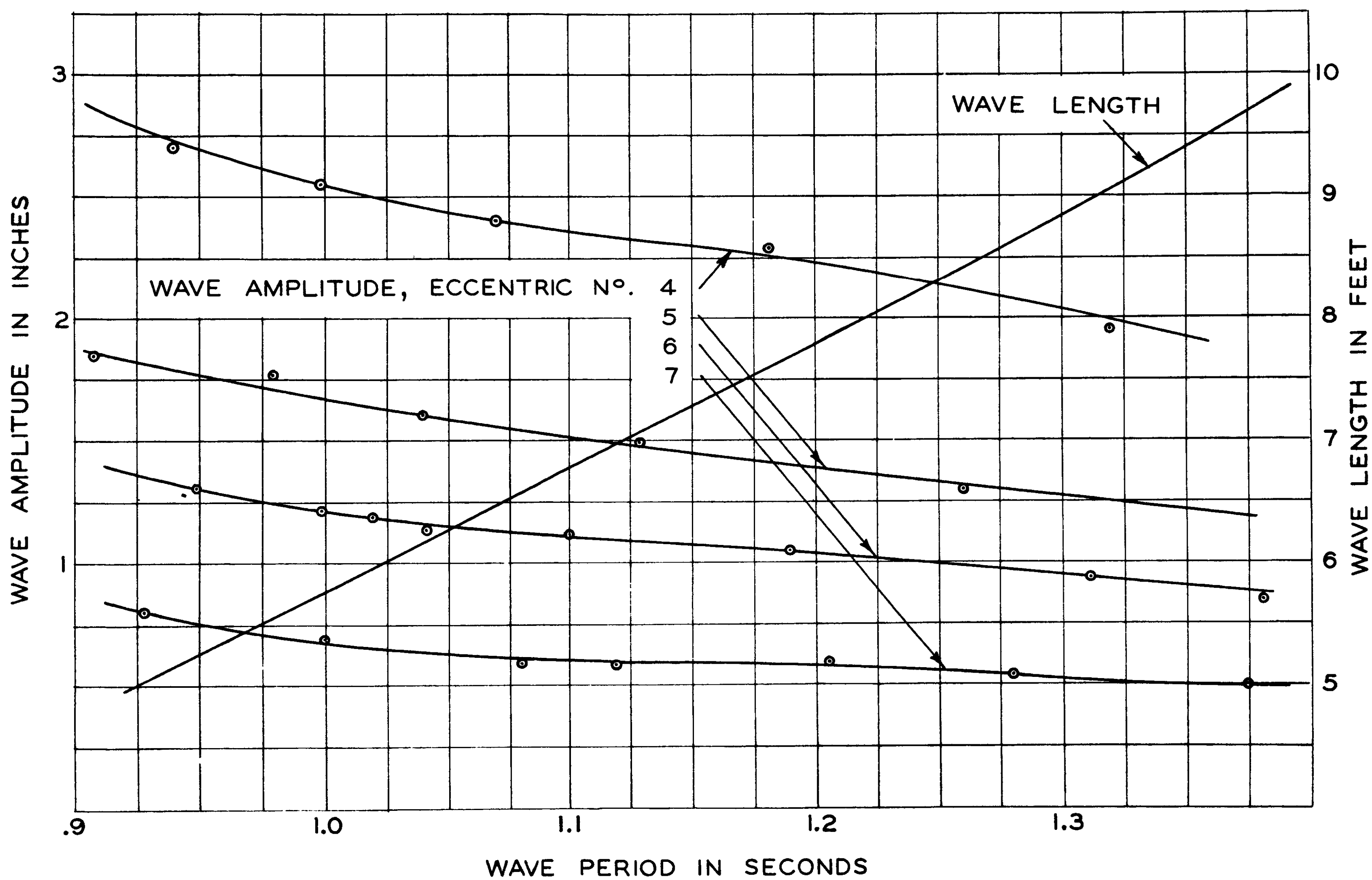


FIG. 5. CALIBRATION CURVES FOR WAVE GENERATOR

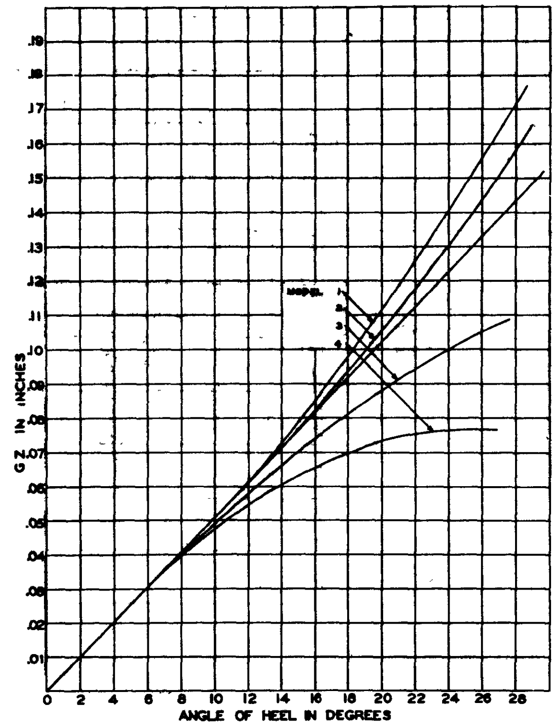


FIG. 6. GZ CURVES FOR SERIES I. GM - 0.294 IN.

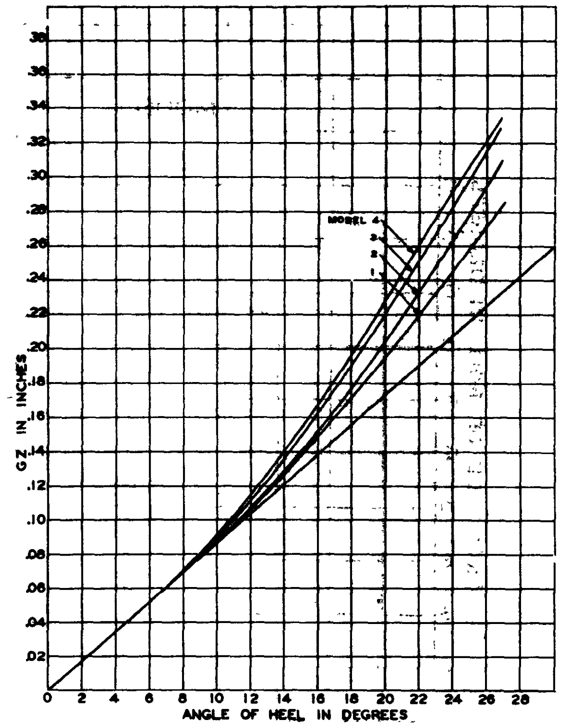


FIG. 7. GZ CURVES FOR SERIES II. GM - 0.496 IN.

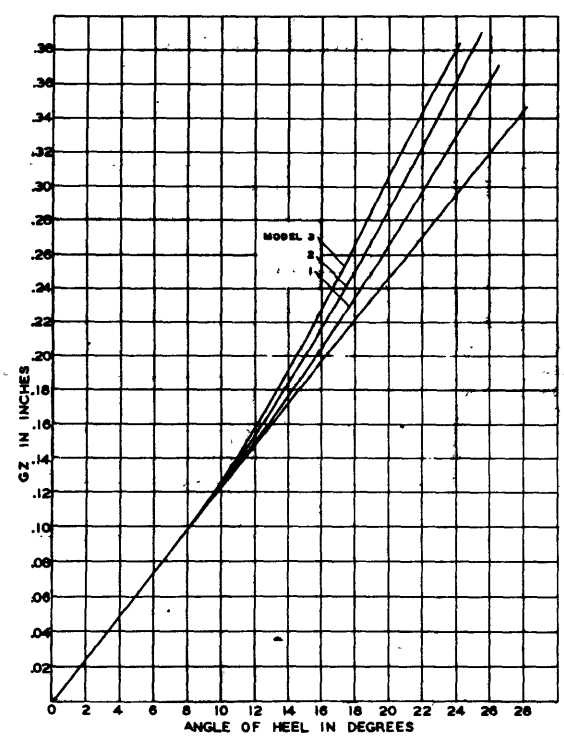


FIG. 8 GZ CURVES FOR SERIES III. GM - 0.705 IN.

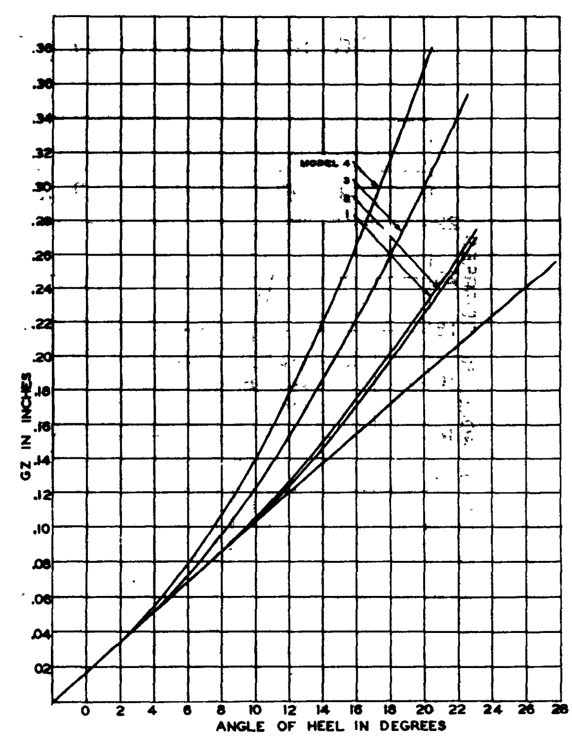


FIG. 9. GZ CURVES FOR SERIES IV. GM 0.493 IN.

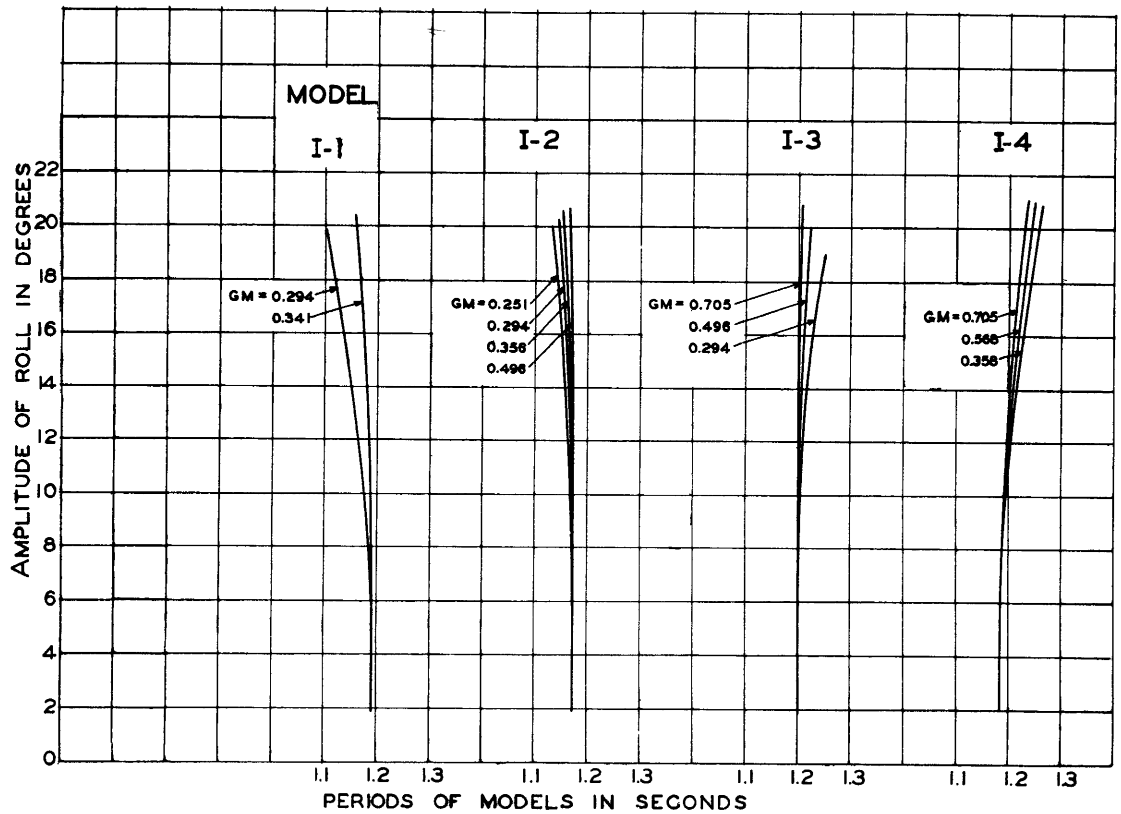


FIG. 10. VARIATION OF PERIOD WITH GM & ANGLE OF ROLL

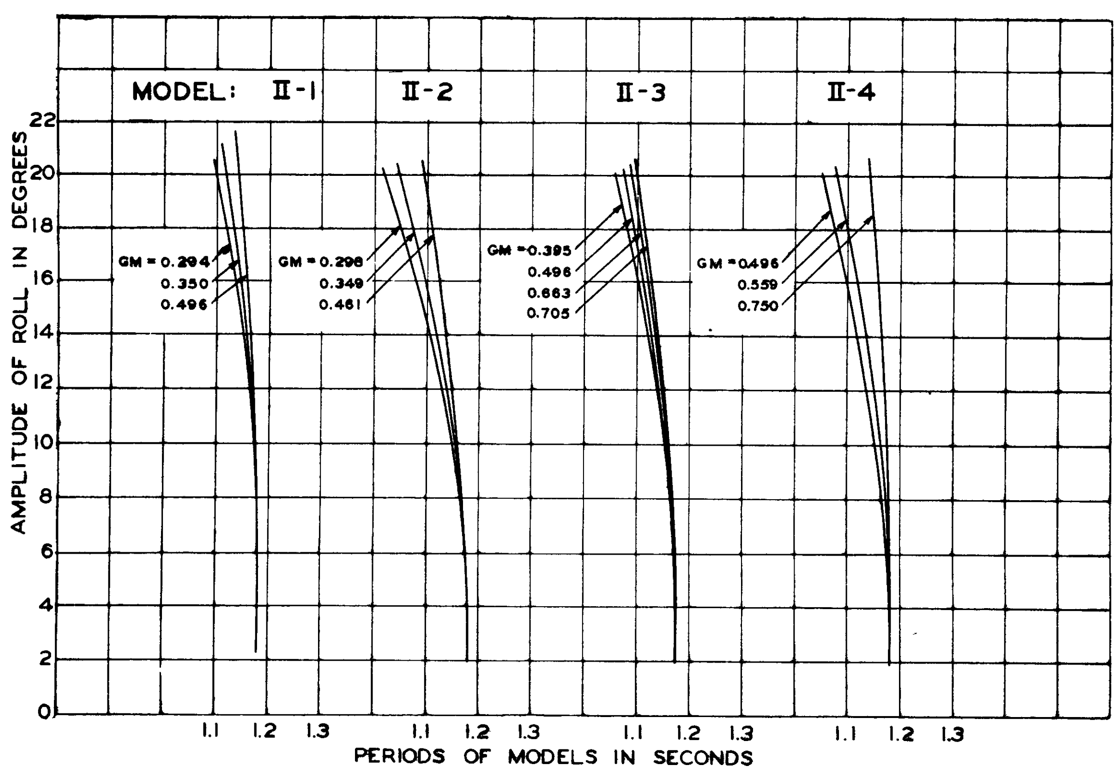


FIG. 11 VARIATION OF PERIOD WITH GM & ANGLE OF ROLL

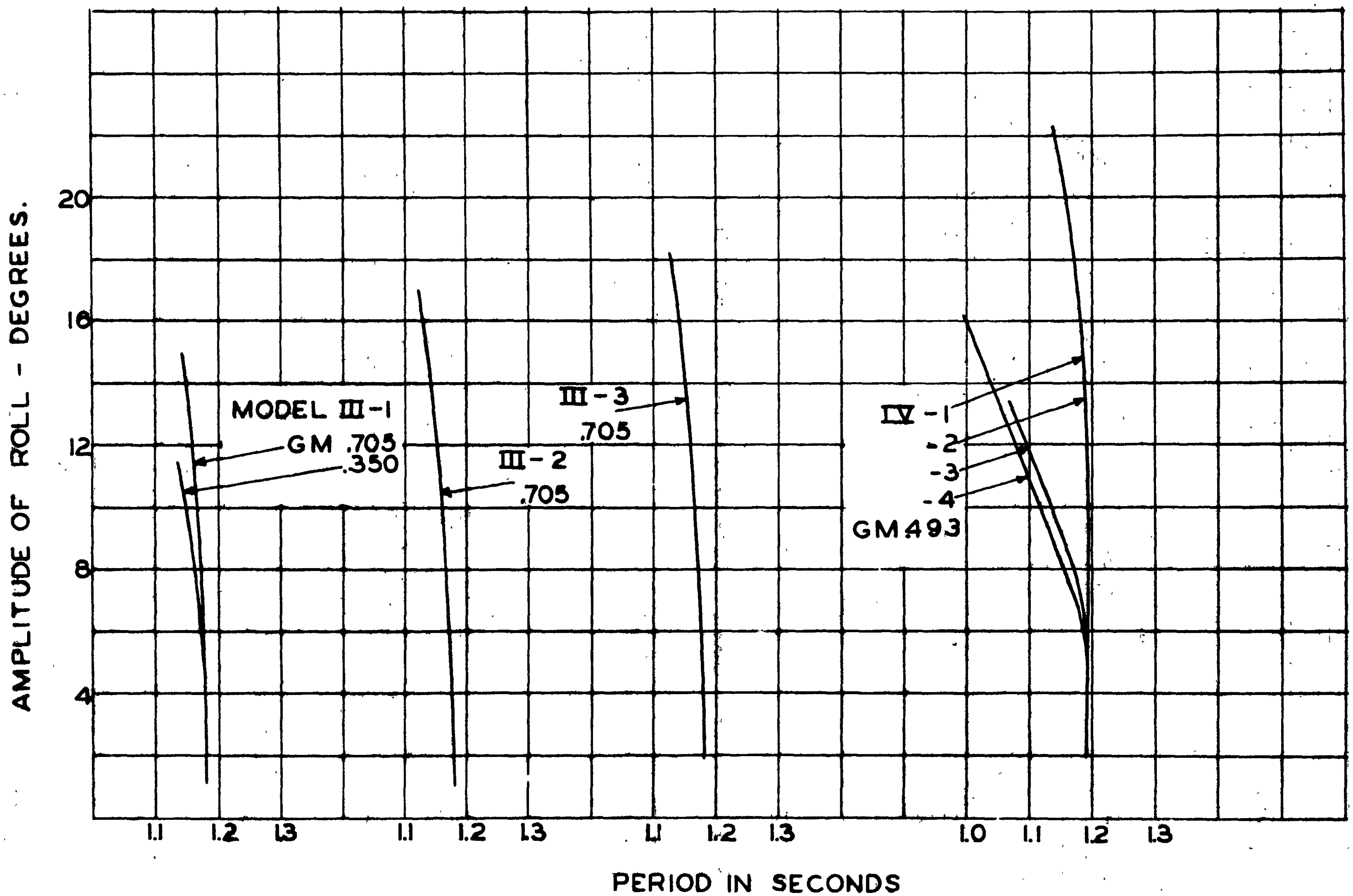


FIG. 12. VARIATION OF PERIOD WITH AMPLITUDE OF ROLL. SERIES III & IV.

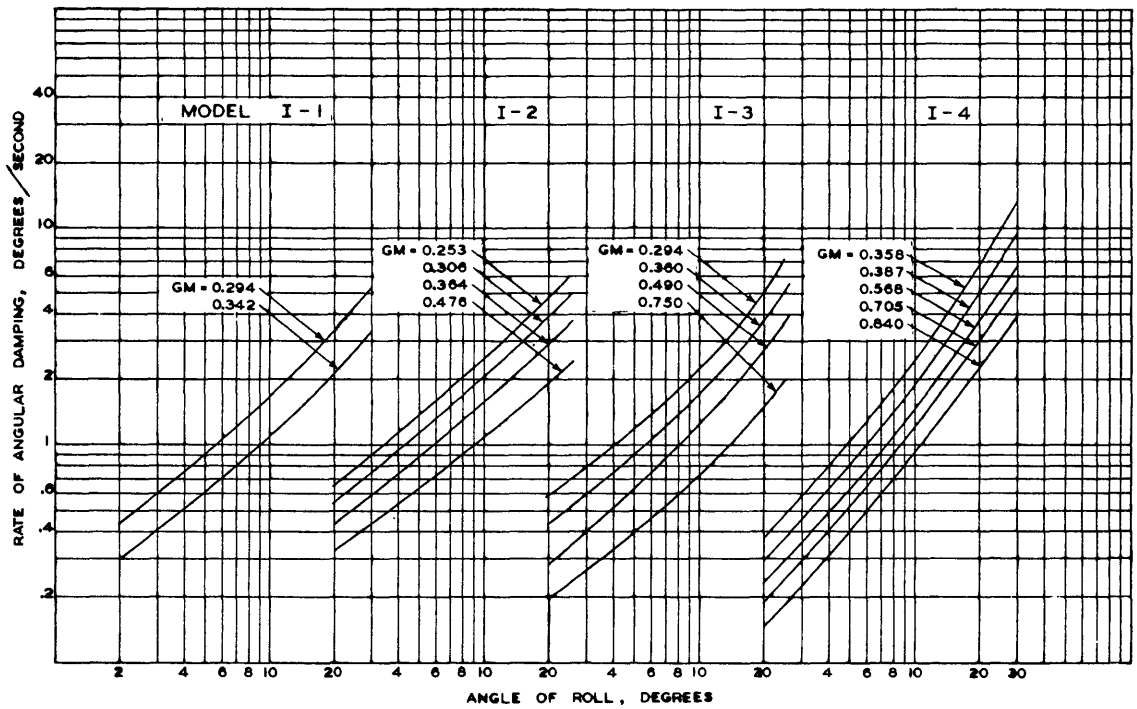


FIG. 13. SERIES I. EFFECT OF CHANGE OF GM ON ANGULAR DAMPING. PERIOD OF MODELS – 1.18 SECONDS.

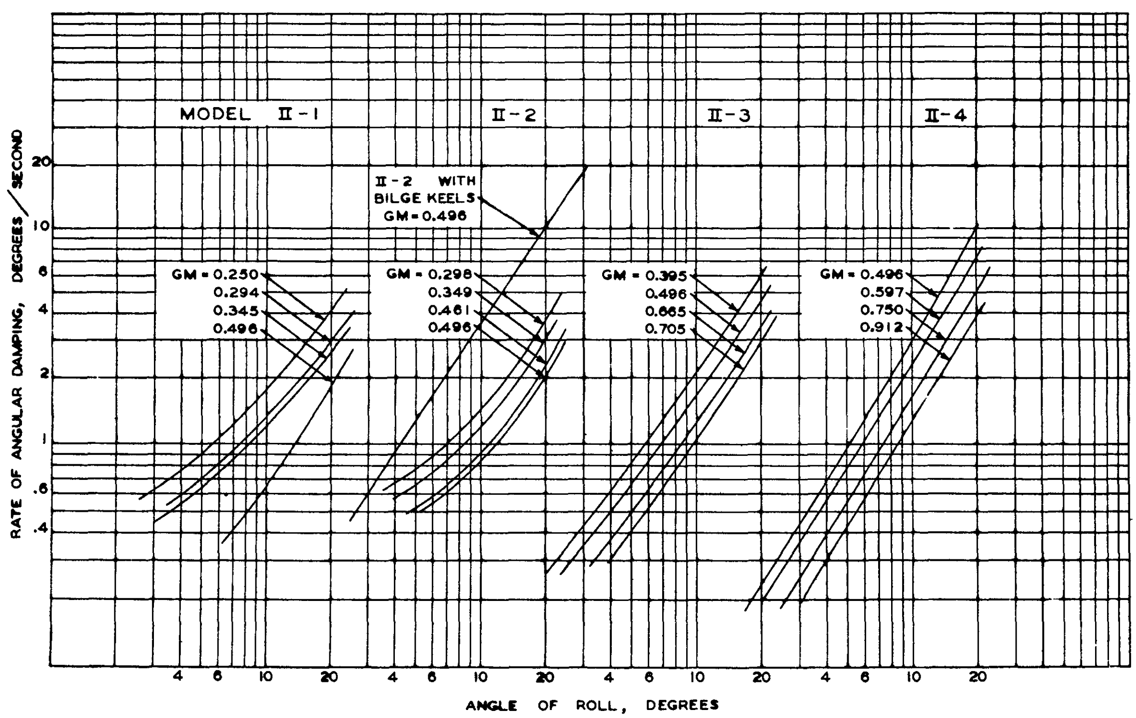


FIG. 14. SERIES II. EFFECT OF CHANGE OF GM ON ANGULAR DAMPING. PERIOD OF MODELS – 1.18 SEC.

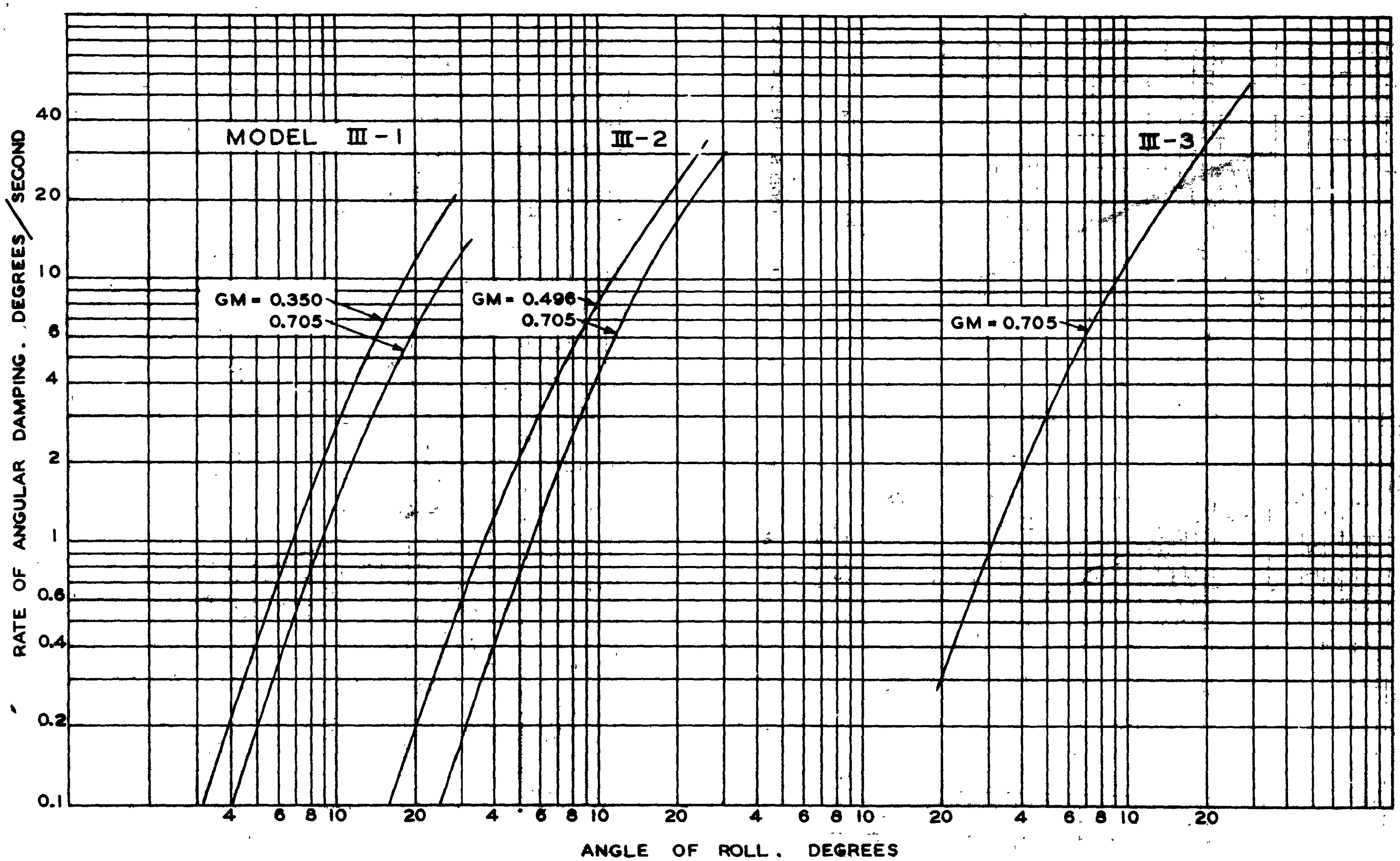


FIG. 15. SERIES III. EFFECT OF CHANGE OF GM ON ANGULAR DAMPING. PERIOD OF MODELS – 1.18 SECONDS.

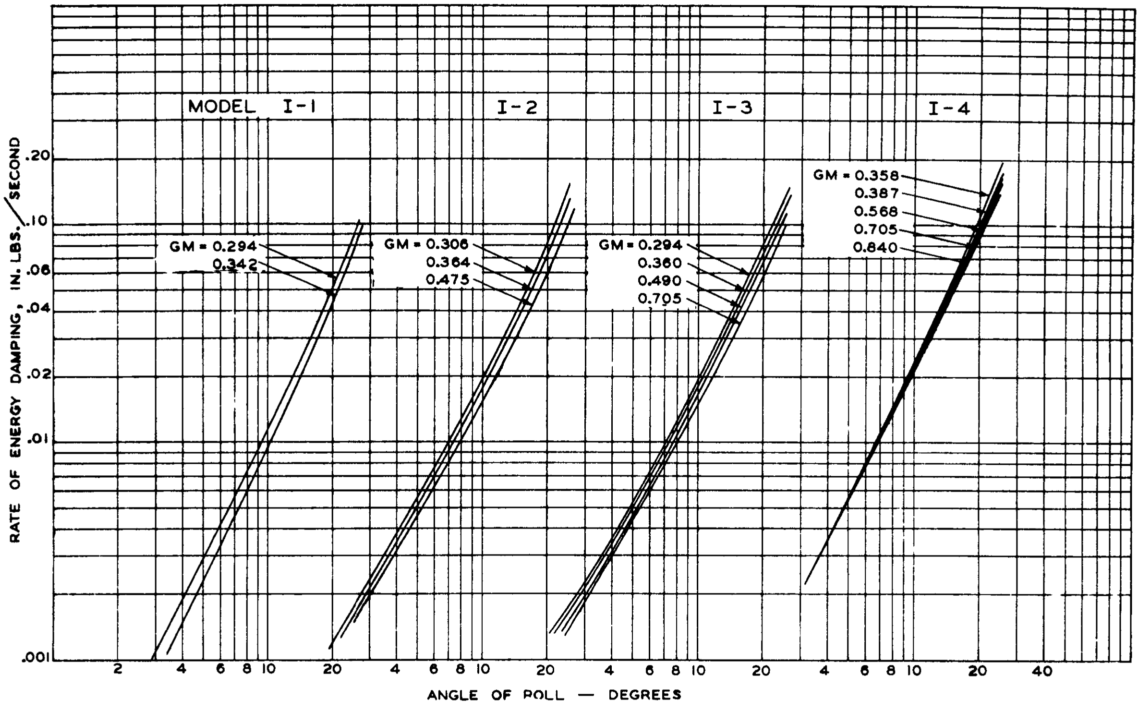


FIG. 16. SERIES I. EFFECT OF CHANGE OF GM ON ENERGY DAMPING. PERIOD OF MODELS - 1.18 SECONDS.

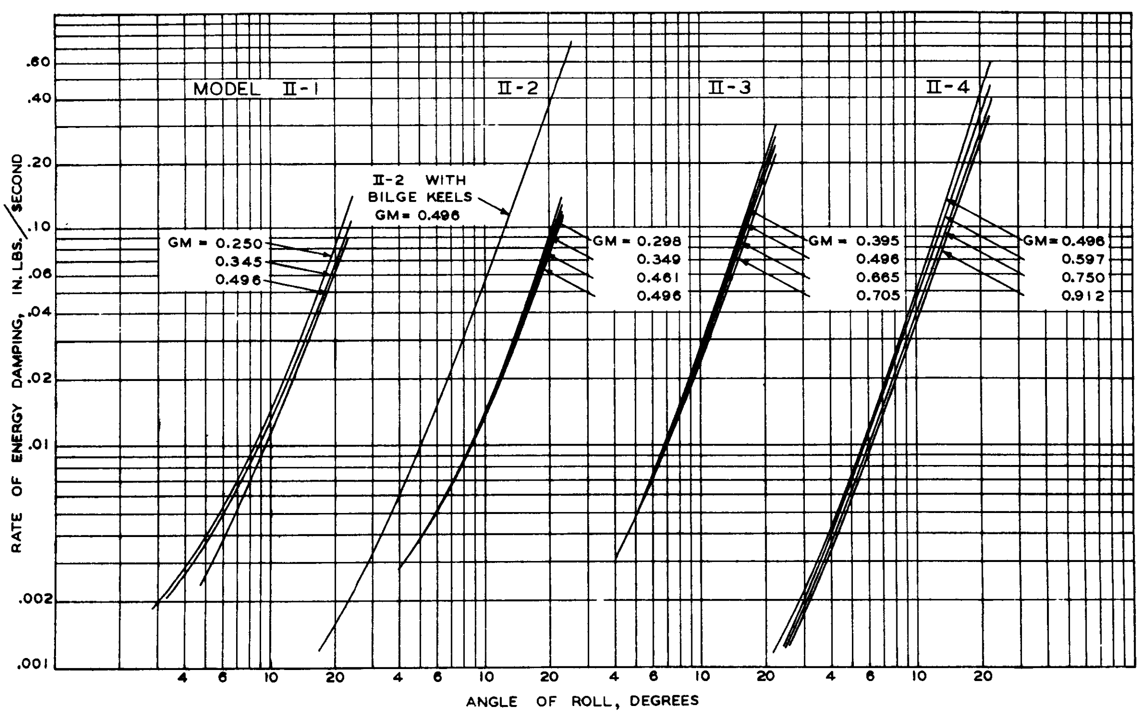


FIG. 17. SERIES II. EFFECT OF CHANGE OF GM ON ENERGY DAMPING, PERIOD OF MODELS - 1.18 SECONDS.

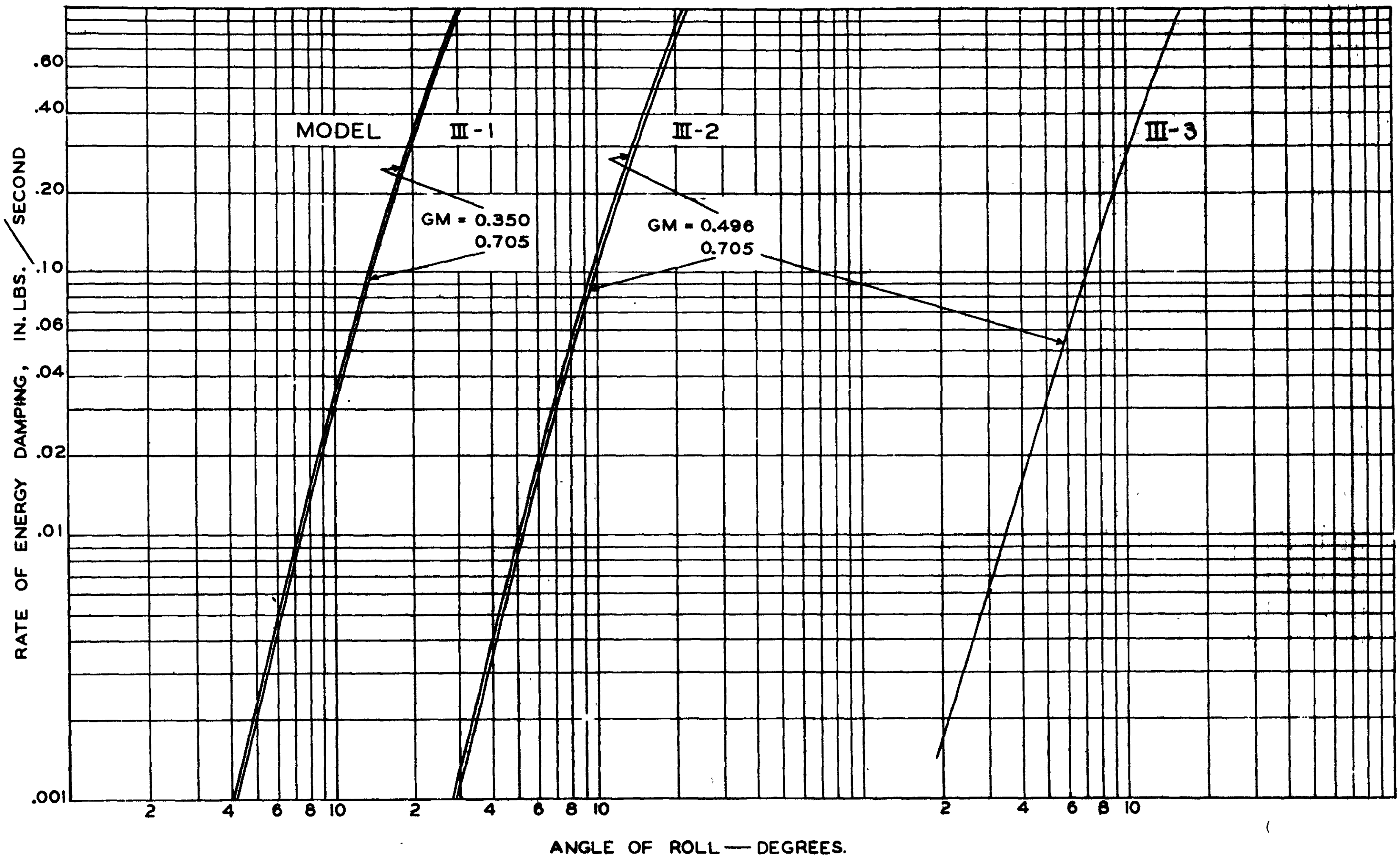


FIG. 18. SERIES III. EFFECT OF CHANGE OF GM ON ENERGY DAMPING. PERIOD OF MODELS - 1.18 SEC.

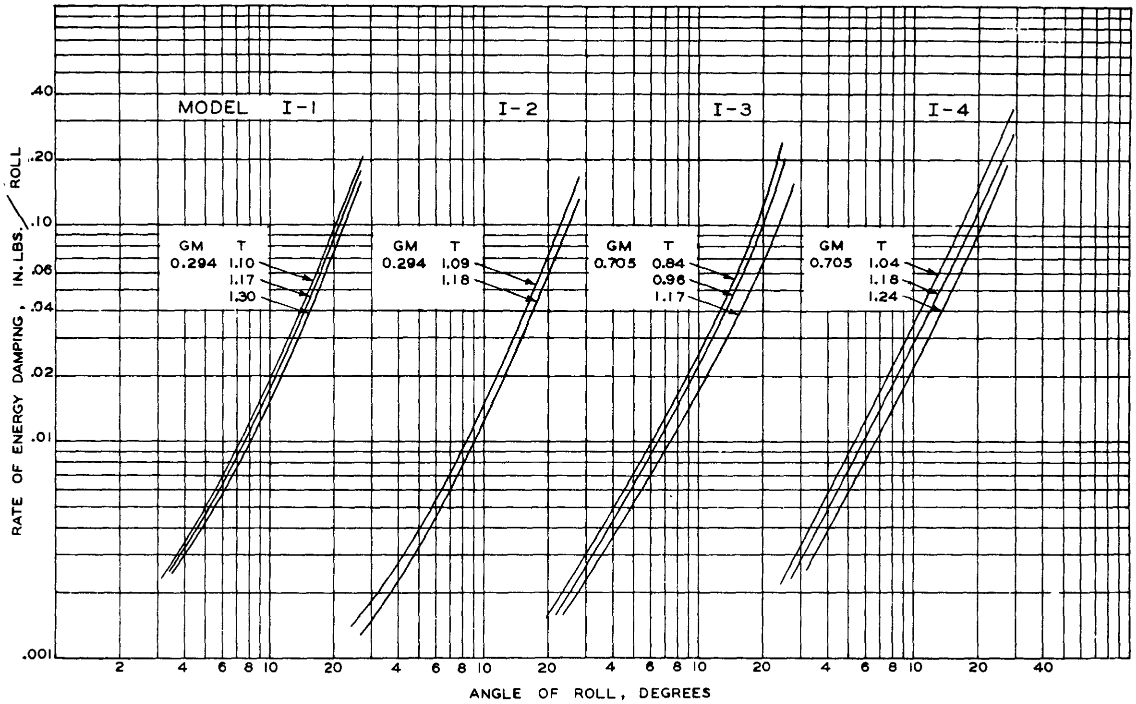


FIG. 19. SERIES I. EFFECT OF CHANGE OF PERIOD ON ENERGY DAMPING

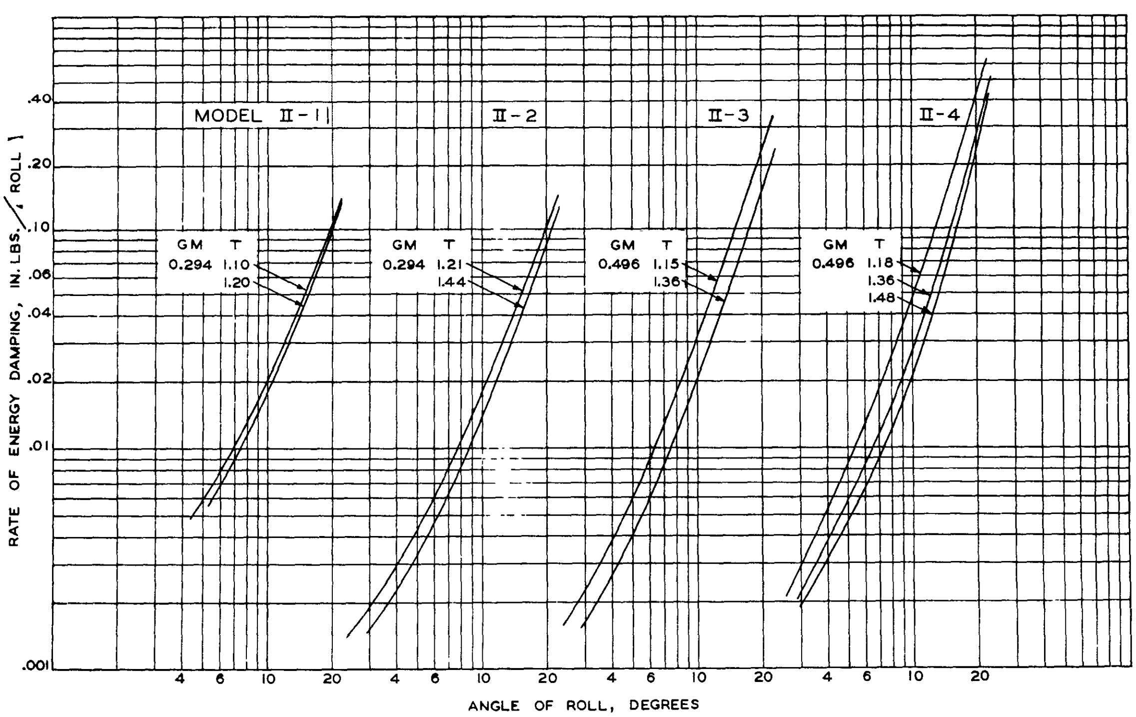


FIG. 20. SERIES II. EFFECT OF CHANGE OF PERIOD ON ENERGY DAMPING

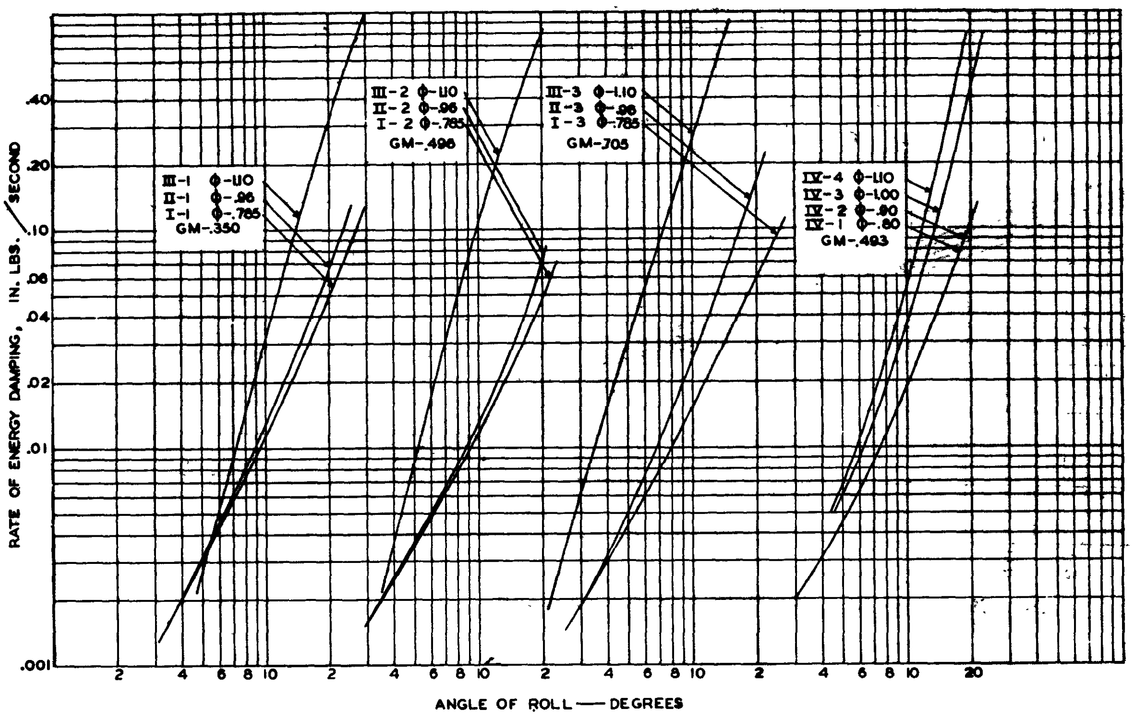


FIG. 21. EFFECT OF CHANGE OF MIDSECTION COEFFICIENT, Φ, ON ENERGY DAMPING. PERIOD OF MODELS - 1.18 SEC.

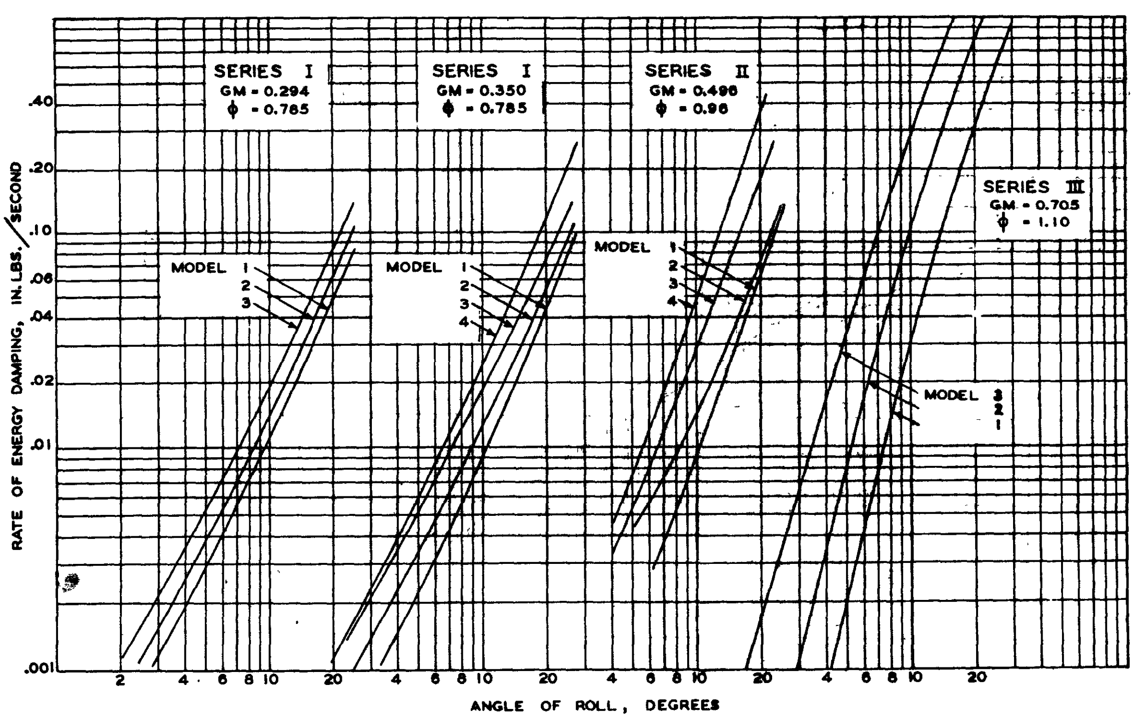
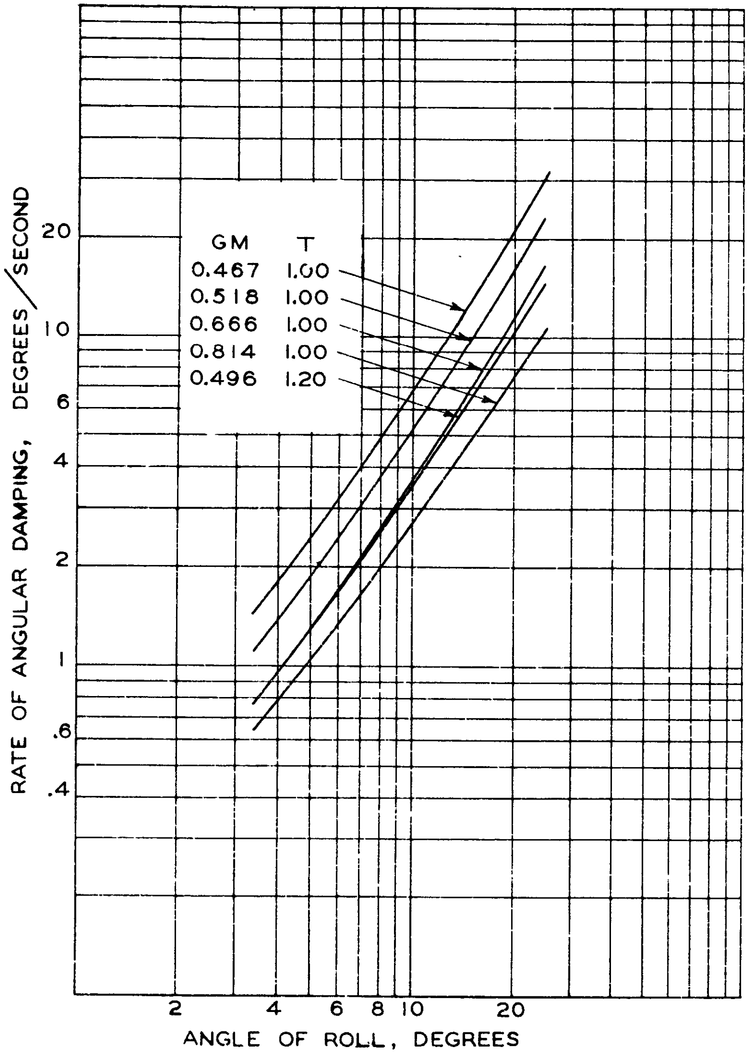


FIG. 22. EFFECT OF CHANGE OF HEIGHT OF "M" ABOVE W.L. ON ENERGY DAMPING. PERIOD OF MODELS - 1.18 SEC.



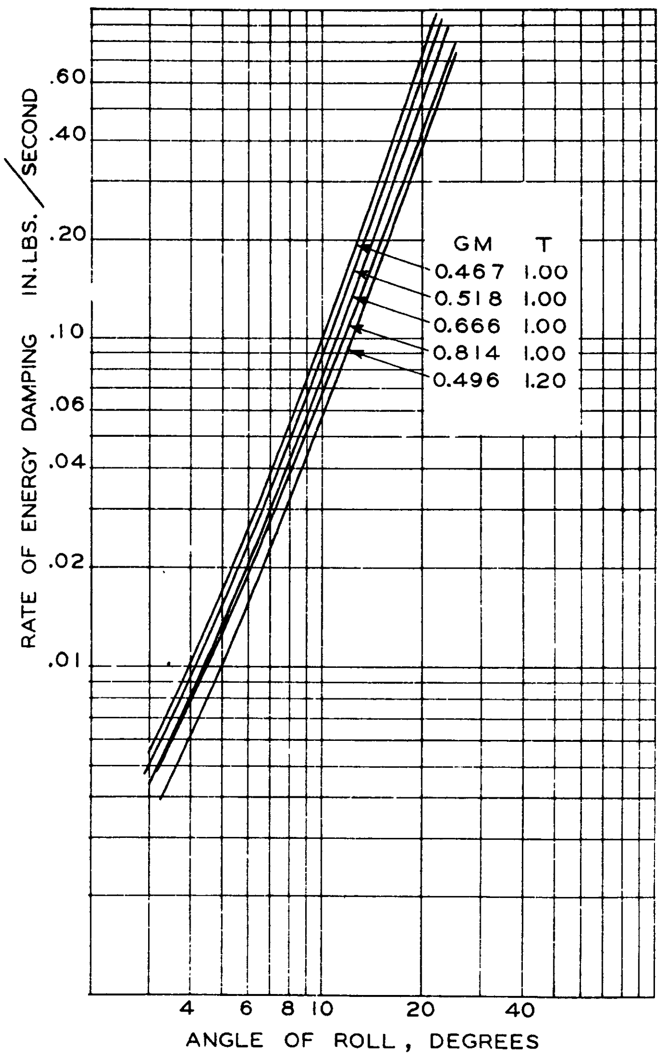


FIG. 23. DAMPING CURVES OF MODEL II-2 WITH BILGE KEELS

APPENDIX 1

PROBABILITY of SYNCHRONISM

In a uniform series of waves the speed of a ship on any course relative to the wave crests to give synchronism with the waves can be computed by the formula

$$V_s \sin \psi = V_w (1 \pm T_w/T_s)$$

where V_s = speed of ship T_s = period of ship

V_w = speed of wave T_w = period of wave

When the length L of a wave is known, V_w and T_w may be computed from the formulae:

$$V_w = 1.34\sqrt{L} \text{ knots}$$

$$T_w = 0.44\sqrt{L} \text{ seconds}$$

Using these formulae the following tables were computed, which give the ship speeds necessary on various courses to attain synchronism with given wave trains. The tables are worked out for two ships, one with a period of 17 seconds and the other 12 seconds.

SHIP PERIOD 17 SECONDS

Wave Length, feet	Course Relative to Crest, degrees	Ship's Speed for Synchronism, knots	
200	0		
	15	100 and	47
	30	52	24
	45	37	17
	60	30	14
400	0		
	15	160	49
	30	83	25
	45	58	18
	60	48	15
600	0		
	15	208	46
	30	107	24
	45	76	17
	60	62	14
800	0		
	15	253	39
	30	131	20
	45	93	14
	60	76	12

SHIP PERIOD 12 SECONDS

Wave Length, feet	Course Relative to Crest, degrees	Ship's Speed for Synchronism, knots	
	0		
	15	111 and	35
200	30	58	18
	45	41	13
	60	33	11
	0		
	15	180	28
400	30	93	14
	45	66	10
	60	53	8
	0		
	15	240	13
600	30	125	7
	45	88	5
	60	72	4
	0	nearly synchronous	
	15	300	–5
800	30	150	–2
	45	110	–1.5
	60	90	–1

The tables indicate that a ship can synchronize with 200 foot waves when steaming at speeds greater than the wave speed only when on courses of 60° or more relative to the crest. On these waves at these courses a 400 foot ship would span two crests. The effective wave slope over the length of the ship would be small, and little rolling would be expected. At speeds less than the speed of the wave the 12 second ship can effect synchronism on all courses greater than 15° relative to the crest; the 17 second ship on courses greater than 22°. However, on courses greater than 30°, a 400 foot ship would span two crests.

In waves 400 feet long and more the ships can synchronize with the waves only by steaming slower than the waves. The 12 second ship can synchronize on all courses greater than 13° relative to the crests, the 17 second ship on courses greater than 23°.

In 600 foot waves the 12 second ship can synchronize on headings greater than 6° relative to the crests, the 17 second ship on courses greater than 22°.

In 800 foot waves the 12 second ship can synchronize on all courses greater than 2° by steaming into the sea. The 17 second ship can synchronize on headings greater than 18°.

The data of the tables are plotted in Figures 1 and 2. In these curves the large area of possible synchronism for the 12 second ship and the small area for the 17 second ship show clearly the great benefit of large periods.

Waves less than 200 feet in length have little effect on most ships. Waves longer than 800 feet are rarely encountered. For these reasons the 200 and 800 foot limits were chosen.

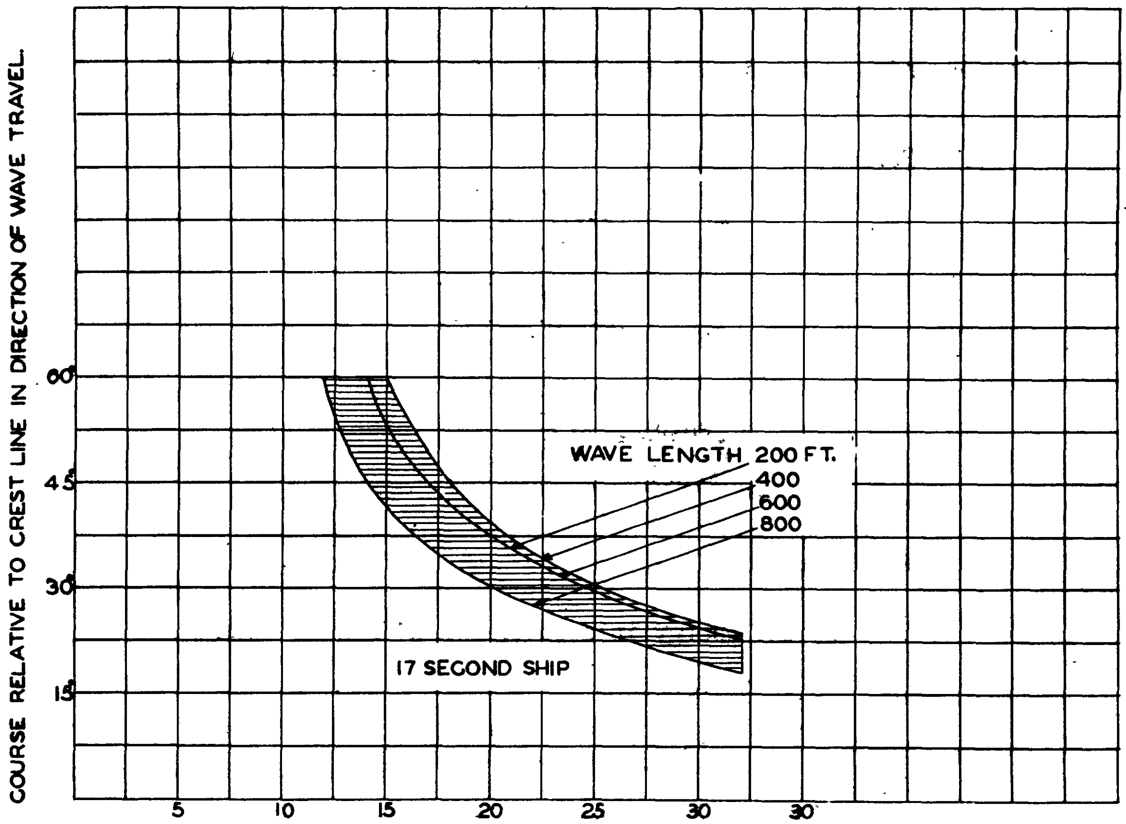


FIG. I. SPEED OF SHIP FOR SYNCHRONISM-KNOTS.

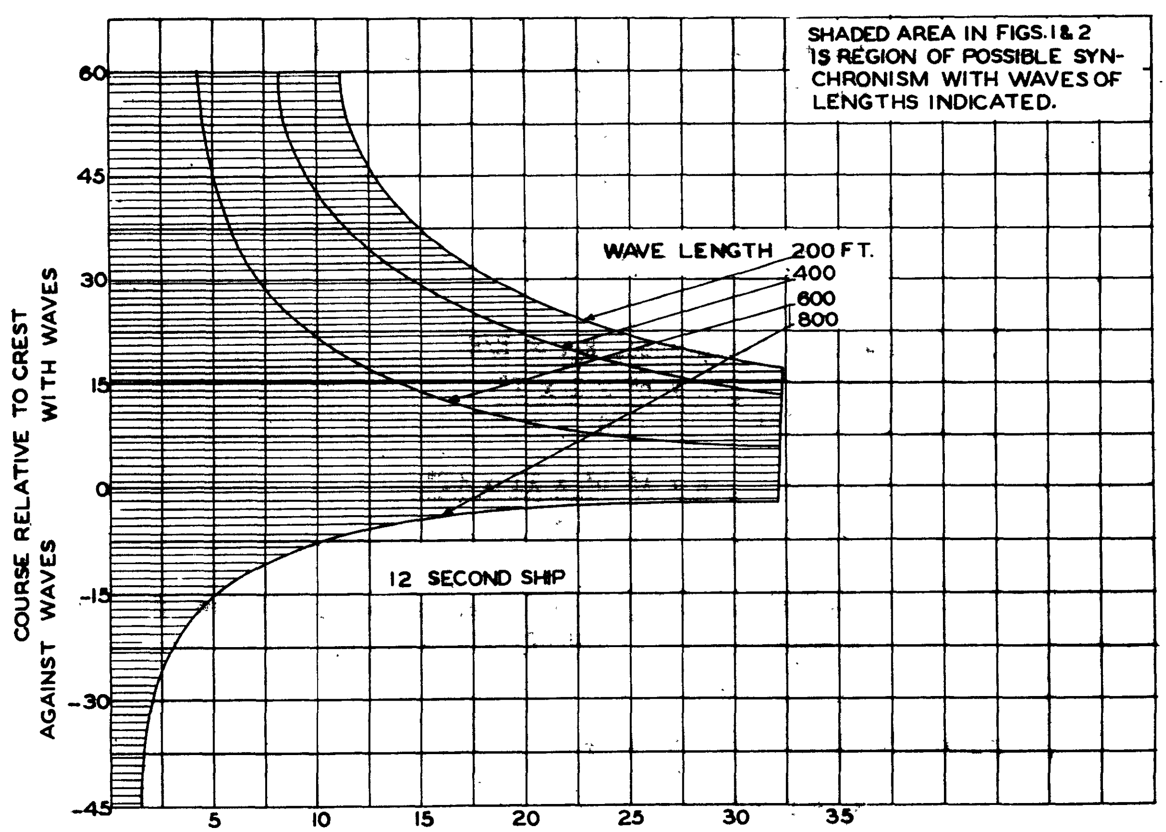


FIG. 2. SPEED OF SHIP FOR SYNCHRONISM - KNOTS.

APPENDIX 2

Corresponding periods and resistances for model and ship

1. Period:

$$T_{model} = 2\pi\sqrt{\frac{K^2}{g \times GM}}$$

$$T_{ship} = 2\pi\sqrt{\frac{\lambda^2 K^2}{g \times \lambda GM}}$$

$$\frac{T_{ship}}{T_{model}} = \sqrt{\lambda}$$

2. Wave Energy:

E, the energy in a wave, $= A\ H^2\ F\ L$ where

H is wave height
F is length of wave front
L is wave length
A is coefficient

In a wave generated by a model in rolling:

$H \propto$ the beam and angle of roll or $b \times \theta$
$F \propto$ the length l of the model
$L \propto T^2$, from Appendix 1

$$E_{model} = A \times b^2 \times l \times T^2$$

$$E_{ship} = A \times \lambda^2\ b^2 \times \lambda l \times \lambda T^2$$

3. Wave-Making Resistance, R_w, $\propto E/H$

$$R_{w\ model} = \frac{A \times b^2 \times l \times T^2}{H}$$

$$R_{w\ ship} = \frac{A \times \lambda^2\ b^2 \times \lambda l \times \lambda T^2}{\lambda H}$$

$$\frac{R_{w\ ship}}{R_{w\ model}} = \lambda^3$$, which is according to the law of comparison.

4. Frictional Resistance, R_f

$$R_f = K\ S\ V^n$$

$V \propto b(\theta/T)$

$S \propto l^2$

In the model, $V^n = V$ (laminar flow)

In the ship, $V^n = V^2$ (turbulent flow)

$$R_{f\ model} = K\ l^2\ T$$

$$R_{f\ ship} = K\ \lambda^2\ l^2\ \lambda^{\frac{1}{2}}\ T$$

$$\frac{R_{f\ ship}}{R_{f\ model}} = \lambda^{5/2}$$, which is not according to the law of comparison.

5. Computation of Height of Wave a Model Would Have to Generate if all the Damping of Roll were Wave-Making.

Take Model II-2 with GM = 0.496 inches and T = 1.18 seconds

The declining angle data for this model are as follows:

No. Roll	θ	time
1/2	25°	
1	23°5	0
2	20°5	1.11
3	18°5	2.23

Between rolls 1 and 2 the model damped 3°, i.e. from 23°5 to 20°5. The GZ at 22° is 0.233 inches.

The energy damping is:

$$W \times GZ \times \Delta\theta = 10.21 \times 0.233 \times 3/57.3 = 0.125 \text{ in. lb.}$$

The wave length corresponding to the model period of 1.11 sec. for this roll is 6.9 ft. or 83 inches.

The energy in a wave = A H^2 F L approximately.

In this case F = length of model = 20 inches.

L = 83 inches.

$$A = W/8 = \frac{62.4}{8 \times 1728} = 0.00451$$

then

$$E_w = 0.00451 \times H^2 \times 20 \times 83 = 0.125 \text{ in. lb.}$$

$$H = \sqrt{\frac{0.1246}{0.00451 \times 20 \times 82.8}} = 0.129 \text{ inches}$$

If the model in this roll had generated a wave 1/8 inch high (crest to trough) all the damping energy would have been expended in wave making. It is thus seen that only a very small wave is necessary to absorb the energy.

APPENDIX 3

BEHAVIOR of 10,000 TON CRUISERS in WAVES

One of the heavy cruisers reported the following rolling:

	TIME	ANGLE of ROLL (SINGLE ROLLS, PORT to STARBOARD, or VICE VERSA.
1.	6.0 sec.	22°.5
2.	5.3 sec.	26°.5
3.	5.2 sec.	29°
4.	5.0 sec.	26°
5.	6.5 sec.	42°
6.	6.3 sec.	44°
7.	5.0 sec.	41°
8.	5.2 sec.	29°
9.	5.6 sec.	33°
10.	6.3 sec.	26°
11.	6.0 sec.	27°
12.	6.2 sec.	43°

True wind 40 knots - direction from 55° (t).

Sea - heavy seas from 45° (t).

Observations taken at sea, steaming at 15 knots, course 311°(t). The readings were taken from the scale of the clinometer in the after engine room instrument board, from extreme of port roll to extreme of starboard or vice versa, thus timing single rolls.

From this information the probable wave length and period are derived as follows. In a well established sea, the speed of the waves is generally less than the speed of the wind. Assuming the wave speed as 36 knots (10 per cent less than wind speed) the wave length by the formula

$$V = 1.34\sqrt{L} \quad \text{(V, knots; L, feet.)}$$

is

$$L = (36/1.34)^2 = 722 \text{ feet.}$$

The corresponding wave period is

$$T = 0.442\sqrt{L} = 11.9 \text{ seconds.}$$

In the rolling data given, the average period of the ship for the rolls over 40° (rolls 5, 6, 7, and 12) is 6.0 seconds. This is nearly the natural half-period of the ship. The period therefore is about 12 seconds.

The angles reported were measured from side to side. The actual roll of the ship from the vertical is one-half the value given as roll.

The computed period of the waves, 11.8 seconds, is so close to the period of the ship, 12 sec., that there is little doubt that the ship and waves were synchronous when the heaviest rolling occurred. So if a wave of 12 sec. period is taken:

$$L = (T/0.44)^2 = 745 \text{ feet}$$

With the ship on course 311° and the sea from 45° the relative direction of the sea was from 94°. In other words the ship was in the trough of synchronous waves 745 feet long.

The clinometer in the engine room is about 20 feet below the axis of roll (taken as in the water plane). The maximum reading is 44° side to side or 22° on a side. Corrected for clinometer location, (Appendix IV), this roll is

$$\theta = \theta_o \times \frac{3.27\, T^2}{3.27\, T^2 - h} = \frac{3.27 \times (12)^2}{3.27 \times (12)^2 - 20} \times 22^\circ = 23^\circ .$$

The actual roll of the ship was 23°.

In the report from the ship no estimate of wave height is given other than the notation "heavy seas." In a later reference to the same occasion the seas were described as moderate. Since no wave height is given, the problem of estimating the ship's roll from the model will be worked backwards. That is, the roll of the ship will be taken as 23° in synchronous waves 745 feet long and from the model data the wave height necessary to cause this roll will be derived.

The only declining angle curve at hand for this type of ship underway at 15 knots was for a 20-foot model and it did not extend beyond 11°. This curve was extended as a straight line to 30° on semi-log coordinates. Any error introduced by this method was on the safe side as the declining angle curves at large angles rise above the straight line. From the semi-log paper a declining angle curve was drawn from 30° on coordinate paper.

At 23° on this declining angle curve the slope or loss of angle per roll is 7°.2. This decrement is π x the wave slope. Therefore $7.2/\pi$ = wave slope = 2.29 degrees. Assuming this as the slope of the wave at the center of buoyancy, the slope at the surface is:

$$\gamma_s = \gamma / e^{-\frac{2\pi d}{L}} = 2.54 \text{ degrees}$$

The slope of a wave is given by:

$$\text{Slope} = \pi \times H/L \times 57.3$$

$$H = \frac{2.54 \times 745}{\pi \times 57.3} = 10.5 \text{ feet}$$

While this wave height may be too small the computation serves as an example of the method. If an error exists it lies in the extrapolation of the existing declining angle curve beyond 11°. It is evident that a curve whose upper limit is 11° cannot be extended and used for values around 25° with a great degree of certainty.

APPENDIX 4

CLINOMETER ERROR

It is generally knownthat a clinometer of the short pendulum type will, unless mounted on the axis of roll, indicate an angle at variance with the true angle of heel. This discrepancy is due to the acceleration of the point of support of the pendulum, and is the greater the farther the point of support is removed from the axis of roll. A clinometer of this type above the axis of roll indicates too large an angle, below the axis of roll too small an angle.

The theory of the pendulum type clinometer is that the pendulum will remain in a vertical line through the point of suspension while the scale moves past it with the ship. This condition is shown in Fig. 1.

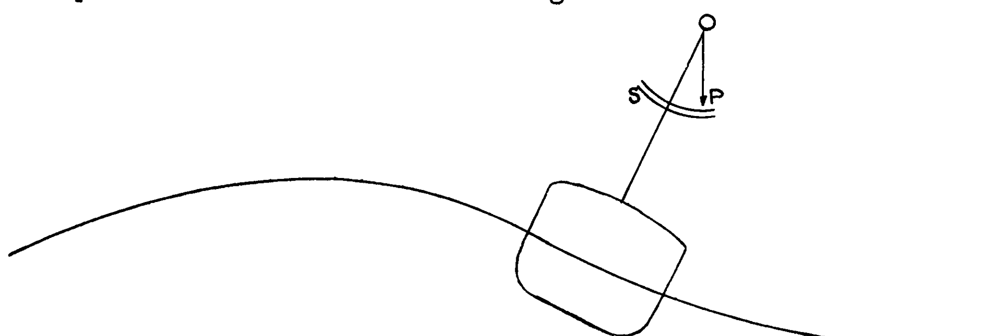


FIG. 1.

O is the point of support of the pendulum OP.
S is the scale secured to the mast and rolling past the pendulum.

Unfortunately the pendulum will not hang in a vertical line through the point of support as shown in Fig. 1. The motion of roll of the ship causes the point O to oscillate about an upright position with varying acceleration. The greater the acceleration of the point of support the greater the deviation of OP from the vertical.

Suppose we have a point of support of a short pendulum as indicated in Fig. 2, the point of support being accelerated as shown and constrained to move

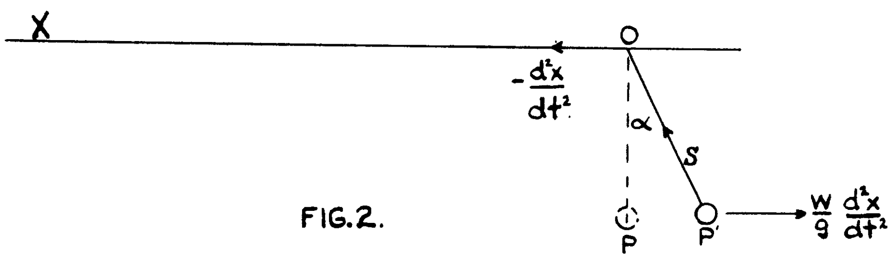


FIG.2.

along OX. If there were no acceleration, the pendulum would hang vertically as at OP, assuming no air resistance. Now as O is accelerated to the left out of the vertical line OP, an additional tension is set up in the cord OP. The vertical component of the total tension balances the weight of the bob P. The horizontal component accelerates the bob, the accelerating force being $-\frac{W}{g}\frac{d^2x}{dt^2}$. The bob will lag behind the point of support until an angle α is reached such that the horizontal component of tension in the cord is equal to $-\frac{W}{g}\frac{d^2x}{dt^2}$.

At the end of a roll the acceleration of a ship is greatest and at the end of a roll the clinometer supposedly indicates the maximum angle of roll attained by the ship. However, as shown previously, the deviation of the pendulum is greatest when the acceleration of the point of support is greatest. Thus the reading of maximum angle on the clinometer contains the maximum error.

A point on a rolling ship, except at large angles of roll, moves approximately in simple harmonic motion. At the maximum angle of swing in such motion the acceleration is:

$$\frac{d^2\theta}{dt^2} = \frac{4\pi^2}{T^2}\,\theta$$

Where: T is the period of the ship.
θ is the maximum angle of swing to either side.

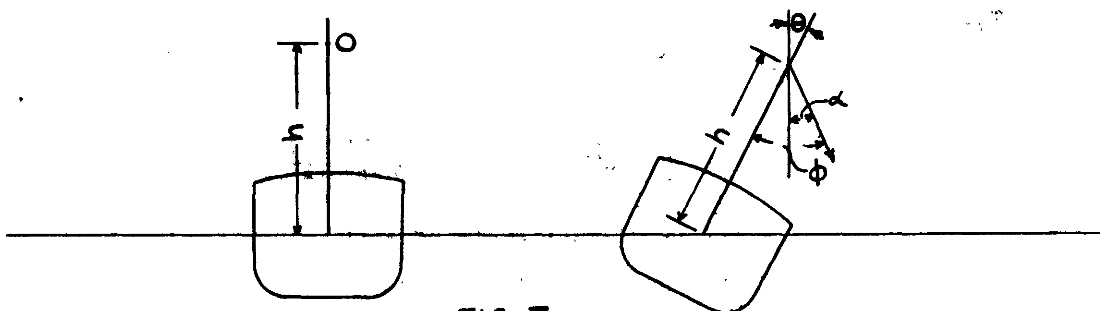


FIG. 3.

In Fig. 3, O is the point of support of the short period pendulum clinometer. h is the height of O above the axis of roll. θ is the maximum angle of roll. ϕ is the clinometer reading, α the deviation of the pendulum from vertical.

$$\text{Then} \quad \theta = \phi - \alpha .$$

From the reasoning of Fig. 2, α is an angle such that if S be the tension in the cord:

$$S \cos\alpha = W$$

$$S \sin\alpha = \frac{W}{g}\, h \,\frac{d^2\theta}{dt^2} \quad \text{(approx.)}$$

$$S = \frac{W}{\cos\alpha}$$

$$\frac{W}{\cos\alpha}\sin\alpha = \frac{W}{g} h \frac{d^2\theta}{dt^2}$$

$$\tan\alpha = \frac{h}{g}\frac{d^2\theta}{dt^2} = \frac{h}{g}\frac{4\pi^2}{T^2}\theta$$

$$\alpha = \frac{h}{g}\frac{4\pi^2}{T^2}\theta \quad \text{(approx.)}$$

$$\theta = \phi - \alpha = \phi - \frac{h}{g}\frac{4\pi^2}{T^2}\theta$$

$$\theta\left(1 + \frac{h}{g}\frac{4\pi^2}{T^2}\right) = \phi$$

Now from the pendulum formula, for a length of pendulum L

$$T = 2\pi\sqrt{\frac{L}{g}}$$

$$\frac{4\pi^2}{T^2} = \frac{g}{L}$$

$$L = g\frac{T^2}{4\pi^2} = \frac{g}{\pi^2}\left(\frac{T}{2}\right)^2 = 3.27\left(\frac{T}{2}\right)^2$$

Then:

$$\theta\left(1 + \frac{h}{g}\frac{4\pi^2}{T^2}\right) = \theta\left(1 + \frac{h}{g}\frac{g}{L}\right) = \phi$$

$$\theta = \phi\left(\frac{L}{L + h}\right) = \phi\,\frac{3.27(T/2)^2}{3.27(T/2)^2 + h}$$

s where θ is the actual angle of roll,
T is the period of the ship,
h is the height of the clinometer above the axis of roll, which axis may be assumed at the water line,
ϕ is the clinometer reading.

EXAMPLE:

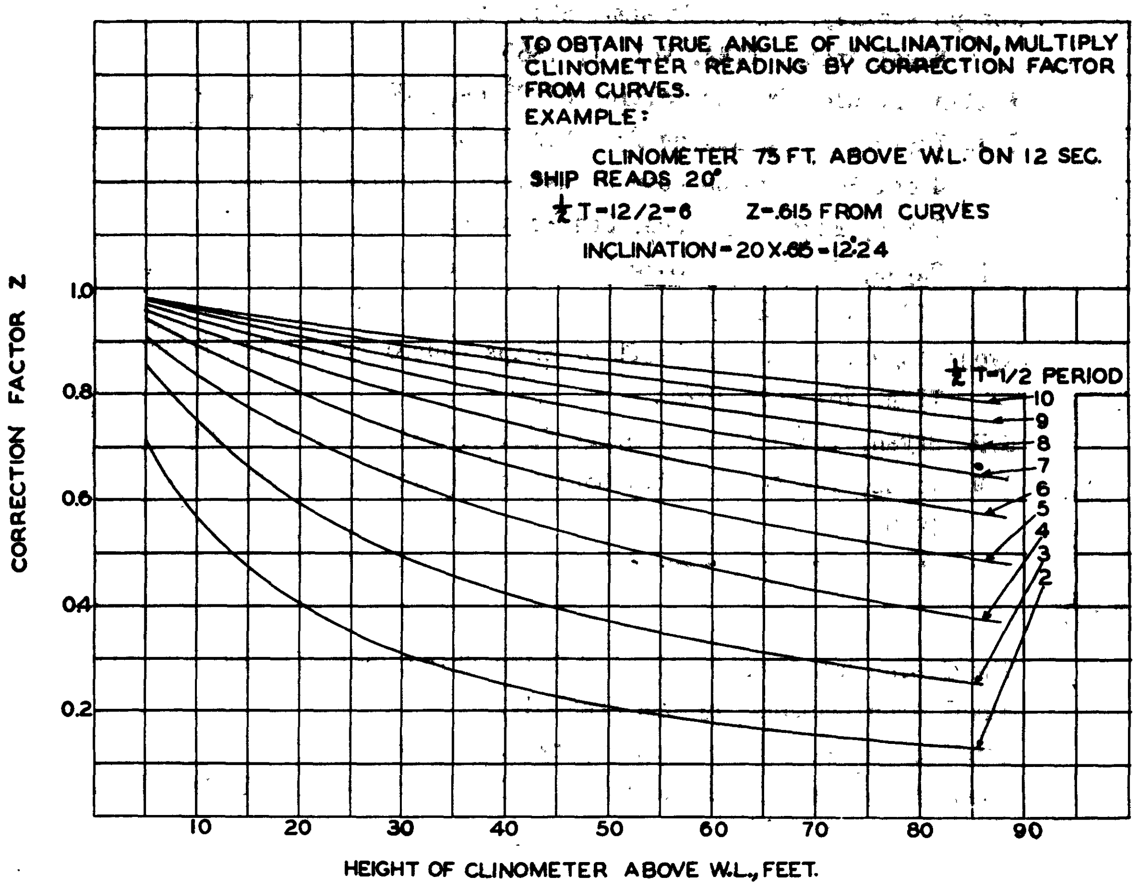
If the bridge of a 12 second ship is 75 feet above the water line, a clinometer mounted there must be corrected as follows:

$$\theta = \phi\,\frac{3.27 \times (6)^2}{3.27 \times (6)^2 + 75} = \frac{117.5}{117.5 + 75} = 0.61\,\phi$$

If the clinometer reading were 20°, the actual clination would be 0.61 of 20° or about 12°

When the clinometer is below the axis of roll h is applied in the formula in the negative sense.

Curves have been plotted for various heights of clinometer above the water plane and various periods of roll, which give the correction factor to multiply into the clinometer reading to get the true angle of heel.



APPENDIX 5

LIST of REFERENCES

A Papers

Joseph Woolley, On the Present State of the Mathematical Theory of Naval Arch., TINA, Vol. I, 1860.

William Froude, On the Rolling of Ships, TINA, Vol. II, 1861.

D.W. Taylor, Calculations for Ship's Forms and the Light Thrown by Model Experiments upon Resistance, Propulsion, and Rolling of Ships, Engr. Congress, San Francisco, Cal., U.S.A., 1915.

M.P. Payne, Results of Some Rolling Experiments on Ship Models, TINA, Vol. 66, 1924.

Kyoji Suyehiro, On the Drift of Ships caused by Rolling Among Waves, TINA, Vol. 66, 1924.

G.H. Bryan, The Action of Bilge Keels, TINA, Vol. 42, 1900.

A.W. Johns, The Accelerated Motion of Bodies in Water, TINA, Vol. 51, 1909.

B Texts

The Design and Construction of Steam Ships, Vol. II, by J.H. Biles.

Naval Architecture, by C.H. Peabody.

Studies in Naval Architecture, by A.M. Robb.

Theoretical Naval Architecture, by E.L. Attwood and H. Pengelly.