UNITED STATES EXPERIMENTAL MODEL BASIN

NAVY YARD, WASHINGTON, D.C.

DISCONTINUOUS ANTI-ROLLING KEELS

BY J. G. THEWS

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

MAY 1938

REPORT NO. 450

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Introduction:

The primary function of bilge keels on a ship is to increase the ship's resistance to rolling motion; i.e., to increase angular damping. The best keels, from a power point of view, are those which increase the angular damping most for a given increase of ship resistance to forward motion.

In the conventional bilge keels a given area is usually utilized in the shape of two long longitudinal strips, one on either side of the hull in the lines of flow on approximately the turn of the bilges. The purpose of this investigation is to determine what gains, if any, can be obtained by holding wetted surface area constant but breaking up the given area of these continuous strips into rows of fins of various length-width ratios. See Table 2 and Figures 1, 2, 3, and 4. A ratio such as

$$\frac{\text{Increase in angular damping provided}}{\text{Increase in E.H.P. due to adding the bilge keels}}$$

may serve as a criterion for evaluating comparative performance.

There are other factors, however, that will also determine whether or not long keels or discontinuous keels as fins are most desirable. The long continuous keels may be made to serve as longitudinal strength members as well as anti-rolling keels. Discontinuous sections or fins may require additional strength in the hull to carry them. Also, long, narrow fins protruding from the sides of the ship may have undesirable features as for example when docking.

Theory:

There appears to be a fundamental difference in the manner in which anti-rolling moments are produced in the two mentioned cases: (a) continuous bilge keels, and (b) fins or hydrofoils. The continuous keels work by obstructing the flow of water around the bilges, producing moments opposing the rolling motion. The discontinuous keels act essentially as hydrofoils where the maximum value of the tangent of the angle of attack is given by the ratio:

$$\frac{\text{Linear velocity in angular motion}}{\text{Model's velocity in forward motion}}$$

It would thus appear that the continuous type of keel is more or less fully effective at all speeds. On the other hand since the fins are most effective when working at some best angle of attack, they should be least effective at zero speed, and most effective at some particular speed. It is conceivable that the fins could be "activated" so as always to be working at the best angle of attack. However, as will be shown later, this may lead into complicated if not practically impossible control mechanisms.

Apparatus and Procedure:

This investigation was conducted in the U. S. Experimental Model Basin with a twenty foot model of the aircraft carrier CV-7.

The apparatus used consisted of the following elements:

(1) Model 3400 permanently fitted with rudder, horn, shafts, and struts.
(2) The series of five sets of bilge keels.
(3) A mechanical rolling gear of the type described in U.S.E.M.B. Report No. 433 but equipped with a three phase motor.
(4) Three phase, portable, motor-generator unit.
(5) Sperry gyro roll recording gear.
(6) Level.
(7) Stop watch.
(8) Carriage and the towing dynamometer of the model basin.

The model was tested for six conditions of roll damping: one condition - model without bilge keels, and five conditions - the model equipped successively with the five sets of the series of bilge keels.

The different sets when applied to the model were mounted on the same stream line on the turn of the bilge. The discontinuous keels were mounted so as to divide into equal spaces the space covered by the continuous, No. 1, set of keels.

For each condition the model was loaded and adjusted to the same rolling period and metacentric height when at rest. For model characteristics see Table 1.

TABLE 1

CHARACTERISTICS OF MODEL 3400
Representing Aircraft Carrier Class CV-7

Characteristic	Model	Ship
Length	20.0 ft.	690.0 ft.
Beam	2.34 ft.	80.6 ft.
Draft	0.64 ft.	22.2 ft.
Displacement	916.2 lb.	17,200 T.
Metacentric Height (V=0)	1.88 in.	5.4 ft.
Rolling Period	2.82 sec.	16.6 sec.
Wetted Surface Area:		
(a) Hull + rudder, horn, shafts and struts	46.40 S.ft.	55,200 S.ft.
(b) Above + the area of a set of bilge keels	48.24 S.ft.	57,400 S.ft.

Length Ratio $\lambda = 34.5$, $\lambda^2 = 1190$, $\lambda^3 = 41,080$

$\sqrt{\lambda} = 5.87$

The series of bilge keels is described in Table 2, and by Figures 1 and 2. Figure 3 shows the model equipped with bilge keel set No. 5.

The model was tested for rolling in still water at the North end of the Model Basin. Figure 4 shows the mechanical rolling gear and the recording gear in the model. To prevent drift the model was secured lightly with rubber bands under 0.1 pound tensions at the bow and stern. The points of attaching these bands were on the approximate rolling axis of the model so as to insure a minimum of interference from their tensions with the free rolling of the model.

The model was check-tested for rolling at zero speed under the carriage, as well as for rolling and resistance at three and five knot speeds. In a few cases several other speeds were also used. For towing, the model was secured to the dynamometer by means of a light, flexible line five feet long. The line was attached to the model at the bow about two inches above the water line, the point in the approximate rolling axis, so as to reduce to a minimum the interference of tow line tension with free rolling.

All measurements were made for synchronous rolling, i.e., the model rolling in its own period. The criterion of synchronous rolling was that the phase relation between the maximum value of the harmonic torque delivered by the rolling gear and the maximum angle of heel of the model in rolling should be ninety degrees.

It was a simple matter to establish synchronous rolling when the model was not under way. In this case the period of the generator was varied slowly by varying the speed of the motor-generator unit until the period for which the model rolled a maximum amount was obtained. Allowing a few minutes for conditions to steady, and to note that the criterion of the ninety degree phase relation was satisfied, the rolling period was taken with a stop-watch and the amplitude of rolling recorded for an interval of at least ten steady rolls on the roll recorder.

When under way the duration of a run was usually too short to allow much adjustment of the period. Then it was necessary to make a number of runs before a successful run satisfying the above criterion could be obtained. Here again the period of rolling was measured with a stop-watch, and the amplitude of synchronous rolling recorded by the roll recorder. Model resistance measurements were made during all of the runs.

TABLE 2

CHARACTERISTICS OF THE SERIES OF BILGE KEELS

Bilge Keel Set No.	W.S.A. Sq.Ft.	Type of Keel	No. per Side on Model	Dimensions: Normal to Model's Length	Dimensions: Parallel to Model's Length
1	1.84	Continuous	1	1.15 in.	57.8 in.
2	1.84	Discontinuous	8	1.81	4.60
3	1.84	Discontinuous	8	2.87	2.88
4	1.84	Discontinuous	8	5.00	1.67
5	1.84	Discontinuous	8	7.06	1.18

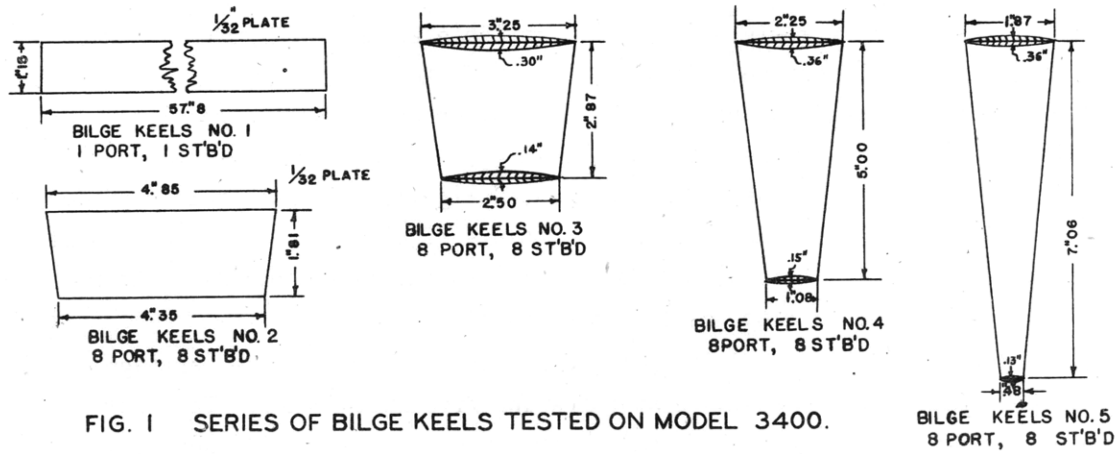

FIG. 1 SERIES OF BILGE KEELS TESTED ON MODEL 3400.

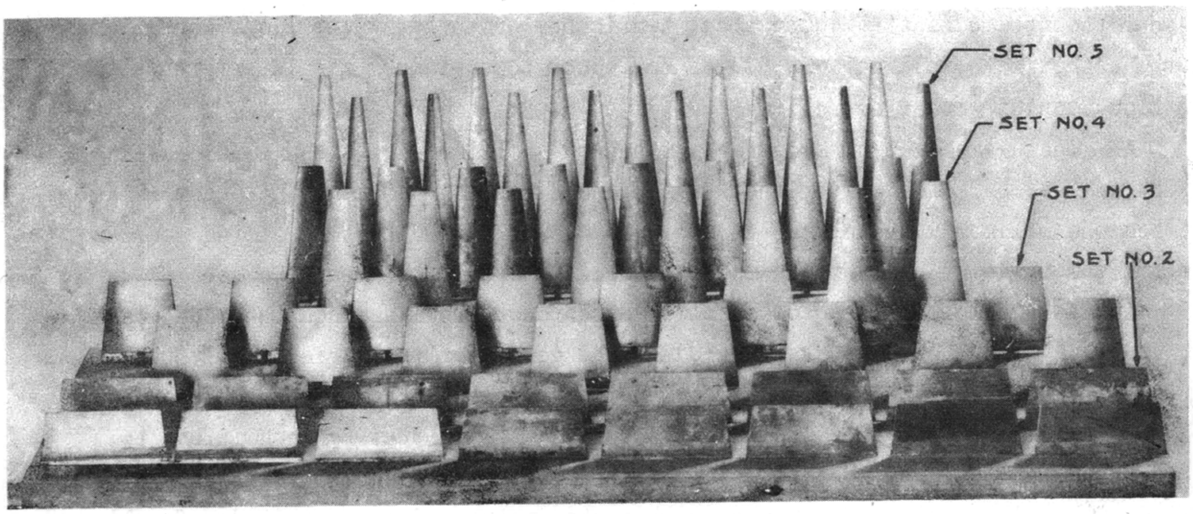

FIG. 2 DISCONTINUOUS BILGE KEEL SETS 2, 3, 4, & 5.

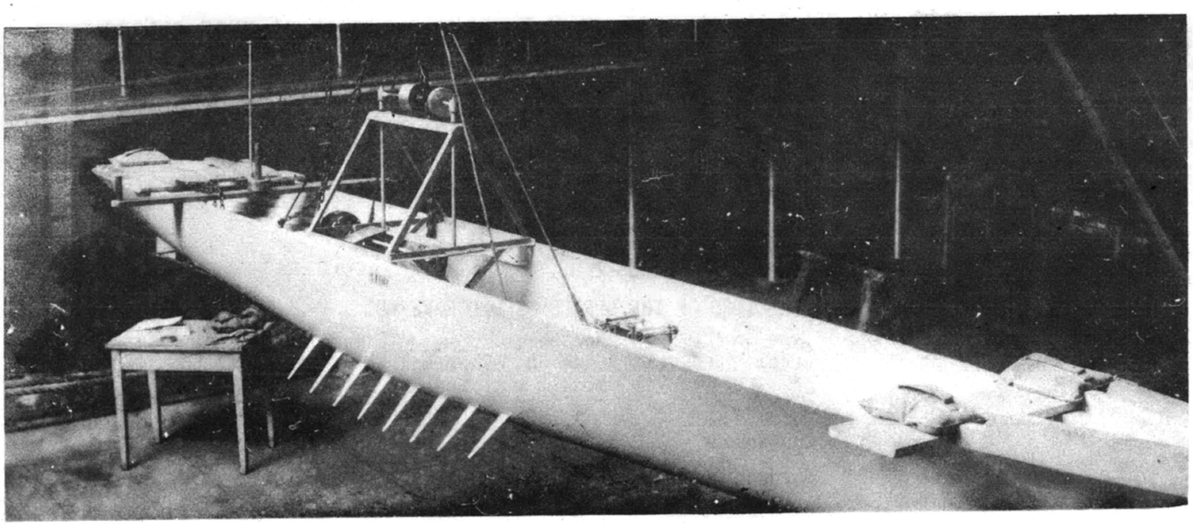

FIG. 3. MODEL 3400 WITH BILGE KEEL SET NO. 5 .

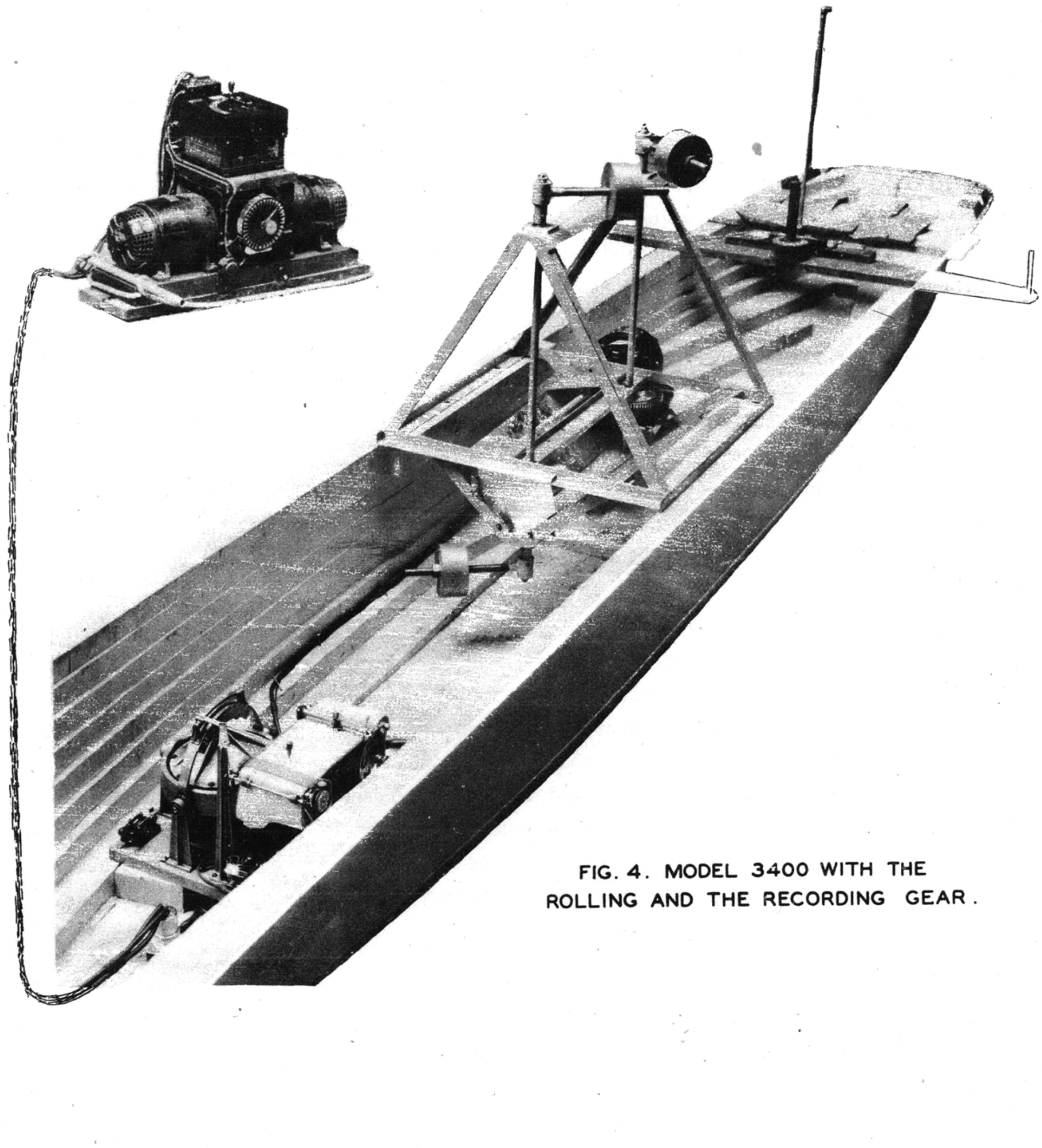

FIG. 4. MODEL 3400 WITH THE ROLLING AND THE RECORDING GEAR.

Results:

The experimental results of this work are given in Figures 5 to 15. In the first nine the results are in terms of total angular damping, $d\Theta/dN$, against the maximum angle of heel in rolling. It is used here as a direct measure and as a means for comparing the anti-rolling qualities of the various model conditions tested. Theoretically, angular damping varies directly as the slope of the synchronous waves required to produce a given angle of heel in rolling. A more complete discussion of this is given in the Appendix and in U.S.E.M.B. Report 433.

Figure 5 gives the angular damping for Model 3400 when without bilge keels. It shows the variation of damping with the angle of heel in rolling and also that damping increases greatly with model speed.

When testing the model in this condition of no bilge keels it was noted that the rolling period of the model for small rolling angles decreased with increasing speed. Since the absolute value of the damping on the model when in this condition is low, the decrease in period was taken as indicating a change in the stiffness or GM of the model from its value at zero speed. The effect of a change in speed and angle of heel on GM, and of a change in GM on angular damping is discussed in the Appendices. The magnitude of this change in period with speed, except for the five knot speed, is not particularly great. At three knots the decrease is about two per cent implying a change of four per cent in GM.

Figs. 6, 7, 8, 9, and 10 give angular damping against the angle of heel in rolling for different speeds when the model is equipped with the indicated sets of the series of keels. In each case angular damping increased greatly with speed.

In order to show comparative total damping as provided by the different sets of keels another set of plots is presented in Figures 11, 12, and 13. These three figures show respectively the total angular damping for each of the six model conditions tested at speeds of zero, three, and five knots. Figure 11 shows that the total damping decreases in the order of increasing bilge keel set number. Thus set No. 1 provides the greatest increase in angular damping and set No. 5 the least.

At speeds of three and five knots, as is shown in Figures 12 and 13, this order is reversed. Moreover it is noted that the increase in total angular damping in the order of increasing bilge keel set numbers is particularly large. However, it is also to be noted, see Figure 14, that the resistance of the model increases about proportionately with this increase of damping. The variation of added bilge keel resistance with speed for the various sets is summarized in Table 3. Bilge keel set No. 1 has the lowest values for both coefficient and exponent. The apparent reasons for this are, that of all the sets, No. 1 lies most completely within the boundary layer around the moving model and also that it has the minimum of form resistance. On the other hand, set No. 5 has the highest values for both these factors. No. 5 extends farthest through the boundary layer, and due to having the greatest thickness-width ratio it would have the most form resistance. Thickness is essential in the longer fins for obvious strength requirements. The results for the other sets of keels lie more or less in proportionate order between the results for sets Nos. 1 and 5.

The above thus indicates that although for speeds of 3 and 5 knots, the angular damping due to the fins increases, the resistance to forward motion also increases. When these results are summarized in terms of the ratio

$$\frac{\text{per cent increase in damping}}{\text{per cent increase in resistance}},$$

see Tables 5 and 6, the different sets show up about equally well for the above speeds and for the model rolling at 4 and 6 degrees to a side.

Table 4 was computed to determine the maximum values of the angles of attack at which the fixed discontinuous bilge keels or fins were working for the different conditions of speed and angles of heel in rolling. It shows that this angle is rather low at five knots but excessive at low speeds for most effective action. That these angles of attack were excessive at low speeds is also indicated by the breakdown of the lift in damping for these conditions in bilge keel sets Nos. 4 and 5. See breaks in the angular damping curves in Figures 9 and 10.

Concerning the effect of the rolling of a model on its resistance, Figure 15 indicates that contrary to popular belief the resistance of a model is practically independent of its angle of heel in rolling, within the limits of rolling obtained. Thus while forward motion increases roll-damping, the converse is not true.

Conclusions:

In general the results of this investigation indicate that for this model, or its prototype, continuous bilge keels are most desirable.

They give most damping at zero speed, the condition where excessive rolling is most probable and greatest damping is most required. At the various model speeds all of the bilge keel sets give approximately the same percentage increase in damping for the same per cent increase in model resistance over the bare hull condition.

The continuous keels are the simplest in design, serve as strength members, and do not require extra strength in the frames of the ship for carrying them as would be the case for fins.

Protruding fins are objectionable for reasons such as space requirements when docking, and for coming alongside other vessels.

However, since bilge keel set No. 2 on the whole gives as much or slightly more damping for a given increase in resistance as compared with set No. 1, a few discontinuous sections as extensions for a continuous set of keels could be used to advantage in those cases where the lines of flow do not follow the turn of the bilges for a sufficiently great length to accommodate extremely long continuous keels should bilge keel area, extended in length, be desirable.

Fins could be activated but the results indicate that this would call for complicated control mechanisms. At some speeds and angles of heel in rolling the angle of attack should be increased to obtain more effective damping action. But if this is done, the resistance of the fins to forward motion also increases and the net gain may again be about zero. In other conditions, those equally if not more important, i.e., the slow speeds, the natural fixed angle of attack should actually be decreased. Complicated controls would be required to make the fins meet both of these requirements. At zero speed, activation is obviously useless.

The above is not meant to imply that under some conditions of speed and rolling an auxiliary set of retractable, activated fins would not be an aid in producing approximately complete roll stabilization. Its useful range of activity though would appear to be quite limited.

The summary of the results and considerations noted in this report, then, strongly indicates that for general and adequate, reliable, all purpose damping the continuous type of bilge keel is most desirable. It may be augmented with discontinuous sections at the ends, or augmented with a few pairs of activated fins, but it remains primary.

TABLE 3

VARIATION OF THE INCREASE IN MODEL RESISTANCE WITH SPEED DUE TO THE ADDITION OF BILGE KEELS

Bilge Keel Set	Resistance in Pounds
No. 1	$R = 0.021\ A\ V^{1.60}$
No. 2	$0.028\ A\ V^{1.63}$
No. 3	$0.040\ A\ V^{1.74}$
No. 4	$0.055\ A\ V^{1.80}$
No. 5	$0.096\ A\ V^{1.81}$

Where: V is model speed in knots, and
A is wetted surface area of a bilge keel set.

In this investigation the area was the same for all the five sets, i.e., 1.84 sq.ft.

The above resistance is the difference in model resistance when it is equipped with and when without the indicated bilge keel set. The variation of the exponent is due to at least two factors: (a) wake and (b) form or thickness. Set No. 1 is thin and a large part of its area lies in the wake near the hull. Its exponent in the resistance formula is smallest. Set No. 5 is thick and a large part of its area extends out beyond most of the wake. Its exponent in the resistance formula is largest.

TABLE 4

THE APPROXIMATE MAXIMUM VALUES OF THE ANGLE OF ATTACK AT VARIOUS SPEEDS AND ANGLES OF HEEL IN ROLLING

Angle of Heel in Rolling, Degrees	Forward Speed of Model in Knots			
	0.5	1.0	3.0	5.0
	Angle of Attack			
2	7.7°	3.8°	1.3°	0.8°
4	15.2	7.7	2.7	1.7
6	22.3	11.6	3.9	2.4
8	28.7	15.3	5.2	3.3
10	34.3	18.8	6.5	4.1
12	39.2	22.2	7.8	4.8
14	43.7	25.6	9.1	5.7

The tangent of the maximum angle of attack is here defined as the ratio of maximum velocity in rolling to the forward velocity of the model.

TABLE 5

COMPARATIVE EFFECTIVENESS OF THE DIFFERENT SETS OF KEELS WHEN MODEL SPEED IS THREE KNOTS

When angle of heel in rolling is 4 degrees

Bilge Keel Set No.	P	Q	P/Q
1	52.	5.	10.4
2	86.	7.	12.3
3	126.	11.	11.5
4	233.	17.	13.7
5	311.	29.	10.7

When angle of heel in rolling is 6 degrees

Bilge Keel Set No.	P	Q	P/Q
1	61.	5.	12.2
2	100.	7.	14.3
3	136.	11.	12.4
4	232.	17.	13.6
5	282.	29.	9.7

Where: P is the per cent increase in angular damping, and
Q is the per cent increase in model resistance.

TABLE 6

COMPARATIVE EFFECTIVENESS OF THE DIFFERENT SETS OF KEELS WHEN MODEL SPEED IS FIVE KNOTS

When angle of heel in rolling is 4 degrees

Bilge Keel Set No.	P	Q	P/Q
1	45.	3.7	12.2
2	78.	5.4	14.4
3	113.	9.	12.6
4	205.	14.	14.6
5	313.	24.	13.0

When angle of heel in rolling is 6 degrees

Bilge Keel Set No.	P	Q	P/Q
1	50.	3.7	13.5
2	87.	5.4	16.1
3	116.	9.	12.9
4	204.	14.	14.6
5	300.	24.	12.5

Where: P is the per cent increase in angular damping, and
Q is the per cent increase in model resistance.

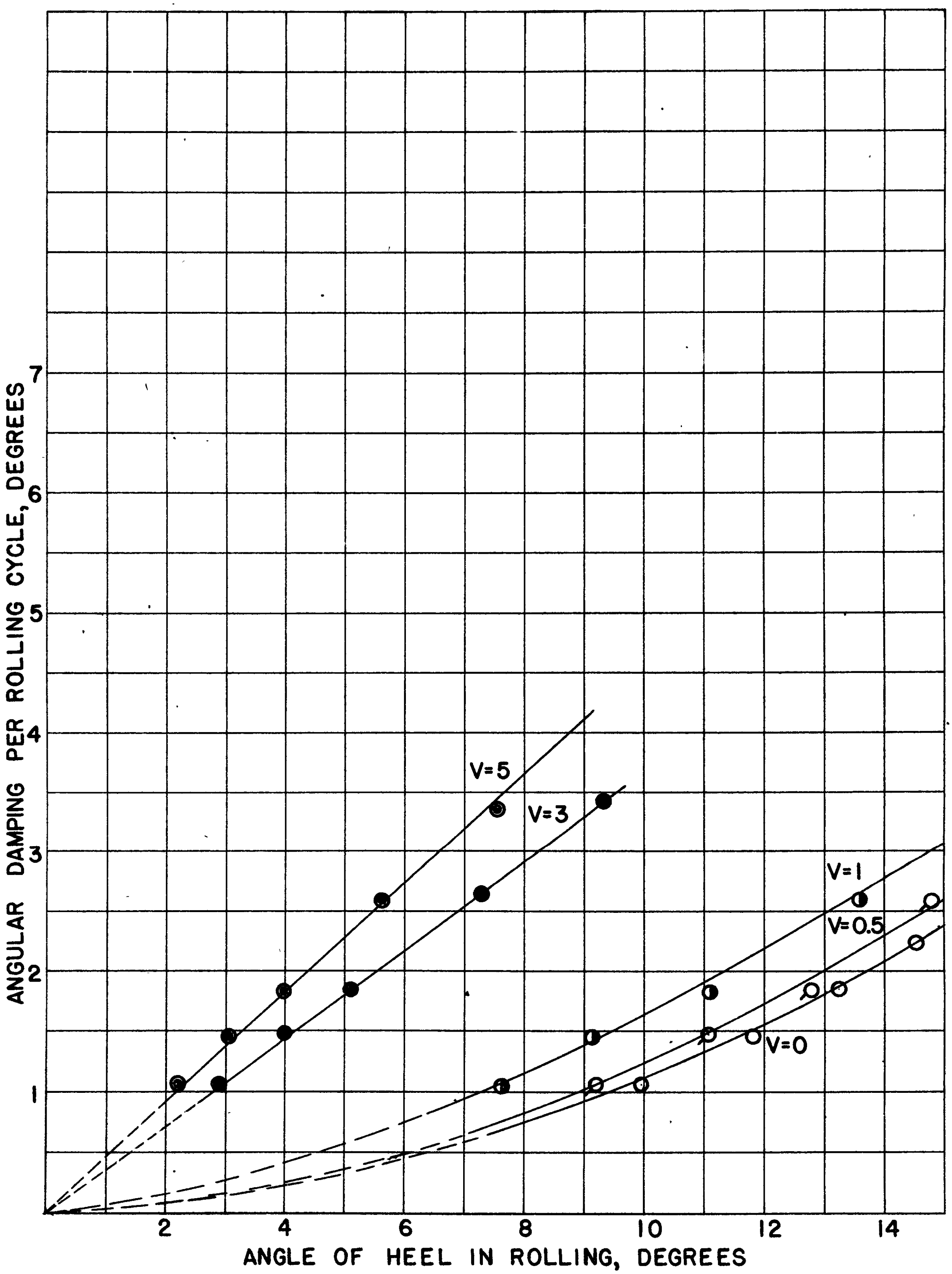

FIG. 5. MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH NO BILGE KEELS AT SPEEDS OF 0, 0.5, 1, 3, & 5 KNOTS.

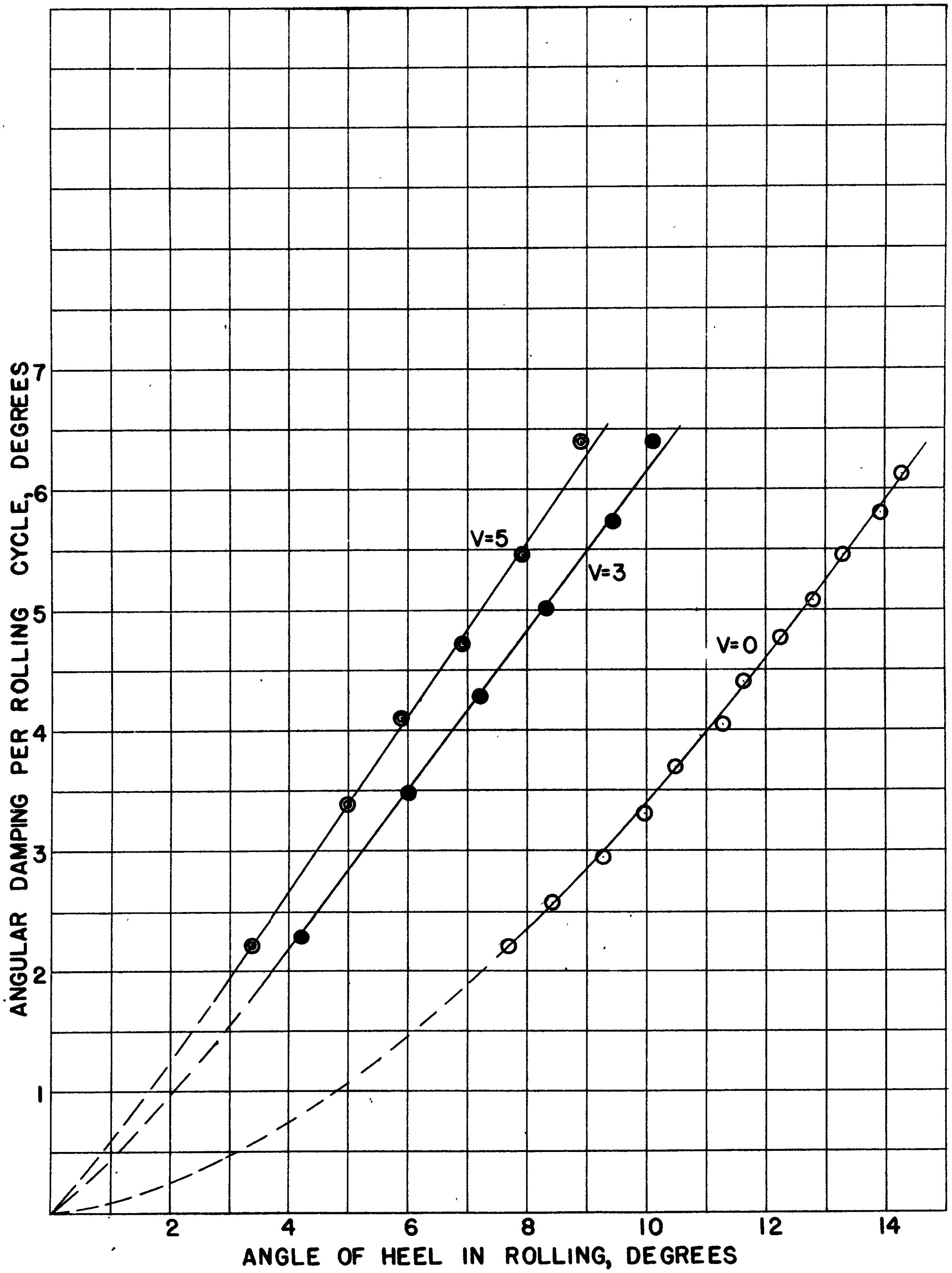

FIG. 6. MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH CONTINUOUS BILGE KEELS, SET NO. 1, AT SPEEDS OF 0, 3, & 5 KNOTS.

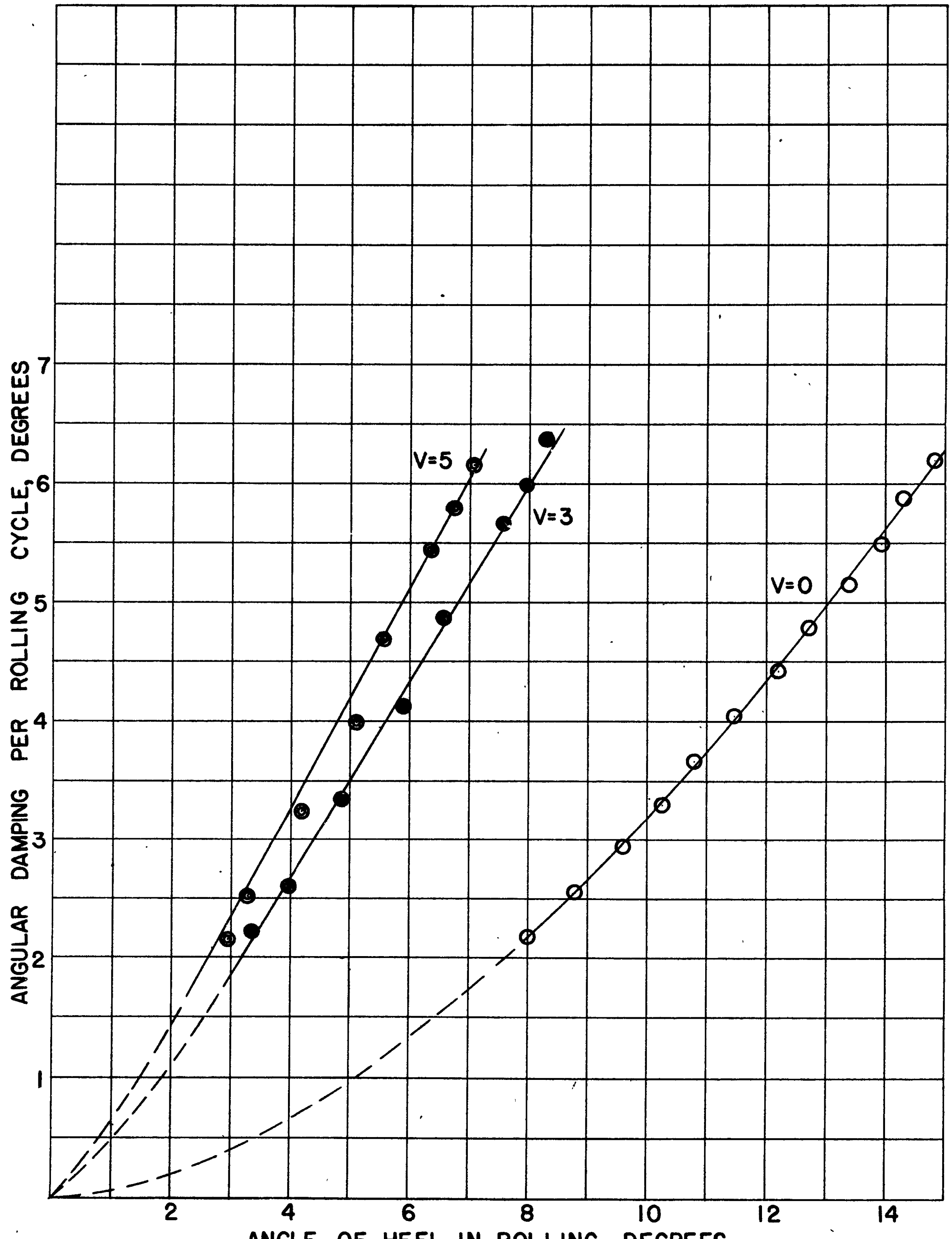

FIG. 7 MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH DISCONTINUOUS BILGE KEELS, SET NO. 2, AT SPEEDS OF 0, 3, & 5 KNOTS.

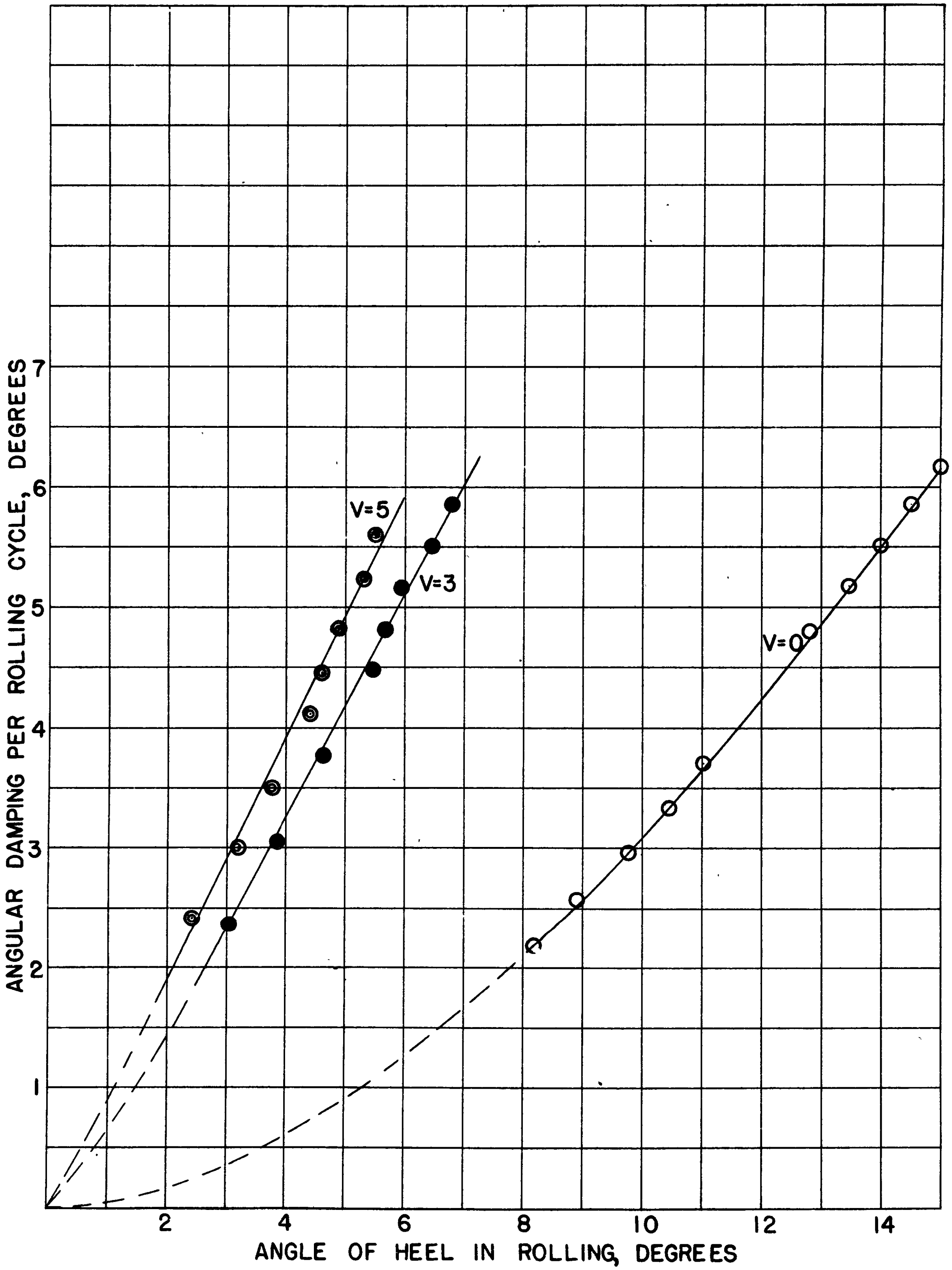

FIG. 8 MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH DISCONTINUOUS BILGE KEELS, SET NO. 3, AT SPEEDS OF 0, 3, & 5 KNOTS.

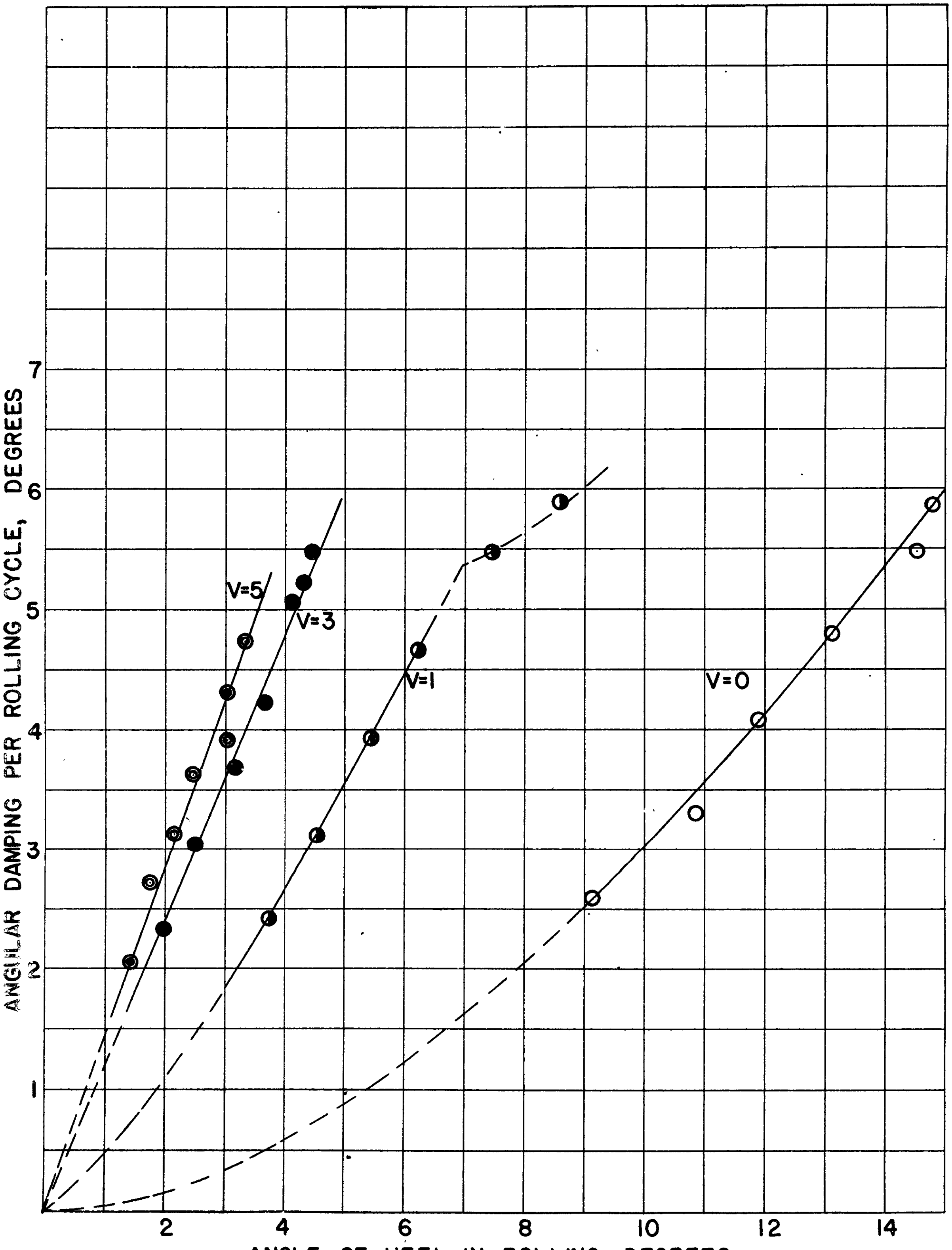

FIG. 9 MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH DISCONTINUOUS BILGE KEELS, SET NO. 4 AT SPEEDS OF 0, 1, 3, & 5 KNOTS.

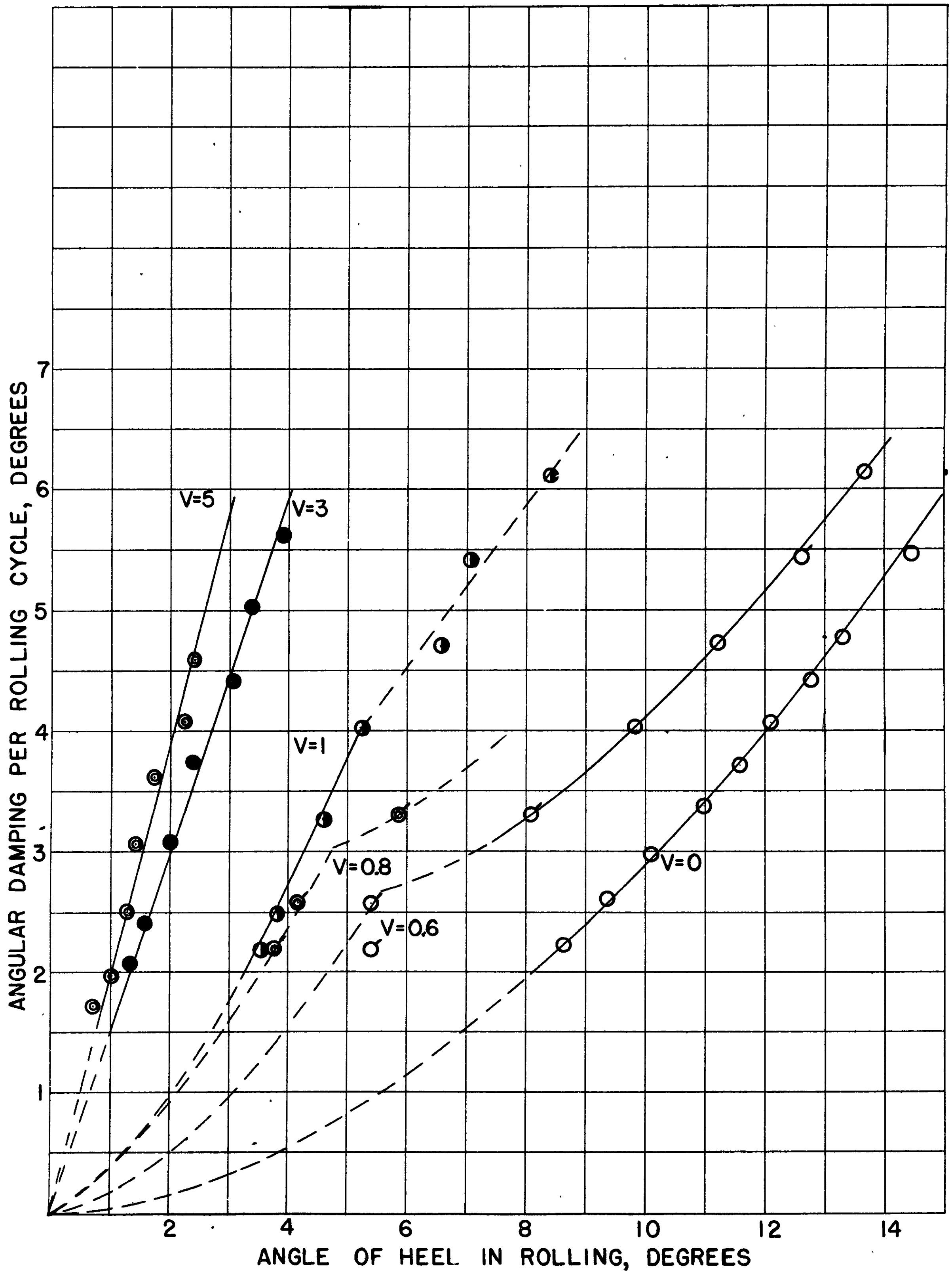

FIG. 10 MODEL NO. 3400. TOTAL ANGULAR DAMPING WITH DISCONTINUOUS BILGE KEELS, SET NO. 5 AT SPEEDS OF 0, 0.6, 0.8, 1, 3, & 5 KNOTS.

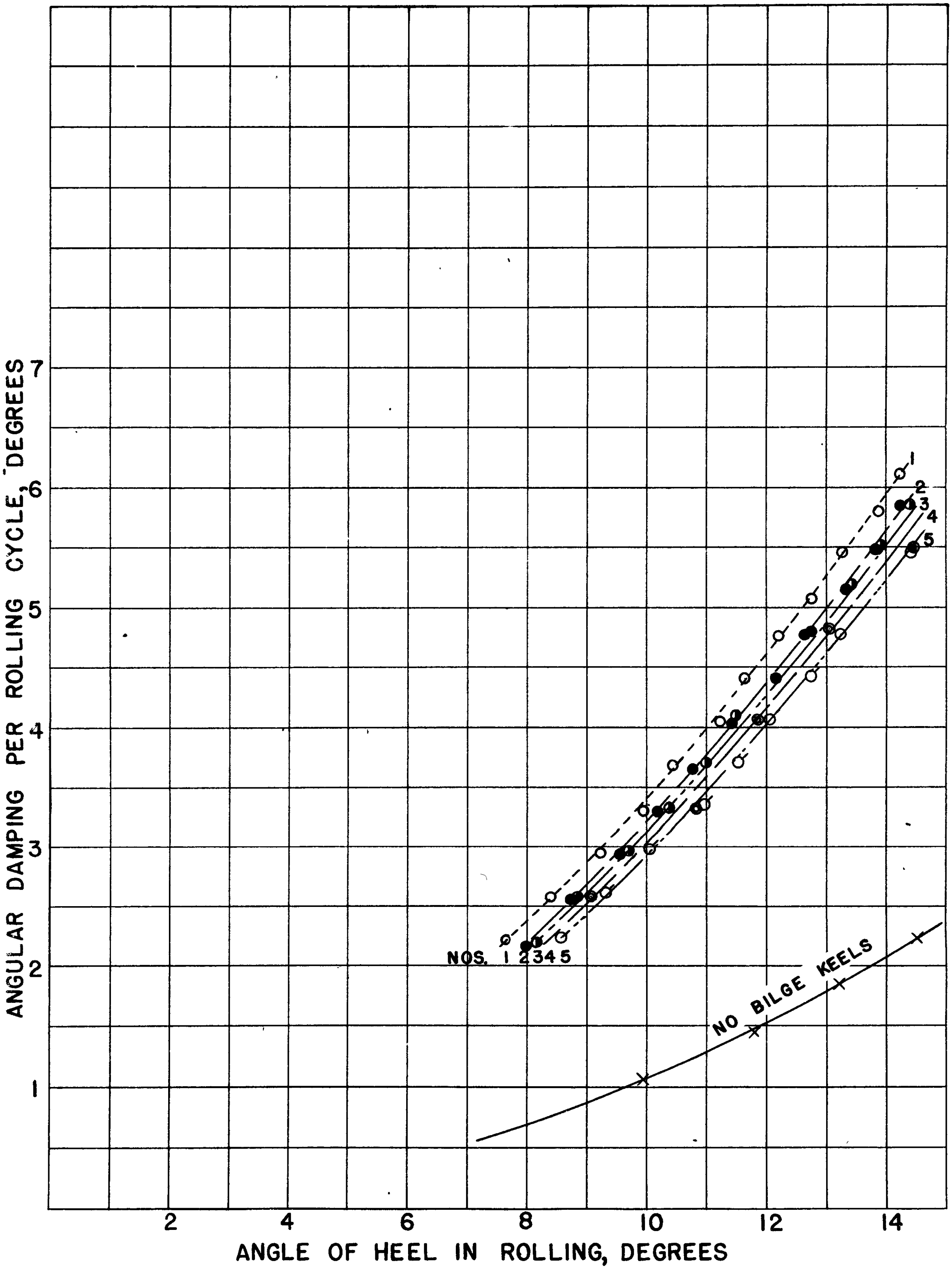

FIG. 11 TOTAL ANGULAR DAMPING ON MODEL NO. 3400 WHEN EQUIPPED WITH THE VARIOUS SETS OF THE DISCONTINUOUS BILGE KEEL SERIES, ROLLING WITH NO WAY ON; V = 0.

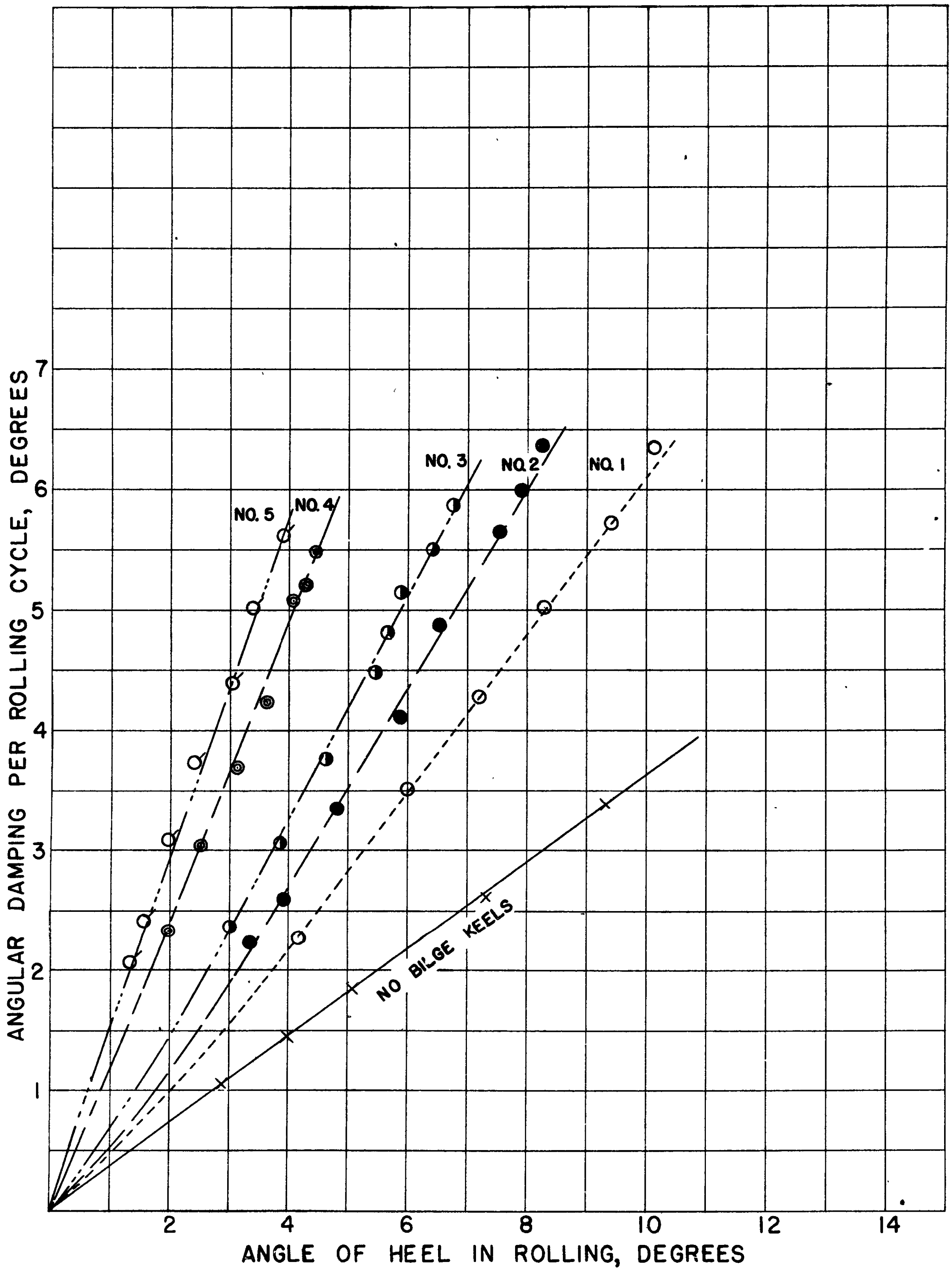

FIG. 12

TOTAL ANGULAR DAMPING ON MODEL NO. 3400 WHEN EQUIPPED WITH THE VARIOUS SETS OF THE DISCONTINUOUS BILGE KEEL SERIES, ROLLING WHEN TOWED AT 3 KNOTS.

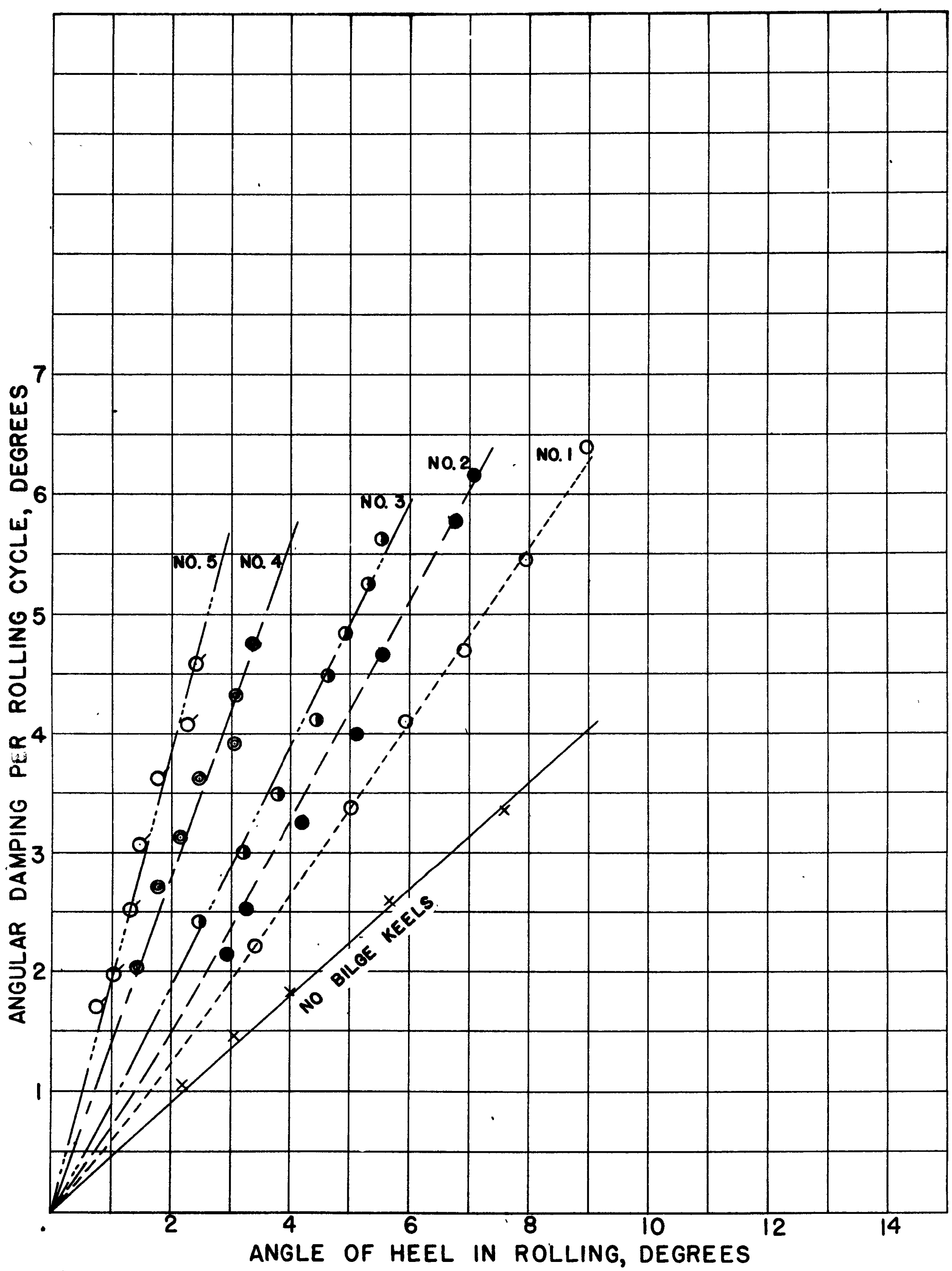

FIG. 13

TOTAL ANGULAR DAMPING ON MODEL NO. 3400 WHEN EQUIPPED WITH THE VARIOUS SETS OF THE DISCONTINUOUS BILGE KEEL SERIES, ROLLING WHEN TOWED AT 5 KNOTS.

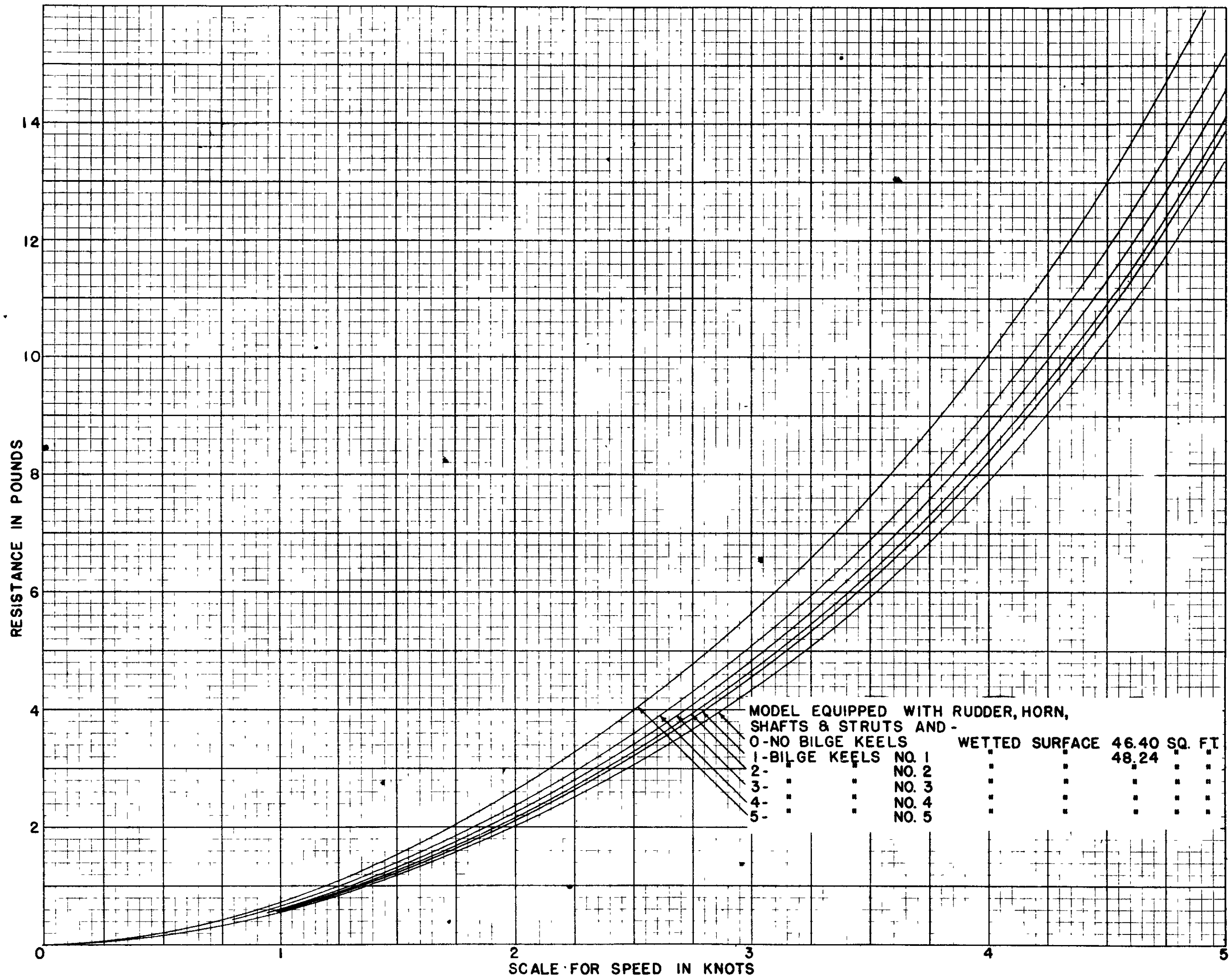

FIG. 14 CURVES OF RESISTANCE FOR MODEL NO. 3400

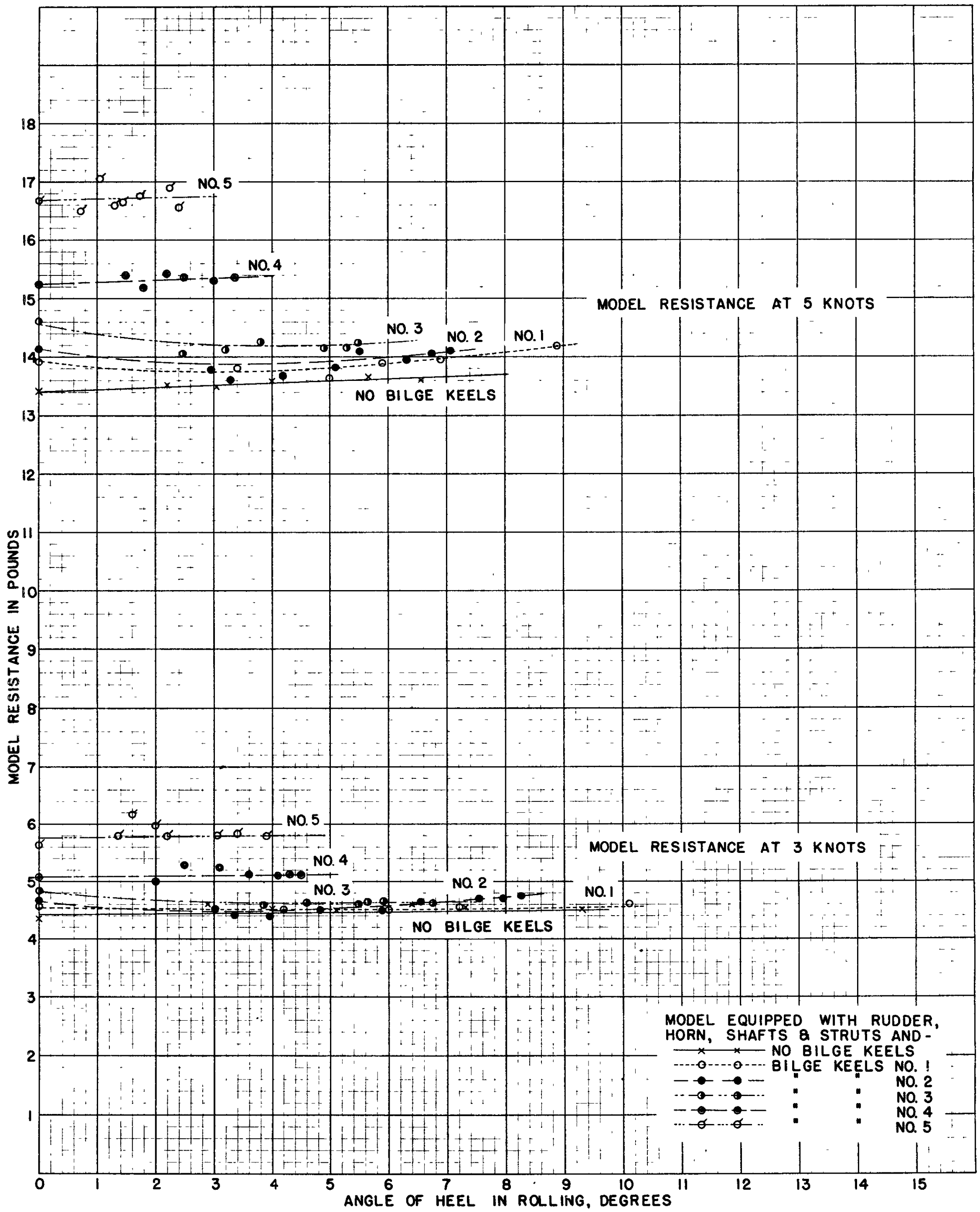

FIG. 15 MODEL NO. 3400 VARIATION OF RESISTANCE WITH ANGLE OF HEEL IN ROLLING

APPENDIX I

VARIATION OF GM WITH SPEED AND ANGLE OF HEEL

The variation of GM of model 3400 with speed for different angles of heel was determined by two different methods. In both cases the model was in the bare hull condition.

A. Model rolling.

The period of roll was measured for different speeds of the model. Attributing the measured change in period to a change in GM of the model under way, i.e. neglecting the effect of angular damping on period, which is a minimum for the bare hull condition, the GM is computed from the familiar formula:

$$T = 2\pi k / \sqrt{g\ GM}$$

where T = period,
k = radius of gyration,
g = acceleration of gravity, and
GM = metacentric height.

The results are shown in Table 7. It is seen that period diminishes and GM increases with speed. But the effect of angular damping is to increase period, and it has been seen that angular damping increases with speed. Hence the variation of speed with GM is at least as great as indicated in Table 7.

TABLE 7

VARIATION OF GM OR THE STIFFNESS FACTOR OF MODEL 3400 WITH SPEED

Speed in Knots	Period in Seconds	Metacentric Height GM in inches
0.0	2.82	1.88
0.5	2.80	1.90
1.0	2.80	1.91
3.0	2.75	1.98
5.0	2.50	2.40

B. Model not rolling.

A constant heeling moment was applied to the model and the change of angle of heel with speed was noted. From this the change in GM was computed. This was done for several different heeling moments. The results, shown in Table 8, verify those determined from the variation of the synchronous rolling period with speed (Table 7). They are also in accord with results similarly obtained for a destroyer model of the FARRAGUT class. (See U.S.E.M.B. Report 336). They are contrary, however, to those obtained for a destroyer model of the PRUITT class. (See U.S. E.M.B. Report 287). The outstanding points of similarity and contrast between these ships which may account for these results is that both CV-7 and U.S.S. FARRAGUT have flat V sterns whereas the U.S.S. PRUITT has a narrow, deep V stern

TABLE 8

VARIATION OF GM WITH SPEED; MODEL NOT ROLLING

Speed of Model in Knots	Virtual GM in Inches	Angle of Heel in Degrees
0	1.875	3.1
1	1.90	3.1
3	1.99	2.9
5	2.77 doubtful	2.1
0	1.877	6.3
1	1.90	6.2
3	1.93	6.1
5	2.34	5.0
0	1.878	9.3
1	1.89	9.2
3	1.92	9.1
5	2.16	8.1
0	1.880	12.2
1	1.88	12.2
3	1.91	12.0
5	2.18	10.5

In all of the calculations in this report, the change of metacentric height due to angle of heel was neglected.

APPENDIX II

COMPUTING ANGULAR DAMPING

The angular damping is computed according to the method as described in U.S.E.M.B. Report No. 433. The interpretation is that the mechanical gear will produce the same amplitude of synchronous rolling as will a train of synchronous waves if the maximum torque due to the gear is equal to the maximum heeling moment produced on the model when the latter is on the maximum slope, γ , of a wave.

According to Froude's theory, steady rolling obtains when the angular damping, $d\theta/dN$, is equal to $\pi\gamma$. The equivalent value of γ from the mechanical gear is $Q_M/W\ GM$, where: Q_M is the maximum value of the mechanical torque, W is the model's displacement, and GM is the metacentric height.

According to the results of this investigation the value of GM changes with speed, (see Table 7), and but negligably so with angle of heel. (see Table 8) It is assumed that its change at different speeds is determined by the variation of the period of rolling for the no bilge keel condition, this being the condition of least damping with a consequent least effect of damping on period. Thus let GM_0 be the metacentric height at V = 0. Other conditions remaining the same, GM is related to period by the formula

$$T = 2\pi k/\sqrt{g\ GM},$$

or GM varies inversely as the square of the period. Then for a change of period with speed, GM_V is equal to $GM_0(T_0/T_V)^2$, where GM_V is the value of GM for speed V.

It is noted that the above method does not overestimate the change that speed produces on GM. The effect of damping is to increase period but unless the damping is excessive the effect on period is small. The results for the no bilge keel condition show that although damping increases with speed, nevertheless the period of rolling decreased considerably. Therefore attributing, in computing, the measured change in period to an increase in GM tends to underestimate, if anything, the change in metacentric height. It is assumed that this variation of GM with speed is independent of the amount of bilge keel damping on the model. The increase in the period of rolling when the model is equipped with keels is taken as being due to heavy damping, and hence does not influence the calculation of $d\theta/dN$.

The expression used in determining $d\theta/dN$ in this experiment when using the five pound weights on the eccentric arms of the mechanical rolling gear was:

$$\frac{d\theta}{dN} = \frac{\pi}{W\ GM}(Q_M) = \frac{\pi}{W\ GM}\left[\frac{1}{T}(19.7 + 30.5\ \bar{x})\right] 57.3$$

where: π = 3.1416

W = model's displacement in pounds,

GM = metacentric height in inches,

T = rolling period of the model for a complete rolling cycle in seconds,

$\bar{x}$ = eccentric setting of the five pound weights in inches,

and the numerical constants are determined by the dimensions and fixed rotating masses of the mechanical rolling gear. The constant 57.3 changes radians to degrees.

When using the ten pound weights on the eccentric arms the expression is:

$$\frac{d\theta}{dN} = \frac{\pi}{W\ GM}\left[\frac{1}{T}\ (20 + 60.4\ \bar{x})\right]\ 57.3$$

In each case $d\theta/dN$ is given in degrees per roll.