Report 2982

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Washington, D.C. 20007

EFFECT OF METACENTRIC HEIGHT ON ROLL DAMPING

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October 1969

Report 2982

EFFECT OF METACENTRIC HEIGHT ON ROLL DAMPING

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Naval Ship Research and Development Center
Washington, D.C. 20007

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DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
WASHINGTON, D. C. 20007

EFFECT OF METACENTRIC HEIGHT ON ROLL DAMPING

by

Alvin Gersten

October 1969

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NOTATION

D	Cylinder diameter
ΔE	Energy loss
GM	Transverse metacentric height (distance between center of gravity and metacenter)
$I_{virtual}$	Virtual mass moment of inertia
n	Cycle number
R	Radius of cylinder
S	Area of cylinder wetted surface
T_ϕ	Natural roll period
VCG	Vertical position of center of gravity
W	Weight of cylinder
δ	Log decrement
ν	Fluid kinematic viscosity
ρ	Fluid mass density
ϕ	Roll Angle
ϕ_0	Initial roll angle

Subscripts:

V	Due to viscosity
WM	Due to wavemaking

ABSTRACT

Experiments have been conducted by the Naval Ship Research and Development Center on a floating circular cylinder to determine the effect on roll damping of changes in transverse metacentric height *GM*. The relationship between log decrement δ and *GM* is defined, both graphically and by means of an empirical equation which shows that δ varies inversely as the square root of *GM*. In addition, the total energy lost per cycle and the energy losses due to wavemaking are discussed.

ADMINISTRATIVE INFORMATION

The study reported herein was requested by the Naval Ship Systems Command in letter Serial 03412B-321 of 20 September 1967, and was funded under Task 1711 of Project S-F013 02 03.

INTRODUCTION

The Naval Ship Research and Development Center, as part of its continuing studies of roll damping[1, 2] has completed model tests on a bare, floating, circular cylinder. During these tests the vertical distance between the center of gravity and transverse metacenter *GM* was varied so that the effect of this design parameter on roll damping could be determined. Since the ship designer usually has some freedom in locating the center of gravity and metacenter of the vessel, it is important to know how this selection will influence roll behavior in a seaway. Computers can be used to predict these trends if the coefficients in the equations of motion, among these the damping coefficient, can be modified appropriately as design changes are made. It has been discovered by previous experiments[3] that once the form of a ship has been determined, the angular damping is affected more by *GM* than any other factor.

As part of an experimental program carried out to investigate the rolling of ships, Serat and Thews[3] employed noncircular cylinders and allowed them to oscillate freely in calm water, and to be forced in roll by synchronous waves. Maintaining all factors but one constant during any given test, they studied the effect of varying the vertical position of the center of gravity *(VCG)*, the roll period, the height of the metacenter above the waterplane, and the midship section coefficient. The moment of inertia was modified as necessary to keep the roll period constant when the *VCG* was altered. The researchers discovered that if the *GM* is decreased by raising the center of gravity (all other parameters being constant) the

[1]References are listed on page 16.

rate of angular damping and the rate of energy damping per unit time increase. Thus, they conclude that a ship with small *GM* will tend to roll less than a similar ship with large *GM*. They also found that when roll period is increased, the rate of energy damping per cycle and per unit time decreases.

Stefun[4] utilized an Ursell form model having constant section and a beam to draft ratio of 2.0 for free oscillation tests. His results, which are appended to this report as Figure A-1, show that if *GM* is decreased by raising the center of gravity, with the roll period permitted to increase accordingly, the rate of energy damping per unit time decreases. It would appear at first that the findings of Stefun are contradictory to those of Serat and Thews since the former reports a decrease in energy damping, and the latter an increase in energy damping, as *GM* decreases. However, it must be remembered that in one case roll period was held constant whereas in the other it was not.

The primary purpose of the present study is to provide a quantitative measure of the way roll damping characteristics of a displacement ship are affected by variations in *GM* which are brought about by vertical motion of the center of gravity. To this end, the *GM* was varied over a wide range (a factor of 19 between the highest and lowest values) and many values between the extremes were investigated.

DESCRIPTION OF THE EXPERIMENT

MODEL PARTICULARS

The model utilized for these experiments is a hollow, nonflooded, circular cylinder 2 ft in diameter and 8 ft-1/2 in. long. Several model particulars were held constant for the entire series of tests; they are listed in Table 1. The metacenter of the cylinder, which was floating with its longitudinal axis horizontal, was fixed at its geometric center. Therefore,

TABLE 1

Constant Model Particulars

Weight	1340 lb
Moment of Inertia about Longitudinal Centerline	265 in lb sec^2
Draft	1.6 ft (0.8D)

in order to vary *GM*, thin ballast rods which ran the length of the model, were moved vertically without changing their distance from the centerline axis. In this way, the *VCG* was changed without altering the moment of inertia about the centerline which is also the static roll axis.

The moment of inertia about the center of gravity was, however, not constant since the position of the latter was modified during successive ballastings.

Table 2 is a listing of the ten *GM* to diameter ratios established for these tests and the average period associated with each *GM*. *Average* period is specified here because the motion was not always isochronous. For the small values of *GM* the period tended to decrease slightly as the roll angle decreased. The magnitude of the transverse *GM* was determined for each distribution of ballast rods by performing an inclining experiment. Thus,

TABLE 2

Values of *GM* and Associated Roll Period Utilized for Tests

GM/D	*GM* in.	Average Period sec
0.0029	0.07	8.30
0.0037	0.09	8.11
0.0058	0.14	6.70
0.0071	0.17	6.20
0.0096	0.23	5.65
0.0154	0.37	4.58
0.0233	0.56	3.88
0.0333	0.80	2.94
0.0437	1.05	2.69
0.0554	1.33	2.39

a heeling moment was applied to the model, the heel angle was measured, and the *GM* computed from

$$GM = \frac{\tilde{M}}{W \sin \phi}$$

where $\tilde{M}$ is the heeling moment,

W is the weight of the cylinder, and

ϕ is the heel angle.

The outer surface of the cylinder was sprayed with Du Pont Preparakote, an alkyd resin paint primer, and wet-sanded to provide an extremely smooth finish.

TEST METHOD AND PROCEDURE

The tests were performed at zero speed near the center of the Rotating Arm Basin, which is a circular tank 260 ft in diameter and 21 ft deep. The test setup is shown in Figure 1. A rod with two pins on it was attached to one end of the model so that a heeling couple could be applied by a cable passing around the pins and thence to a system of pulleys, which permitted the hanging of weights at the ends of the cable. The model was released impulsively by burning a piece of nylon line between the aforementioned pins. The weights hanging from the cable were changed as necessary so that three values of initial angle, ranging from approximately 8 to 26 deg, were established for each *GM*.

A Minneapolis-Honeywell pitch and roll gyroscope was used as the roll angle transducer. Measurements of the waves generated by the rolling cylinder were made by means of a microwave interferometer. This device generates a signal of precisely known wavelength (0.3372 inches in air) which is directed from a stationary antenna to the water surface whence it is reflected back to the source and compared with the original signal in a phase detector. If the target moves, a phase difference exists between the reflected and reference signals, which is supposed to be proportional to the amount of target motion. A water surface movement of 0.001 inch is well within the resolution of the device. The outputs of the gyro and interferometer were amplified and recorded on a Honeywell Visicorder oscillograph.

RESULTS AND DISCUSSION

The damped oscillatory motion of the cylinder after release was, as noted above, recorded on a strip chart. Amplitude extinction curves have been derived from these time histories by reading the average of the clockwise and counterclockwise roll amplitudes for successive cycles. Averaging was necessary to cancel the effect of drift in the zero on the oscillograph trace. This drift has occurred during earlier, similar experiments[1, 2] and it is believed to be caused by hydrodynamic forces rather than instability in the recording electronics. Typical examples of the extinction curves, plotted on semilogarithmic paper, are presented in Figure 2 for several values of *GM* and for essentially one initial angle (the differences in initial angle ϕ_0, extant in this figure, are small compared to the range of ϕ_0 investigated). Extinction curves for intermediate values of *GM*, which are not shown here, have slopes intermediate to those presented. All of the extinction curves, except the ones for $GM = 0.07$ in., were found to be linear after one or two cycles of motion had been executed and conditions had stabilized. The curves for $GM = 0.07$ in. generally exhibited instability over several cycles; however, they too eventually became linear as is demonstrated in Figure 2. It has been pointed out in Reference 2 that the free rolling motion of circular cylinders which are smaller than the one used for these experiments will not damp exponentially. For the 2-ft-diameter model utilized in this study, with the possible exception of the $GM = 0.07$ in. condition, damping proportional to the first power of velocity can be assumed in the equation of motion.

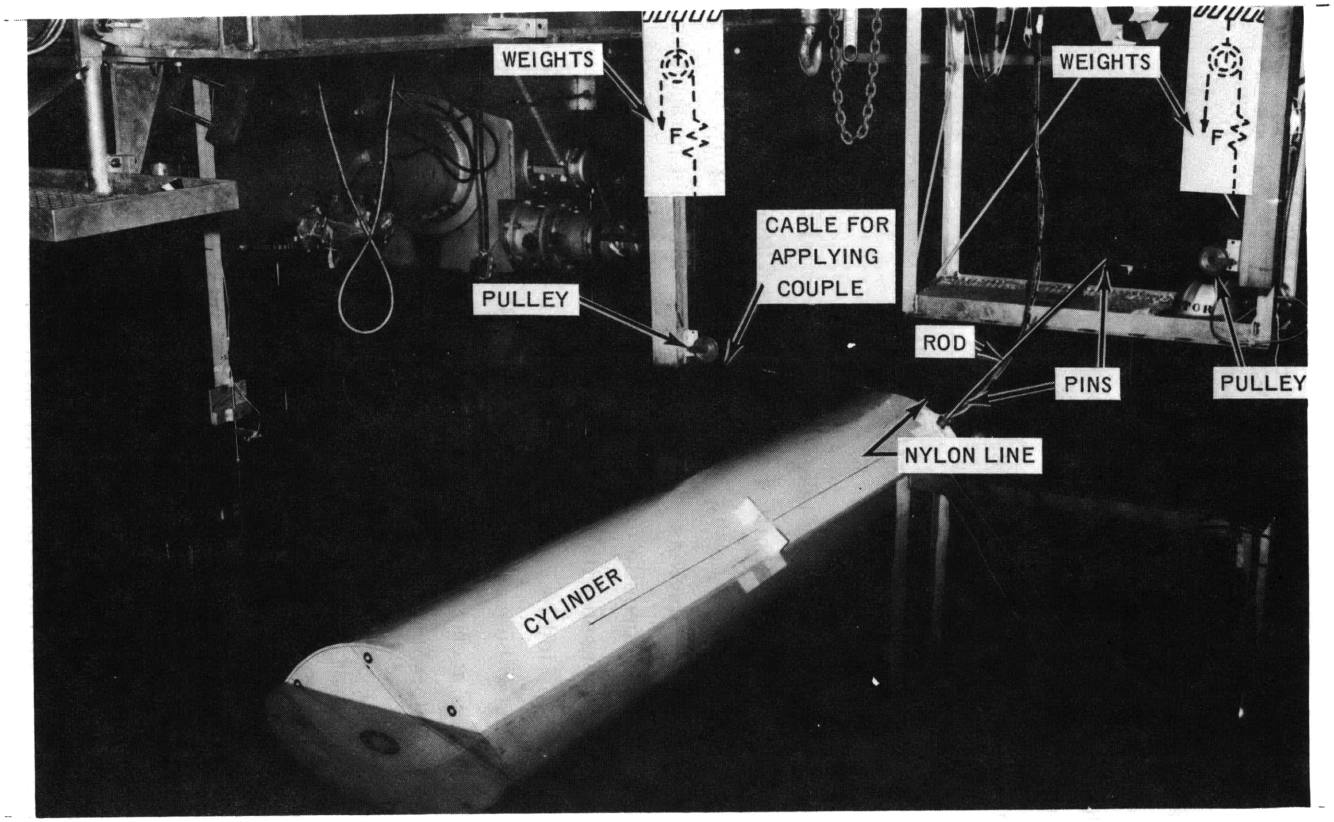

Figure 1 – The Test Setup

The δ-values given in Figure 2 represent the logarithmic decrement which is defined by

$$\delta = \frac{1}{q} \ln \frac{\phi_n}{\phi_{n+q}}$$

where ϕ_n is the amplitude of oscillation at cycle number n, and ϕ_{n+q} is the amplitude q cycles later. There is clearly an increase in angular damping* as GM is decreased. It must be emphasized that during these experiments, when GM was changed, the natural roll period T_ϕ was permitted to change also. That is, the moment of inertia was not adjusted to keep T_ϕ constant. For the light damping occurring here, the period and GM are related by

$$T_\phi = 2\pi \sqrt{\frac{I_{\text{virtual}}}{W \cdot GM}} \qquad [1]$$

where the moment of inertia, I_{virtual}, is taken about the virtual center of mass. During this investigation, the roll period was permitted to increase as GM decreased, and conversely because this is what is usually done in ship design. The results of Reference 3 show that although roll period will normally increase as GM decreases, all other parameters being constant, these factors have opposite effects on damping if one is altered while the other is not. That is, if GM is decreased with period kept constant, the rate of energy damping increases; whereas, if roll period is increased with GM held constant, the rate of energy damping decreases. It must also be emphasized that when GM is changed by relocating the metacenter (for fixed displacement, this necessitates a change in hull form), the effects on damping can be quite different from those produced by a movement of the center of gravity.

In order to determine whether initial angle significantly affected damping, and also ultimately to permit the delineation of log decrement as a function of GM for constant initial angle, plots of δ versus ϕ_0 were made. Representative examples are given in Figure 3. For all values of GM except 0.07 in. the initial angle effect is not great, and the least-square lines drawn fit the data points quite well. The lines for GM equal to 0.80 and 1.05 in., which are not shown here, indicate that δ increases rather than decreases with ϕ_0, but again, the slope is small. The curve for $GM = 0.07$ in. fits into the general trend of the results when ϕ_0 is greater than approximately 14 deg (this will be shown more clearly in the next figure); however, the sharp rise in the curve for smaller angles is not consistent with the other plots. The fact that the curve for $GM = 0.09$ in., representing an increase in GM of only 0.02 in.,

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*For the small values of δ being considered here, the damping coefficient is related to δ by $C = \frac{\hat{\omega} I_{\text{virtual}}}{\pi} \delta$, where $\hat{\omega}$ is the undamped natural roll frequency and I_{virtual} is the virtual mass moment of inertia.

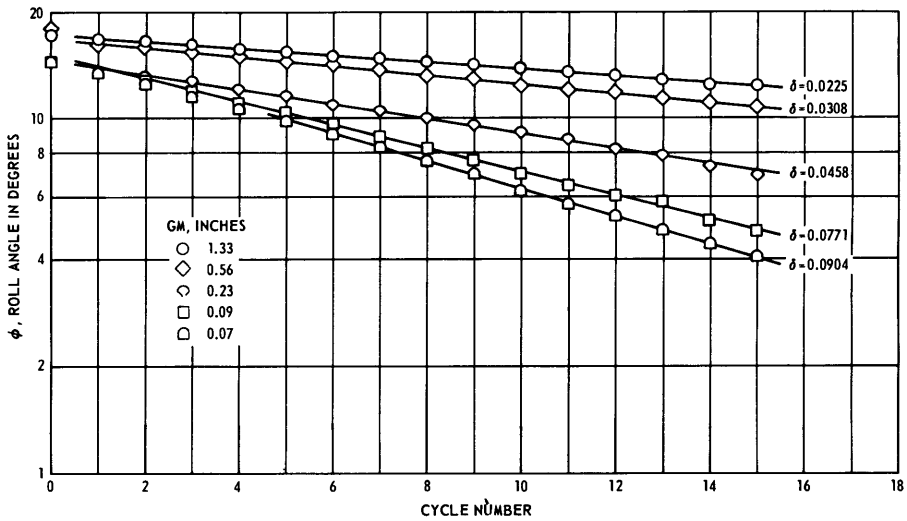

Figure 2 – Amplitude Extinction Curves

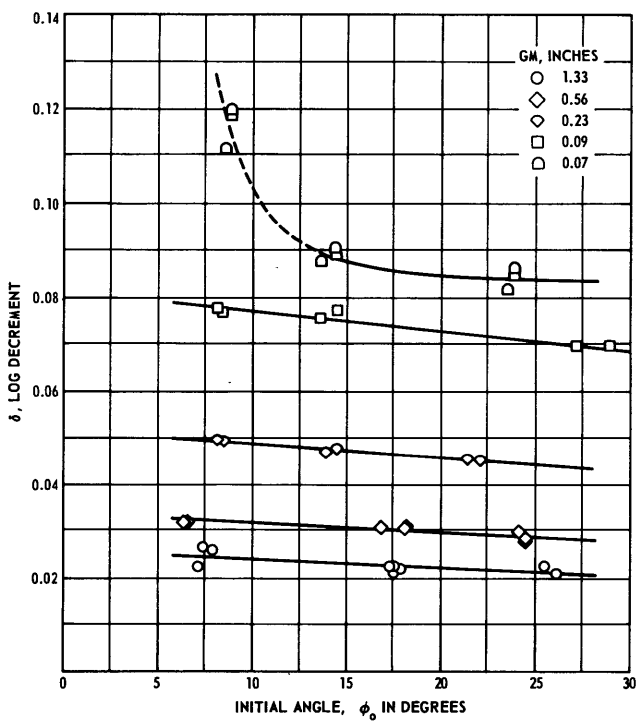

Figure 3 – Variation of Log Decrement with Initial Angle *GM* as a Parameter

exhibits not even a hint of this increase in slope, is particularly disturbing. Therefore, even though it is supported by three data points, the $GM = 0.07$ in. curve is drawn dashed when ϕ_0 is less than 14 deg, to emphasize its questionability. In subsequent figures, values derived from the solid portion of the curve only will be used.

Values of δ were read from Figure 3 and similar plots available for intermediate GM, at initial angles of 8, 18, and 28 deg. They were then plotted as a function of GM to diameter ratio GM/D in Figure 4a. It can be seen that δ increases monotonically as GM/D decreases. The rate of increase of δ is very low when GM/D is large and it becomes quite pronounced when GM/D is less than 0.005. The initial angle effect for all values of GM investigated can now be seen. When GM/D is greater than 0.03, the difference between curves does not exceed approximately 6.0 percent; in the region $0.005 < GM/D < 0.03$ the maximum difference between the curves for 8 and 28 deg is 16.0 percent; further, when $GM/D < 0.005$, the largest difference is approximately 10.0 percent. Although in the last mentioned region it is difficult to ascertain the difference accurately because the curves have such a large slope, it is evident from examination of the graphs that they do tend to merge. The variation of δ with initial angle is not negligible for some values of GM/D; however, it is small enough to be disregarded if, as here, one is mainly interested in examining the dependence of δ on GM.

In order to obtain a quantitative measure of the relationship between δ and GM/D, the curves in Figure 4a were plotted on logarithmic paper (see Figure 4b). The resulting graphs are almost linear, especially for the two smaller angles. The principal nonlinearities occur at the high values of GM/D where all of the curves have a short segment of approximately zero slope, and the curve for 28 deg undulates somewhat. In the region $0.0035 < GM/D < 0.045$ all of the plots can be represented quite well by an equation of the form

$$\delta = k \left(\frac{GM}{D}\right)^p$$

The difference in k and p for the several curves is small; therefore, average values were obtained. The equation resulting from use of these average constants is

$$\delta = 0.0045 \left(\frac{GM}{D}\right)^{-0.5} \qquad [2]$$

This empirical equation indicates that the log decrement varies inversely as the square root of GM to diameter ratio if roll natural period is permitted to change when GM is changed. Whether corrections have to be applied to this relationship for different size cylinders (i.e., to handle scale effect) is not known at present. Values of δ computed by means of Equation [2] are represented by the solid circles in Figure 4a. For the most part these points fall on the intermediate (18-deg) curve. Log decrement, which depends upon angular damping,

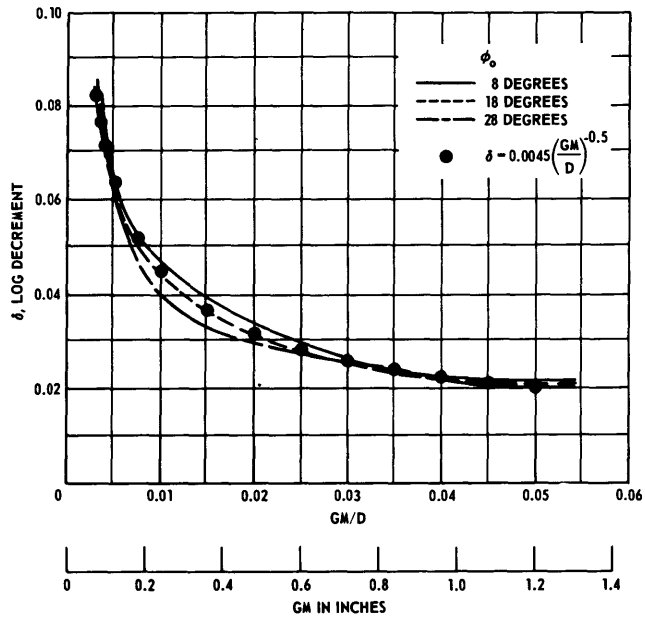

Figure 4a – Rectangular Co-ordinate Plot

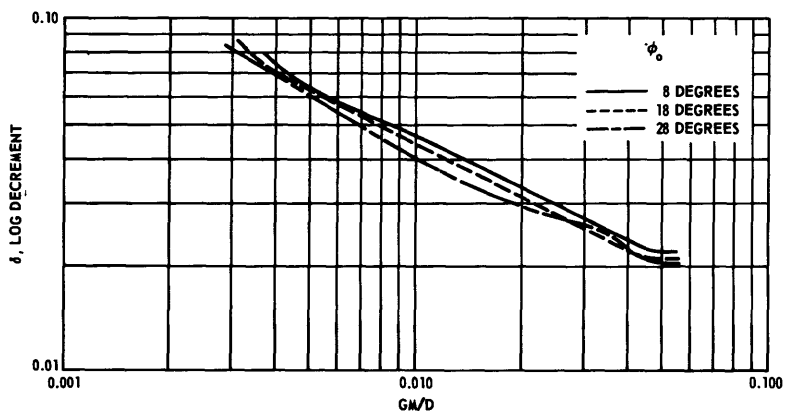

Figure 4b – Logarithic Plot for Determination of Empirical Relationship

Figure 4 – Log Decrement as a Function of *GM* to Diameter Ratio

generally decreases as GM increases because damping energy is dissipated with a smaller angular decrement when GM is large (energy losses are considered in more detail in the next few paragraphs).

A discussion of the effect of GM on roll damping should contain comparisons of the energy consumed in the rolling process. An examination of the equation for energy loss per cycle will clarify this point. This equation is

$$\Delta E_{\text{total}} = W(GM) \sin \phi \frac{d\phi}{dn} \qquad [3]$$

where $d\phi/dn$ is the loss in roll amplitude per cycle. According to Equation [3], two identical ships ballasted to have different GM's, can have different angular damping (represented by a difference in $d\phi/dn$) and yet have the same energy damping. Energy damping is useful in providing a way of comparing the moments resisting rolling.

Since we are dealing here with essentially linear damping once the motion has stabilized (see Figure 2 and discussion), the decrement of angle per cycle will be taken as[5]

$$\frac{d\phi}{dn} = -\phi_0 \, \delta \exp\left[-\frac{\delta \hat{\omega} t}{2\pi}\right] \qquad [4]$$

Combining Equations [3] and [4] we obtain

$$\Delta E_{\text{total}} = -W(GM) \, \phi_0 \, \delta \sin \phi \exp\left[-\frac{\delta \hat{\omega} t}{2\pi}\right] \qquad [5]$$

The rate of energy damping for several values of GM was obtained from Equation [5], and is represented in Figure 5 by the solid lines. It is evident that the energy damping decreases significantly with decrease in GM. This is mainly attributable to the decrease of frictional energy loss, which is brought about by a decrease in the average velocity of the cylinder surface over a half-cycle according to the equation

$$\bar{v} = \frac{2D\phi}{T_\phi}$$

The roll period varies with GM in conformance with Equation [1].

Quantitative evidence of the decrease in viscous energy loss with GM is provided by the studies of Kato,[6] who experimented with circular cylinders completely immersed in water. He obtained the following formula for the work done during one cycle by the frictional resistance to roll.

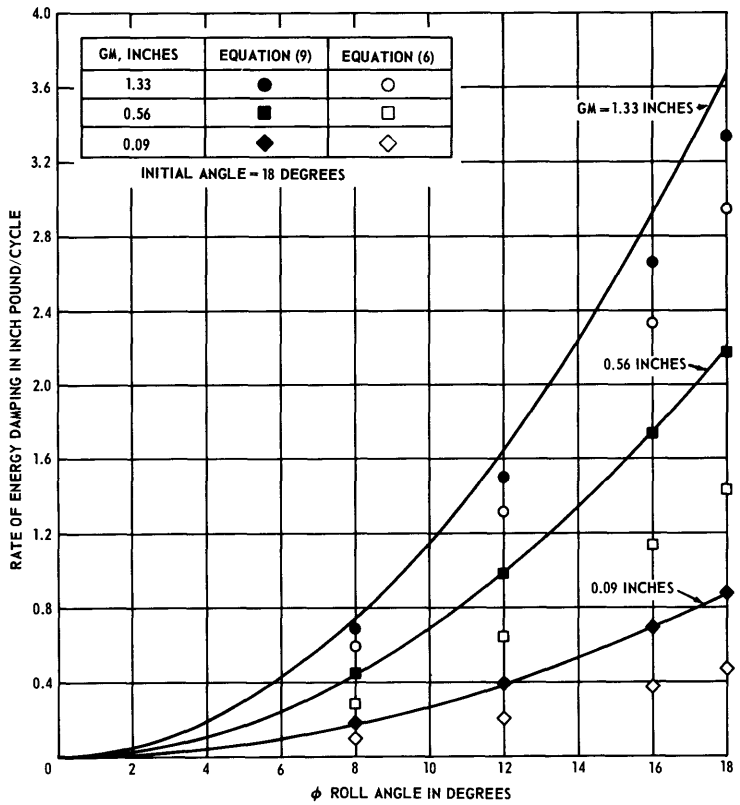

Figure 5 – Effect of Change of *GM* on Energy Damping

$$\Delta E_v = \frac{16}{3} \rho \pi^2 \left(0.74\sqrt{\frac{T_\phi \nu}{R^2}}\right) SR^3 \phi^2 \left(\frac{1}{T_\phi}\right)^2 \qquad [6]$$

where ρ is the fluid mass density,

ν is the fluid kinematic viscosity,

R is the cylinder radius, and

S is the cylinder wetted surface.

Values of ΔE_v calculated by means of Equation [6] are plotted as open symbols in Figure 5. These points always fall below their respective lines computed by Equation [5] since energy loss due to wavemaking and surface tension* is included in Equation [5] but not in Equation [6]. Nevertheless, the viscous losses do predominate, and they are clearly *GM* dependent (primarily because roll period is *GM* dependent).

The empirical relationship between log decrement and *GM/D* provided in Equation [2] can be utilized in the calculation of the *total* energy loss, since for small values of δ the following is true[5]

$$\Delta E_{total} = 2 \delta E_{pot} \qquad [7]$$

where E_{pot}, the potential energy at angle of roll ϕ, is given by

$$E_{pot} = W (1 - \cos \phi) GM \qquad [8]$$

Combining Equations [2], [7], and [8] we obtain

$$\Delta E_{total} = 0.009 \left(\frac{GM}{D}\right)^{0.5} WD (1 - \cos \phi) \qquad [9]$$

The solid symbols in Figure 5 represent values of energy loss obtained from Equation [9]. The agreement between this method of computing ΔE_{total} and the method of Equation [5] (the latter is represented by the curves in Figure 5) should be good as long as Equation [2] accurately delineates the relationship between δ and *GM/D*. As noted previously, a satisfactory representation exists for *GM/D* less than 0.045. This is borne out by the fact that solid symbols fall on the curves for the two smaller values of *GM* but not for *GM* = 1.33 in. (*GM/D* = 0.055).

The attempt to measure model-generated waves met with only limited success. One problem encountered was nonlinearity in the interferometer calibration. The device appeared

*As discussed in Reference 2, the energy loss due to surface tension should be small for the surface finish on this cylinder.

to be highly nonlinear when motion of the water surface exceeded approximately 0.02 in. towards the antenna (wave crest direction); it was almost linear for target motion up to approximately 0.04 in. away from the antenna (wave trough direction). The cause of this nonlinearity could not be resolved during the course of the experiments; it was apparently inherent in the interferometer rather than being introduced by the recording electronics. In order to extract some useful information from the wave records, deflections between the mean water level and wave trough were read from the strip charts and the waves were assumed to be sinusoidal. Sample plots of wave height (distance from crest to trough) as a function of cycle number are presented in Figure 6 where it can be seen that the values approach 0.06 in. for a roll amplitude of approximately 16 deg. Least squares straight lines have been drawn through the data points even though they exhibit a pattern of oscillation about the lines. Similar results were obtained for GM = 1.05 in., the only other condition for which wave measurements were made.

The energy contained in waves emanating from both sides of the model can easily be computed since negligible energy dissipation occurs in the waves as they travel 2.5 ft to the point of measurement. The energy is given by

$$\Delta E_{WM} = \frac{1}{8} \rho g h^2 A \qquad [10]$$

where h is the wave height,

A is the surface area contained in a wave having a length along its crest equal to the model length and a length between crests appropriate for the roll period, and

g is the acceleration due to gravity.

The ratio of energy loss per cycle due to wavemaking (Equation [10]) to total energy loss (the latter obtained by combining Equations [7] and [8]) is shown in Figure 7. The results are incoherent and do not exhibit any clear trends even though the wave transducer is supposedly capable of resolving much smaller oscillations of the water surface than actually occurred. One bit of information that can be gleaned from Figure 7 is that the energy lost by the cylinder due to wavemaking is on the order of 20 to 35 percent of the total energy lost. Since the model is not constrained in sway and heave, it could have a tendency to translate while rolling because the noncoincidence of the center of gravity and roll axis would result in a transverse centrifugal force. Visual observations of the model during the tests indicated that no heave or sway actually occurred. This is indirectly corroborated by Figure 5, wherein an estimation of the energy loss due to wavemaking can be obtained by subtracting the computed viscous energy loss from the total energy loss, since surface tension losses should be small* and those due to eddymaking are also virtually nonexistent. By this procedure it was found that the energy contained in waves produced by rolling without translation ranges

*See footnote on page 12.

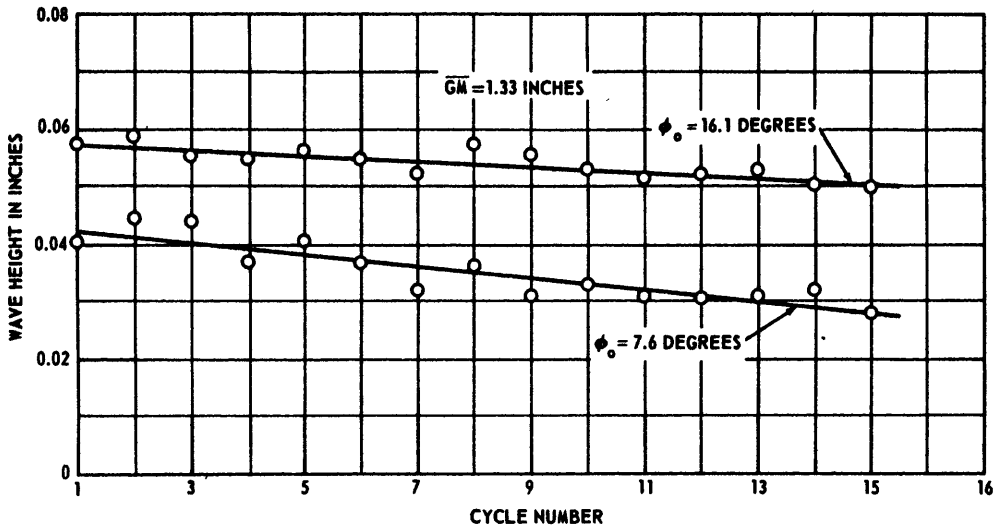

Figure 6 – Distance from Crest to Trough for Model-Generated Waves versus Cycle Number

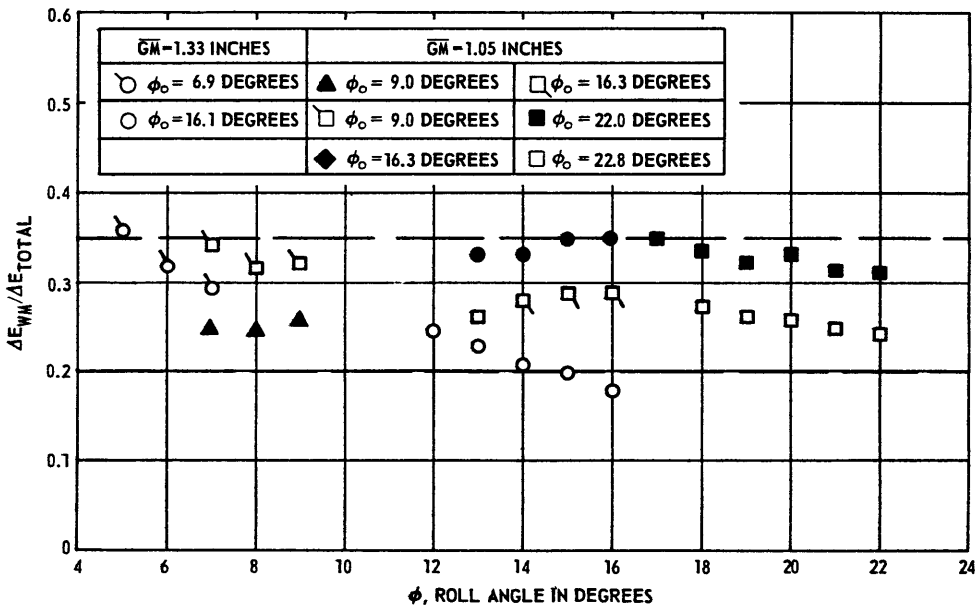

Figure 7 – Ratio of Energy Loss Due to Wavemaking to Total Energy Loss

from 20 to 45 percent of the total losses. These values are in reasonable agreement with the 20 to 35 percent derived from Figure 7, which indicates that energy contained in the measured waves was not imparted to the water by heave or sway. It is known that when a body of revolution rolls about its centerline axis, the resistance to motion is almost exclusively due to friction. The fact that in the present case significant energy is consumed in wavemaking reveals that for this unconstrained cylinder the dynamic roll axis (which is probably not even fixed in the body) is not coincident with the centerline (static roll axis).

CONCLUSIONS

This investigation has concerned itself with determining how the roll damping of a cylinder is affected if *GM* is varied by relocating the center of gravity and roll period is permitted to change accordingly. It has been concluded that the angular damping is linear for *GM* to diameter ratios *GM/D* ranging from approximately 0.003 to 0.055 (this will not be true for cylinders having a diameter much smaller than the one employed for the present study, viz. 2 ft). Thus, damping proportional to the first power of velocity can be assumed in the equation of motion. The log decrement, which is dependent upon angular damping, was found to vary inversely as the square root of *GM/D* in the region $0.0035 < GM/D < 0.045$. Since scale effects may exist, the relationship is possibly somewhat different for bodies larger than 2 ft in diameter. The effect of initial angle on the free roll damping proved to be small but not insignificant.

In order to obtain a true measure of the variation in forces or moments of damping produced by changes in *GM*, the rate of energy damping was examined. It was found to decrease appreciably as *GM* was made smaller, primarily because of the reduction in energy loss due to friction as the average roll velocity decreases. Although viscous energy losses predominated during these tests of an unappendaged body of revolution, the losses due to wavemaking were by no means negligible. They ranged from approximately 20 to 40 percent of the total energy lost, and resulted in the propagation of waves approaching 0.06 in. between crest and trough.

ACKNOWLEDGMENT

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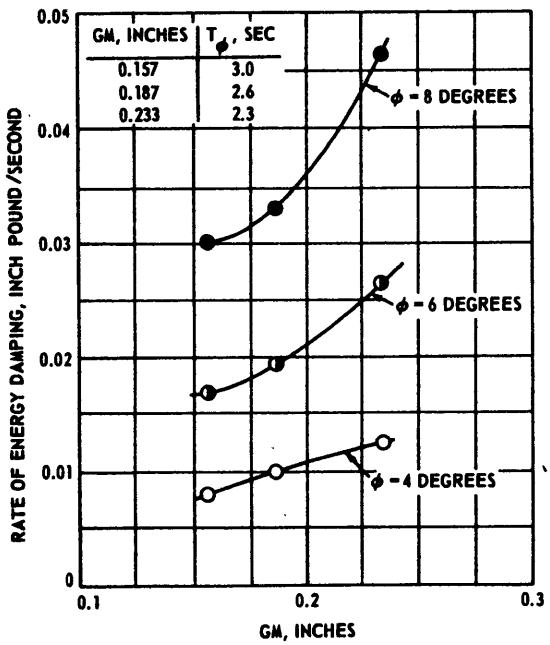

Figure A-1 – Rate of Total Energy Loss as a Function of *GM* (from Reference 4)

REFERENCES

1. Gersten, A., "Effect of Forward Speed On Roll Damping Due to Viscosity and Eddy Generation," Naval Ship Research and Development Center Report 2725 (Aug 1968).

2. Gersten, A., "Roll Damping of Circular Cylinders With and Without Appendages," Naval Ship Research and Development Center Report 2621 (Oct 1969).

3. Serat, M. E. and Thews, J. G., "An Investigation of Some of the Factors Affecting the Rolling of Ships," David Taylor Model Basin Report 348 (Feb 1933).

4. Stefun, G. P., "Experimental and Theoretical Investigation of Roll Damping," David Taylor Model Basin Hydromechanics Tech Note No. 4 (Jun 1955).

5. Thomson, W. T., "Mechanical Vibrations," Prentice-Hall, Inc. Publishers (Jun 1963).

6. Kato, H., "On the Frictional Resistance to the Rolling of Ships," J. of Zosen Kiokai, Vol. 102 (1958) in Japanese.

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2. Submarines--Roll--Damping--Model tests
I. Gersten, Alvin
II. Title: Roll damping, effect of metacentric height

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