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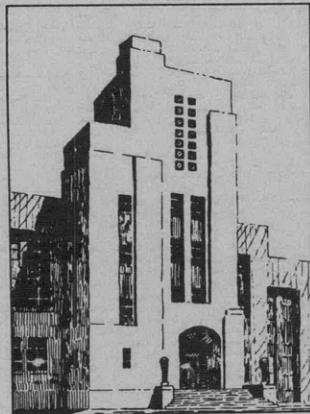
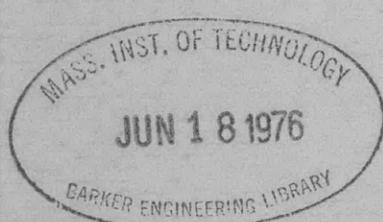
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UNSTEADY AND AMPLITUDE EFFECTS ON THE MOMENT DERIVATIVES OF A PROLATE SPHEROID

by

V.G. Szebehely, Dr. Eng. and

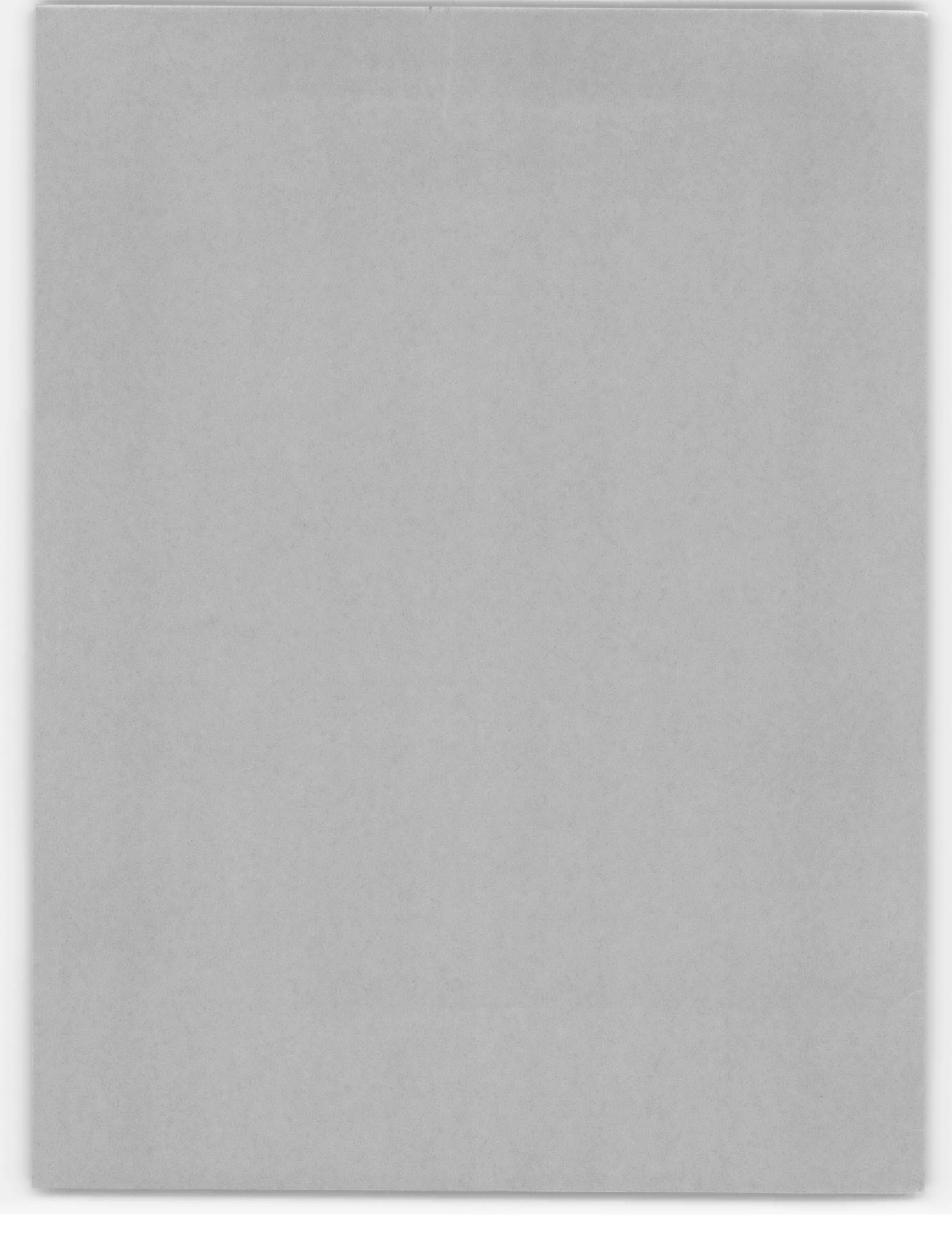
O.C. Niederer



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Report 828

NS 715-102



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ABSTRACT

This report discusses the effect of dimensionless frequency and amplitude of oscillation on certain hydrodynamic derivatives of a prolate spheroid with seven to one fineness ratio.

The results of the investigation show that the coefficient of the rotary moment derivative studied (yawing moment due to angular velocity of yaw) decreases with increasing dimensionless frequency of yawing oscillation (except at the maximum amplitude used). The above frequency effect was large for small yaw angles and small for large yaw angles. The added moment of inertia showed no frequency or amplitude effects at zero speed of advance. The yawing moment rate N_y' was found to be independent of the amplitude but showed some unsteady effects.

The experiments were performed at different frequencies (approximately 1 to 4 rad/sec) and amplitudes (1 to 5 deg) of oscillation, and at several speeds (0.5 to 4 knots). The dimensionless frequency varied from 1 to 8, the Reynolds number from 10^6 to 7.5×10^6 .

INTRODUCTION

This report presents the first part of an investigation, the final aim of which is to elucidate the effect of unsteadiness on submarine motion. The research program was initiated because aircraft motion under certain conditions was found to be influenced by unsteady effects.

The significance of frequency dependence of the hydrodynamic derivatives of submarines is somewhat analogous to that of nonlinearity; in both cases the derivatives depend on the motion.

A submarine might be considered as a body of revolution (hull) with low aspect ratio wings (appendages). Some theoretical and experimental results are available regarding low aspect ratio wings; information with respect to unsteady effects on bodies of revolution is lacking. Therefore, a bare hull spheroid of seven to one fineness ratio was selected for the initial investigation.

The effect of frequency and amplitude of oscillation was studied using free oscillation technique. The decay curves were analyzed and the results presented in the form of graphs.

The report consists of a description of the experimental apparatus used, method of data reduction and accuracy obtained, the results, and suggestions for future research.

EXPERIMENTAL APPARATUS AND MODEL

The results presented in this report were obtained from tests on the TMB yaw oscillator, shown schematically in Figure 1. The yaw oscillator is essentially a torsional spring system on which an underwater body is oscillated in yaw about a vertical axis, usually through the

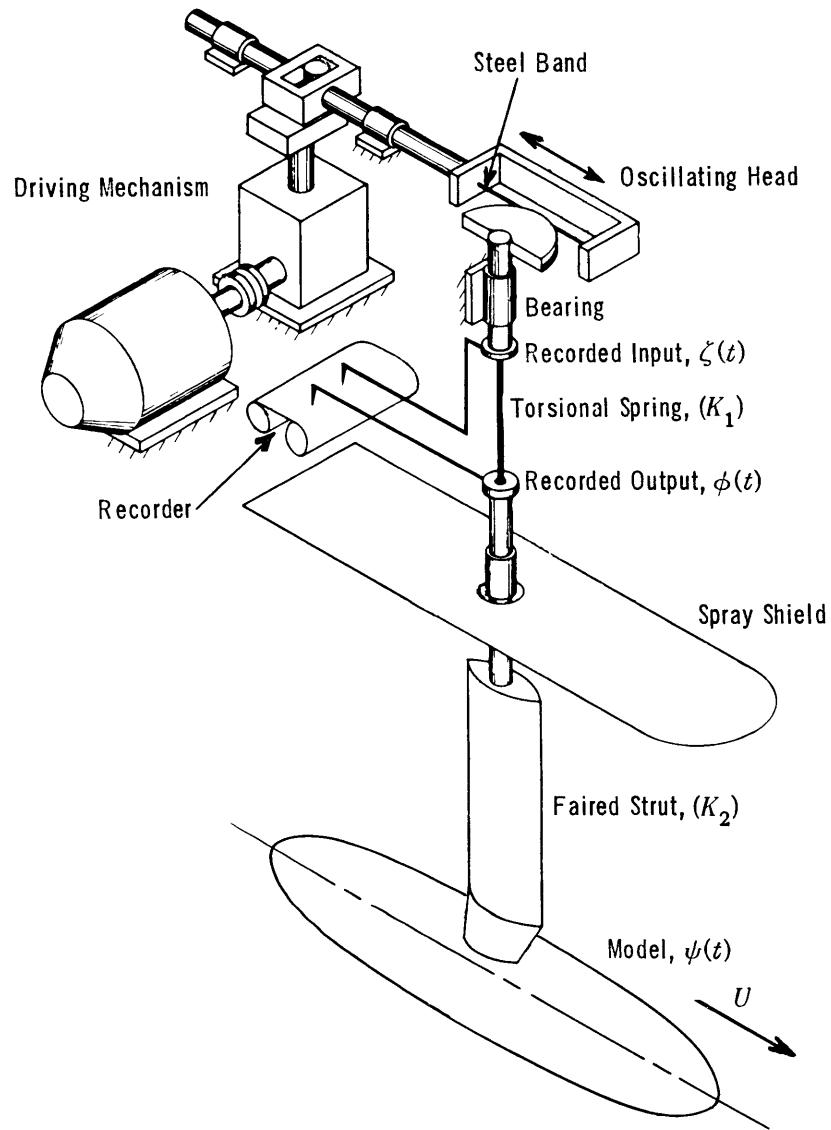


Figure 1 - Principle of Yaw Oscillator

center of gravity of the body. The instrument consists of the following basic parts: (1) A driving mechanism that produces a sinusoidal displacement of adjustable amplitude and frequency to the upper end of a torsion spring. (2) The torsion spring which consists of two parts: the upper part which is exchangeable, and the lower part which is covered with a fairing and is the same for all experiments. The body under test is mounted at the end of this lower element. (3) The main elements of the recording system are two arms connected to the upper and lower ends of the exchangeable torsion spring. The angular amplitudes of the two ends of this

torsion spring are recorded on a paper strip. The upper end of the exchangeable torsion spring can be locked in place for free oscillation tests.

Forced oscillation tests are used when the model damping is comparatively large, e.g., a submarine with all appendages. For smaller damping (bodies without appendages), the free oscillation method is used. All tests described in this report were conducted by the free oscillation technique.

The model used for this investigation was a spheroid of seven to one fineness ratio, 9 feet long and made of mahogany. It was oscillated about its minor axis.

The tests were performed at a constant depth-diameter ratio $h/d = 3.08$, which corresponds to a depth of 3.96 feet, and at model speeds of 0, 1/2, 1, 1 1/2, 2, 3, and 4 knots using 3 different exchangeable torsion springs. A few experiments were performed to show that, using the above h/d ratio, the presence of the free surface had no measurable effect.

A schedule of tests is given in Figure 2, each circle representing a test.

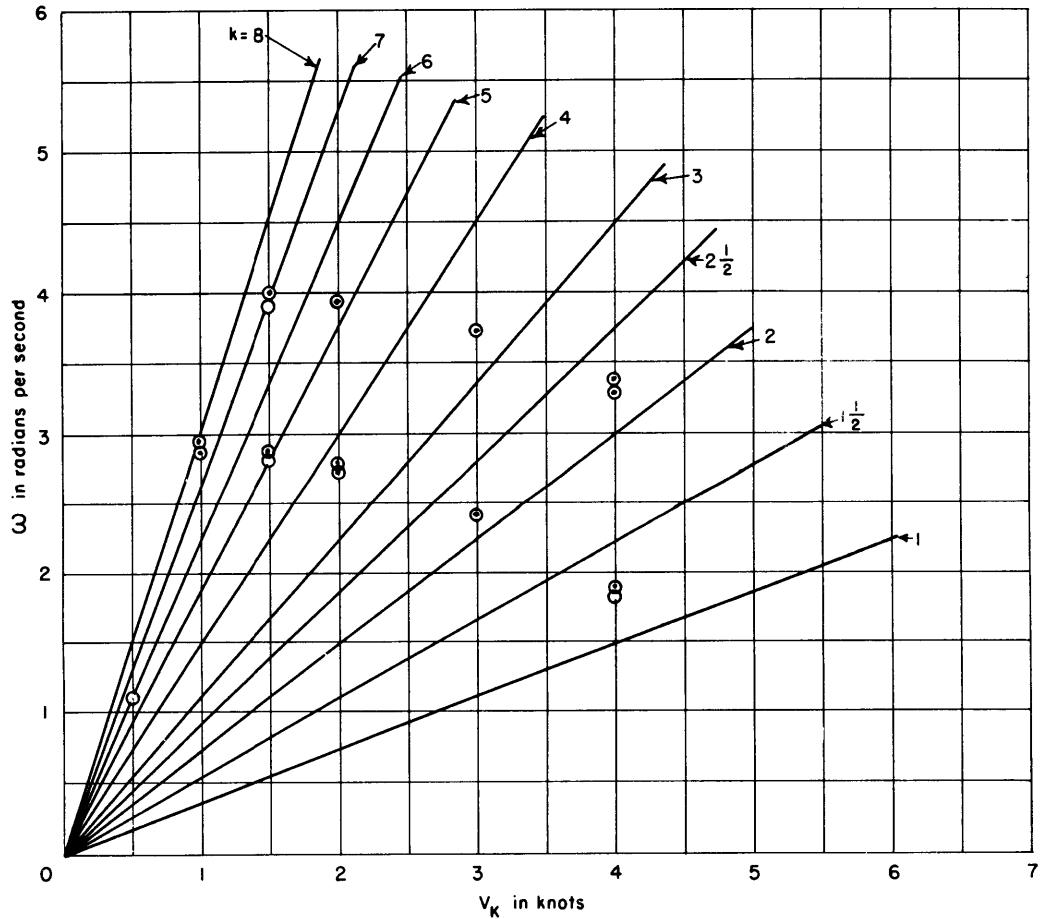


Figure 2 - Test Schedule, $k = \frac{\omega l}{2U}$

GOVERNING EQUATIONS

The differential equation representing the system shown in Figure 1 is assumed to be linear. The results, however, show nonlinearity, therefore, it seems to be necessary to clarify the assumptions made using the conventional linear oscillation equation as the basis for data analysis. First it is assumed that the instantaneous damping obtained from a decaying oscillation corresponds to the damping of a steady oscillation, i.e., to an oscillation with constant amplitude. With this assumption the effect of the varying amplitude is eliminated. The supporting factor for this assumption is the experimental fact that the starting amplitude of the decaying oscillation had no effect on the motion. The second assumption is that the nonlinear system is replaced instantaneously by an equivalent linear system.

The governing differential equation is

$$I_t \ddot{\Psi} + \eta_t \dot{\Psi} + K_t \Psi = K \zeta \quad [1]$$

where I_t is the total moment of inertia, $I_b + I_a$,

I_b is the moment of inertia of the body,

I_a is the added moment of inertia, $-N_r$,

η_t is the total damping, $\eta + \eta_i$,

η is the hydrodynamic damping of the body, $-N_r$,

η_i is the instrument damping,

K_t is the total restoring moment, $K + UN_v$,

U is the speed of advance,

N_v is the yawing moment rate,

K is the combined spring constant, $K_1 K_2 / (K_1 + K_2)$,

K_1 is the spring constant of the exchangeable spring,

K_2 is the spring constant of the lower spring,

Ψ is the yaw angle of the model, and

ζ is the angular position of the upper end of the exchangeable spring.

The elasticity of the shaft is expressed by the equation:

$$K_1 \Phi + K_2 (\Phi - \Psi) = K_1 \zeta \quad [2]$$

where Φ is the angular position of the junction between the exchangeable and lower springs.

For free oscillation the governing differential equation is obtained by setting $\zeta = 0$.

The fundamental differential equation for free oscillation is then:

$$I_t \ddot{\Psi} + \eta_t \dot{\Psi} + (K + UN_v) \Psi = 0 \quad [3]$$

From Equation [2] with $\zeta = 0$ the relationship between Φ and Ψ is given by

$$\Psi = \Phi \frac{K_1 + K_2}{K_2} \quad [4]$$

A solution of Equation [3] may be written as

$$\Psi = \Psi_0 e^{(i\omega - \bar{\omega}t)} \quad [5]$$

where ω is equal to the angular frequency,

$$\bar{\omega} \text{ is equal to } \frac{f}{n} \ln \frac{\Psi_i}{\Psi_{i+n}},$$

f is the frequency, $\omega/2\pi$,

n is the number of cycles,

Ψ_i is the amplitude of the i -th cycle, and

Ψ_{i+n} is the amplitude of the $(i + n)$ th cycle.

If this solution is substituted in Equation [3], the total damping becomes

$$\eta_t = \frac{2\bar{\omega}(K + UN_v)}{\omega^2 + \bar{\omega}^2} \quad [6]$$

and the equation for the total moment of inertia is

$$I_t = \frac{K + UN_v}{\omega^2 + \bar{\omega}^2} \quad [7]$$

It is only possible to determine two of the three quantities, η_t , I_t , and N_v from the foregoing equations of a free oscillation test. At zero speed of advance, however, η_t and I_t are readily found. The assumption is then made that I_t is the same when underway as at zero speed of advance.

This assumption might be supported by the fact that as Equation [7] shows, UN_v is the difference between the effect of the elasticity and the effect of the inertia of the system. Both effects are large, as compared to UN_v , therefore, small changes in N_v will not affect the constancy of I_t . (From this it also follows that the values reported for N_v are somewhat uncertain, as will be pointed out later.)

Rewriting Equations [6] and [7] in terms of I_t , the total damping becomes

$$\eta_t = 2I_t \bar{\omega} \quad [8]$$

The yawing moment rate is

$$N_v = \frac{1}{U} \left[I_t (\omega^2 + \bar{\omega}^2) - K \right] \quad [9]$$

The added moment of inertia, hydrodynamic damping and yawing moment rate are nondimensionalized as follows

$$I_a = -N_r' = \frac{I_t - I_b}{\frac{1}{2} \rho l^5} \quad [10]$$

$$\eta' = -N_r' = \frac{\eta_t - \eta_i}{\frac{1}{2} \rho l^4 U} \quad [11]$$

$$N_v' = \frac{N_v}{\frac{1}{2} \rho l^3 U} \quad [12]$$

where ρ is the density of the water,

l is the length of the model, and

U is the speed of advance.

METHOD OF DATA REDUCTION

Values for the quantities ρ , l , U , K_1 , K_2 , f , $\frac{1}{n} \ln \frac{\Psi_i}{\Psi_{i+n}}$, η_i , and I_b are necessary in order to determine N_r' , N_r' , and N_v' . This section deals with the method of determining these quantities.

The density ρ of the water in the TMB test basin is 1.937 slugs per cubic foot, ± 0.1 percent.

The over-all length l of the model tested is 9 feet.

The speed of advance U is the carriage speed which can be set to ± 0.02 knot over the entire speed range of these tests.

The spring constants K_1 and K_2 are the torsional spring constants of the exchangeable and lower torsion springs. These spring constants are determined by fixing one end of the spring and applying a torsional load at the other end. The twist in the spring is then measured and plotted against torsional load. The slope of this line is the torsional spring constant. The spring constants were checked a number of times during the course of the tests and the

variation was found to be less than 0.5 percent. The spring constants of the exchangeable springs are $K_1 = 1933$, 954.3, and 125.7 foot-pounds per radian. The spring constant of the lower spring is $K_2 = 9726$ foot-pounds per radian.

The values of frequency f and logarithmic decrement $\frac{1}{n} \ln \frac{\Psi_0}{\Psi_{0+n}}$ are determined from the records. A 28-inch arm is attached to the lower end of the upper spring with a ball point pen. There is also a timer recording 1/2-second intervals on the paper. The period of oscillation varied between 6.28 sec and 1.56 sec; these values correspond to 25 inches and 6.3 inches on the records. Since these records were read with a ± 0.01 -inch error, the maximum possible measurement errors in the periods and the frequencies were ± 0.04 percent and ± 0.16 percent, for the low- and high-frequency oscillations respectively.

It was found that the frequency was constant for any given run, and did not vary with the amplitude of oscillation within the limits of accuracy of the measurements.

The logarithmic decrement is determined by measuring successive peak amplitudes on the record. These amplitudes varied from 0.25 to 3.75 inches and could be measured to ± 0.01 inch. This results in 4 percent and 0.27 percent errors for small and large amplitudes respectively. Since the length of the recording arm is known, the peak amplitudes could be converted to the angular displacement Φ at the junction of the exchangeable and fixed torsion springs. Since Φ is related to the angular displacement of the model by $\Psi = \Phi [(K_1 + K_2)/K_2]$ it is possible to determine the values of Ψ with a maximum error of 4.2 percent and 0.5 percent for small and large oscillations respectively. The values of the \ln of maximum Ψ at successive oscillations are then plotted against number of cycles and the curve through these data points is drawn. The slope per cycle of the tangent at any given value of Ψ is the value of the logarithmic decrement at that value of Ψ .¹

From this value, using Equation [8], the total damping is found. After the instrument damping is subtracted and the result made dimensionless, η' versus Ψ is plotted for various k -values. These curves are extrapolated to $\Psi = 0$ and cross-plotted in order to obtain the conventional η' versus k curves with Ψ as parameter.

Tests were conducted oscillating the body in air to determine the moment of inertia of the body I_b and the instrument damping η_i . These tests were conducted at different frequencies by using different sizes of exchangeable torsion springs. Additional inertia weights were added to the system at the model in order to extend the range of frequencies for the determination of instrument damping. The moment of inertia of the body was found to be 45.5 lb-ft-sec². The instrument damping was found to be dependent on the frequency and amplitude of oscillation at the junction of the two torsion springs. The empirical formula for the instrument damping is

$$\eta_1 = \frac{3 \times 3}{\sqrt[4]{\omega^2 \Phi}} \pm 0.6 \quad [13]$$

*References are listed on page 20.

where η_i is in ft-lb-sec/rad,

ω is in radian/sec, and

Φ is in degrees.

Tests were conducted by deflecting the model to angles up to 8 degrees and then releasing it and recording the resulting motion. A number of tests were conducted releasing the model at different amplitudes to determine if the starting amplitude had any effect on the resulting motion. No effect of starting amplitude was detected, nor was there any detectable variation of frequency during any given completely decaying oscillation tests.

RESULTS

The initial tests were conducted at zero velocity in order to determine the value of I_t , using Equation [7]. The variation in the value of the logarithmic decrement squared was negligible compared to $4\pi^2$; therefore no amplitude variation of I_t was determinable. These tests were conducted using three different exchangeable springs, and covered a frequency range from

1.12 to 4.08 radians per second. It was found that I_t did not vary with frequency in this range. The value of I_t was determined as 97.5 ± 0.8 ft-lb-sec 2 . Since I_b was found to be 45.4, the value of I_a is 52.1 ft-lb-sec 2 , see Figure 3.

The theoretical result for the added moment of inertia of a spheroid of fineness ratio l/d deeply submerged is well known:²

$$I_a = k' I_0$$

where k' is the added moment of inertia coefficient, and

$$I_0 = \frac{\pi}{120} \rho l^5 \left(\frac{d}{l}\right)^2 \left[1 + \left(\frac{d}{l}\right)^2\right]$$

is the moment of inertia of the displaced water. This gives $I_a = 51.9$ ft-lb-sec 2 in close agreement with the experimental value.

The majority of the tests were conducted at various constant forward velocities from 0.5 to 4.0 knots, using three different exchangeable springs. Changing

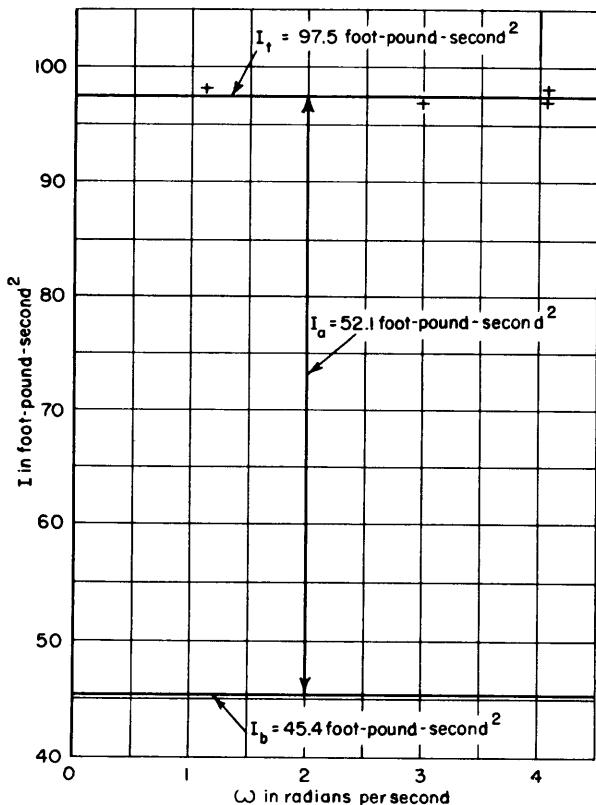


Figure 3 - Experimental Moment of Inertia at Zero Speed of Advance

either velocity or torsion spring resulted in a change of frequency. The frequency range of these tests was from 1.10 to 4.01 radians per second. Expressed as a nondimensional frequency

$$k = \frac{\omega l}{2U} \quad [14]$$

the tests covered a range of 1.22 to 7.86. The decay curves showing $\ln \Psi$ versus cycles are presented in Figure 4. The computed values of η' against Ψ for various values of k are shown on Figure 5. These curves were then used to determine values of η' over a range of dimensionless frequencies for model amplitudes of 0, 1, 2, 3, 4, and 5 degrees, see Figure 6.

Repeat runs were made for most of the test conditions. The different symbols used on Figure 4 indicate different runs. If the data of two separate runs agreed exactly a single curve was drawn through the data. If there was a difference, separate curves were faired through each set of data. The starting points of some of the data on Figure 4 were shifted horizontally for clarity. If all the data for a given test condition fall on one curve (on Figure 4) then a single symbol is used on Figure 5 for that test condition. If more than one curve is drawn for a given condition on Figure 4 then on Figure 5 different symbols are used.

The data on Figure 5 were extrapolated to $\Psi = 0$. The solid circles on Figure 6 indicate the values of the faired curves of Figure 5 for which data exist, the broken circles on Figure 6 indicate the extrapolated portion of the curves of Figure 5.

The curves on Figure 6 were obtained by a three point fit of the equation

$$\eta' = \frac{k^2 + a}{b k^2 + c}$$

Table 1 shows the faired values of the constants in the foregoing equation as obtained from Figure 6.

TABLE 1
Faired Values from Figure 6

Ψ_0 degrees	a	$b \times 10^{-3}$	$c \times 10^{-4}$
0	59.0	9.523	7.3732
1	54.7	8.197	7.4941
2	47.3	5.780	7.1631
3	49.6	3.876	8.4021
4	154.5	2.653	29.7082
5	15.6	1.477	3.1736

Figure 4 - Decay Curves

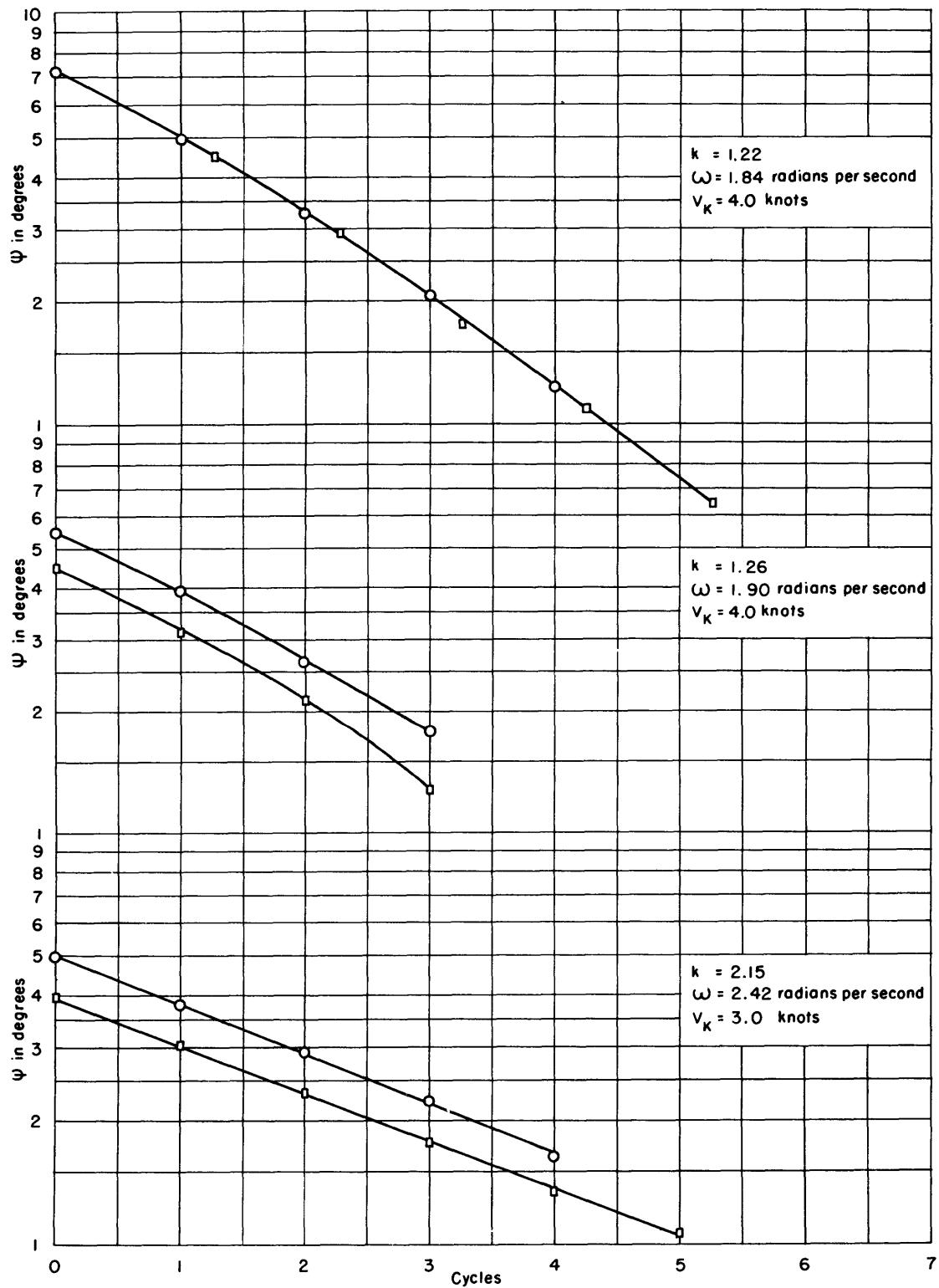


Figure 4 (Continued)

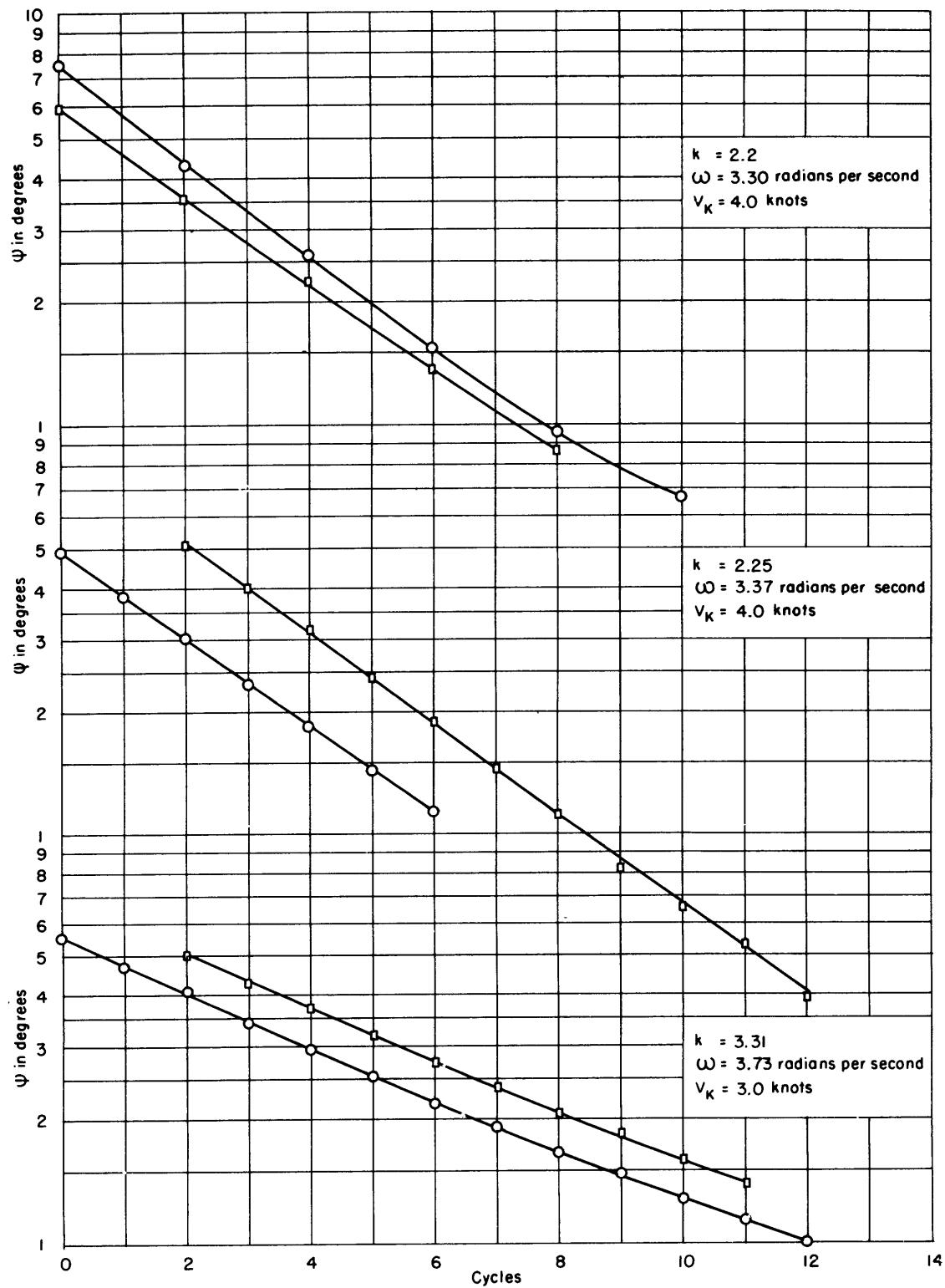


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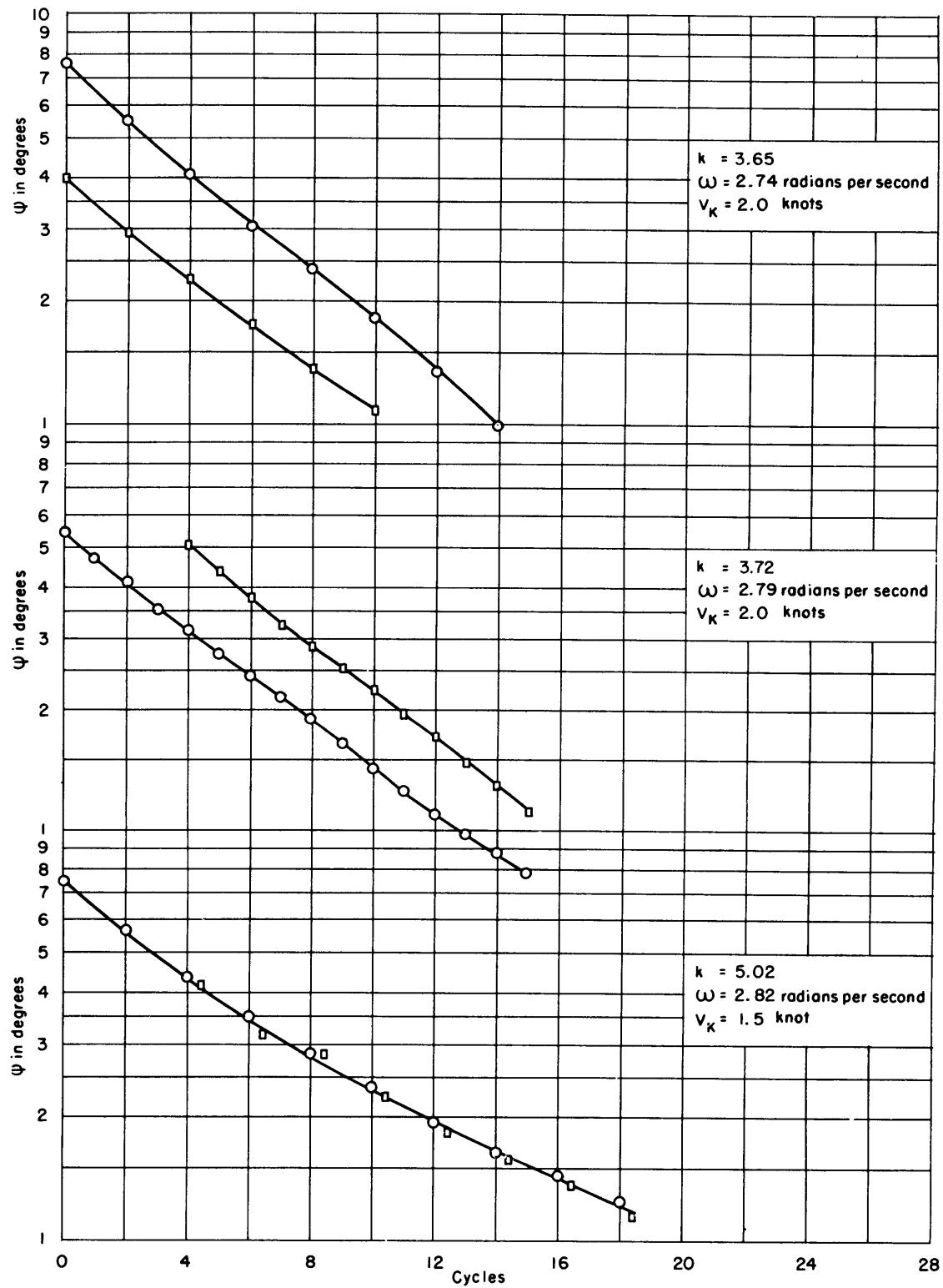


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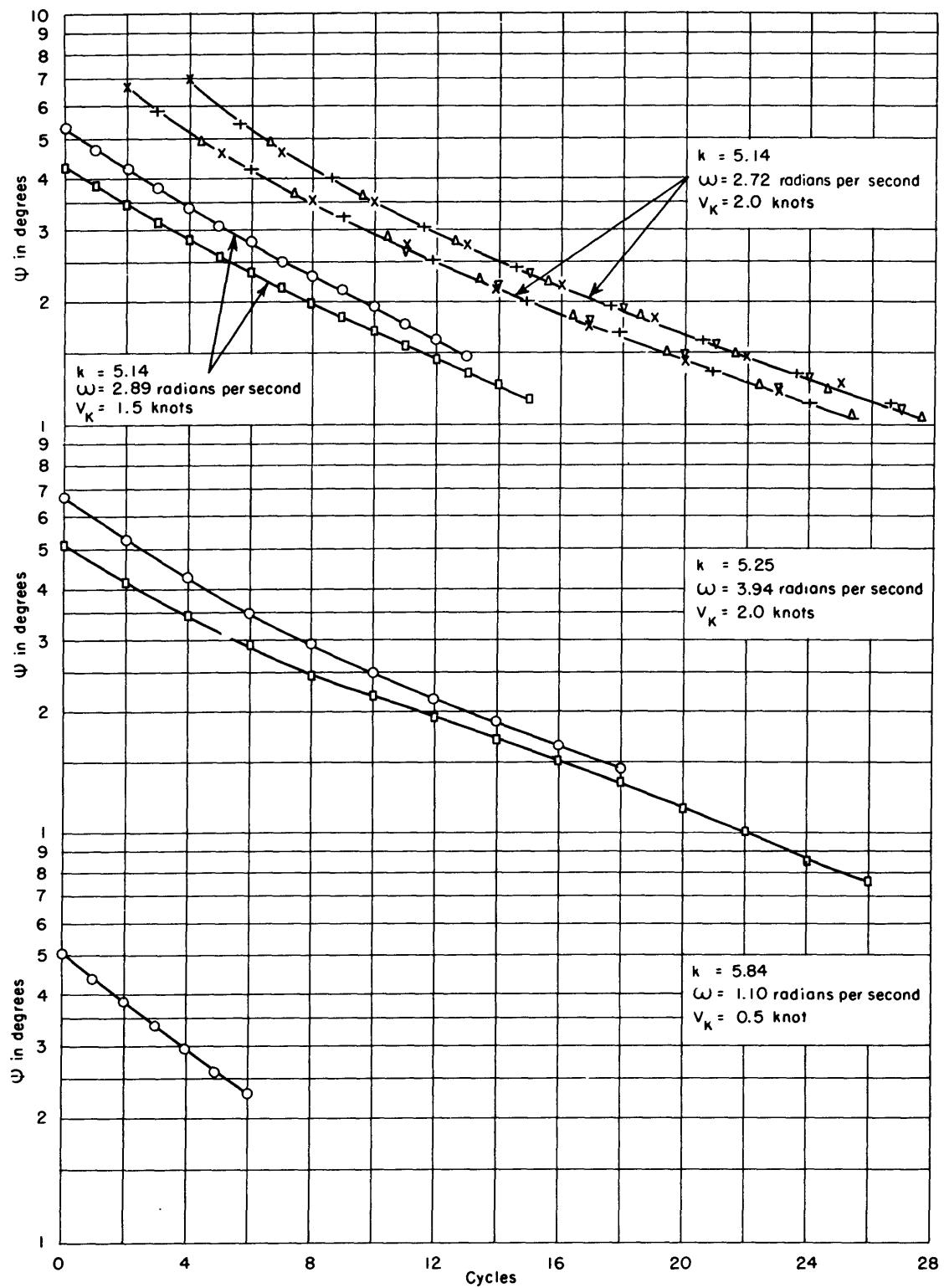


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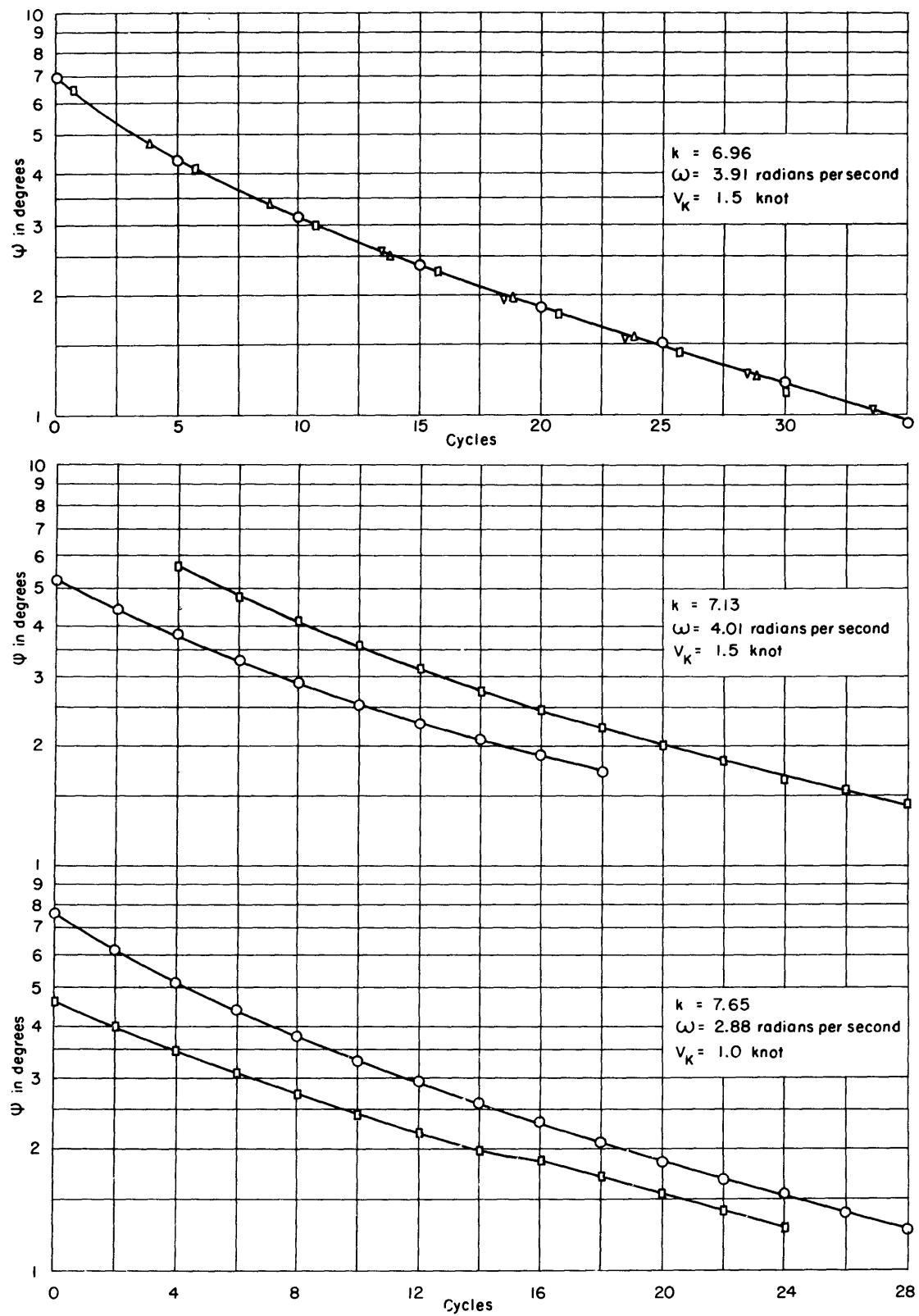
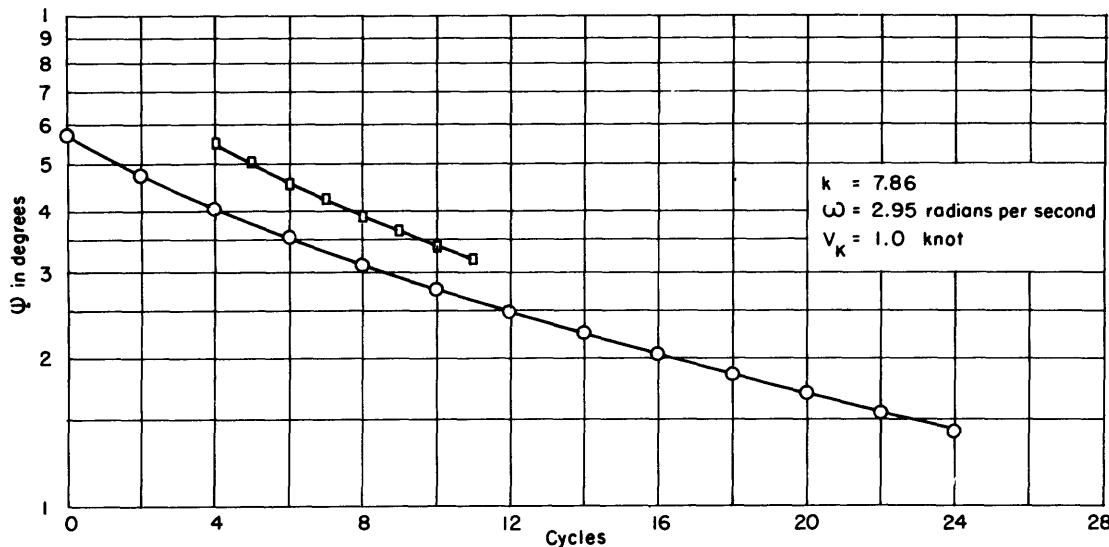


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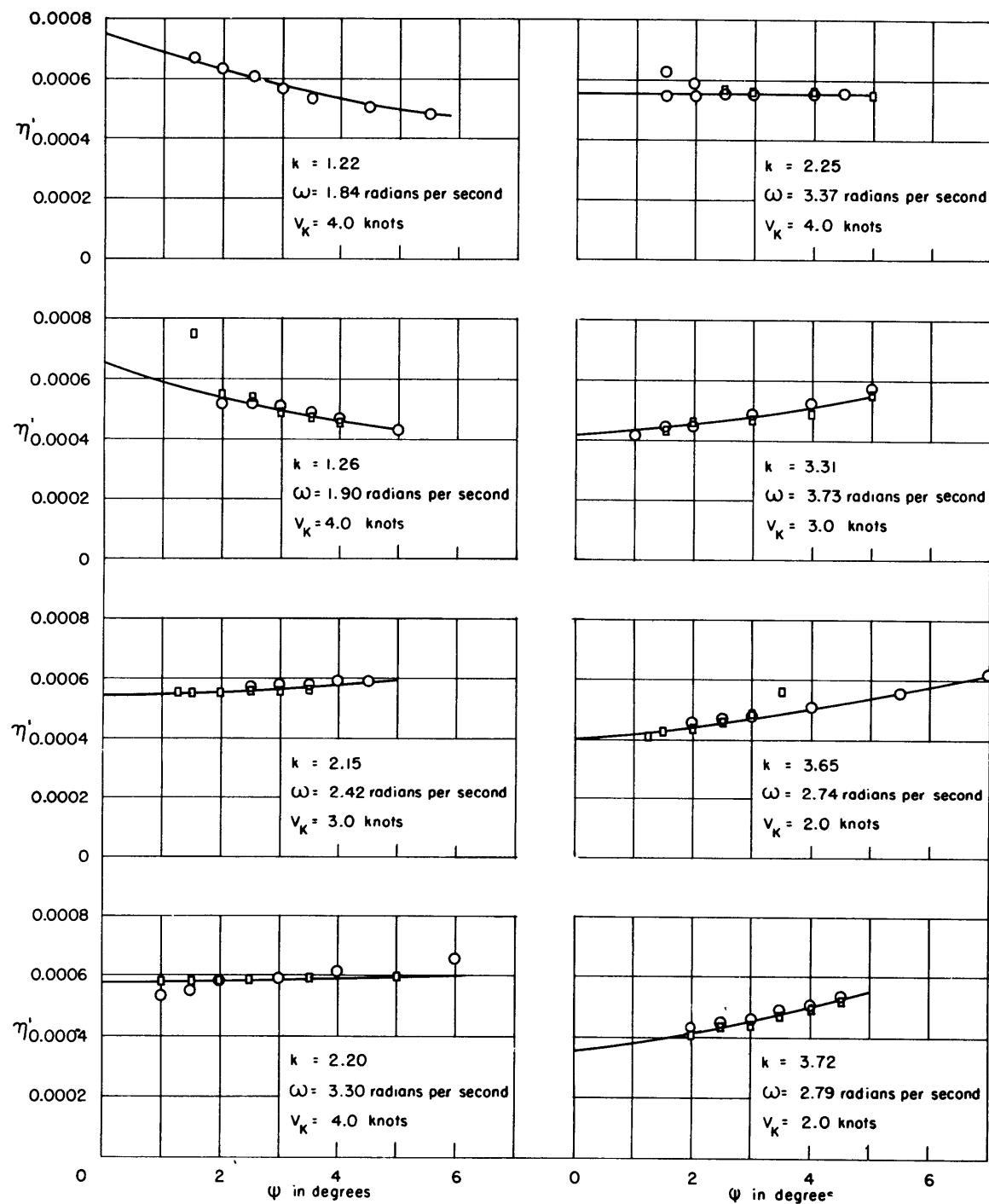
The value of N_v' was determined using Equation [9]. Again, since the variation of the logarithmic decrement is negligible compared to $4\pi^2$, no amplitude variation was determinable. The values of N_v' were nondimensionalized using Equation [12]. Since N_v' appears as a small difference of two large quantities, the only conclusion which can be drawn from Figure 7 is that there is an indication of variation of N_v' with k . The reader's attention is called at this point to the previously mentioned assumption that $I_t = \text{constant}$. Any small variation in I_t would greatly affect Figure 7. These experiments were not designed to obtain the frequency dependence of N_v' . This might be obtained with greater reliability by measuring moments on the model in heave experiments.

The dimensionless moment rate (extrapolated to zero frequency) is 0.0162. This value was checked by using the yaw oscillator as a moment measuring instrument. From such static test $N_v' = 0.0167$. The foregoing values can be compared with the theoretical values given by the Munk formula³

$$N_v' = \frac{\pi}{3} (k_2 - k_1) \left(\frac{d}{l}\right)^2$$

where k_1 and k_2 are the added mass coefficients along the two axes of the spheroid.

The theoretical moment rate is 0.0191 which is higher than the experimentally obtained values, as is to be expected.



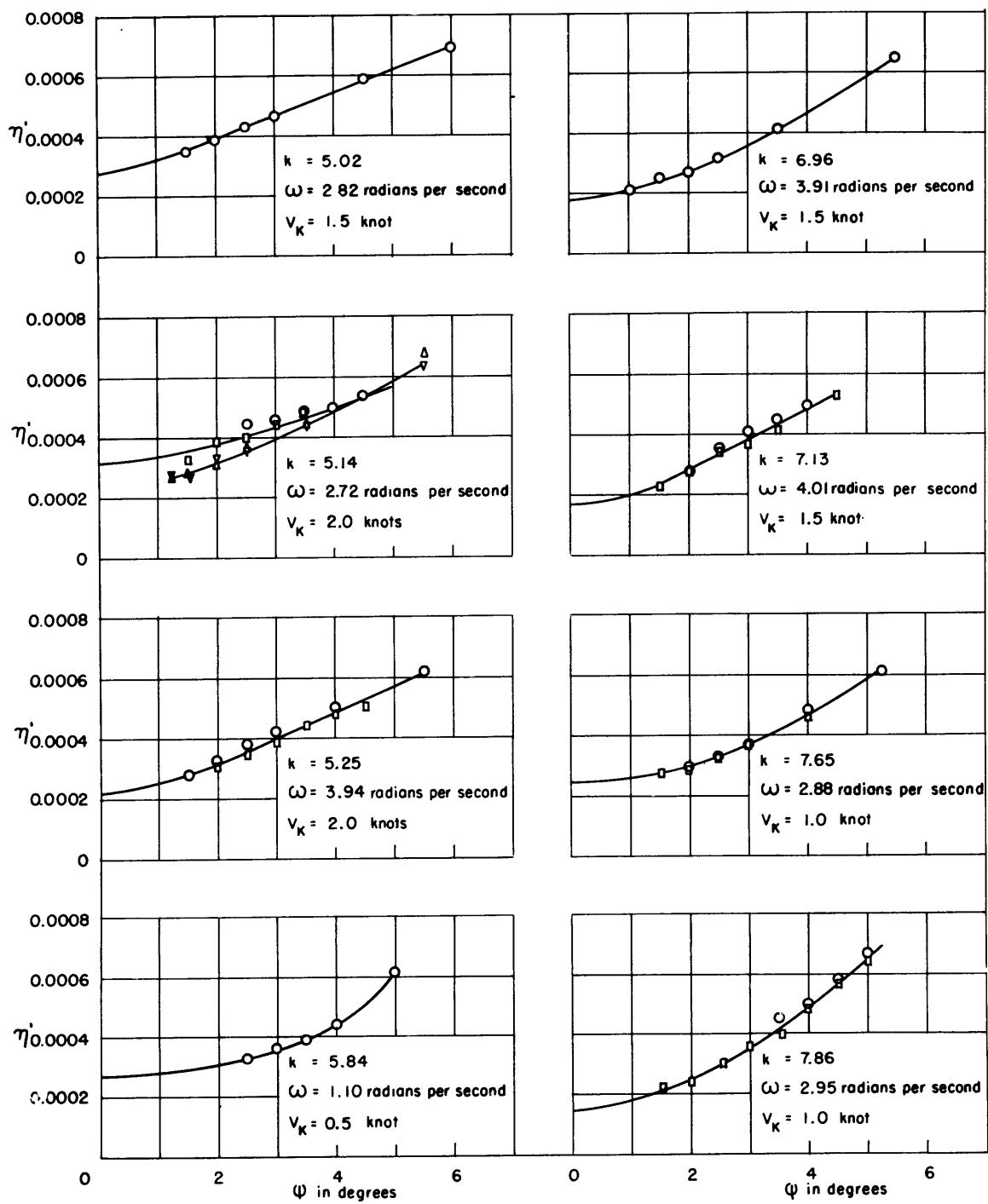
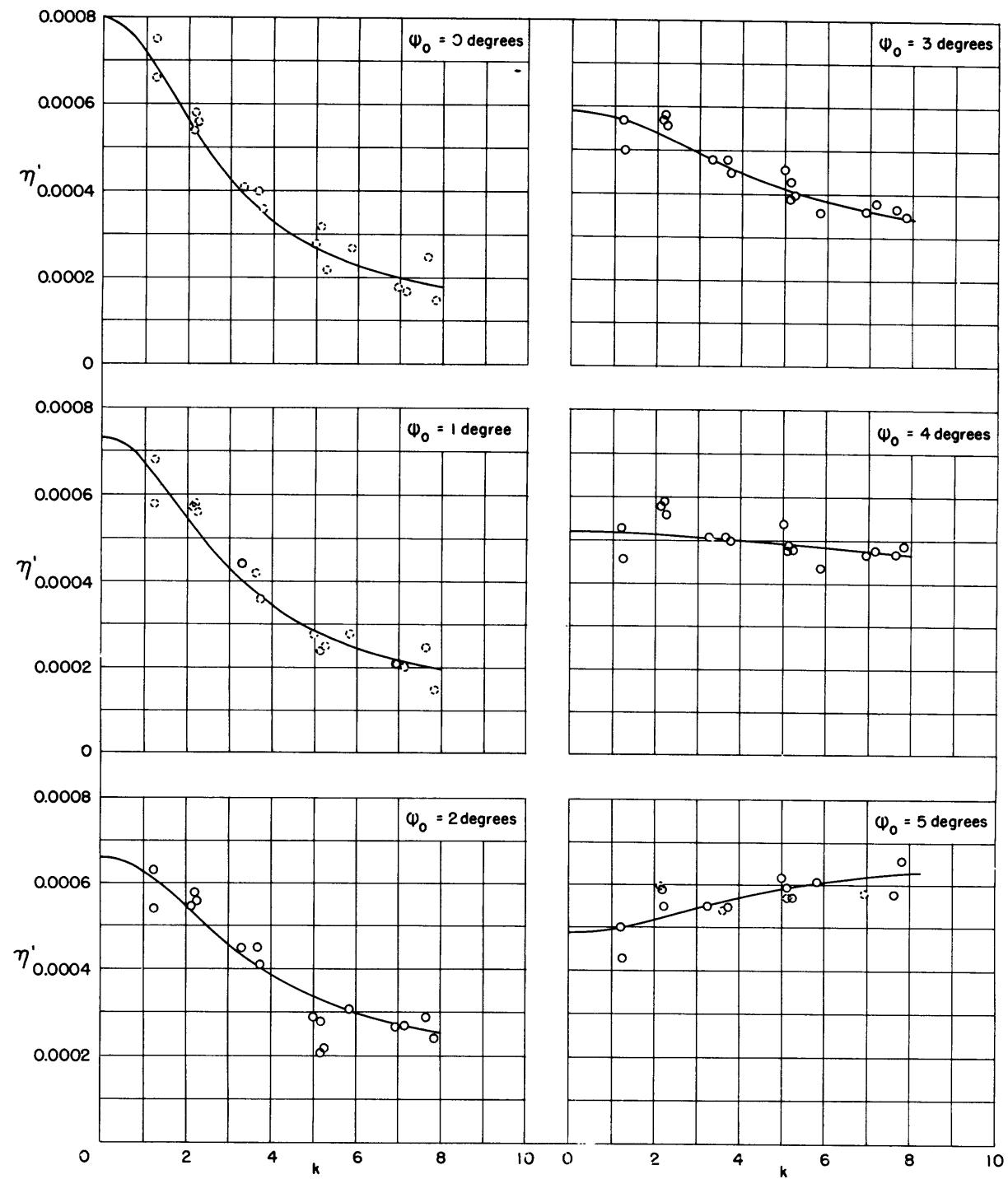


Figure 5 - Dimensionless Damping versus Amplitude for Various Values of the Dimensionless Frequency

Figure 6 - Damping Curves for Ψ_0

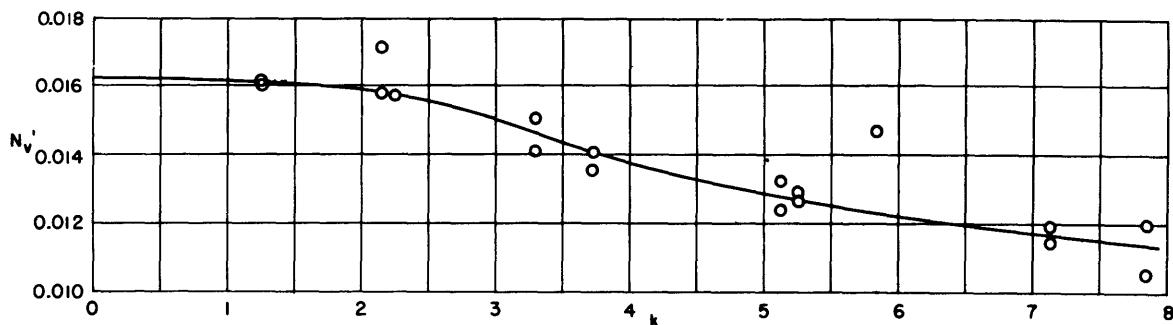


Figure 7 - Static Yawing Moment Rate versus Frequency Parameter

SUGGESTIONS FOR FUTURE RESEARCH

1. Probably the most urgent next step in improving and completing the findings of this report is to obtain the value of the damping derivative N_v' at zero frequency. The values of N_v' at zero frequency given in this report are extrapolated values and therefore rather uncertain.
2. The experimental results reported in this report were obtained using one model. It is suggested that models of several different fineness ratios be tested and the effect of l/d be studied in conjunction with unsteady effects.
3. The extension of the range of the dimensionless frequency used presently seems to be of great importance. Especially it is recommended that the range $0 < k < 2$ should be investigated. This requires low frequency and high speed operating conditions. Using the free oscillation technique, low frequency (soft spring) and high speed (large N_v' , hard spring) are incompatible. Therefore, the forced oscillation technique is recommended, using the present experimental facilities with a much lower frequency range. The minimum angular frequency obtainable presently with the forced oscillation technique is approximately 1 rad/sec. It is recommended that by selecting proper gear reduction ratios this lower limit be of the order of 0.1 rad/sec.
4. The classical result, that infinite aspect ratio wings show no unsteady effects if oscillated around the forward quarter point is well known. For bodies of revolution no analogous result is expected. Nevertheless a study of the effect of the location of the axis of rotation on the hydrodynamic derivatives is recommended.
5. Pressure measurements on oscillating bodies can be correlated with potential flow calculations and time lag effects can be studied by this method. The potential flow pressure distribution on a yawed and oscillating prolate spheroid may be readily derived. Actually measured pressure variations, however, on an oscillating spheroid are lacking and should be obtained.

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1 DIR, Inst for Math and Mech, New York Univ	1 Engin Libr, Curtiss-Wright Corp, Propeller Div, Caldwell, N.J.
1 DIR of Res, The Tech Inst, Northwestern Univ	1 Main Libr, Carnegie Inst of Tech, Pittsburgh, Pa.
2 Newport News Shipbldg and Dry Dock Co, 1 for Senior Nav Arch, 1 for Sup, Hydraulic Lab	1 Librarian, Franklin Inst, Philadelphia, Pa.
1 New York Shipbldg Corp, Camden, N.J. via SupShip	1 Tech Libr, Glenn L. Martin Co, Baltimore, Md.
1 DIR, Robinson Hydraulic Lab, Ohio St Univ	1 Tech Libr, Grumann Aircraft Engin Corp, Bethpage, Long Island, N.Y.
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1 Head, Dept of Aero Engin and App Mech, Polytech Inst of Brooklyn	1 Tech Libr, Lockheed Aircraft Corp, Burbank, Calif.
1 DIR, Hydraulics Lab, Penn St College	1 Tech Libr, McDonnell Aircraft Corp, St. Louis
1 DIR, Russell Sage Lab, Rensselaer Polytech Inst, Troy, N.Y.	1 Tech Libr, N Am Aviation, Inc, Downey, Calif.
1 Dept of Mech Engin, Stanford Univ	1 Tech Libr, N Am Aviation, Inc, El Segundo, Calif.
1 DIR, ETT, Stevens Inst of Tech, Hoboken, N.J.	2 Prof. M.L. Albertson, Head, Fluid Mech Res, Colo. A and M College, 1 for Prof. A. Yih
1 Dean, Sch of Engin, Univ of Texas	
1 DIR, Engin Exp Station, Univ of Tenn.	

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1	Prof. G. Birkhoff, Dept of Math, Harvard Univ	1	Dr. J.H. McMillen, Natl Sci Foundation
1	Prof. R.C. Binder, Dept of Mech Engin, Purdue Univ	1	Prof. J.W. Miles, Univ of Calif.
1	Prof. N.W. Conner, N C St Col, Raleigh, N.C.	1	Dr. A. May, Aero Div, USNOL
1	Dr. E.O. Cooper, USNOTS, Pasadena, Calif.	1	Dr. George C. Manning, Prof. Nav Arch, MIT
1	Dr. F.H. Clauser, Chairman, Dept of Aero, Johns Hopkins Univ	1	RADM A.I. McKee, USN(Ret), General Dynamics Corp, Electric Boat Div, Groton, Conn.
1	VADM E.L. Cochrane, USN (Ret), MIT	1	Prof. C.J. Peirce, Hdqtrs, USAFE
1	Prof K.J. DeJuhasz, Penn State College	1	Mr. J.B. Parkinson, Langley Aero Lab, Langley Field
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1	Dr. D. Gilbarg, Dept of Math, Indiana Univ	1	Prof. A. Weinstein, Dept of Math, Univ of Md.
1	Prof. L.M. Grossman, Col of Engin, U of Calif.	1	Dr. J.V. Wehausen, Exec Editor, Math Rev
1	Dr. N.J. Hoff, Polytech Inst of Brooklyn	1	Dr. G.F. Wislicenus, Mech Engin Dept, Johns Hopkins Univ, via INSMAT
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1	Prof. W.S. Hamilton, Tech Inst, Northwestern U.	1	Dr. L.G. Straub, DIR, St. Anthony Falls Hydraulic Lab, Univ of Minn.
1	Prof A.D. Hay, Sch of Engin, Princeton Univ	1	Dr. V.L. Streeter, DIR, Fundamental Fluid Res, III Inst of Tech
1	Dr. A.T. Ippen, DIR, Hydro Lab, Dept of Civil and Sanitary Engin, MIT	1	Dr. F.B. Seely, Fluid Mech and Hydraulics Lab, Univ of Ill.
1	Dr. A. Kantrowitz, Cornell Univ	1	Dr. C.R. Soderberg, Dept of Mech Engin, MIT
1	Dr. G.H. Keulegan, Natl Hydraulic Lab, NBS	1	Dr. K.E. Schoenherr, Col of Engin, U of Notre Dame
1	Prof. B.V. Korvin-Kroukovsky, Stevens Inst of Tech, Hoboken, N.J.	1	Prof. W. Sears, Grad Sch of Engin, Cornell Univ
1	Dr. Th. von Kármán, Pasadena, Calif.	1	Dr. Stanley Corrsin, Dept of Aero, Johns Hopkins U.
1	Dr. R.T. Knapp, Hydro Lab, CIT, via INSMAT	1	Dr. C.A. Truesdell, Dept of Math, U of Indiana
1	Dr. C. Kaplan, Langley Aero Lab, Langley Field	1	Mr. F.L. Thompson, Langley Aero Lab, Langley Field
1	Mr. C.A. Lee, Res and Dev Lab, Kimberly-Clark Corp, Neenah, Wis.	1	Prof J.K. Vennard, DIR, Hydraulic Lab, Stanford Univ
1	Dr. C.C. Lin, Dept of Math, MIT	1	Prof. E.V. Laitone, Univ of Calif.

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| 1 | Dr. George K. Morikawa, Inst of Math Sci, N.Y. U | 1 | Prof. L. Rosenhead, Univ of Liverpool |
| 1 | Head, Aero Div, Natl Physical Lab, Teddington | 1 | Prof. J.L. Synge, Sch of Theoretical Physics Natl Univ of Ireland |
| 1 | Head, Aero Dept, Royal Aircraft Establishment | 1 | Prof. Dr. H. Schlichting, Inst für Stromungs, Tech Hochschule |
| 1 | DIR, Aero Res Inst of Sweden | 1 | Prof. K. Stewartson, Dept of Math, Univ of Bristol |
| 1 | Australian Council for Aeronautics | 1 | Sir R.V. Southwell, Oxford, England |
| 1 | Canadian Natl Research Establishment | 1 | Dr. R. Timman, Natl Luchtvaartlaboratorium |
| 1 | Admiralty Research Laboratory, Teddington | 1 | Supt, Nederlandsh Scheepsbouwkundig |
| 1 | Armament Research Establishment | 1 | Prof. Dr. G. Weinblum, Ingenieur Sch, Hamburg |
| 1 | Univ of Liverpool, Math Inst, Dept of Appl Math, Grace Library | 1 | Mr. C. Wigley, London EC-1, England |
| 1 | DIR, British Shipbldg Research Association | 1 | DIR, Hydro Lab, Natl Res Council, Ottawa |
| 1 | Editor, Bulletin of the British Hydro Res Assoc | 1 | Australian Sci Liaison Office |
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