CHAPTER 51

MODEL STUDIES OF THE DYNAMICS OF AN LSM MOORED IN WAVES

by

R. L. Wiegel, K. E. Beebe and R. A. Dilley
University of California
Berkeley, California

ABSTRACT

Presented in this report are the results of model tests performed t determine the motions of a moored LSM (Landing Ship Medium) and the associated mooring cable forces when subjected to the action of uniform periodic water waves. Details are given of the design and construction of the 1:80 scale model LSM and the dynamic balancing of the model. Pr ciples of the designs of the model mooring cables and of the meter for measuring the cable forces are also presented. The use of the laborato equipment, such as the wave-towing tank, the model basin, the photograp equipment, and the force and wave height meters are described, and the testing procedure is outlined. The data are presented in terms of the prototype in graphical form. Resonance conditions in the surging and heaving motions, and the associated high cable forces, are shown to exi for some initial cable tensions within the range of wave periods normal encountered in many ocean areas. The effect of a roll damping device i shown.

INTRODUCTION

One type of mobile platform which has possibilities in the offsho oil program for core boring or well drilling operations is an existing suitably-modified vessel. Such a vessel must be moored within narrow limits or boring and drilling operations must be modified to allow for considerable oscillatory movements; probably the solution will be a co bination of both. The solution of the problem from a mathematical sta point is complicated by the fact that the mooring cables have non-line characteristics.

In order to work at sea it is necessary to moor a vessel so that will not drift under the action of wind, currents or the net motions associated with wave action. Further, it would simplify the operatior coring or drilling through a well in the ship if the oscillatory motic associated with waves could be minimized. In any case, the magnitudes these motions have to be determined. At the same time, the forces ex on the mooring cables have to be predicted. In addition, devices for damping any induced motions should be tested to rate their effectiven

A model of the dynamics of a moored LSM was made by the Wave Res Laboratory, University of California, Berkeley, California, for the C ornia Research Corporation.

MODEL STUDIES OF THE DYNAMICS OF AN LSM MOORED IN WAVES

MODEL LAWS

Gravity, inertia, elastic, surface tension and viscous forces exist in a moored floating body system, neglecting compressibility effects. From a practical standpoint it is not possible to model the system in compliance with all modeling laws simultaneously. The vessel and the waves were modeled in accordance with Froude's modulus. The effect of Reynolds' modulus was neglected in the development of the model (however, turbulence existed in the flow) in conformity with standard naval architectural practice. The effect of surface tension was assumed to be of little importance as the model was to be made large enough that the waves would be well into the "gravity regime" and the cables were to be large enough that surface tension forces would not interfere with their motions.

The most serious question in a model of this sort is the neglecting of the effect of Reynolds' modulus (viscous forces). However, a brief analysis by Dr. Kitter (California Research Corporation, La Habra) indicated that the order of magnitude of viscous forces on the mooring cable would be small compared to gravity and inertia forces, and for the range of variables to be considered, the drag coefficient would be relatively insensitive to Reynolds number.

The following model laws were used in the design of the ship model, model mooring cable and the cable force meter:

Let A = cable area (cross-section).
C = a constant of the system; for the case considered herein it is related to the angle the mooring cable makes with the force meter.
E = modulus of elasticity of cable.
g = acceleration of gravity (32.2 ft./sec.^{2}).
I = moment of inertia of cable (cross-section).
L = cable length.
P = applied force.
S = geometric scale ratio (1:80).
W = weight of a quantity.
$-_m$ = refers to a model quantity.
$-_p$ = refers to a prototype quantity.
$-_r$ = refers to a ratio between model and prototype quantities.
ΔL = axial deflection of cable.
γ = unit weight of a quantity.
ϕ = force ratio.

For Froude similitude, set the dimension of gravity force equal to the dimension of inertia, axial elastic and bending elastic forces, and obtain:

(1) Gravity forces

$$\frac{\gamma_m L_m^3}{\gamma_p L_p^3} = \phi_G = \gamma_r L_r^3 \qquad (1)$$

(2) Inertia forces

$$\phi_I = \frac{\gamma_m L_m^3 g L_p T_m^2}{\gamma_p L_p^3 g L_m T_p^2} = \gamma_r T_r^2 L_r^2 = \phi_G \qquad (2)$$

also $\qquad \gamma_r T_r^2 L_r^2 = \gamma_r L_r^3$

therefore $\qquad \sqrt{L_r} = T_r$,

(3) Axial elongation forces in the cable

$$\Delta L = \frac{PL}{AE}; \quad AE = \frac{P}{\Delta L/L}; \text{ let } K = AE \qquad (3)$$

$$\frac{K_m}{K_p} = \phi_{AE} = \phi_G = \gamma_r L_r^3; \text{ let } AE = K, \text{ then } K = \gamma_r L_r^3 .$$

(4) Forces causing bending in the cable

$$\Delta = \frac{CPL^3}{EI}, \quad \frac{P_m}{P_p} = \phi_B = \frac{\Delta_m (EI)_m L_p^3}{\Delta_p (EI)_p L_m^3} = \gamma_r L_r^3 = \phi_G \qquad (4)$$

$$\frac{\Delta_m}{\Delta_p} = L_r, \text{ and } (EI)_r = \gamma_r L_r^3 .$$

These relationships will be referred to in the following paragraphs on the design and construction of the ship model, the mooring cable model and the mooring cable force meter.

SHIP MODEL

DESIGN

Before designing the ship model, it was necessary to choose a scale ratio that would satisfy three criteria:

1. The effects of surface tension would not be important.
2. The model would be small enough for use in the wave-towing tank, yet large enough that minor variations, when magnified to prototype, would not prove to be excessive.
3. The model would be large enough that a proper scale mooring system could be constructed and the expected mooring cable forces would be of sufficient magnitude that they could be easily measured.

A scale ratio of 1:80 was chosen. The model was scaled from a U. Navy drawing (Bureau of Ships, LSM (1)-S0701-112485, ALT. and LSM (1)-S0103-112380, ALT. 5), and from California Research Corporation Drawing (Nos. LC7990-7999, 9000-9007). Transverse cross section drawings for n stations along the ship were prepared to assure accurate ship dimension (Figure 1). The superstructure, except for the foreward superstructure deck, was left off the model, as were the several decks, and the model was designed to built to its own freeboard. It was necessary to approx mate successively sections C-C from station 0 on, as drawings for these sections were unavailable. For the region near the bow where the shape changes considerably, many cross sections were drawn. The skegs and rudders were drawn up separately, since they were left off the basic model shell. Because the model hull form was to built up in the manner shown in Figure 1, a series of drawings were prepared of horizontal cross sections through the model at 3/4-inch intervals above the bottom tangent.

The weight of the completely balanced model was to be 3.78 pounds while the model shell was designed to weigh 1.20 pounds, leaving 2.58 pounds to be added for static and dynamic balancing.

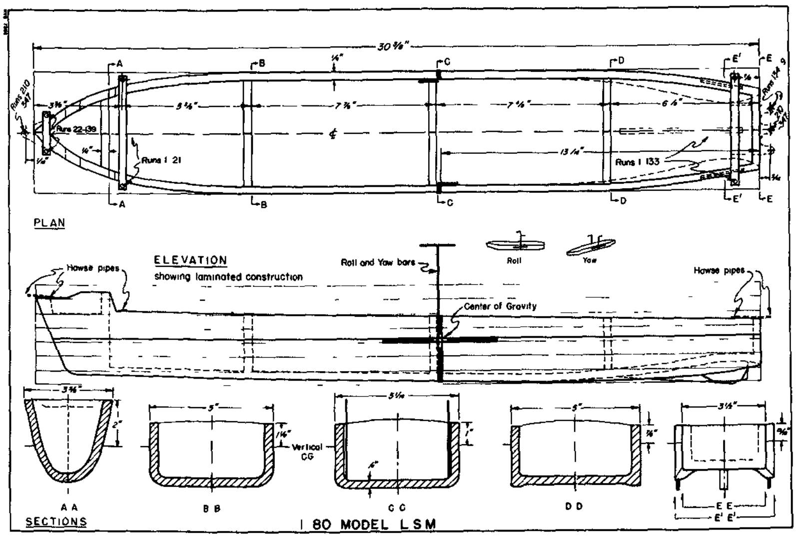


Figure 1.

CONSTRUCTION

The model LSM was constructed of clear soft pine. The wood was planed smooth to a 3/4-inch thickness. Then individual horizontal cross sections (at vertical distance 3/4 inch below each water line plane) were scaled off the drawings and a section of pine was cut to approximate this water plane area. The sections were glued together to make a rough hull form which was finished to the outside dimensions of the ship and to a 1/4-inch wall thickness. Bulkheads were added to approximately the quarter points of the hull to give the model strength to resiste the lateral forces which were likely to be encountered in handling. The model was then covered with several coats of spar varnish.

The points of attachment of the mooring cables (through bars) are shown in Figure 1. Originally these bars were extended completely across the ship model in order to guard against failure of the side wall of the model due to excessive mooring cable loads. However, after the first series, this system was modified as shown, eventually leading to centerline mooring both bow and stern.

BALANCING

After the basic model shell was completed, weights were added to bring the model up to its correct scale weight. These weights were place in such a manner that the center of gravity of the model was properly located, and so that the natural periods of roll and pitch would be correct This static and dynamic balancing was performed as follows: The model wa suspended fore and aft by suspension bars as shown in Figure 2a. The weight of the foreward suspension was counterbalanced on the scale prior to placing the model on the scale. Since the distances from the aft suspension bar to the center of gravity, from the aft suspension to the fore ward suspension bar, and the total weight of the model were known, it was possible to calculate the weight needed to balance the model when the longitudinal center of gravity was correctly positioned; this was done by taking moments about the aft suspension bar. Small pieces of lead were used as weights for adjusting the balance.

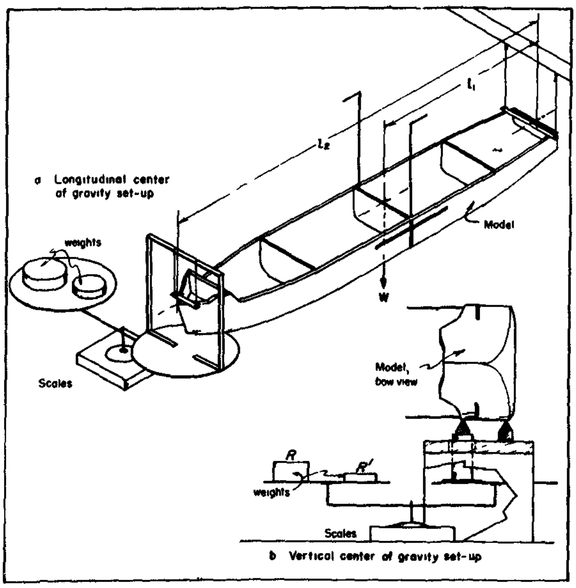


Figure 2. Balancing proceedure.

The model was placed on the device illustrated in Figure 2b and moments were taken about a given point (varied for each trial to minimize the effects of human error) and the necessary weight was calculated and set on the scale. The movable weights then were a justed until the vertical center of gravity was prope located; this was completed after about twenty trials. After locating the vertical center of gravity the perio of roll was adjusted.

The model was placed in the model basin, inclined and released. The natural period of roll was observec and recorded. The transverse position of the cent of gravity was obtained by adjusting weights until ze list was observed. Then lead weights were moved in a direction parallel to the axis of pitch, until the correct period of roll was obtained. B moving the weights parallel to the axis of pitch, the weights remained i the same position with respect to the vertical, so that the vertical ce ter of gravity was unchanged. A few trials with the device used to loc the vertical center of gravity confirmed the fact that the vertical cen of gravity had not shifted.

The last step in the dynamic balancing of the model was the adjust ment of the period of pitch. The experimental method used is illustrat in Figure 3, and the calculations required for this method are presente below. The period of pitch of a vessel is proportional to the radius of gyration of the vessel in the pitching direction, and is given by the equation (Rossell and Chapman, 1939)

$$T_n = \frac{1.108\ K_1}{\sqrt{GM}} \tag{5}$$

where T_n = natural period of pitch,
K_1 = radius of gyration of the model,
GM = longitudinal metacentric height of the model, and
1.108 = $2\pi/\sqrt{g}$ (where $g = 32.2$ ft/sec.^{2}).

Severe damping of the pitching motion of the structure precluded accurate direct measurement of the period of pitch so that it was necessary to determine the radius of gyration of the model about the pitching axis by using the bifilar pendulum method as given by Timoshenko (1937). By hanging the model as shown in Figure 3, it can be shown that the period of oscillation of the bifilar pendulum so set up is a function of the radius of gyration of the vessel about the yaw axis. In addition, the radius of gyration about the yaw axis, and the radius of gyration about the pitch axis are essentially equal (personal communication, Dr. A. D. K. Laird, University of California, Berkeley). From Timoshenko (1937) it can be shown that

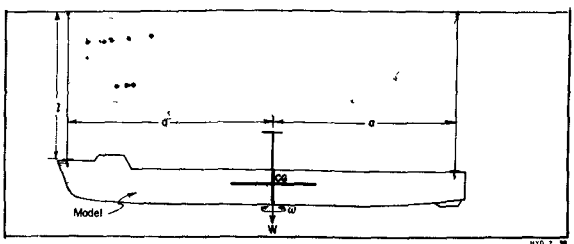


Figure 3. Bifilar pendulum setup.

$$T_p = \frac{2\pi K}{a}\sqrt{\frac{l}{g}} \tag{6}$$

where T_p = natural period of oscillation of suspended model in air,
l = length of suspending lines, and
a = equal distance from CG to suspending lines.

In the experimental adjustment of the period of pitch $l = 7.125$ feet, $a = 1.0625$ feet, $g = 32.2$ ft./sec.^{2}, and $k_1 = 63.4$ feet/80 = 0.792 foot. Substituting these values in Equation 6, it was found that the period of the pendulum would have to be 2.2 seconds for the radius of gyration in the pitching direction to be properly located. The weights in the model were then adjusted until this period of the pendulum was obtained. The longitudinal metacentric height was adjusted by other means.

Following this final adjustment of the weights, the complete balancing procedure was repeated, and the model was found to be balanced, and thus both geometrically and dynamically similar to the prototype, within the limits discussed in the introductory remarks.

MOORING CABLE MODEL

Inspection of the model relationships previously derived indicates that for geometric similarity the diameter of the model cable must be scaled according to the relationship

$$d_m = \frac{d_p}{80} \quad . \tag{7}$$

In the same unit weight properties are to be maintained, it is necessary to scale the cable according to the relationship

$$d_m = \frac{d_p}{(80)\,(b)} \tag{8}$$

where $b > 1$ since the cable is stranded and the resulting unit weight for a given diameter is less than that of a solid wire. If the axial deflection forces of the mooring system are to be maintained in scale, t diameter of the mooring cable must scale according to the rule

$$(AE)_r = \gamma_r L_r^2, \quad \text{but} \quad E_r = \frac{\text{elastic modulus of model}}{\text{elastic modulus of prototype}}$$

$$= \frac{3 \times 10^7}{10^7} = 3 \tag{9}$$

$$(AE)_r = 3\, d_r^2 = \gamma_r L_r^3 \; ; \qquad \therefore \; d_r = \sqrt{\frac{\gamma_r}{3}} \; L_r^{3/2} \quad .$$

If the bending properties of the cable are to be in scale, it is necessary to scale the bending resistance of the cable cross section accordi to the relationship

$$(EI)_r = \gamma_r L_r^5 \quad \text{or} \quad d_r^4 = \gamma_r L_r^5$$

or

$$d_r = \sqrt[4]{\frac{\gamma_r}{3}} \; L_r^{1.25} \quad . \tag{10}$$

It was not possible to satisfy the four model criteria by choosin a proper cable diameter. Therefore, the cable diameter was chosen so t the moment of inertia of the section would correspond to and be in sca with that of the prototype stranded cable. This meant it was necessar choose a diameter somewhat smaller than the outside diameter of the pr type stranded cable, since a geometric scale would mean that the model cable extrapolated to prototype conditions would correspond to a steel rod in bending stiffness. Split lead shot were added to the mooring cable at one-inch intervals to bring the cable up to the proper weight requirements. An arbitrary spacing of 1 inch between shot having been assumed, the required shot diameter was 0.050 inch, which was readily available. The axial deflection characteristics of the cable were calculated and found to be less than those required; hence, some axial flexibility of the cable system was built into the force meters. This kept the total mooring system deflection in scale. The only criteria not satisfied was that of geometric scale of the diameter, which would result in the viscous drag and inertia forces being even more out of scale. However, as was assumed in the case of the ship model, these forces would be small compared to other forces acting on the cable.

FORCE METER

The force meter served two purposes: it was used as a sensing element in a force recording system, and it was used in the modeled mooring system to satisfy scale factor requirements for cable elongation due to axial loads. In designing the meter it was necessary to satisfy the similitude requirements for cable deflection (as determined from model laws) and to insure sufficient sensitivity so that the meter could measure the smallest expected forces.

In order to provide the proper deflection sharacteristics it was necessary to use other than a simple structural shape (Figure 4). The deflection characteristics of the beam used were calculated through application of the principles of virtual work. The force measuring system was designed to provide maximum possible recorder sensitivity to applied cable force. Strain gages were used for the force measuring elements; force was measured indirectly by measuring the strains induced in the meter beam by bending moments caused by the force in the mooring cable. The strain measurements were recorded with a Brush Electronic Company recording system.

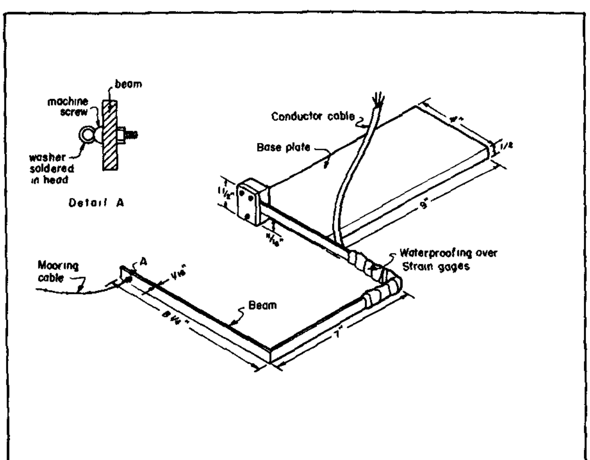
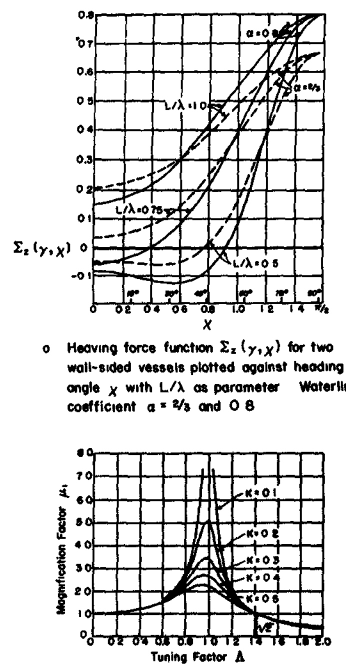


Figure 4. Force meter

Details of the force meter design, construction and calibration will not be included as they have been published elsehwere (Beebe, 1956).

GENERAL CONSIDERATIONS

The motion of a freely-floating vessel in a seaway is extremely complex. Studies have been made in the past (Froude, 1861; Kriloff, 189ε of the motion of rolling and pitching of such vessels. Heaving has been studied by Haskin (1946). Other investigators have studied these proble recent summaries have been given by Weinblum and St. Denis (1950) and Weinblum (1955). They present equations and graphs of various ship moti functions, among which are the magnification (response) factors (for the various degrees of freedom) which are shown to be functions of the ratio of the wave period to the natural period of the vessel, and the exciting factors which are shown to be functions of the ratio of the wave length to the ship length (see Figure 5 for example). Both of these sets of factors are, of course, dependent upon several other wa\ and vessel characteristics. The authors state that little is known of the surge, sway and yaw motions of floating vessels and that knowledge of the total motion of a vessel, including phase relationships between the various motions, is a most nil, although it is known that certain couplings between the motions in t different degrees of freedom exist. Of particular importance to studies of moo ing problems are the possibilities of induced roll, sway and yaw even when th vessel is encountering only head seas (Grim, 1952).



a Heaving force function $\Sigma_z(\gamma,\chi)$ for two wall-sided vessels plotted against heading angle χ with L/λ as parameter. Waterline coefficient $\alpha = 2/3$ and 0.8

b Magnification factor $\mu_1 = \frac{\sqrt{1+\kappa^2\Lambda^2}}{\sqrt{(1-\Lambda^2)^2+\kappa^2\Lambda^2}}$

From Weinblum & St Denis

Figure 5.

The above-mentioned studies were concerned with periodic waves of unifor amplitude. Recently, a few studies of ship motion in non-uniform waves have been published (St. Denis and Pierson, 1953; Fuchs, 1955; Sibul, 1955).

The details of ship motion are beyond the scope of this report and the reader is referred especially to the paper by Weinblum and St. Denis (1950) for the necessary background.

In considering a moored vessel the problem becomes more complicat especially as the elastic restraining force (the mooring system) is no linear. The motions of surge, sway and yaw become of prime importance

It appears that only a few studies have been made of the motion c a moored vessel (Wilson, 1950; Carr, McGraw and Shapiro, 1953; Beebe, 1955 a,b; O'Brien, 1955; Wilson and Abramson, 1955). These studies, w the exception of Beebe's, are of a greatly simplified problem, primari that of the longitudinal motion of a vessel moored alongside a pier, t motion being induced by relatively long period harbor seiches of small amplitude. All motions excepting surging are neglected, although Wilson (1950) commented upon the transverse motion.

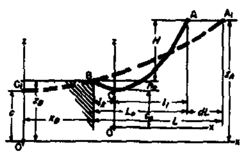


Fig. 6. Geometry of mooring rope suspension.

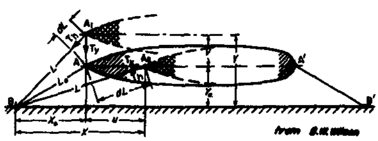


Fig. 7. Geometry of longitudinal and transverse ship motion.

The pioneering effort on the mooring problem was made by Wilson (1950). The generalized geometry of the dockside mooring rope suspension is shown in Figures 6 and 7. Referring to Figure 6 for an explanation of the symbols (where in the generalized case the lowest point of cable sag is at C_1 which is outside of A_1 B) the equations of the catenary were given as

$$z = c \cosh\left(\frac{x}{c}\right) \tag{11a}$$

$$s = c \sinh\left(\frac{x}{c}\right) \tag{11b}$$

where s is the length of the hypothetical cable from point C_1 to any point (x, z) on the catenary. Further

$$z_B + H = c \cosh \frac{x_B + L}{c} \tag{12a}$$

$$z_B = c \cosh \frac{x_B}{c} \tag{12b}$$

and thus

$$H = c \left(\cosh \frac{x_B + L}{c} - \cosh \frac{x_B}{c}\right) \tag{13a}$$

$$S = c \left(\sinh \frac{x_B + L}{c} - \sinh \frac{x_B}{c}\right) . \tag{13b}$$

After certain simplifications were made, Wilson (1950) gave the horizontal component of rope tension T_h, at points A_1 and B as

$$T_h = \frac{W_c L^2}{\sqrt{12 \left[S^2 - (H^2 + L^2)\right]}} \tag{14}$$

where W_c is the weight per unit length of the cable.

The next step taken by Wilson (1950) was to determine the relationships between cable tension and elongation for several types and sizes of standard mooring cables (coir rope and steel wire rope). In order to utilize these data, a further simplification was made wherein it was shown that for common dockside mooring the following equation was of sufficient accuracy

$$L = \sqrt{S^2 - H^2} \quad . \tag{15}$$

Utilizing this approximation, and referring to Figure 7 for an explanatic of the symbols, the relationship between the components of cable tension and the components of ship movements were developed. These relationships are shown in Figure 8. Also shown in Figure 8 are the best-fit expenenti curves, which are of the form

$$T_{x,\,y} = k\ (u \ \text{ or } \ v)^n \tag{16}$$

where k is a constant and n is a numerical exponent. For the case o a ship with many mooring lines, this was expressed for the longitudinal directions as

$$\Sigma\, T_x = C\, u^n \tag{17}$$

where C is a constant which depends upon the number, size and conditio of the cables and n depends upon the tension in the cables.

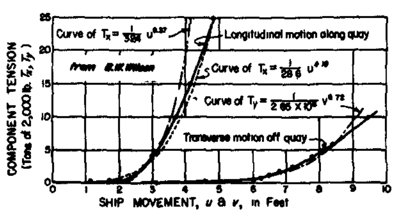


Figure 8. Relationship between rope tension and ship movement.

A harbor seiche has a relatively long period (usually in the range of a minute or more — sometimes much longe and usually has a low amplitude. It i possible to describe the water particl velocities and accelerations rather simply compared with the case of seas and swell. These approximations were used by Wilson (1950), together with a approximation by Havelock (1940) whick expresses the wave force on a rigid vessel which extends to the bottom. I is not necessary here to go through the various steps, but merely to present the final result

$$\frac{d^2u}{dt^2} + \frac{K}{2M} \cdot \frac{du}{dt} + \frac{C}{2M}\, u^n = \frac{KV}{2M} \cos pt - \frac{Vp}{2} \sin pt \tag{18}$$

where K is a constant which depends essentially upon the size and sha of the vessel, M is the mass of the ship and p is the angular frequency of the surge. V is given by

$$V = \frac{Ap}{qd} \sin qx \tag{19}$$

where A is the seiche amplitude, q is the nodal frequency of the seiche, and d is the water depth. It should be noted that the phase angle has been neglected and the damping is shown as being proportional to the first power of the velocity rather than the square of the veloci

The natural frequency of the system thus depends upon the amplitude of the forcing function as well as upon the spring and mass characteristics of the system.

After certain other simplifications were made, Wilson (1950) showed the relationships between resonant period of ship oscillation, τ, and maximum individual cable tension, T_x, versus seiche amplitudes, A, for several conditions of cable tension (Figure 9). The effect of cable tension on the periodicity of the system is apparent: the higher the tension the lower the resonant period. The effect of amplitude is relatively unimportant for cables with high tension, but very important for cables with low tension: the greater the seiche amplitude the lower the resonant period of the system.

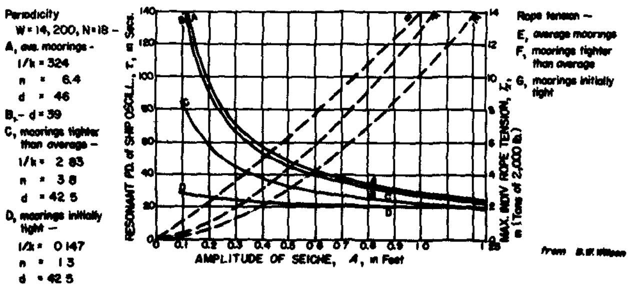


Figure 9. Influence of rope tightness on the resonance in longitudinal ship motion.

Recently Equation 18 has been treated by Wilson and Abramson (1955) using the Ritz method (which is useful for certain non-linear differential equations). Typical results are shown in Figures 10 and 11. In Figure 10 is shown the relationship between the maximum amplitude of horizontal ship displacement, u, and η^2 for various values of seiche amplitude. η is

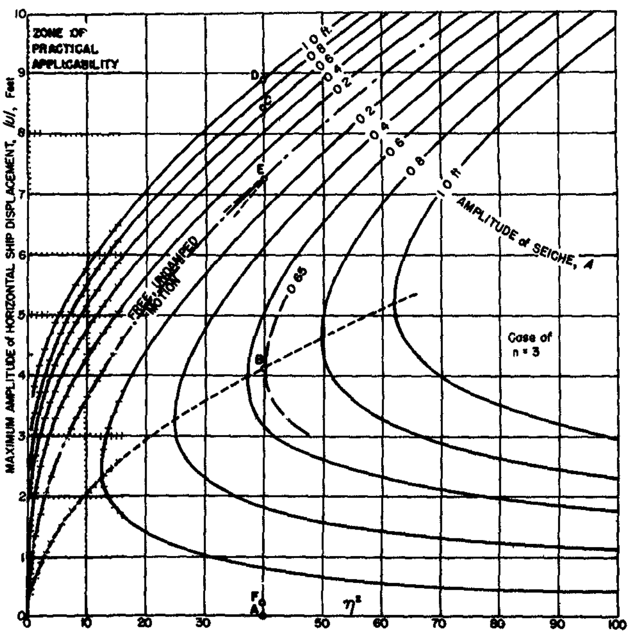
$$\eta = \frac{p}{\omega} \tag{20}$$

where p is the angular frequency of the seiche. ω may be considered as the non-linear equivalent of the natural frequency

$$\omega^2 = \frac{C}{2M} = \frac{Nk}{4M} \tag{21}$$

although the non-linearity, entering through k results in a departure from the ordinary dimensions of frequency.

The above information on mooring has been presented although it is a great simplification compared with the problem of the LSM moored at sea. It does point to the great importance of initial cable tension and to the possible importance of wave amplitude.



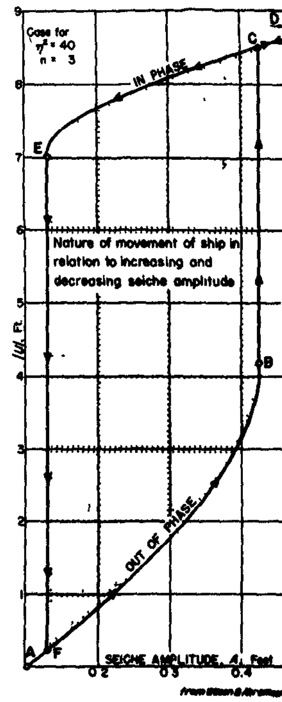


Figure 10. Typical response curves of longitudinal ship displacement

Figure 11.

LABORATORY EQUIPMENT

The laboratory equipment consisted of:

1. Four mooring cable force meters (Figure 4).
2. A six-channel Brush Electronic Company recording oscillograph, and six Brush Universal Analyzers.
3. A 6-foot by 8-foot by 200-foot wave-towing tank, with bulkhead type wave generator (Figure 12).
4. A 2.5-foot by 64-foot by 150-foot model basin with a flapper-type wave generator.
5. Two 35mm. Bell and Howell movie cameras.
6. Two clocks and a neon glow tube.
7. A camera box and a camera base plate.

Before the force meters were used their deflection characteristics and their sensitivity to applied cable forces were measured.

Two experimental set-ups were used, one in the wave-towing tank, other in the model basin. The wave-towing tank was used to determine effect of moored vessel dynamics in head seas and the model basin was used to investigate the moored vessel dynamics in quartering and beam

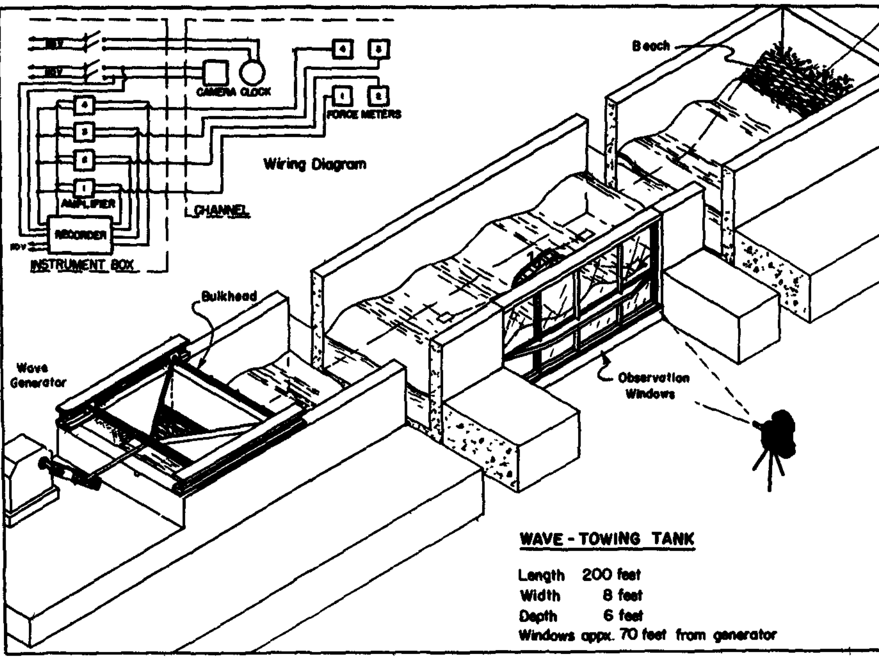


Figure 12.

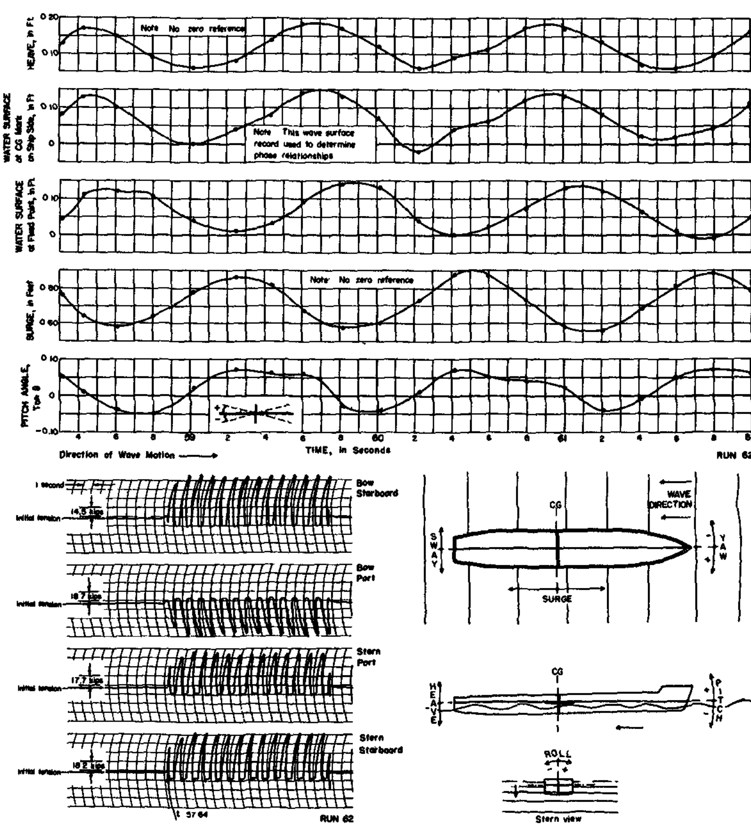


Figure 13. Sample data with model LSM in head seas.

A few tests also were run in the madel basin for head seas in order to correlate the results obtained by use of the two facilities. The wave-towing tank would have been used for all tests because of the superior control possible with it; however, its transverse dimensions were not ad quate to permit the use of the necessary mooring cable patterns for quar tering and beam seas.

The use and disposition of the cameras and timing equipment (clocks are discussed in the section on Testing Procedure.

TESTING PROCEDURE

Three testing procedures were followed: one for the head sea tests in the wave-towing tank, one for the quartering sea, beam sea and head s tests in the model basin, and one for the tests in the wave-towing tank of the effectiveness of the large bilge keels.

WAVE-TOWING TANK TESTS

The following procedure was used:

1. The depth of water was adjusted to the desired value.
2. A grid was hung from supports across the top of the channel in a plane through the location of the longitudinal axis of model LSM during the tests. Photographs of the grid were taken with 35mm. movie camera.
3. The grid was removed and the model LSM, mooring cables, and mooring cable force meters were placed in the channel. The mooring cables were attached to the force meters and to the ship model.
4. A desired initial tension was set into the mooring cable system and the force meters were oriented so that the deflection of the entire system would be in scale.
5. A clock was placed just above the model.
6. The wave generator was adjusted for a pre-determined wave height and period and the wave generator started.
7. About eight waves were allowed to pass the leeward force meter, then the camera was started, and about two seconds later both the clock and the force meter recording system were started.
8. After the forces resulting from about ten to twelve waves were recorded on the force-meter recorder, the recorder and clock were stopped. The camera was stopped two seconds later.
9. Steps 7 and 8 were repeated for each wave condition to be tested at one particular mooring condition (scope, water depth, initial tension).

The clocks and force meter recorders were started and stopped at same time while the camera was running for the purpose of synchronizat Although the clock took about 0.25 second to come up to speed, the fra speed of the camera was known, so that any desired phase relationship tween motions and associated mooring cable forces could be determined.

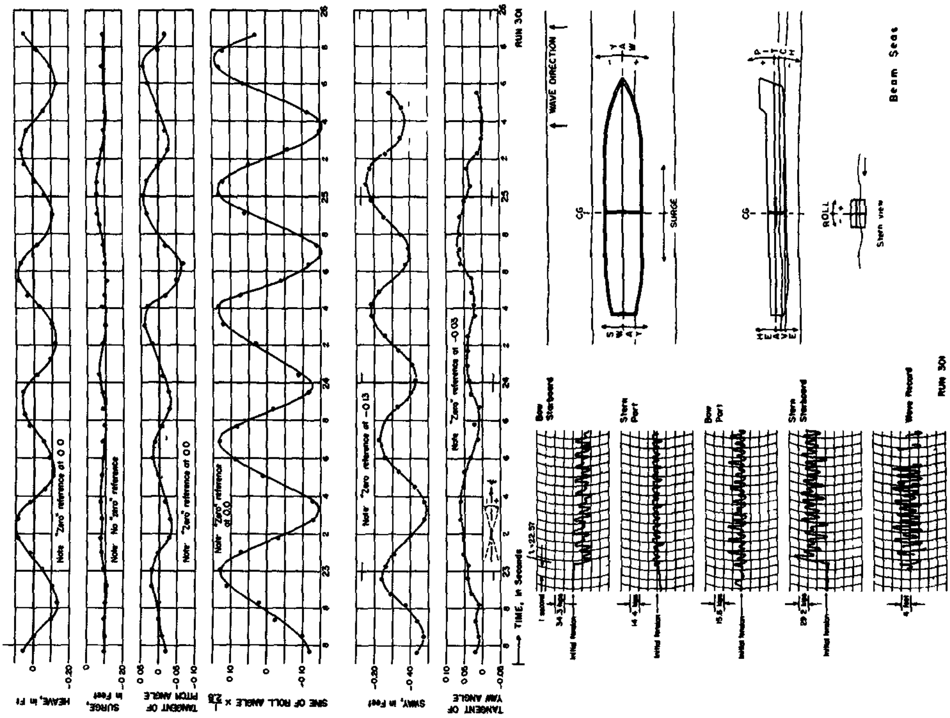


Figure 15. Sample data with model LSM in beam seas.

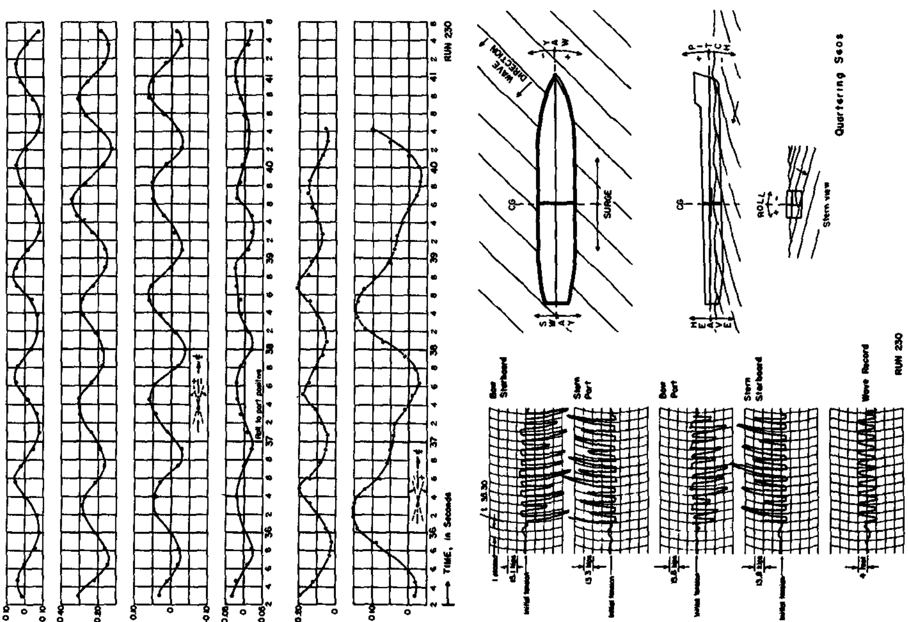


Figure 14. Sample data with model LSM in quartering seas.

The reference for the grid coordinate system consisted of two strip of black tape, one horizontal and one vertical, pasted to the glass of the channel wall.

MODEL BASIN TESTS

The model basin tests were performed in the same manner as the wave towing tank, with the exception that two cameras were used. A grid was placed in the plane through the center of the model before the model was placed in the water and a few feet of film were exposed.

ROLL DAMPING TESTS

The effectiveness of an enlarged bilge keel was tested in the wave-towing tank under "freely floating" conditions; that is, no mooring line were attached. The model was centered in the tank in such a manner that it was under the action of beam seas. The data were recorded on 35mm. movie film.

EXPERIMENTAL RESULTS AND DISCUSSION

DATA INTERPRETATION

Since all experimental data were recorded on either 35mm. movie fi or on six-channel recording oscillograph paper, it was necessary to reduce this data to such a form that it could be effectively plotted.

The data obtained from the film were plotted as shown in Figures 1 14 and 15. In Figure 13 are shown data for Run 62 for the model LSM in head seas; in Figure 14 are shown data for Run 230 in quartering seas; in Figure 15 are shown data for Run 301 in beam seas. The ranges of cc ditions tested are shown in Table I.

FIRST SERIES OF TESTS

The first series of tests were conducted to determine the mooring forces and ship motions of a model LSM (1:80 scale) moored in head sea: These tests were made in the wave-towing tank. The parameters studied this series of tests were initial cable tension, the cable scope, the water depth, the wave height and the wave period.

Two geometric configurations were used in regard to "hawse pipe" cations at the ship's bow. This was because it was noticed that the w spacing of the take-off points of the forward cables was responsible f an induced roll of the model vessel when the vessel was at even a very small angle to the waves; hence, centerline mooring was introduced.

The results of the tests for the centerline-bow, outboard-stern hawse pipe locations are given in Figures 16 and 17. Data were obtair for wave periods between 6 and 15 seconds and for wave heights betweer 4 and 12 feet (prototype). The "least-count" accuracy of the data was about plus or minus five percent. The scatter of data was considerabl

TABLE I. MOORING CONDITIONS FOR MODEL LSM

			Model			Prototype		
Runs	Mooring	Cable Scope	Water Depth ft.	Cable Length ft.	Initial Cable Tension lbs.	Water Depth ft.	Cable Length ft.	Initial Cable Tension kips
1- 9*	outboard bow and stern	6.0	2.5	15	0	200	1200	0
11- 21	" "	6.0	2.5	15	0.0195	200	1200	10
22- 39	¢-bow, outboard stern	6.0	2.5	15	0.0058	200	1200	3
40- 53	" "	6.0	2.5	15	0.0012	200	1200	6
54- 64*	" "	6.0	2.5	15	0.0195	200	1200	10
66- 81	" "	15.0	1.0	15	0.0058	80	1200	3
82- 96	" "	9.0	1.0	9	0.0058	80	720	3
97-119	" "	6.0	2.5	15	0.00585	200	1200	3
124-127	bow starb'rd line dropped	6.0	2.5	15	—	200	1200	—
128-130	¢-bow, outboard stern	6.0	2.5	15	0.0195	200	1200	10
131-133	bow, starb'rd line dropped	6.0	2.5	15	—	200	1200	—
134-136	¢ bow, ¢ stern	6.0	2.5	15	0.0195	200	1200	10
137-139	bow starb'rd line dropped	6.0	2.5	15	—	200	1200	—
140-151	freely floating roll tests	—	2.5	—	—	200	—	—
152-161*	bilge keel roll tests	—	2.5	—	—	200	—	—
172-174	freely floating roll tests	—	2.5	—	—	200	—	—
175* **	natural period of roll							
210-235	direct ¢ mooring bow & stern	6.0	2.0	12	0.0195	160	960	10
236-250	" "	6.0	2.0	12	0.0117	160	960	6
251-265	" "	6.0	2.0	12	0.0058	160	960	3
266-277	" "	6.0	2.0	12	0.0058	160	960	3
278-289	" "	6.0	2.0	12	0.0117	160	960	6
290-301	" "	6.0	2.0	12	0.0195	160	960	10
302-313	" "	6.0	2.0	12	0.0117	160	960	6
314-326	" "	6.0	2.0	12	0.0058	160	960	3
327-339	" "	6.0	2.0	12	0.0195	160	960	10
339-347	" "	6.0	2.0	12	0.0058	160	960	3

* Runs 10, 65, 162-171 and 200-210 were test runs and are not included.
** Runs number 176-199 were not used.

and much of this was due to the difficulty imposed by the least-count when working with a model of this scale. However, the trends were apparent, and the scatter of data of heave, surge and pitch were probably within the necessary limits from an operational standpoint.

A sample of the data on the horizontal component of cable force at the meter for each cable have been tabulated in Table II, together with the averages of the bow cables, the stern cables and all four cables. T data presented for the individual cables are the maximum recorded forces as measured from the initial tension, i.e., the actual horizontal component of force is the tabulated force plus the initial tension. The data on the force records did not show much scatter from wave to wave; thus the scatter is due to the least-count errors and to the fact that the sy tem is rather unstable. Some of the variation in cable force was due tc the inability of the investigators to adjust all four cables to the same initial tension. This difficulty, and the result of this difficulty, wa particularly apparent in Runs 40 to 53. It is expected, however, that similar difficulties would be encountered in prototype; hence, the varia tion of data (particularly in regard to the largest forces measured) should be of considerable value.

The most important fact that was evident in these data was in regai to the relationship between surging motion (and hence cable force) and the wave characteristics. The data showed a resonance condition occurring for certain combina tions of wave and mooring characteris tics. A check of t surging characteris tics of the test sy tem was undertaken. It was found that t natural period of surge (for the 2 mi wire with lead shot was about 16 seconc for the case of a cable scope of 6, a water depth of 200 feet, and an initia tension of 10 kips (Figure 18). As tl determination of tl natural period was done with a new se of model cables, a due to the difficu in obtaining exact initial tensions, natural period of surge during Runs 1

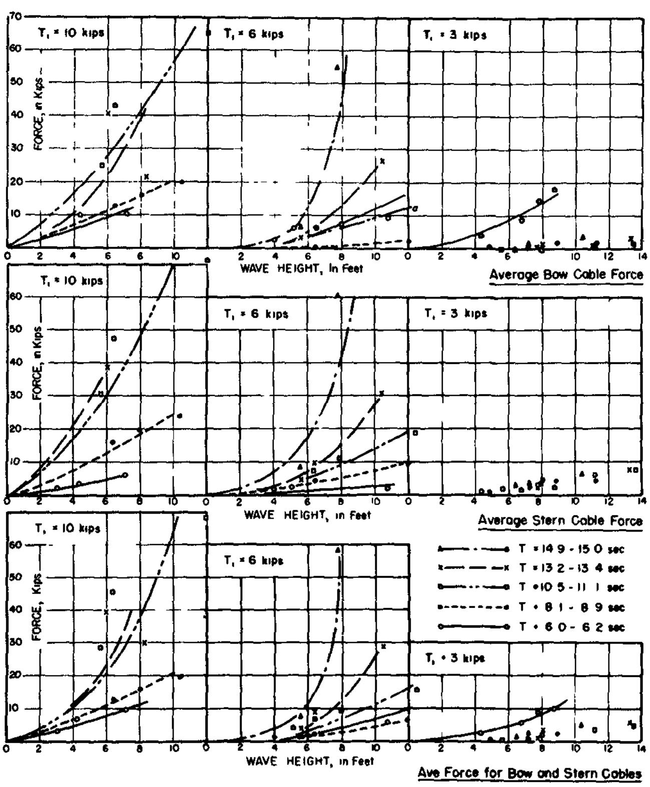


Figure 16. Mooring cable forces in head seas, Runs 22-64.

TABLE II. SAMPLE DATA OF MOTIONS
AND MOORING FORCES FOR MODEL LSM IN HEAD SEAS

Run No.	Wave Period sec.	Wave Height ft.	Surge ft.	Heave ft.	Pitch deg.	F_{BP} kips	F_{BS} kips	F_{SP} kips	F_{SS} kips	$F_{B_{ave}}$ kips	$F_{S_{ave}}$ kips	F_{ave} kips
Runs 22–39: scope = 6, water depth = 200', initial cable tension = 3 kips												
22	6.0	4.4	1.5	0.8	1.6	2.7	4.6	0.4	1.6	3.7	1.0	2.4
23	6.0	6.8	1.6	0.8	2.3	8.9	9.0	1.5	2.3	8.9	1.9	5.4
24	6.0	7.8	2.0	2.4	4.0	15.2	13.7	2.1	4.4	14.5	3.2	8.9
25	6.0	8.8	2.0	2.4	4.3	15.2	21.1	1.4	3.0	18.1	2.2	10.2
26	8.1	4.8	6.9	3.2	2.3	0.3	0.3	1.2	1.2	0.3	1.2	0.8
27	8.1	7.2	8.7	5.2	2.9	1.0	0.5	2.3	1.9	0.8	2.1	1.5
28	8.1	8.8	7.6	6.4	4.0	2.0	1.1	4.0	3.5	1.5	3.8	2.7
29	8.1	11.2	8.8	8.0	4.6	1.0	1.6	5.5	4.4	1.3	5.0	3.2
30	10.5	5.6	6.0	4.0	1.7	-1.1	0.3	2.2	2.0	-0.4	2.1	0.9
31	10.5	8.0	7.2	8.0	2.3	-0.3	0.9	5.3	3.2	0.3	4.3	2.3
32	10.5	11.2	8.8	8.8	3.4	0.5	1.7	7.2	4.6	1.1	5.9	3.5
33	10.5	1.36	10.4	11.2	3.4	1.5	2.6	9.2	6.8	2.1	8.0	5.1
34	13.4	7.8	8.3	6.6	1.7	0	1.0	3.7	2.0	0.5	2.9	1.7
35	13.4	8.0	9.6	7.6	2.6	2.4	0.3	3.9	2.7	1.3	3.3	2.3
35a	13.4	—	—	—	—	2.4	-0.4	4.5	3.3	1.0	3.9	2.5
36	13.4	13.3	14.4	11.0	2.9	5.0	2.9	9.1	6.4	4.0	7.7	5.9
37	15.0	6.4	6.8	6.0	0.9	1.7	-2.2	3.4	2.6	-0.3	3.0	1.4
38	15.0	7.2	6.8	6.0	1.0	2.0	1.1	4.0	3.0	1.6	3.5	2.6
39	15.0	10.4	11.2	9.6	1.5	3.6	2.9	7.4	5.2	3.3	6.3	5.0
Runs 40–53: scope = 6, water depth = 200', initial cable tension = 6 kips												
40	6.2	4.0	1.2	3.2	1.5	-1.5	4.9	1.4	1.1	1.7	1.3	1.5
41	6.2	5.2	1.6	2.4	2.9	3.4	8.4	2.8	1.3	5.9	2.1	4.0
42	6.2	10.8	3.2	3.6	4.3	7.2	11.0	2.3	1.4	9.1	1.9	5.5
43	8.8	6.4	5.6	5.6	2.9	-1.2	1.4	6.6	2.1	0.1	4.3	2.2
44	8.8	8.0	8.0	6.4	3.4	—	—	—	—	—	—	—
45	8.8	12.0	8.8	7.6	4.9	0.2	5.8	13.2	6.4	3.0	9.6	6.4
46	10.9	6.4	7.2	6.0	1.5	5.2	7.7	11.0	3.4	6.5	7.2	6.9
47	10.9	8.0	9.6	7.2	2.3	2.7	11.6	16.6	6.4	7.1	11.5	9.3
48	10.9	12.4	13.6	5.2	3.2	5.7	18.7	26.0	11.9	12.2	18.9	15.6
49	13.2	5.6	5.6	3.6	1.1	0.4	6.2	7.6	1.5	3.3	4.6	4.0
50	13.2	6.4	8.8	6.4	1.4	2.6	10.4	14.4	4.7	6.5	9.6	8.1
51	13.2	10.4	19.2	9.6	2.4	13.8	39.1	42.1	19.7	26.5	30.9	28.7
52	14.9	5.5	7.7	4.4	1.0	2.2	10.8	13.0	4.0	6.5	8.5	7.5
53	14.9	7.7	33.5	7.6	1.4	50.2	59.0	61.8	61.2	54.6	61.5	58.1

Note: F_{BP}, force measured for port bow cable; F_{BS}, for starboard bow cable; F_{SP}, for port stern cable; and F_{SS}, for starboard stern cable.

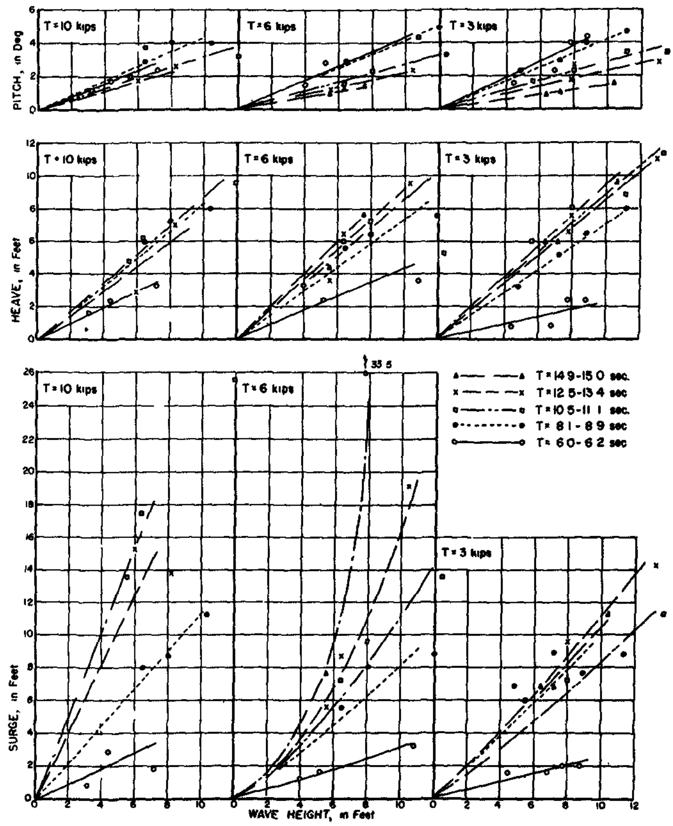


Figure 17. Pitch, heave and surge in head seas, Runs 22-64.

might well have been a few seconds less. It was evident from the data in Table II and Figures 16 and 17 that the relationship between both surging and cable force and the wave height was non-linear, at least when near resonance. Both the surging motion and the cable force increased quit rapidly for the greater wave heights

It is apparent that this difficulty would not be encountered when operation were conducted in an area where the wave period was in the vicinity of 5 to 8 seconds, nor would i become apparent for low waves (say, in t neighborhood of 3 fe due to the inability of a person to judge the extent of such small motion.

It was found that for the case of low initial cable tension, the highest mooring cable forces were associated with the shortest wave period; however, as the initial tension increases, the highest forces were associated with the longer periods — those nearer, or at, resonan

In regard to the vessel motions, what was really needed was its spatial location as a function of time. The tremendous amount of calcu lations necessary to present this information precluded obtaining it on this investigation, and instead the individual motions were shown in re lation to the wave height and period. These data have been presented i Figure 17. It was found that the pitching angle was nearly a linear fu tion of wave height with the shortest period (within the limits of the experiments) being responsible for the greatest pitch. The pitching angle appeared to be independent of the initial cable tension. Heave w greatest for the longest wave periods and appeared to be independent of the initial cable tension.

Surging motion was dependent upon initial cable tension to a grea degree. In addition, it was not linearly related to wave height; rath it increased with wave height at an increasing rate, at least where the period was in the vicinity of resonance.

SECOND SERIES OF TESTS

The model cable first used (2 mil diameter wire with lead shot attached for weight) was found to deteriorate very rapidly in use; hence, very small forces would break the cables during tests. California Research Corporation and University of California personnel agreed that a 10 mil wire should be used if tests indicated that the result would correspond with those obtained using the 2 mil-with-shot wire, and providing swivels were used at points of attachment, and kinks in the wire avoided.

In order to determine the difference in effects in mooring dynamics due to the use of two types of mooring wires, a series of tests were run. At the same time the effect of "breaking" one cable was studied, as was the effect of introducing a centerline mooring "hawse pipe" at the stern of the model. The data were compared with the results of previous tests and were found to be in fair agreement provided the differences in natural period of surge are kept in mind. For example, in the case of an initial cable tension of 10 kips, a resonance, or near-resonance, condition for the 2 mil-with-shot cable occurred for both Runs 63 and 18 (12.5 and 13.0 second wave, respectively) while for the 10 mil wire this condition occurred for Run 129 (a 9.2-second wave period). This can readily be understood by examining the curves of natural period of resonance versus initial cable tension in Figure 18.

As a part of this same series of tests data were obtained which showed the effect of one mooring cable breaking. The tension in the diagonally opposing cable dropped off considerably and the vessel yawed slightly, slacking off the remaining two cables (from an "initial tension" standpoint). This caused an increase in the natural period of surge. Hence, the resonance occurred at a greater wave period. For example, a resonance

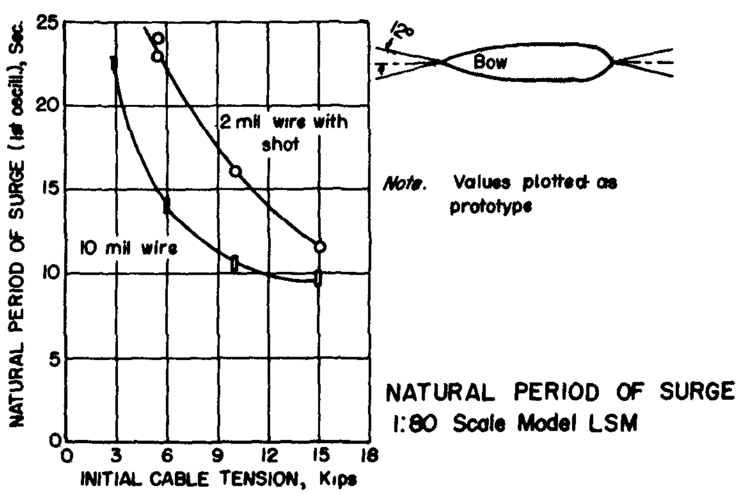


Figure 18.

or near-resonance condition occurred for a wave period of 9.2 seconds fo the 10-kip initial cable tension with four mooring lines, but shifted to 13.5 seconds when the starboard bow cable was dropped. It was not possi ble to tell conclusively from these data whether dangerously high forces will be experienced when one cable breaks, because of the spread of wave periods tested, with the resulting probability that the peak resonance condition might have been encountered for the 13.5-second wave but not f the 9.2-second wave, vice versa, or neither.

Data were also obtained for a centerline stern mooring. The effect of this type of mooring was not apparent unless there was an induced rol

THIRD SERIES OF TESTS

In order to test the effect of roll-damping devices, it was necessa to use the wave-towing tank, which in turn prevented the testing of a properly-moored vessel. Because of this, the effect of the device was studied for the freely-floating condition. The data have been given in Table III. The roll was considered in two parts, as shown in the follo ing sketch:

Direction of Wave Motion ⟶ 

$\text{Roll} = \frac{\alpha + + \alpha -}{2}$

$\alpha+$ was the angle of roll as measured upwards on the up-wave side of th vessel, while $\alpha-$ was the angle of roll as measured downwards on the u wave side of the vessel. It can be seen in Table III that $\alpha+$ was con sistently larger than $\alpha-$. This was a dynamic characteristic of the interaction between the waves and the vessel and was probably a result diffraction. It did not occur during tests for natural period of roll; hence, it was not caused by some unbalance in the vessel. This "dynami list" was most apparent for the case where bilge keels were added. The bilge keels were very effective (especially for the short period waves) when one considered the mean roll from its dynamic equilibrium positior (i.e., $\alpha+ + \alpha-/2$); however, it was not nearly so effective when the maximum roll ($\alpha+$) from the horizontal was considered.

FOURTH SERIES OF TESTS

The fourth series of tests was performed to determine the vessel motions and mooring forces in quartering and beam seas. In addition, tests were made of the vessel in head seas. This was done so that a co parison could be made between the tests in the model basin and the tes in the wave-towing tank. Due to the limitations of the model basin it was possible to moor the vessel in no more than 160 feet of water (pro totype). 10-mil model mooring cables were used. Some of the data hav been plotted in Figures 19 to 21. In addition to a least count accura of ±5% the data obtained in the model basin are subject to variations as the wave generator motion is not as consistent as in the wave-towin tank and because it was not possible to have complete protection from wind effects on the model.

TABLE III. EFFECT OF ROLL DAMPING DEVICES FOR FREELY FLOATING MODEL LSM IN BEAM SEAS

Run No.	Wave Period sec.	Wave Height ft.	Ave. $\alpha+$ deg.	Ave. $\alpha-$ deg.	Range of Roll deg.
Runs 140-151, no roll damping devices					
140	6.3	1.2	5.0	4.2	3.3 - 4.5
141	6.3	2.1	10.0	8.0	8.5 - 9
142	6.3	6.3	12.3	10.2	11.0 - 11.5
(143)					
144	7.8	4.6	5.0	3.7	4.3 - 4.5
145	7.8	7.9	8.2	7.0	6.3 - 8
(146)					
147	7.8	7.1	7.5	6.7	7 - 7.3
148	7.8	11.6	11.5	10.0	10.5 - 11
149	12.5	3.2	2.5	1.7	1.5 - 2.0
150	12.5	5.8	2.5	1.5	1.8
151	12.5	8.2	3.9	3.2	2.3 - 3.6
Runs 152-161, with bilge keel					
152	natural period of roll = 11.9 seconds				
153	6.3	5.4	4.3	1.0	1.5 - 3.5
154	6.3	10.1	10.2	0.9	3 - 7
155	6.3	1.6	3.0	0	1.3 - 1.8
156	7.9	3.8	4.6	0	1.8 - 3.3
157	7.9	7.7	6.5	0.3	2.5 - 4.0
158	7.7	11.0	8.4	0.7	3.5 - 6.5
159	12.9	3.5	2.0	1.0	1.3 - 1.8
160	12.9	6.6	2.7	2.0	2.3
161	12.9	9.5	3.5	2.5	3.0
Runs 172-175, no roll damping devices					
172	6.1	1.4	9.4	8.0	7.3 - 9.5
173	6.1	4.6	12.3	11.8	11 - 15
174	6.1	7.5	20.6	18.6	19 - 22
175	natural period of roll = 5.1 seconds				

Note:

1. All values tabulated are for the prototype.
2. $\text{Roll} = \frac{\alpha+ \; + \; \alpha-}{2}$, where 

3. Maximum variation of ±1 degree for roll angle for no damping device. The variation was up to ±2 degrees for the case of the bilge keel; near resonance conditions may be larger.
4. The time history records of the roll motion of the freely floating model LSM can be considered to be of two types: 1. the rolls were nearly uniform; and 2. the roll were irregular. The data presented in Table III

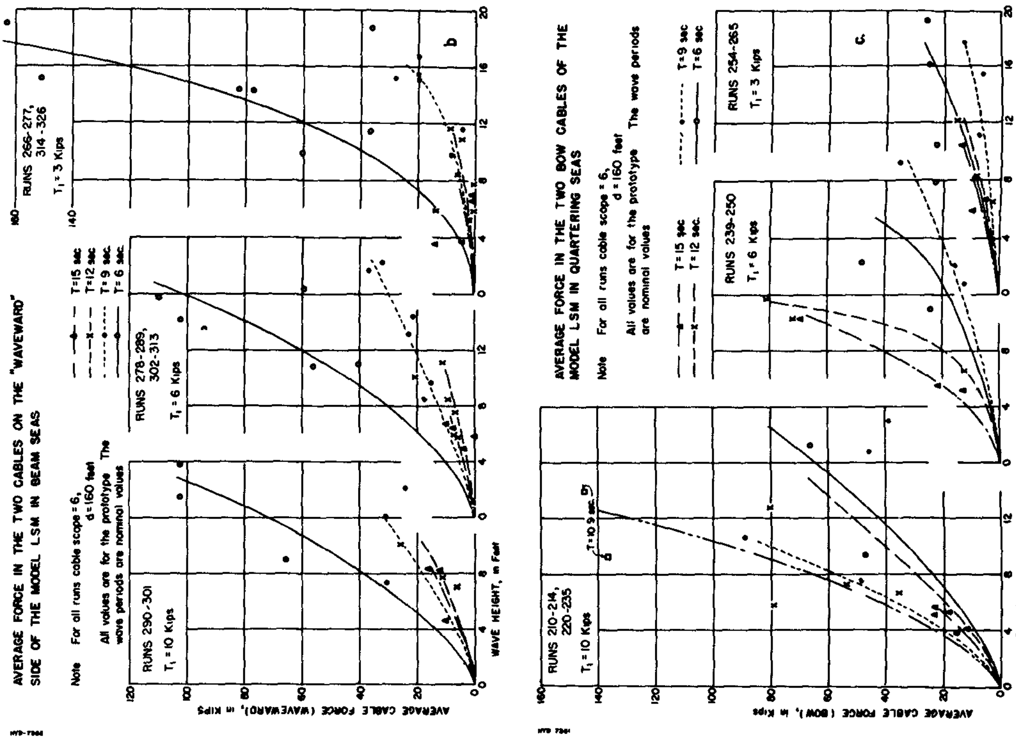
TABLE III. Note (cont.)

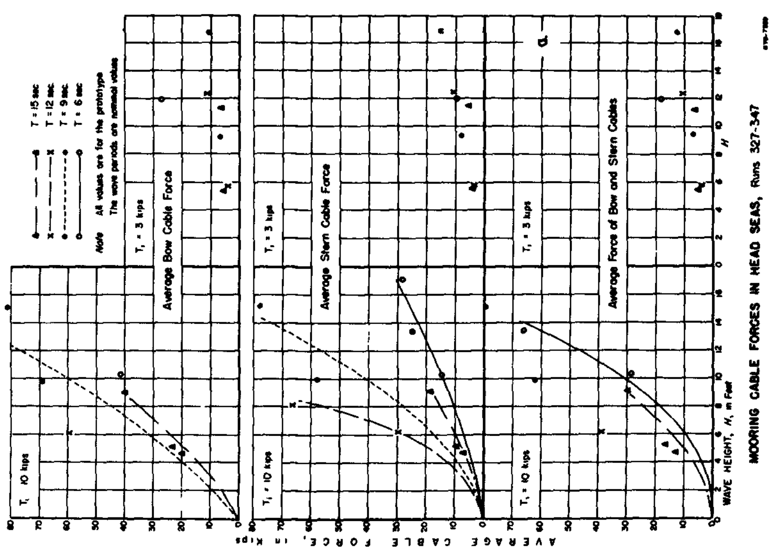
are of two types: 1. $\alpha+$ and $\alpha-$ which are the values of straight lines put on the records by eye to represent the average position of the roll up and the roll down; and 2. range of roll, which shows the range of roll angles as measured from the roll down position to the following roll up position.

An examination of the forces in the mooring cables for head seas as obtained in the wave-towing tank and the model basin for the same initial cable tensions and cable scopes, but different water depths, (Fi ure 16 and 21a) showed that they compared reasonably well considering th difference in model cables. This was also true of the pitching and hea ing motions (Figures 17, 20a and 21a). Considering the fact that ocean waves are non-uniform in both amplitude and period and the possibility exists of a particular wave period component forcing the vessel in resonance, it would appear that the comparisons of the two sets of data wit respect to maximum probable vessel motions and mooring cable forces are good.

It can be seen that the vessel rolled, yawed and swayed even thoug it was in "head seas". It is not possible to fix the vessel heading exactly, and any induced motion would be emphasized by the elastic mooring cables. In addition, there may be an inherent instability as discussed by Grim (1952).

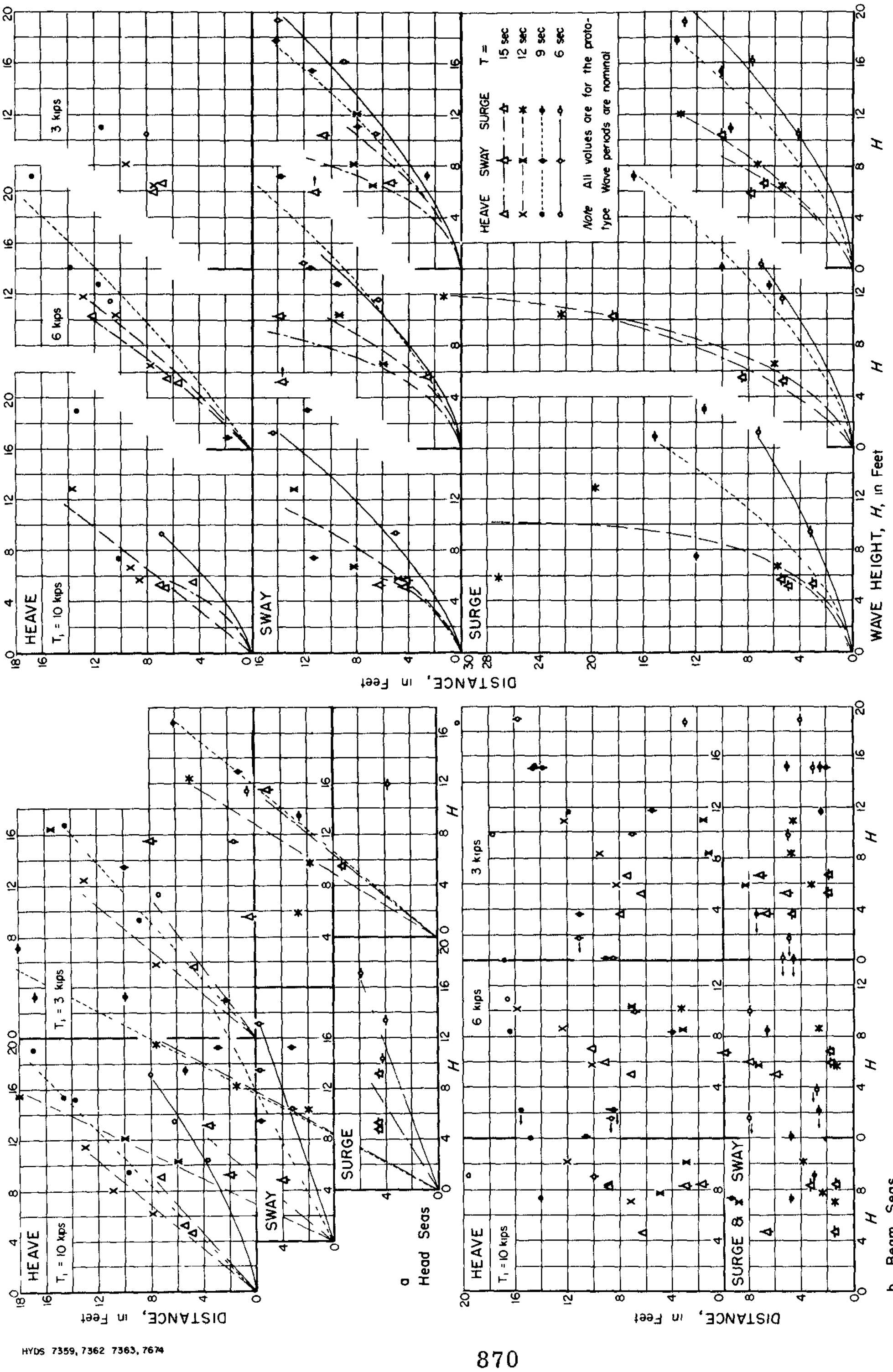
In regard to motions in quartering seas, it can be seen that the surge and pitch amplitudes are of the same order of magnitude as for th head seas tests in the model basin. The difference in water depth (160 feet rather than 200 feet) should not be of any significance as both depths are relatively deep as far as the water particle velocities and accelerations within the surface layer of the same thickness as the ves sel's draft. The heaving amplitude is greater than for head seas; in fact, the heaving exceeded the wave height on many occasions. A portic of this can be attributed to the effect of angular distortion; however, it is mainly due to the fact (Weinblum and St. Denis, 1950) that the heaving force function increases with increasing angle between the shi bow and the wave direction (see Figure 5a). This, combined with the ma nification factor (Figure 5b) for a damping coefficient of 0.4 (approx mately the value for an average ship), leads to a heaving amplitude wh can be in excess of the wave amplitude. In addition, there is considerable sway, roll and yaw. An example of the type of data obtained ha been given in Figure 14. It was apparent from the tests that the sway and yaw records may be either fairly uniform or quite non-uniform. Th record in Figure 14 cannot be said to be typical; rather, there was an entire spectrum of variations. These two motions appeared to get in a out of phase for certain wave periods; maximum values of sway and yaw often as much as 25 percent greater than the average values reported i the tables. The mooring cable forces were of the same order of magnit as in head seas and the trends appeared to be the same as in head seas



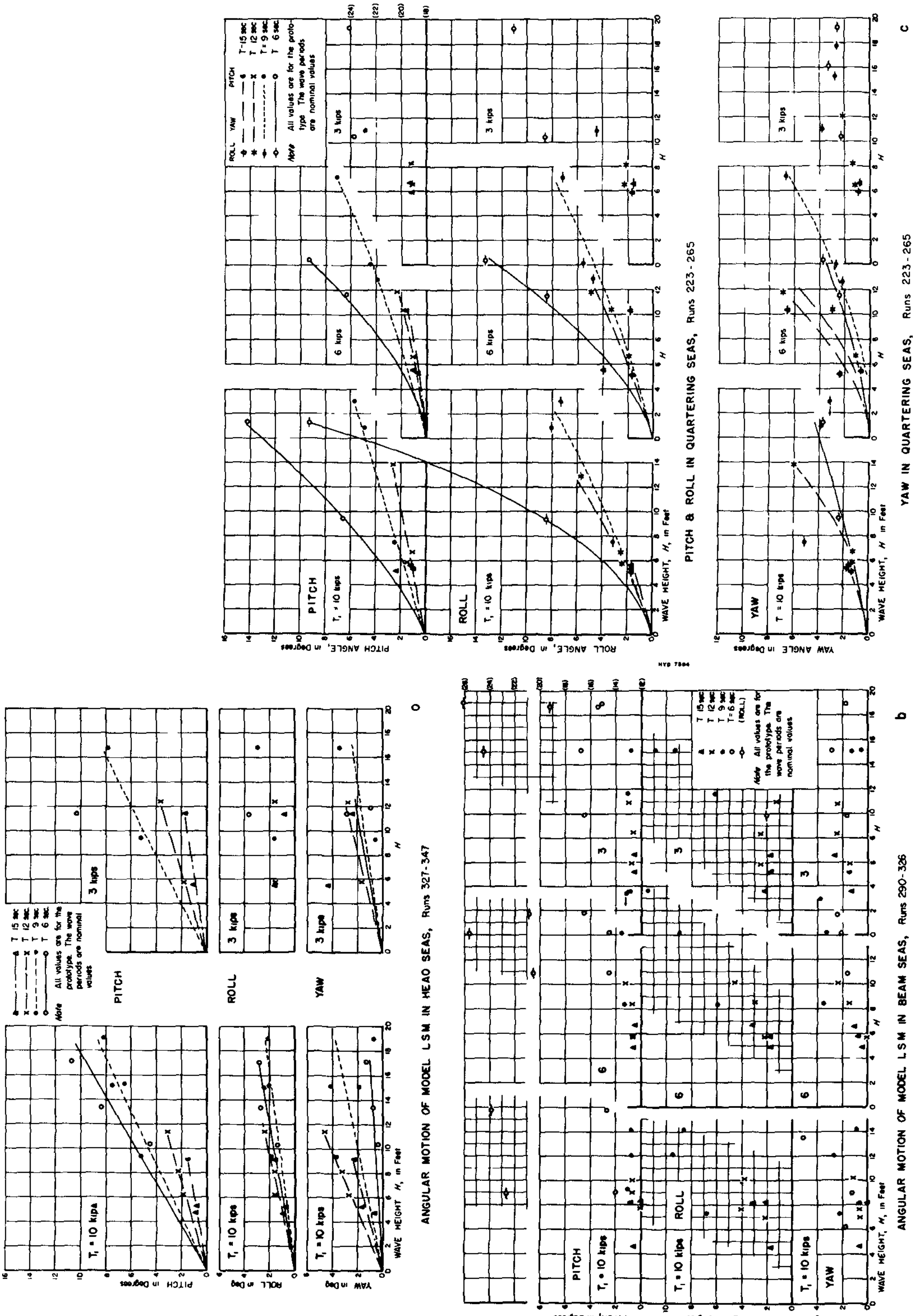


MODEL LSM MOORING CABLE FORCES
IN HEAD, QUARTERING AND BEAM SEAS

Figure 19



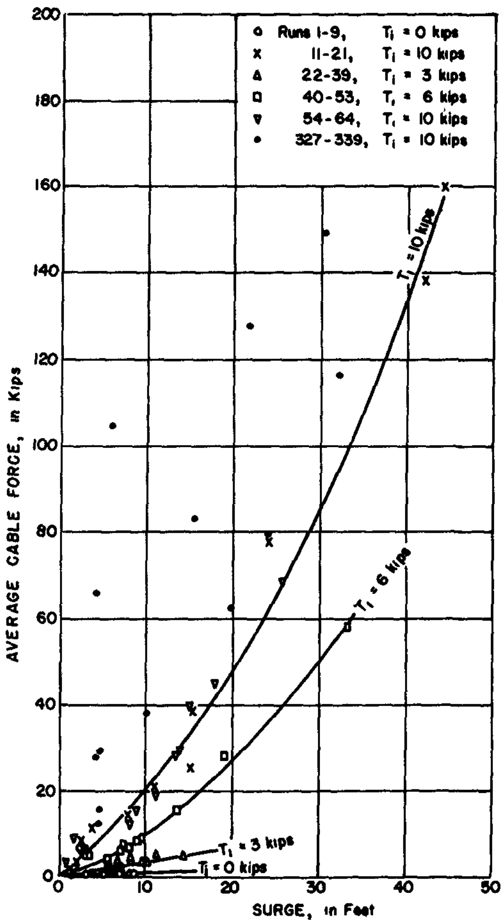
MODEL LSM HEAVE, SWAY AND SURGE IN HEAD, QUARTERING AND BEAM SEAS



MODEL LSM PITCH, ROLL AND YAW IN HEAD, QUARTERING AND BEAM SEAS

Figure 21

In beam seas the surging motion decreased considerably, although it did not go to the zero. This was possibly due to a small error in the positioning of the vessel, unequal initial cable tensions, or both. The same was true for pitching. The yawing was appreciable, although the magnitude was not as great as for the case of quartering seas. The roll- ing motion appeared to be of about the same order of magnitude for beas < for quartering seas. The sway increased. It was evident that large mo- tions could be expected for certain combinations of wave heights and periods. The reason for the apparent "resonance" condition occurring fo sway in beam seas was not apparent considering the long natural period. It was evident from Figure 21b that it was nearly independent of initial cable tension. However, it well may be explained if curves similar to Figure 5 were available. Certainly the "swaying force function" must be very large. The ratio of the maximum values of sway to wave height neve approach the maximum value of the ratios of surge to wave height.



RELATIONSHIP BETWEEN AVERAGE MOORING CABLE FORCE AND SURGE IN HEAD SEAS

Figure 22.

The maximum cable forces occurred for lower wave peri- ods in beam seas than in eithe head or quartering seas. Thu it might be necessary to head the vessel differently, deper ding upon the wave period (say, local seas or swell).

GENERAL

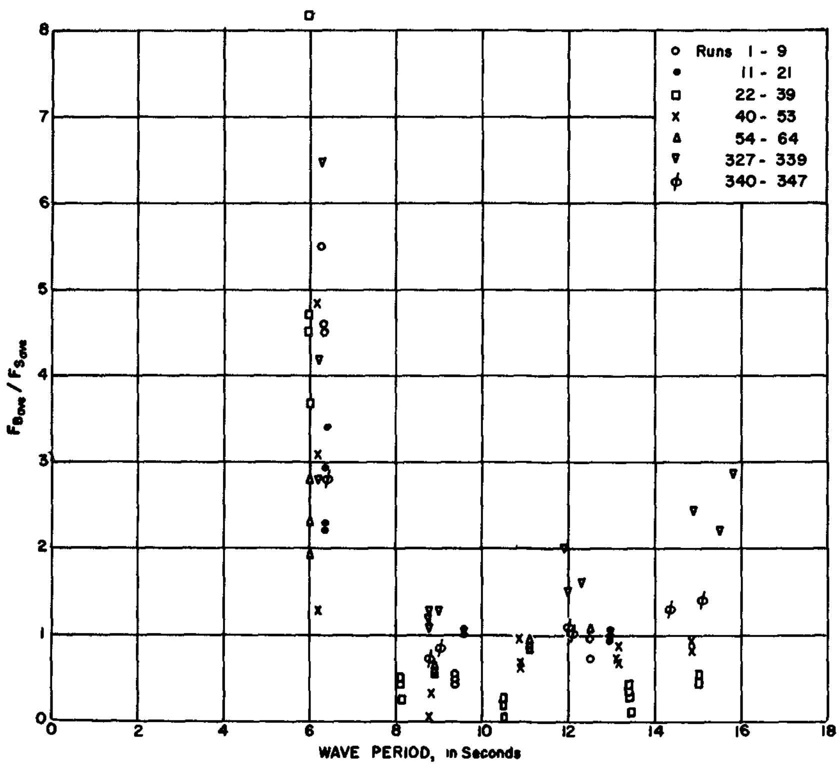
The average cable force data have been plotted in Figure 22 in relation to the vessel surge for three initia cable tensions for the vessel in head seas. The data taker in the wave-towing tank show a marked degree of correlati In addition, the data taken the model basin (for an init cable tension of 10 kips) we plotted. Some of the data were not consistent. Some waves used in the model basi were considerably higher tha was the case for the tests i the wave-towing tank and the data which were most out of agreement were those associa with the highest waves and t accompanying large pitching and heaving. It is believed that for waves under, say, 12 feet in height, the rela- tionship shown in Figure 22 should be valid.

The bow cable forces for the model in head seas were considerably higher than the stern cable forces for the shortest wave periods used. For longer wave periods this relationship was reversed, while the longest waves tested showed the relationship often reversed again. The ratio of the average bow cable forces to the average stern cable forces have been plotted in relationship to the wave period in Figure 23. The curve was found to drop abruptly at about $6\frac{1}{2}$ seconds to a minimum value and then to increase with increasing wave period.

The data could have been plotted as a function of the dimensionless parameters λ/L (ratios of vessel length to wave length) and H/L (ratio of wave height to wave length). This was done for a few cases for checking purposes. However, it does not clarify the understanding of the phenomena as only one ship model length, λ, was used; hence, the dimensionless numbers would have no significance.

CONCLUSIONS

The problem of the prediction of motions of a freely floating vessel in a seaway has not been solved completely. The motions of a moored



RELATIONSHIP BETWEEN THE WAVE PERIOD AND THE RATIO OF THE AVERAGE BOW MOORING CABLE FORCE AND AVERAGE STERN MOORING CABLE FORCE

Figure 23.

vessel are much more complicated and require an empirical solution at the present time. From a practical standpoint the most important difference between the motions of a freely floating and a moored vessel is the possibility of resonance conditions occurring in the surging, swaying and yawing motion of a moored vessel, as sell as in the heaving, pitching and rolling motions.

Resonance conditions were found to occur in the surging motion of th model in both head and quartering seas; resonance conditions were found t occur in swaying and heaving motion in both quartering and beam seas (esp cially in beam seas), although the magnification factor for swaying was not nearly as high as for the case of surging. The greatest forces in th mooring cables occurred at these resonance conditions.

The natural periods of surge, sway and yaw were found to be critica dependent upon the mooring cable configuration and initial tension, with the greater the initial tension the shorter the natural period. Heaving, pitching, and rolling appeared to be essentially independent of the initial cable tension within the limits of the experimental range of conditions; if they were not independent the relationship was masked by the experimental scatter. The natural periods of sway and yaw for the range of initial cable tension used in the tests were found to be much greater than the periods of waves normally encountered in the ocean. The resonance condition for surging for the higher initial cable tensions used i the tests was found to occur within the range of wave periods normally e pected along the Pacific Coast of the United States. The relationship between the surging motion (and mooring cable forces) and wave height wa non-linear, at least when near the resonance condition. The surging motions and cable forces were found to increase at increasing rates with increasing wave height.

It was found that the higher the initial cable tension the greater were the maximum cable forces experienced when the vessel was subjected to wave action in head or quartering seas. This was because resonance conditions occurred for wave periods in the range of 10 to 15 seconds. However, in the case of beam seas the cable forces were found to be rela tively independent of the initial tension. In this case the maximum cable forces occurred for the shortest wave period tested (about 6 seconds). These occurred in the cables on the "waveward" side of the model. At the same time, the forces on the "downwave" cables were relatively small. It would appear that the high forces on the "waveward" cables were due to a combination of diffraction and second order effect for this case.

The data on heaving, pitching, rolling and yawing were relatively consistent and it should be possible to determine these motions for the prototype with an acceptable degree of accuracy.

Considering the difficulties inherent in obtaining quantitative results using a small model, and where no prototype measurements are available to use as a guide, the results of the mooring cable force mea urements are not too inconsistent. Certainly the trends can be relied upon as can the order of magnitude of the motions and the cable forces.

This is especially true when the non-uniformity of ocean waves is considered.

None of the motions or cable forces appear to be excessive for a wave height in the neighborhood of 5 feet, regardless of wave period. Waves in excess of 8 feet (more or less), on the other hand, might result in high mooring cable forces and large surging, swaying or heaving motions, depending upon initial cable tension, wave period and vessel heading. If the characteristics of the waves in a certain location were known, it should be possible to use the curves presented in this report to predict the dangerous conditions.

In regard to roll-damping devices, it was found that the bilge keels decreased the periodic roll angle considerably (especially for the short period waves); however, when bilge keels were used, a "dynamic list" was developed.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the California Research Corporation for making this study possible, and to Drs. G. A. Schurman, L. W. Thrasher and R. E. Kitter of the California Research Corporation for their suggestions and encouragement during the study; to R. C. Wiley for his workmanship in construction of the model and force meters; to A. L. Arnold for his help in conducting the experiments; to Dr. R. W. Clough for his comments on the model laws, the theoretical consideration and the design of the force meters; to John Williams, Jaak Kukk, S. K. Mihara, E. Bennett and Stephen Whisenand for helping to analyze the data; and to M. M. Lincoln for preparing the manuscript.

REFERENCES

Beebe, K. E. (1955). Mooring forces caused by wave action on floating structures: Proc. First Conference on Ships and Waves, Council on Wave Research, Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 474-488.

Beebe, K. E. (1955). A preliminary study of forces in ship moorings due to wave action: Institute of Engineering Research, University of California, Berkeley, California, Tech. Report Series 91, Issue 1, 9 pages.

Beebe, K. E. (1956). Mooring cable force meter for models: Proc. First Conference on Coastal Engineering Instruments, Council on Wave Research, The Engineering Foundation, Berkeley, California, pp. 134-143.

Carr, McGraw and Shapiro (1953). Investigation of ship mooring forces: final report: Carr, McGraw and Shapiro, Mechanical and Electrical Engineers, Sierra Madre, California, Report to Bureau of Yards and Docks, Dept. of the Navy, Contract NOy-27482, 19 pages.

Froude, W. (1861). On the rolling of ships: Trans. Institution of Naval Architects, vol. 2, pp. 180-227.

Fuchs, R. A. (1955). A linear theory of ship motion in irregular waves: Proc. First Conference on Ships and Waves, Council on Wave Research, The Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 186-193.

Grim, Otto (1953). Rolling, stability and safety in a seaway: Forschung shefte fur Schiffbautechnik, vol. 1, 1952, a translation and summary of the original paper by E. V. Lewis, Experimental Towing Tank, Stevens Inst. of Technology, Note No. 234, 12 pp.

Haskind, M. D. (1946). The hydrodynamical theory of the oscillations of a ship in waves: Prikladnaya Matematika i Mekhanika (translation b the Society of Naval Architects and Marine Engineers).

Havelock, T. H. (1940). The pressure of water waves upon a fixed obstac Proc. Royal Society of London, Series A, vol. 175, pp. 409-421.

Kent, J. L. (1941). Experiments in rough water with a single screw ship model: Trans. The Inst. of Engineers and Shipbuilders in Scotland, Paper No. 1017, pp. 212-252.

Kriloff, Captain A. (1898). A general theory of the oscillations of a ship on waves: Trans. Inst. of Naval Architects, vol. 40, pp. 135-190.

O'Brien, J. T. (1955). Forces on moored ships due to wave action: Proc First Conference on Ships and Waves, Council on Wave Research, The Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 455-473.

Rossell, H. E., and Chapman, L. B. (1939). Principles of Naval Architecture, vol. II: The Society of Naval Architects and Marine Engineers, New York, New York, 242 pages.

Sibul, O. J. (1955). Laboratory studied of the motions of freely floating bodies in non-uniform and uniform long crested waves: Pr First Conference on Ships and Waves, Council on Wave Research, The Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 366-396.

St. Denis, M., and Pierson, Jr., W. J. (1955). On some recent developments in the theory of ship motions: Proc. First Conference on Ships and Waves, Council on Wave Research, The Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 160-184.

Timoshenko, S. (1937). Vibration problems in engineering (2nd edition 2nd printing): O. Van Nostrand Co., Inc., 470 pages.

Weinblum, G. P. (1955). Progress of theoretical investigations of ship motions in a seaway: Proc. First Conference on Ships and Waves, Council on Wave Research, The Engineering Foundation, and Society of Naval Architects and Marine Engineers, pp. 129-159.

Weinblum, G. P., and St. Denis, M. (1950). On the motions of ships at sea: Trans. The Society of Naval Architects and Marine Engineers, vol. 58, pp. 184-248.

Wiegel, R. L. (1949). An analysis of data from wave recorders on the Pacific Coast of the United States: Trans. American Geophysical Union, vol. 30, no. 5, pp. 700-704.

Wiegel, R. L., Patrick, D. A., and Kimberley, H. L. (1954). Wave, longshore current and beach profile records for Santa Margarita River beach, Oceanside, California, 1949: Trans. American Geophysical Union, vol. 35, no. 6, pp. 887-896.

Williams, A. J. (1953). An investigation into the motions of ships at sea: Trans. Inst. of Naval Architects, vol. 95, pp. 70-84.

Wilson, B. W. (1950). Ship response to range action in harbor basins: Proc. A.S.C.E., vol. 76, Separate No. 41, 29 pages.

Wilson, B. W., and Abramson, H. N. (1955). A further analysis of the longitudinal response of moored vessels to sea oscillations: The A & M College of Texas, Texas A & M Research Foundation, A & M Project 24, Reference 55-16T, 13 pages.