Report 995

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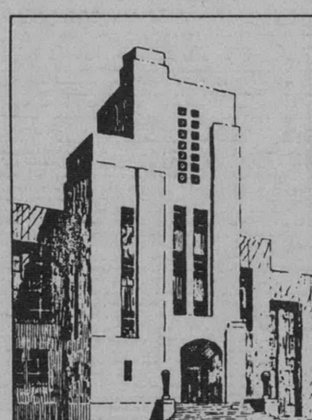
THE DAVID W. TAYLOR MODEL BASIN

WASHINGTON 7, D.C.

ON SLAMMING

by

V.G. Szebehely, Dr. Eng.
with the cooperation of
M.A. Todd and S.M.Y. Lum



RESEARCH AND DEVELOPMENT REPORT

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CONTENTS

NOTATION

A_F	Area under curve of unbalanced force from time zero to time of slamming
A_M	Area under curve of unbalanced moment from time zero to time of slamming
A_W	Waterplane area
B	Beam
F	External forces, Froude number
F_B	Buoyancy force
F_z	Unbalanced hydrostatic force
H	Draft at even keel
I	Moment of inertia
I_a	Added moment of inertia
J	Moment of inertia of waterplane area
L	Length between perpendiculars
M_B	Buoyancy moment
M_W	Moment due to weight of model
M_Ψ	Unbalanced moment
N_z	Damping coefficient in heave
N_Ψ	Damping coefficient in pitch
P	Impact force
T_e	Period of encounter
$(T_n)_z$	Natural heaving period
$(T_n)_\Psi$	Natural pitching period
V_o	Velocity of wedge before impact
V	Ship speed, velocity of wedge after impact
W	Weight of model
a	Acceleration

c	Instantaneous semi-width of wedge, modified beam coordinate considering piled up water
g	Acceleration due to gravity
h	Wave height
k_z	Dimensionless damping coefficient in heave
k_Ψ	Dimensionless damping coefficient in pitch
m	Mass
m_a	Added mass
r_m	Wave amplitude
s_m	Slope of added mass versus time curve at instant of slamming
s_i	Slope of added moment of inertia versus time curve at instant of slamming
t	Time
w	Relative velocity between bow and wave
x	Coordinate along longitudinal axis
y	Coordinate along transverse axis
z	Depth of immersion, heave coordinate
Λ_z	Tuning factor in heave
Λ_Ψ	Tuning factor in pitch
β	Deadrise angle
γ	Wave length parameter
ϵ	Phase angle
ϵ_b	Phase of bow motion
Ψ	Pitch angle
λ	Wave length
ρ	Water density
ω_o	Wave frequency
ω_e	Frequency of encounter

Slamming of the USS MISSOURI

I Introduction

The most important problem of Naval Architecture is probably the extension of speed range. The maximum speed of a surface vessel is not determined by the power but by the ship's behavior in a seaway. In spite of the available power the speed of advance must be reduced if too violent motions are to be avoided. The most violent attack of the sea on a vessel is probably the heavy blow delivered by the waves on the reentering bow. The ship vibrates for some time after such an impact and plates under the fore foot are damaged.

The present paper together with previously published work (references 8,10) attempts to describe the practical aspects of the hydrodynamics of ship slamming. It is regrettable that many theoretical and experimental results are omitted from the paper in order to make it more concise. The reader interested in mathematical details or in the results of extensive computations is referred to the original unabbreviated report by the same authors, (reference 12).

The suggestions and cooperation of Dr. Weinblum, Dr. Todd, and Dr. Landweber are gratefully acknowledged.

II General Considerations

1. Definition of slamming

It seems justifiable to attempt a clear description and definition of the phenomenon to which this paper is devoted. Slamming is felt by the ship's personnel in the sudden change of the acceleration. Motion records do not show any peculiarity at the instant of slamming. An accelerometer, located near the bow will, however, show large deflection and deviation from the normal record when slamming occurs. When the bow of a ship hits the water (this will be discussed later in more detail), the ship suddenly decelerates which shows up on the acceleration record. This sudden deceleration, as felt by the personnel of the ship, sometimes creates the impression that the motion is arrested. There is no theoretical, experimental or full scale test result which would substantiate the existence of arrested motion. To arrive at a definition of slamming, which is applicable from the practical and acceptable from the theoretical points of view, we base our definition on the aforementioned deceleration process.

<u>Slamming is the sudden change of the acceleration of the ship.</u> The acceleration (as well as the motion) is largest at the bow and the stern. Therefore the most violent sudden change of the acceleration will take place at these places. The personnel of the ship feel the sudden deceleration and refer to the phenomenon as slamming. Therefore, the above-given definition certainly satisfies the practical requirements. As is shown elsewhere in this paper, it satisfies, also, the theoretical requirements. The damage on the bottom plates is caused by the pressure

developed when slamming takes place. The personnel on the ship have no knowledge of the excessive pressures, only of the sudden deceleration. The captain of the ship associates the sudden deceleration with high pressures on the bottom intuitively and tries to avoid slamming. Besides the sudden deceleration, there is another danger signal, which the personnel are aware of, and that is the elastic vibration which is generated by the sudden build-up of pressure (generally called "blow"). On the few existing full-scale records obtained by bow accelerometers and on the several hundred slamming records obtained by us in model tests, the acceleration record with no exception showed a high frequency vibration following a slam. The frequency of the vibration corresponds to that of the elastic vibration of the hull and it can be observed for quite some time (30 sec, 1 min.) depending on the violence of the slam (reference 7). Therefore, the elastic hull vibration is a safe way of detecting slamming. It is realized that hull vibration might be caused by the propulsion machinery and other sources besides slamming. The combined sudden deceleration and the following vibration, however, cannot be confused with vibrations arising from other sources. First a very high frequency vibration is generated which, however, dies out quickly and the fundamental frequency will remain.

The integrated effect of the pressure on the bottom is largest at the instant of slamming, since the sudden deceleration requires large forces which come from the pressure on the bottom. It is of great practical significance to establish the fact that the highest loading occurs at the instant of slamming. The fact that the integrated pressure effect is largest when the deceleration is largest does not necessarily mean that the local pressures cannot be dangerously high at other instants (i.e., immediately before or after the maximum deceleration is reached). Since pressure computations on the bottom of a slamming ship are very tedious and lengthy, it is important from the design viewpoint to know whether the peak local pressure is reached at the instant of slamming. Elsewhere (reference 12) it is shown that the answer to this question is in the affirmative.

2. Mechanism of slamming.

The existence and importance of the similarity between slamming and the landing of seaplanes was pointed out some time ago (reference 5). In the process of simplification the next step is to reduce the problem of the landing of seaplanes to that of a V-wedge dropped on a smooth water surface.

When a wedge is dropped on an originally smooth water surface, the impulse momentum principle can be applied in the following form: (momentum at any time after impact) - (momentum at the time the wedge touches the surface) = time integral of the forces.

The "momentum" of the above equation, of course, refers to the total momentum of the system. If the mass of the wedge is m and it arrives at the water surface with a velocity V_o, its momentum is mV_o. After penetration the velocity is V and the momentum of the system is $(m + m_a)V$, where m_a is the so-called added mass of the wedge. The forces acting on the wedge are the buoyancy force, the weight of the wedge, friction drag, etc. If all these forces are neglected in a very rough first approximation, the momentum of the system is conserved and

$$(m_a + m)V = mV_o. \tag{1}$$

The critical term is the added mass. As the wedge penetrates the water the added mass increases. It can be approximated by the formula

$$m_a = \ell \frac{\pi \rho c^2}{2} \tag{2}$$

where ρ is the density of the water, ℓ the length of the wedge, and c the instantaneous semi-width of the wedge (Figure 1). We note that equation (2) gives the mass of water included in a semi-cylinder of diameter 2c, filled with water (reference 4). It is also noted

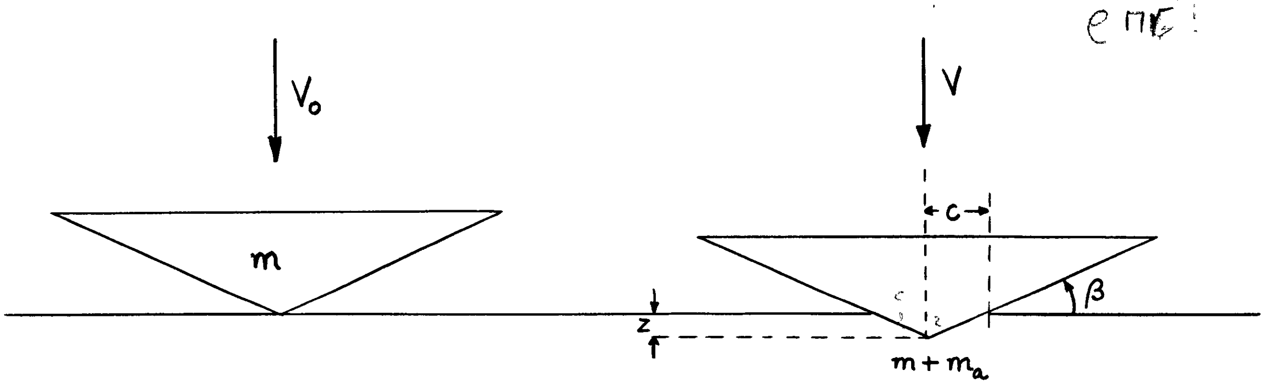

Figure 1 - Impact of a Wedge on an Undisturbed Surface

that formula (2) applies to a wedge of small deadrise angle ($\beta \sim 0$, Figure 1); it needs an aspect ratio correction (because of the finite length of the wedge) plus a so-called piled up water correction since the surface will not remain undisturbed after impact. Roughly, however, the added mass of a penetrating wedge will be proportional to the square of the beam at the water surface. If the depth of penetration is z, then $z = c \text{ tg } \beta$ or for small deadrise angle $z = c\beta$ so the added mass becomes

$$m_a = \ell \frac{\pi \rho z^2}{2\beta^2} \tag{3}$$

or simply $m_a = k' z^2$, where k' is a constant. Substituting this value of m_a in equation (1) and dividing by m, we have:

$$(kz^2 + 1)V = V_o \tag{4}$$

where k is another constant, $k = k'/m$. Since $V = dz/dt$, the acceleration is $a = d^2z/dt^2$, which can be computed from equation (4):

$$a = - \frac{V_o{}^2 \pi \rho z \ell}{m\beta^2 (1+kz^2)^3}$$

At the instant of impact z = o and so a = o, the wedge is not accelerating (since its weight was neglected). After penetration the wedge is decelerating (a negative). Maximum impact force is associated with maximum deceleration:

$$P_{max} = .65 \frac{V_o{}^2 \sqrt{m\rho \ell}}{\beta}$$

The purpose of the above simple derivation was to point out the essential facts in hydrodynamic impact calculations. If external forces (F) cannot be neglected the impulse momentum principle becomes (writing $V = \dot{z} = dz/dt$)

$$(m + m_a)\dot{z} - mV_o = \int_{t_o}^{t} F dt$$

An important and characteristic equation is obtained by differentiating the above equation with respect to time:

$$(m + m_a)\ddot{z} + \dot{m}_a \dot{z} = F \tag{5}$$

We see that the force is not equal to mass times acceleration in an impact process since the added mass (m_a) is not constant but also a function of time. The $\dot{m}_a \dot{z}$ term, or for rotational motion the $I_a \dot{\Psi}$ term, will be responsible for the sudden changes in the acceleration. (I_a added moment of inertia, Ψ pitch angle).

Computation of the added mass even for a wedge is a rather difficult process, as pointed out before. The added mass problem being a potential flow problem, one can solve in principle at least the impact problem for an arbitrary cross section. Only the geometry of the body enters the calculation. If the added mass is determined and its variation with the depth of submergence is known the acceleration can be computed from equation (5). It is repeatedly emphasized that the impact force depends on the variation of the added mass.

The above-outlined fundamental principles can be applied to any impact phenomenon, such as ship slamming. This was shown in some of our previously published work (references 8 and 10) especially in reference 10 where a detailed slamming calculation is presented for a ship pivoted aft of midship.

We saw that slamming depends on the magnitude of the time rate of change of the added mass. This is influenced seriously by the geometry of a penetrating body. If the lines of a penetrating bow are fine, no large change in the added mass will take place (m_a being roughly proportional to the square of the beam at the instantaneous surface). The largest sudden change in the added mass occurs if the bottom is flat. Effects such as the elasticity of the bottom and the compressibility of the water, orginally secondary, now become very important. . In fact, impact calculations were performed assuming compressibility of the water and elasticity of the bottom and neglecting completely any hydrodynamic effects (reference 9). The results are rather unrealistically too high.

The use of the concept of variable added mass makes our problem one of "unsteady hydrodynamics." Neglecting unsteady effects, computations were presented in the literature (reference 5) from steady hydrodynamic considerations with unrealistically small results.

The computation of the pressure distribution on the bottom of a slamming ship, in the present paper, is based on the unsteady flow about the rapidly submerging bow. This is very difficult even for a wedge dropped on the undisturbed free surface. The velocity of the flow along the wedge is found from the solution of a potential flow problem (in fact the same problem which gave the added mass). Substituting the expression for the velocity distribution in the generalized Bernoulli equation gives the pressure distribution. Potential flow solutions result often in infinite velocities which prevent realistic calculation of the pressure. Since not even the steady state solution of the flow around the bow is available, some rather crude approximations are necessary to perform actual pressure computations.

The above comments and simplified discussion cover the basic mechanism of slamming. In summarizing, we repeat that slamming is an unsteady flow problem and its solution depends on the recognition of the importance of variable added mass.

3. Effects of slamming.

Three types of stresses are generated by slamming. The most obvious and most frequently described is the one due to high pressures on the plates under the forefoot. Figure 2 shows the distance from the bow of that part of the ship generally liable to damage due to slamming (reference 2).

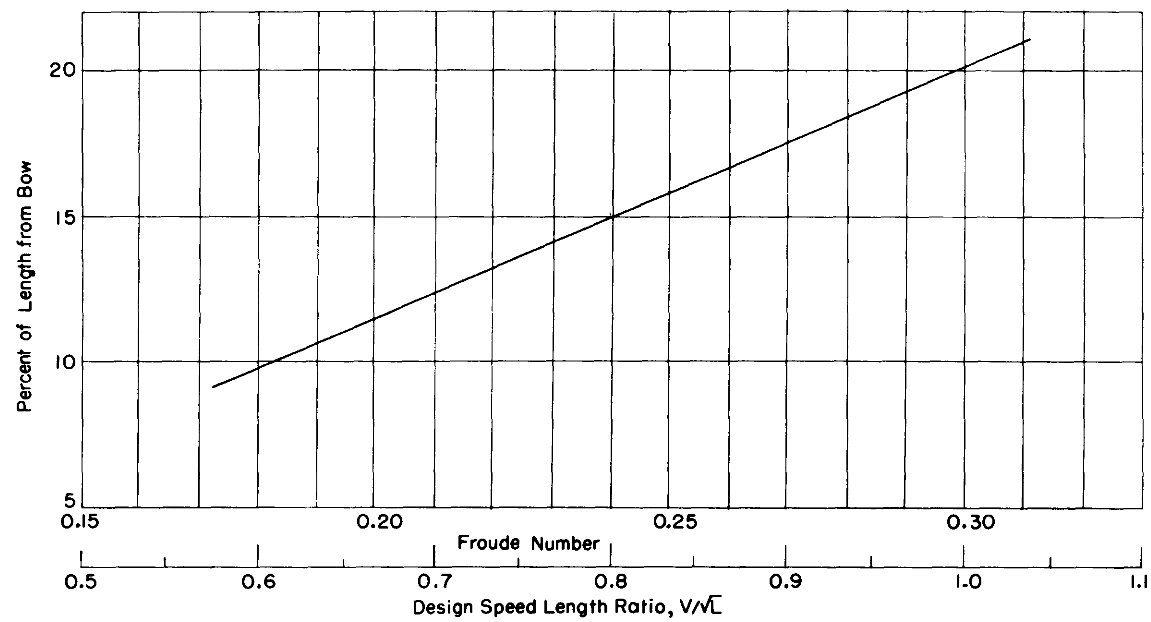

Figure 2 - Distance of Damaged Part of Bottom from Bow in Percent of Length

The part most susceptable to damage is the area of the bottom from 10% to 25% of the ship's length; in the transverse direction the keel to 25% of the beam is the most dangerous part (reference 6). Ships of slender form suffer damage further aft than ships of full form.

It should be pointed out, however that vibration produced by slamming might also damage the superstructure. Severe stresses in light superstructure may result in cracked plates and loose rivets there. The third type of stress generated by slamming increases the sagging stress amidships produced by normal wave action by some 30% (reference 1).

From damage reports, it seems to be rather certain that riveted ships suffer more than welded ones; also that generally it is not one slam that causes the damage but repeated action.

III Conditions Leading to Slamming

Since slamming is caused by sudden changes in the added mass and added moment of inertia, an investigation of factors conducive to slamming must be based on an analysis of the factors producing these changes. The added mass and moment of inertia depends on the square of the beam at the water level. There are, therefore, two basic factors which influence the slamming tendencies of the ship : the lines at the bow and the velocity and position of the bow relative to the waves. The first factor will be referred to as the "geometric slamming factor" the second will be called the "kinematic slamming factor". In this chapter the kinematic slamming factor is discussed in detail, and only few comments are made regarding the geometric factor.

For a given ship with given transverse sections, changes in the added mass are connected with the variation of the water level at the bow. The time rate of change of the added mass will depend on the time rate of change of the water level, i.e., on the relative velocity between wave and bow. Since conventional transverse sections have zero or positive slopes, i.e., the local beam increases if the water level rises and the increase in beam is large at the bottom, the time rate of change of the added mass is generally largest immediately after the bow enters the water. In short, the reason why bow out condition is generally associated with slamming is that small draft variation at the bottom results in large beam variation and therefore large changes in the added mass and added moment of inertia. A bulbous bow, when entering the water will result in large changes in the added mass.* Fine lines at the bow will not give too sudden changes in the added mass. It is emphasized that the time rate of change of the local beam is important. Therefore

*This does not mean that ships with bulbous bow are always bad slammers, since the bulbous bow has the tendency of damping pitching. If the bow does not emerge and the bulb stays under the wave all the time, the probability of bulb slamming is zero. If, however, a bulbous bow broaches and re-enters the water, slamming can be very heavy.

if the bow enters the water very gradually, no sudden changes in the added mass can be expected even if the transverse sections are full. Therefore, bow emergence is not a sufficient condition for slamming. Neither is it necessary since even without bow emergence one can think of sudden changes in the added mass if the flare at the bow increases rapidly and if the water level reaches this part of the bow. Considering the damage at the bottom plating caused by slamming one might want to concentrate on the conditions which result in such "bottom slamming". In this case the bow emergence is necessary from a practical point of view, since, as pointed out before, this is the case when large changes in the added mass will occur. If an emerged bow moving downward meets an upward moving wave, the rise of water level is more sudden, than if the downward moving bow enters a downward moving surface. Evidence of this is shown in the experimental part of this paper. Therefore, the phase between wave and bow motion should be such that these two oppose each other when the bow re-enters the water. Furthermore, even when the bow motion and wave motion are 180° out of phase (which corresponds to the above described case), a sudden change in the added mass requires reasonably large magnitude of the relative velocity, i.e. large bow velocity and large wave velocity. Therefore, there are three kinematic conditions to be investigated:

(1) Bow emergence
(2) Phase lag between bow motion and wave motion
(3) Magnitude of the relative velocity

If the bow emerges and suddenly re-enters an opposing wave, slamming will take place. Large slamming results if the relative velocity is large. In what follows we investigate these three conditions separately and present quantitative criteria for each*.

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*Regarding the magnitude of the slamming force a fourth criterion is to be considered. If at the instant of impact the angle between the wave surface and the keel is small, the slamming force will be very large provided other conditions for slamming are also met. The large slamming force is the result of high pressures acting on a relatively large area. This area is large if the above "slope condition" is satisfied.

1. Bow Emergence

We formulate the problem in the following way: will the bow of a given ship in given waves emerge? The answer is given for an "average ship" heading into waves, in terms of the ship's length, draft, and speed. The sea is assumed to be regular and defined by the wave length and the wave height. For the many carefully listed assumptions and derivations, the reader is referred to reference 12. Figure 3 shows the limiting value of the draft/wave-height ratio as a function of the Froude number. The meaning of the plot is illustrated by the following example.

Determine if the bow of an "average ship" of length 400 ft., and draft 25 ft., emerges when heading into 630 ft. long and 20 ft. high waves at a speed of 20 kts.

The Froude number for this case is .3, the wave-length parameter is 2. With these values the figure gives 2.3 for the limiting value of H/h. The actual value of the draft-wave height ratio is 1.25. Since the limiting value (2.3) is larger than the actual (1.25), bow emergence can be expected. If the speed is reduced to 7 kts., the Froude number becomes approximately 0.1 and the limiting value is 1.5. The bow will still emerge. If the draft is increased so that H/h becomes larger than 1.5, i.e. H larger than 30 ft., the bow will stay in the water. The speed at which the bow will not emerge (at the original draft of 25ft.) is approximately 3 kts.

For wavelength/shiplength ratios not given on figure 3, the limiting draft can be computed using formulae given in reference 12.

It is interesting to point out that if the ship is in hove-to condition, (F = 0 on figure 3) the bow might still emerge. In fact for relatively short waves ($\lambda / L = .79$) bow emergence is more probable in hove-to condition than if the ship is advancing. If the above mentioned 400 ft. long ship is in 316 ft. waves, ($\gamma = 4$) the limiting H/h ratio in hove-to condition is 1.1. Therefore the bow will not emerge if the draft is larger than 1.1 x wave height. Assuming 15 ft. waves (wave length-wave height ratio 21), this requires 16.5 ft. draft, which corresponds approximately to ballast condition as given by the Maritime Administration (mean draft equals 4 percent of length). If the ship has a speed of advance of 20 knots, the Froude number is .3 and the critical H/h ratio is reduced to approximately 0.4. Therefore the bow will not emerge if the draft is larger than .4 x 15 = 6 ft.

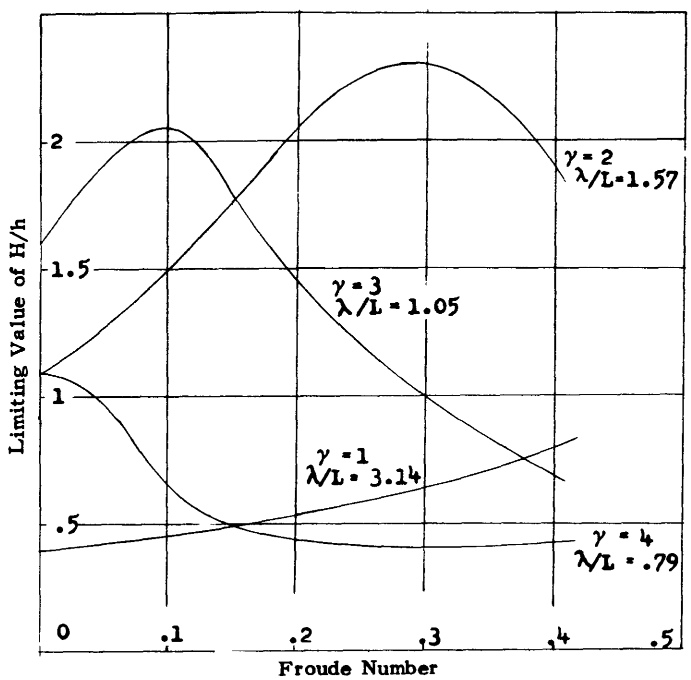

Figure 3 - Emergence of Bow

Bow does not emerge if the limiting value of draft/waveheight (H/h) as obtained from the curves is smaller than the actual H/h. Wavelength parameter $\gamma = \pi L/\lambda$.

From a practical point of view this calculation means no more than that the probability of slamming is higher in hove-to condition than under way in such relatively short waves.

2. Phase lag between bow motion and wave motion.

The vertical wave velocity and the vertical bow velocity oppose each other if they are 180° out of phase. The problem under discussion might be formulated the following way; will the downward moving bow of a given ship meet an upward moving wave? The answer is again given for an "average ship" heading in the waves, in terms of the ship's length, draft, and speed. Details are given in reference(12). Figure 4 shows the phase difference between wave motion and bow motion. If the phase difference ($\gamma - \epsilon_b$, γ being $\frac{\pi L}{\lambda}$ and ϵ_b the phase of the bow motion) is 180° the two motions will oppose each other; if it is zero or 360°, the bow will move together with the wave. An example is given to explain the use of the graph.

Assume the same ship as before ($L = 400$ ft., $h = 20$ ft.) moving into the waves at $V = 20$ kts. The wave length parameter is $\gamma = 2$ and $F = .3$, which gives for the phase difference 135°. This latter becomes dangerously close to the critical 180° value if the speed is increased. In hove-to condition it is reduced to 70°. In shorter waves ($\lambda = 316$ ft., and $\gamma = 4$) the hove-to condition is dangerous since the phase shown in the graph is 210°. At higher speeds the phase becomes negligible.

From figure 4 one might conclude that there is a corresponding dangerous speed for every wave length for a given ship. For instance for 400 ft. ship in 420 ft. waves the most dangerous speed is 7.06 kts. and in 630 ft. waves, 31.6 kts. Also from figure 4 one can see that long waves ($\gamma = 1$, $\lambda \cong 3L$) are not dangerous, since the phase difference is of the order of 30°-40°. The most dangerous wave for hove-to condition is approximately 10% shorter than the ship length.

3. Relative velocity

The question can be formulated as follows: how large will the relative vertical velocity be between waves and bow? The answer will be given under the same assumed conditions as before. Figure 5 shows the maximum relative velocity as a function of the Froude number (for details see reference 12). For the previously mentioned 400 ft. ship in 630 ft. waves at 20 kts., one obtains from the figure $w_m / \omega_o r_m - 7$.

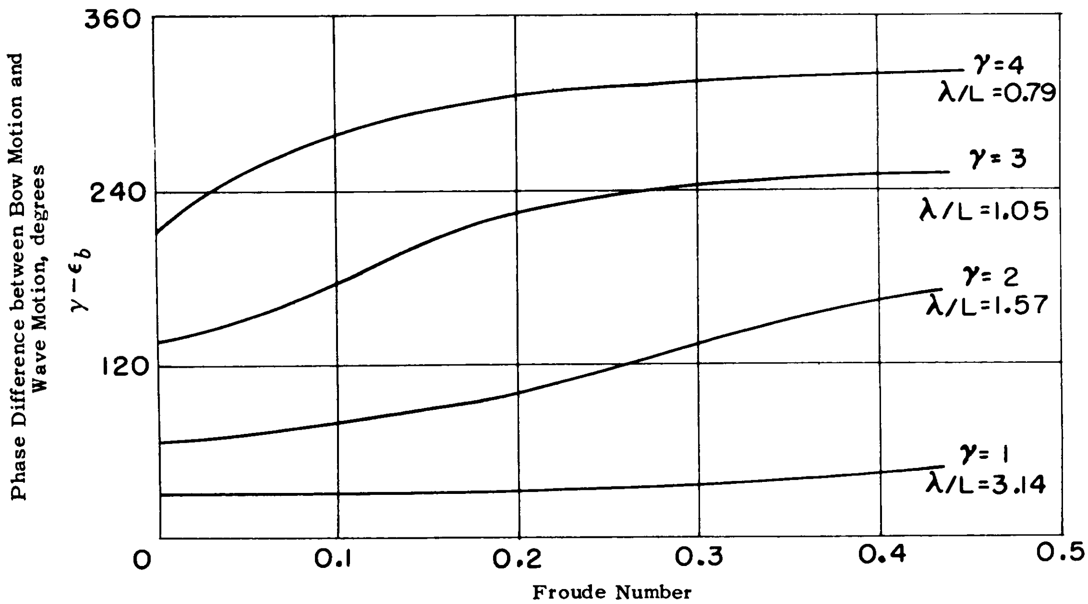

Figure 4 - Phase Lag Between Bow Motion and Wave Motion

If $\gamma - \epsilon_b^{\cdot} = 180°$, the downward-moving bow meets an upward-moving wave. Wavelength parameter $\gamma = \pi L/\lambda$.

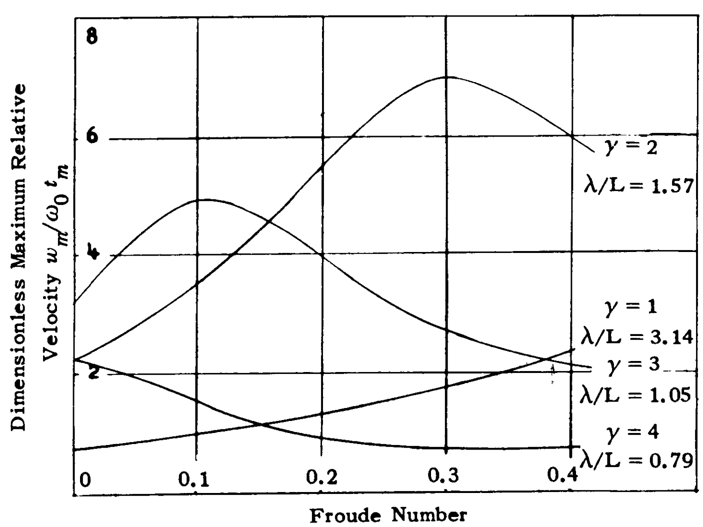

Figure 5 - Velocity of Bow Relative to Wave

w_m is the maximum vertical velocity of bow relative to to wave. $\omega_0 = \sqrt{2\pi g/\lambda}$ is the absolute wave frequency. $t_m = h/2$ is the wave amplitude. $\gamma = \pi L/\lambda$ is the wavelength parameter.

The actual wave frequency $\omega_0 = \sqrt{2\pi g / \lambda} = 0.568$ sec and the wave amplitude is $r_m = h/2 = 10$ feet. The maximum relative velocity becomes $w_m \cong 40$ ft/ sec. We see that if the ship is moving faster or slower than the above critical speed, the relative velocity decreases. In a hove-to condition in 630 ft. waves the relative velocity is still $w_m = 12.5$ ft./ sec. In the case of short waves ($\gamma = 4$) the hove-to condition is more dangerous than when the ship is advancing. For a given ship there are certain dangerous speeds associated with certain given waves. For $\lambda / L = 1.57$, or 1.05 either a decrease or an increase in speed (from the critical) will reduce the relative velocity, for short waves ($\lambda / L = .79$) an increase in speed is recommended; for long waves ($\lambda / L = 3.14$) a reduction.

Conclusions

From the above discussed role of the three most important factors we arrive at the following conclusions:

(1) If the wave length is approximately equal to the ship length ($\gamma \cong 3$) the speed corresponding to Froude number 0.1 is dangerous. Either reducing or increasing the speed will help.

(2) In long waves ($\gamma = 1$) neither the bow-out condition, nor the magnitude of the relative vertical velocity, nor the phase between bow and wave motion is critical. If, however, the draft is drastically reduced and the bow-out condition is met speed should be reduced.

(3) In short waves ($\gamma = 4$) the hove-to condition or slow speed are the most dangerous and generally a speed increase reduces the probability of slamming.

(4) Very roughly in the conditions for bow emergence, large relative vertical velocity is associated with opposing wave and bow velocity. The complete picture is more complicated, however, since for instance in waves 57% longer than the ship ($\gamma = 2$), the critical Froude number from the point of view of bow emergence and relative velocity is approximately 0.3, therefore either a speed increase or a decrease would reduce the probability of slamming. From the point of view of phase between bow and wave velocities, the F = .3 is not as dangerous as the F = .4 or .5 speed, therefore the previous recommendation is to be modified to say that in these waves definitely a speed reduction is recommended.

(5) Hove-to condition might easily result in slamming. The most dangerous waves are approximately of

the same length as the ship. The remedy should be motion forward in relatively short waves, provided the power plant permits.

(6) The probability of bow emergence increases if the draft is reduced, keeping other conditions the same. If this happens the impact velocity might be of the same order of magnitude as the ship velocity.

IV Estimation of slamming force, acceleration, and pressure distribution on the bottom of a slamming ship.

1. Introduction

In the present paper only heaving and pitching motions are investigated, therefore the governing equations might be written as

$$\left.\begin{aligned} (m + m_a)\ddot{z} + N_z \dot{z} + K_z(z,\Psi) &= F(z,\Psi;\, t) \\ \text{and} \qquad (I + I_a)\ddot{\Psi} + N_\Psi \dot{\Psi} + K_\Psi(z,\Psi) &= M(z,\Psi;t) \end{aligned}\right\} \qquad (6)$$

The two equations state that the inertia force (moment), the damping force (moment), and the hydrostatic restoring force (moment) keep equilibrium with the exciting force (moment). If coupling is neglected, these equations reduce to

$$\left.\begin{aligned} (m + m_a)\ddot{z} + N_z\dot{z} + A_w \rho g z &= F_z \cos \omega_e t \\ (I + I_a)\ddot{\Psi} + N_\Psi\dot{\Psi} + J\rho g \Psi &= M_\Psi \sin \omega_e t \end{aligned}\right\} \qquad (7)$$

Therefore, if the coefficients in the equations are known, the motion can be investigated and the position of the ship can be determined at every instant.

The coefficients F_z and M_Ψ are functions of the wave parameter ($\gamma = \frac{\pi L}{\lambda}$) and also depend on the form of the hull. In reference (11) a method is presented for estimating F_z and M_Ψ for wall-sided vessels. The added mass and added moment of inertia can also be estimated and they are of the same order of magnitude as the corresponding terms for the ship. The damping factors might be estimated from reference (3) for instance, therefore a fairly reliable estimate for the amplitude and for the phase of the heaving and pitching motion can be obtained.

If the period of encounter is close to the natural heaving or pitching period, the phase lag predictions become extremely uncertain, since in this case the damping strongly influences the motion. In fact motion with very small damping has zero phase lag below resonance, and 180° above resonance. Around resonance the amplitude is also very sensitive to damping, therefore motion predictions near resonance are not always entirely satisfactory.

For vessels not wall sided, and for vessels not symmetric with respect to the midship the estimations of the exciting force and moment amplitudes become very tedious and uncertain. For coupled motions (which is a relatively simple problem for heave - pitch coupling) no details have appeared as yet in the literature, at least not in easily usable form. Added mass estimations are in a somewhat more advanced state than for instance damping computations, probably due to the fact that solution of ship vibration problems essentially depend on added mass estimation.

From this short discussion the rather dark picture emerges, that motion predictions of ships seem to be in a rather preliminary state, even if regular waves are assumed. Especially the fact might be rather disturbing that under certain conditions the damping in waves might be one fourth of its steady state value or even less. Furthermore, the natural pitching and heaving period is seldom known with sufficient accuracy, so it is quite reasonable to think of cases when it cannot be determined if the ship motion is below or above resonance.

Slamming investigations are necessarily connected with motion studies, in fact they are based on the ability of properly estimating amplitudes and phase lags of the motion. As will be shown later, some modifications (in fact complications) are to be introduced in the aforementioned basic equations. Since even in over-simplified cases, motion predictions are not always very accurate, any further complications of the basic equations might make the situation hopeless. Progress in motion studies undoubtedly will improve the method of slamming investigations which will be outlined in the following pages.

Slamming depends very strongly on phase relations between wave motion and ship motion and slamming generally is the result of violent ship motion. Motion predictions are uncertain around resonance, which condition is very often (but not necessarily) connected with the most violent motion. Again it is not a necessity, but generally true, that slamming occurs when part of the ship emerges. The ship most certainly cannot be considered a wall sided vessel if part of it leaves the water. Coupling between pitch and heave cannot be neglected in slamming calculations, since phase relations are strongly influenced by coupling effects.

2. Method of slamming computation in waves.

Nevertheless we make the following very crude and bold proposition regarding an explanation and computational method for the slamming phenomenon.

(1) For given ship and given waves, from equations (6) and (7), the pitching and heaving motions are estimated. One might use the assumption that the vessel is wall sided, that the damping has its steady state value, that in spite of the fact that the ship emerges, her added mass and added moment of inertia are constant, etc.

The important fact is that a reasonably good estimate of z_m (heaving amplitude), ϵ_z (heaving phase), Ψ_m (pitching amplitude), and ϵ_Ψ (pitching phase) is obtained for a certain given condition. Since the motion is assumed to take place in regular waves, it is sufficient to study one cycle of the motion, which we may assume to repeat itself.

The above motion prediction results in harmonic motion and therefore no sudden peaks in either the motion or in the acceleration curves can be expected. In fact the ship will not slam but will move with the predicted amplitudes and phases.

(2) The second step in the calculation is less uncertain than the first one, but far more tedious. For one cycle, at suitable time intervals, the wave surface is drawn with the ship in the waves, in the position which can be computed from the previously found amplitudes and phase lags. Figure 6 shows four such drawings with the corresponding photographs taken of the model. Slamming is expected to occur at the time the bow re-enters the water. To obtain accurate results it is suggested that around this critical time many drawings be prepared at very short time intervals. This can easily be done since the position of the ship relative to the waves can be computed for any time without difficulty.

Returning now to figure 6 we point out that $t = 0$ corresponds to the instant when the wave crest is at midship. The bow is out of the water at $t = 0$ and is already approaching the water surface. At $t = .13$ sec it is in the water. At $t = .16$, the bow is moving downward and it reaches its lowest point around $t = .35$ sec. Slamming takes place about $t = .16$ sec.

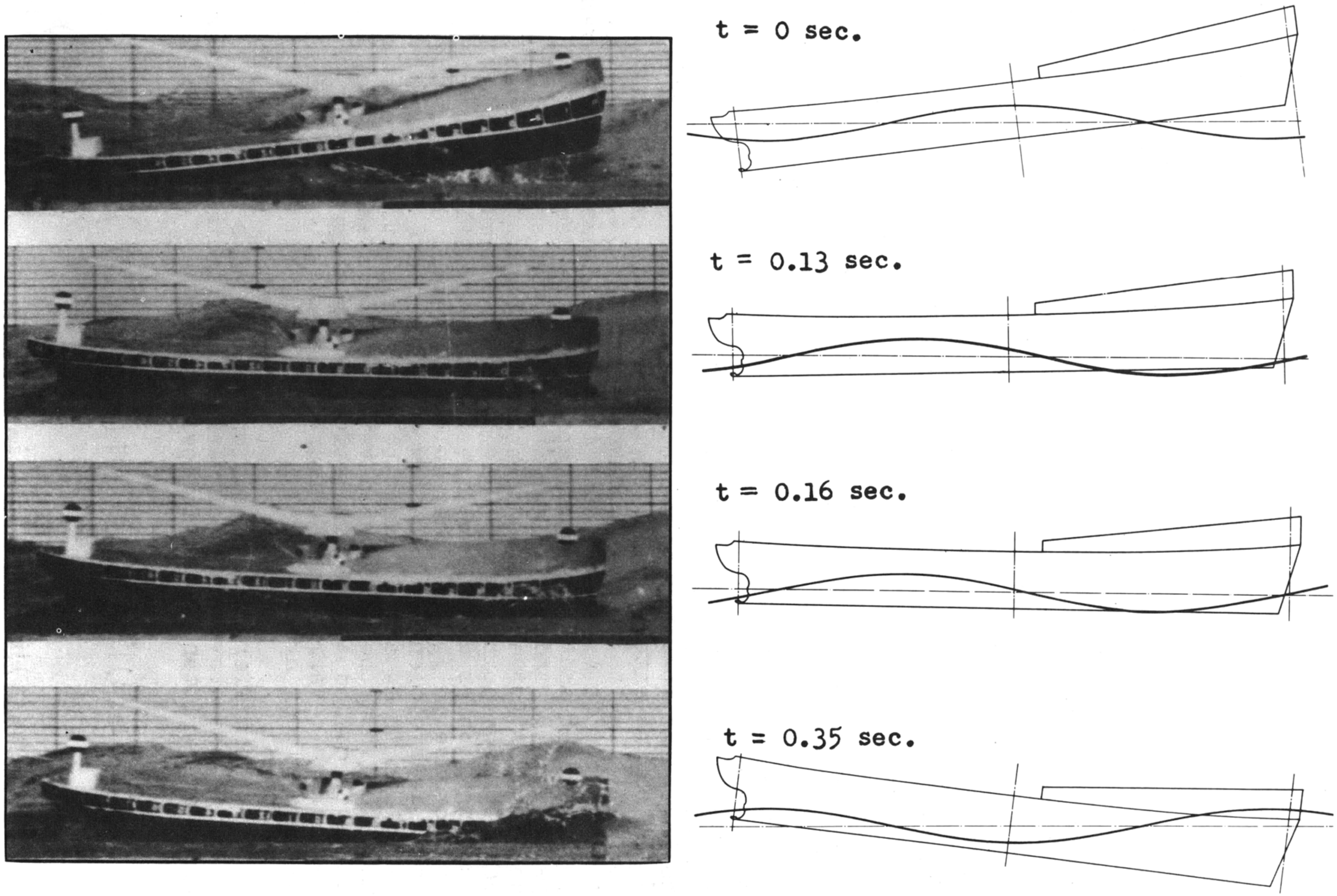

Figure 6 - Comparison Between Actual Motion of the Model in Waves
and the Assumed Harmonic Motion (First Approximation)

After $t = .35$ sec the bow begins to move up and will again emerge.

(3) Using the drawings the buoyancy force and moment can be determined for every instant (i.e. for those instants for which drawings were prepared). Also the waterplane area, moment of inertia of same, the added mass and the added moment of inertia can be found without difficulty but with a large amount of calculation. This way the time dependence of the above mentioned quantities is determined for this hypothetical case. It should be mentioned that the drawings do not represent the actual motion of the ship, since even if the bow would not emerge, the motion prediction was only approximate. The time variation of force, moment, added mass, and added moment of inertia are therefore to be considered as approximations, in fact second approximations, since the first approximation was sinusoidal force and moment and constant added mass, as shown in equations (7).

The following figures show the variation of the aforementioned quantities. Figure 7 shows the variation of the added mass (vertical direction). Point A corresponds to a time when the bow is emerging. At point B the added mass is minimum which corresponds approximately to maximum bow emergence. This of course is not necessarily so since the added mass might be reduced due to stern emergence, or simply to the fact that the ship as a whole heaves up. Between B and C the bow re-enters the water, and between C and D, the whole ship is in the water. Somewhere between D and A' the bow again emerges. It is significant that the increase in added mass (slope between B and C) is more rapid than the decrease (slope between D' and B). Figure 8 shows the same characteristics for the added moment of inertia. The sudden increase between points B and C is again an indication of slamming. Ships with fine lines at the bow will show much slower increase in I_a when they enter the water. Also if the motion is less violent and the bow does not leave the water, the variation in m_a and I_a might be insignificant. Figures 9 and 10 show the unbalanced vertical force and buoyancy moment. Attention is called to the distortion of the theoretically assumed harmonic variations. Figure 11 shows the variation of the waterplane area.

(4) The differential equation of motion is now solved using the above obtained variable coefficients. The new equations are written in the following form:

$$\left.\begin{aligned} &[I + I_a(t)]\ddot{\Psi} + N_\Psi(t)\dot{\Psi} + \dot{I}_a(t)\dot{\Psi} = M_\Psi(t) \\ &\text{and} \\ &[m + m_a(t)]\ddot{z} + N_z(t)\dot{z} + \dot{m}_a(t)\dot{z} = F_z(t) \end{aligned}\right\} \qquad (8)$$

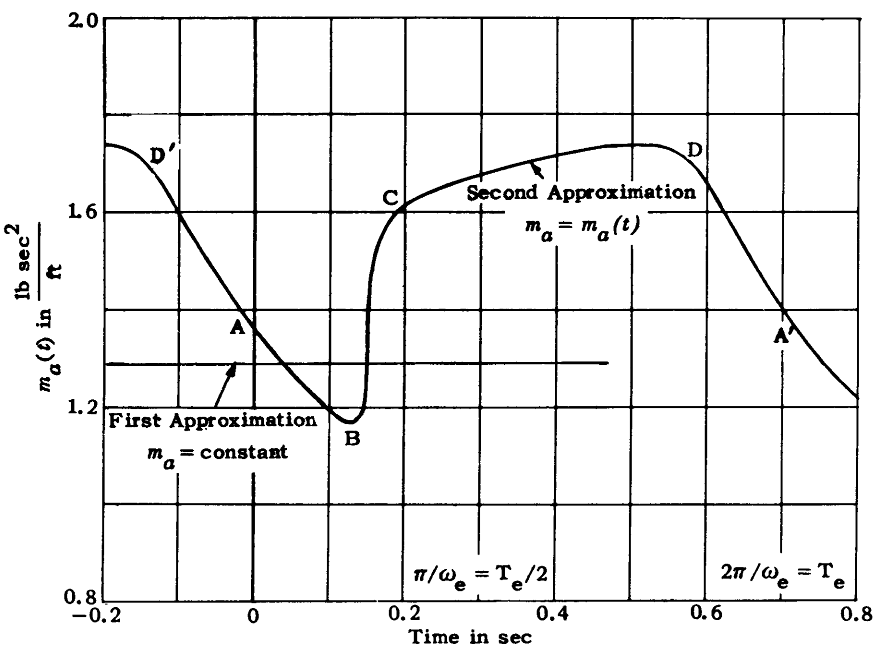

Figure 7 - Variation of the Added Mass

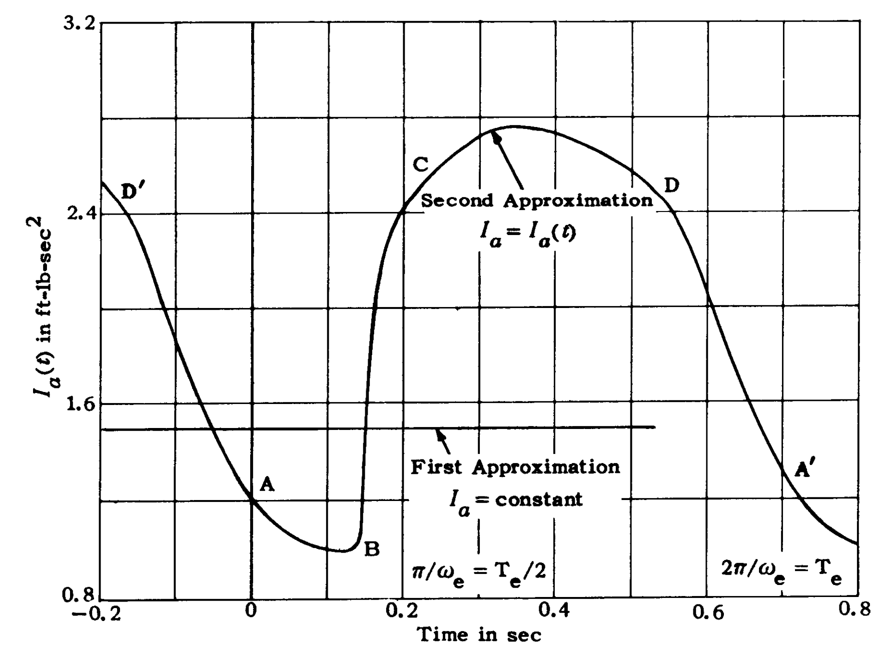

Figure 8 - Added Moment of Inertia

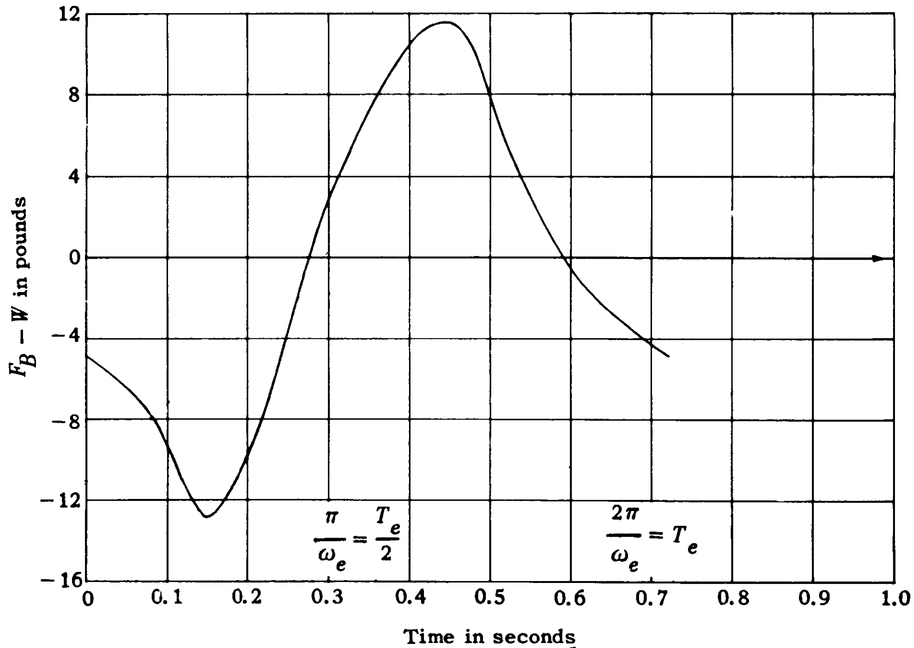

Figure 9 - Unbalanced Buoyancy Force

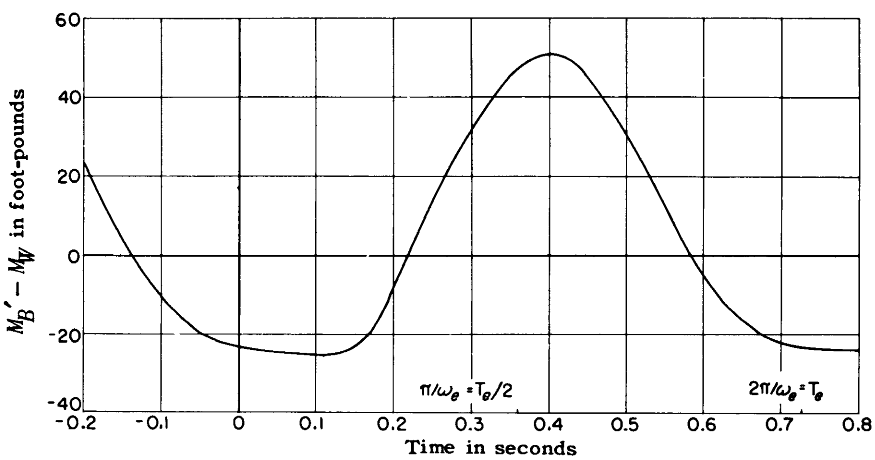

Figure 10 - Unbalanced Buoyancy Moment

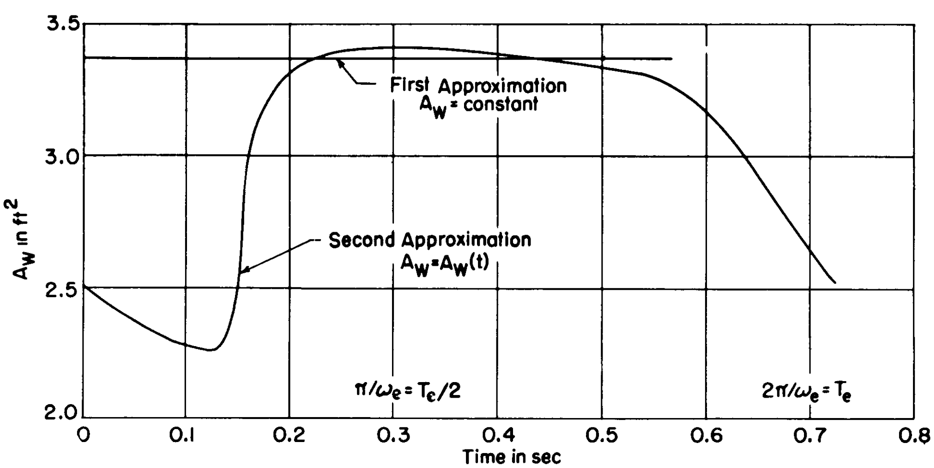

Figure 11 - Waterplane Area

Comparing these equations with equations (6) the following changes can be observed. The added mass and moment of inertia become functions of the time; $m_a = m_a(t)$ and $I_a = I_a(t)$. The same change occurs in connection with the damping factors; $N_z = N_z(t)$ and $N_\Psi = N_\Psi(t)$. The exciting and restoring terms merge into one. The most significant change is the addition of terms containing the time derivative of the added mass and of the added moment of inertia. Since slamming is due to the sudden change in the added mass and in the added moment of inertia, the above mentioned terms ($\dot{m}_a \dot{z}$ and $\dot{I}_a \dot{\Psi}$) are the ones which determine the magnitude of slamming. The difficulties in connection with estimating the damping factors were already pointed out. To compute variable damping is an even more difficult proposition, fortunately however, this is expected to have little influence on slamming. The proportionality between damping coefficient (N_z) and the square of the waterplane area gives a variation of N_z^z with time and from the moment of inertia of the waterplane area, $N_\Psi(t)$ can be obtained.

A correction for relative velocities can be included in equations (8), and also the correction for the orbital velocity of the wave can be made. It is shown in reference (12) that the inclusion of the relative velocity results in a slight reduction in force and moment terms on the right hand side of the equation. The effect of the wave structure, i.e. correction for finite draft seems to be more important. This correction is applied only for a part of $M_\Psi(t)$ and $F_z(t)$, therefore the inclusion of the effect of the wave structure is more or less an estimation.

Solutions of equations (8) satisfying the proper initial conditions can be obtained by numerical or graphical methods.

(5) These new solutions will be different from the originally assumed simple harmonic motions, since variable added mass, damping, etc. were taken into consideration. It can be expected that the acceleration curves will show sudden changes, but the velocity curves and especially the displacement curves might differ very little from the originally assumed harmonic variation. Figure 12 shows the comparison between the

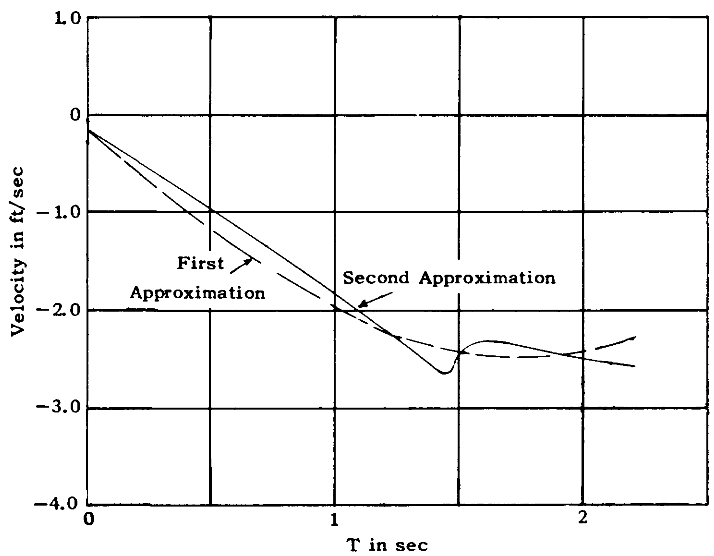

Figure 12 - Vertical Bow Velocity

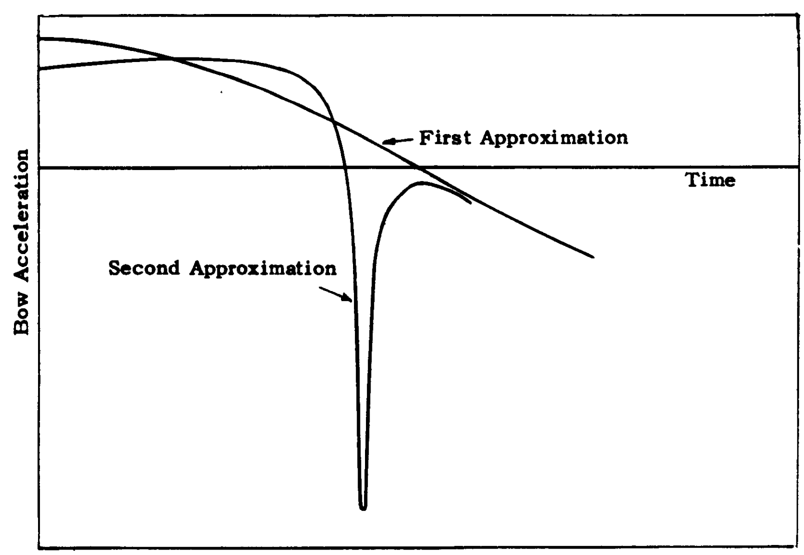

Figure 13 - Effect of Slamming on Bow Acceleration

first approximation (harmonic motion) and the second approximation for the velocity of the bow. It can be seen that the change due to slamming is very small as far as the velocity is concerned.

Figure 13 shows the effect of slamming on the bow acceleration. The influence of slamming on the acceleration is striking.

The influence of slamming on the motion is small. Some theoretical results supporting this statement are shown in reference 12.

The second approximation can now be considered an improved representation of the motion. Corresponding to the second step in the procedure, one can again make new drawings of the ship in the waves, based on the new solution.

(6) This step corresponds to step 3. The new added mass, damping, force, etc. variations with time are obtained from the drawings and the new differential equation is set up.

(7) Corresponding to step 4, the new differential equation is solved and the third approximation is obtained.

The above process can be repeated until no significant difference between successive solutions is obtained. The labor involved in this method is tremendous, the use of graphical or numerical methods introduces computational errors and the assumptions on which for instance the estimation of the damping factor is based will not improve from the first approximation to the second.

If the study of the motion as influenced by slamming is of secondary importance, then a much shorter method can be recommended. This consists of the same steps #1, #2, and #3 as before. First, one estimates roughly the expected heave and pitch amplitudes as well as phase lags (1st step) then one draws the ship in waves at various times for one cycle (2nd step) and finally one obtains the added mass, added moment of inertia, unbalanced hydrostatic force, and moment as functions of time for one cycle. Now the differential equation is written in a greatly simplified form by neglecting the effect of damping, of relative velocity, and of orbital velocities. The equations now become

$$\left.\begin{aligned}(I + I_a)\ddot{\Psi} + \dot{I}_a\dot{\Psi} &= M_\Psi \\ \text{and} \qquad\qquad & \\ (m + m_a)\ddot{z} + \dot{m}_a\dot{z} &= F_z\end{aligned}\right\} \tag{9}$$

where of course I_a, m_a, M_Ψ and F_z are functions of time and were obtained from the drawings. Without going into the mathematical details one sees that both of the above equations can be integrated and after some computation the following strikingly simple result is obtained:

Sudden deceleration of the bow due to slamming $\cong$

$$\frac{s_i L A_M}{8I^2} + \frac{s_m A_F}{4m^2} \tag{10}$$

where s_i is the slope of the added moment of inertia versus time curve at the instant of slamming (this can be taken approximately as the largest slope), s_m is the slope of the added mass versus time curve at the same time, L the length of the ship, I and m her moment of inertia and mass, A_M the area under the moment versus time curve between the time corresponding to zero pitching velocity and the time corresponding to slamming, A_F the corresponding area under the force curve.

The simplicity of the above result is due to some assumptions, such as for instance that the added mass at the instant of slamming is the same as the mass of the ship, etc. Therefore at best the order of magnitude of the slamming acceleration will be obtained from the above equation.

Generally a submerging bow causes changes in the added mass and in the added moment of inertia, therefore slamming is due to both pitching and heaving motion.

The contributions of heave and pitch to the acceleration are shown separately in figure 14, according to which the heave

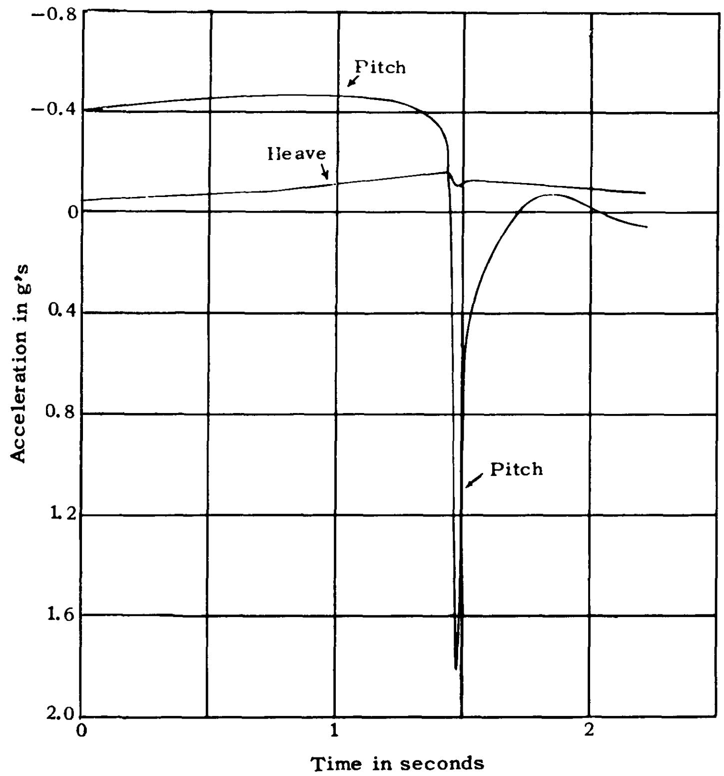

Figure 14 - Vertical Bow Acceleration Showing Contribution of Pitch and Heave

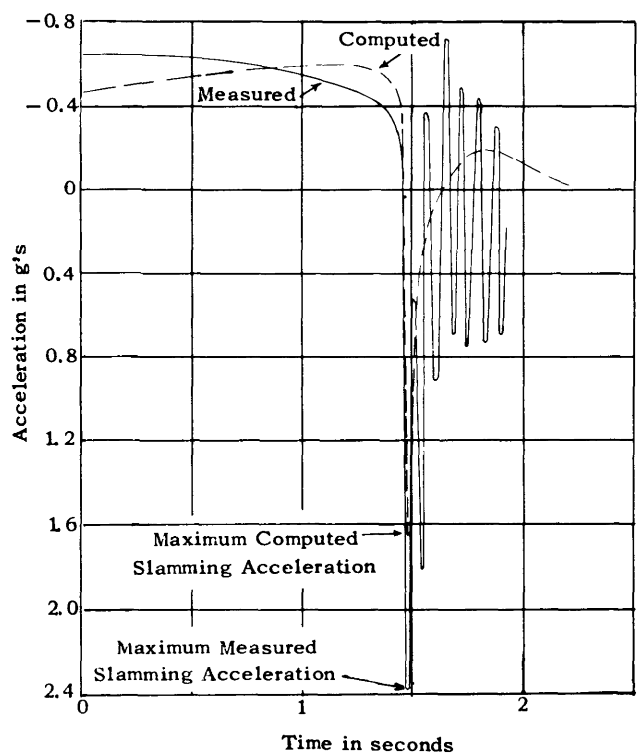

Figure 15 - Comparison of Measured and Computed Vertical Bow Acceleration

has very little influence on slamming, and the pitch is almost totally responsible for acceleration peak.

Figure 15 shows the measured and computed bow accelerations. The computed curve does not show the high frequency elastic vibration picked up by the accelerometer.

3. Pressure on the bottom

By means of the above outlined method the magnitude of the slamming acceleration and the instant of slamming can be estimated. Sudden decelerations, however uncomfortable for passengers and dangerous in cargo shifting, will not damage the bottom of the ship. This is done by the pressure developed on the bottom during slamming.

To arrive at some conclusion useful for design purposes an estimate of the pressure distribution has to be obtained. The effect of the relative velocity between ship motion and wave motion is now very important. It is also important to point out the fact that the pressure on the bottom is a function of the time as well as of the location, and that the pressure depends on the instantaneous relative velocity and relative acceleration. From theoretical unsteady flow considerations (reference 8) one can arrive at the result that the location of the maximum pressure (at every instant) is very near the spray root, i.e. at the edge of the instantaneous beam. Figure 16 shows a transverse section and the location of the maximum pressure point. As the bow enters the water the pressure peak moves outward. It should be emphasized that the pressure right at the keel is not the largest. From structural point of view the pressure distribution and its time variation are important. Large pressures which last for micro-seconds are of no practical importance.

To obtain a complete picture of the pressure distribution as a function of the time, therefore, is of great importance and estimating maximum pressures is of little practical significance. To arrive at simple design criteria is very difficult and thorough series investigation of various bows in several wave conditions should be undertaken. It is known (reference 10) that the slope of the transverse sections under the fore-foot and the velocity of the impact have more influence on the maximum pressure thar does the acceleration. The instantaneous relative velocity of the bow and the instantaneous draft of the section are known if the motion of the ship is known. Since neither the bow velocity nor the motion is influenced very much by slamming, an approximate pressure distribution calculation might be based on assumptions involving harmonic motion. The pressure

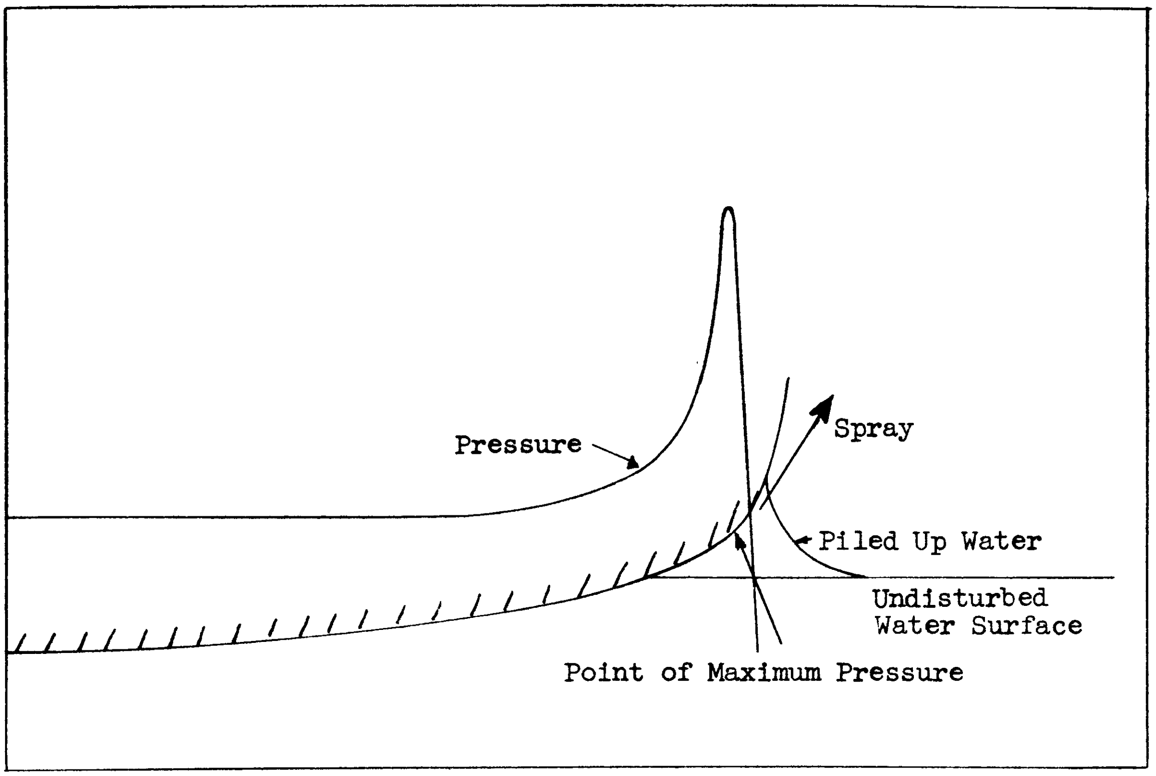

Figure 16 - Pressure Distribution on the Bottom

at the keel is mostly influenced by the relative acceleration. Therefore at the instant of slamming, pressures are to be computed at the keel as well as at other locations. It can be expected that at some locations the pressure reaches very high values before and after slamming. The magnitude of the area of high pressures is of importance as well as the time duration of the pressure peaks. It is not sufficient to compute the pressure distribution at the instant of slamming, but it is also necessary to obtain pressure distributions for several instants before and after slamming.

As a result of the aforementioned considerations we must refer the reader to references 10 and 12 for detailed pressure mappings.

At this place a few words might be mentioned regarding the effect of the forward motion of the vessel on the pressure. Depending on the speed, the relative motion of bow and wave can show large variations. The period of encounter changes with speed, therefore also the tuning factor, which in turn has great influence on the motion of the vessel. As shown in the chapter on conditions leading to slamming, bow emergence might occur at certain speeds and not at others. Since pressure calculations are based on the normal component of the relative velocity (i.e. normal to the keel), the forward velocity might have a fair contribution to this component. If the pressure is computed at an instant when the pitch angle is zero, the forward speed will have no component normal to the keel. Slamming does not necessarily take place at $\Psi = 0$, and furthermore as it has already been pointed out, maximum pressures are not developed necessarily at the instant of slamming. Nevertheless, in practically important cases, except for planing boats, it is recommended that forward speed be disregarded when performing pressure calculations, especially due to the fact that our present day technique of performing pressure calculations is rather approximate anyway.

Figures 17 and 18 show pressure distributions on the bottom of a slamming Liberty ship, whose transverse sections are shown on figure 19. Slamming occurs at $t = 1.285$ second. The maximum pressure at station 3 is obtained 11 ft. from the keel. A short time later (figure 18) the pressure at this point is only 40 psi. The maximum pressure on figure 18 occurs at station $3\frac{1}{4}$, 15 feet from the keel. This illustrates the fact that the magnitude and the location of the maximum pressure vary considerably during the impact process.

V Experiments

A total of 200 experiments were performed with a $5\frac{1}{2}$ foot model of a Liberty ship using two different draft conditions.

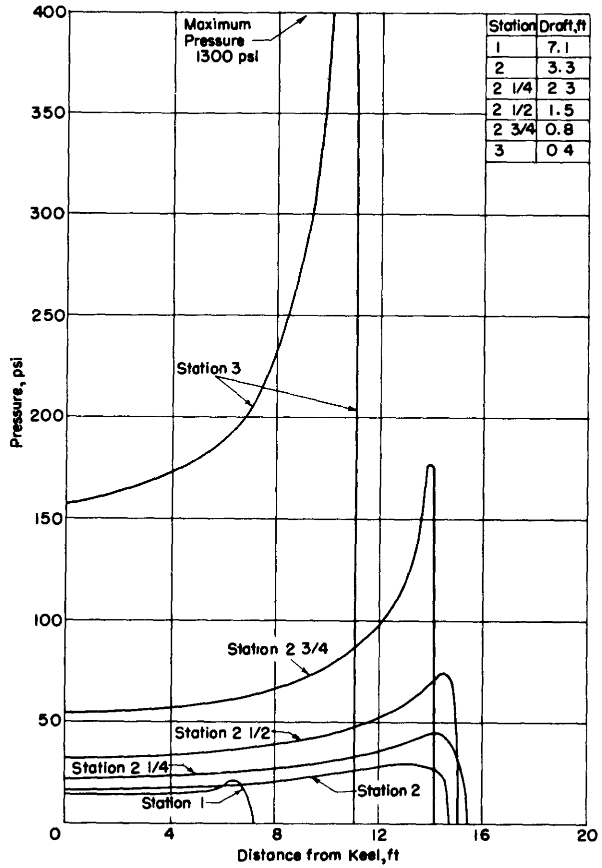

Figure 17 - Pressure Distribution on Forefoot of Ship at Time = 1.285 sec

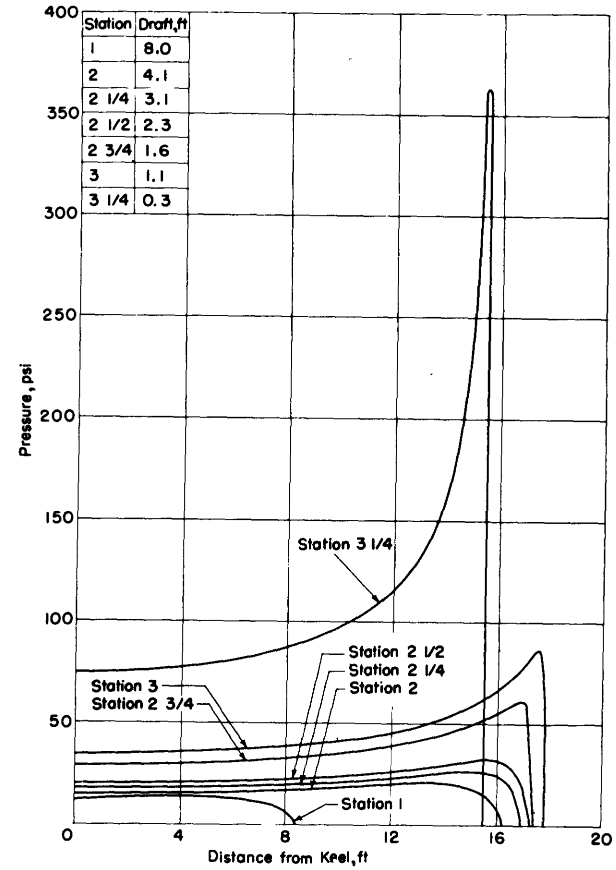

Figure 18 - Pressure Distribution on Forefoot of Ship at Time = 1.31 sec

The pertinent form characteristics of the model and of the ship are given in the table. The transverse sections are shown in figure 19.

Hull Characteristics of Model and Ship (LIBERTY)

	MODEL	SHIP
Length between perpendicular	5.50 ft.	416 ft.
Length on waterline, design	5.65 ft.	427 ft.
" " " ballast	5.35 ft.	405 ft.
Maximum beam on waterline, design	.75 ft.	56.9 ft.
" " " " ballast	.75 ft.	56.9 ft.
Draft at even keel, design	.36 ft.	21.3 ft.
" " " " ballast	.21 ft.	15.9 ft.
Displacement, bare hull, design	70.12 lb.	13,950 T.
" " " ballast	38.19 lb.	7,600 T.

Figure 20 shows the towing force versus model speed for the two displacements in still water.

Speed-reduction curves obtained in regular waves of $\lambda/h = 23$ at ballast condition for various tow forces, are shown in Figure 21. For convenience, scales for the Froude number, wave length - ship length ratio and for the wave-length parameter ($\gamma = \pi L/\lambda$) are also shown. Without analysing these results in detail at this stage it might be pointed out that the largest percentage of speed loss:

$$v\% = \frac{V_o - V_{min}}{V_o} \times 100$$

for .4 lbs thrust, corresponding to a still water speed of 1.96 knots is 61%, and that for 1.2 lbs. (2.65 knots) is only 34%.

This bears out the fact that the relative speed loss is smaller at high still water speeds than at low still water speeds, or that a low-powered vessel encounters more speed loss in a heavy sea, than a high-powered one.

Another characteristic of the speed-reduction curves is the shift of maximum speed loss toward higher wave lengths as the tow force or corresponding still water speed is increased. From the point of view of speed loss, the critical λ/L ratio for 1.96 knots still water speed (corresponding to a .4 pound pull) is .95 and for a still water speed of 2.65 (corresponding to a 1.2 pound pull) the maximum loss occurs at a $\frac{\lambda}{L}$ of 1.19.

It is not the purpose of the present paper to present

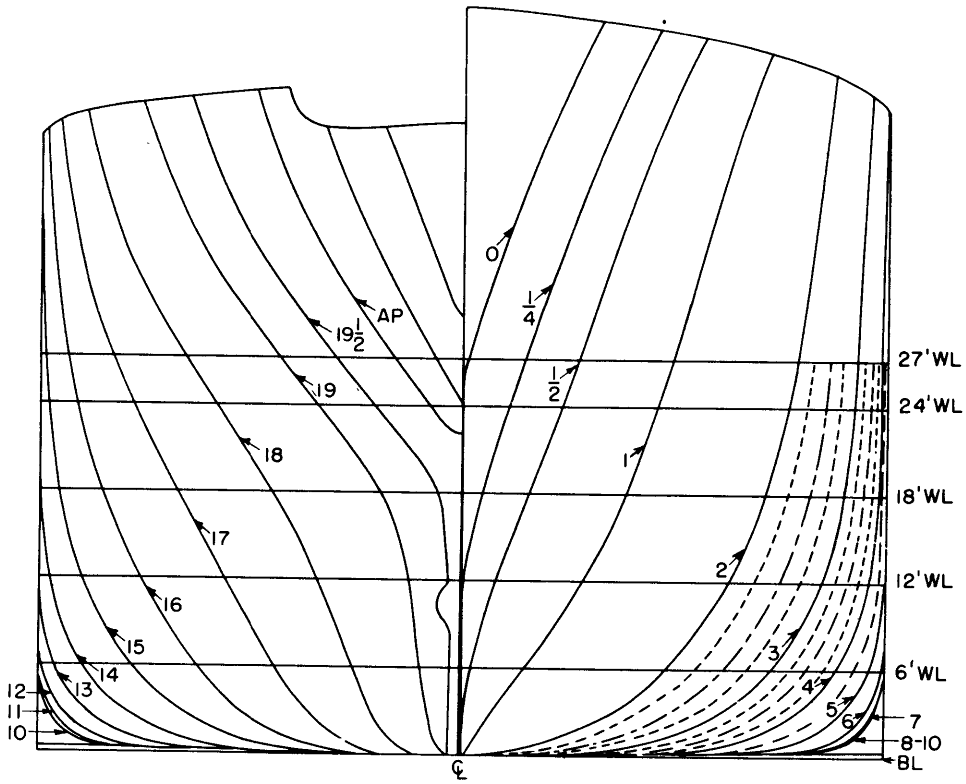

Figure 19 - Transverse Sections of LIBERTY Ship

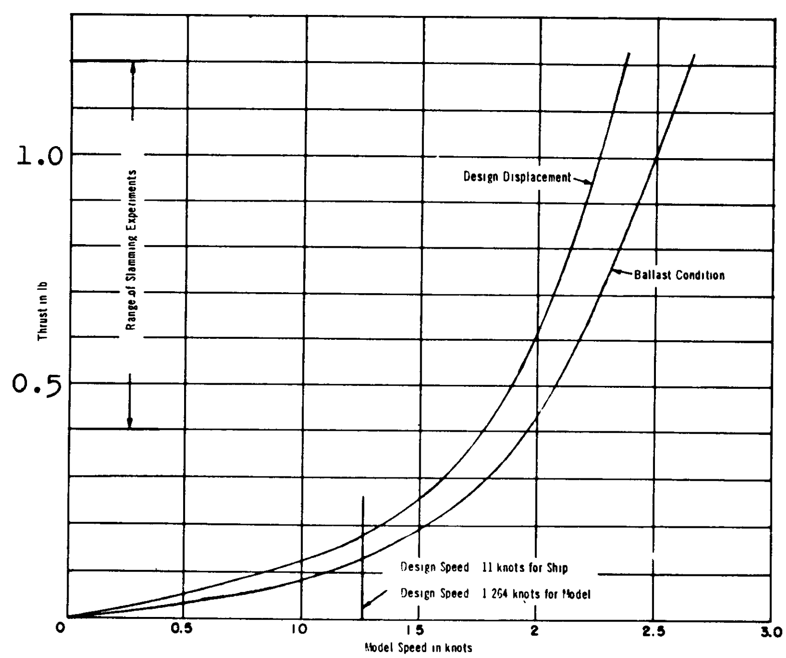

Figure 20 - Total Resistance in Still Water

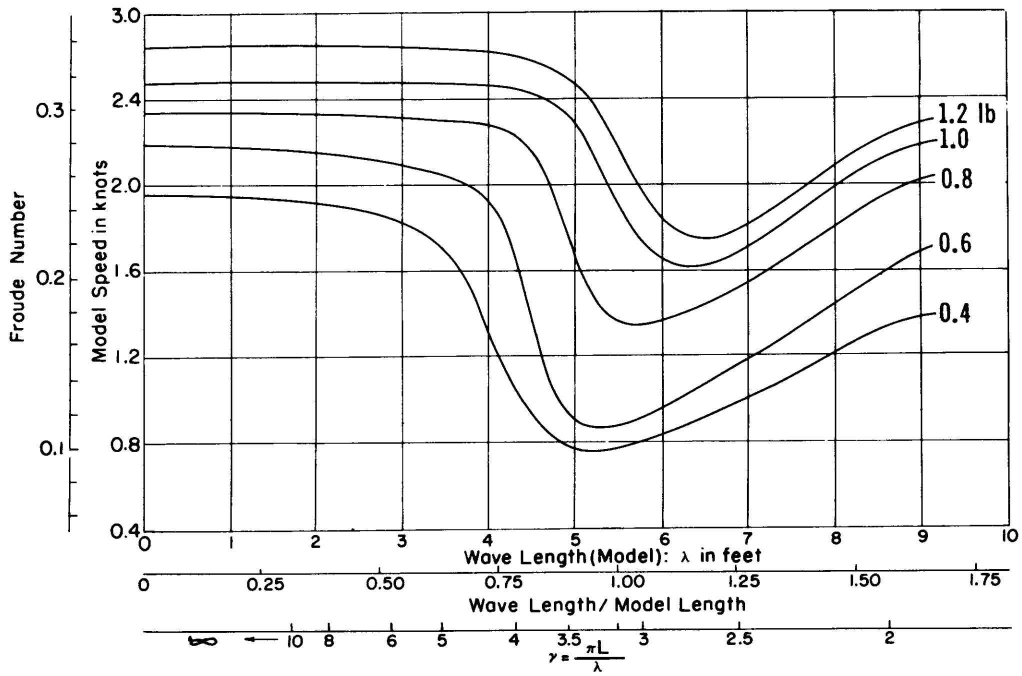

Figure 21 - Speed Reduction Curves

Ballast Condition: Regular Sea

Wavelength/Wave Height = 23

Thrusts as shown.

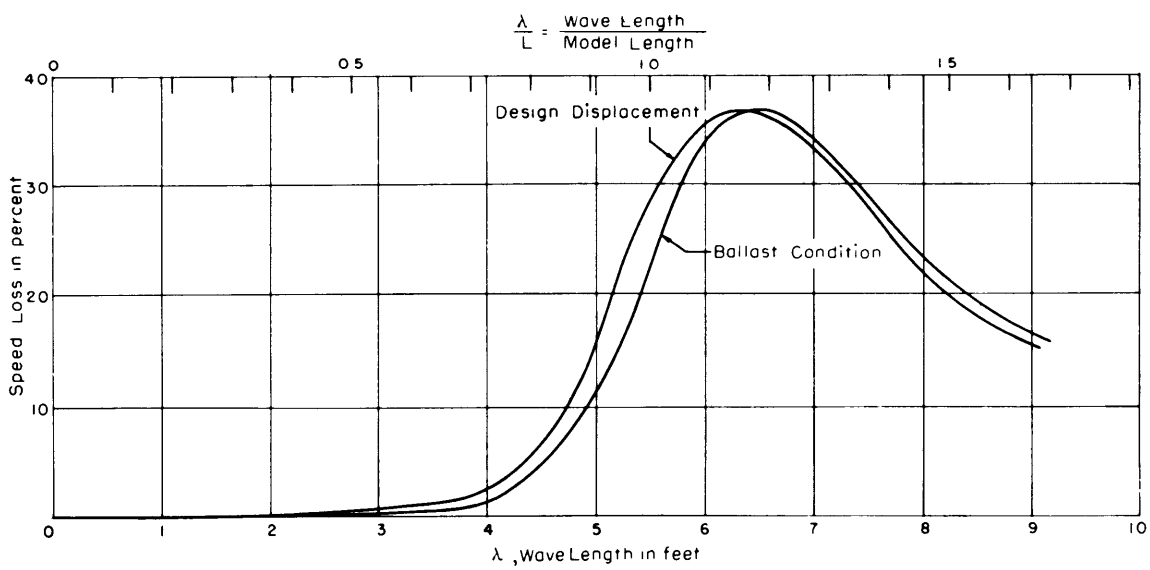

Figure 22 - Effect of Draft on Percentage Speed Loss for 1.2 lb Thrust and Wavelength/Wave Height Ratio 20

a thorough seaworthiness study; therefore speed-reduction curves for design displacement will be omitted and only a comparison will be made between the two displacements. Figure 22 shows the effect of draft on the percentage speed loss for 1.2 pound tow force at $\lambda/h = 20$. It can be seen that the relative speed loss percentage wise is practically independent of the draft. It must be realized, of course, that the still water speed is smaller at the larger draft by some 10%; therefore the absolute speed loss is greater for the lighter draft.

Figure 23 shows the variation of the pitching amplitude with wave length. The wave length - wave height ratio is kept constant ($\lambda/h = 20$), the constant thrust of .8 pounds corresponds to a still water speed of 2.36 knots for ballast condition and 2.14 knots for design displacement.

The plot therefore is <u>not</u> a constant Froude number plot, neither is it a constant wave height plot. A comparison of the curves for the two displacements suggests that ships in ballast condition respond more violently in pitch under identical sea condition and thrust. Bow-out condition is more easily established at reduced draft than at the heavier draft corresponding to normal displacement. Violent motion plus probability of bow emergence due to reduced draft go hand in hand to produce large slamming. The figure also shows the corresponding dimensionless scales.

Figure 24 shows the variation of the heaving amplitude with wave length for the two drafts. Again the thrust and wave length - wave height ratioare kept constant so the speed and the wave height are not the same for the various points on the curves. It is seen that while pitching motion is more violent in ballast condition than at design draft, the heave shows just the opposite trend. Slamming is more sensitive to pitch than to heave, therefore the fact that more violent heaving motion is expected at heavy draft than at light does not contradict the generally known danger of light draft from the point of view of slamming.

The total vertical bow acceleration (due to pitch and heave) is shown on Figure 25 for $\lambda/h = 20$, and for a thrust corresponding to 2.36 knots still water speed for ballast condition, and to 2.14 knots for design draft. It is noted that the slamming acceleration is <u>not</u> included in the values shown on the figure. The bow acceleration as well as the period of encounter show considerable variations within one run, especially if slamming is present. For 5 ft waves, these variations are shown on Figure 26. It is remarked that this figure corresponds to regular sea condition. Detailed analysis of pitch, heave, accelerations, velocities and their variation within one run

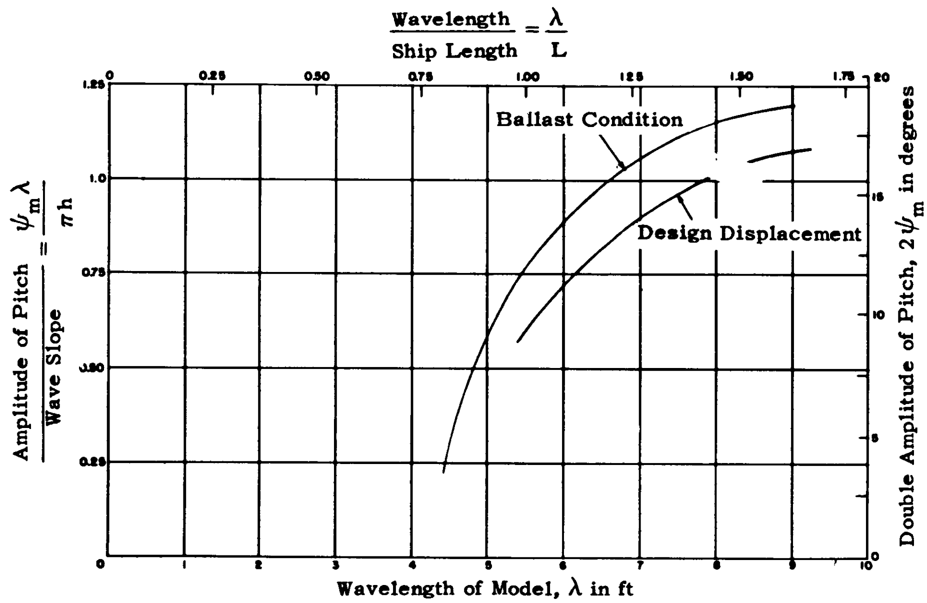

Figure 23 - Pitching Amplitude for Constant Thrust and Wavelength-Wave Height Ratio

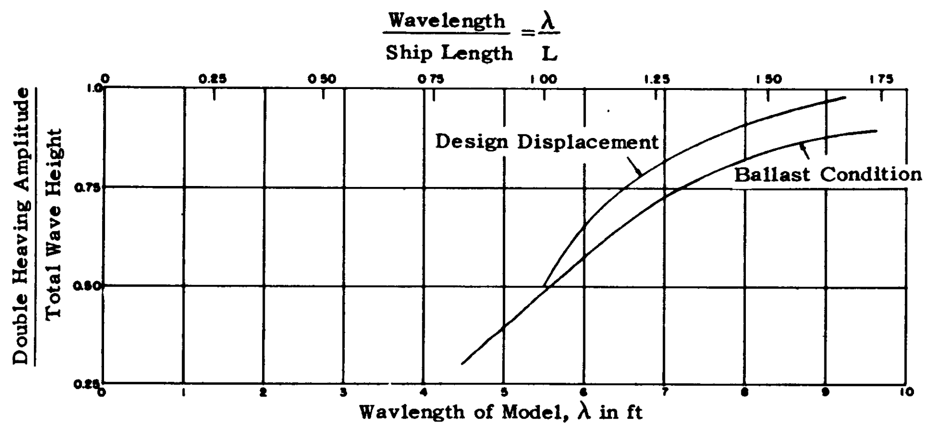

Figure 24 - Dimensionless Heaving Amplitude for Constant Thrust and Wavelength-Wave Height Ratio

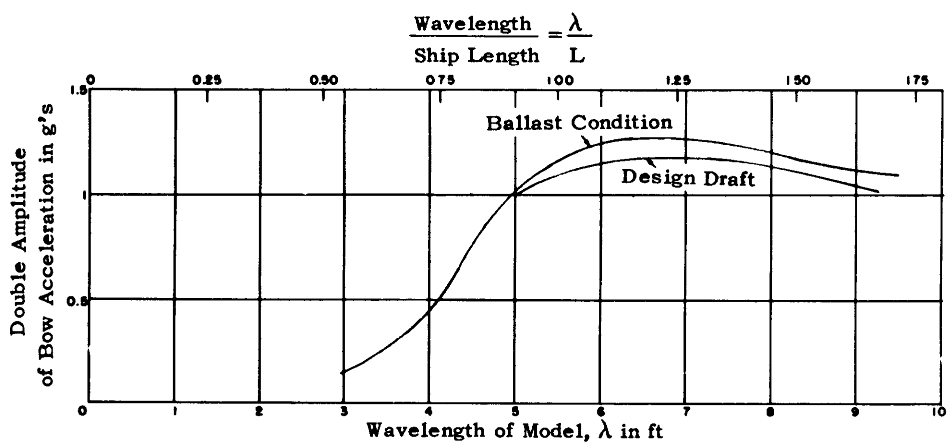

Figure 25 - Bow Acceleration for Constant Thrust and Wavelength-Wave Height Ratio

will be presented elsewhere in this part. The significance of Figure 26 at this place is that it reduces the importance of the difference between the two curves shown on Figure 27.

After this short motion study we are ready to present a discussion of the slamming accelerations measured. Attention is called to the fact that the preceeding as well as the following plots refer to regular sea condition. Due to variation of the acceleration and motion within one run, the slamming acceleration varies also. Therefore, it seemed advisable to obtain maximum slamming accelerations as well as average values. Slamming acceleration is defined for the purpose of the following plots as the magnitude of the sudden peaks on the acceleration records. Figure 27 shows a typical acceleration curve as recorded by the accelerometer in the bow. Figure 28 shows the maximum and the average slamming accelerations plotted against wave length for a still water speed of 2.48 knots corresponding to a 1.0 lb pull (ballast condition). The thrust and the wave length - wave height ratio was constant for this plot (1.0 lb pull and $\lambda/h = 23$). There are two critical wave length - ship length ratios, the first one approximately 1, the second approximately 1.4. The tuning factor in pitch ($\Lambda_\psi = (T_n)_\psi/T_e$) is .98 for the first case, in the second case .8, the reduced (actual) speed for both cases is approximately 1.9 knots, the Froude number is .24. (See Figure 21).

The actual values of the slamming accelerations are of less significance than the conditions which produce slamming. It should be mentioned however, that while the bow acceleration due to regular motion is of the order of 1g, the slamming acceleration might be as high as 4g. According to the Froude scaling law, the scale factor for acceleration is unity; therefore, the values given for slamming acceleration obtained from model experiments apply directly to the ship. The slamming acceleration for an .8 pound thrust corresponding to a still water speed of 2.36 knots at ballast condition also shows two maxima. The first one occurs at $\lambda/L = .91$, with a magnitude of 2g; the corresponding tuning factor and Froude numbers are, $\Lambda_\psi = 1.1$ and $F = .21$. The second critical λ/L is 1.5, the corresponding slamming acceleration is 1.5g with $\Lambda_\psi = .77$ and $F = .24$. Since the tuning factor is connected with the speed of the model, which is not constant for figure 28, figure 29 is presented, showing the relation between wave length, wave length - ship length ratio, wave length parameter and tuning factor, for two thrusts corresponding to still water speeds of 2.36 knots ($F = 0.3$) and 2.48 ($F = .32$). The reader, using simultaneously Figures 20 28 and 29 can analyse the data in terms of variables of his own choice.

The fact that even in regular waves ship motion is

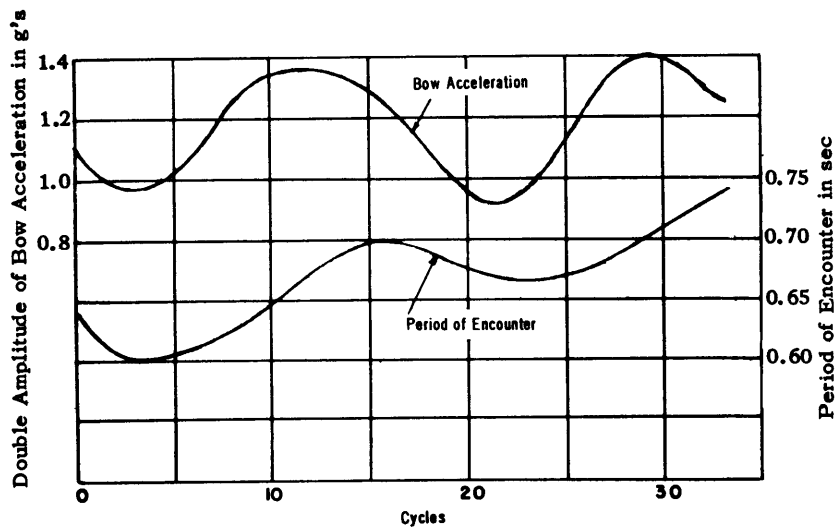

Figure 26 - Variation of Bow Acceleration and Period of Encounter in Regular Sea

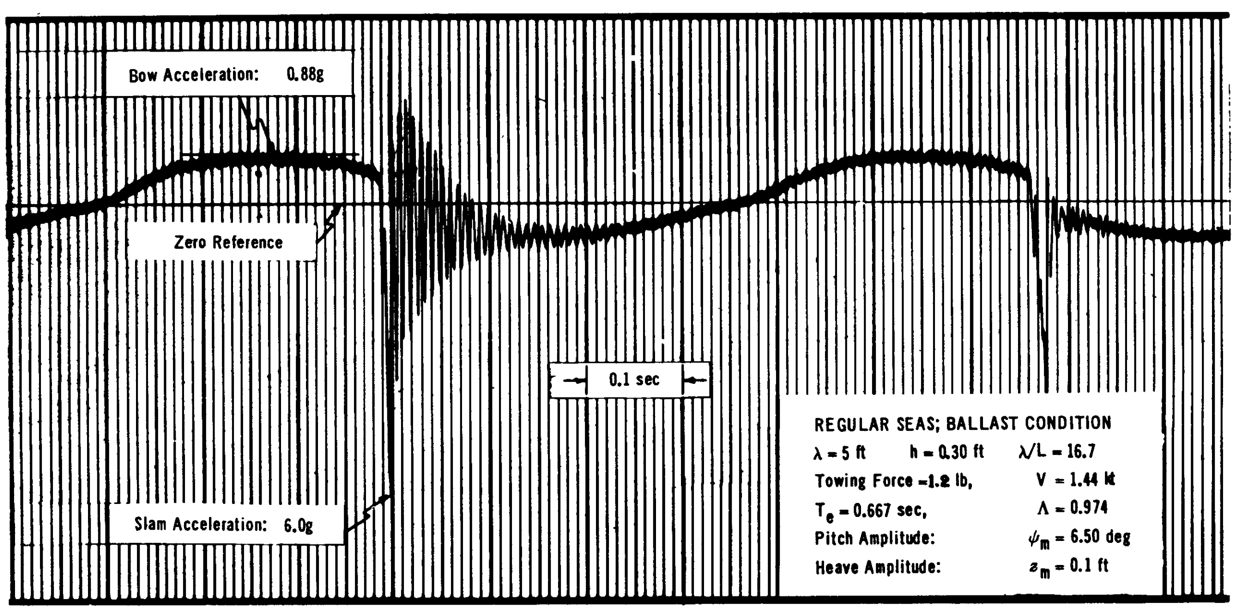

Figure 27 - Typical Slamming Record

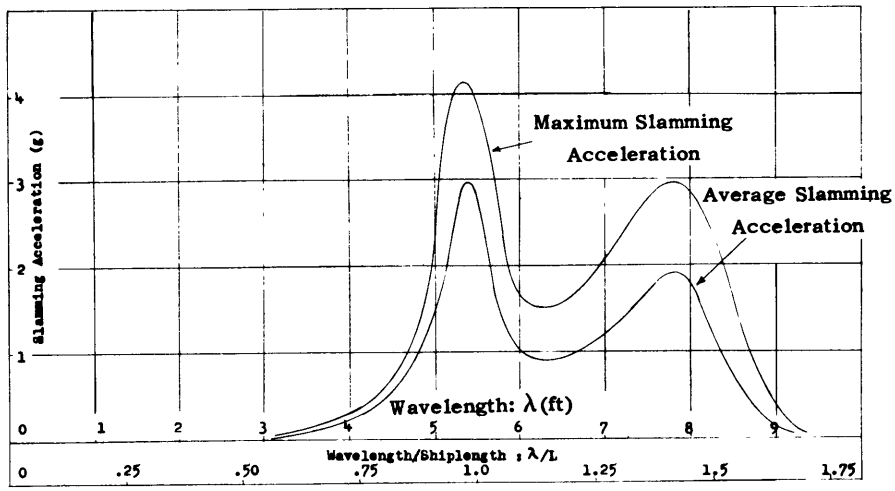

Figure 28 - Slamming Acceleration

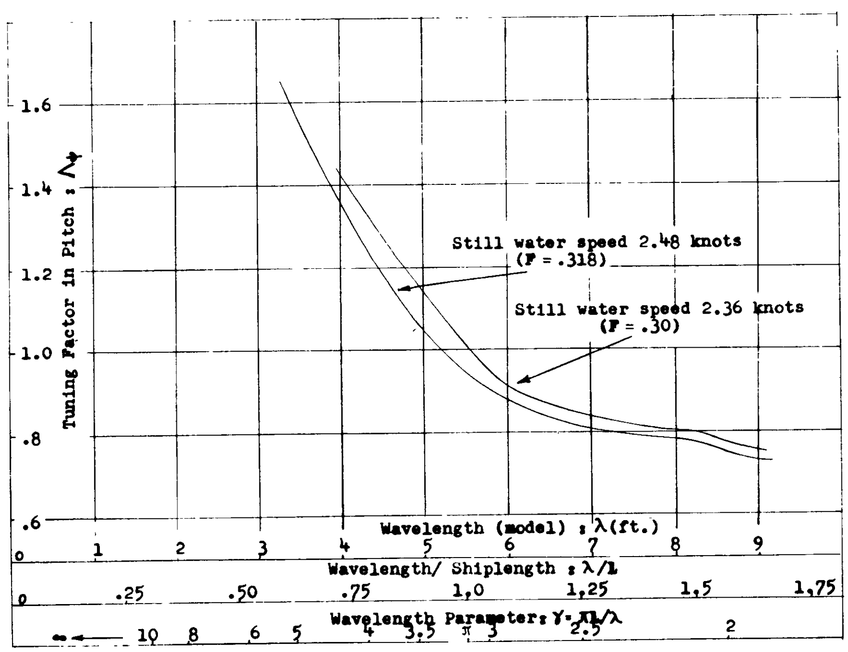

Figure 29 - Tuning Factor in Pitch

not harmonic has already been pointed out. To illustrate the importance of instantaneous values, two experiments performed in regular seas in the light displacement condition will be presented in figures 30 and 31. Only selected time histories of the entire runs will be presented to illustrate the effect of phase relations, the irregularity of pitch and heave motions, velocities and accelerations. The two examples were chosen in order to study also the effect of a 1.2 lb. pull (corresponding to a 23 knots smooth water speed) resulting in very large slams as compared to an .8 lb. pull (corresponding to a 20.4 knots smooth water speed) giving small slams. Only the tow force was different in the two experiments, other parameters were kept constant. The different performances of the model can be attributed to the changed phase relations between waves and ship motion caused by the change in speed. The experimental data of each of the runs are given on the respective plots of the time history.

In each of the runs, the first set of three curves gives the heaving motion (z) the pitching motion in degrees (Ψ) and the resultant motion of the bow (z_b) at the location of the forward accelerometer. The second set of curves plotted on the second horizontal axis show the vertical components of the bow and wave velocities at the bow. The bow acceleration is recorded on the third axis. The last set of curves shows the horizontal keel emergence as a percentage of the length between perpendiculars. All the curves were obtained from movie records except the acceleration which was taken from the oscillograph trace. All are plotted on a frame-by-frame or time basis, (one frame represents 1/24 sec.).

The previously emphasized fact that large slamming occurs if large negative bow velocity combines with large positive wave velocity, is clearly shown. If the relative velocity is small at the instant the fore foot re-enters the water as in Figure 31, there will be little or no slamming. We may also conclude that large pitching and bow acceleration do not always result in large slamming but depend also on other parameters. Large pitch induces large bow acceleration but not necessarily slamming if the ship is able to follow the waves. From the history shown on Figures 30 and 31 the slamming is largest when the heave lags the pitch by about 40 degrees to 60 degrees.

The envelopes of the pitch and heave curves for a given run show irregularity in the form of beating. Such beats occur especially when there is serious slamming. The explanation of this might be that a serious slam results in loss of energy which will reduce forward speed and the amplitude

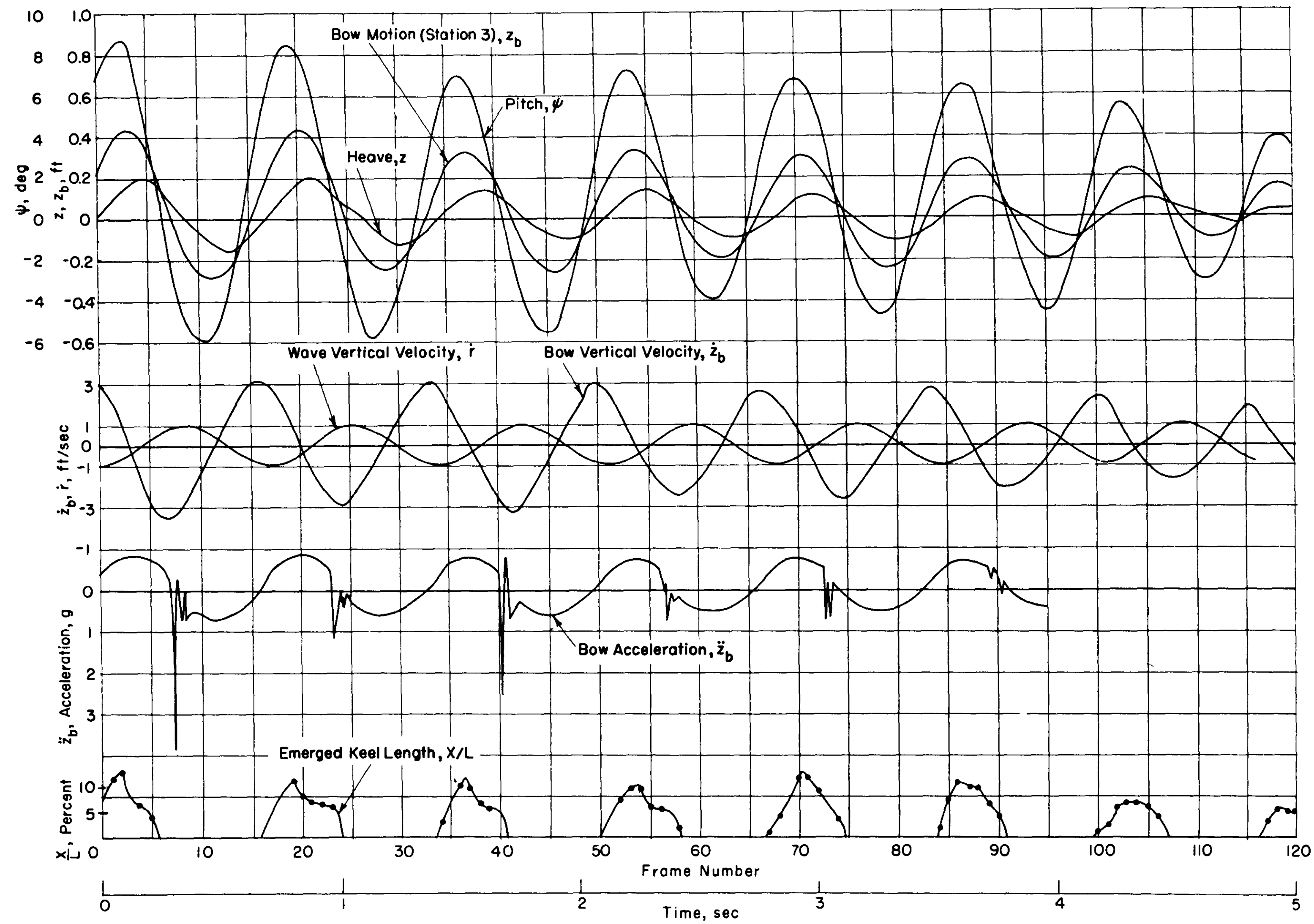

Figure 30 - Experimental Motion Study, 1.2 lb Towing Force

Regular Seas: $\lambda = 5$ ft, $\lambda/h = 16.7$ **Natural Periods:** $(T_n)_\psi = 0.65$ sec, $(T_n)_z = 0.70$ sec

Ballast Condition: $\Delta_m = 38.19$ lb **Gyradius:** 1.394 ft

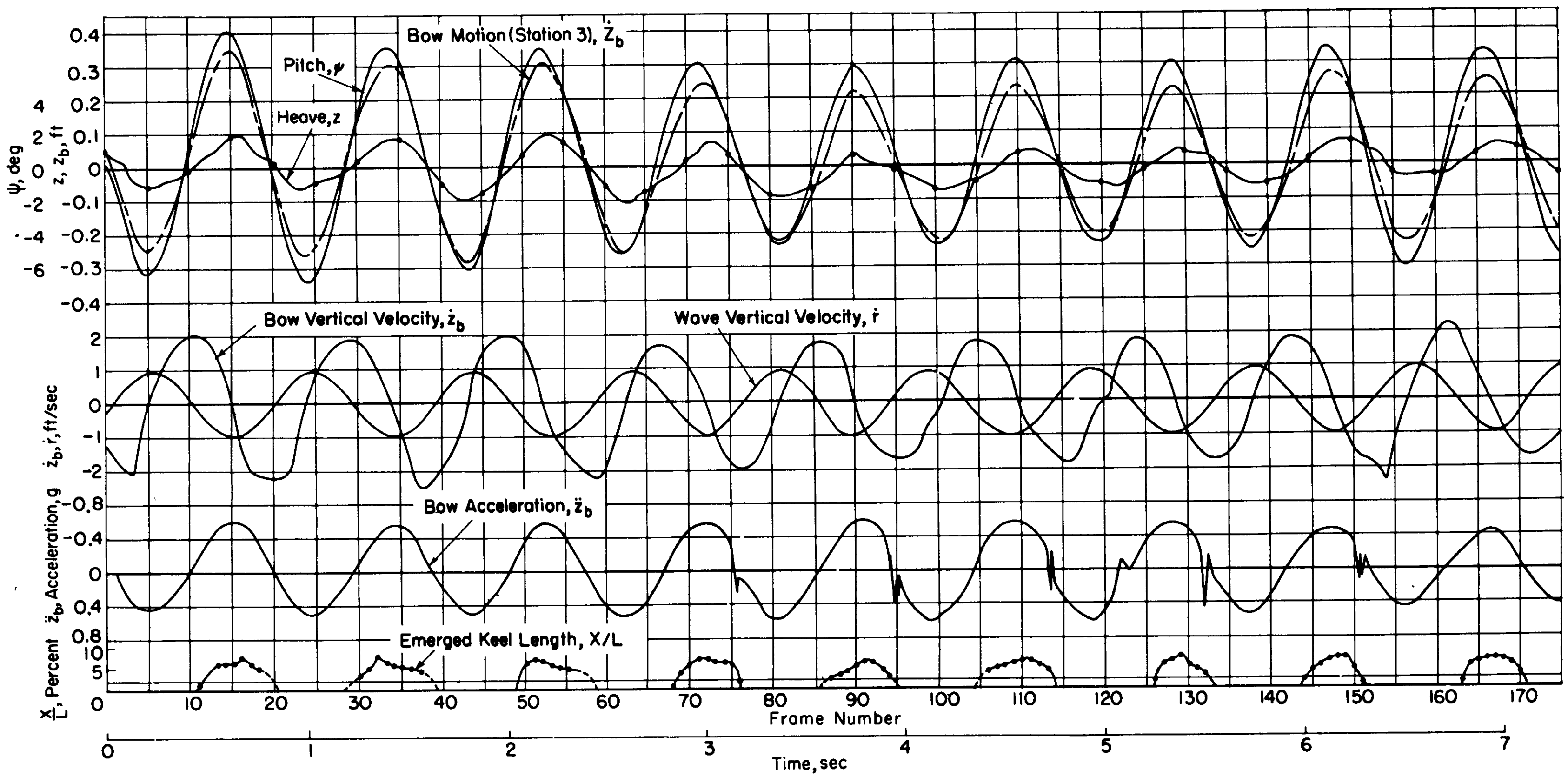

Figure 31 - Experimental Motion Study, 0.8 lb Towing Force

Regular Seas: $\lambda = 5$ ft, $\lambda/h = 16.7$ Natural Periods: $(T_n)_\psi = 0.65$ sec, $(T_n)_z = 0.70$ sec

Ballast Condition: $\Delta_m = 38.19$ lb Gyradius: 1.394 ft of the motion. The next slam, therefore, will be less severe enabling the ship to recover the lost energy and regain its speed.

In conclusion it might be pointed out that successful slamming experiments can be performed in regular waves if the draft is sufficiently reduced and if higher than design speed is used. Since the first purpose of this paper is to present a physical picture of the slamming phenomenon, the use of high speed is justified. The pertinent factors influencing slamming, and listed in the theoretical part of this paper,were also found experimentally. The variation of experimental results is not to be attributed to experimental errors, due to the fact that slamming introduces non-uniformity in the motion. The repeatability of seaworthiness tests is questionable even without slamming. Slamming depends very strongly on phase relations and it often takes place near resonance. The slightest changes in the experimental conditions might influence the phase relations and, therefore, slamming. Repeatability of slamming experiments can be considered good if the successive experiments performed under identical conditions result in less than 10% deviation, considering average values.

REFERENCES

A review of the literature of slamming is not included in this paper, therefore, the following short list of references does not intend to be complete. A bibliography, consisting of some 180 items was prepared at the David Taylor Model Basin recently.

1. Admirality Ship Welding Committee, "S.S. OCEAN VULCAN Sea Trials", 1953.

2. Hansen, K. E., "Pounding of Ships and Strengthening of Bottoms Forward", Shipbuilding and Shipping Record, Vol. 45, page 656-658, June 1935.

3. Haskind, M. D., "The Hydrodynamical Theory of the Oscillation of a Ship in Waves", Translated as SNAME Technical and Research Bulletin, No. 1-12, 1953.

4. Kármán, T., "The Impact on Seaplane Floats During Landing", NACA TN 321, 1929.

5. Kent, J. L., "The Causes and Prevention of Slamming on Ships in a Seaway", North East Coast Institution of Engineers and Shipbuilders, Vol. 65, page 451-458 and D 133 - 138, April 1949.

6. Lehmann, G., "Bodenschäden im Vorschiff", 1936

7. Schnadel, G., "Ship Stresses in Rough Water", North East Coast Institution, Trans. Vol. 54, page 120-136, 1937.

8. Szebehely, V. G., "Hydrodynamics of Slamming of Ships", TMB Report 823, 1952.

9. Taylor, W. F. and West, G. L., "A Brief Investigation of Impact Forces on Ships", Newport News Shipbuilding and Drydock Co., Report 48, 1952.

10. Todd, M. A., "Slamming Due to Pure Pitching Motion", TMB Report 883, 1953.

11. Weinblum, G., and St. Denis, M., "On the Motion of Ships at Sea", Transactions SNAME, Vol. 58, 1950.

12. Szebehely, V. G., Todd, M. A. and Lum, S. "Fundamentals of Ship Slamming in Head Seas", TMB Report, 1954.

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David W. Taylor Model Basin. Rept. 995.
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3. Ships - Motion
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5. Naval architecture
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