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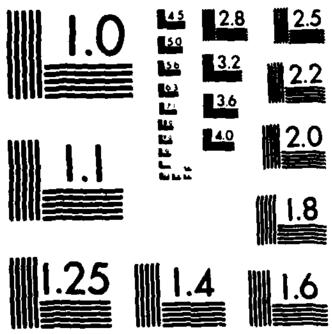
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

ZERO SPEED SEAKEEPING CHARACTERISTICS OF A CAUSEWAY FERRY CONSISTING OF FOUR PONTOONS CONNECTED END-TO-END

Charles R. Turner

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Ship Performance Department

June 1983

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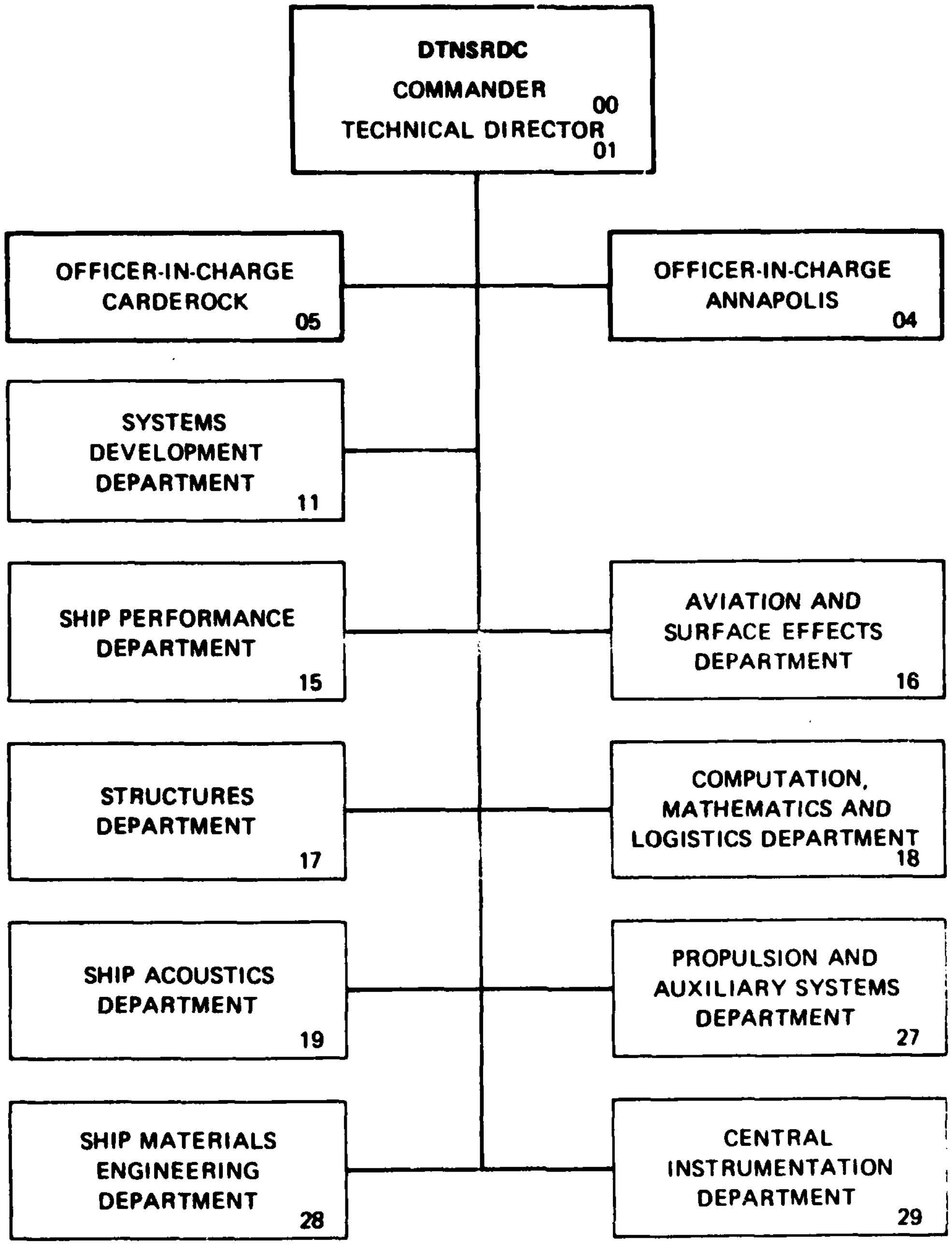

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Seakeeping experiments were conducted to evaluate the performance of a causeway ferry consisting of four pontoons connected end-to-end which would be used to transport cargo from a floating platform to the beach during container-ship off-loading in support of assault operations where no port facilities exist. The aft pontoon contains propulsion units to drive the ferry with the forward three pontoons being assembled from standard watertight cans. Heave, roll, and pitch of the aft pontoon, heave of the forward pontoon, and the relative angular displacements between individual sections were measured in random and

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regular waves at zero speed for unloaded and loaded conditions. A spectral analysis of the random wave data was performed to yield transfer functions for comparison with transfer functions obtained from the regular wave runs. Values of significant double amplitudes from the random wave runs are also reported. In general, transfer function and significant double amplitude results for the two displacements are not greatly different, although in the loaded condition, the causeway ferry did experience considerable deck wetness for headings between beam and bow quartering. Performance improved as heading angle increased and was best in head seas.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATION

$\bar{H}_{1/3}$ Significant Wave Height

L Overall Length of Causeway Ferry; 4 times individual pontoon length

β Ferry Heading Angle With Respect to the Waves

λ Wavelength

ABSTRACT

Seakeeping experiments were conducted to evaluate the performance of a causeway ferry consisting of four pontoons connected end-to-end which would be used to transport cargo from a floating platform to the beach during container-ship off-loading in support of assault operations where no port facilities exist. The aft pontoon contains propulsion units to drive the ferry with the forward three pontoons being assembled from standard watertight cans. Heave, roll, and pitch of the aft pontoon, heave of the forward pontoon, and the relative angular displacements between individual sections were measured in random and regular waves at zero speed for unloaded and loaded conditions. A spectral analysis of the random wave data was performed to yield transfer functions for comparison with transfer functions obtained from the regular wave runs. Values of significant double amplitudes from the random wave runs are also reported. In general, transfer function and significant double amplitude results for the two displacements are not greatly different, although in the loaded condition, the causeway ferry did experience considerable deck wetness for headings between beam and bow quartering. Performance improved as heading angle increased and was best in head seas.

ADMINISTRATIVE INFORMATION

This work was funded under the Container Offloading and Transfer System Program by the Naval Civil Engineering Laboratory, Program Element 63719N, Work Unit Number 1562-104.

INTRODUCTION

Present Department of Defense planning for logistical support necessary to sustain major contingency operations such as Amphibious Assault Landings and Logistics-Over-the-Shore evolutions relies upon the utilization of U.S. flag commercial shipping. Materiel ultimately intended to be transported on vehicles lends itself to the utilization of containerized shipping. Since the availability of developed port facilities in an assault follow-up situation is unlikely, special portable facilities are required for off-loading container-ships at undeveloped beaches.

The currently proposed system employs standard Navy pontoons which would also be transported to the off-loading site on the container-ships. A floating platform would be assembled by interconnecting several of the pontoons and mooring them to the ship. This platform would support the lower end of an off-loading ramp connected to the ship. Vehicles would be driven off the ship onto the platform via the ramp. Self-propelled causeway ferries consisting of several standard pontoons driven by a powered pontoon section would then transport the vehicles from the platform to the beach.

To define the operational characteristics of the causeway ferry in a seaway and to provide an experimental data base for validation of a computer simulation presently under development, a model experiment was conducted in the Maneuvering and Seakeeping Facility at the David Taylor Naval Ship Research and Development Center (DTNSRDC). Motions of the causeway ferry were measured at a variety of headings in regular and irregular waves for two load conditions. The results of the analysis of these data are documented in this report. Platform motions measured during a previous experiment have been reported by Zarnick, et al[1].

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1. Zarnick, E., C. Turner, and J. Hoyt, "Model Experiments of RO/RO Ships Off-Loading System in Waves and Current", Report DTNSRDC/SPD-1046-01 (Dec 1982)

DESCRIPTION OF PONTOON DIMENSIONS AND INERTIAL CHARACTERISTICS

PONTOON DIMENSIONS

The full-scale pontoons for use in container-ship off-loading are composed of Navy Lighter (NL) flotation cans. These watertight cans are constructed of 3/16 in. (4.76 mm) thick plate steel with internal reinforcing ribs. Standard cans (as opposed to the bow-stern modules) have planform dimensions of 5 ft by 7 ft (1.52 m by 2.13 m) and a depth of 5 ft (1.52 m). The bow-stern units are not rectangular in cross section, but have one inclined side and planform dimensions of 7 ft by 7 ft (2.13 m by 2.13 m). In the assembled barges, the inclined side faces outward toward the bow or stern to aid in movement through the water. The cans are bolted together along steel angle sections and can be assembled in various arrangements to form different size pontoons. A 3 by 15 arrangement is used in the causeway ferry to form individual pontoons 21 ft (6.40 m) wide and, considering a longitudinal gap between adjacent cans of approximately 9 in. (0.23 m) and the 7 ft (2.13 m) length of the end units, an overall length of 90 ft (27.43 m).

Models used in the experiment were constructed of 1/4 in. (6.35 mm) plywood on wooden frames to a scale of 1/15 as shown in Figure 1. No attempt was made in the construction of the models to duplicate the individual cans since this would not influence model motions significantly and would have added considerably to the cost. The models for the standard and powered pontoons were of identical construction. Differences in mass and inertial characteristics were provided during the ballasting operation.

Full scale pontoons are fastened together by steel and rubber composite connectors called flexors. These allow a degree of angular movement in pitch between individual pontoons while maintaining a constant spacing. No attempt was made in the experiment to model the flexors. Instead, ordinary door hinges were used. These allowed the required degree of angular displacement while maintaining the correct spacing.

INERTIAL CHARACTERISTICS

In order to model both the unloaded and loaded causeway ferries, five different ballasting configurations were required. Nominal specifications for all variations are listed in Table 1. From this table it can be seen that the different configurations consist of the standard pontoon section 1) unloaded, 2) half loaded, and 3) fully loaded; and the powered pontoon section 4) unloaded, and 5) half loaded. The arrangement of pontoons in the causeway ferry model tested in the experiment is shown in Figure 2. Four pontoons are connected end-to-end in a single file arrangement. The first three are standard sections with the aftermost unit being a powered section.

Unloaded Causeway Ferry

Addition of ballast weight was required to adjust the inertial characteristics of the models to represent those of the full scale pontoons. The masses and moments of inertia of the different sections in the unloaded causeway ferry as tested along with the percentage of deviation from the nominal specifications are listed in Table 2. In this table, the bow and stern pontoons are numbered 1 and 4 respectively.

In the unloaded ferry, the first three pontoons are unloaded standard sections. All values are fairly close to the nominal specifications with the exception of the radius of gyration about the longitudinal axis, Rxx. The reason for this is that the models used were constructed for a prior study and the bare hull moment of inertia about the longitudinal axis was larger than the nominal value specified for the unloaded case. Moments of inertia are adjusted by moving ballast weights nearer or farther from the respective axis of rotation. In this case, the ballast weights were placed on the longitudinal centerline to yield a minimum value of Rxx.

The deviation from the nominal in the aftermost pontoon, which was ballasted to model an unloaded powered section, was more severe. Mass of the bare hull, heave staff, and pitch-roll gimbal slightly exceeded the nominal value for this configuration. Since it was considered more important to maintain the correct mass than the correct moments of inertia, no additions for adjustment of inertial characteristics were possible. As will be seen later in the analysis of results section, this discrepancy probably had a very minor influence on model motions since the variation between results for the loaded and unloaded systems, which had large inertial differences, turned out to be small.

Loaded Causeway Ferry

The loaded causeway ferry consisted of the same basic arrangement of pontoons, but with the addition of deck loads as shown in Figure 3. The first pontoon in the string is a standard section with a loading equivalent to two 32,063 lbm (14,543 kg) containers on the aft half. On the next two pontoons, numbers 2 and 3, four of the loading containers were distributed for a total load of 128,250 lbm (58,173 kg). The aftermost model represents the powered pontoon and was loaded on the forward half with two 32,063 lbm (14,543 kg) containers.

In performing the model experiment, the essential item was to have ballast weights arranged to provide the nominal inertial characteristics listed in Table 1. For the first and third pontoons in the loaded causeway ferry model, the required locations of the additional ballast weights were calculated. Vertical positioning of the ballast was maintained by placing weights on styrofoam spacing blocks. The second pontoon was ballasted by the conventional method of oscillating it as a pendulum. This served as a check on the calculated locations, but either method was satisfactory. The aftermost pontoon, which modeled the half loaded powered section, was also ballasted by oscillation. Once again, the attainable value of the moment of inertia about the longitudinal axis was restricted by the allowable amount of ballast and structural constraints. In this case, however, the deck loads were moved to the sides of the deck — as far from the longitudinal axis of rotation as possible — for the maximum attainable roll moment of inertia.

INSTRUMENTATION AND DATA COLLECTION

During data collection in waves, the causeway ferry model was connected to a heave staff by a pitch-roll gimbal. This arrangement allowed the model freedom in heave, pitch, and roll. Although motion was constrained in surge, sway, and yaw, this arrangement was required to maintain an accurate heading with respect to the waves. Potentiometers on the gimbal and heave staff provided voltage output changes to accurately measure heave displacement and pitch and roll angles. Figure 2 shows the coordinate axis system utilized. This is a right-handed system having its origin at the nominal center-of-mass of the aftermost pontoon, i.e., at the CG location listed in Table 1. The Z axis is directed vertically upward and the X and Y axes lie on the undisturbed water surface. In all configurations, the gimbal was located so that the Z axis passed through the pivot point even if ballasting limitations prevented the center-of-mass from coinciding with the origin. The vertical height of the pivot point, the minimum value of which was fixed by the height of the gimbal, was 0.349 ft (0.106 m) above the bottom hull surface. This precluded the ideal condition of coincidence between the CG of the aft pontoon and its pivot point.

Three specially designed potentiometer-type transducers were located at the junctions between the pontoons to provide an accurate measurement of the relative angular displacements between adjacent sections. Each transducer consisted of a high resolution potentiometer mounted on a bracket so that the axis of the potentiometer shaft coincided with the hinge line at a pontoon junction. One end of a lightweight high tensile strength aluminum shaft approximately 3 ft (0.914 m) long was attached perpendicularly to the potentiometer shaft. The other end was held by an elastic band against the adjacent pontoon deck. By having a lever arm of this length, the effect on the relative angle output due to the slight amount of vertical play which existed in the hinge joint became insignificant. The sign of relative angular displacement was defined such that an angle between two adjacent pontoons which tended to form them into the shape of a V was positive.

Ultrasonic transceivers were used to measure wave height and vertical displacement of the forward pontoon section. In all test configurations, the wave height probe was located to minimize reception of waves reflected from the model or generated by its motions.

Data analysis and collection were performed during the test by an Interdata Model 70 minicomputer. Pertinent statistical values and calculated results were provided after each run to yield valuable feedback for optimizing the test plan during the experiment. Prior to digital processing, signals from the transducers were passed through 6 pole Butterworth low pass filters which provided an attenuation of 3dB at a frequency of 5 Hz. Data were recorded at a sample rate of 30 per second for each channel and stored on magnetic tape in both digital and unfiltered analog form for future use.

TEST PROGRAM AND DATA ANALYSIS

The model test was designed to measure the dynamic responses of the pontoon causeway ferry for two conditions of loading in random and regular waves. Random long-crested waves approximating a Pierson-Moskowitz spectrum with a full scale significant wave height of 5 ft (1.52 m) and a modal period of 6.2 seconds were generated to model a realistic sea state. Although a given wave spectrum is not identically reproducible for each run, a typical example of the actual spectrum used is shown in Figure 4. Measurements were made in random waves at seven headings from 90 deg (beam) to 180 deg (head) in increments of 15 deg for both loadings. The run length times were approximately 15 minutes model scale which is equivalent to one hour full scale. The values of local minima and maxima of the data signals of all channels measured were processed to obtain mean values, standard deviations (RMS about the mean), and significant double amplitudes (average of the highest one-third double amplitudes). A spectral analysis was also performed to determine transfer functions (T.F.'s) from the random wave data for correlation with the regular wave results.

Regular wave runs were also made for both load configurations to determine ferry response as a function of wave frequency at headings of 90 deg (beam), 135 deg (bow quartering), and 180 deg (head). Waves of ideally sinusoidal profiles were generated and harmonic analyses were performed on the motion response data to define transfer functions. From each harmonic analysis, the amplitude and wave frequency of the fundamental harmonic were determined. All runs were checked to ensure that the amplitude of the fundamental frequency was a sufficiently high percentage of the total data signal, i.e., to make sure the wave was sufficiently sinusoidal. Any run with questionable waves was repeated. Transfer functions are nondimensional response amplitudes defined as follows:

$$\text{transfer function for angular measurement} = \frac{\text{amplitude of angle response}}{\text{wave slope}}$$

$$\text{transfer function for displacement measurement} = \frac{\text{amplitude of displacement}}{\text{wave amplitude}}$$

where:

wave amplitude = $a = H/2$

wave slope = $\pi H/\lambda$

H = double amplitude of wave or wave height

λ = wavelength

Plots of the transfer functions were made during the test to aid in selection of wave frequencies to optimize definition of response peaks.

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

RANDOM WAVE RESULTS

Causeway ferry responses were required in a Pierson-Moskowitz Spectrum with a significant wave height, $\overline{H}_{1/3}$, of 5 ft (1.52 m) at seven headings from 90 to 180 deg in 15 deg increments. A representative energy spectrum of a typical sea state generated for these runs is compared to the ideal Pierson-Moskowitz Spectrum in Figure 4. The modal period is 6.2 seconds which places the peak energy at a wavelength/craft length of 0.54. Significant double amplitudes (average of the highest one-third double amplitudes) are plotted in Figures 5 through 11 for the random wave runs. All values were normalized by multiplying by the ratio of the desired significant wave height (5ft, 1.52 m) to the value actually obtained. This was done in order to give more realistic comparisons among data from individual runs because the actual values of significant wave heights obtained did vary somewhat — from a minimum of 4.67 ft (1.42 m) to a maximum of 5.91 ft (1.80 m). Minimum and maximum values of the significant double amplitudes and the headings at which they occur are given for all data channels in Table 4.

Figure 5 shows the significant double amplitudes of heave at the CG of the powered pontoon section as measured by the heave staff. Maximum values occur at 105 deg and are 4.31 ft (1.31 m) and 4.07 ft (1.24 m) for the unloaded and loaded ferries respectively. Values decrease as a heading of 180 deg is approached. Typical differences between responses for the two displacements are about 0.5 ft (0.15 m) with heave for the unloaded ferry being greater at all headings investigated.

Roll response, shown in Figure 6, is greatest in beam seas (β = 90 deg) and decreases as the heading approaches 180 deg. The rate of decrease is very large from β = 90 to 120 deg and more gradual thereafter. For headings up to 135 deg, the loaded condition experienced larger roll angles with typical values about 0.5 deg greater than for the unloaded condition. At headings of 150 deg and greater, the effect of loading was insignificant.

Differences in pitch between the two displacements, shown in Figure 7, are not great. Pitch response reaches its maximum at a heading between 135 and 150 deg for both load conditions with the value for the loaded ferry being more severe. At headings of 105 and 120 deg, however, the unloaded ferry exhibits higher pitching. Plots of the significant double amplitudes of angular displacement, Figures 8, 9, and 10, are very similar in shape to pitch, but not unexpectedly, reach peak values approximately twice that of pitch. All three relative angle responses for the loaded ferry demonstrate almost identical trends — all three have similar shapes and peak at a heading of approximately 150 deg. Peak values for the relative angular displacement at the second and third junctions are both 13.1 deg. For the most forward junction, the value is slightly higher at 15.0 deg. Plots of significant double amplitudes of the relative angles in the unloaded ferry have greater differences, but in all cases their peak values are approximately 0.5 deg less than for the loaded condition. In particular, plots of relative angular displacements for the unloaded ferry tend to be skewed with respect to those of the loaded ferry. For the two forward junctions (Significant Relative Angle 1 and 2), the peak values occur at β = 165 deg, but for the aft junction, the peak occurs at 135 deg.

Heave of the forward pontoon section, measured by an ultrasonic transceiver, is shown in Figure 11. For the unloaded ferry, the heave response is notably flat up to 135 deg. It reaches a peak value at 150 deg and after 165 deg, drops sharply. The heave response of the loaded ferry reaches a minimum at a heading of 105 deg with a value 1.4 ft (0.43 m) less than that of the unloaded condition at that heading. At 150 deg, the curve reaches its maximum which is 1.6 ft (0.49 m) greater than for the unloaded ferry.

Visual observations were also made to obtain quantitative estimates of deck wetness. In no instance did the unloaded ferry experience anything more than minor splashing onto the deck. To simplify the description of deck wetness, the following numerical coding scheme was devised:

0 - No deck wetness
1 - Minor splashing and droplets on the deck
2 - Waves impacting vertical surfaces and splashing over the edges
3 - Waves slightly higher than deck and breaking onto the deck
4 - Waves breaking over the deck with moderate magnitude
5 - Waves breaking over the deck with great magnitude
6 - Intolerable

The loaded causeway ferry experienced the following:

1. β = 90 deg - No deck wetness (0).
2. β = 105 deg - Numerous 3 and 4 encounters and one 5 encounter occurred on the powered pontoon section. On the middle two pontoon sections there were numerous 2 and 3 encounters. The leading section fared better with approximately the same number of encounters as the middle pontoons, but only of severity 2.
3. β = 120 deg - Numerous 2 and 3 encounters occurred over all pontoons with several impacts of severity 4 on the powered section.
4. β = 135 deg - Wetness conditions between 3 and 4 on the forward sections tending to be more toward 4 on the powered section. Water sloshes up through spaces between pontoons.

5. β = 150 deg - Conditions ranged between 2 and 3 with some water sloshing through the spaces between pontoons.
6. β = 165 deg - Condition 1 on the bow of the leading pontoon.
7. β = 180 deg - No deck wetness (0).

REGULAR WAVE RESULTS AND COMPARISON WITH SPECTRAL ANALYSIS OF RANDOM WAVE DATA

Transfer functions for all data channels are plotted in Figures 12 through 18. The symbols are values derived from regular wave runs. The lines are results of a spectral analysis performed on the random wave data and are plotted with the symbols for comparison. In the regular wave runs, waves of a sinusoidal profile were generated and transfer functions were computed for the discrete frequencies obtained. The spectral analysis of random wave data determines the energy in the seaway at a given frequency and from the model response at that frequency computes the transfer functions. This analysis is important to yield information on the linearity of craft response, i.e., to indicate to what degree the total system output is the sum of outputs due to the individual excitations. For a linear system, results of the two methods of analysis would be identical. Linearity was also checked by conducting multiple runs with different wave amplitudes at a constant frequency chosen at which a peak occurred in the plots of the transfer functions to ensure a high response per unit wave amplitude. In an absolutely linear system, the data points from the multiple runs would superimpose.

It should be noted that in the lower range of frequencies, results of the spectral analysis often deviate drastically from the regular wave data. This indicates an indeterminate result since the energy in the wave spectrum is very small at frequencies less than 0.75 rps. The resultant wave amplitude components at these frequencies would be very small and result in very large transfer functions if any response motion existed in this range. For frequencies below 0.75 rps, results of only the regular wave runs (symbols) should be considered.

Transfer functions for heave and roll, shown in Figures 12 and 13, demonstrate remarkable similarities in beam seas. A definite peak exists for both at a full scale wave frequency of 0.75 rps which corresponds to a wavelength to craft length ratio (λ/L) of 1.0. In bow quartering seas, the roll T.F. is very small for frequencies greater than 0.75 rps, but increases for frequencies below that. This is reasonable because in shorter waves the segments of the causeway ferry would be angled relative to each other which would tend to restrict roll motion. For longer waves, relative angular displacement decreases at each junction and roll is therefore less inhibited.

Pitch T.F.'s are shown in Figure 14 and for bow quartering and head seas are very similar in shape to the heave T.F.'s. In bow quartering seas, the heave and pitch T.F.'s are double peaked. The first peak occurs at a wave frequency of about 0.6 rps or $\lambda/L = 1.5$. This corresponds to a wavelength twice as long as the projection of the longitudinal axis of the causeway ferry onto the wave profile. The second peak occurs at a frequency of 0.95 rps or a $\lambda/L = 0.62$. This wavelength is close to the length of the projection of the longitudinal axis onto the wave profile and is analogous to a head sea $\lambda/L = 1.0$. Results of the spectral analysis miss the low frequency peak due probably to the small amount of energy present in the random wave spectrum at these frequencies. In head seas, the heave and pitch T.F.'s have only one peak which occurs at 0.75 rps or a $\lambda/L = 1.0$.

Transfer functions for the relative angles between pontoon sections are given in Figures 15, 16, and 17. Relative angle 1 corresponds to the most forward junction, 2 to the middle, and 3 to the aft junction. For the same heading, T.F.'s at each junction are very similar to one another and all possess some similarities to the T.F. for pitch. In bow quartering seas, all relative angle T.F.'s have two peaks as does pitch. These also occur at wave frequencies of approximately 0.6 rps ($\lambda/L = 1.5$) and 0.95 rps ($\lambda/L = 0.62$). The relative angle T.F.'s in head seas also have double peaks which occur at wave frequencies of 0.75 rps ($\lambda/L = 1.0$) and 1.05 rps ($\lambda/L = 0.5$).

The T.F.'s for heave of the forward pontoon section, derived from measurements made by an ultrasonic transceiver, are shown in Figure 18. Except for beam seas, similarities with the heave T.F. of the aft pontoon are slight. Although the frequency at which the peak occurs in the heave T.F.'s are the same for both forward and aft pontoons in beam seas (0.75 rps), magnification was higher for the forward section. For bow quartering and head seas, the shape of the heave T.F. for the forward section bears closer similarity to the relative angle T.F.'s.

In general, the T.F.'s for the loaded and unloaded ferries differ only slightly. Correlation between results of the spectral analysis of random wave runs and the regular wave runs is good except in the regions of low spectral energy. Multiple regular wave runs of the same wave frequency but with different amplitudes were conducted at the frequency at which peaks occurred in the aft pontoon's heave transfer function. In general, variation in results from the individual runs was a small percentage of the total value which indicates a fairly linear system.

SUMMARY AND CONCLUSIONS

Motions of the causeway ferry were measured and analyzed to define its seakeeping capabilities. Two displacements (unloaded and loaded) were investigated at zero speed in random waves approximating a Pierson-Moskowitz spectrum (significant wave height = 5.0 ft = 1.52 m) and in regular waves over a range of frequencies. The random wave runs were conducted at seven headings from 90 deg (beam seas) to 180 deg (head seas) in increments of 15 deg. Regular wave runs were conducted at headings of 90, 135, and 180 deg.

In contrast to the unloaded configuration which handled all headings quite easily with only minor deck wetness, the loaded ferry experienced difficulty in the Pierson-Moskowitz sea. Headings of 105 and 135 deg were the most critical with considerable deck wetness occurring. Plots of the values of significant double amplitudes show that the largest differences between the two load conditions exist for heave and that the heave of the loaded ferry is less than that of the unloaded ferry for all headings. This indicates that the increased deck wetness is the result of decreases in freeboard and significant heave response. The peak in the pitch response, which occurs at 135 deg, indicates that the severe deck wetness at this heading may be dominated by pitch motion. Although deck wetness was minor in beam seas, the significant roll double amplitude was about 14.0 deg which would also cause problems. The loaded ferry's motions improve as heading angles increase above 150 deg. Of the headings investigated, head sea operation (β = 180 deg) appears to be best for minimum motions and also deck wetness.

Spectral analysis was performed on the random wave data to determine transfer functions (plotted as lines) for comparison with the transfer functions from regular wave data (plotted as symbols). In general, results of the two analyses agree quite well for wave frequencies greater than 0.75 rps. The low frequency discrepancy can readily be explained with the plot of the spectral energy distribution which shows that for frequencies less than 0.75 rps, wave energy is very small.

ACKNOWLEDGMENT

The author wishes to express his thanks to John G. Hoyt whose advice and expertise in model testing proved most valuable.

TABLE 1 - NOMINAL INERTIAL CHARACTERISTICS OF PONTOON CONFIGURATIONS

				Center of Gravity in feet (m)			Radius of Gyration in feet (m)		
	Mass lbm (kg)	Mean Draft ft (m)	Trim deg	X_{cg} from stern	Y_{cg} from ℄	Z_{cg} from bottom plate	Rxx	Ryy	Rzz
A	129,870 (58,908)	1.22 (0.372)	0.0	45.00 (13.72)	0.0	2.51 (0.76)	6.23 (1.90)	24.0 (7.32)	24.8 (7.54)
B	193,937 (87,968)	1.85 (0.562)	1.05	39.00 (11.89)	0.0	4.64 (1.41)	6.93 (2.11)	22.4 (6.81)	22.8 (6.95)
C	258,003 (117,028)	2.43 (0.739)	0.0	45.00 (13.72)	0.0	5.73 (1.75)	7.02 (2.14)	22.5 (6.86)	23.0 (6.99)
D	179,820 (81,565)	1.65 (0.503)	1.6	35.55 (10.84)	0.0	2.51 (0.76)	7.59 (2.31)	25.4 (7.73)	25.8 (7.86)
E	243,887 (110,625)	2.30 (0.700)	0.5	42.75 (13.03)	0.0	4.22 (1.28)	7.80 (2.38)	25.5 (7.77)	25.8 (7.86)

A: Standard Causeway Section, unloaded
B: Standard Causeway Section, half loaded
C: Standard Causeway Section, fully loaded
D: Powered Causeway Section, unloaded
E: Powered Causeway Section, half loaded

TABLE 2 - ACTUAL INERTIAL CHARACTERISTICS OF PONTOONS IN UNLOADED CAUSEWAY FERRY*

				Center of Gravity in feet (m)			Radius of Gyration	
NO.	CONF.	Mass lbm (kg)	Mean Draft ft (m)	X_{cg} from stern	Y_{cg} from ℄	Z_{cg} from bottom plate	Rxx ft (m)	Ryy ft (m)
1	A	129,870 (58,908) 0%	1.22 (0.372) -	45.00 (13.72) 0%	0.0 -	2.46 (0.75) -2.0%	6.59 (2.01) +5.8%	23.7 (7.22) -1.3%
2	A	129,870 (58,908) 0%	1.22 (0.372) -	45.00 (13.72) 0%	0.0 -	2.31 (0.70) -8.0%	6.81 (2.08) +9.3%	24.1 (7.36) +0.6%
3	A	129,870 (58,908) 0%	1.22 (0.372) -	45.00 (13.72) 0%	0.0 -	2.42 (0.74) -3.6%	6.78 (2.07) +8.8%	24.0 (7.32) 0%
4	D	181,913 (82,514) +1.2%	1.65 (0.503) -	41.60 (12.66) +17.0%	0.0 -	3.51 (1.07) +39.8%	5.61 (1.71) -26.1%	20.3 (6.20) -20.0%

*Percentages given in the table are the percentage of deviation above or below (+ or -) the nominal value given in Table 1.

TABLE 3 - ACTUAL INERTIAL CHARACTERISTICS OF PONTOONS IN LOADED CAUSEWAY FERRY*

				Center of Gravity in feet (m)			Radius of Gyration	
NO.	CONF.	Mass lbm (kg)	Mean Draft ft (m)	X_{cg} from stern	Y_{cg} from ℄	Z_{cg} from bottom plate	Rxx ft (m)	Ryy ft (m)
1	B	193,995 (87,995) 0%	1.85 (0.562) -	39.00 (11.89) 0%	0.0 -	4.64 (1.41) 0%	7.16 (2.18) +3.3%	22.4 (6.81) -0.2%
2	C	258,120 (117,081) 0%	2.43 (0.739) -	45.00 (13.72) 0%	0.0 -	5.72 (1.74) -0.2%	7.07 (2.15) +0.7%	22.5 (6.86) 0%
3	C	258,120 (117,081) 0%	2.43 (0.739) -	45.00 (13.72) 0%	0.0 -	5.73 (1.75) 0%	7.02 (2.14) 0%	22.5 (6.86) 0%
4	E	246,139 (111,647) +0.9%	2.30 (0.700) -	42.75 (13.03) 0%	0.0 -	4.53 (1.38) +7.3%	6.62 (2.02) -15.1%	24.5 (7.45) -4.1%

*Percentages given in the table are the percentage of deviation above or below (+ or -) the nominal value given in Table 1.

TABLE 4 - MAXIMUM AND MINIMUM VALUES OF SIGNIFICANT DOUBLE AMPLITUDE RESPONSES

	MAXIMUM VALUES				MINIMUM VALUES			
	Unloaded		Loaded		Unloaded		Loaded	
	β	S.V.	β	S.V.	β	S.V.	β	S.V.
HEAVE	105	4.31	105	4.07	180	1.77	180	1.64
ROLL	90	14.30	90	14.82	180	0.17	180	0.23
PITCH	135	6.33	135	6.70	90	0.86	90	1.05
R.A. 1	165	14.15	150	15.01	90	1.26	90	1.49
R.A. 2	165	12.46	150	13.10	90	1.09	90	1.33
R.A. 3	135	12.69	150	13.13	90	1.53	90	1.57
HEAVE2	150	5.62	150	7.23	180	4.40	105	3.81

	MODEL SCALE	FULL SCALE
Length:	6.0 ft (1.83 m)	90.0 ft (27.43 m)
Beam :	1.4 ft (0.43 m)	21.0 ft (6.40 m)
Depth :	4.0 in. (0.10 m)	5.0 ft (1.52 m)

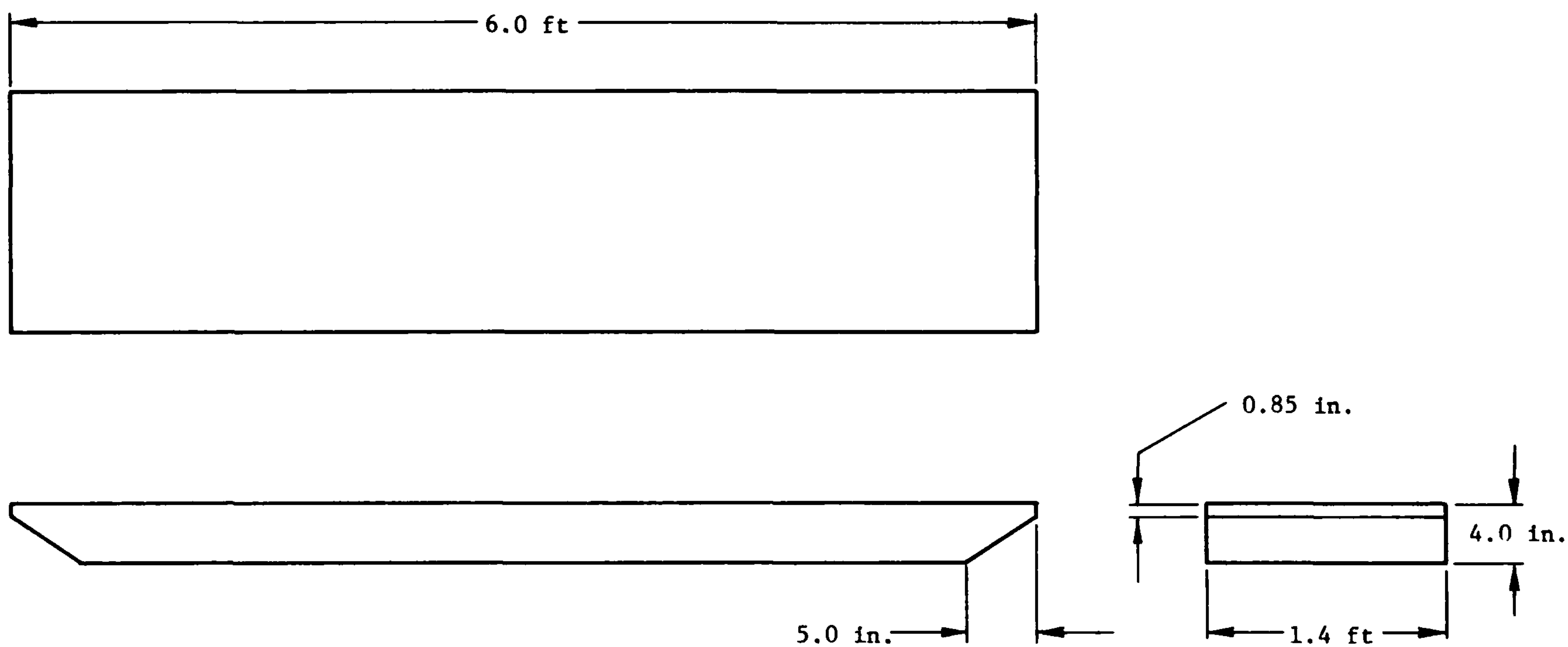


Figure 1 - Dimensions of Pontoon Model

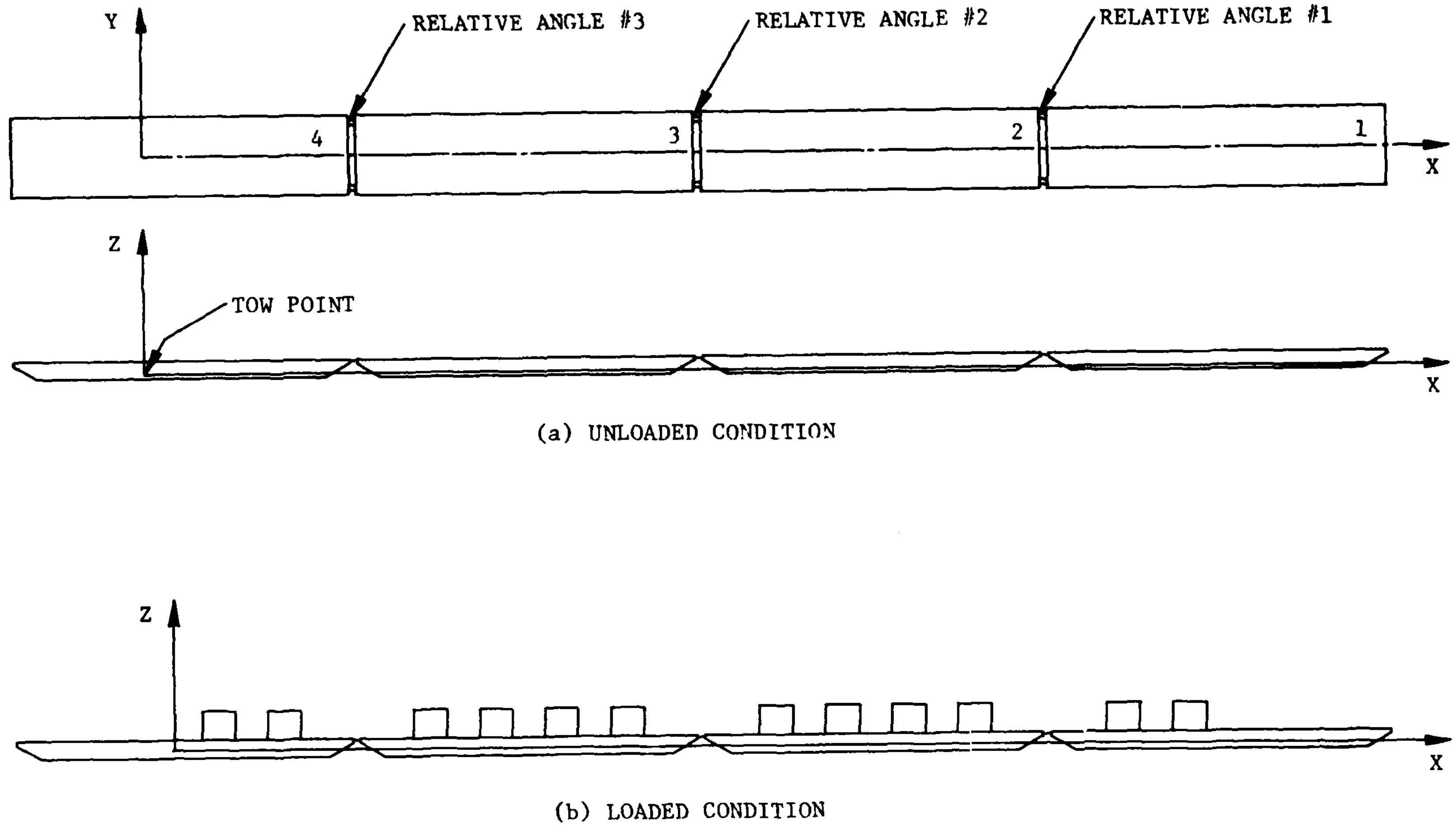
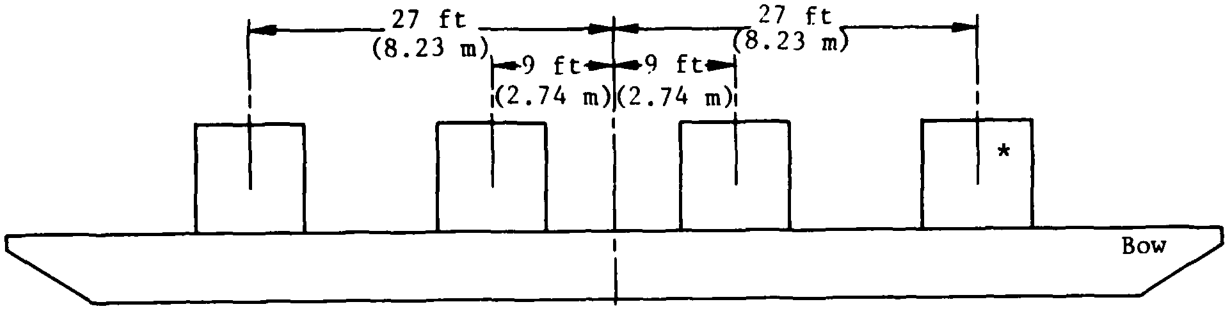
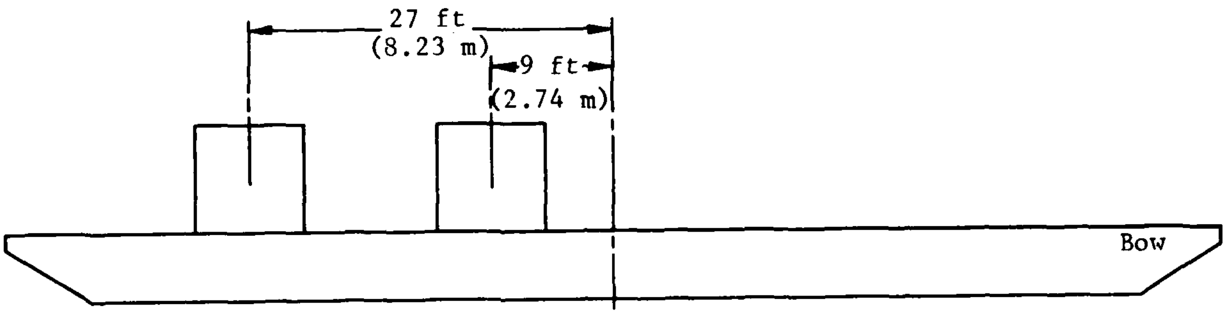


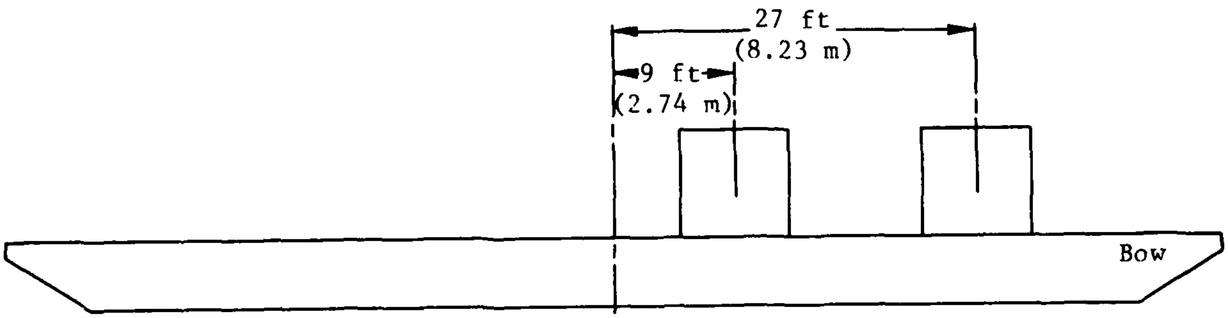
Figure 2 - Pontoon Configuration in Causeway Ferry and Coordinate System



Standard Pontoon - Fully Loaded



Standard Pontoon - Half Loaded



Powered Pontoon - Half Loaded

*Each container represents a 32,063 lb (14,543 kg) load

Figure 3 - Deck Loading on the Loaded Causeway Ferry

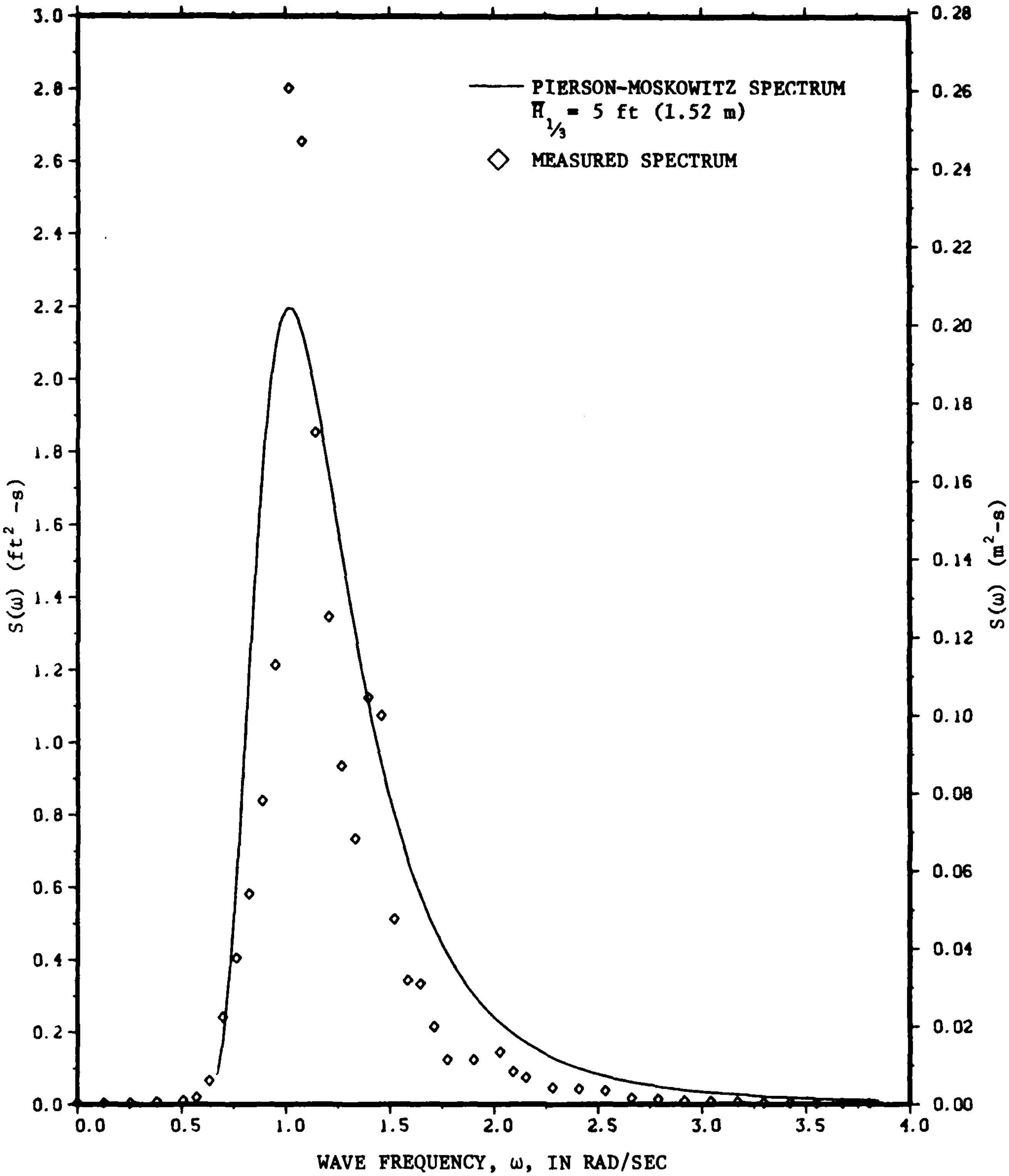


Figure 4 - Irregular Wave Spectrum Obtained During Experiment

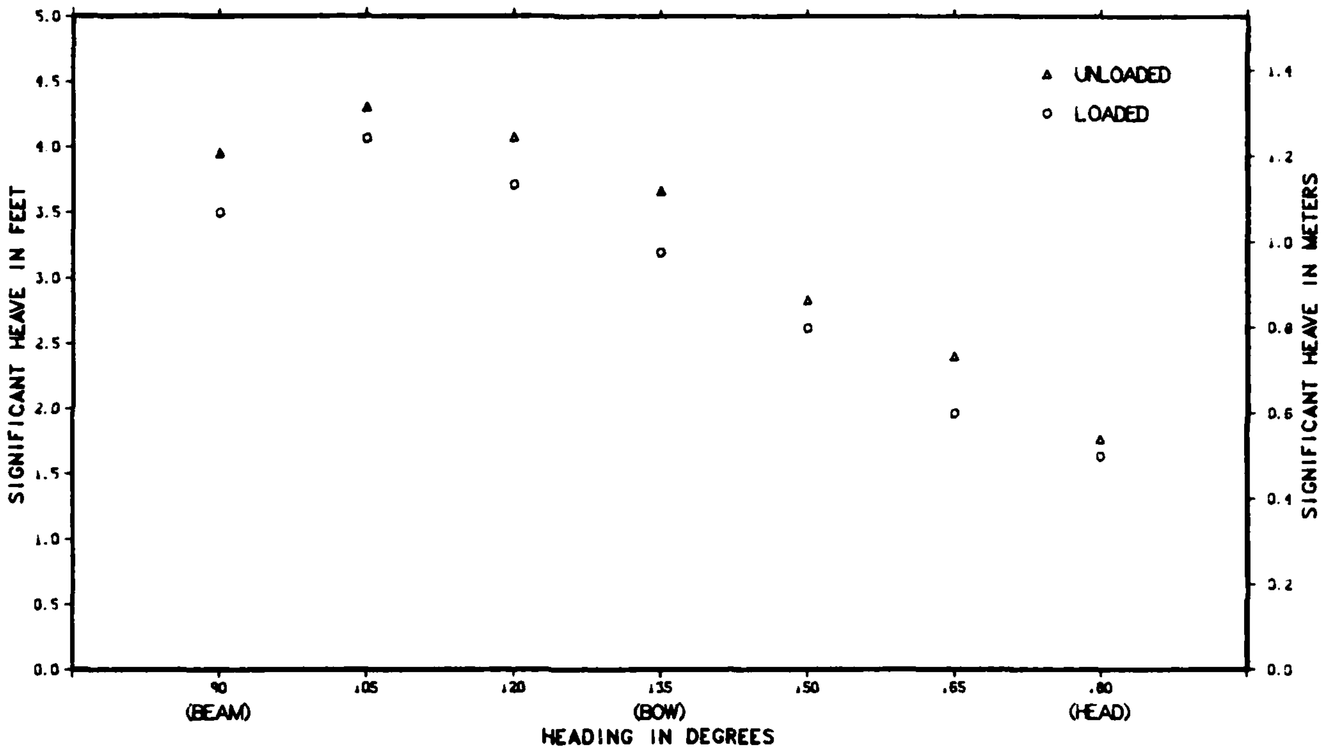


Figure 5 - Significant Double Heave Amplitude of Aft Pontoon

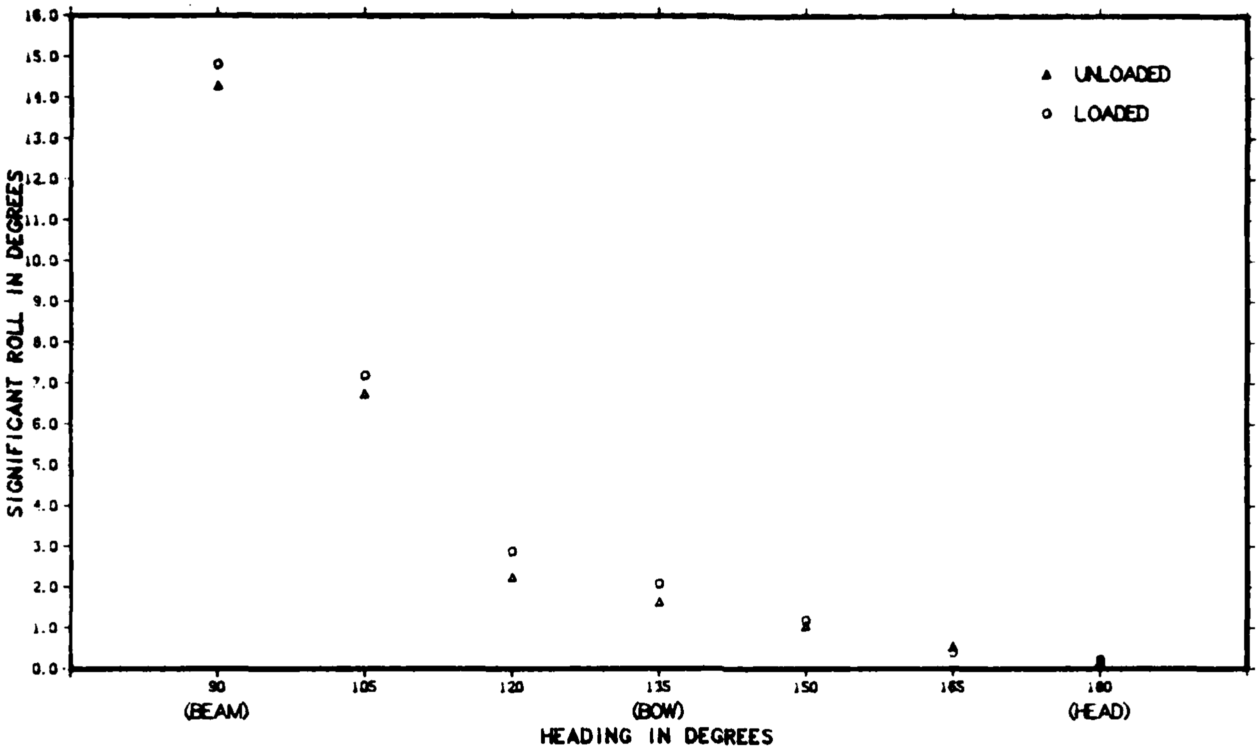


Figure 6 - Significant Double Roll Amplitude of Aft Pontoon

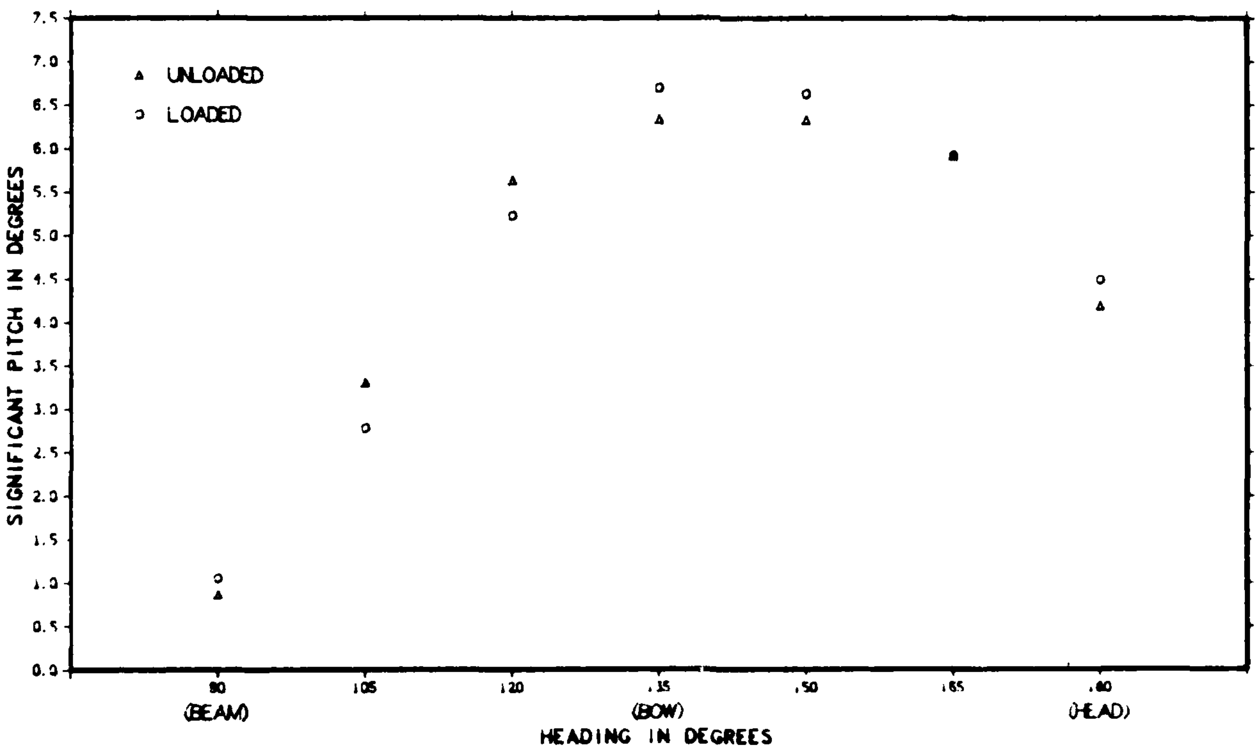


Figure 7 - Significant Double Pitch Amplitude of Aft Pontoon

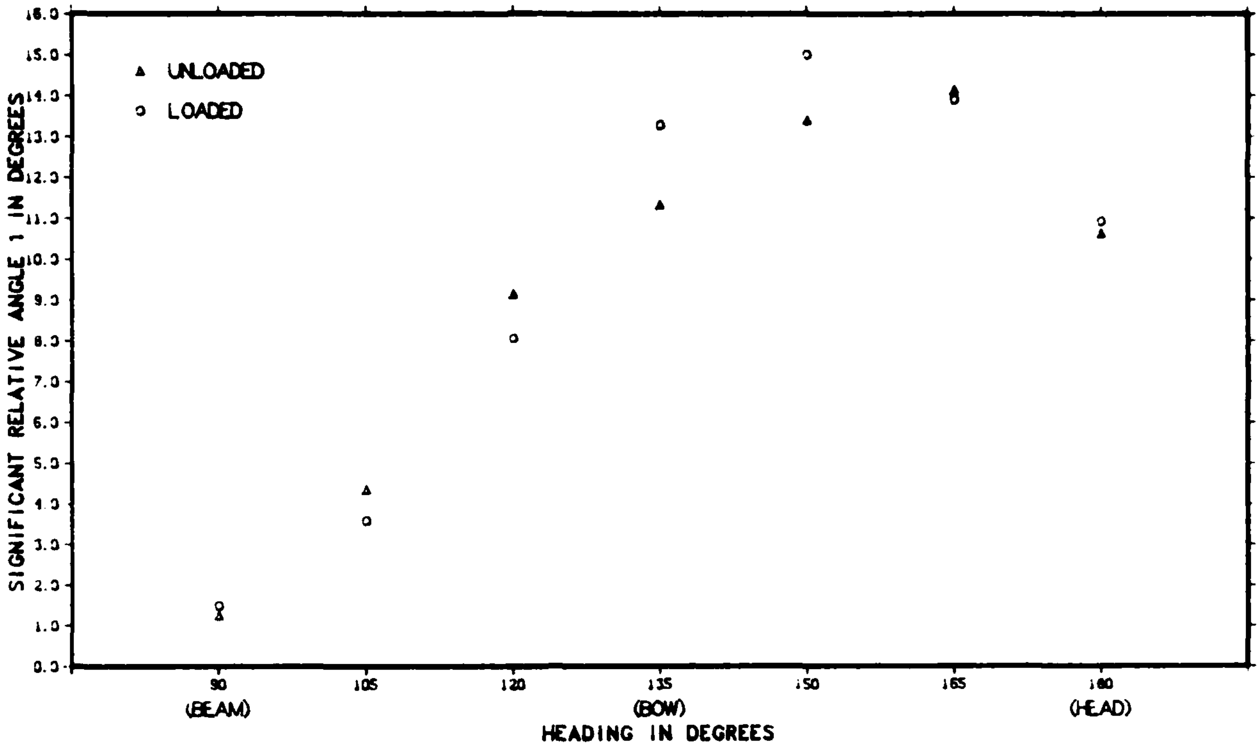


Figure 8 - Significant Double Amplitude of Relative Angle Between First and Second Pontoons

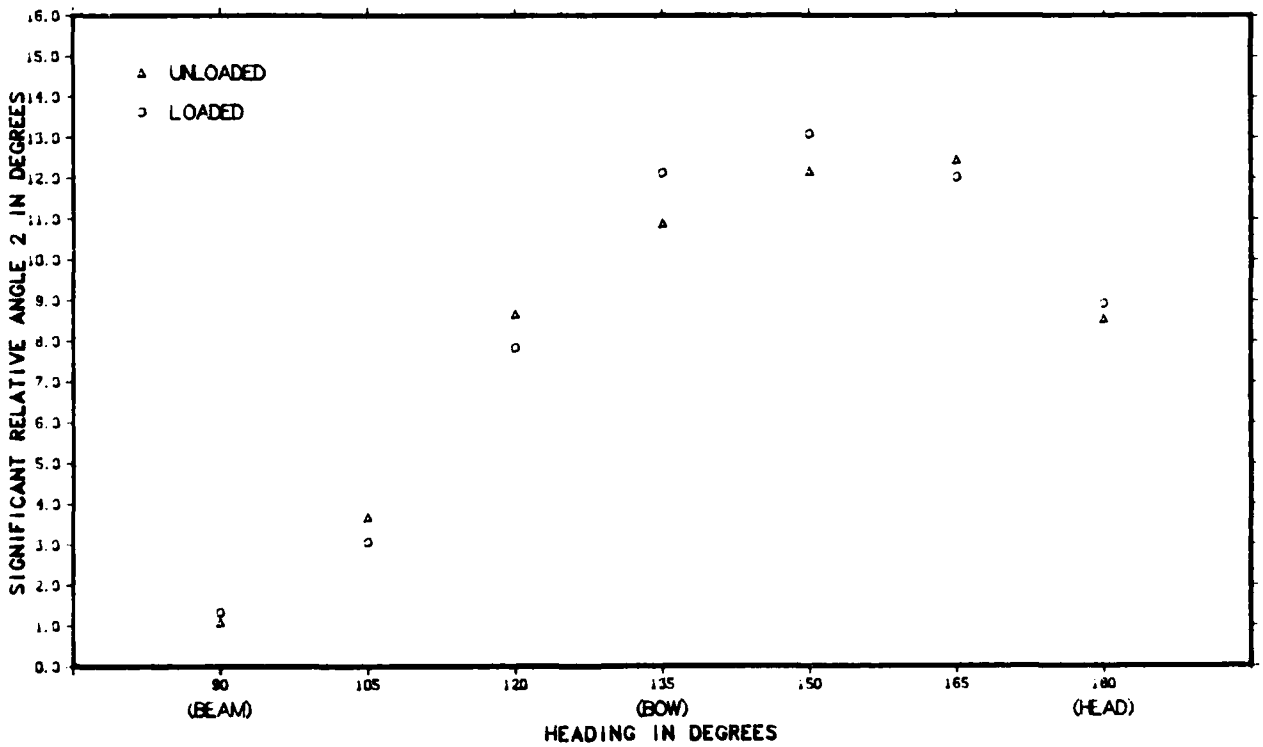


Figure 9 - Significant Double Amplitude of Relative Angle Between Second and Third Pontoons

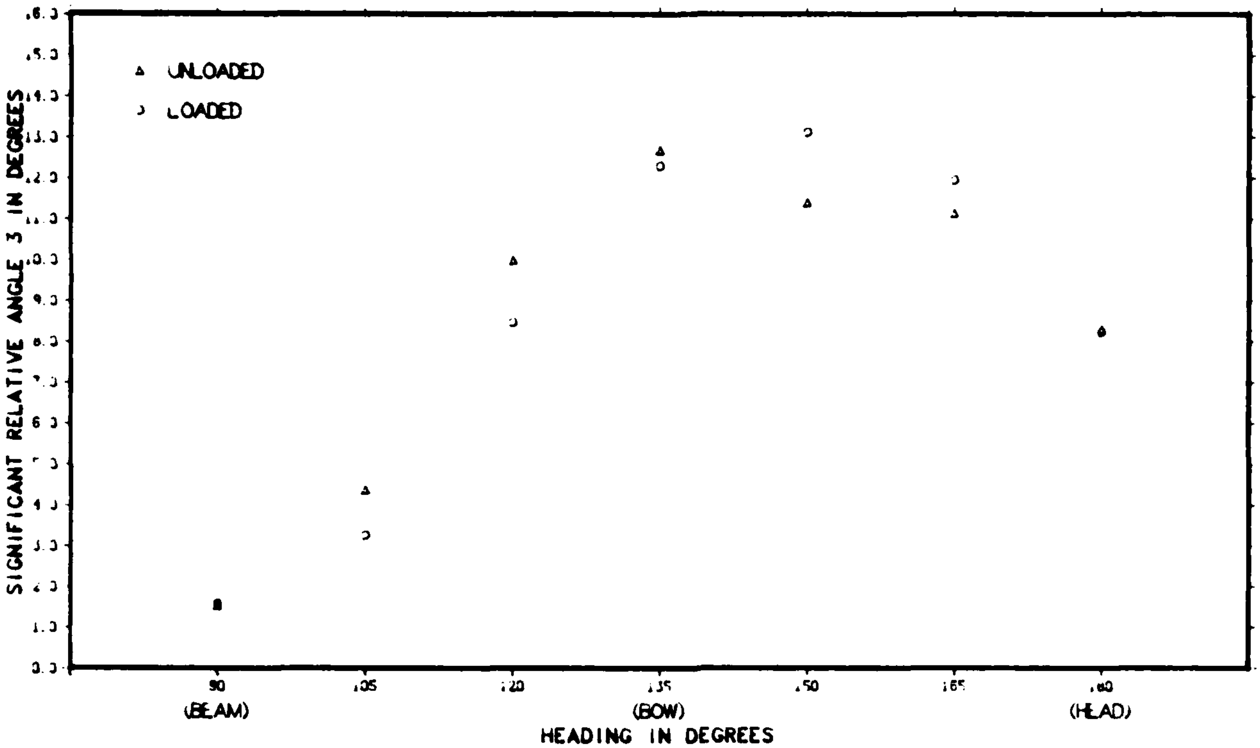


Figure 10 - Significant Double Amplitude of Relative Angle Between Third and Fourth Pontoons

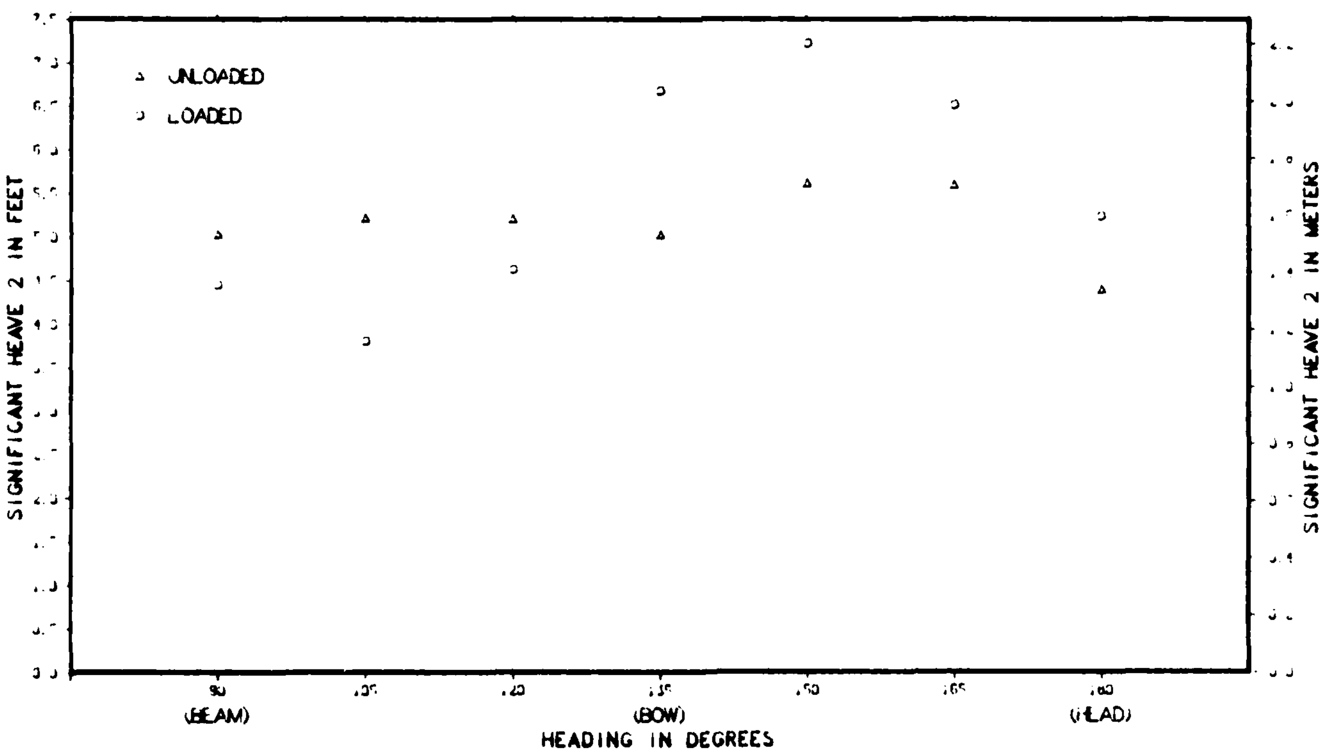


Figure 11 - Significant Double Heave Amplitude of Forward Pontoon

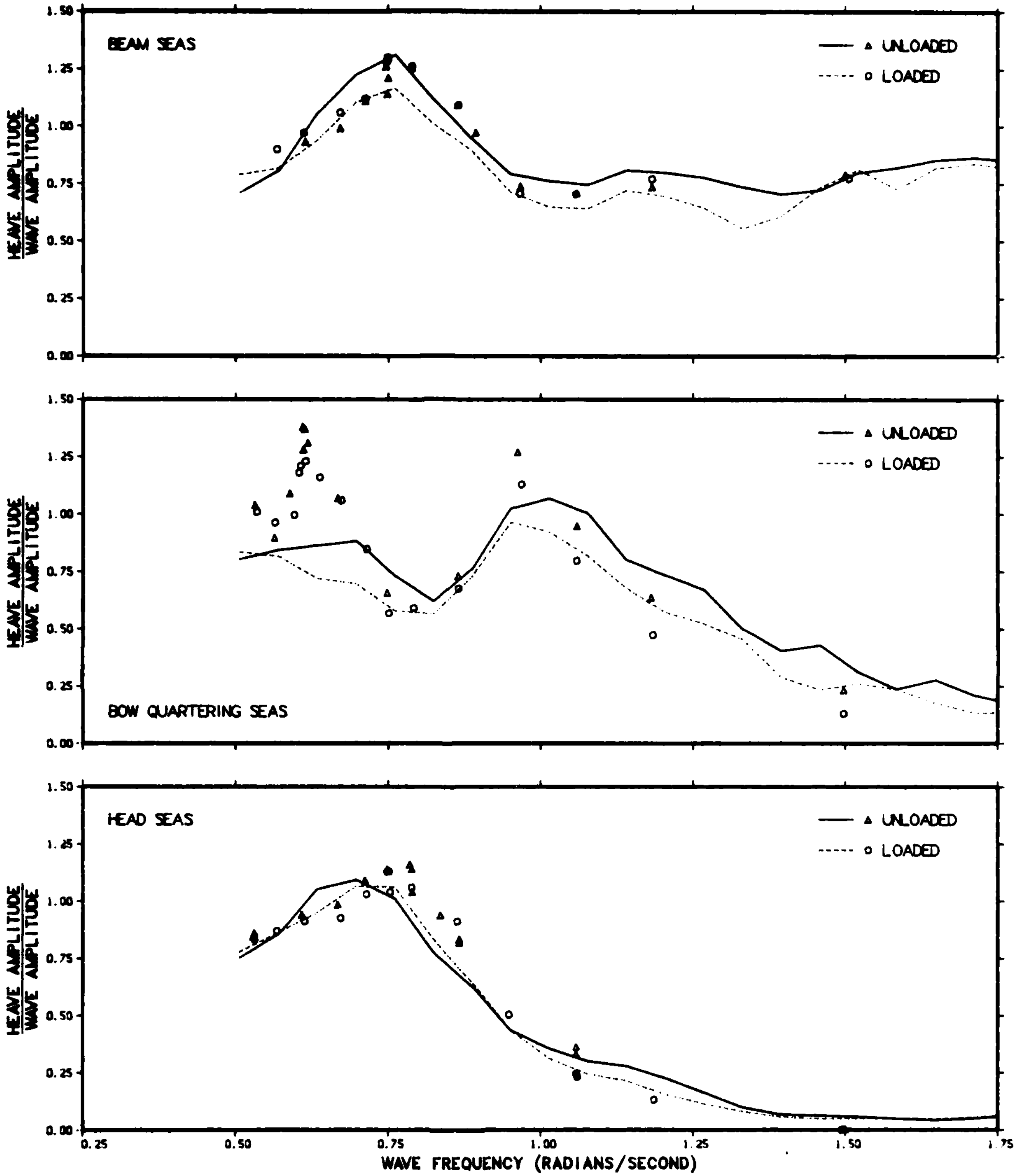


Figure 12 - Heave Transfer Function of Aft Pontoon -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

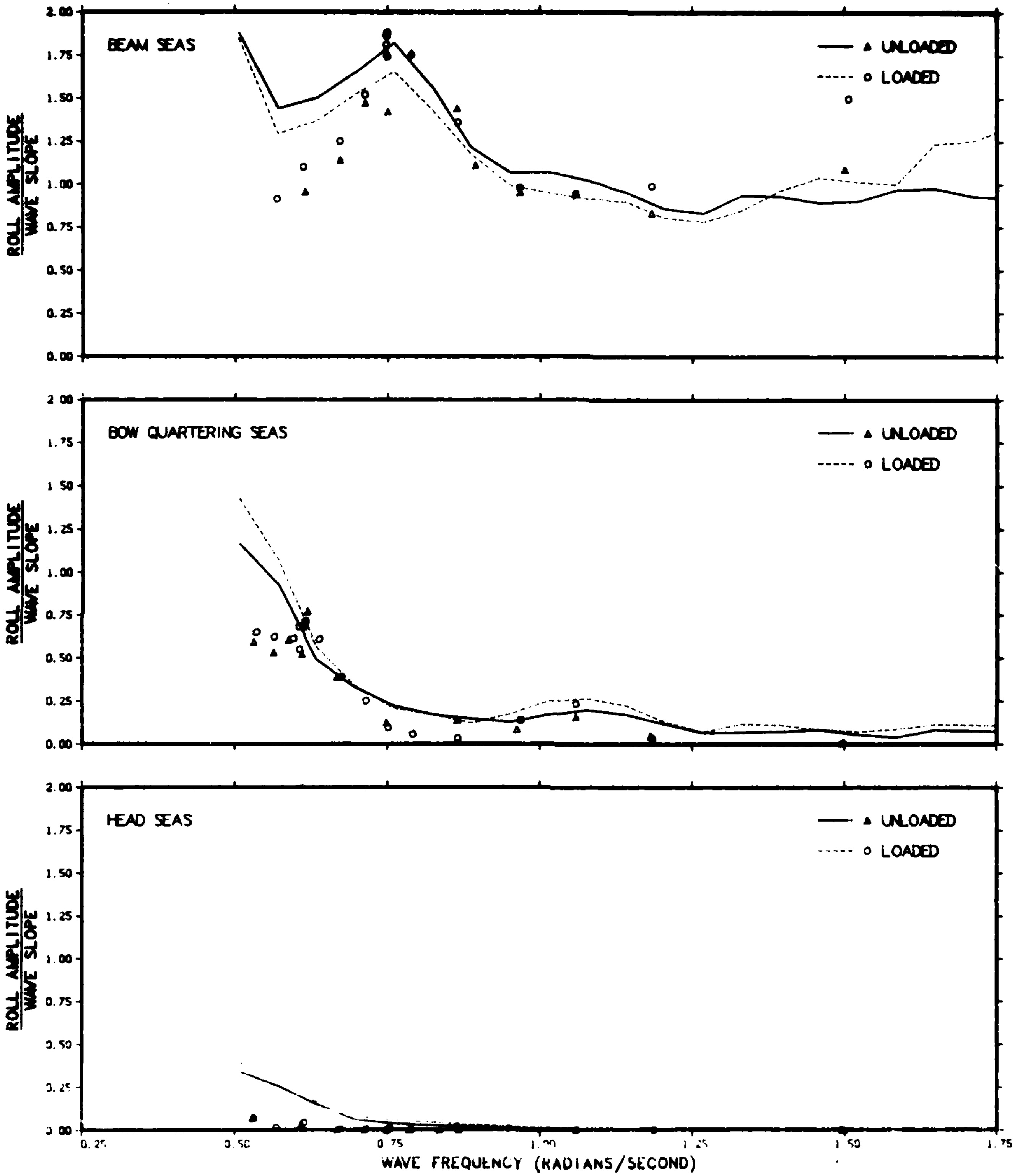


Figure 13 - Roll Transfer Function of Aft Pontoon -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

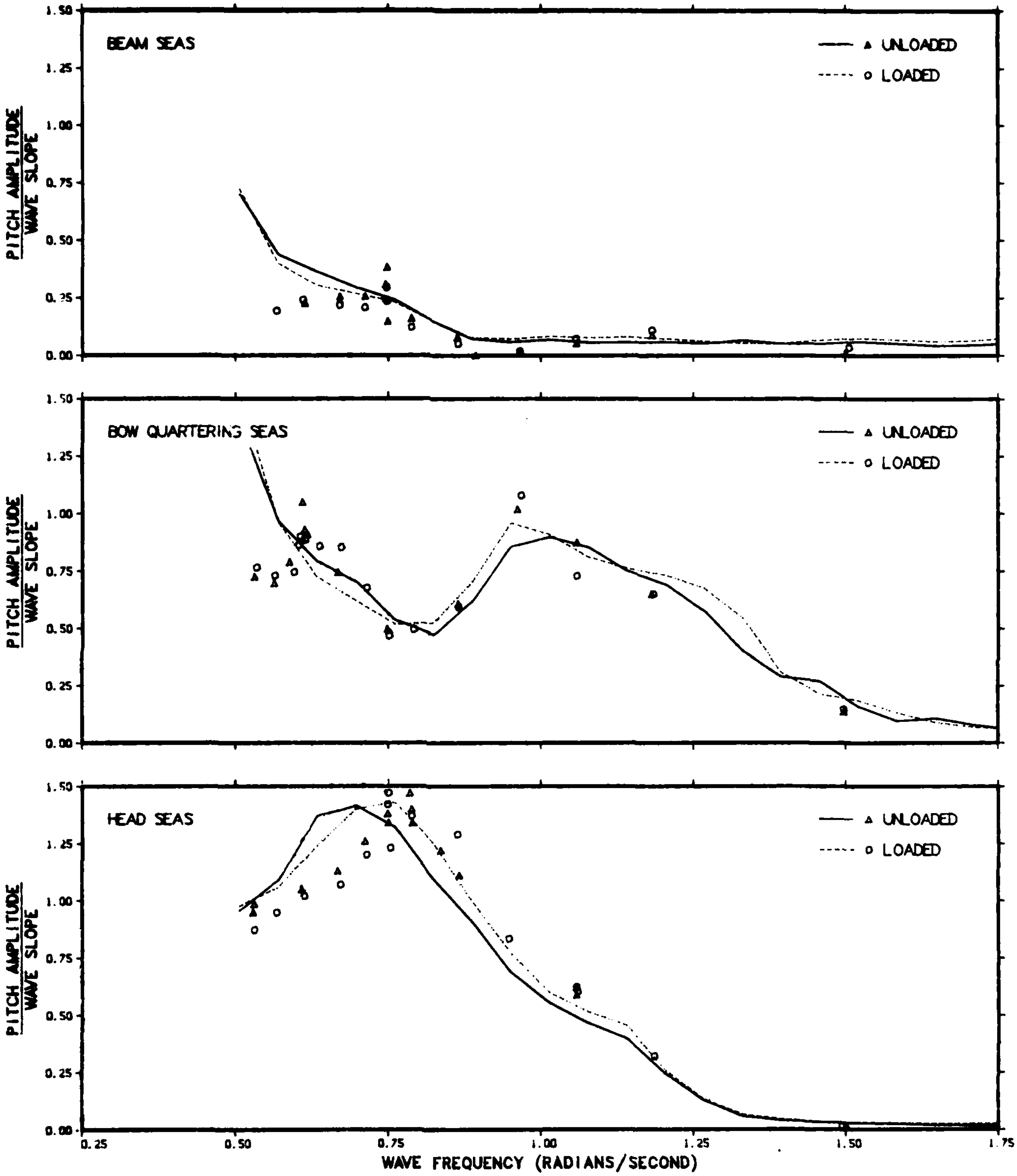


Figure 14 - Pitch Transfer Function of Aft Pontoon -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

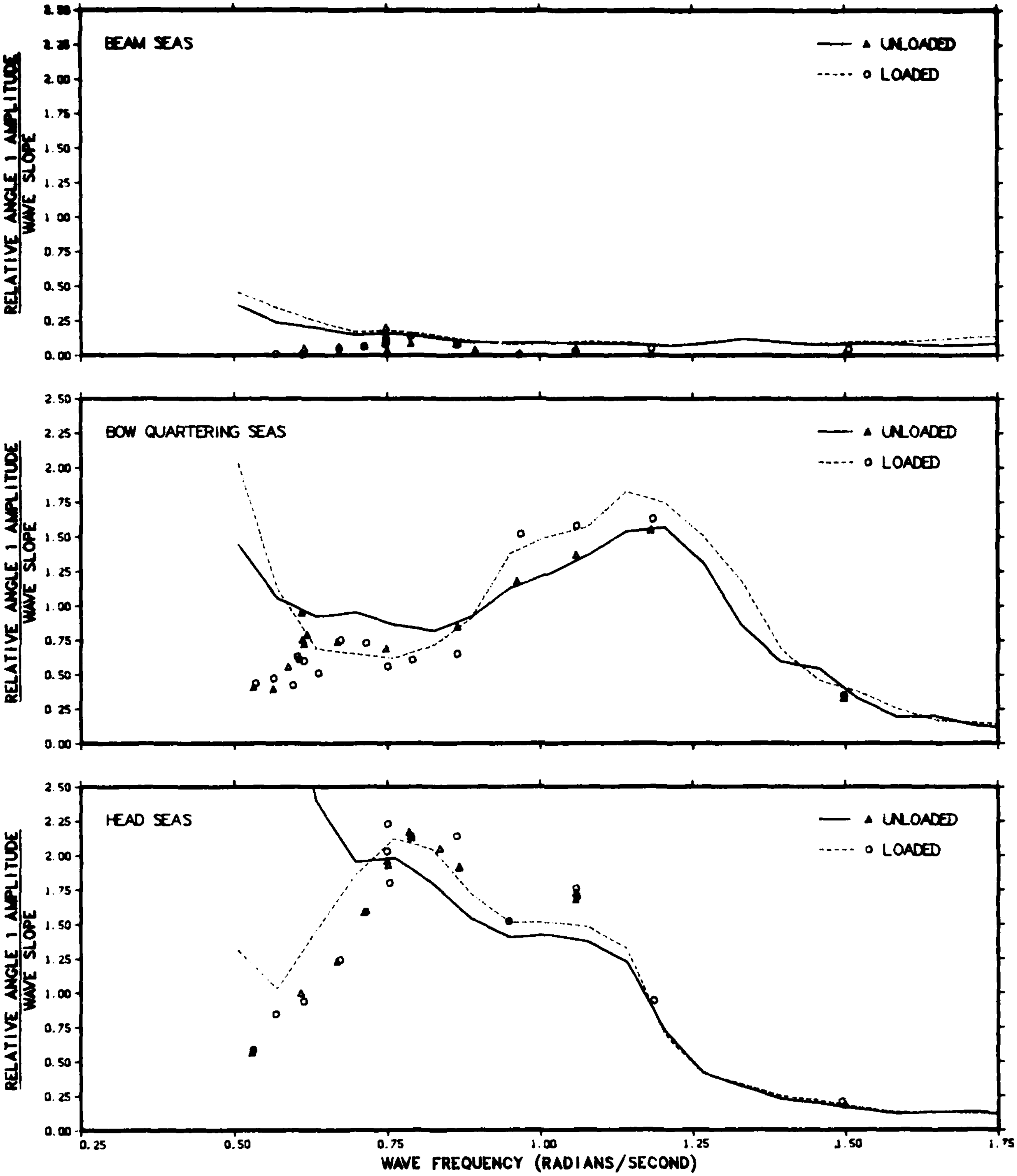


Figure 15 - Transfer Function of Relative Angle Between First and Second Pontoons -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

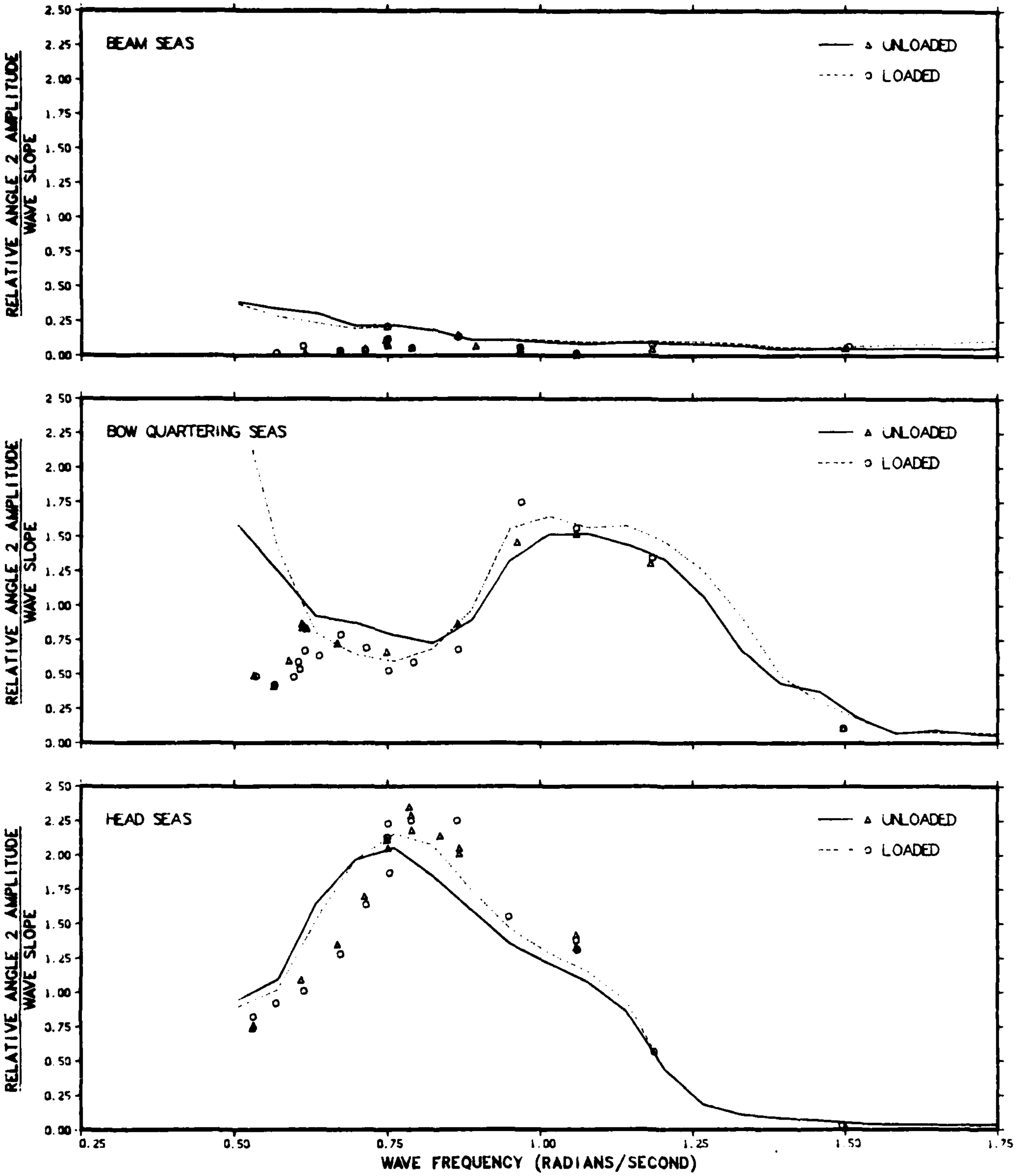


Figure 16 - Transfer Function of Relative Angle Between Second and Third Pontoons -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

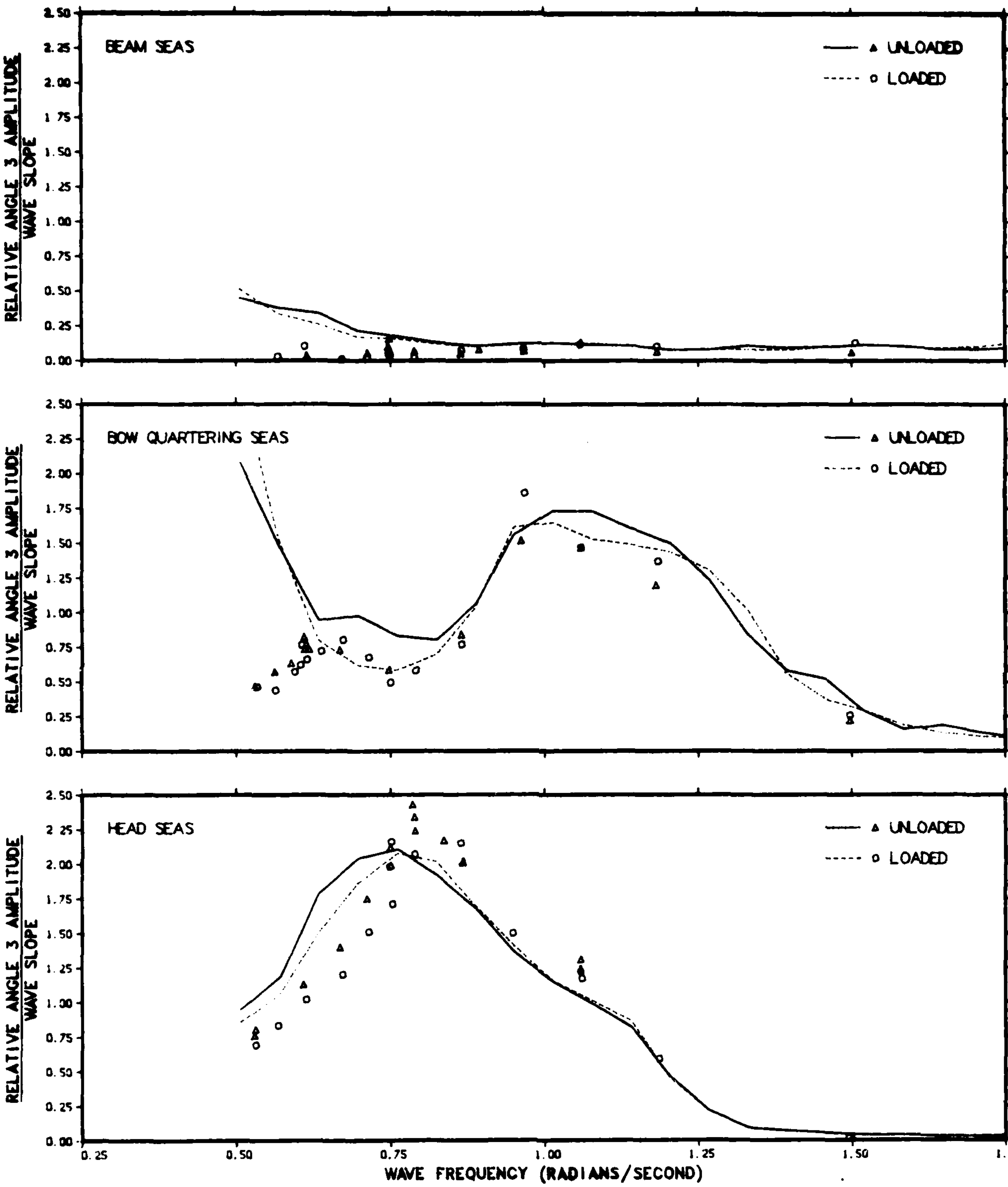


Figure 17 - Transfer Function of Relative Angle Between Third and Fourth Pontoons -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

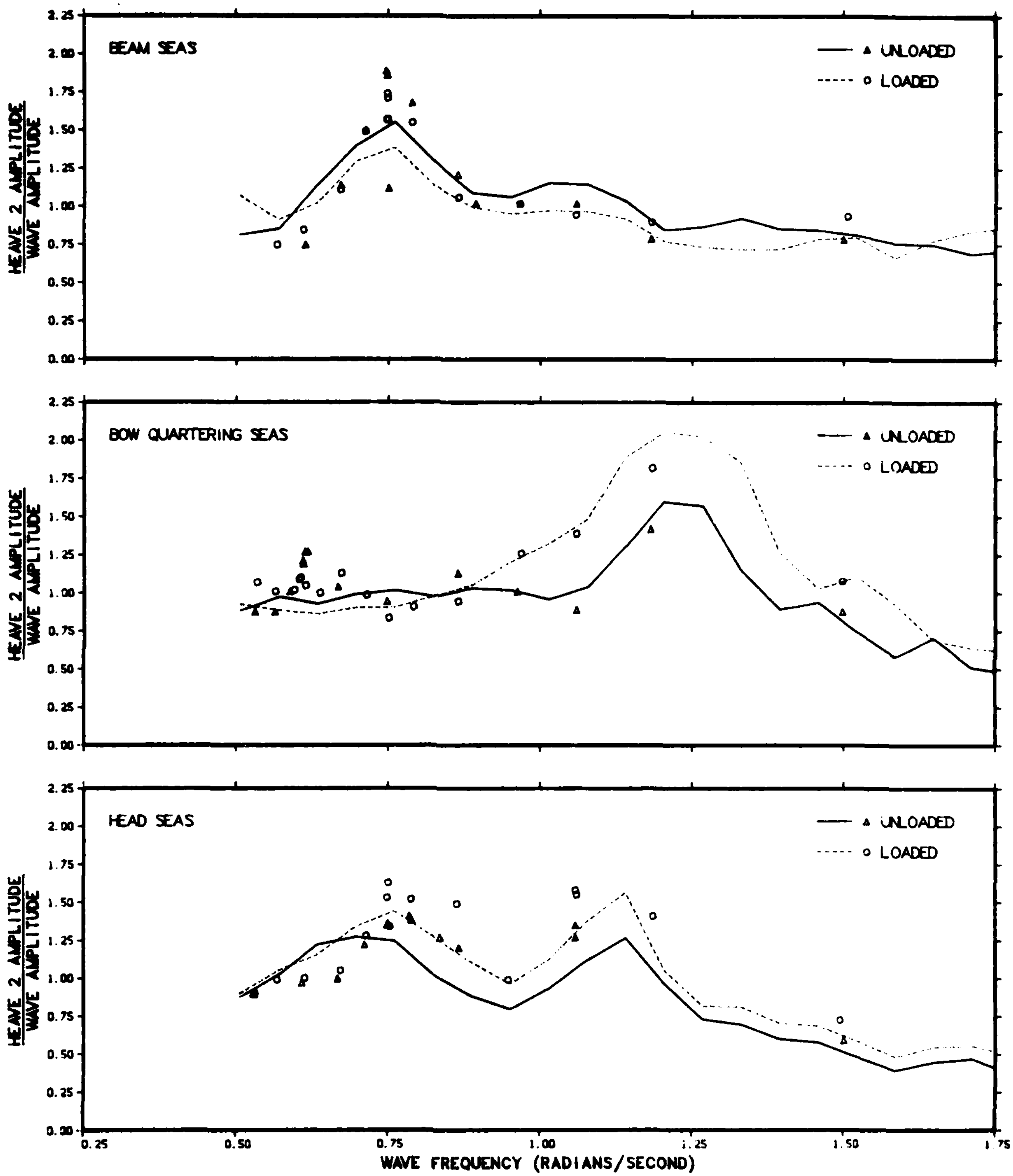


Figure 18 - Heave Transfer Function of Forward Pontoon -- Regular Wave Runs (Symbols) and Spectral Analysis of Random Wave Data (Lines)

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