Report 2997
STRUCTURAL RESPONSES AND MOTIONS OF USS WILLIS A. LEE (DL-4)

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Washington, D.C. 20007

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RESEARCH AND DEVELOPMENT [redacted]

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Report 2997

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Naval Ship Research and Development Center
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DEPARTMENT OF THE NAVY
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STRUCTURAL RESPONSES AND MOTIONS OF USS WILLIS A. LEE (DL-4)

by

John N. Andrews

March 1969

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NOTATION

B	Ship breadth amidship (49.67 ft)
E	Area under spectrum
g	Acceleration due to gravity (32.17 ft/sec^2)
L_s	Ship length between perpendiculars (476 ft)
ρ	Mass density of sea water (64 lb/ft^3)
$\Omega_e = \frac{\omega_e}{\omega_L}$	Nondimensional encounter frequency
ω_e	Encounter frequency
ω_L	Frequency of wave equal to ship length

ABSTRACT

This report presents test results derived from trials conducted aboard USS WILLIS A. LEE (DL-4) in the North Atlantic.

Response amplitude operators, obtained from test data, and theoretical wave spectra are utilized to produce prediction curves for ship responses.

ADMINISTRATIVE INFORMATION

To aid in design evaluation, seaworthiness trials were conducted aboard USS WILLIS A. LEE (DL-4) in the North Atlantic during the month of May 1966. This work was authorized by NAVSEC letter F-013 03 01 Serial 442-202 of 11 October 1963 and was funded under Task 1973 of Task Area S-F 35-422.301 (Formerly Subproject S-F013 03 01).

INTRODUCTION

Structural seaworthiness trials were conducted aboard WILLIS A. LEE in the North Atlantic during the period between 9 and 19 May 1966 in conjunction with sonar dome evaluation tests.

The objective of the structural seaworthiness tests was to evaluate the adequacy of present design criteria. This was accomplished by using response amplitude operators (RAO's) derived from the test results together with theoretical Neumann sea spectra to obtain prediction curves which permit estimates of maxima wave-induced responses for a particular sea state.

TEST SHIP AND INSTRUMENTATION

WILLIS A. LEE, a member of the DL-2 Class of destroyers, was especially fitted with a new type of sonar dome. The general characteristics of the ship are shown in Table 1.

Figure 1 is a cabling diagram showing the cable runs and the general location of the sensor elements. Table 2 depicts the location of the sensors and the information measured. Figure 2 shows a typical strain gage installation. A 14-channel tape recorder together with an oscillograph recorder were employed to record the response and wave information.

TABLE 1

General Characteristics of WILLIS A. LEE

Length overall	492 ft - 9 1/2 in.
Length between perpendiculars (LBP)	476 ft - 0 in.
Breadth, molded, maximum (Frame 143)	49 ft - 8 in.
Breadth, outside of plating maximum	49 ft - 9 1/4 in.
Depth, molded at side M.P. (Frame 119)	28 ft - 2 5/8 in.
Design waterline (DWL)	14 ft - 0 in.
Freeboard molded at bow to DWL	30 ft - 6 in.
Freeboard molded at stern to DWL (Frame 236 at side)	12 ft - 7 1/8 in.
Displacement to DWL (tons S.W.)	4675 tons
LCG (aft of midship section)	4.1 ft
Longitudinal radius of gyration	0.24 LBP
Coefficients of form:	
Block C_b	0.49
Midship $C_{\otimes}$	0.80
Waterplane C_{wp}	0.75
Displacement - length ratio $\Delta/(L/100)^3$, Full load,	45
Frames numbered from 0 at FP to 238 at AP	
Frame spacing is 24 in. throughout	

TABLE 2

Measuring Positions and Locations

Sensor Number	Measuring Position**	Quantity	Location
(1)*	1-10-AV	Vertical acceleration	Centerline
2	1-10-AA	Athwartship acceleration	Centerline
3	1-25-SV	Vertical strain	Port and Stbd Plating
4	1-25-SA	Athwartship strain	↓
5	2-25-SS	Shear strain	↓
6	1-50-SV	Vertical strain	↓
7	1-50-SA	Athwartship strain	↓
8	2-50-SS	Shear strain	Port and Stbd Plating
(9)	B-50-P	Pressure	Centerline
(10)	1-75-SV	Vertical strain	Port and Stbd Plating
(11)	1-75-SA	Athwartship strain	↓
12	1-100-SV	Vertical strain	↓
13	1-100-SA	Athwartship strain	Port and Stbd Plating
14	B-100-P	Pressure	Centerline
(15)	1-120-SV	Vertical strain	Port and Stbd Plating
(16)	1-120-SA	Athwartship strain	Port and Stbd Plating
(17)	2-120-AV	Vertical acceleration	Centerline
18	2-120-AA	Athwartship acceleration	Centerline
19	B-120-SV	Vertical strain	Port and Stbd Plating
(20)	B-120-P	Wave height	↓
21	1-160-SV	Vertical strain	↓
22	1-160-SA	Athwartship strain	Port and Stbd Plating
23	2-175-Rs	RPM starboard	↓
24	2-175-Rp	RPM port	↓
25	1-200-SV	Vertical strain	Port and Stbd Plating
26	1-200-SA	Athwartship strain	Port and Stbd Plating
27	1-230-AV	Vertical acceleration	Centerline
28	1-230-AA	Athwartship acceleration	↓
(29) *	3-20-PA	Pitch angle	↓
(30) *	3-20-RA	Roll angle	Centerline

*The circled quantities pertain to those quantities reported herein.

**The symbol describes the measurement; the first number of symbol refers to deck location, the second to frame position.

TEST CONDITIONS

Only a limited number of tests were conducted during the trials because of ship failure (only one screw was operable due to boiler problems) and lack of suitable environmental conditions, i.e., heavy seas. An unsteady Sea State 3 was encountered and tests were performed in this sea for 20-minute intervals at ship speeds of 4, 10, 20, and 33 knots and for five headings.

The confused character of the sea encountered made it difficult to determine specific headings. (This is explained in more detail later in this report.) Therefore only these relative headings are given and identified by the symbols A, B, and C, with Heading A employed as the reference heading. Thus Heading B is 45 deg and Heading C 90 deg relative to Heading A.

The results of tests reported herein are for the following conditions: Heading A, B, and C for ship speeds of 4 and 20 knots.

ANALYSIS

Spectral analysis is a useful method of deriving response characteristics which may be used to compare model and prototype. Briefly, a spectrum of a random process is a frequency decomposition of the process and a plot of the mean-squared value of the process per unit of frequency versus frequency.

Some of the important properties of a spectrum of a random process are given in Reference 1.* One of the most important properties of a spectrum is that the area E enclosed by the spectrum may be employed to estimate maximum peak-to-peak variations of the process.** The most useful aspect of spectral analysis is in determination of RAO's which characterize

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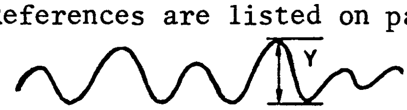
*References are listed on page 21.

** 

$Y_{max} = 2\sqrt{\text{area under spectrum x } \log_e N} = 2\sqrt{E \log_e N}$ where Y_{max} is the estimated peak-to-peak variation of the process and N is the total number of peak-to-peak variations in the process.

response from a knowledge of the excitation and response spectra. An RAO is a plot of the square of response per unit of excitation versus frequency. In the case of ships, the random excitation is the waves and the random response may be considered to be the motions of the ship and/or the accompaning structural loads (bending moment, shear force, etc.).

To directly compare model and prototype, it is advantageous to non-dimensionalize the RAO's as shown herein. Although RAO's are useful in defining the ship response characteristics, it should be emphasized here that the RAO's are valid only for the ordinary wave-induced responses, exclusive of vibratory (whipping) responses. In order to obtain the RAO for wave-induced response, the response records must be filtered so that the vibratory components are removed.

WAVE DATA

As mentioned previously, the heaviest sea condition encountered during the trials was only a Sea State 3. An examination of the wave and response records showed that a very low frequency response component was present in addition to the higher frequency response induced by the wind waves. Spectral analysis clearly indicates the presence of two distinct frequencies; see Figure 3. This is the spectrum for ship Heading A at a speed of 4 knots. Figure 4 is a wave spectrum for the same ship heading but for a ship speed of 20 knots.

At first it was assumed that the peak at the lower encounter frequency was caused by swells upon which the wind-generated waves were superimposed. However, an examination of Figures 3 and 4 shows that the low encounter frequency peak in Figure 3 has been displaced to the left and the higher encounter frequency peak in Figure 3 has been displaced to the right compared with the corresponding peaks in Figure 4. Inasmuch as ship speed is the prime difference between the two figures, it was concluded that there were actually two opposing seas simultaneously acting on the ship. The low encounter frequency peak in both figures is associated with a following sea with respect to the ship heading whereas the higher encounter frequency peak is associated with a head sea with respect to the ship heading. This is true since in a following sea, an increase in ship speed would tend to shift the peak encounter frequency represented by a following sea to a lower encounter frequency. In contrast, the peak encounter frequency represented by a head sea would tend to shift the peak encounter frequency toward the higher end of the frequency scale since the ship sees more waves in a given interval of time, i.e., the two peaks should spread apart more when going to higher ship speeds. This effect is quite apparent when Figure 3 is compared with Figure 4. From the above considerations only a general direction of the ship heading with respect to the waves can be made. Since a knowledge of the precise headings is required in obtaining the response spectra, Headings A, B, and C are assumed to represent head, quarter head, and beam seas, respectively.

The particular occurrence of the sea described above leads to other difficulties; since we wish to obtain an RAO for only a single sea condition, we eliminated the lower frequency peak by fairing after the RAO was obtained as described in the analysis section. All RAO's were faired to a zero value at an encounter frequency (circular) of 0.29 sec^{-1} (this corresponds to a wave equal to approximately five times the ship length). The RAO amplitudes also were adjusted to reflect the correction for the Tucker wave meter employed to record wave height.[2]

PRESENTATION AND DISCUSSION OF RESULTS

Figures 5 through 13 are prediction curves of response based on theoretical Neumann sea spectra for wind speeds of 20, 30, 40, 50, and 60 knots, a ship speed of 4 knots, and head, quarter head, and beam seas. The curves are obtained from the RAO's which are derived from the ratio of the response and wave spectral densities at corresponding frequencies. The RAO amplitudes are then multiplied by the Neumann spectral densities for corresponding frequencies to obtain the response spectral densities. The area E of the response and wave spectra are then determined and the root values of E for the wave input as abscissa and the root values of E for the response as ordinates are plotted as shown in the figures.

Figure 5 is a plot of midship vertical bending moment together with the line representing the hog-to-sag design bending moment of 229,600 ft-tons. The value of 50,000 ft-tons which represents the design moment in terms of $\sqrt{E}$ is obtained as follows:

$$Y_{max} = 2\sqrt{E \log_e N}$$

where Y_{max} = 229,600 ft-tons and N is the number of peak-to-peak variations (200) which occur in a record of duration equal to approximately 30 min. Substituting these values into the above formula and solving for $\sqrt{E}$, we obtain the value 50,000 ft-tons in terms of a single amplitude value.

From Figure 5, the intersection of the curve representing a head sea with the design moment line is seen to occur in the sea state 9-10 range. This sea condition, however, is rarely if ever encountered during a ship mission; hence conventional criteria has resulted in a "realistic" design moment for this ship if it is remembered that the structural transient response (whipping) has not been considered. Because of the low sea state encountered during the trials, little or no whipping response was observed. However, it is found from Reference 3 that the slope of the nondimensional whipping response ratio $\left(M_w/2\sqrt{E_{120-SV}}\right)$ is 0.1 for zero ship speed. If the values in Figure 5 are adjusted to include the whipping response, then the total moment response is that given by the dashed line in Figure 5. This shows that the intersection of the design moment line with the line representing the total moment occurs in a Sea State 7 and this is a realizable sea. Figure 5 was employed instead of Figure 14 because it gives more conservative results. The ship may possibly be able to withstand one or two such loads, but if several such loads are applied in succession or if superposition of two such loads in phase occurs, buckling of the main hull girder is a possibility.[4,5] Reference 5 contains tests results reported on the sister ship USS WILKINSON (DL-5). WILKINSON experienced a low Sea State 7 and incurred buckling of the deckhouse longitudinals during a run. The run was terminated after 1 min. because of the danger of damage to the ship. It appears quite evident that if the test had not been discontinued, serious structural damage to the main hull girder might have occurred.

Figures 14 through 22 are similar to Figures 5 through 13 except that ship speed is 20 knots. Because of the variability and confusion of the sea encountered, trends with ship speed as well as heading are difficult to assess. Figures 3 and 4 show the variability of the sea.

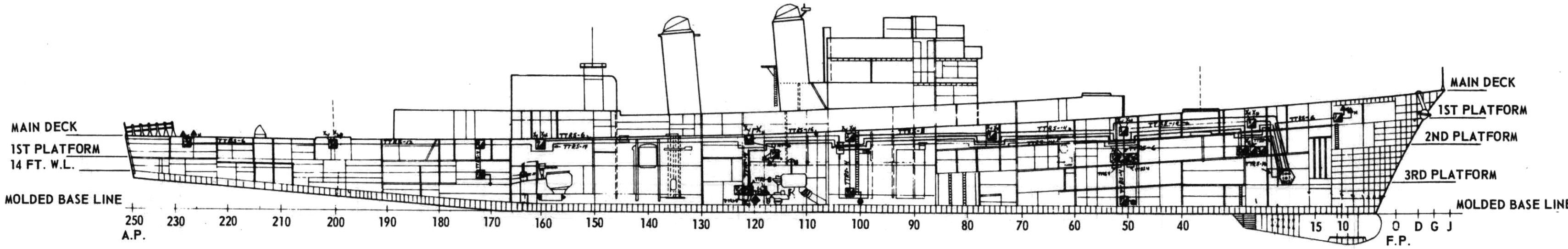
Figures 23 through 31 are plots of RAO's for ship speed of 4 knots and for the 3 heading conditions A, B, and C as defined earlier. The values are given in terms of full-scale and nondimensional units.

CONCLUSION

Theoretical Neumann sea spectra together with midship vertical bending moment RAO shows that present design criteria are realistic when only ordinary wave-induced responses are considered. However, if whipping response is included in the wave-induced response, then the hull girder strength may not be adequate and therefore whipping response becomes of primary importance.

ACKNOWLEDGMENTS

The author wishes to thank Mr. A. Dinsenbacher of the Surface Ship Structures Division for his help during the pretrial calibration, for his assistance in preparing the cabling diagrams, and for his help in the analysis and data reduction portion of this work. Thanks are extended to Mr. J. Daniel of the Industrial Department who supervised the preparation of the instrumentation suit and who, together with Messrs A. Chalk and J. Gregson, assisted in the installation of instrumentation and recording of the information during the trial period. Thanks are also expressed to Mr. J. Hardison of the Surface Ship Structures Division who was primarily responsible for the strain gage installation. Lastly, the effort of Mr. M. Chernick of the Applied Mathematics Laboratory is gratefully acknowledged. His effort enabled the analysis to be performed in a very short time.



- ● PRESSURE TRANSDUCER (BOTTOM, ℄)
- ⬡ RECORDING ROOM AREA AND JUNCTION BOXES (3)
- ◪ ℄ JUNCTION BOX AND NUMBER (n)
- ▨ PORT OR STARBOARD JUNCTION BOX AND NUMBER (n)
- ◆ WAVE HEIGHT TRANSDUCER (EITHERSIDE)
- $\times_V$ STRAIN (VERTICAL)
- $\times_H$ STRAIN (HORIZONTAL)
- $\times_S$ STRAIN (SHEAR)
- $\blacktriangle_V$ ACCELERATION (VERTICAL)
- $\blacktriangle_H$ ACCELERATION (HORIZONTAL)
- ↓ RPM PICKUP

Figure 1 – Cable Runs and General Location of Sonar Elements

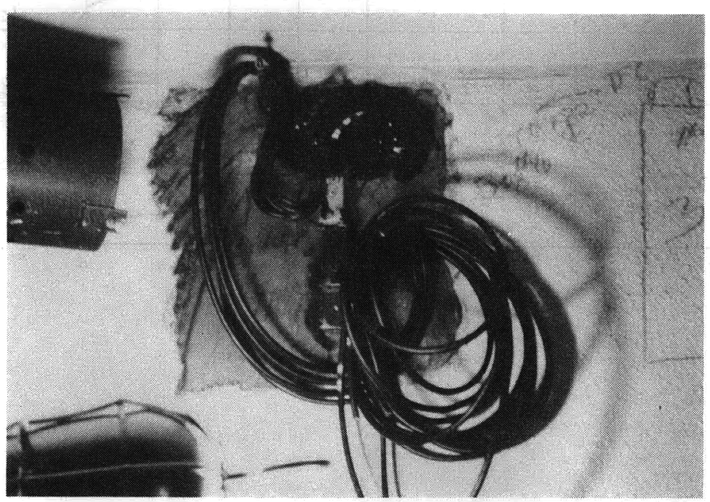


Figure 2 – Typical Strain Gage Installation

Port; Frame 120; Gage Location, 1.6 Ft Fwd Frame 120 3 Inches from Deck

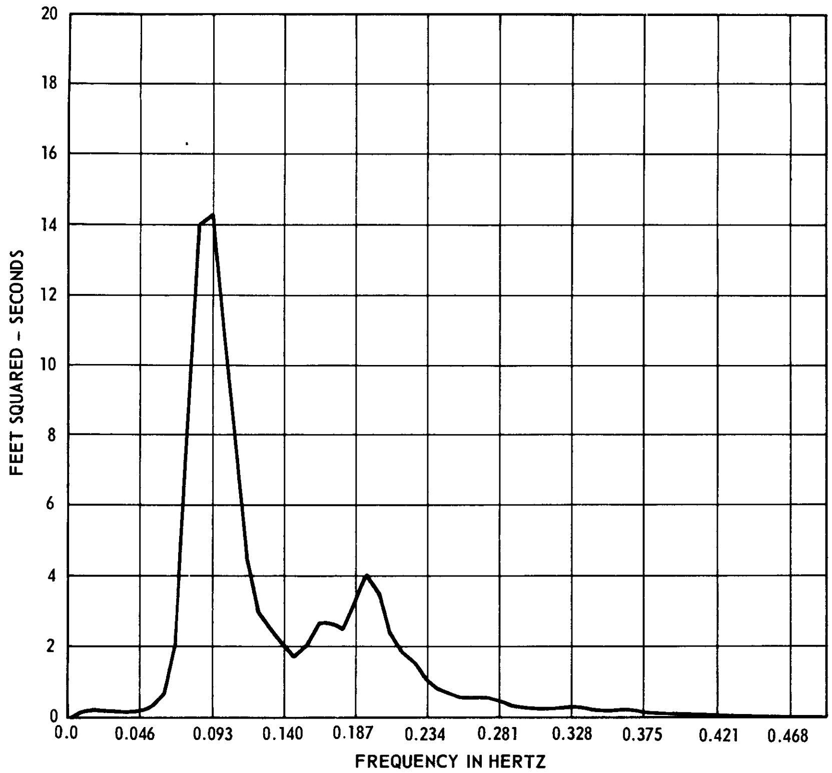


Figure 3 – Wave Spectrum for Heading A and Ship Speed of 4 knots

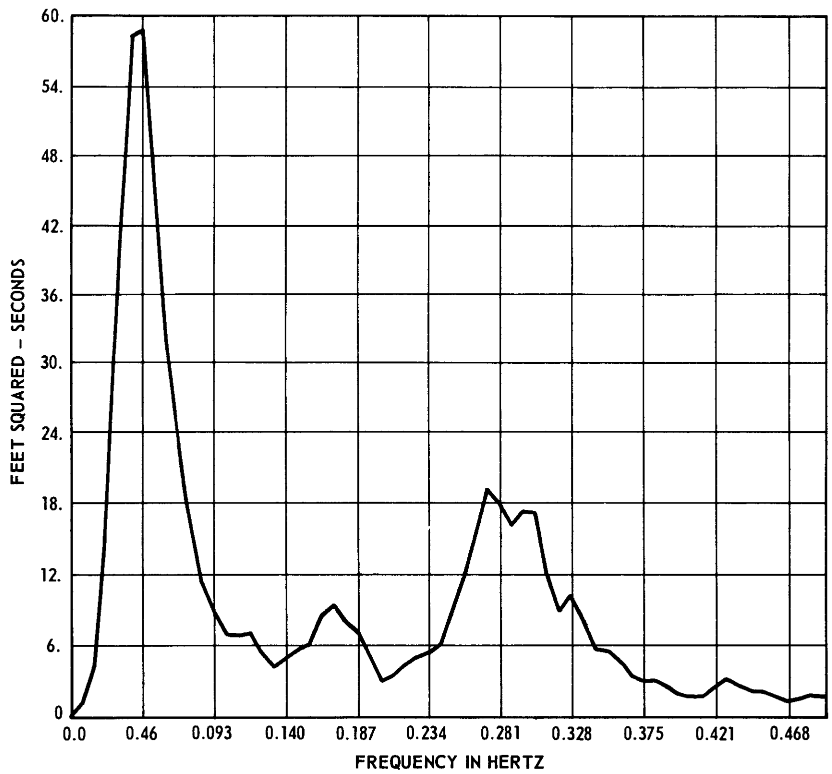
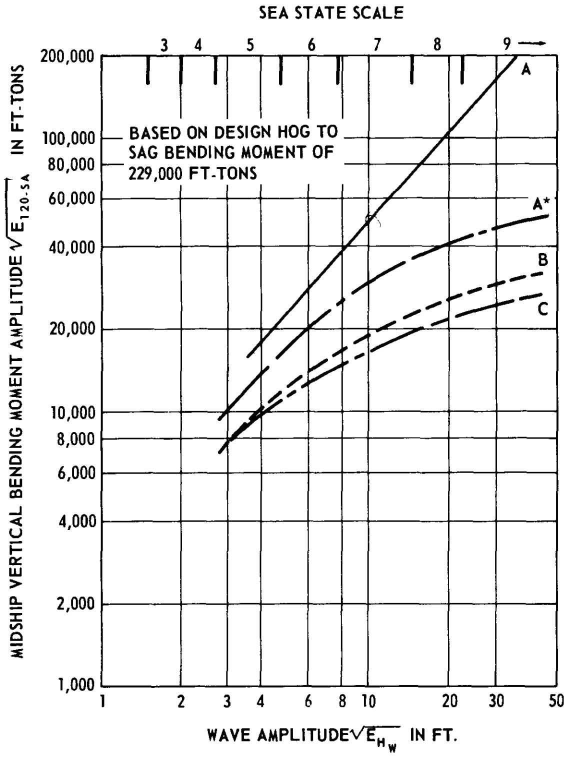


Figure 4 – Wave Spectrum for Heading A and Ship Speed of 20 knots



*SYMBOLS A, B AND C REFER TO HEADINGS AS DEFINED IN THE TEXT.

Figure 5 – Midship Vertical Bending Moment for Ship Speed of 4 knots

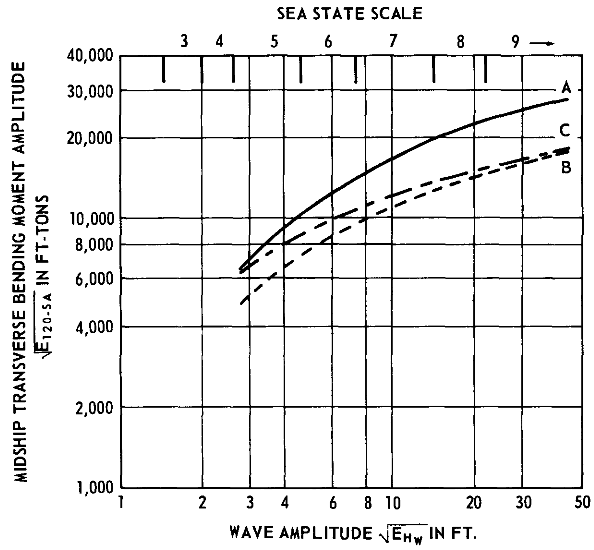


Figure 6 – Midship Transverse Bending Moment for Ship Speed of 4 knots

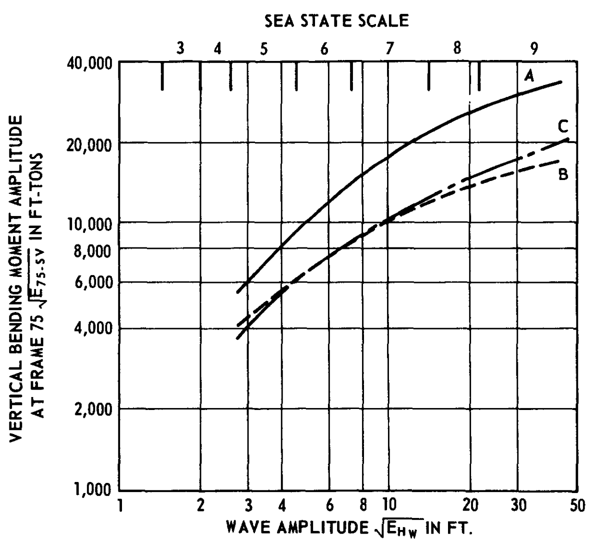


Figure 7 – Vertical Bending Moment at Frame 75 for Ship Speed of 4 knots

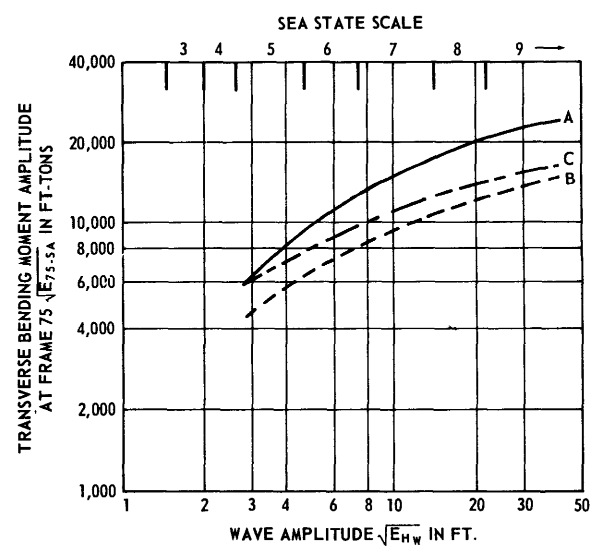


Figure 8 – Transverse Bending Moment at Frame 75 for Ship Speed of 4 knots

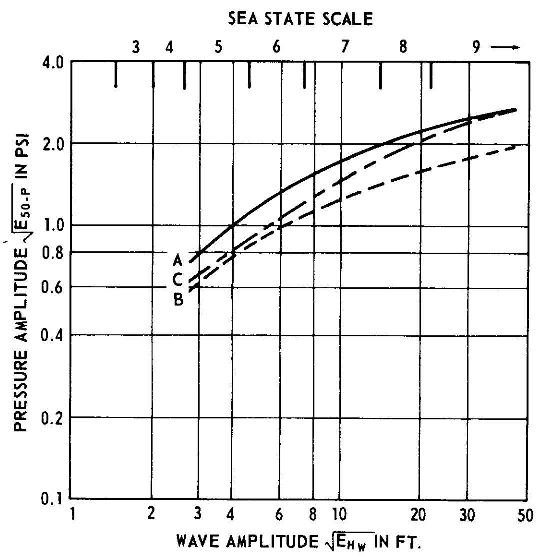


Figure 9 – Bow Pressure for Ship Speed of 4 knots

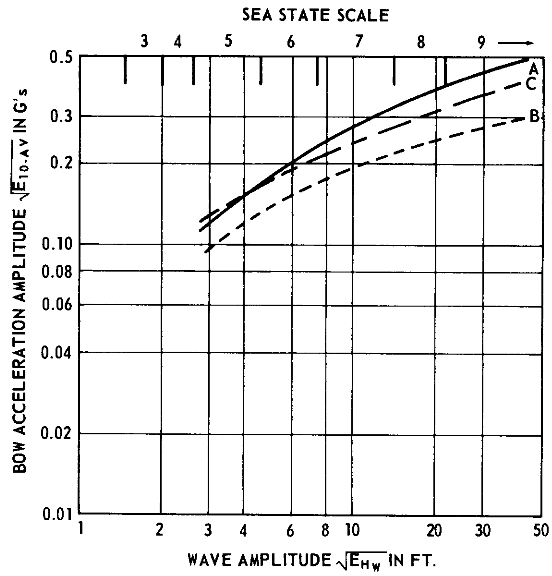


Figure 10 – Bow Acceleration for Ship Speed of 4 knots

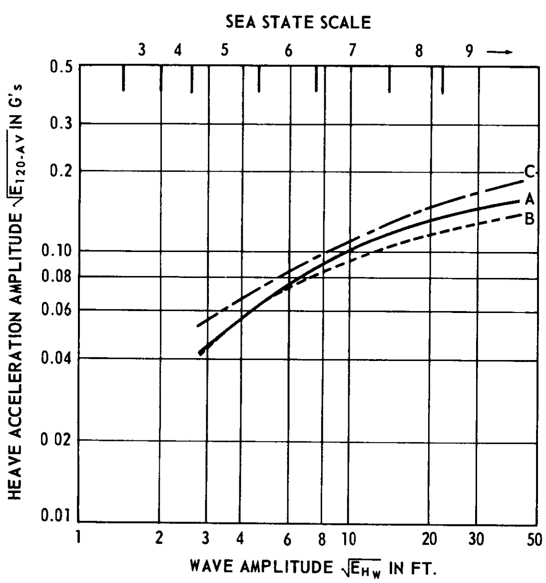


Figure 11 – Heave Acceleration for Ship Speed of 4 knots

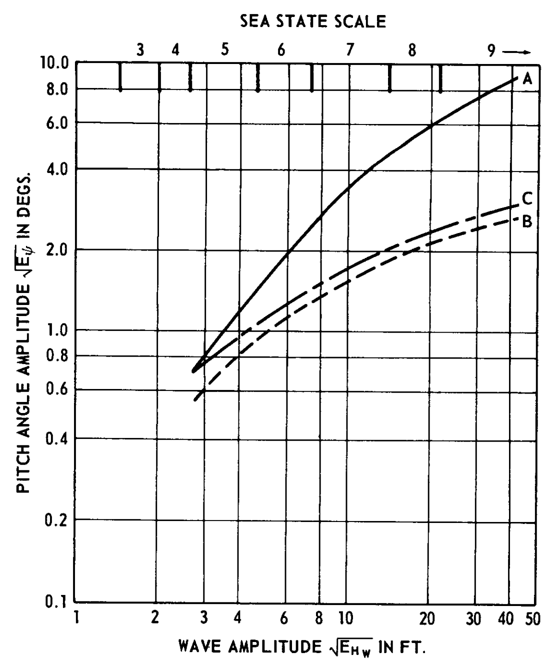


Figure 12 – Pitch Angle for Ship Speed of 4 knots

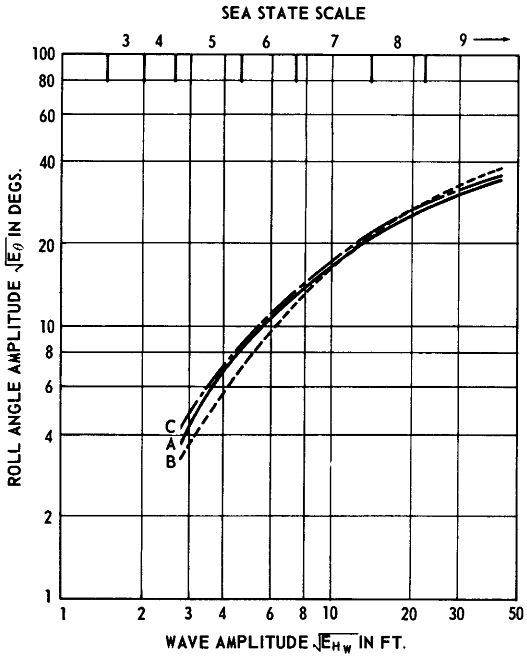


Figure 13 – Roll Angle for Ship Speed of 4 knots

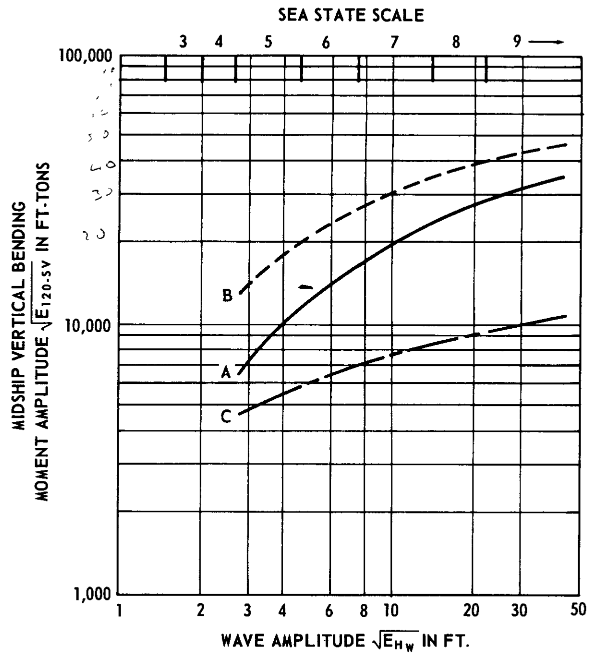


Figure 14 – Midship Vertical Bending Moment for Ship Speed of 20 knots

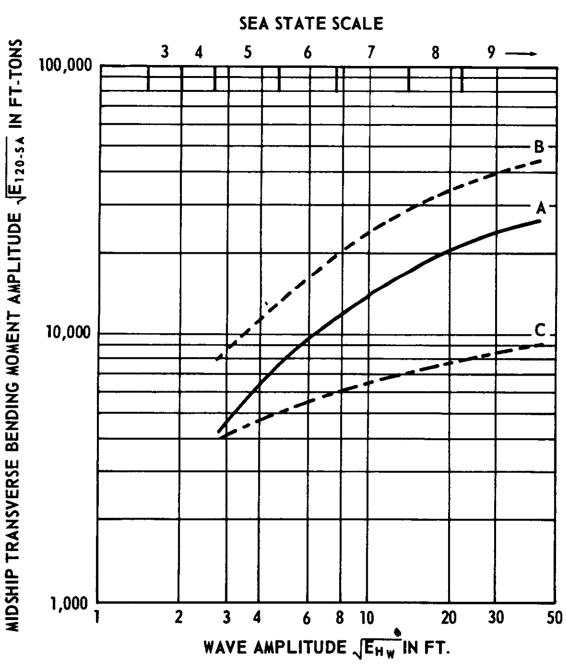


Figure 15 – Midship Transverse Bending Moment for Ship Speed of 20 knots

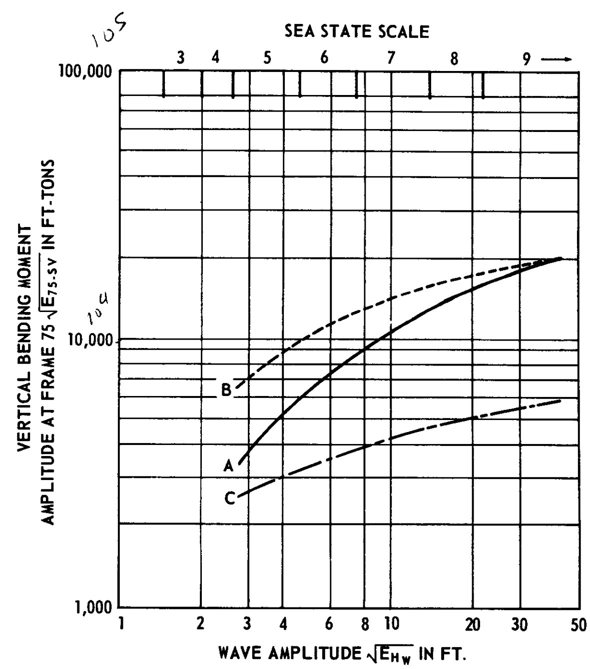


Figure 16 – Vertical Bending Moment at Frame 75 for Ship Speed of 20 knots

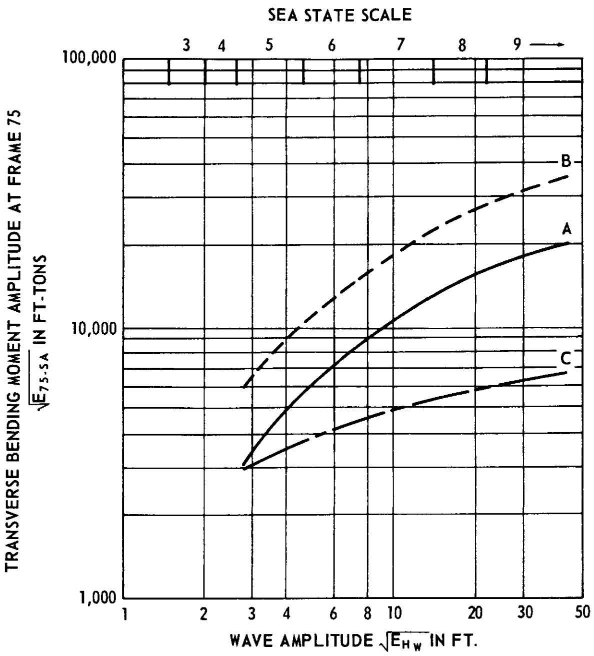


Figure 17 – Transverse Bending Moment at Frame 75 for Ship Speed of 20 knots

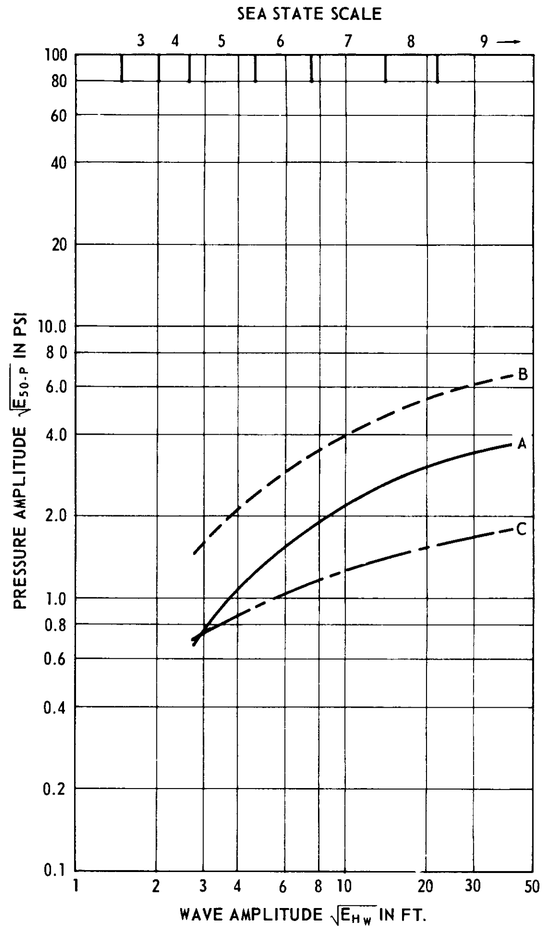


Figure 18 – Bow Pressure for Ship Speed of 20 knots

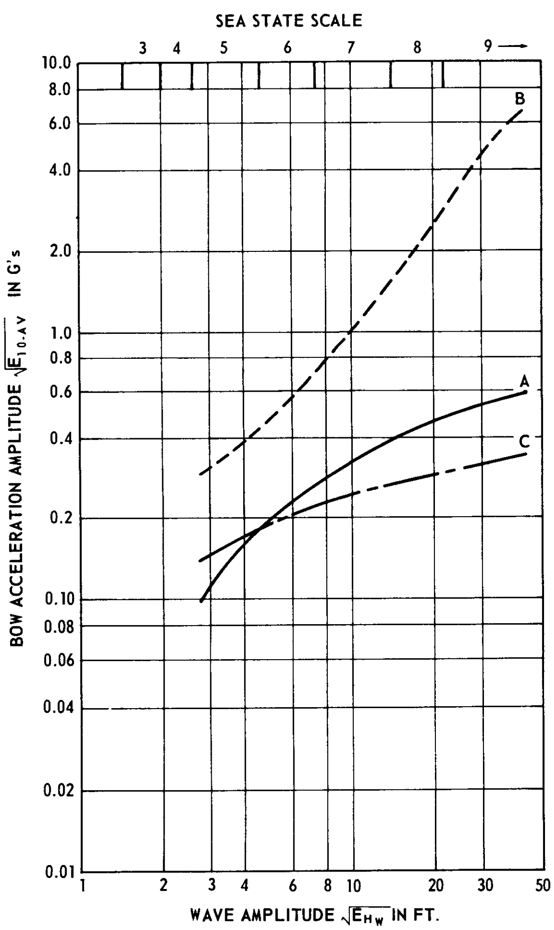


Figure 19 – Bow Acceleration for Ship Speed of 20 knots

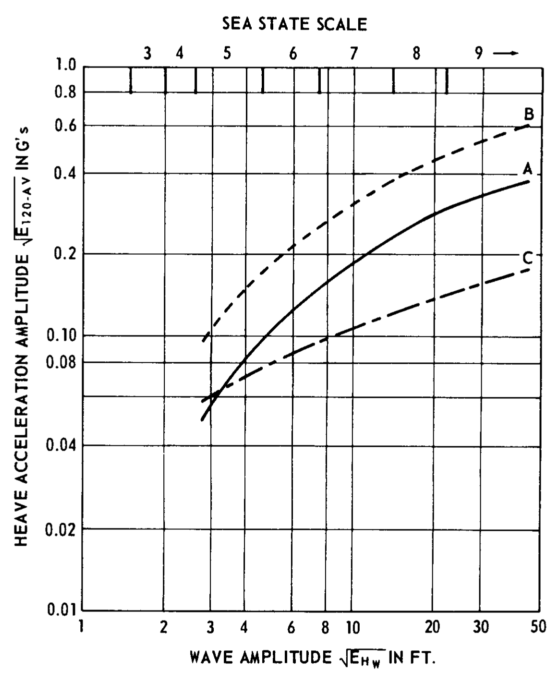


Figure 20 – Heave Acceleration for Ship Speed of 20 knots

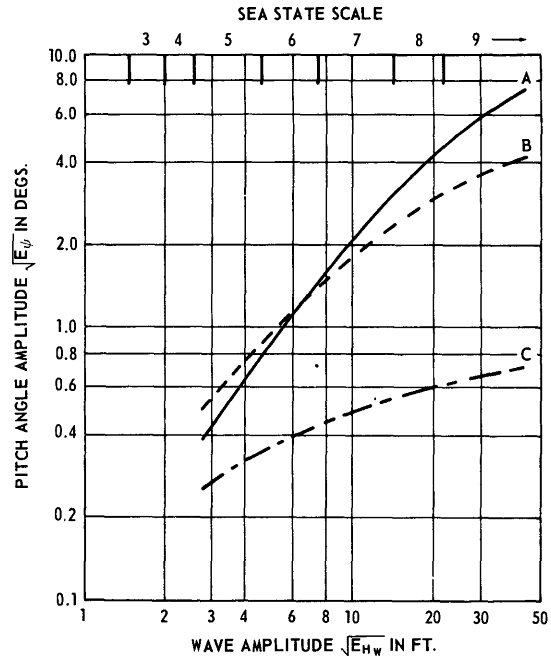


Figure 21 – Pitch Angle for Ship Speed of 20 knots

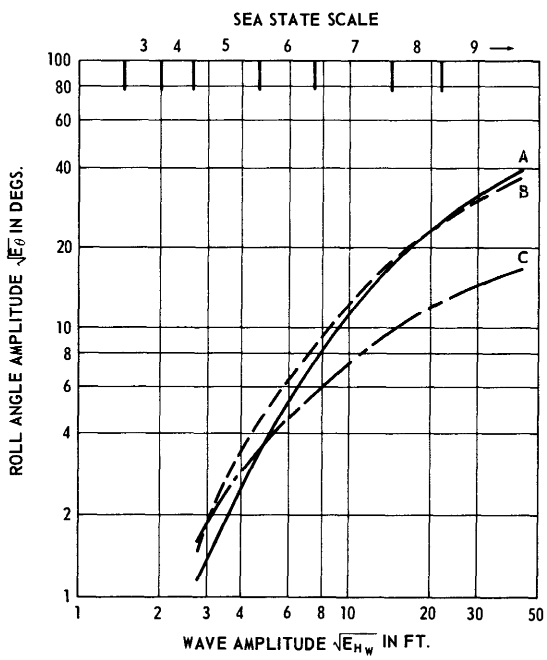


Figure 22 – Roll Angle for Ship Speed of 20 knots

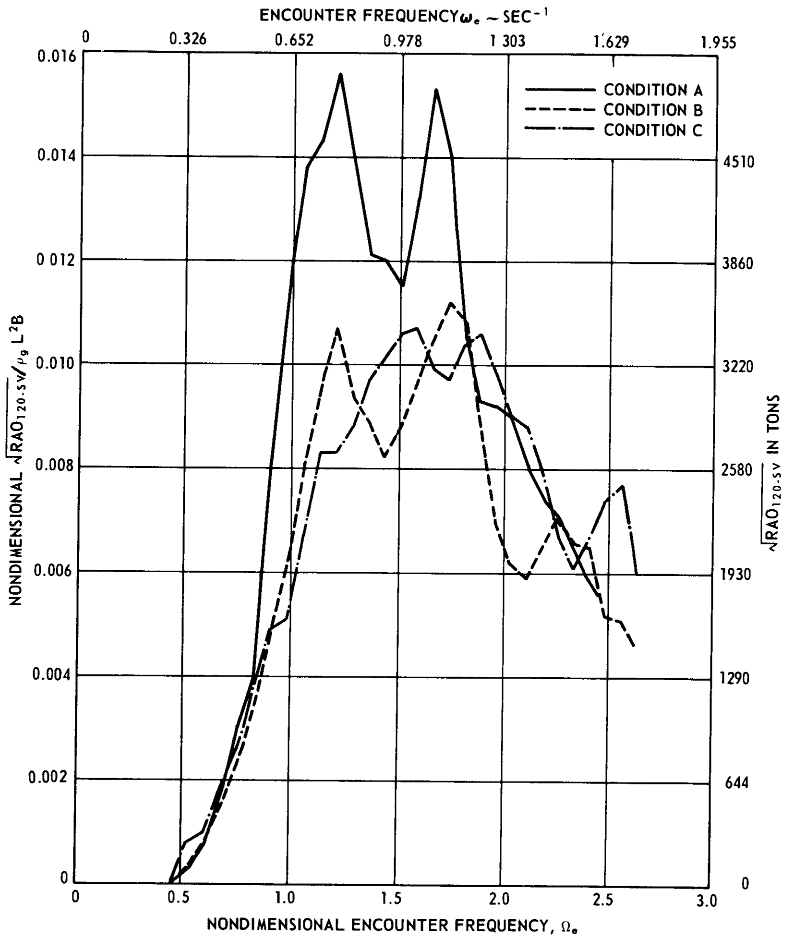


Figure 23 – Root of Midship Vertical Bending Moment RAO for 4-knot Ship Speed

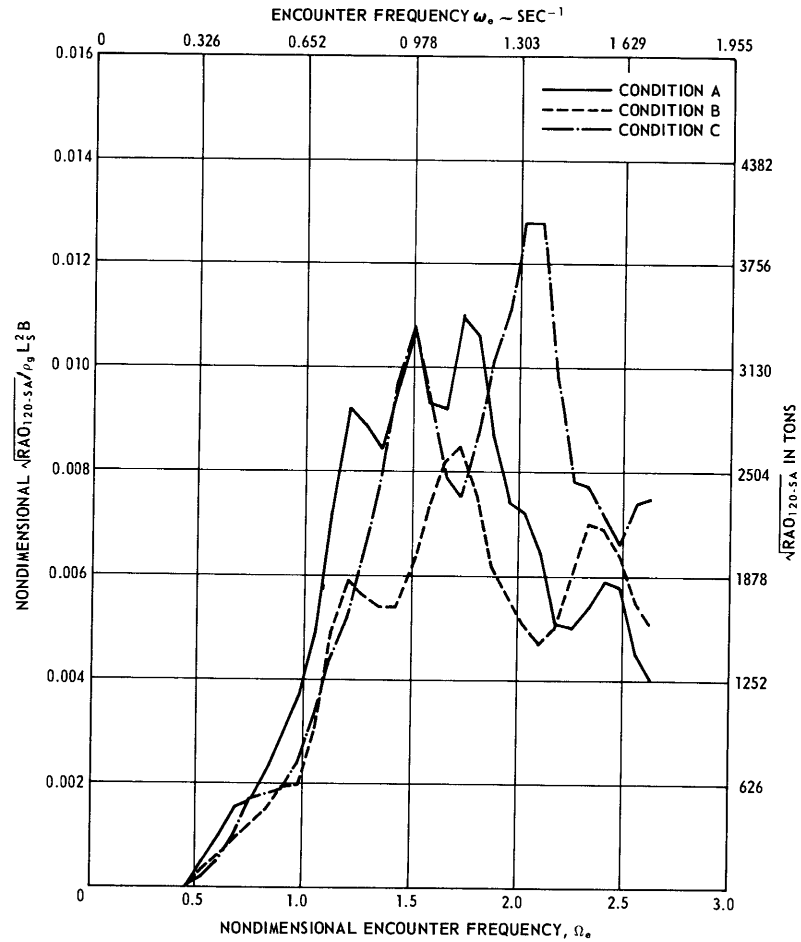


Figure 24 – Root of Midship Transverse Bending Moment RAO for 4-knot Ship Speed

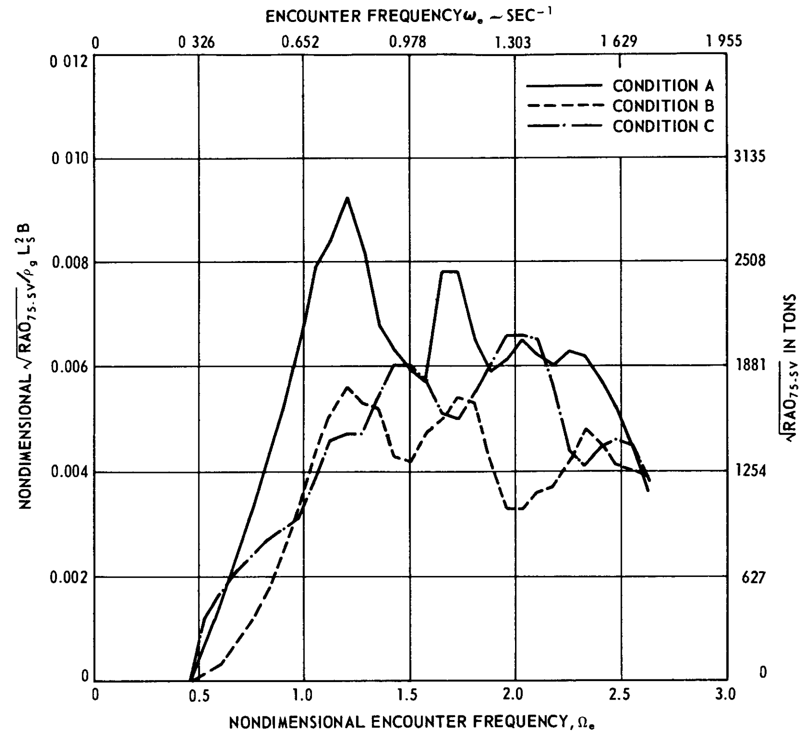


Figure 25 – Root of Forward Vertical Bending Moment RAO for 4-knot Ship Speed

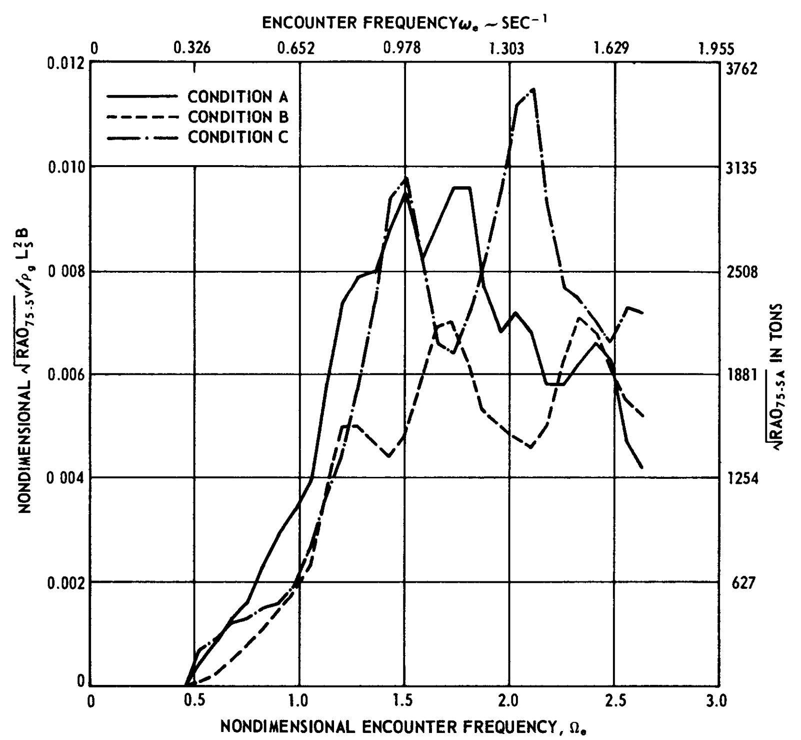


Figure 26 – Root of Forward Transverse Bending Moment RAO for 4-knot Ship Speed

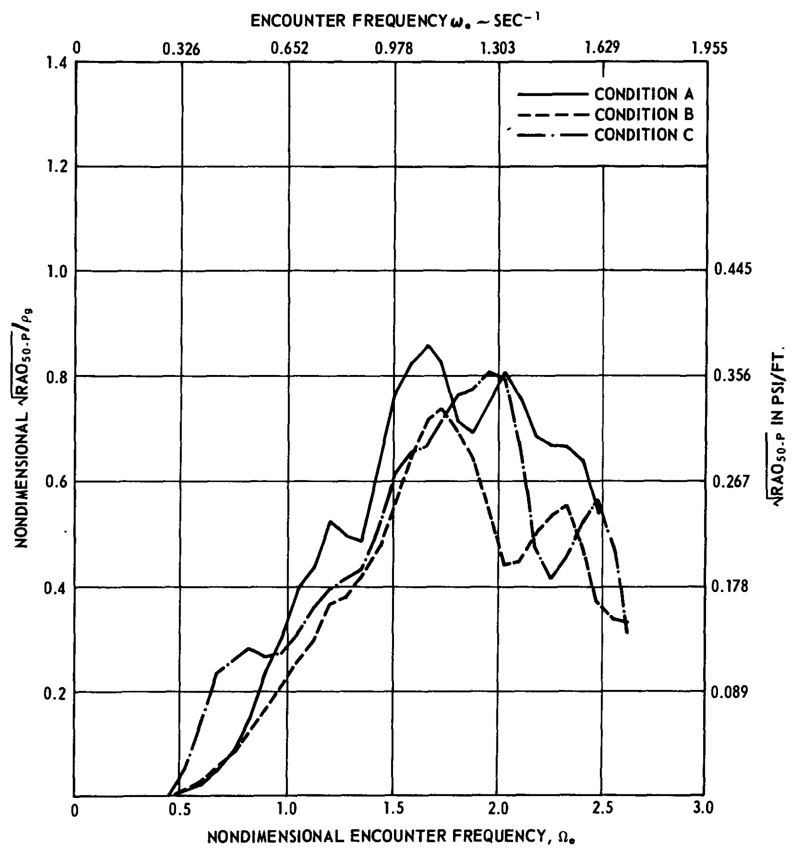


Figure 27 – Root of Pressure RAO for 4-knot Ship Speed

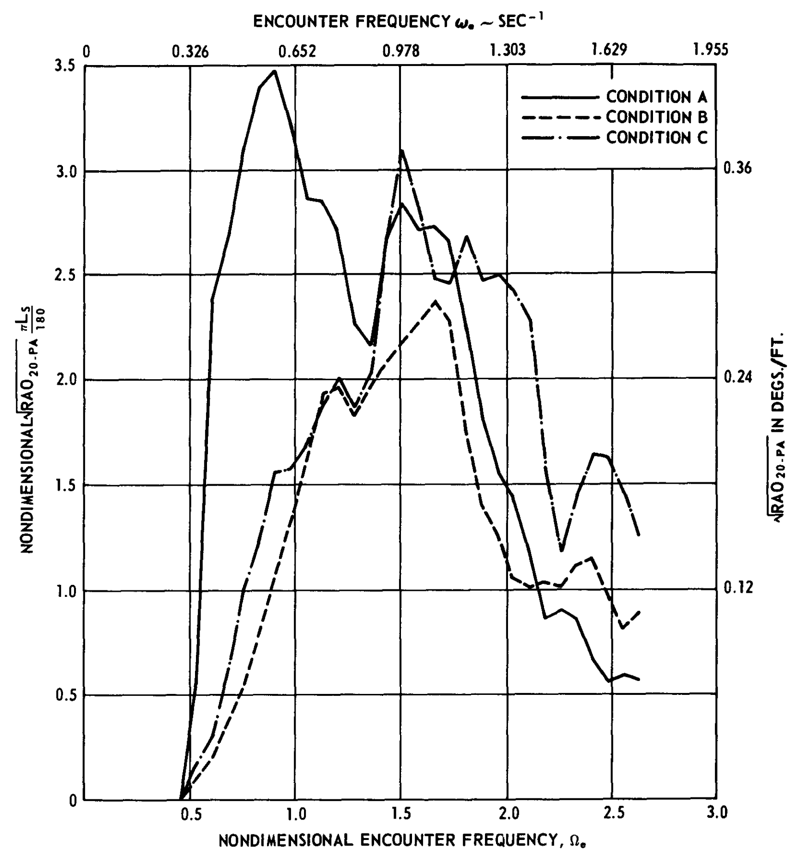


Figure 28 – Root of Pitch Angle RAO for 4-knot Ship Speed

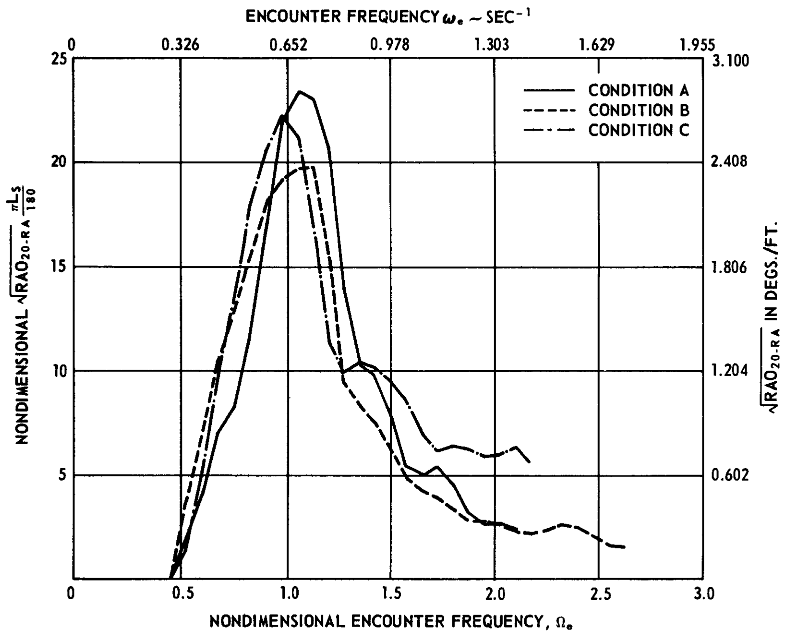


Figure 29 – Root of Roll Angle RAO for 4-knot Ship Speed

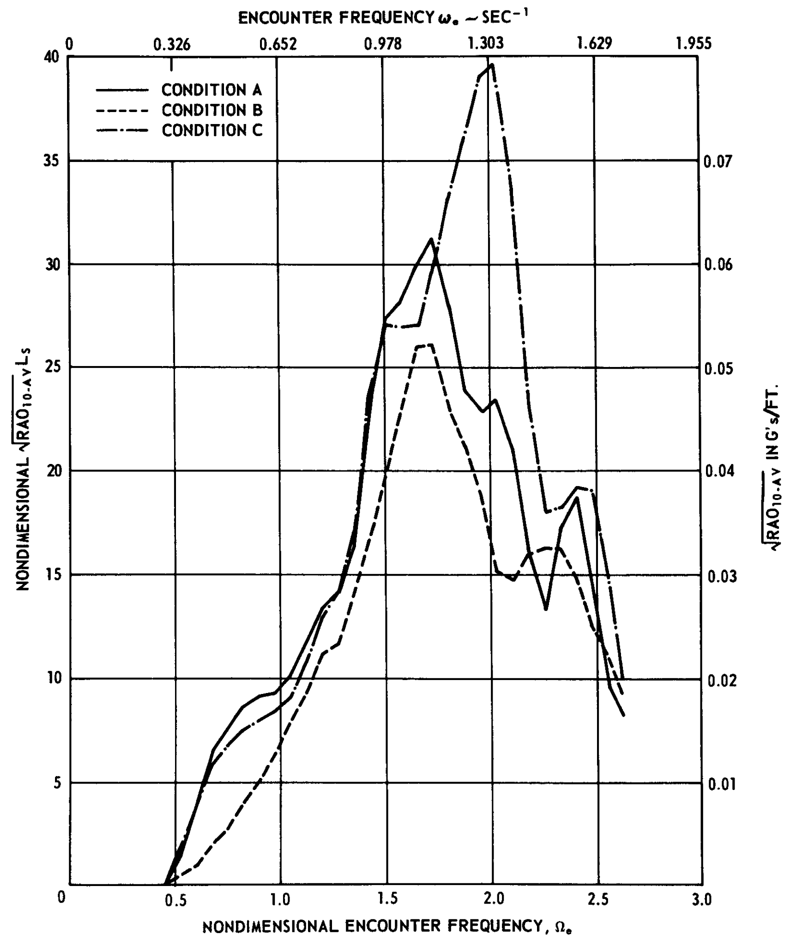


Figure 30 – Root of Bow Vertical Acceleration RAO for 4-knot Ship Speed

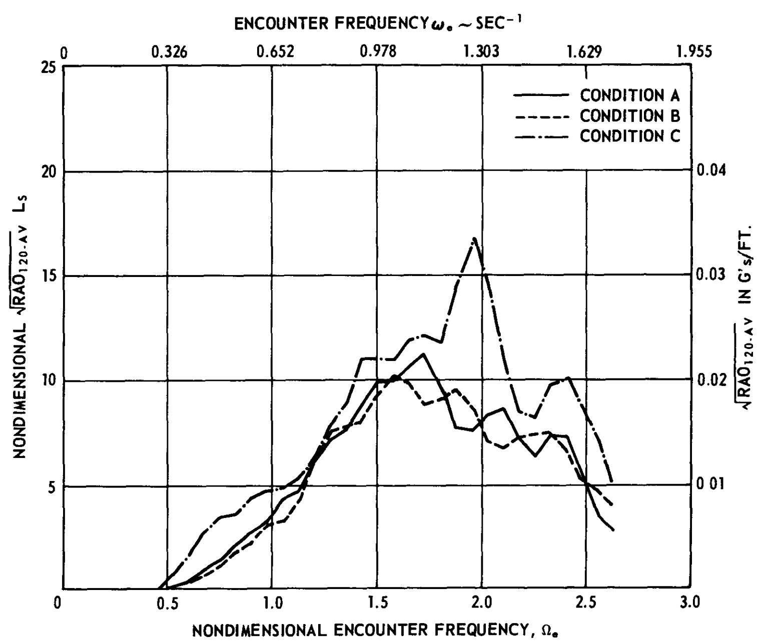


Figure 31 – Root of Heave Acceleration RAO for 4-knot Ship Speed

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13. ABSTRACT

This report presents test results derived from trials conducted aboard USS WILLIS A. LEE (DL-4) in the North Atlantic.

Response amplitude operators, obtained from test data, and theoretical wave spectra are utilized to produce prediction curves for ship responses.

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