SSC-201

MIDSHIP WAVE BENDING MOMENTS IN A MODEL OF THE CARGO SHIP "WOLVERINE STATE" RUNNING AT OBLIQUE HEADINGS IN REGULAR WAVES

SHIP STRUCTURE COMMITTEE

SEPTEMBER 1969

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U.S. COAST GUARD HEADQUARTERS
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September 1969

Dear Sir:

Ship model studies were undertaken by the Ship Structure Committee to determine if models of actual ships traveling through similar, but towing-tank sea states experienced strains and bending moments corresponding to those of ships in real seas. The results of the towing-tank data on one of the ships, the *Wolverine State*, are presented herein. Another study has tentatively reported that these data are comparable to those obtained for the actual ship.

This report is being distributed to individuals and groups associated with, or interested in, the work of the Ship Structure Committee. Comments concerning this report are solicited.

Sincerely,

C. P. Murphy
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-201

Technical Report
to the
Ship Structure Committee
on
Project SR-165 "Bending Moment Determination"

MIDSHIP WAVE BENDING MOMENTS IN A MODEL OF THE CARGO SHIP "WOLVERINE STATE" RUNNING AT OBLIQUE HEADINGS IN REGULAR WAVES

by

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under

Department of the Navy
NAVSEC Contract 92299

U. S. Coast Guard Headquarters
Washington, D. C.

September 1969

ABSTRACT

Vertical and lateral wave bending moments were measured at the midship section of a 1/96-scale model of the C4-S-B5 cargo ship WOLVERINE STATE. The model was self-propelled through a ship speed-range of 8 to 17 knots at seven headings to regular waves of lengths between 0.3 and 1.8 times the length between perpendiculars; moderate wave heights not exceeding 1/50 of the model length were used. Results are presented in charts of moment-amplitude/wave-amplitude versus ship speed,with wave length as the parameter. Two ship conditions, light load and full load, are covered.

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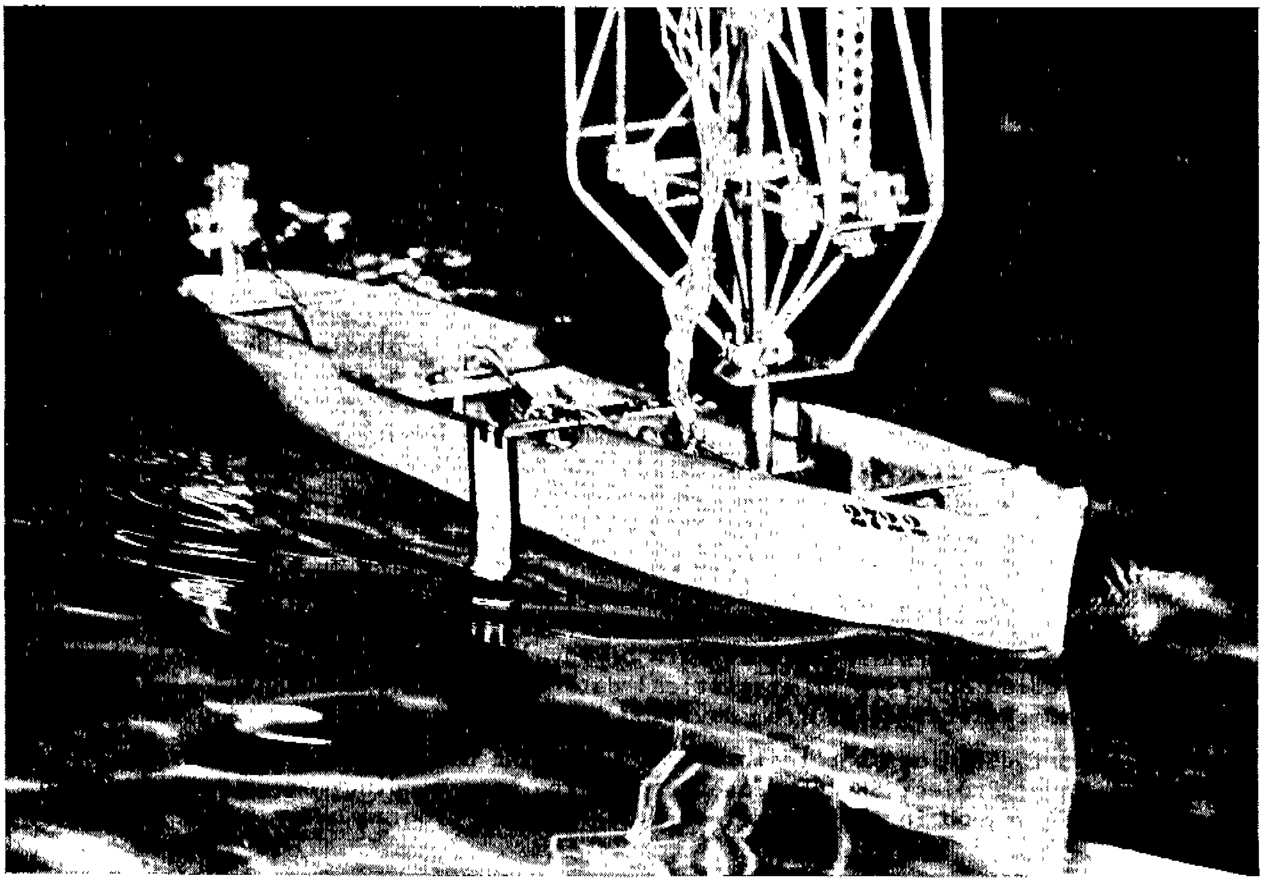

MODEL OF "WOLVERINE STATE" RUNNING IN OBLIQUE WAVES

INTRODUCTION

In 1960 the Ship Structure Committee authorized Davidson Laboratory to initiate a research program entitled "Bending Moment Determination," using ship-model tests to investigate hull bending moments in regular and irregular waves.

The initial phase of this program, Project SR-157, covered investigations of trends of midship bending moment as a function of wave steepness in models of (1) a MARINER-class cargo ship with variations in freeboard and weight distribution, (2) a destroyer, and (3) a tanker. Dalzell [1,2] concluded that, within practical operational and design limits, no dramatic upper limit of wave bending moments at amidships is to be expected as the ratio of wave height to wave length increases to a value of about 1:9.

Since this conclusion was limited to midship bending moments, and it was known that maximum moments under certain circumstances could occur elsewhere, the next phase of the study, Project SR-165, examined the longitudinal distribution of bending moments in a MARINER-class cargo-ship model in regular waves of extreme steepness. Maniar [3,4] concluded that, within practical operational limits of speed for the MARINER, maximum wave bending moments would occur in the region from amidships to 0.125L aft of amidships. Thus the practice of concentrating on midship bending moments both in design studies and in full-scale measurements appears to be justified.

Another part of the investigation involved the testing of the MARINER model in high irregular waves to obtain time history records of wave bending moment and wave elevation. Wave and bending moment energy-spectra were computed and used to derive equivalent regular-wave bending-moment "response operators" which were shown to be in reasonable agreement with response results obtained from model tests in regular waves.

Such favorable agreement inspires confidence in the alternate procedure of using a "response operator" from tests in regular waves to predict the energy spectrum of bending-moment response of either a ship model in a known wave-spectrum or a ship in a real seaway the energy spectrum of which can be determined. Before taking this latter step, however, it is necessary to demonstrate satisfactory correlation between model and ship bending-moment responses.

Over a period of years, full-scale statistical data on midship bending-moment responses have been collected by the Teledyne Materials Research Company (under Project SR-153), on the cargo vessel WOLVERINE STATE operating on the United States-Northern Europe route in the North Atlantic Ocean. Davidson Laboratory proposed the conduct of scale-model tests of this vessel in regular waves, to obtain bending-moment response operators. Webb Institute of Naval Architecture, in a parallel effort, proposed an analysis of statistical data for the ship and the prediction of ship bending-moment statistics from Davidson Laboratory's model-test results.

This report describes the tests of the WOLVERINE STATE model at Davidson Laboratory, under Project SR-165, and presents the wave-bending-moment results which have been used by Webb in their model-ship correlation program under Project SR-171.

DESCRIPTION OF THE EXPERIMENT

Model

A 1/96-scale wooden model of the WOLVERINE STATE was constructed according to U. S. Maritime Commission Drawing C4-S-B1, S5-0-1, Lines Plan. Figure 1 is the body plan. The model was cut amidships, at a point corresponding to a location 6 inches forward of the ship's frame-104 or 248 feet aft of the ship's fore perpendicular. An electric propulsion motor was installed to turn a stock, four-bladed propeller of approximately the desired scale diameter. The rudder was built to scale and was operated by a servomotor which formed part of an automatically controlled steering system.

The two halves of the model were connected by the standard Davidson Laboratory two-component bending-moment balance. This balance consists of two pedestals with an integral flexure beam of cruciform cross-section milled from a single block of aluminum alloy. The componental deflections of the beam in its vertical and lateral planes of symmetry are mechanically amplified by linkages and sensed by linear variable differential transformers. Figure 2 is a sketch of the balance.

Loading Conditions

Two representative loading conditions were used for ballasting the model. The first represented a typical low-density, dry-cargo loading resulting in a displacement

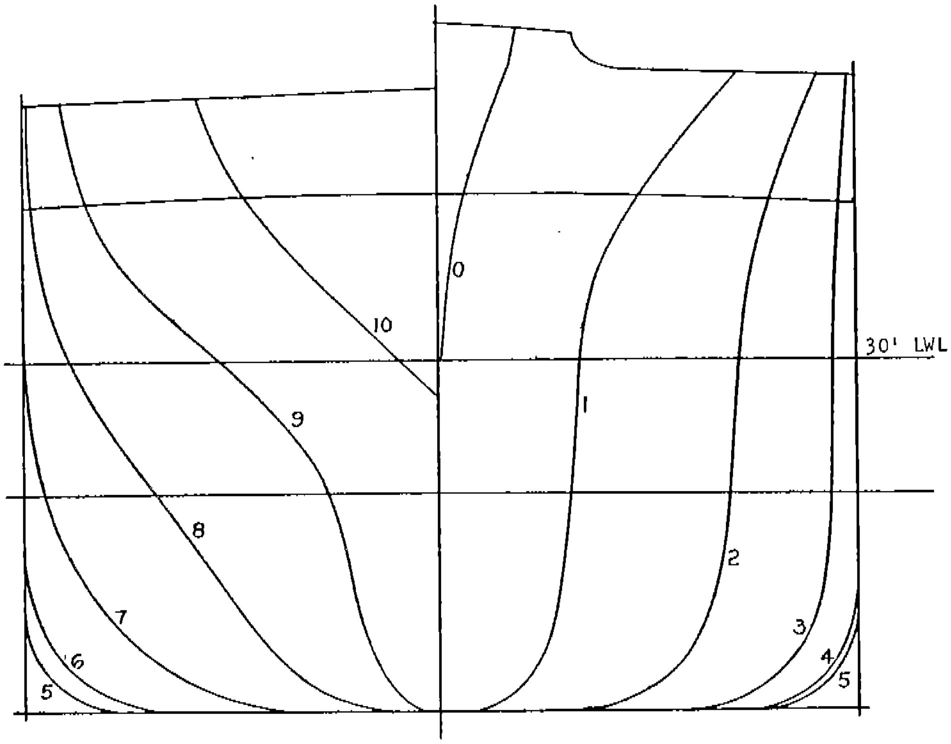

Fig. 1. Body Plan of WOLVERINE STATE

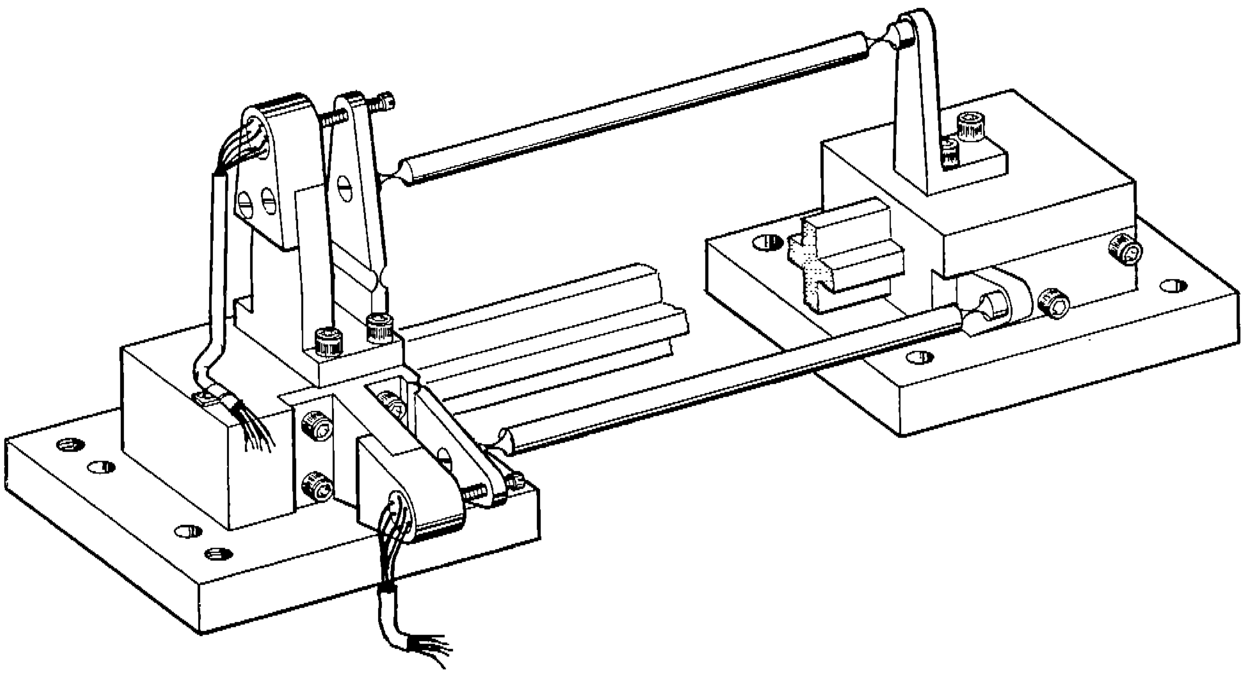

Fig. 2. Vertical and Lateral Bending Moment Balance

of 12,105 tons at a mean draft of 19'3" with a trim of 4'5" by the stern. Figure 3 is the weight-distribution diagram based on an average of eastbound and westbound voyage data supplied by the States Marine Lines.

The second condition was meant to represent a full load of cargo giving a displacement of 19,875 tons at an even-keel draft of 30'0". This loading was adapted from the 32'10" draft condition shown in the States Marine Lines booklet Ballasting and Stability, Type C4-S-B5, by decreasing the assumed density of homogeneous cargo. Figure 4 is the resulting weight-distribution diagram. Both light load and full load include 1,970 tons of permanent ballast in No. 3 Deep Tank.

Each diagram was integrated to obtain, for the fore and aft halves of the ship, the weight, the longitudinal center of gravity (LCG), and the weight inertia about the LCG. The pitch gyradius for each half was derived from the weight inertia.

To simulate a given loading condition, each model-half was ballasted to the desired scaled values of weight, LCG, and pitch gyradius. Gyradius was checked by suspending each model-half from a knife edge, oscillating it as a compound pendulum, and measuring its natural period. With period and distance-from-knife-edge-to-CG known, the gyradius could be calculated. Tare weights were substituted for the bending-moment balance to permit separate ballasting of the model-halves.

The vertical center of gravity of each half was adjusted to a common value based on the assumed loading. Ballast was adjusted laterally to obtain the scaled value of the natural rolling period of the complete model. The midships cut was sealed with thin sheet-rubber taped to both halves of the model. Ship characteristics are tabulated below.

TABLE OF SHIP CHARACTERISTICS

Length Between Perpendiculars, ft	496.0
Beam, ft	71.5

	Light Load	Full Load
Displacement, long tons	12,105	19,875
Draft		
Fore perpendicular, ft	17.1	30.0
Aft perpendicular, ft	21.5	30.0
LCG forward of amidships, ft	0.74	3.20
Pitch radius of gyration, ft	125.0	116.5
Natural rolling period, sec	12.0	16.5
Forebody		
Displacement, long tons	6,070	10,325
LCG forward of amidships, ft	107.0	96.6
Pitch gyradius, ft	62.5	61.3
VCG above baseline, ft	22.5	25.5
Afterbody		
Displacement, long tons	6,035	9,550
LCG aft of amidships, ft	106.0	97.8
Pitch gyradius, ft	67.0	67.2
VCG above baseline, ft	22.5	25.5

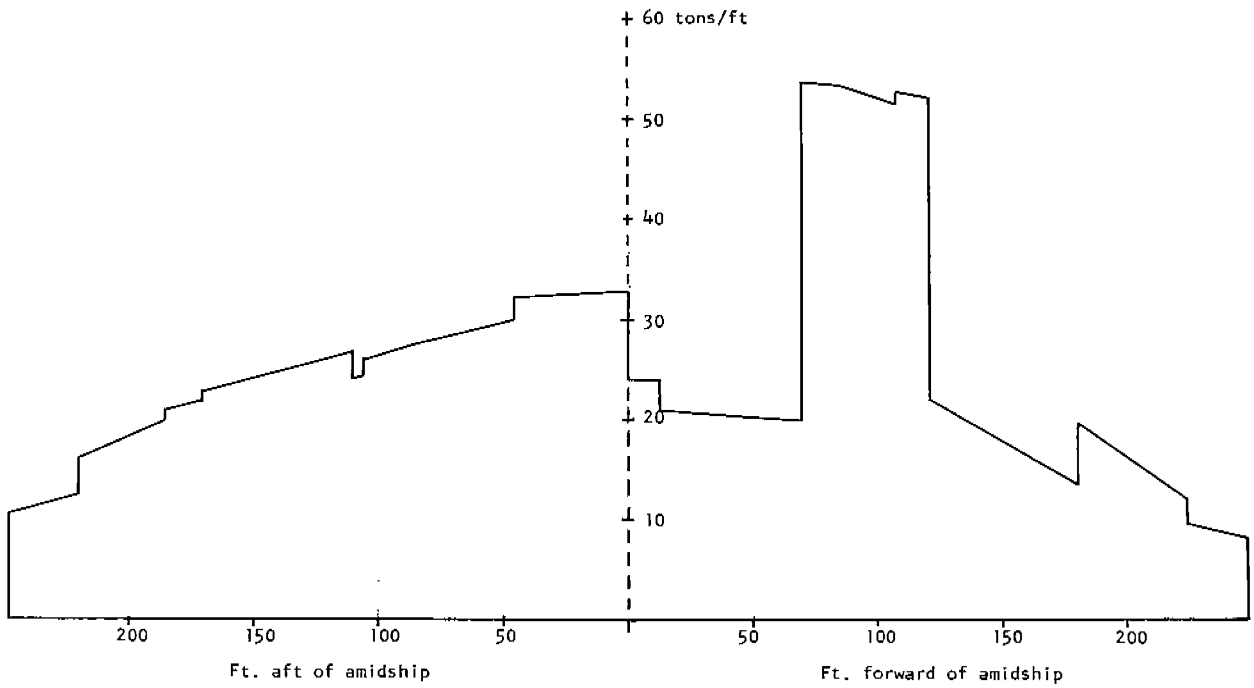

Fig. 3. Weight Distribution Diagram, Light Load

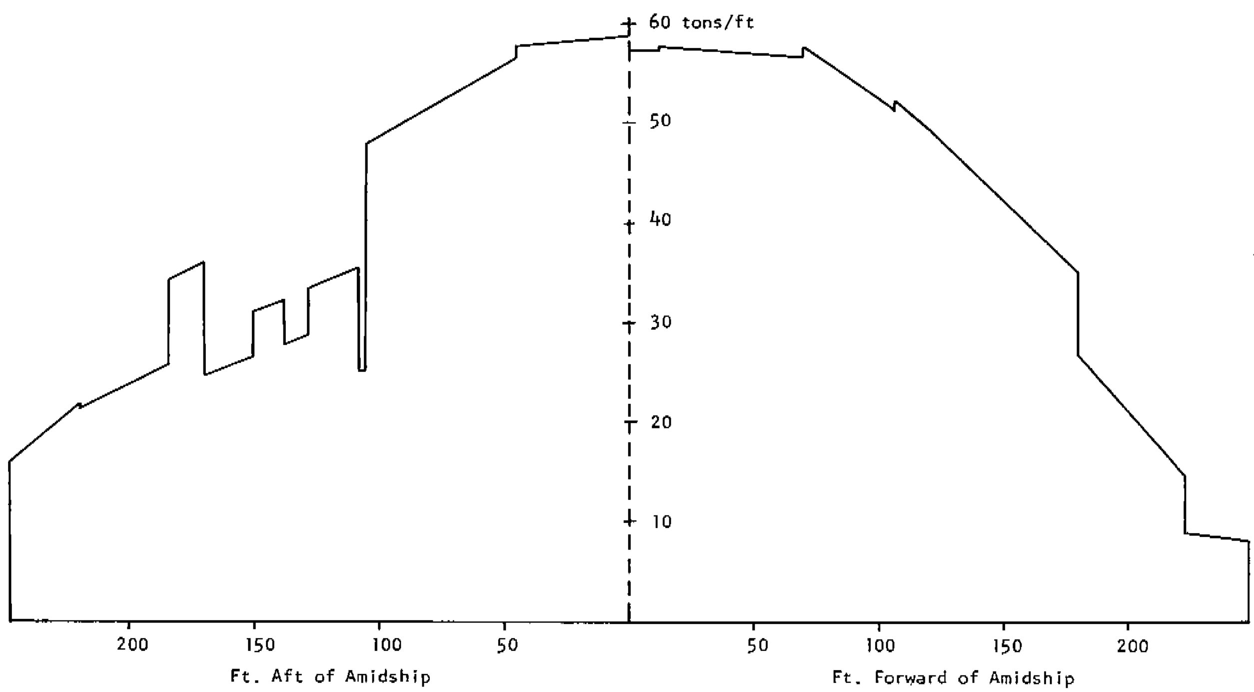

Fig. 4. Weight Distribution Diagram, Full Load

Apparatus

The experiment was conducted in Davidson Laboratory's Tank 2 (75' x 75' x 4.5'). This facility includes a wavemaker along one 75-foot side of the tank, a wave absorber along the opposite side, and a movable bridge spanning the tank. The bridge supports a monorail carriage driven by a servo-controlled motor.

Suspended from the carriage is a six-degree-of-freedom motions apparatus which is servo-driven to follow a self-propelled, automatically steered model in waves. A vertical heave rod rides in bearings on the apparatus and is attached to the model through a three-degree-of-freedom gimbal. Power and control wires for the rudder and propulsion motors, as well as signal cables from the bending-moment balance, are led upward to the carriage and thence to a recording and control station at tankside.

The vertical and lateral bending-moment signals from the balance were conditioned by a Sanborn Series 350 carrier amplifier system and the output was produced on chart paper (as a time history) by a Sanborn heated stylus oscillograph. In order to minimize high-frequency noise in the records, KROHN-HITE low-pass active filters were inserted between the preamplifiers and the recorder.

The heights of all regular waves were calibrated before the model test, by traversing the "reading" section of carriage travel with a resistance-type wave probe at the model location. The resulting records of wave-elevation time history were reduced to obtain the average wave-height for each wave length at each bridge heading. During the model test, the wavemaker speed-control was adjusted to maintain the wave periods used during wave calibrations. This procedure was preferred to the measuring of wave elevation during each model run, because it is known that model-generated waves can influence wave-probe readings.

Test Procedure

The bridge was positioned for model heading angles of 180 degrees (head seas), 150 degrees, 120 degrees, 90 degrees, 60 degrees, 30 degrees, and zero degrees. At each heading angle, at least six wave lengths were tested and the model was run at a minimum of three speeds in the range of 8-17 knots, full scale. A nominal wave height of 1/50 of the model length was used for all waves except the relatively short ones, for which a reduced height was substituted. The mean speed of the model was averaged over a distance of four model lengths (20 feet).

The bending-moment balance was calibrated periodically by applying known moments to the model while it was afloat.

Data Reduction and Presentation

Time histories of vertical and lateral bending moments were reduced to obtain the average range of moment during the 20-foot interval of model travel. The phase between the two moments was also determined.

The moment data are presented in dimensional form (moment-amplitude/wave-amplitude in ft-tons/ft) as trends versus ship speed for all wave-length/ship-length ratios at a given heading angle; separate charts are presented for vertical and lateral moments. Figures A-1 through A-14 of the Appendix contain the results for the light-load condition; Figs. A-19 through A-32 present the full-load results. The reported bending moments are due solely to wave-induced loads and are measured with respect to a still-water datum.

Phase is presented as the lag of lateral moment behind vertical moment for a given wave-length/ship-length ratio. The phase results are consistent with a heading-angle convention of representing head seas by 180 degrees and following seas by zero degrees. At intermediate heading angles, the waves approach the port bow (150 deg, 120 deg), the port beam (90 deg), or the port quarter (60 deg, 30 deg). Each phase angle is the lag of starboard lateral moment behind hogging vertical moment, with a starboard lateral moment corresponding to a hull-deflection curve which is concave to starboard. In certain cases, there was a variation of phase with ship speed; hence trends versus speed are presented in chart form. The remaining results, which were independent of speed, are presented in tabular form; a single phase value is given for each combination of heading angle and wave-length to ship-length ratio. The charted phase results are given in Figs. A-15 through A-18 of the Appendix; Tables A-1 and A-2 of the Appendix contain the remaining results.

DISCUSSION

The object of this investigation was to obtain wave-bending-moment response data from model tests and reduce them to a form usable by Webb Institute in their prediction-and-correlation project. The moment curves and phase results in the Appendix are convenient and practicable for the purpose. Sample response-curves for a ship speed of 16 knots have been constructed from the charts in the Appendix and are shown in Figs. 5-8.

The prominent double peaks in Fig. 7 have been documented by investigators of the St. Albans Tank in England (most recently by Murdey[5]), but only for head seas. Murdey, with the help of analytical predictions of the inertial and hydrodynamic components of vertical moment, explains why the peaks occur. He shows that each component contributes one peak to the total vertical moment. Fukuda,[6] using an analytical prediction technique, has found double peaks in vertical-moment response curves for other heading angles.

Figures 5 through 8 show that the lateral- and vertical-moment peaks tend to shift to shorter wave lengths as the heading angle changes from 180 to 90 degrees or from 0 to 90 degrees. In 180-degree head seas (Fig. 5), the peak vertical moment occurs in a wave length nearly equal to the ship length. Therefore, a maximum moment would occur when the ship perpendiculars are in wave crests and a wave trough is amidships. To obtain a similar wave-ship geometry for other headings, the wave length λ should be about equal to the <u>effective</u> ship length, $L \cos \mu_W$, where L is ship length and μ_W is heading angle.

Figures 9 through 12 show trends of wave bending moments versus $\lambda / L \cos \mu_W$ for the heading angles tested. Since $\cos \mu_W$ becomes zero at $\mu_W = 90$ degrees, moment values at this heading are not shown. These plots show that the moment peaks generally occur in the region of $\lambda / L \cos \mu_W = 0.9$. Figures 13 and 14 present cross-plots of moments versus heading angle for this wave-length ratio. When a peak moment does not occur at a wave-length ratio of 0.9, an additional point is shown marked with an asterisk and, in parentheses, its wave-length ratio.

Data were obtained at too few headings to permit definition of the angles at which maximum values occur. In general, however, vertical moment tends to be highest in 180-degree head seas, with a secondary peak in the region of 50 degrees. Lateral moment is highest at heading angles of either 130 degrees or 60 degrees. These trends are in general agreement with analytical calculations by Fukuda[6] for a ship of similar proportions and fullness.

CONCLUDING REMARKS

The primary objective of this experimental model investigation was to obtain

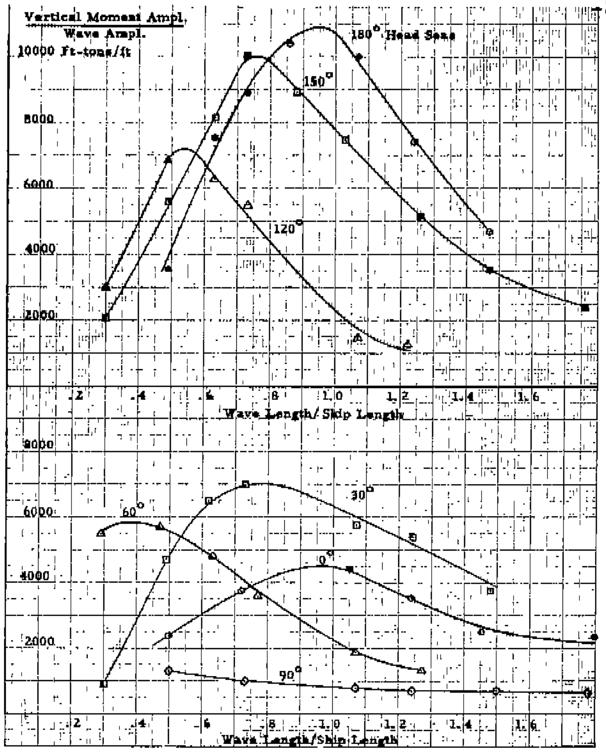

Fig. 5. Vertical Wave Bending Moments
Drafts: 17.1' Fwd, 21.5' Aft 16 Knots

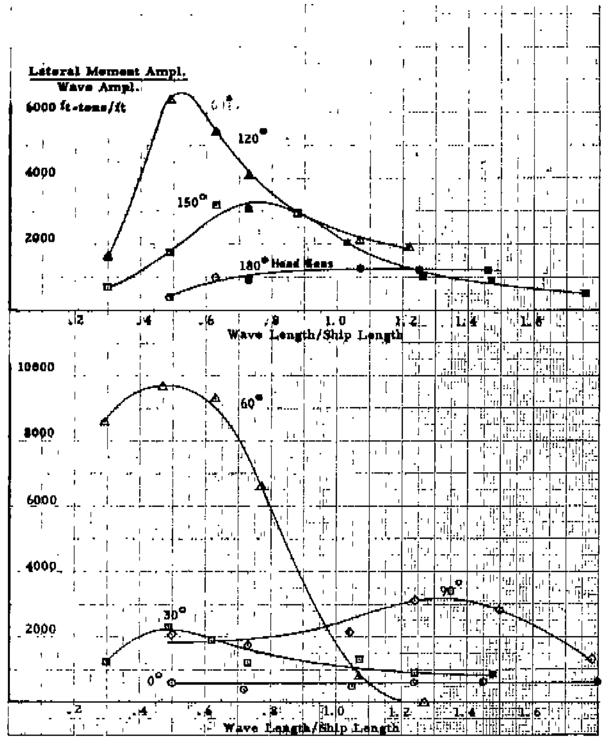

Fig. 6. Lateral Wave Bending Moments
Drafts: 17.1' Fwd, 21.5' Aft 16 Knots

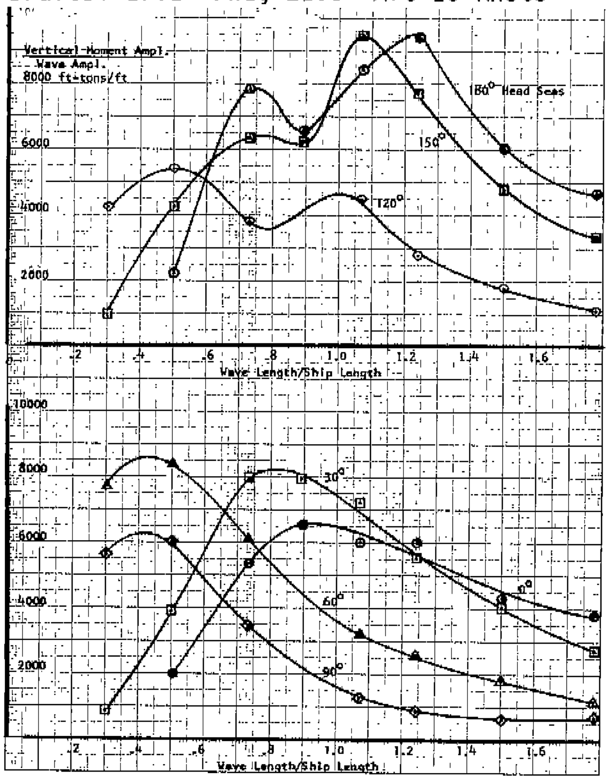

Fig. 7. Vertical Wave Bending Moments
Draft: 30' Even Keel 16 Knots

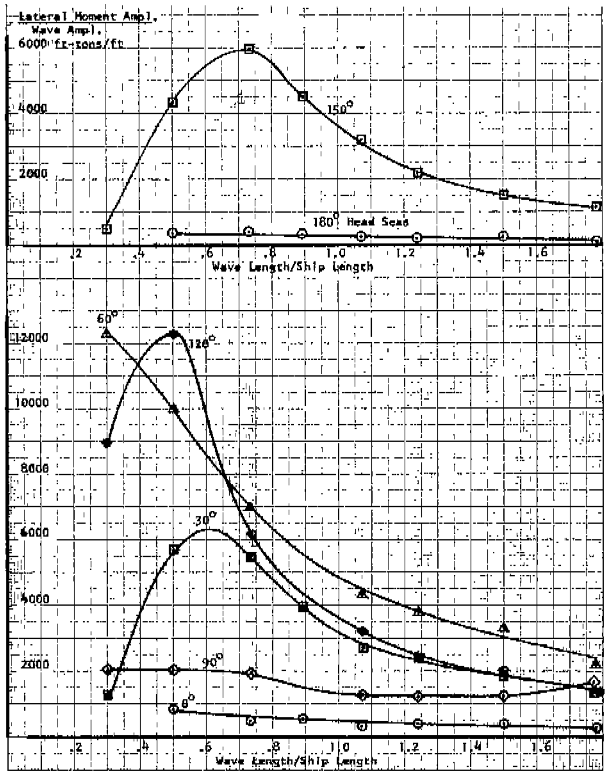

Fig. 8. Lateral Wave Bending Moments
Draft: 30' Even Keel 16 Knots

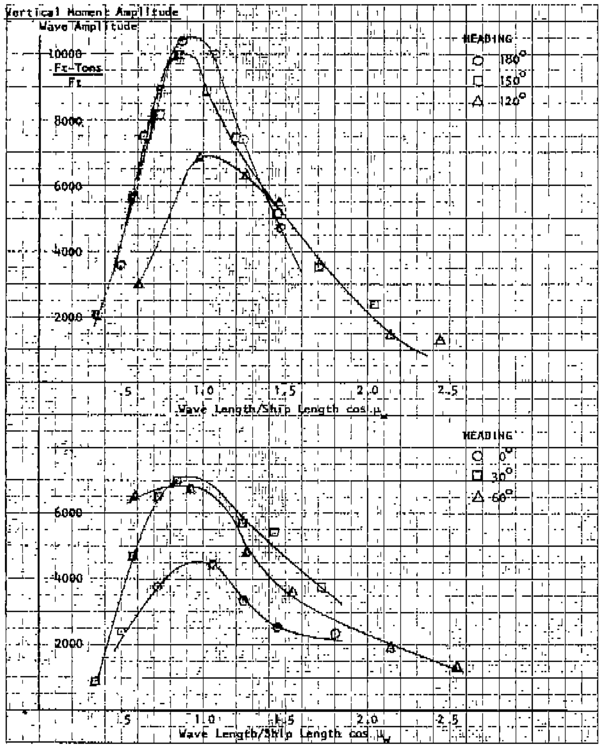

Fig. 9. Vertical Wave Bending Moments
Drafts: 17.1' Fwd, 21.5' Aft Speed 16 Knots

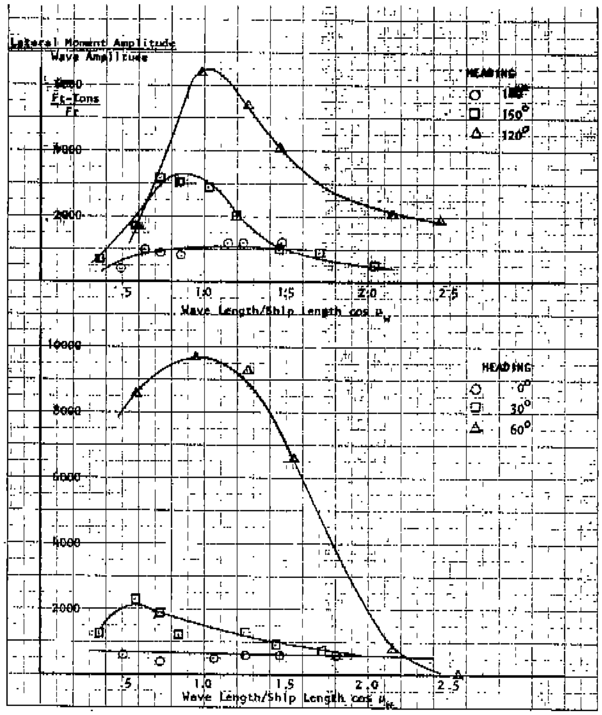

Fig. 10. Lateral Wave Bending Moments
Drafts: 17.1' Fwd, 21.5' Aft Speed 16 Knots

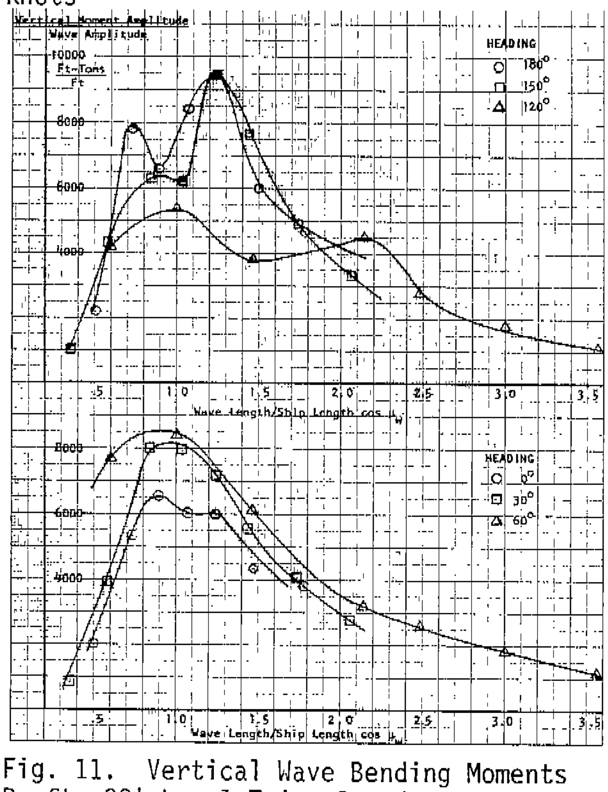

Fig. 11. Vertical Wave Bending Moments
Draft: 30' Level Trim Speed 16 Knots

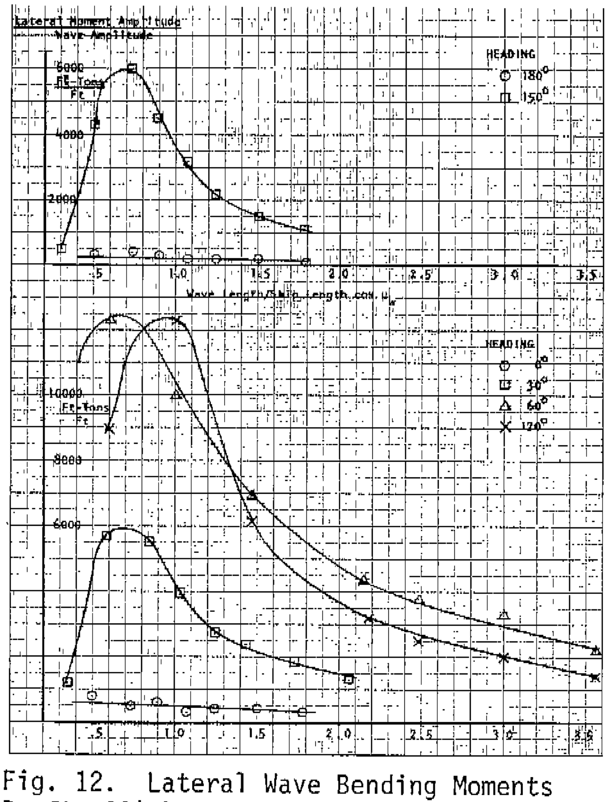

Fig. 12. Lateral Wave Bending Moments
Draft: 30' Even Keel Speed 16 Knots

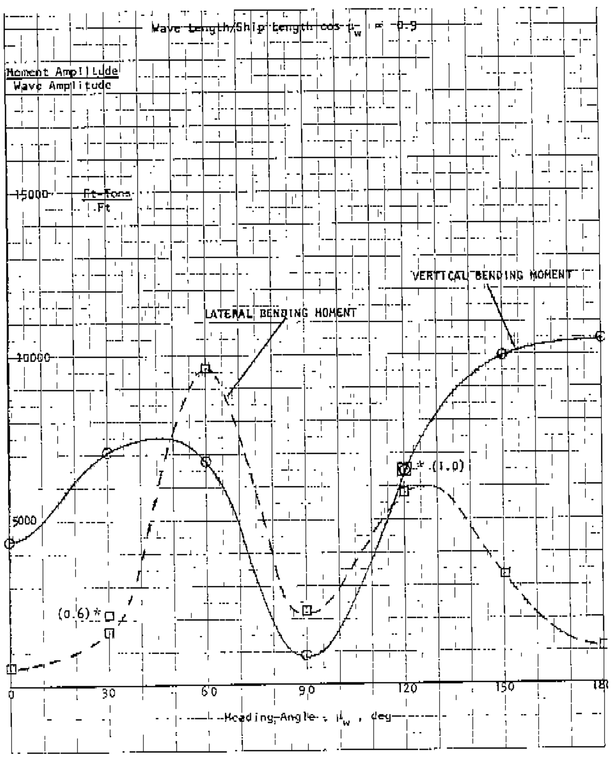

Fig. 13. Wave Bending Moments
Drafts: 17.1' Fwd, 21.5' Aft speed
16 Knots

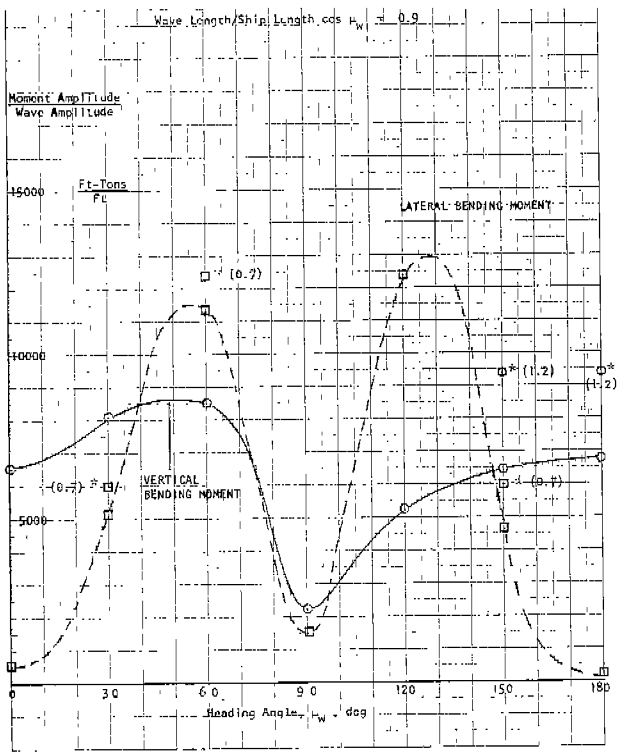

Fig. 14. Wave Bending Moments
Draft: 30.0' Level Trim Speed
16 Knots

wave-bending-moment data and to reduce them to a form usable by Webb Institute for correlation with full-scale measurements. This has been accomplished and the general trends of the results appear reasonable when compared with published data of similar nature.

Analysis of wave-bending-moment trends for this vessel shows that peak moments tend to occur --

(a) At a constant value of wave length/ship length, and

(b) In head seas for vertical moment and in either bow or quartering seas for lateral moment.

In view of the self-sufficient nature of these results, it is recommended that no further model-testing be conducted for the WOLVERINE STATE.

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APPENDIX

TABLE A-1. MOMENT PHASE ANGLES

Drafts: 17.1' Fwd, 21.5' Aft

Wave Length / Ship Length	Headings 90°	120°	150°
0.30	-	135	290
0.50	240	150	175
0.62	-	150	155
0.75	240	145	150
0.87	-	-	115
1.00	225	150	135
1.25	180	140	145
1.50	150	-	130
1.75	105	-	40

Phase angle is lag of lateral moment behind vertical moment.

See Figs. A-15 through A-18 of the Appendix for phase angles at 180°, 60°, 30°, and 0°.

TABLE A-2. MOMENT PHASE ANGLES

Draft: 30' Even Keel

Wave Length / Ship Length	Headings 30°	60°	90°	120°	150°
0.30	130	160	-125	145	175
0.50	185	150	- 15	155	145
0.73	155	150	55	100	135
0.89	145	-	-	-	115
1.07	145	130	110	115	120
1.24	140	125	140	110	130
1.50	115	105	160	105	130
1.78	125	65	170	105	110

Phase angle is lag of lateral moment behind vertical moment.

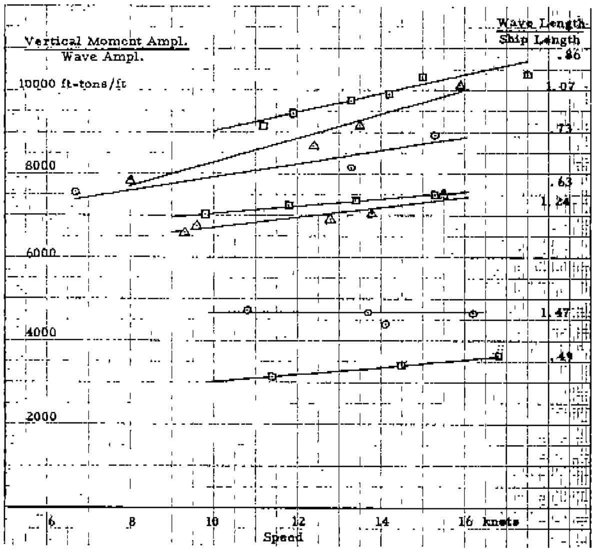

Fig. A-1. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 180° Heading

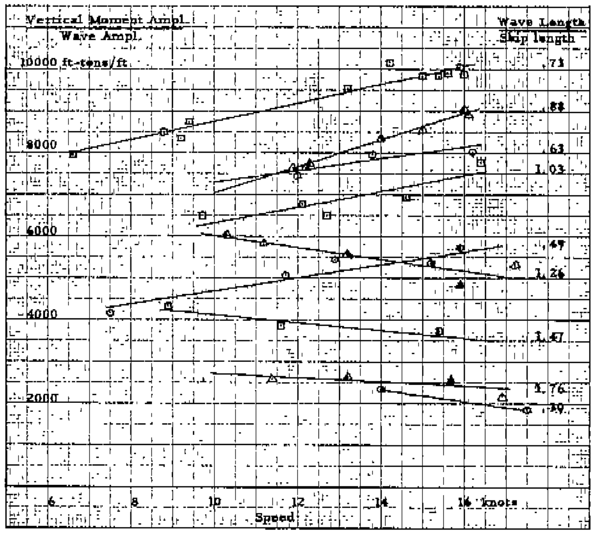

Fig. A-2. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 150° Heading

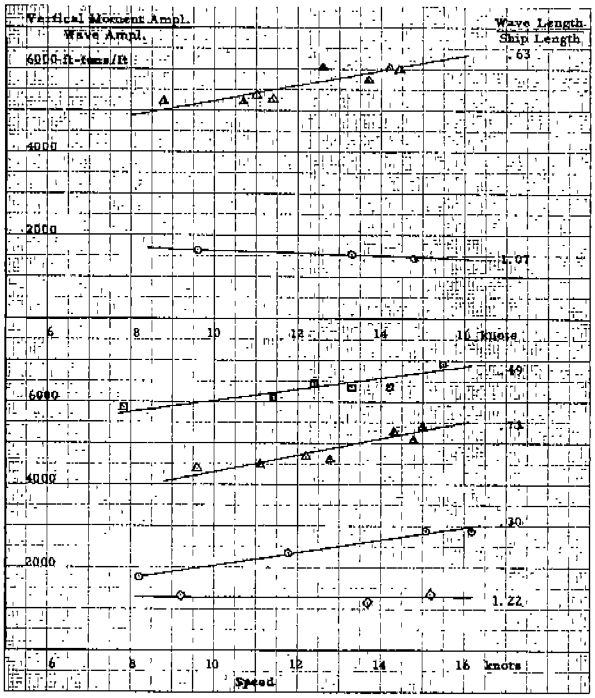

Fig. A-3. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 120° Heading

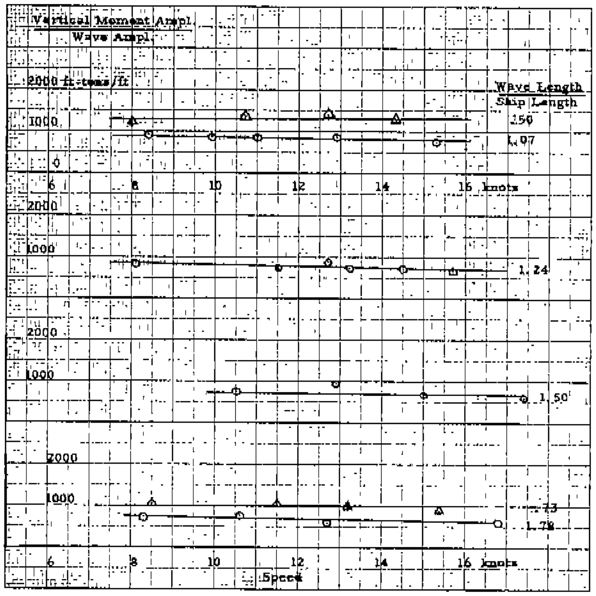

Fig. A-4. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 90° Heading

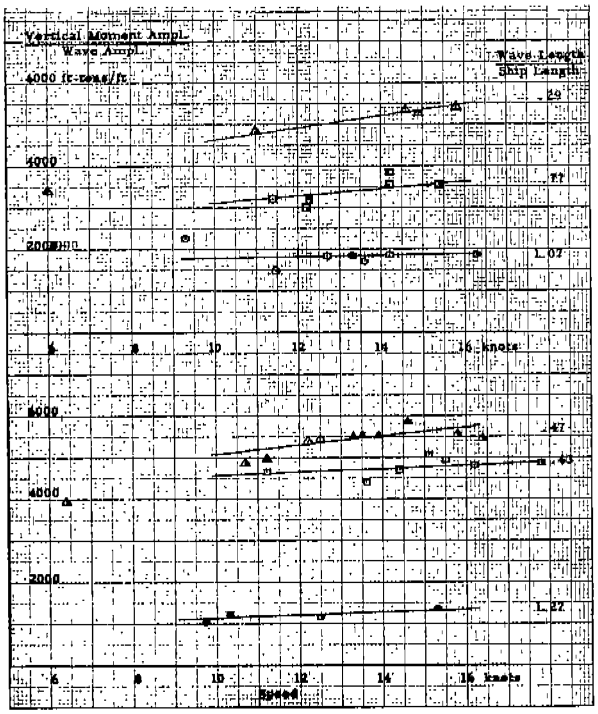

Fig. A-5. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 60° Heading

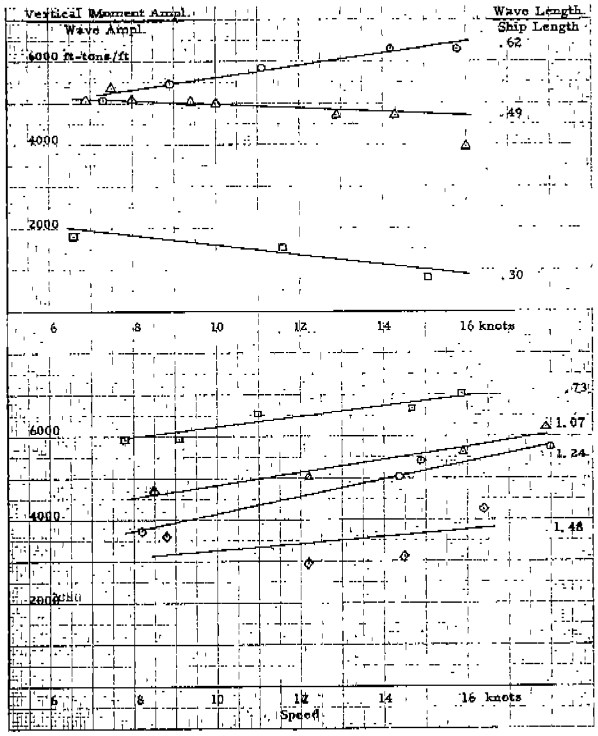

Fig. A-6. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 30° Heading

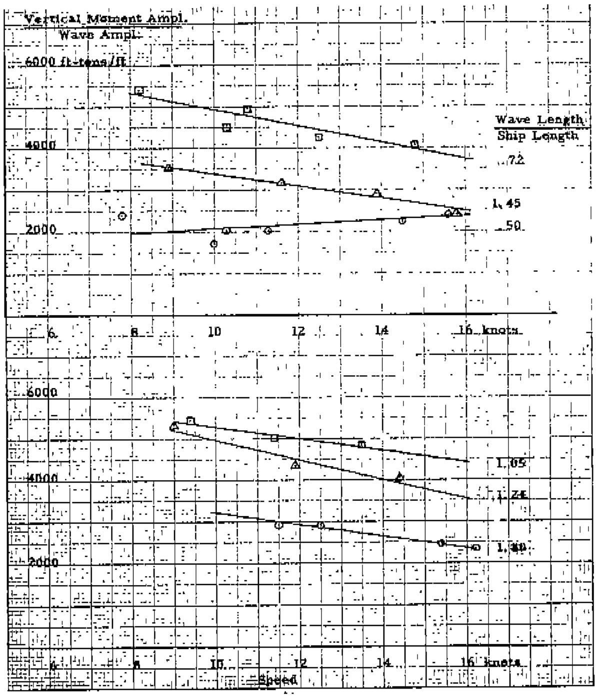

Fig. A-7. Vertical Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 0° Heading

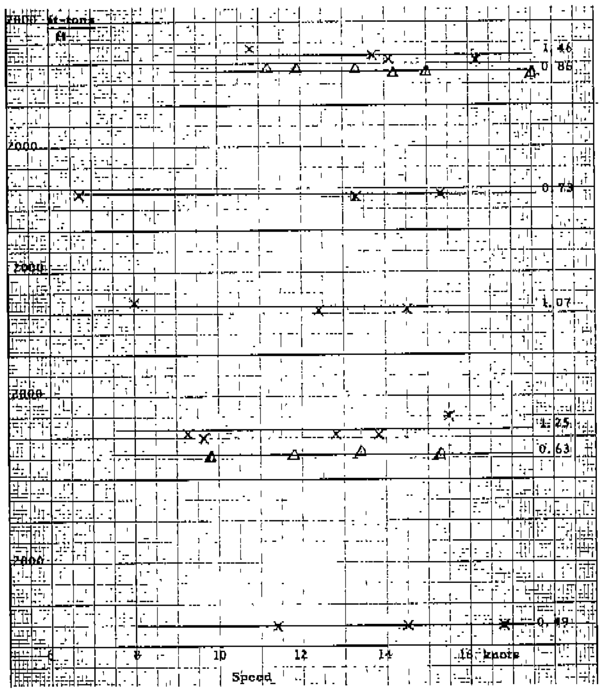

Fig. A-8. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 180° Heading

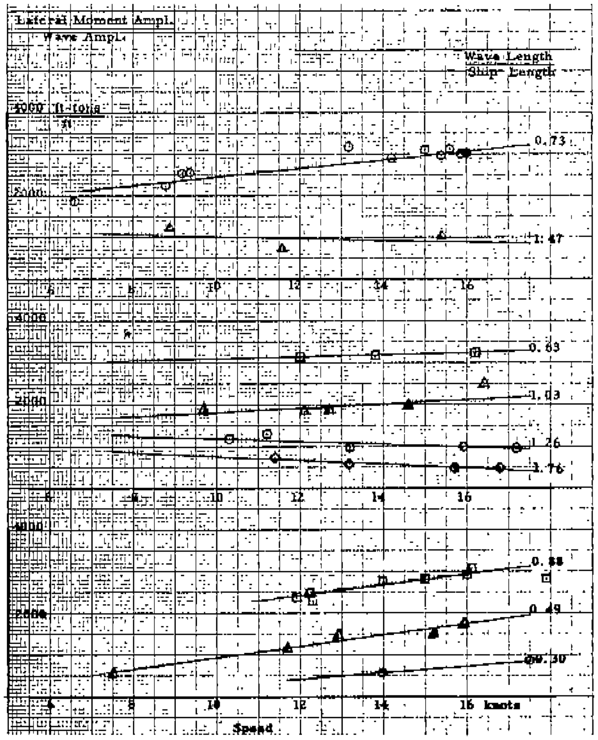

Fig. A-9. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 150° Heading

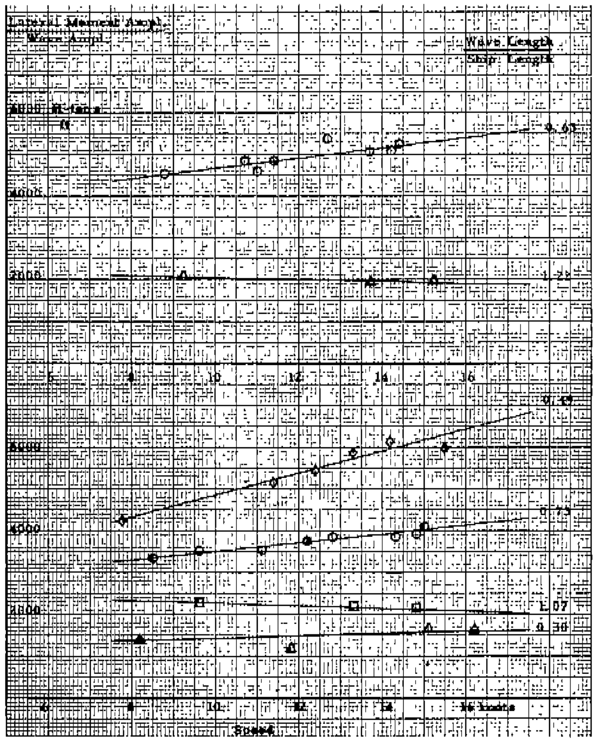

Fig. A-10. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 120° Heading

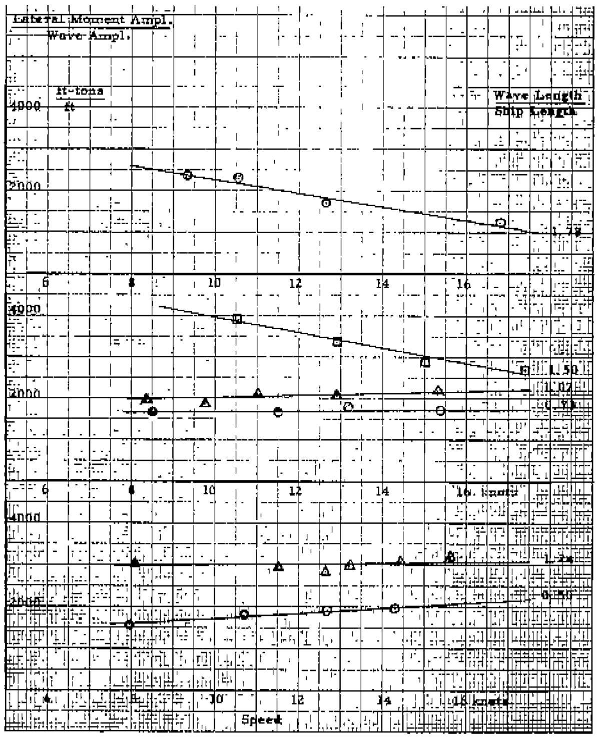

Fig. A-11. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 90° Heading

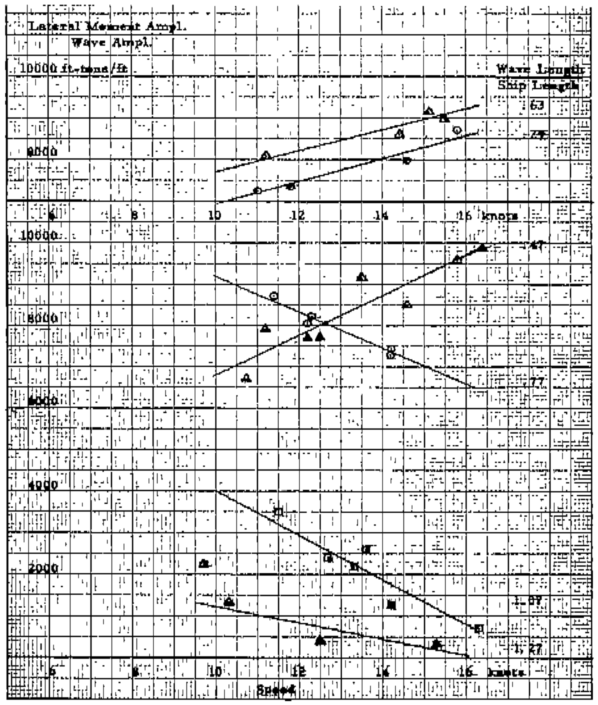

Fig. A-12. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 60° Heading

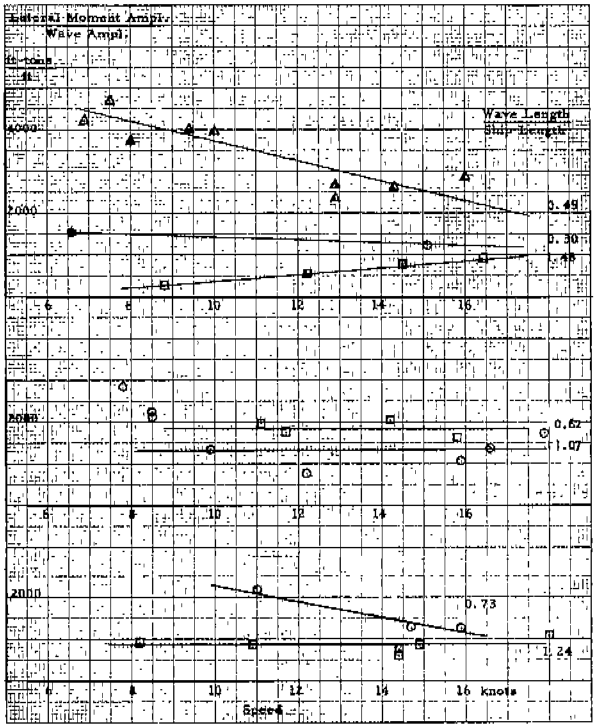

Fig. A-13. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 30° Heading

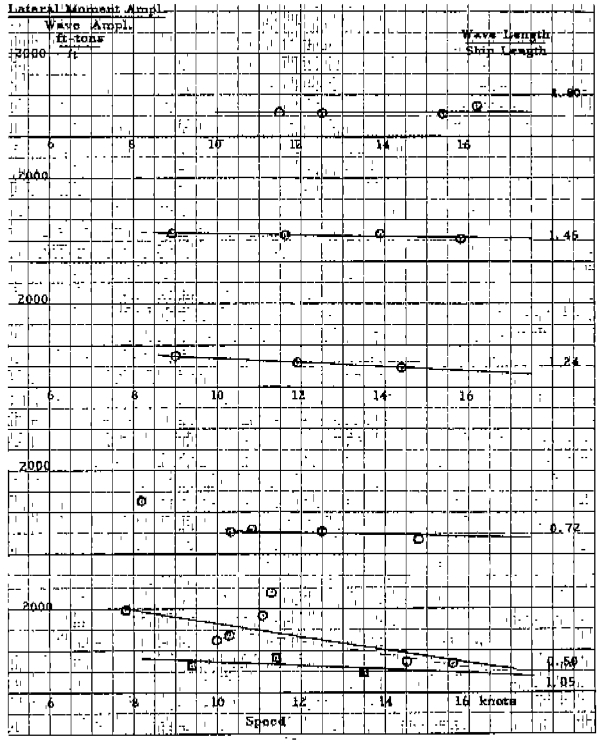

Fig. A-14. Lateral Wave Bending Moments Drafts: 17.1' Fwd, 21.5' Aft 0° Heading

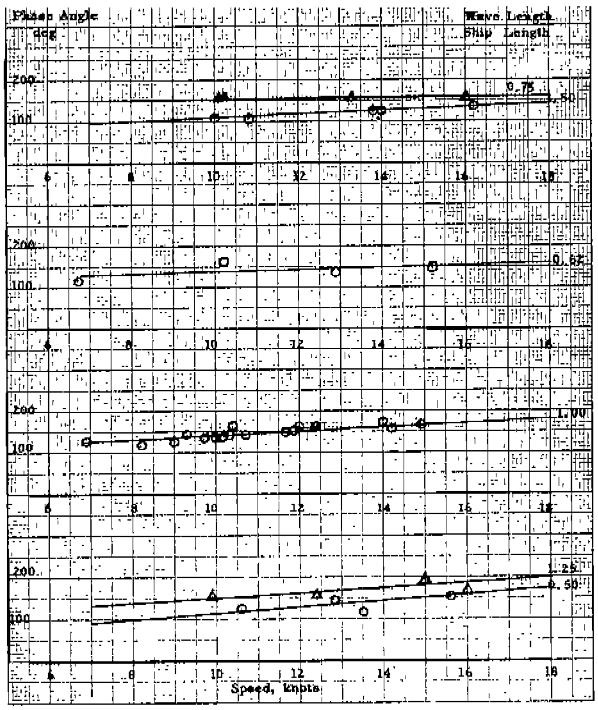

Fig. A-15. Moment Phase Angle Drafts: 17.1' Fwd, 21.5' Aft 180° Heading

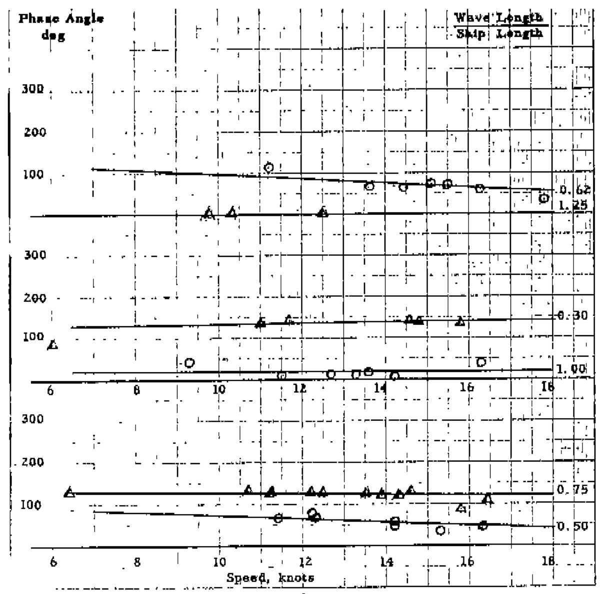

Fig. A-16. Moment Phase Angle Drafts: 17.1' Fwd, 21.5' Aft 60° Heading

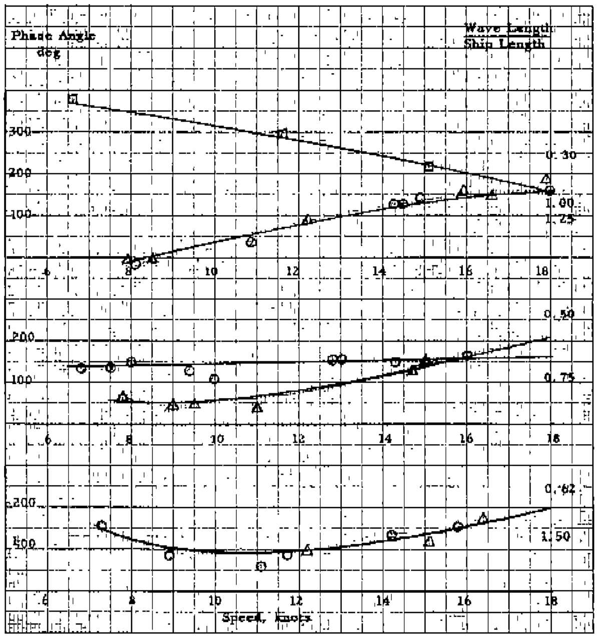

Fig. A-17. Moment Phase Angle Drafts: 17.1' Fwd, 21.5' Aft 30° Heading

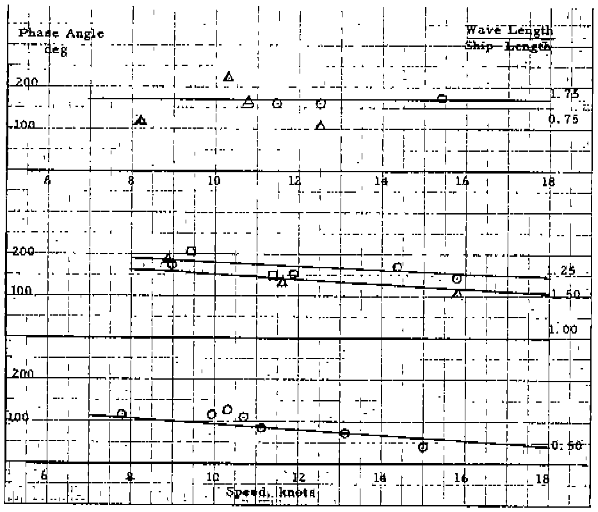

Fig. A-18. Moment Phase Angle Drafts: 17.1' Fwd, 21.5' Aft 0° Heading

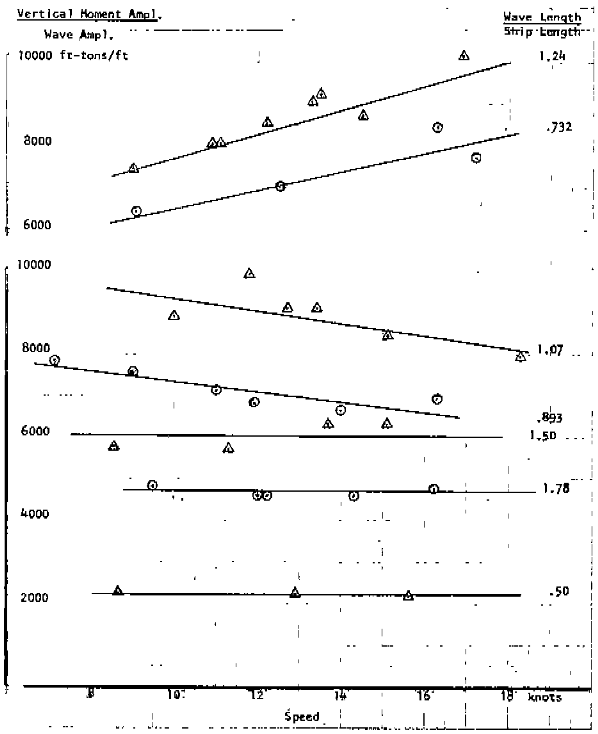

Fig. A-19. Vertical Wave Bending Moments Draft: 30' Even Keel 180° Heading

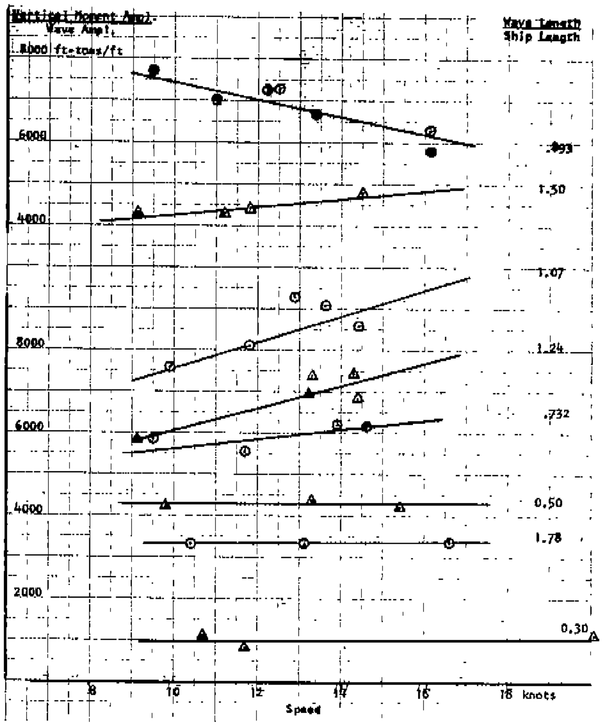

Fig. A-20. Vertical Wave Bending Moments Draft: 30' Even Keel 150° Heading

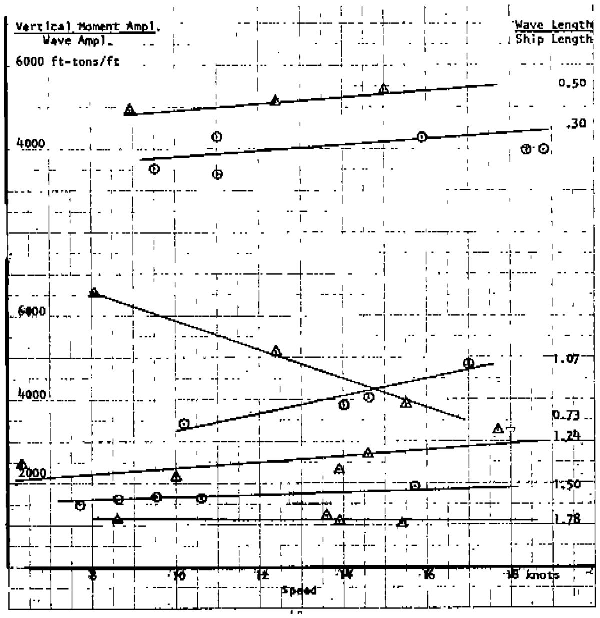

Fig. A-21. Vertical Wave Bending Moments Draft: 30' Even Keel 120° Heading

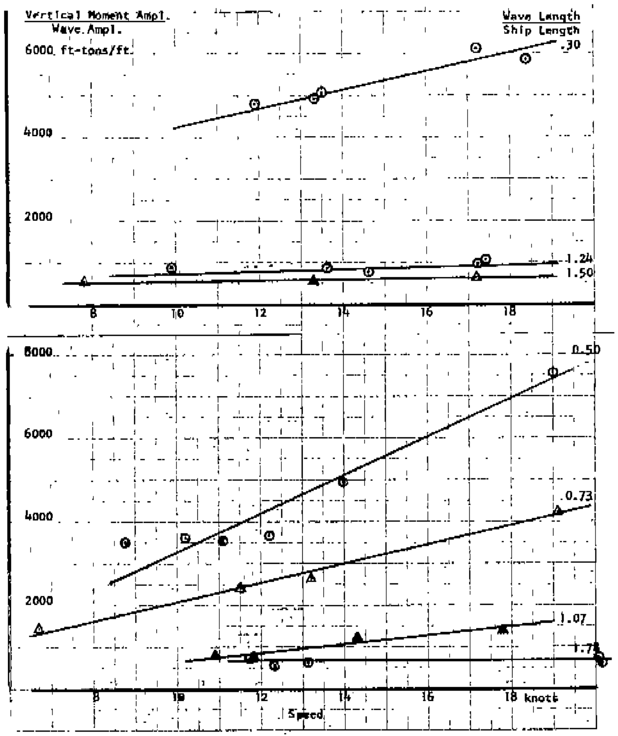

Fig. A-22. Vertical Wave Bending Moments Draft: 30' Even Keel 90° Heading

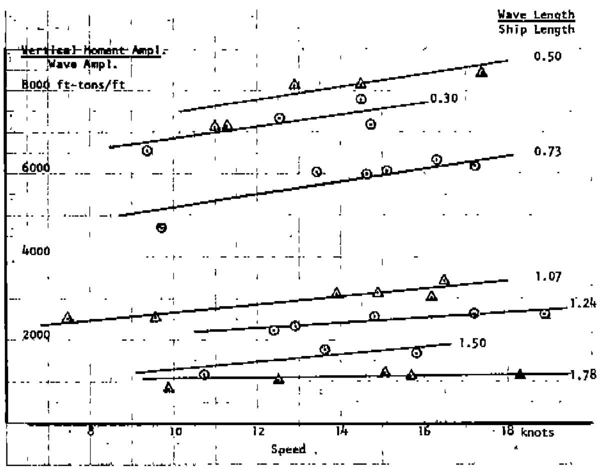

Fig. A-23. Vertical Wave Bending Moments Draft: 30' Even Keel 60° Heading

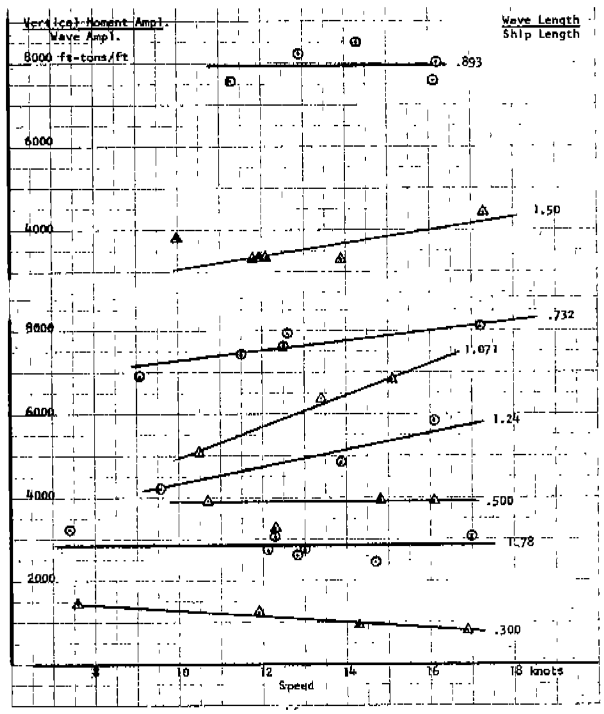

Fig. A-24. Vertical Wave Bending Moments Draft: 30' Even Keel 30° Heading

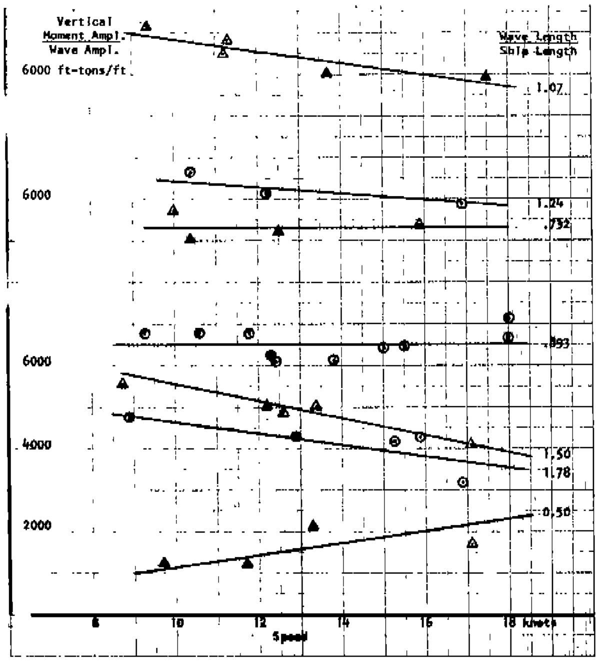

Fig. A-25. Vertical Wave Bending Moments Draft: 30' Even Keel 0° Heading

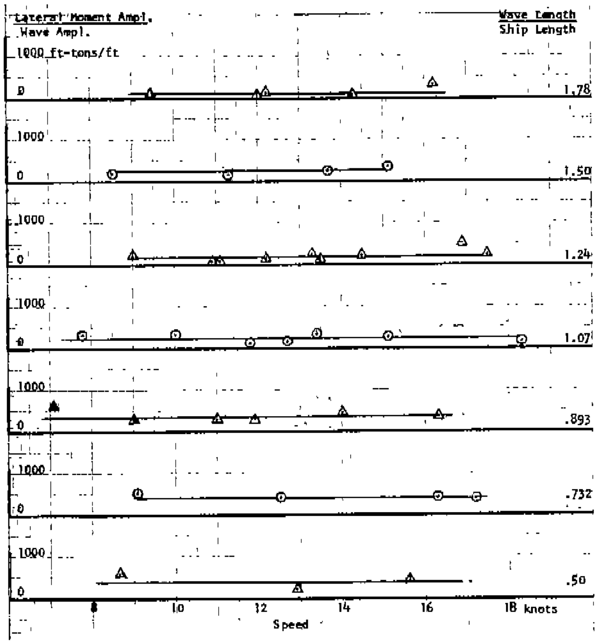

Fig. A-26. Lateral Wave Bending Moments Draft: 30' Even Keel 180° Heading

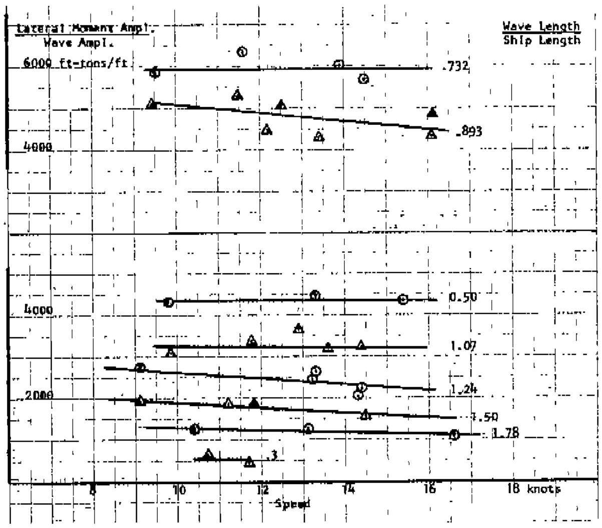

Fig. A-27. Lateral Wave Bending Moments Draft: 30' Even Keel 150° Heading

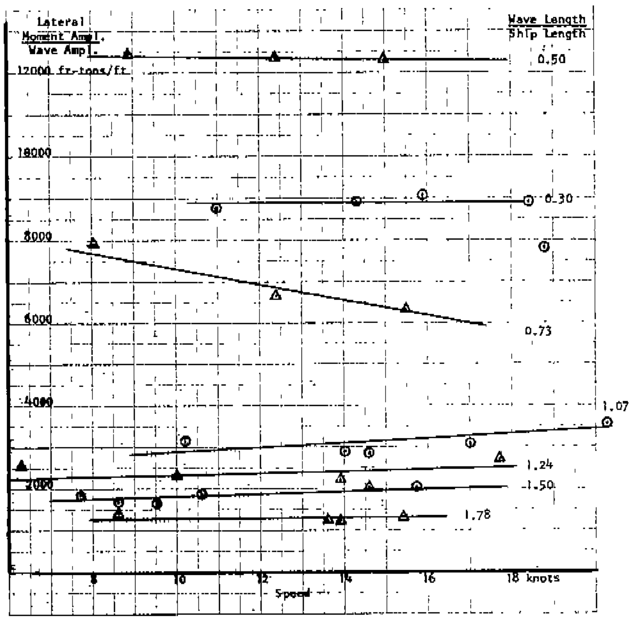

Fig. A-28. Lateral Wave Bending Moments Draft: 30' Even Keel 120° Heading

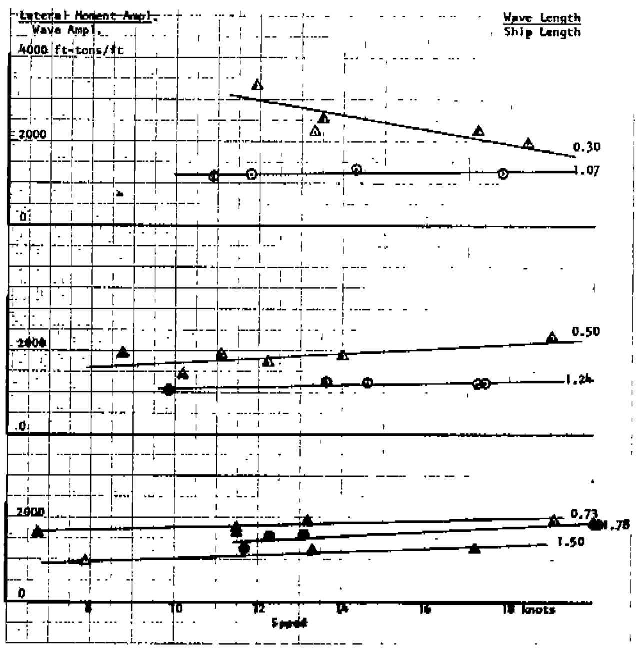

Fig. A-29. Lateral Wave Bending Moments Draft: 30' Even Keel 90° Heading

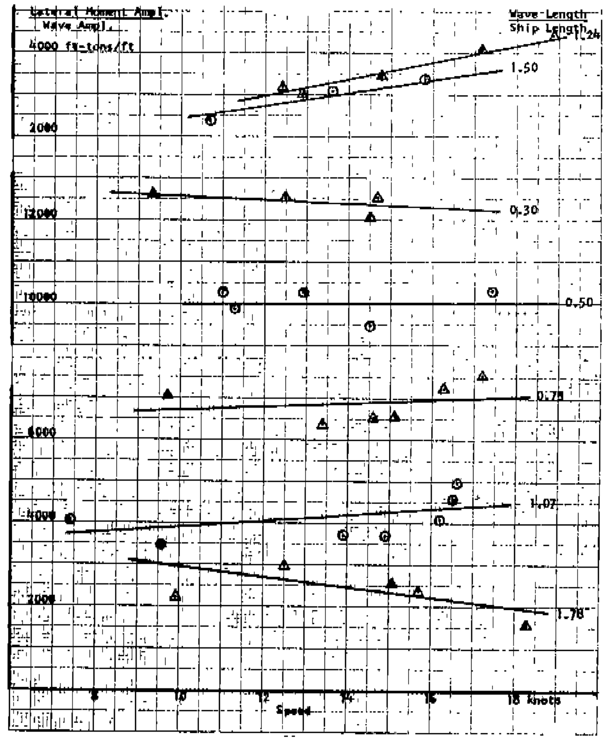

Fig. A-30. Lateral Wave Bending Moments Draft: 30' Even Keel 60° Heading

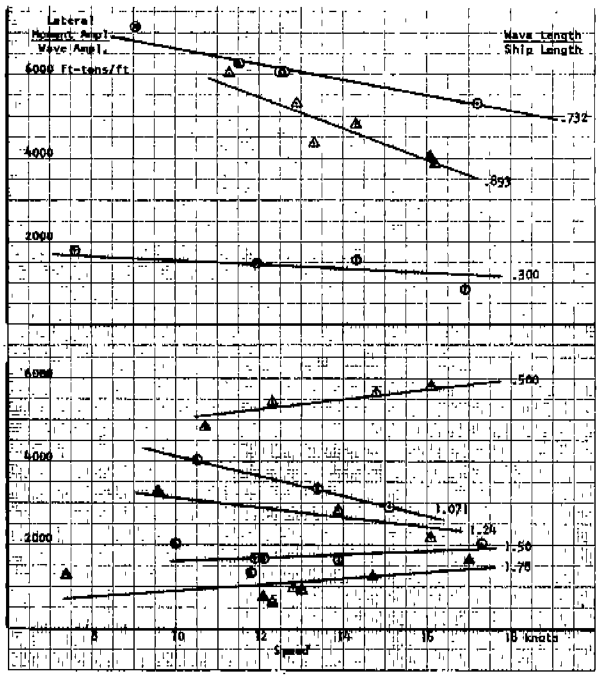

Fig. A-31. Lateral Wave Bending Moments Draft: 30' Even Keel 30° Heading

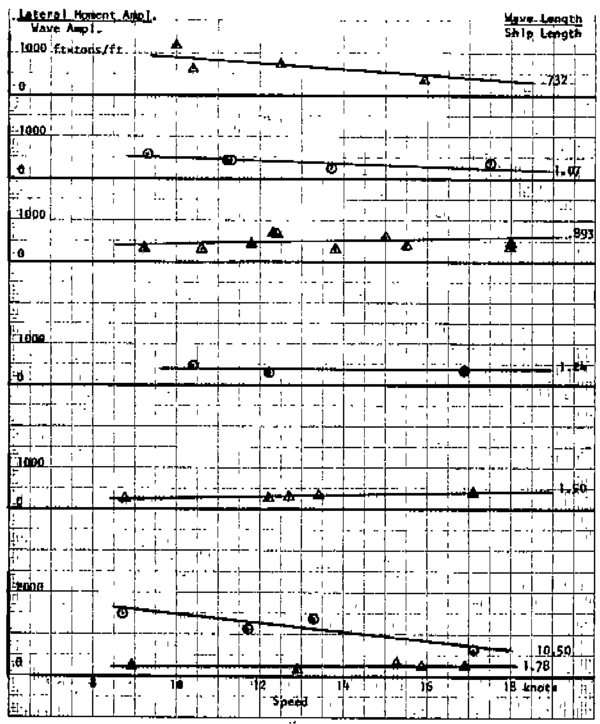

Fig. A-32. Lateral Wave Bending Moments Draft: 30' Even Keel 0° Heading

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