SSC-239

(SL-7-2)

WAVE LOADS IN A MODEL OF THE SL-7 CONTAINERSHIP RUNNING AT OBLIQUE HEADINGS IN REGULAR WAVES

SHIP STRUCTURE COMMITTEE

1973

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SR-204

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This report is one of a group of Ship Structure Committee Reports which describes the SL-7 Instrumentation Program. This program, a jointly funded undertaking of Sea-Land Service, Inc., the American Bureau of Shipping and the Ship Structure Committee, represents an excellent example of cooperation between private industry, regulatory authority and government. The goal of the program is to advance understanding of the performance of ships' hull structures and the effectiveness of the analytical and experimental methods used in their design. While the experiments and analyses of the program are keyed to the SL-7 Containership and a considerable body of data will be developed relating specifically to that ship, the conclusions of the program will be completely general, and thus applicable to any surface ship structure.

The program includes measurement of hull stresses, accelerations and environmental and operating data on the SS Sea-Land McLean, development and installation of a microwave radar wavemeter for measuring the seaway encountered by the vessel, a wave tank model study and a theoretical hydrodynamic analysis which relate to the wave induced loads, a structural model study and a finite element structural analysis which relate to the structural response, and installation of long term stress recorders on each of the eight vessels of the class. In addition, work is underway to develop the initial correlations of the results of the several program elements.

Results of each of the program elements will be published as Ship Structure Committee Reports and each of the reports relating to this program will be identified by an SL- designation along with the usual SSC- number. A list of all of the SL- reports published to date is included on the back cover of this report.

This report describes the hydrodynamic model test phase of the program and presents experimental results for a range of test sea conditions. These data will be compared with theoretical calculations for the same ship in the same conditions and these calculations and comparisons will be the subject of a separate report.

W. F. REA, III
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

SSC-239

(SL-7-2)

Final Technical Report

on

Project SR-204, "SL-7 Torsional Model Study"

to the

Ship Structure Committee

WAVE LOADS IN A MODEL OF THE SL-7 CONTAINERSHIP RUNNING AT OBLIQUE HEADINGS IN REGULAR WAVES

by

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under

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ABSTRACT

Vertical, lateral and torsional wave bending moments, and vertical and lateral shears were measured at two sections of a 1/140-scale model of the SL-7 containership. The model was self-propelled through a ship speed range of 24 and 32 knots at seven headings to regular waves of lengths between 0.25 and 2.0 times the length between perpendiculars. Motions were also measured. Two ship conditions: light and full load were covered. Results are presented in charts of load or motions amplitude/wave amplitude vs. wave length and phase lag vs. wave length, with heading, ship speed and loading condition as parameters.

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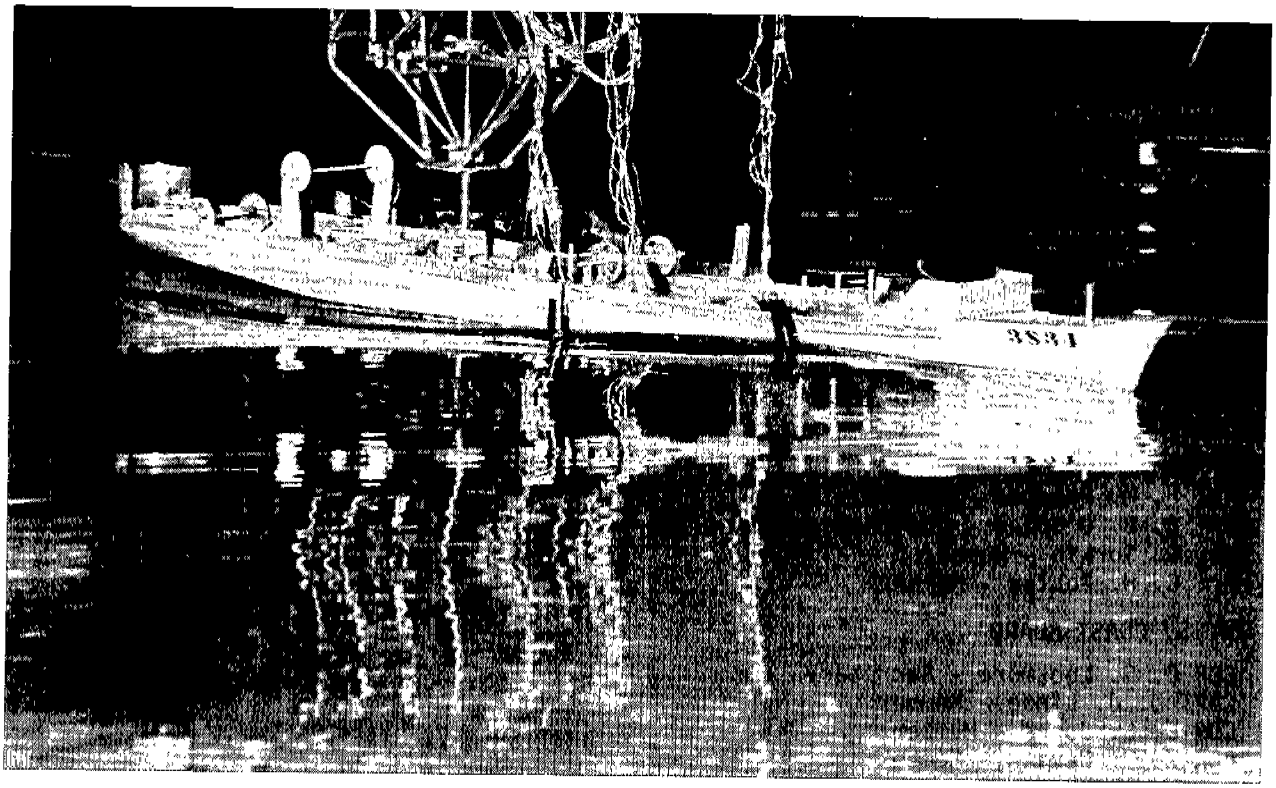

MODEL OF SL-7 CONTAINERSHIP
RUNNING IN OBLIQUE WAVES

INTRODUCTION

The present work, in common with its predecessors at Davidson Laboratory[1,2,3,4,5,6], had as its primary objective the acquisition of basic wave data. It is a part of a much larger program involving an eventual correlation between theory, and model and full-scale measurements of motions, accelerations, implied wave loads and stresses on the SL-7 type containership.

The current state of art with respect to prediction of motions or wave loads involves an essentially linear systems approach. In this approach it is recognized that full-scale experience is essentially statistical. In order to make a statistical prediction of response; 1) a transfer function is computed by theory or derived from model tests, 2) this function is combined with wave spectra (hypothesized or actual) so as to result in an estimated response spectrum which is 3) integrated over frequency to result in an estimate of the statistical variance of response. Finally 4) the predicted variances are employed in conjunction with the assumed distribution of maxima to predict averages and/or quantile averages; or used directly as an essential ingredient in the synthesis of a long-term distribution. In effect, the results of the present model study were intended to provide indirect correlations with full scale. The data was expected to contribute to overall correlation in two ways:

1. Direct prediction of response statistics using model data and estimated full-scale wave spectra.

   In this type of correlation the model data should be appropriate to an average ship loading condition and speed. The data itself must be in the form of a transfer function: that is, the response amplitude/(unit wave amplitude) and phase with respect to harmonic wave excitation of various wave lengths and headings.

2. Verification of theoretical computations of transfer function.

   In this type of correlation the model data is used to evaluate theory. If the theory is vindicated, full-scale correlations may be made for a wider range of ship conditions than are economically feasible in the model tests. In this case exact reproduction of full-scale ship loading is not as important as full documentation of model conditions.

In summary, this project was intended to provide data for use as part of the necessary input in the completion of full-scale/theoretical/model correlation. The possible directions in which these correlations may take place required that the experiments be designed with due regard to the theoretical correlation problems already outlined in Reference 7 as well as with respect to a realistic simulation of ship conditions and full-scale instrumentation configuration.

The general modeling techniques to be used in the present study were to be the same as those used previously[5,6], that is: a rigid model is segmented, and the segments connected by a suitable relative load measuring system. However because the ship is a containership, torsional moments and lateral shearing loads are of particular interest. As a consequence, the present work differed importantly from immediately previous work[5,6] in that torsional moment and lateral and vertical shear loads were to be measured at each segment in addition to vertical and lateral longitudinal bending loads. Because full-scale strain instrumentation was planned for installation approximately at the quarter points of the ship as well as at midship, at least two load measuring stations were to be involved in the present experiments.

General test technique was to be similar to that previously used[5,6], that is, the instrumented model would be self-propelled and automatically steered in a range of regular waves and wave headings. Two ship loadings were to be simulated and a representative speed range was to be covered. Measurements of heave, pitch and roll motions were also to be included as an aid in correlating motions with loads.

SHIP CHARACTERISTICS AND LOADING

Previous studies[5,6] have been "after the fact", in that extensive voyage information was available to aid in the selection of representative load conditions. In the present case the first of the SL-7 containerships was still under construction when the loading specification had to be made for the model tests. The owner developed two loading specifications. The first specification represented the anticipated typical full loading for an SL-7 fleet operation in the North Atlantic. The second, lighter loading represented typical loading for initial operation of one SL-7 in conjunction with a fleet of slower ships. An average speed of 30 knots was anticipated for the first loading condition and 25 knots for the second.

Table 1 indicates overall ship characteristics for the two specified loadings. As indicated in the table an abbreviated notation for loadings was adopted for simplicity. The normal full load condition is denoted by "heavy," the second loading by "light." This abbreviation will be carried through in the remainder of the report.

In order to properly ballast the model, considerable detail with respect to weight distribution was also required. It was pointed out by Kaplan[7] that when torsional moments are involved, attention must be paid to the distribution of vertical centers and (roll) inertia as well as to the longitudinal distribution of weight. Normally, distributions of vertical centers, and detailed distributions of inertias are not extensively developed during the course of design. Accordingly estimates of the missing quantities were made for present purposes with the aid of a variety of design information.

For convenience in design investigations of trim and stability, the ship had been divided longitudinally into 22 loading segments. The limits of these segments coincide with main watertight bulkheads, hatch ends, tank bulkheads, etc. Figure 1 indicates the extent of each loading segment with respect to frame numbers and lines-plan stations (20 stations on LBP). For purposes of expanding upon information furnished, these load segments were retained. The loading of the ship was assumed to be representable by 22 "lumps," each of which was defined by a centerline weight, its longitudinal and vertical centers, and three inertias (pitch, roll, yaw) about its principal axes. The athwartship principal axis was assumed normal to the centerplane, and the fore-and-aft axis was assumed parallel to the base-line for each "lump."

The load specifications furnished included the position and weight of each of a heterogeneous load of containers as well as the locations and weight of fuel and ballast. The gyradii* of the containers were readily estimated by assuming homogeneous loading of each. Gyradii of fuel and ballast were estimated with the aid of the general arrangement plans. These taken together comprised the contribution of deadweight to each segment. Because ballasting is to be done as fuel is consumed, departure and arrival deadweights are very little different, and it was found that there was little difference in gyradii (inertias) between the two conditions. As noted in Table 1 the departure condition was arbitrarily taken for both loadings.

TABLE I - SHIP CHARACTERISTICS

Length:	Overall	946.6 Feet (288.518 m.)	
Length:	Between Perpendiculars	880.5 Feet (268.376 m.)	
Breadth:	Maximum	105.5 Feet (32.156 m.)	
Load Designation (for purposes of this study)		"HEAVY"	"LIGHT"
Load Designation: Specified		Normal Full Load (Departure)	Initial Part Load (Departure)
Draft at LCF		32.6 ft.(9.95 m.)	29.1 ft.(8.86 m.)
Trim, by stern		0.14 ft.(42 mm.)	1.83 ft.(.56 m.)
LCG	Aft of midship	38.6 ft.(11.75 m.)	37.5 ft.(11.42 m.)
VCG	Above baseline	41.7 ft.(12.70 m.)	39.8 ft.(12.14 m.)
$\overline{GM}_t$		3.30 ft.(1.00 m.)	5.79 ft.(1.76 m.)
$\overline{GM}_t$	Corrected for free liquids	2.63 ft.(0.80 m.)	5.32 ft.(1.62 m.)
Displacement		47686 L.T.(48400 M.T.)	41367 L.T.(41900 M.T.)

The distribution of vertical centers and the gyradii for light-ship were not so readily available. The owner furnished the detailed shipyard light weight estimate as of June 1971, and the contents were used to apportion steel, machinery and outfit into the appropriate load segments. At the end of this apportionment the contribution of light-weight to each segment was broken down into 15 to 20 major items (decks, shell, frames, girders, machinery, piping, etc., etc.) and vertical and longitudinal centers, and three gyradii were estimated for each item. Because of a multitude of small items left out, the resulting estimate of total light weight was about 5% short of the total light-weight estimate furnished with the specified loading data; the overall centers compared reasonably well however. The vertical centers and gyradii for each segment from the detailed estimates were combined with the light-ship weights and longitudinal centers available from the original loading specification to make up the "complete" light-ship specification for present purposes. (Minor proportional adjustment of all vertical centers was necessary to make the resulting center for the whole ship coincide with that originally specified.)

*Gyradius = $\sqrt{\text{mass inertia/mass}}$

It was decided that the influence of free liquids on transverse metacentric height would be simulated in the model by an increase in height of vertical center of gravity. Accordingly after the deadweight and light ship estimates had been combined for each segment the resulting vertical centers were adjusted proportionately so as to result in a vertical center of gravity for the "ship" equal to the original specification plus the free liquid correction. In addition, various rounding errors, assumed position of weight margin, and differences in arithmetic methods produced a slightly differeng LCG than specified and the weight curve was "swung" to compensate.

Tables 2 and 3 are the final results of the foregoing estimates. Table 2 is for the "heavy" load, Table 3 for the "light." The discrepancies in total ship weights and centers which may be noted between Tables 1 and Tables 2 and 3 represent the level at which it was felt the law of diminishing returns had taken over. As previously noted, the vertical center is appropriate to the ship without free liquids but having the corrected transverse metacentric height, Table 1.

The full-scale instrumentation plans for the SL-7 containership had not quite been finalized at the time decisions had to be made about the positions of the moment and shear measurements. It was clear however that the bulk of the strain instrumentation would be near midships. Accordingly the first model measuring station was specified as lines plan Station 10 (Frame 181). Full-scale torsional shear instrumentation was to be installed in Hold No. 4 which includes the forward quarter point. On the premise that an analysis of lateral deformations in the structure must probably deal with an entire hold at least, the second model measuring station was selected to be the mid-point of Hold No. 4 which is Frame 258 (lines plan Station 14.38). There was also to be full-scale instrumentation in way of the after quarter point of the ship. A preliminary study of various practical modeling considerations indicated that provision in the model of a third measuring station in the after quarter would be over-ambitious. The locations of the two measuring stations adopted are shown in Figure 1.

TABLE II - ESTIMATED WEIGHTS, CENTERS AND GYRADII FOR "HEAVY" LOAD CONDITION

SEGMENT	WEIGHT[1]	LCG[2]	VCG[3]	KXX[4]	KYY[5]	KZZ[6]
1	765.2	421.25	44.50	23.8	30.5	22.0
2	1847.7	355.93	33.40	24.9	30.0	22.9
3	1205.7	297.07	59.67	35.5	31.2	31.1
4	1613.4	254.73	47.96	30.6	27.6	20.3
5	1943.6	214.75	48.08	33.0	28.3	23.2
6	2379.2	174.71	44.49	34.2	26.6	24.4
7	2305.6	134.72	40.46	36.0	29.3	26.4
8	2610.8	94.72	38.31	37.3	28.7	28.7
9	3148.7	54.73	37.75	38.2	29.2	29.4
10	3343.7	14.74	36.62	38.7	29.2	30.2
11	3299.0	-27.74	31.63	38.7	28.1	31.7
12	3179.2	-72.74	31.07	39.0	28.4	31.7
13	3293.3	-109.75	43.27	41.8	29.5	31.9
14	3039.8	-147.25	45.69	45.7	33.7	36.6
15	2661.3	-194.75	43.48	39.3	26.8	32.3
16	2898.7	-234.10	44.73	37.9	27.3	31.6
17	2116.1	-275.85	50.13	35.9	25.6	29.9
18	1678.3	-316.15	50.57	33.4	25.5	27.6
19	1597.2	-355.30	51.48	32.4	25.4	26.1
20	1244.5	-395.25	50.08	31.9	27.1	24.9
21	897.7	-429.25	44.36	23.8	20.5	18.5
22	691.3	-460.25	51.90	22.0	17.5	18.2
TOTAL	47760.3	-38.61	42.31	37.3	215.1	215.1

1. Long Tons (2240 lb)
2. Feet Forward of Midship
3. Feet Above Baseline
4. Roll Gyradius, Feet
5. Pitch Gyradius, Feet
6. Yaw Gyradius, Feet

TABLE III - ESTIMATED WEIGHTS, CENTERS AND GYRADII FOR "LIGHT" LOAD CONDITION

SEGMENT	WEIGHT[1]	LCG[2]	VCG[3]	KXX[4]	KYY[5]	KZZ[6]
1	777.4	421.25	43.40	24.9	31.4	21.8
2	1859.9	355.93	32.88	25.3	30.3	22.6
3	1217.9	297.07	58.52	36.7	32.6	31.0
4	1151.8	254.73	47.36	30.0	25.9	21.7
5	1379.2	214.75	48.67	33.2	27.2	25.1
6	1844.3	174.71	44.99	33.6	26.7	25.7
7	1990.6	134.72	33.36	32.7	25.6	25.9
8	2429.0	94.72	35.89	35.6	26.6	28.5
9	2547.5	54.73	34.42	36.1	26.3	29.4
10	2707.6	14.74	33.81	36.6	26.2	30.4
11	2714.9	-27.74	31.54	37.0	25.6	31.7
12	2697.9	-72.74	31.49	37.0	25.7	31.6
13	3284.9	-109.75	42.97	42.2	30.0	31.9
14	3031.4	-147.25	45.39	46.2	34.2	36.7
15	2726.3	-194.75	41.65	37.9	24.8	32.3
16	2757.4	-234.10	42.03	37.3	26.2	31.8
17	1631.3	-275.85	46.21	36.8	26.1	31.0
18	1217.7	-316.15	47.13	35.1	26.4	29.4
19	982.5	-355.30	41.47	32.7	24.1	26.4
20	901.2	-395.25	40.77	31.2	25.1	27.0
21	889.3	-429.25	44.36	24.3	21.1	18.6
22	682.9	-460.25	52.05	22.5	18.1	18.9
TOTAL	41422.8	-37.43	40.26	36.7	214.8	215.0

1. Long Tons (2240 lb)
2. Feet Forward of Midship
3. Feet Above Baseline
4. Roll Gyradius, Feet
5. Pitch Gyradius, Feet
6. Yaw Gyradius, Feet

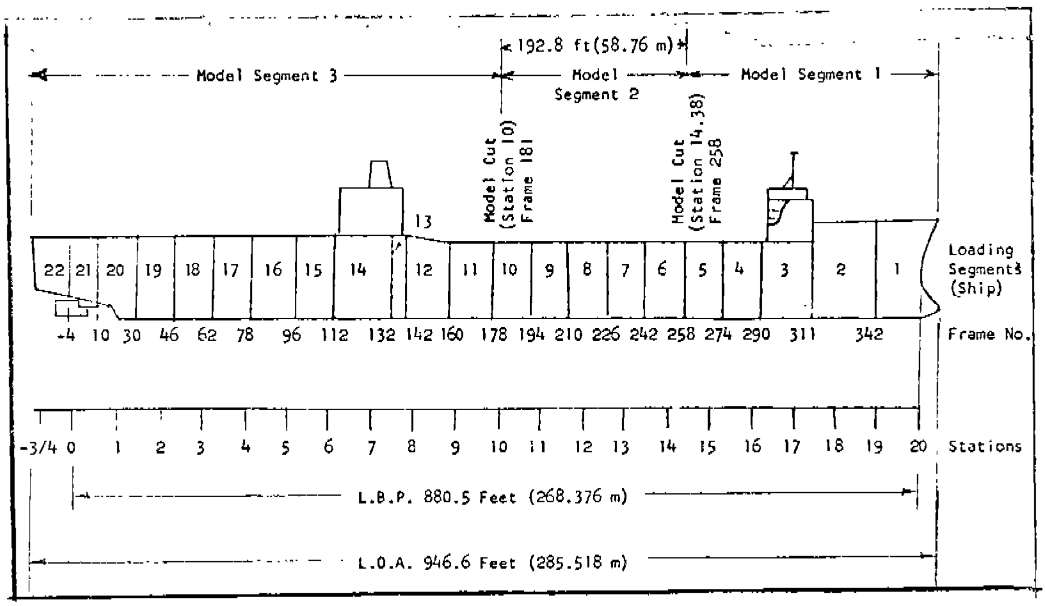

FIGURE 1 - LONGITUDINAL SEGMENTATION: SL-7 CONTAINERSHIP

MODEL CHARACTERISTICS

Model

A 1/140-scale wooden model of the SL-7 containership was constructed up to design sheer according to the owners drawings C.C.C. 10.057 and C.C.C. 10.059, (fore and afterbody lines). This model was cut transversely at Stations 10 and 14.78 resulting in three rigid segments which were numbered from the bow, Figure 1. Plate bilge keels 2 feet (.61 m.) deep full scale were installed along a trace established from the shell expansion (Dwg C.C.C. 10.010H) and extended from Frame 126 (Sta 6.88) to Frame 202 (Sta 11.20) with an interruption in way of the midship cut in the model. A scaled centerline rudder (Dwg C.C.C. 13.027C) was installed and was operated by a servomotor which formed part of an automatic steering system. The propulsion appendages were simplified owing to the small scale. Main struts were installed approximately to scale (Dwg C.C.C. 13.033B). Model outboard propulsion shafting was installed at the scaled locations and angles but was encased in a tube which increased the apparent diameter of the outboard shafting by an approximate factor of 2. The intermediate struts were omitted. A stock (right and left hand) pair of 4 bladed propellers was installed (outboard turning). Their diameter corresponded to a scaled diameter of 24.5 feet (7.47 m.) instead of 23 feet (7.02 m.) as specified for the ship. The propellers were driven by a single D.C. motor through a small gear box.

Outfit

The three model segments were connected together by two balances (to be later described), and the gap between segments was bridged with light, flexible rubber sheeting. The origin of the balance axes (point about which moments are measured) was located at the nominal location of the split (Station 10 or Station 14.38), on the center plane and 23.3 feet (7.12 m.) full scale above the baseline. Torsional moments were measured about an axis parallel to the baseline, lateral moments were measured about the body vertical axis, and "vertical" moments were measured about an athwartship axis.

In addition to "half" a balance, the outfit of model segment # 1 (forebody) consisted of a breakwater in the position of the ship's forward house, a fore deck, sundry fittings to aid in calibrations, ballast, and light sheet plastic extensions to freeboard aft of the breakwater. These were installed to minimize chances of sinking which was an experimental hazard since the model was without transverse bulkheads or decks. The outfit of segment No. 2 was similar.

In addition to "half" a balance, the plastic freeboard extensions, sundry calibration fittings and ballast, the outfit of segment # 3 (aft body) had to include rudder and propulsion motors, and the gimbal which is connected to the 6 degree-of-freedom motions apparatus so that pitch, heave and roll can be measured. These latter items of outfit were disproportionately heavy and concentrated relative to the requirements for ballasting. It was therefore necessary to position these items in accordance with ballasting considerations rather than convenience. It was thus necessary to accept a location of the motions apparatus gimbal (the longitudinal location of the heave measurement) 141 feet (43. m.) aft of Sta 10, full scale (Station 6.79), Frame 124.

Balances

Because the balances were required to measure 3 moments and at least one shear, the balances used in previous work[5,6] were not suitable. Other available 4 and 5 component balances were too heavy. Consequently new balances had to be provided for the present experiments. These took the form of simple strain-gaged beams.

Each balance beam was machined out of a 1-1/4" x 2" x 9" block of 7075-T6 aluminum. The active part of each balance was 4 inches in length and had an 0.550 inch square cross section. At either end relatively massive blocks of aluminum were left and drilled to allow a substantial bolted attachment to mounting plates which were fastened in turn to the wooden model.

To each beam 20 semi-conductor strain gages were applied and connected so as to make 5 full bridge circuits. The gages are specified to have a nominal gage factor of 55, a temperature coefficient of gage factor of 0.2% per 10°F., and a linearity of ±0.02%. The active length is approximately 0.12 inches, and active width is 0.02 inches. Installation, trimming, inter-connection, and water proofing of all gages was done by the manufacturer at their gaging facility.

The vertical bending bridge was a conventional bending bridge located in the middle of the beam top and bottom. The lateral bending bridge was the same but installed on the sides instead of top of the beam. The torsional moment bridge was also located near the center of the beam. In this case two gages were located at plus and minus 45° to the longitudinal beam axis on two sides of the beam. The inter-connection was such that this bridge sensed torsional shearing strains. The shear force bridges were made up of gages arranged so as to sense "double-S" bending of the balance beam.

Each balance was checked on the bench for linearity and coupling. Linearity in all bridges was within 1/2% of full scale, which probably represents the net precision of mechanical loading apparatus, balance and amplifier equipment. Coupling of axial force into the moment and shear bridges was barely resolvable with amplification equipment at maximum gain. Accordingly coupling of fore and aft (surge direction) forces into the measured shears and moments was considered entirely negligible.

The results of the cross coupling checks among the five components are summarized in Table 4. In the table the coupling coefficients are displayed in matrix form. The vector on the left side of the equation represents the "true" moments and shears, corrected for coupling. The vector on the right hand side represents the apparent moments and shears -- these are the results which would be obtained by application of calibrations obtained from single component loading to strain observations for multi-component loading. The coefficients shown are those suitable for correcting model data in (pound-inches) and pounds. As a consequence, some of the coefficients are dimensional and these are underlined.

As multi-component balances go, the couplings between the various moments and shears were considered reasonably small. Prior to the experiments the magnitude of the model vertical and lateral moments was estimated to be 60 lb-inches, that of model torsional moment 3 lb-inches, and that of model shearing forces about 1 lb. On this basis the influence of other components upon vertical and lateral moments was expected to be limited to about 1%. Similarly, if all moments and forces were in phase, a possible influence of other components on torsion might be 4% for the midship balance and as much as 30% for the balance at Frame 258 due to coupling from the relatively high lateral moments. On the same basis the coupling of vertical and lateral moments into the shears could influence the results by as much as 10 to 20%.

Because of these possibilities all the couplings between components could not be assumed to be negligible.

Before and after the experiments, with the balances in the model and the model afloat, the calibration of all 5 bridges on each balance was re-checked. Small percentage changes in the calibrations for pure component loading from those obtained in the bench calibration were noted. These differences were attributable to the influence of the rubber seals at the model cuts. So far as it was possible

TABLE IV - BALANCE COUPLING COEFFICIENTS

MIDSHIP BALANCE

$$\begin{bmatrix} M_V \\ M_L \\ T \\ S_V \\ S_L \end{bmatrix} = \begin{bmatrix} 1.0000 & -.0070 & -.0141 & \underline{.0031} & \underline{-.0048} \\ -.0040 & 1.0000 & .0170 & \underline{-.0017} & \underline{.0107} \\ .0001 & -.0022 & .9997 & \underline{-.0209} & \underline{.0427} \\ \underline{-.0110} & \underline{-.0023} & \underline{.0151} & .9997 & .0137 \\ \underline{.0023} & \underline{-.0014} & \underline{.0010} & .0027 & 1.0000 \end{bmatrix} \cdot \begin{bmatrix} \hat{M}_V \\ \hat{M}_L \\ \hat{T} \\ \hat{S}_V \\ \hat{S}_L \end{bmatrix}$$

BALANCE AT FRAME 258

$$\begin{bmatrix} M_V \\ M_L \\ T \\ S_V \\ S_L \end{bmatrix} = \begin{bmatrix} 1.0000 & .0075 & -.0082 & \underline{-.0041} & \underline{-.0029} \\ .0022 & 1.0000 & -.0025 & \underline{.0056} & \underline{-.0029} \\ .0013 & .0202 & 1.0000 & \underline{.0037} & \underline{-.0055} \\ \underline{.0045} & \underline{.0001} & \underline{-.0053} & 1.0000 & -.0021 \\ \underline{.0017} & \underline{-.0010} & \underline{-.0081} & .0052 & 1.0000 \end{bmatrix} \cdot \begin{bmatrix} \hat{M}_V \\ \hat{M}_L \\ \hat{T} \\ \hat{S}_V \\ \hat{S}_L \end{bmatrix}$$

M_V = Vertical Bending Moment S_V = Vertical Shear

M_L = Lateral Bending Moment S_L = Lateral Shear

T = Torsional Moment (^ denotes an apparent quantity)

Moments taken with respect to nominal balance axes.

Dimensional quantities underlined.

to produce valid multi-component calibration loadings with the model afloat, the bench coupling coefficients appeared to be confirmed.

The afloat calibration constants were used in the reduction of data and further refinement of the coupling investigation was deferred until it could be determined if the actual data was particularly sensitive to the coupling corrections implied by the bench investigation.

Model Ballasting

Reproduction of the mass distributions shown in Tables 2 and 3 was entirely out of the question at 1/140 model scale, because of the disproportionate concentrations of mass in essential apparatus. Since the model was composed of three rigid bodies connected by springs, the model ballast specification was produced by lumping the results shown in Tables 2 and 3 in accordance with model segment boundaries. Referring to Figure 1, the specifications for Model Segment No. 1 were arrived at by combining load segments 1 through 5, those for Model Segment No. 2 were made using Load Segments 6 through 10, and Model Segment No. 3 specifications involved all remaining load segments.

The properties of a rigid body are specified by mass, 3 centers, three inertias and 3 products of inertia. Because the ship specifications, Tables 2 and 3, assume centerplane mass symmetry, two of the products of inertia drop out. Thus for each model segment the indicated ship loading segments were combined to result in a ballasting specification involving a weight, 3 centers, 3 inertias and one product of inertia.

Tables 5 and 6 summarize the resulting specifications (in the column marked "desired") along with measured model results to be described. All values in the table are quoted full size in English units. Longitudinal centers are quoted with reference to nominal midship which is lines plan Station 10. Vertical centers are feet above baseline. Gyradii in roll, pitch, and yaw correspond to inertias computed about the center of mass. The product of inertia was divided by mass for presentation purposes. This quantity is also derived with respect to center of mass. In derivation of product of inertia, longitudinal locations were assumed positive forward and vertical locations were assumed positive upward. Thus since the product of inertia is a summation of the product (mass x vertical distance x longitudinal distance) a positive value of product of inertia corresponds to a principal axis which inclines upward in the direction of the bow. The computed angle of inclination of the principal axis in the centerplane is given in the last full line of the table.

The model segments were ballasted and checked individually with suitable tare weights in place to simulate the motions apparatus gimbal and the balances. Centers were obtained to about 0.3 foot full-scale accuracy with a simple balance beam technique. Weights could be measured to within ± 10 tons full scale. Pitch inertia (gyradii) were obtained by swinging the model as a compound pendulum which is the standard Davidson Laboratory technique. Roll and yaw inertias were measured by the bi-filar pendulum technique. In obtaining roll inertia, the period of oscillation of the model segment mounted on the pendulum was observed for oscillations about an axis through the center of mass and parallel to the baseline. Measurement of products of inertia were obtained with two experiments on the pendulum. In the first, the model period was observed for oscillations about an axis through the center of mass and inclined at +5^{o} to the baseline. The second experiment was the same but with a -5^{o} inclination. The product of inertia is proportional to the differences of the squares of these periods.

TABLE V - SUMMARY OF MODEL BALLAST: "HEAVY" CONDITION
(Model Properties Scaled to Full Size)

Model Segment	1		2		3		Entire Model	
Ship Loading Segments	1 through 5		6 through 10		11 through 22		1 through 22	
	Desired	Achieved	Desired	Achieved	Desired	Achieved	Desired	Achieved
Weight, Long Tons	7375.6	7380.	13788.0	13800.	26596.4	26600.	47760.0	47780.
Longitudinal Center, ft. from	293.74 fwd	293.9 fwd	86.68 fwd	86.8 fwd	195.74 aft	196.7 aft	38.61 aft	39.0 aft
Vertical Center, ft. above	45.90	44.6	39.20	35.2	42.93	42.3	42.31	40.6
Roll Gyradius, K_{xx}, ft.	31.38	28.2	37.23	35.6	38.72	37.8	37.31	36.0
Pitch Gyradius, K_{yy}, ft.	74.61	72.4	63.82	68.4	126.31	123.8	215.09	215.0
Yaw Gyradius, K_{zz}, ft.	72.15	65.1	63.38	66.7	126.80	119.3	215.07	213.0
(Product of Inertia)/Mass K^2_{xz}, ft^2	-268.72	248.	144.71	-48.2	-719.80	-408.	-383.02	-342.
Angle of Principal Axis, deg.	-3.6	4.1	3.2	-0.9	-2.8	-1.8	-0.5	-0.4
Transverse Metacentric Height, $\overline{GM}$, ft.							2.63	2.57
Free Roll Period, seconds, T_r							-	27.8
Apparent Roll Gyradius = T_r $\overline{GM}$/1.108, Feet							-	40.2
(Apparent Roll Gyradius)/(Measured Roll Gyradius)							-	1.11

TABLE VI - SUMMARY OF MODEL BALLAST: "LIGHT" CONDITION
(Model Properties Scaled to Full Size)

Model Segment	1		2		3		Entire Model	
Ship Loading Segments	1 through 5		6 through 10		11 through 22		1 through 22	
	Desired	Achieved	Desired	Achieved	Desired	Achieved	Desired	Achieved
Weight, Long Tons	6386.2	6360.	11519.0	11520.	23517.7	23450.	41422.9	41330.
Longitudinal Center, ft. from	303.91 fwd	304.0 fwd	86.80 fwd	78.8 fwd	190.97 aft	190.0 aft	37.43 aft	39.1 aft
Vertical Center, ft from	45.07	45.4	36.10	32.8	40.99	40.8	40.26	39.3
Roll Gyradius, K_{xx}, ft.	31.64	30.4	35.38	33.3	38.43	38.6	36.74	36.3
Pitch Gyradius, K_{yy}, ft.	74.69	78.2	61.66	59.2	122.99	121.3	214.83	212.6
Yaw Gyradius, K_{zz}, ft.	72.39	66.2	62.42	58.7	123.86	112.2	215.03	209.0
(Product of Inertia)/Mass, K_{xz}^2, ft^2	-315.71	432.	152.79	136.	-454.16	-135.	-218.43	7.8
Angle of Principal Axis, α, deg.	-4.2	7.0	3.3	3.3	-1.9	-0.7	-0.3	0.0
Transverse Metacentric Height, $\overline{GM}$, ft.							5.32	5.60
Free Roll Period, seconds, T_r							-	20.0
Apparent Roll Gyradius = $T_r \sqrt{\overline{GM}}/1.108$, Feet							-	42.8
(Apparent Roll Gyradius)/(Measured Roll Gyradius)							-	1.18

Results of the model ballasting are shown in the column labeled "achieved" in Tables 5 and 6. Precision in results for gyradii is estimated to be ±5%, that for the product of inertia ±50 ft^2 at best, owing to the technique. The results for weights and inertias, quoted as "achieved" for the entire model were calculated from the results for segments 1 through 3 and not actually measured. During the ballasting procedure care was exercised to make the mass distribution as symmetric as possible about the centerplane. It was assumed that this precaution was sufficient to insure negligible products of inertia in the athwartship and horizontal planes.

Upon running inclining experiments on the assembled model at both loading conditions, it was found that the transverse metacentric heights were low by roughly the same amount in each condition. There was small but measurable static model deflection in the hogging sense because the calculated static moment was hogging and fairly high. The mean drafts and trims were as specified within the precision possible in measuring draft at 1/140 scale (about 0.3 feet full scale). It was assumed that the observed low transverse metacentric heights were attributable to a reduced metacenter due to the deflection of the model and to model-making inaccuracies. Accordingly a ballast weight was shifted in Segment 2 so as to bring the transverse metacentric height in the heavy load condition up to the desired level. This alteration in ballast of Segment No. 2 was accounted for by calculation and is reflected in the final results in Tables 5 and 6.

Periods of free roll were obtained and are cited in the tables. These periods combined with the results of the inclining experiment result in an apparent roll gyradius as shown in Tables 5 and 6. As noted, the added hydrodynamic roll inertia has the effect of increasing the measured roll gyradii by 11 to 18%.

The net result of the alteration in ballast to better achieve specified metacentric height is that the model vertical centers corresponds more closely to the originally specified ship vertical centers (Table 1). Effectively, by chance accumulation of errors, it appears that the influence of free liquids has been roughly accounted for in the model by a virtual decrease in metacenter rather than a virtual rise in center of gravity.

An overview of the correspondence achieved between desired and achieved ballast indicates that a reasonable simulation was achieved, excepting the vertical center problem just discussed, and the products of inertia. The relatively large deviations in products of inertia in Segment No. 1 (forebody) had to be accepted because there was far too little re-locatable ballast available. The deviation in the heavy displacement case for Segment No. 2 was accentuated by the use of ballast in this segment for correction of overall vertical center.

DESCRIPTION OF EXPERIMENTS

Mechanical Apparatus

The experiment was conducted in Davidson Laboratory's Tank 2 (75'x75'x4.5'). This facility includes a wavemaker along one 75-foot side, 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 for each measured parameter are led upward to the carriage and thence to a recording and control station at tankside.

The six-degree of freedom motions apparatus involves three levels of protection against the imposition of horizontal thrust on the model through the gimbal. The first level is the attachment of the heave mast and bearing assembly to a sub-carriage via a linkage system so counterbalanced that no lateral forces are imposed on the model for up to ±2" horizontal motion of the gimbal. (The lower portion of the heave mast and linkage assemblies are visible in the Frontispiece.) The second level of protection is two servoed sub-carriages. The linkage system is attached to the first servoed sub-carriage which moves laterally and has as its function the maintenance of the top of the linkage within about ±1" laterally of the center of the gimbal. The second sub-carriage carries the first and performs the same function in the fore and aft direction. These two sub-carriages and the linkage allow the model to run free of horizontal restraint anywhere within ± 2-1/2 feet (half a model length) fore and aft and within ± 1-1/2 feet laterally of the center of the main carriage. When the model is too close to the lateral subcarriage limits the run is aborted. The last level of protection against horizontal restraint is provided for the fore and aft direction and involves servo control of the main carriage speed so as to keep the main carriage and everything hung on it over the model.

In addition to the motions apparatus and carriage, a resistance wave probe was mounted on a subsidiary carriage a fixed distance from the main carriage. It was in such a position that it would always be "up-wave" from the model during the experiments.

For each heading the heights of all regular waves were calibrated by traversing the probe over the "recording" section of carriage travel without the model in place.

Instrumentation and Basic Data Processing

There were in all 18 potentially useful channels of information. The two balances account for 10 channels. A wave elevation measurement, and pitch, heave and roll motions account for 4 more. Because there was theoretical concern[7] about the influence of rudder motion on torsional moments, the 15th channel was rudder angle. Similarly, there was concern about documentation of the actual mean model heading, and the 16th channel was devoted to the measurement of heading angle relative to the nominal course. The last two pieces of information are related to the surge and sway degrees of freedom. Oscillatory surge and sway are ordinarily very small and are customarily ignored. In the present experiment it was intended that the approximate phase relations between wave and motions be developed. It is customary to report phases with respect to wave elevation at some point on the model. This means that the distance between the actual location of the wave probe and the model must be known. Thus there was use for surge and sway related measurements, -- in fact, the mean deviations of the position of the model from the nominal centerpoint of the six-degree of freedom motions apparatus.

There was available enough equipment to instrumentally record only 16 channels of data. Fortunately, in a good data run the model position relative to the six-degree of freedom apparatus carriage is reasonably steady, and the geometry of the apparatus is such that an adequate estimate of relative horizontal position of the model may be made by eye by two observers at their normal operating stations. This procedure was adopted in the present case.

The signals from the 16 transducers or bridges were conditioned by Sanborn Series 350 carrier amplifiers. The lowest mode of model vibration was about 8 Hz in longitudinal bending. This was sufficiently above the wave encounter frequencies involved that the wave encounter frequency component of output does not require correction for magnification. In order to clean up the noise on oscillographic records and to avoid problems with numerical data reduction, the signals from all 10 balance outputs were fed into low-pass filters. The frequency response of the filters was re-checked in place so that a good basis for later correction of phase data was obtained. The filter outputs and amplifier outputs in the case of motions and wave elevation were led to oscillographic recorders.

The basic data processing was done in the Davidson Laboratory PDP8e digital computer. At the time only 15 channels of information could be processed at once. Because the 16th channel, heading angle, contained no substantial wave induced components it was omitted from the computer data processing. The mean heading angle was read directly from the oscillograph records as the experiments progressed. The filtered signals from the 10 balance channels, the wave elevation signal, and the pitch, heave, roll and rudder angle signals were thus connected to the computer's A/D converter as well as to the oscillograph.

During a run the computer performed two functions. The first was to digitize the 15 analog signals and store the results. The second function was carried out simultaneously with the digitization and was to count zero crossings of the wave elevation signal and keep track of the elapsed time.

Immediately after the run, the computer performed a harmonic analysis on the data previously stored using the fundamental period computed from the wave zero crossing count and elapsed time. There were occasions when the machine failed to measure the correct encounter period due to extraneous noise on the analog wave signal. Accordingly the results of each run were checked against the theoretical encounter period and the oscillograph records. Where 1 or 2% differences were found a program option was exercised to re-analyze the data with a different fundamental period. The harmonic analysis was restricted to the mean value and the fundamental component of each signal. Higher harmonics were not computed. At the conclusion of each analysis the results were stored on tape for later final reduction.

The use of harmonic analysis as a data reduction method represents a departure from past practice[5,6]. It was selected for the present work for several reasons. The intended uses of the data involve the assumption of linearity. As a consequence, only the fundamental component is meaningful. The methods used involve averaging over as many encounter cycles as desired. In the present case the averaging was over all the data recorded in the steady part of the run -- whether this involved 2 or 20 encounter cycles. Phases were considered important in the present work. Harmonic analysis was considered the only convenient way to make good estimates of phase. Further detail on the mathematical model involved in this analysis is contained in a later section.

Test Procedure

Nominal model-wave headings were established by the orientation of the movable bridge to the wave maker. Seven headings were involved, 180° through 0° on 30° intervals. The heading convention followed is that 180° heading is head seas and 0° heading is following seas. At intermediate headings the convention is that waves approach the model from the port side (port bow for 150° and 120°, port beam for 90°, and port quarter for 60 and 30° headings). However the geometry of the facility as well as economic considerations dictate that this convention not be followed exactly. For the quartering sea headings the bridge and direction of model travel are such that the waves approach the port quarter as required. To achieve bow sea headings, the direction of model travel is reversed without changing the bridge orientation so that waves approach the starboard instead of the port bow.

In accordance with the above convention the nominal test headings used in the experiments were as follows:

0°	(Following Seas)
30°	(Waves approach Port Quarter)
60°	(Waves approach Port Quarter)
270°	(Waves approach Starboard Beam)
240°	(Waves approach Starboard Bow)
210°	(Waves approach Starboard Bow)
180°	(Head Seas)

At each heading angle the model was run in a number of wave lengths over a speed range corresponding to 23 to 32 knots full scale. At the start of each run the model is accelerated to approximately the correct speed at which time all carriage and motions apparatus servo systems are activated so that in the remainder of the run down the tank rail the speed and heading of the model are dictated only by the (pre-set) revolutions of the propellers and the activity of the automatic steering system. It is not ordinarily possible to pre-set propeller revolutions so that the steady speed will be exactly as desired. This is the reason for a speed range instead of discrete speeds. Thus for any given wave condition a sufficient number of runs at various speeds in the range must be made so as to allow cross fairing of results against speed.

The mean speed of the model was computed over a distance of 24 feet (about 4 model lengths). The segment of bridge rail used for speed averaging was located so that the model had attained steady speed upon entry into the segment. The computer data reduction system was so conditioned that it digitized data over as much as possible of the time that the model was in the speed averaging area. The number of wave encounter cycles actually averaged by the computer varied from 2 to 25 depending on heading and speed.

Test Program

An outline of the test program is contained in Table 7. There were three special short duration test series performed in addition to the primary wave testing program.

The first special tests involved a few smooth water runs to measure the vertical moments and vertical shears induced by the ship wave pattern for both displacement conditions. These have been found previously to be worth knowing for high-speed ships.

The second special test series involved only three runs in smooth water to obtain roll extinction curves, at zero speed and at one forward speed.

The third special test series was to generate some approximate ideas about the influence of oscillatory rudder motions upon forces and moments. These were carried out in smooth water in both light and heavy displacement conditions. In smooth water the rudder does not oscillate. The technique involved a normal smooth water run with an oscillatory signal added to the normal rudder position command signal which is provided by the automatic control system. The amplitude and frequency of this signal was varied, the rudder was forced to oscillate, and the resulting data were analyzed by the computer in the manner described in a previous section.

The primary regular wave program consisted of approximately 200 runs involving combinations of model displacement, speed, wave length and height and heading. The speed range and headings are noted in Table 7. The choice of wave lengths for each heading was based upon the observed trends of forces and moments during the experiment. These trends dictated shorter wave lengths as heading approached beam seas. The wave length to ship length (LBP) ratios actually used are noted in the table.

It was intended that standard practice be followed with respect to regular wave height; that is a wave height equal to 1/50 ship length. Head and following sea tests (180° and 0°) were done with this wave height but control of the model proved so marginal due to large rudder induced heel angles that it was necessary to restrain the roll. This decision of course invalidates much of the lateral and torsional moment and lateral shear results for these headings, and was entered into on the basis that those results which were obtained without roll/heel restraint were quite small as would be expected in head and following long-crested waves.

Chronologically, the head and following sea cases were completed first and the 30° and 210° cases next. In these first oblique headings the model proved to be unmanageable without heel restraint in waves of L/50 to L/70 height. Heel and thus roll restraint cannot be justified at oblique headings. It was found that an L/120 regular wave height could be coped with, and this height was adopted for the bulk of the tests at 30° and 210° headings as well as for the entire tests at 60° and 240° headings. In those few cases where both L/50 or L/70 wave heights and L/120 wave heights were available, linearity of response with wave height appeared to be reasonable.

The last heading to be run was beam seas (270°), and in this there was some surprise. Beam sea control is ordinarily good if quartering seas can be negotiated. In beam seas it was found possible to achieve marginal control in waves longer than 1/3 ship length only if wave heights of 1/250 of ship length were used. Such wave heights (1/4 inch to model scale) were considered much too small for reliability of data. No difficulty with control was experienced in beam seas if heel was restrained. However since this alternative would invalidate the data of primary importance, the program was curtailed at this point.

TABLE VII - TEST PROGRAM

Part	Speeds	Heading	Wave Lengths/LBP	Nominal Wave Heights	Remarks
Smooth Water	25 to 31 kt.	-	Smooth Water	0	Moments and Shears induced by ship wave pattern
Roll Extinction	0 and 28 kt.	-	Smooth Water	0	
Rudder Oscillation	27 to 31 kt.	-	Smooth Water	0	Influence of Rudder Motion on Forces and Moments
Primary Regular Wave Program	23 to 32 kt.	0°	0.75,1.00,1.25,1.50,2.00	L/50	Rolling Restrained
	"	30°	0.50,0.75,1.00,1.25,1.50,2.00	L/120,L/50	
	"	60°	0.25,0.33,0.50,0.75,1.00	L/120	
	"	270°	0.33,0.75	L/120,L/240	Program Curtailed, Heavy Displacement only
	"	240°	0.25,0.33,0.50,0.62,0.75,1.00	L/120	
	"	210°	0.33,0.50,0.75,1.00,1.25,1.50	L/120,L/70	
	"	180°	0.5 ,0.75,1.00,1.25,1.50,2.00	L/50	Rolling Restrained

In the present context, adequate control of the model was a prerequisite, but not an object of the study. The problems with model control which prevented completion of every facet of the tests are not considered "results" of the present program. However it is necessary to discuss model control more fully in view of statements of fact previously made.

The usage of the word "control" in the present work is not precisely the same as in normal usage. Herein, if the model has been adequately "controlled":

1) It has been accelerated from a standing start in waves to nearly steady speed in less than two model lengths,

2) By the time the model has reached about 4 or 5 model lengths from a standing start all the starting transients of 4 servo systems must have died out, the model speed and heading must be essentially steady, and the lateral displacement of the model from the nominal course must be less than about two model beams,

3) During the next 4 model lengths of travel the model heading must vary no more than ± 2 or 3 degrees, its lateral position relative to the nominal course (the rail) must not vary more than about ± 1 model beams.

Broadly, the start is everything. If steps 1 and 2 above can be successfully achieved, step 3 is not a problem and thus wave-induced response data may be obtained. In the present case at the 270° heading the model would consistently develop a large heel angle (15 or 20°) during step 2 and yaw sufficiently that recovery of heading was impossible. (As noted, heel restraint was a cure for this behavior.) In those runs achieved, oscillatory roll was small. No large oscillatory roll was to be expected in beam seas since the roll periods involved were out of the important range of wave periods.

The difficulties which necessitated reduction of wave height at other headings were of a similar nature; that is, they primarily involved the starting-up transients.

Because a large-scale model of the same ship has been successfully run at another facility in irregular beam and quartering seas having a significant height as much as 16 feet full scale (L/55), it seems unlikely that the control problems experienced with the present model are very meaningful with respect to the ship. Present test techniques were developed with models of slower ships and with relatively stiff high speed craft. Modifications to equipment and technique for tender high-speed ships appear feasible in retrospect, but were not available during the tests.

RESULTS

Sense Conventions

With respect to phase results sense conventions are of considerable importance. The sense conventions about the heading or nominal course angle relative to the direction of wave approach were given explicitly for the seven test headings in the section entitled "Test Procedure."

The sense conventions adopted for the moments and shears are represented in the sketches in Figure 2. The conventions for both balances are the same. Positive vertical bending is sagging moment, positive lateral bending produces a deflection concave on the starboard side. Positive torsional moment produces a deflection such as to rotate the foredeck in the starboard direction relative to the stern. Positive vertical shear is such as to deflect the bow downward, and positive lateral shear produces a deflection of the bow to starboard.

The sense conventions adopted for motions and wave are shown in the sketches in Figure 3. The motion conventions follow a right hand rule with vertical axis positive downward and longitudinal axis positive forward. Positive wave elevation has been defined to be positive downward; that is, trough positive.

Smooth Water Moments and Shears

The results from the special smooth water tests are contained in Table 8. As would be expected, only the vertical moments and shears were significant. The numbers in the table are presented in full-scale units (Froude Scaling) of long tons and feet. Sign conventions are as in Figure 2. All the moments in Table 8 are sagging moments. The numbers quoted represent the steady difference between those moments and shears existing with the model at rest in calm water and those moments and shears existing with the model at speed in calm water.

Both vertical moments and the vertical shear at frame 258 plot as reasonably straight lines vs. speed. Previous model experience suggests that the trends and magnitudes are reasonable. The vertical shear amidships is around 1/10 that at frame 258 and the data does not plot as straight lines vs. speed. The reason is that in this portion of the experiment the shear resolution was about ± 15 tons and as a consequence much of the variation indicated for the smooth water midship vertical shear is scatter.

Roll Extinction Results

A minor input to most theoretical developments is an empirical estimate of linearized roll damping at resonance. As an aid to experimental-theoretical correlation, three roll extinction experiments were performed. The results are shown in Figure 4. These experiments were all done with the model in the as-tested condition, that is, attached to the motions apparatus. The zero speed roll extinction result was obtained by recording roll after releasing the model from a steady 8 or 10^{o} heel. The two at-speed results were obtained by inducing a steady resonant roll with an electrically produced rudder oscillation, then stopping the rudder oscillation and observing the roll decay.

The differences shown between zero and at-speed roll extinctions are in line with previous model experiments as is the magnitude of decay. Since the model was attached to the apparatus, there is a small amount of friction involved. Because of this as well as the exceptionally small scale of the model, the results in Figure 4 should be considered as un-extrapolated model data.

TABLE VIII - VERTICAL MOMENTS AND SHEARS INDUCED BY SHIP WAVE PATTERN

Load Condition	Ship Speed (Knots)	Vertical Moment Midship (Ton-Ft)	Vertical Moment Frame 258 (Ton-Ft)	Vertical Shear Midship (Tons)	Vertical Shear Frame 258 (Tons)
"Heavy"	25.1	69000	19800	-25	-252
	27.2	83600	27900	-50	-300
	30.2	114000	39600	+13	-454
"Light"	25.7	57200	11700	-76	-239
	27.7	69000	17600	-76	-290
	30.6	98200	30800	-38	-416

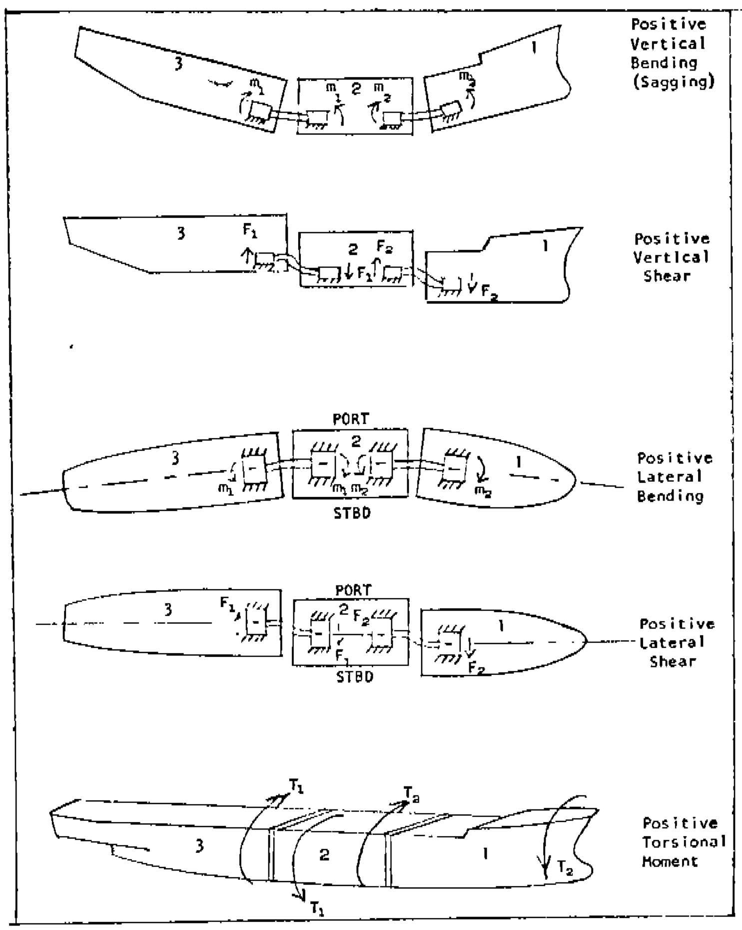

FIGURE 2 - SENSE CONVENTIONS: MOMENTS AND SHEARS

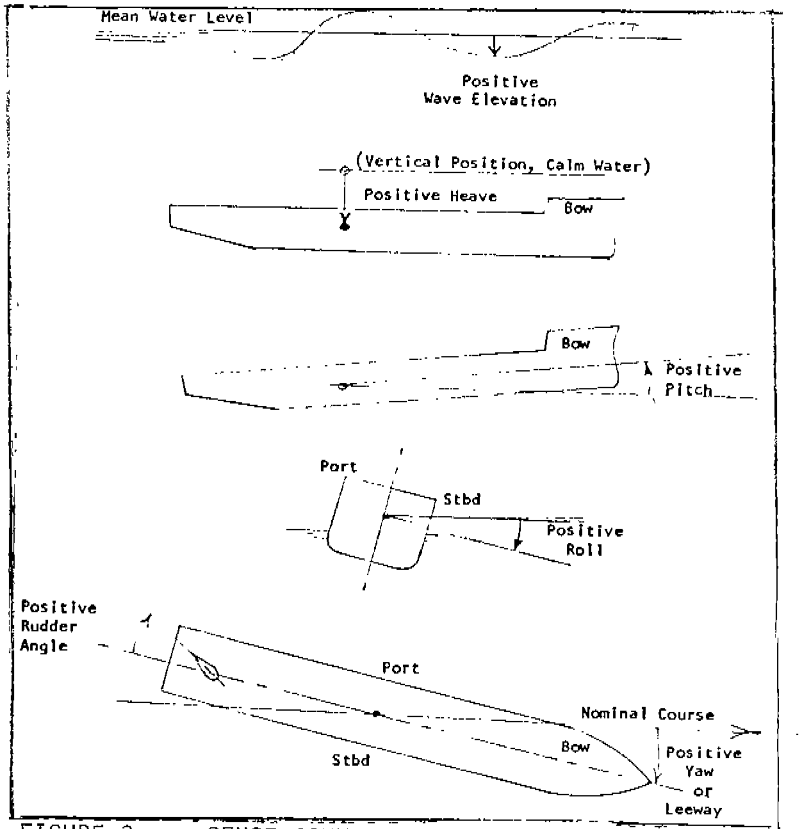

FIGURE 3 - SENSE CONVENTIONS: MOTIONS AND WAVES

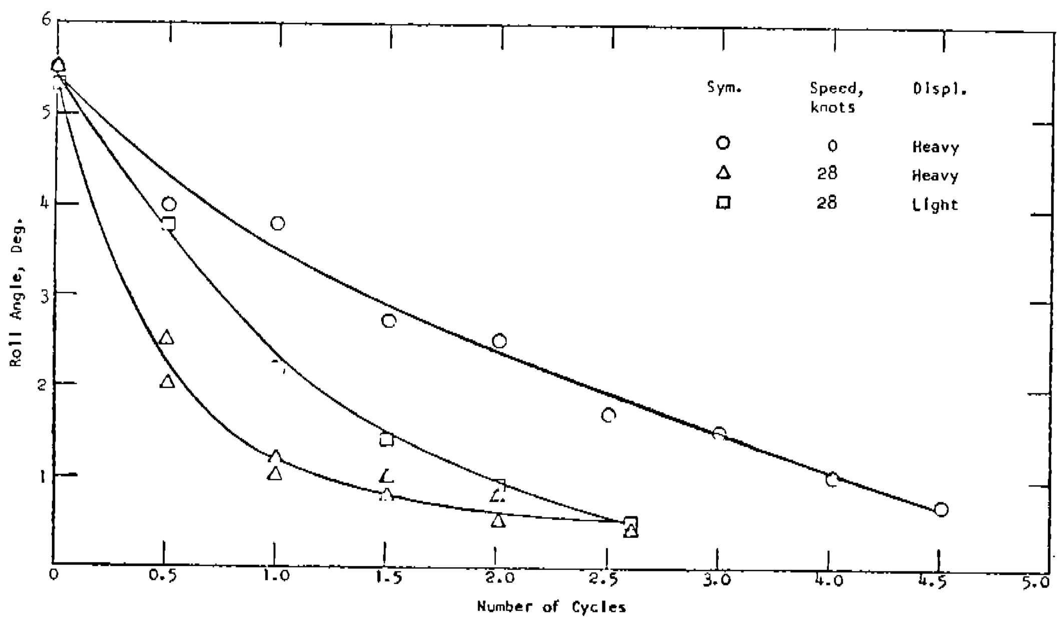

FIGURE 4 - ROLL EXTINCTIONS

Wave Test Data Reduction

As has been noted in a previous section the on-line computer data processing system performed an harmonic analysis on each of the fifteen fluctuating electrical signals corresponding to the 15 measurements. The form of this result was fifteen fundamental amplitudes and 15 phases. (No harmonics were calculated, just the amplitude and phase of the Fourier component having the same period as the ideal wave encounter period.) In a few cases where the wave encounter period approached the length of data run no computer analysis was possible and amplitudes (but no phases) were read from the oscillograph records.

The results of the first stage of analysis sufficed for preliminary plotting during the tests but required further manipulation for presentation.

The first modification to these results was to correct moments and shears for the amplitude and phase response characteristics of the low-pass filters. The primary influence this manipulation had on the results was to align the relative phases correctly. The phase of wave elevation was then corrected so as to represent the ideal phase of the undisturbed wave which would have been measured amidships (Station 10) on the model had the model not been present. This correction involves computing the fraction of a wave length between midships on the model and the position of the wave probe. The visually estimated mean surge and sway data was used at this stage.

The second major modification to the data was to apply the coupling corrections detailed in Table 4 to the moments and shears. This was carried out by resolving the initial amplitudes and phases into in-phase and quadrature components, applying the transformations shown in Table 4 and then converting the result to the amplitude-phase form. The amplitudes and phases before and after this correction were listed side by side so that the magnitudes of change could be inspected. As pointed out previously there was a potential that the torsional moment and shears might be very sensitive to coupling from the longitudinal moments. An overview of the data before and after coupling corrections indicated that this was not the case. The torsions and shears were in the main between 45 and 135° out of phase with the longitudinal moments so that the amplitudes and phases were not too sensitive to the correction. Percentage changes as large as those feared occurred only in cases where there was relatively little torsion or shear in the first place, and it was concluded that further refinement of the coupling correction technique or numbers would yield little or no improvement in the data.

The last manipulation of the data involved the division of moment, shear and motions amplitude by wave amplitude and the Froude scaling of the results to ship scale.

The final step in the wave data reduction was to cross-fair all amplitudes and phases on a base of ship speed in an exactly similar way to the procedures shown in References 5 and 6. One example of this type of cross fairing is shown in the Appendix. The cross-faired results are omitted from this report. Owing to the relatively restricted range of speed involved in the present tests, almost all of the data could be faired as straight lines. Scatter about the faired lines was similar in magnitude to that shown in References 5 and 6.

Results of Regular Wave Tests

Of the 16 channels of data instrumentally recorded, the data reduction procedure just described applied to the first 15. The 16th channel was the measurement of leeway. Leeway is the mean difference between the course angle or track of the ship and the ship's heading. In the present experiments leeway was resolved to about the nearest degree. No case was observed in which the mean leeway during the data taking portion of the run differed significantly from zero. In the typical case the model heading would waver slowly during the data taking portion of the run, from one side of zero to the other. This waver was apparently not related to the wave encounter frequency except when the encounter frequency was near zero. In no valid data run was the magnitude of this waver more than 4^o. The results of the leeway measurements may be simply stated as follows: observed model leeway was zero plus or minus 1^o or 2^o typically, with a small fraction of all runs having a variation up to $\pm 4^o$. Thus the actual and nominal headings were practically the same in all cases.

The final results of the program have been gathered for convenience into an Appendix containing 70 charts, Figures A-1 through A-70. Table 9 is a compact index of the data presented. The initial program contained a parameter variation of 7 headings, 2 displacements, 3 speeds and a number of wave lengths. After normalization of data by the wave amplitude there are 14 items of measured data. There was thus a potential of about 500 plots of amplitudes and phases vs. wave length. It was seen even during the experiments that the great bulk of the data was not sharply speed dependent in the specified range and that there was often relatively little change with load condition. Accordingly the procedure adopted was to pick off amplitudes and phases from the cross plots against speed at the two nominal speeds of 25 and 30 knots and to plot amplitudes and phases for these two speeds at each displacement on the same chart as functions of wave length. This produces a potential of 98 charts corresponding to the 7 heading by 14 data item Table 9. Various problems already discussed served to reduce the number of figures presented still further. As indicated in Table 9, heel and roll restraint invalidate everything except pitch, heave, vertical moments, and vertical shears in head (180^o) and following (0^o) seas. Control problems reduced the valid data for the 270^o heading to that for one wave length. In this case Figures A69/70 contains all the data of significance plotted vs. ship speed. In addition, in bow seas (240^o and 210^o headings) roll amplitudes were too small to satisfactorily resolve and this data was also omitted.

Each of Figures A-1 through A-68 pertains to an item measured at a particular heading. At the top of the figures are plotted amplitude ratios vs. wave length and the lower part of the figure contains phases. The points are not actual data points, they serve to indicate the wave lengths for which cross plots on ship speed were developed. When data for both speeds are the same only one "point" is indicated and only one connecting line is drawn. (Two speeds are always represented in these charts.)

Amplitude ratios for moments are presented in units of foot-tons/foot of wave amplitude full scale. Similarly, shear amplitude ratios are in units of tons per foot of wave amplitude. (Long tons of 2240 pounds in both cases.) Heave ratios are non-dimensional (feet of heave amplitude/foot of wave amplitude). Amplitude ratios for angular oscillations (pitch, roll, rudder) are presented in units of degrees/foot of wave amplitude.

Phases are presented as lags in degrees from 0^o to 360^o. (In this notation a phase of 270^o corresponds to a 90^o lead for example.) When phases change from lags to leads or vice versa within the tested wave length range they may be shown plotted in the vicinity either of 0^o lag or 360^o lag as best suits the graphical presentation. Phases are relative and in this case the phase reference was chosen to be midship vertical moment. The relations between the phases of the various items of data may be described as follows. The assumed mathematical model for data channel (j) is:

TABLE IX - SUMMARY OF FIGURE NUMBERS CONTAINING FINAL RESULTS

Source	Component	Heading 0°	30°	60°	270°*	240°	210°	180°
Midship Balance	Vertical Moment	A-1	A-8	A-22	A-69/70	A-36	A-49	A-62
	Lateral Moment	A-3#	A-10	A-24	A-69/70	A-38	A-51	A-64#
	Torsional Moment	#	A-12	A-26	A-69/70	A-40	A-53	#
	Lateral Shear	#	A-14	A-28	A-69/70	A-42	A-55	#
	Vertical Shear	A-4	A-16	A-30		A-44	A-57	A-65
Balance at Frame 258	Vertical Moment	A-2	A-9	A-23	A-69/70	A-37	A-50	A-63
	Lateral Moment	#	A-11	A-25	A-69/70	A-39	A-52	#
	Torsional Moment	#	A-13	A-27	A-69/70	A-41	A-54	#
	Lateral Shear	#	A-15	A-29	A-69/70	A-43	A-56	#
	Vertical Shear	A-5	A-17	A-31		A-45	A-58	A-66
Motions Instruments	Heave	A-6	A-18	A-32	A-69/70	A-46	A-59	A-67
	Pitch	A-7	A-19	A-33	**	A-47	A-60	A-68
	Roll	#	A-20	A-34	A-69/70	**	**	#
	Rudder Angle	#	A-21	A-35	**	A-48	A-61	#

* Cross plot vs. speed for one wave length only.
** Angular motions amplitudes less than 0.1 deg/foot of wave amplitude.
\# Data invalidated by heel and roll restraint.

$$X_j(t) = \sum_{p=0} a_{pj} \cos(p\omega_e t) + \sum_{p=1} b_{pj} \sin(p\omega_e t)$$

in which $X_j(t)$ is the (periodic) time history of channel (j)

ω_e is ideal wave encounter frequency

a_{pj} and b_{pj} are Fourier coefficients

In concert with the demands of linear analysis, only the component corresponding to p=1 is considered, and thus the model for the data presented may be written:

$$X_j(t) \approx a_{1j} \cos(\omega_e t) + b_{1j} \sin(\omega_e t)$$

Converting the representation to an amplitude and phase form:

$$X_j(t) = c_j \cos(\omega_e t - \epsilon_j)$$

In the above the ϵ_j are the phases. In this convention a positive value of ϵ_j corresponds to a time delay and thus a phase lag. To reference the phases to a particular channel is simply a matter of introducing a uniform time shift in all channels so that the "phase" for the reference channel is zero. Then the model implied by the data presentation in Figures A-1 through A-68 is:

(Midship Vertical Moment) =

= (Wave Amplitude) $\cdot$ (Amplitude Ratio) $\cdot \cos(\omega_e t)$

(Any Other Channel) =

= (Wave Amplitude) $\cdot$ (Amplitude Ratio) $\cdot \cos(\omega_e t - \delta_j)$

and the δ_j are the phase lags with reference to midship vertical moment.

In order to conserve space the phase lags of the wave elevation relative to the midship vertical moment have been plotted on the same figure as the midship vertical moment.

The precision of the results presented in Figures A-1 through A-68 is best assessed on the basis of scatter in results of runs which are near repeats as well as upon minimum instrument and transducer resolution. An assessment of the present results on this basis results in estimates of the precision of all amplitude ratios to be ± 5 to 10% or a fixed threshold, whichever is greater. The estimated values of the precision thresholds were as follows:

Vertical and Lateral Moments	:	2000 foot tons/foot
Torsional Moments	:	200 foot tons/foot
Vertical and Lateral Shears	:	10 tons/foot
Heave	:	0.1 foot/foot
Pitch	:	0.03 degrees/foot
Roll and Rudder	:	0.1 degrees/foot

Precision in phase angle depends largely upon the magnitude of the corresponding amplitude ratio. A precision of $\pm 10^{\circ}$ is estimated for phase results corresponding to relatively high level amplitude ratios. Phase results corresponding to amplitude ratios near the thresholds cited above are apt to have much larger errors, Figure A-3 is an example where the amplitude ratio is below the threshold. In this particular case possible phase errors of $\pm 90^{\circ}$ could be easily shown.

Results of Rudder Oscillation Experiments

With the exception that the resulting amplitude ratios were normalized by roll angle and the phases were referred to rudder angle, the data in the smooth water rudder oscillation experiments was obtained and reduced exactly as in the wave experiments. The significant results are shown in Figures 5, 6 and 7. All data runs were obtained with a rudder oscillation amplitude of 8 to 11°. The period of the rudder oscillation was varied through roll resonance in the light displacement case but only up to just below roll resonance in the heavy displacement case because the available signal generator would go no lower in frequency.

No significant pitch, heave, vertical moments or vertical shears were observed and these results are omitted from the presentation.

Figure 5 for roll shows some not surprising results. The peak roll amplitude per degree rudder is larger for the heavy displacement case than the light. This is a reflection of the much larger $\overline{GM}$ in the light case. The phase lags for heavy and light cases collapse rather well. Because of the sense conventions adopted for rudder and roll, a constant positive rudder angle induces a negative roll moment. Thus the 180° phase lags for long rudder oscillation periods are reasonable. As shown, the roll phase lag shifts about 180° as the oscillation period shifts through resonance toward lower periods.

The results for lateral moments, torsional moments, and lateral shears are shown in Figures 6 and 7. Plotting conventions are the same as in Figure 5. The phases of torsional and lateral moments and of lateral shears were all very nearly the same as roll. To the degree of precision attained in these tests the result is that these reactions were all in-phase with roll. That the lateral and torsional reactions are related more directly to roll amplitude than to rudder amplitude is strongly indicated by the above phase result and by the similarity to the roll amplitude trends of the amplitude trends of the lateral reactions. If the moment and shear results in Figures 6 and 7 are normalized by roll angle instead of rudder angle, there results an approximate collapse of the data for light and heavy displacements.

In summary of the results of the rudder oscillation experiments, it appears that measurable lateral moments, torsions and shears are related to rudder angle only according to the amount of roll induced by the rudder.

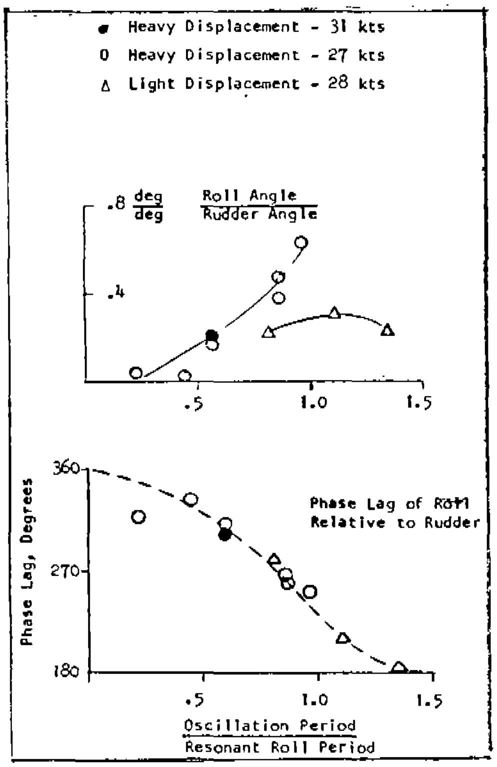

FIGURE 5 - RESULTS OF RUDDER OSCILLATION EXPERIMENT: ROLL ANGLE

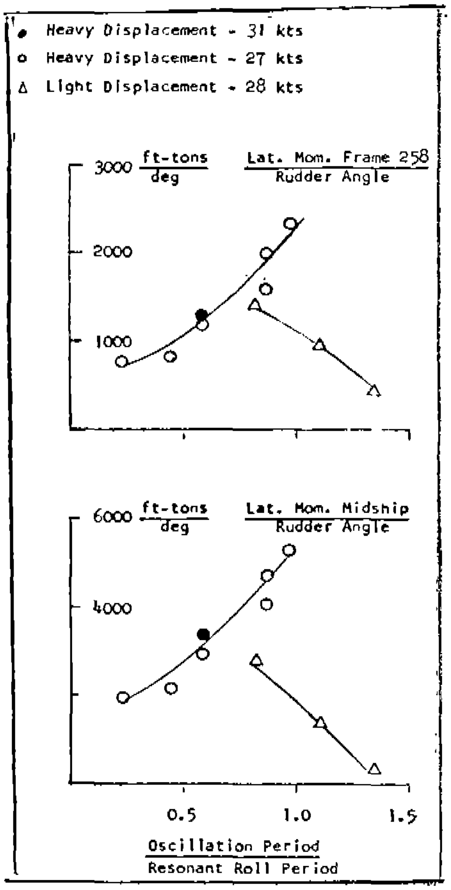

FIGURE 6 - RESULTS OF RUDDER OSCILLATION EXPERIMENT: LATERAL MOMENTS

DISCUSSION

The objective of this investigation was to obtain data for use in later correlations between theory, model tests and full-scale experiment. The figures in the Appendix summarize all of the significant data obtained in a form which is believed convenient for use in correlations. Some comparisons of the results for the various headings has been carried out. For example, Figures 8 through 11 contain amplitude response curves for heavy displacement, 30 knot speed, for all headings for midship vertical and lateral moments, torsional moments and lateral shears. In contrast to the results in References 6 and 7 relatively little double peaking of amplitude response was observed.

Vertical moments, Figure 8, peak at progressively shorter wave lengths as heading shifts toward beam seas. Peak lateral moments, Figure 9, occur at headings of 60^{o} and 240^{o}. Altogether, vertical and lateral moment trends as well as magnitudes are very much what would be expected on the basis of prior tests (Refs. 5,6).

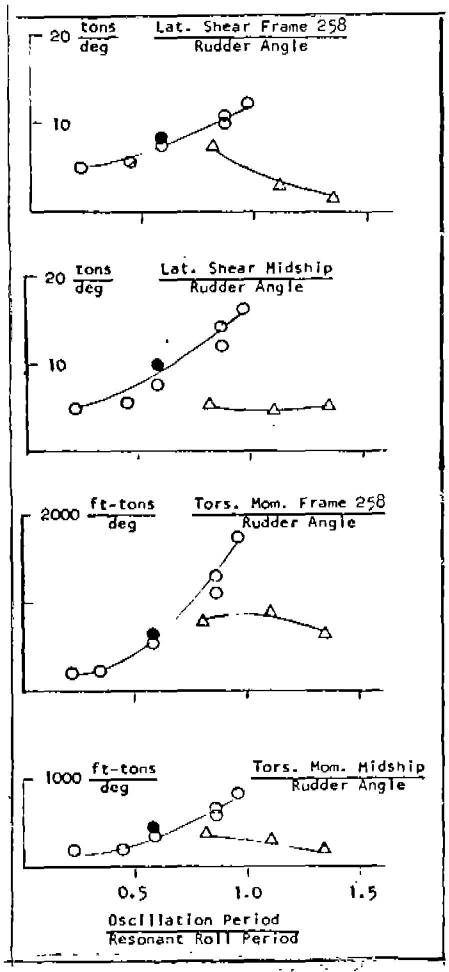

FIGURE 7 - RESULTS OF RUDDER OSCILLATION EXPERIMENT: TORSIONAL MOMENTS AND LATERAL SHEARS

Lateral shears and torsional moment amplitudes also peak at 240° and also probably somewhere between 30 and 60°. The highest torsional moments and lateral shears were obtained at these latter headings in a wave of about 1/3 ship length. These peaks are associated with roll resonance. It is probable that data were obtained at too few headings to fully define resonant roll behavior and thus the details of maximum torsion and lateral shear response.

The influence of the rudder upon the lateral reactions may be approximated with the aid of Figures 6 and 7. For 210° and 240° headings the wave encounter period was half of or less than the resonant roll period, while the maximum rudder amplitude response was about 1/2° per foot of wave amplitide. Using these numbers and the results in Figures 6 and 7, estimates of the magnitude of rudder induced moments and shears are as follows:

Lateral Moment Midship	--	1000 foot tons/foot
Lateral Moment Frame 258	--	400 foot tons/foot
Torsional Moment Midship	--	50 foot tons/foot
Torsional Moment Frame 258	--	100 foot tons/foot
Lateral Shear Midship	--	3 tons/foot
Lateral Shear Frame 258	--	3 tons/foot

These magnitudes are less than the precision thresholds cited in the last section. It appears that the rudder degree of freedom has no measurable effect on the results in bow seas.

In the 30 to 60° headings there was much resonant rolling and the peak lateral reactions occurred near resonant roll. The peak roll response was about 2-1/2° per foot of wave height. Corresponding to these peaks the rudder response was about 1° per foot of wave height. According to Figure 5 about 1/2° of roll might be induced per degree of rudder. Consequently one way of approaching the influence of rudder would be to say that the rudder induced about 20% (1/2°/foot) of the observed roll and that consequently, by the implications of the rudder oscillation tests, there may be as much as 20% of the peak lateral and torsional moments, and lateral shears attributable to rudder action. Alternately, applying the same procedures as was done for bow seas, the estimated magnitude of rudder induced moments and shears become:

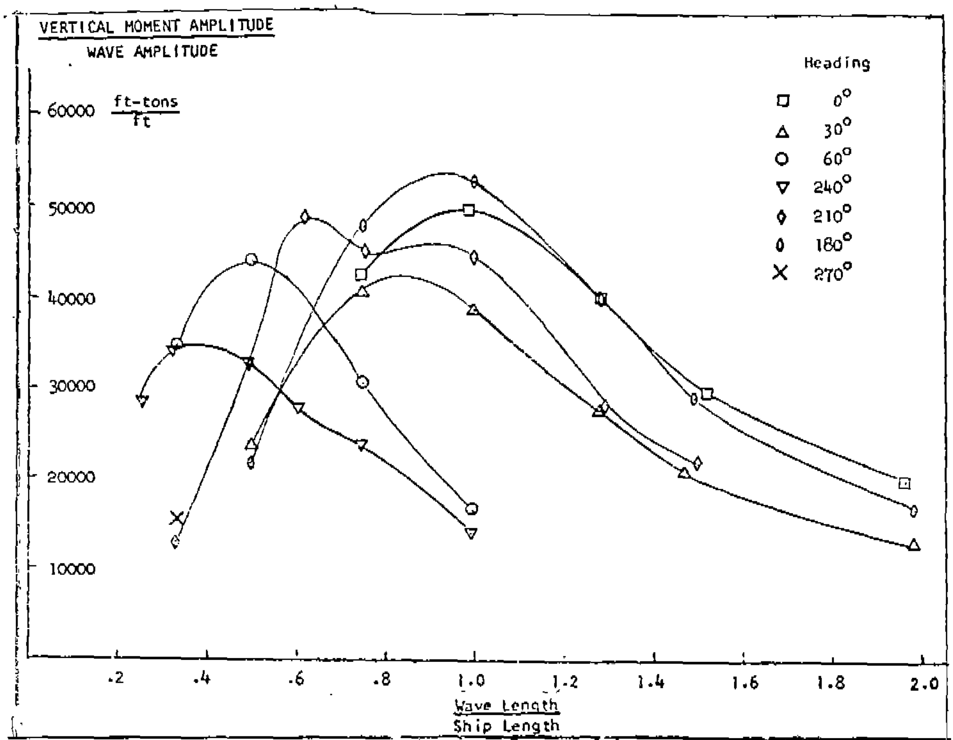

FIGURE 8 - MIDSHIP VERTICAL WAVE BENDING MOMENT AMPLITUDES
HEAVY DISPLACEMENT, 30 KNOTS SHIP SPEED

Lateral Moment Midsnip	--	6000 foot tons/foot
Lateral Moment Frame 258	--	2500 foot tons/foot
Torsional Moment Midship	--	1000 foot tons/foot
Torsional Moment Frame 258	--	2000 foot tons/foot
Lateral Shear Midship	--	20 tons/foot
Lateral Shear Frame 258	--	20 tons/foot

A comparison of these magnitudes with the data in the Appendix for 60° and 30° headings bears out the above conclusion with respect to the influence of the rudder degree of freedom upon torsional and lateral moments, and shears.

In summary, there appears to be an appreciable influence of rudder oscillation upon torsion, lateral moments and lateral shears only at headings and in wave lengths in which appreciable resonant roll is experienced. In these cases the magnitude of the influence approximates 20%. With respect to simulation of full scale, the influence of rudder motion on internal reactions must probably be considered an indirect scale effect. The amount of roll excited by the full scale rudder depends upon the full-scale ship damping and rudder control system, neither of which have necessarily been simulated in the present experiments.

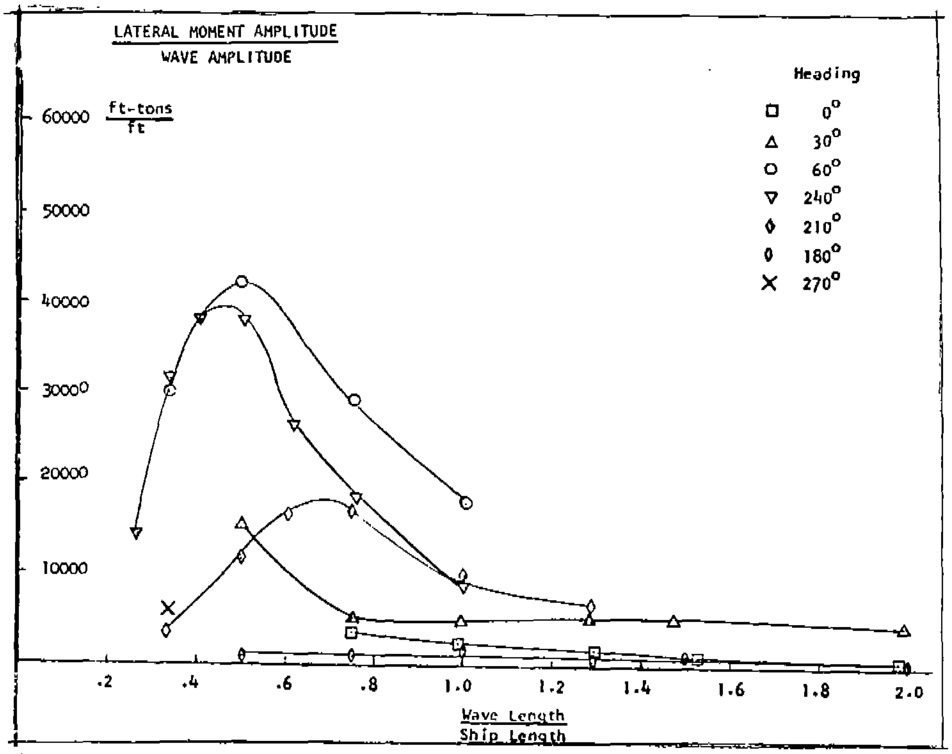

FIGURE 9 - MIDSHIP LATERAL WAVE BENDING MOMENT AMPLITUDES
HEAVY DISPLACEMENT, 30 KNOTS SHIP SPEED

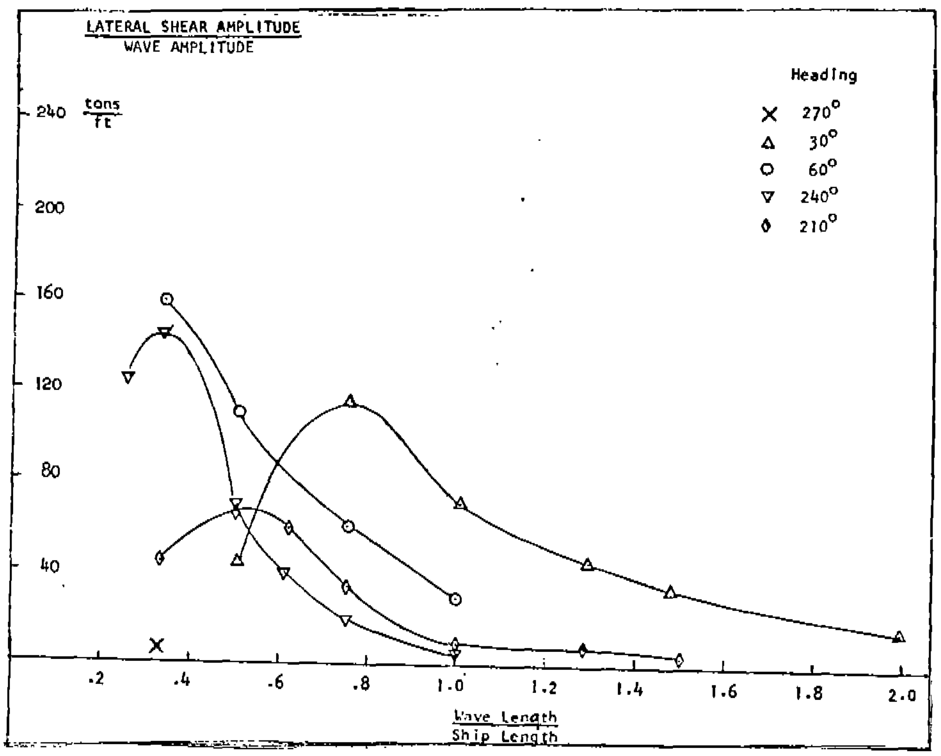

FIGURE 10 - MIDSHIP LATERAL WAVE SHEARING AMPLITUDES
HEAVY DISPLACEMENT, 30 KNOTS SHIP SPEED

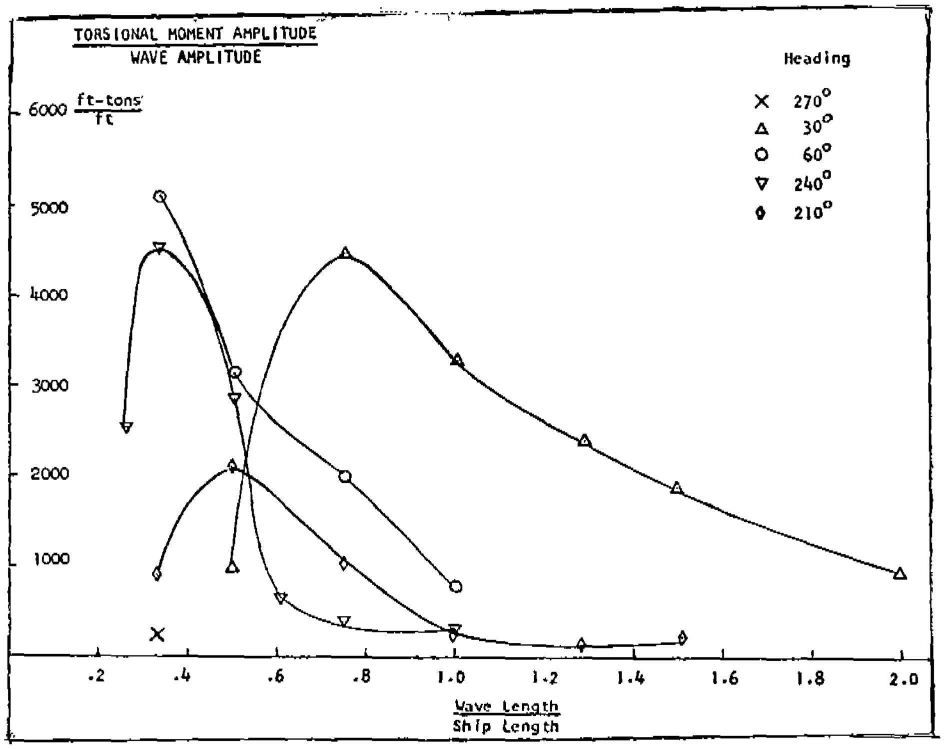

FIGURE 11 - MIDSHIP TORSIONAL WAVE MOMENT AMPLITUDES
HEAVY DISPLACEMENT, 30 KNOTS SHIP SPEED

In addition it is very doubtful that the lateral forces generated on the model rudder will scale properly.

In the literature there is often reference to torsional moments computed about a "center of twist" or shear center. In the present experiments torsion is given about an axis 23.3 feet above the baseline in the centerplane. It is therefore in order to mention some aspects of possible manipulations of present data. If it is desired to alter the reference point for torsional moment it will be necessary to do a vector sum with the torsional moment and lateral shear data. Observing the senses in Figure 2, the torsional moment about some new axis a distance X <u>below</u> the baseline is computed as follows:

$$\vec{T}_2 = \vec{T}_1 + (23.3 + X)\vec{S}_L$$

where

$\vec{T}_2$ = torsional moment about the new axis (per unit wave amplitude)

$= |T_2|\cos(\omega_e t - \delta)$

$\vec{T}_1$ = torsional moment/unit wave amplitude about an axis 23.3 feet above the baseline

$= T_1 \cos(\omega_e t - \delta_t)$

$\vec{S}_L$ = lateral shear per unit wave amplitude

$= S_L \cos(\omega_e t - \delta_{SL})$

Expanding:

$$\vec{T}_2 = [T_1 \cos\delta_t + (23.3+X) S_L \cos\delta_{SL}]\cos(\omega_e t)$$
$$+ [T_1 \sin\delta_t + (23.2+X) S_L \sin\delta_{SL}]\sin(\omega_e t)$$

continuing the expansion:

$$|T_2| = [(T_1\cos\delta_t + (23.3+X)S_L\cos\delta_{SL})^2 + (T_1\sin\delta_t + (23.3+X)S_L\sin\delta_{SL})^2]^{1/2}$$

$$\delta = \tan^{-1}\left[\frac{T_1\sin\delta_t + (23.3+X)S_L\sin\delta_{SL}}{T_1\cos\delta_t + (23.3+X)S_L\cos\delta_{SL}}\right]$$

As an example, a near maximum torsional moment for the heavy displacement was measured in the 60^o heading in a wave of 0.5 ship lengths. For torsion at frame 258, from the Appendix:

$$T_1 = 5900 \text{ foot tons/foot}, \ \delta_t = 305^o$$

$$S_L = 150 \text{ foot tons/foot}, \ \delta_{SL} = 325^o$$

Assuming as in Reference 8 that the center of twist is 0.4 ship depths below the keel, $X \approx 30$ feet, and evaluating the above expressions:

$$|T_2| \approx 13700 \text{ foot tons/foot}, \ \delta = 314^o$$

In this example altering the position of the axis has altered the "torsional moment" from about 20% of the corresponding lateral bending moment to about 50%. The magnitude of this ratio corresponds reasonably well to results in the recent literature for torsion about "centers of twist" (see 8, for example).

Some comparisons made with previous ship motions data indicate that while pitch amplitudes are reasonable, the heave amplitudes reported herein are too high -- perhaps by as much as a factor of two. All of the test logs, the computer data and the oscillographic records were rechecked for consistency and for numerical errors. The only source of error which could be found was the possibility that the heave calibration of both the oscillograph and computer was in error. The heave calibration procedure involved the physical calibration of the heave transducer against the position of a calibrated zero suppression potentiometer in the signal conditioning amplifier. With this calibration the zero suppression potentiometer was later used to set the level of a switched step signal of an appropriate level for computer and oscillograph calibration. In the present tests the heave zero suppression potentiometer was set just once at the start. An error at this point would introduce a systematic error in the present heave data; that is, all heave data presented could be wrong by the same factor. Heave phase would not be affected.

CONCLUDING REMARKS

The primary objective of the present investigation was to obtain 3 components of wave moment and two components of wave shear forces at two sections of a high-speed container ship. This has been accomplished for the significant ship-wave headings. In addition, coordinated data has been obtained of the model motions.

In advance of results of correlations of the present data with theory no positive recommendations can be made as to the necessity of further testing.

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APPENDIX A

DATA OBTAINED IN REGULAR WAVES

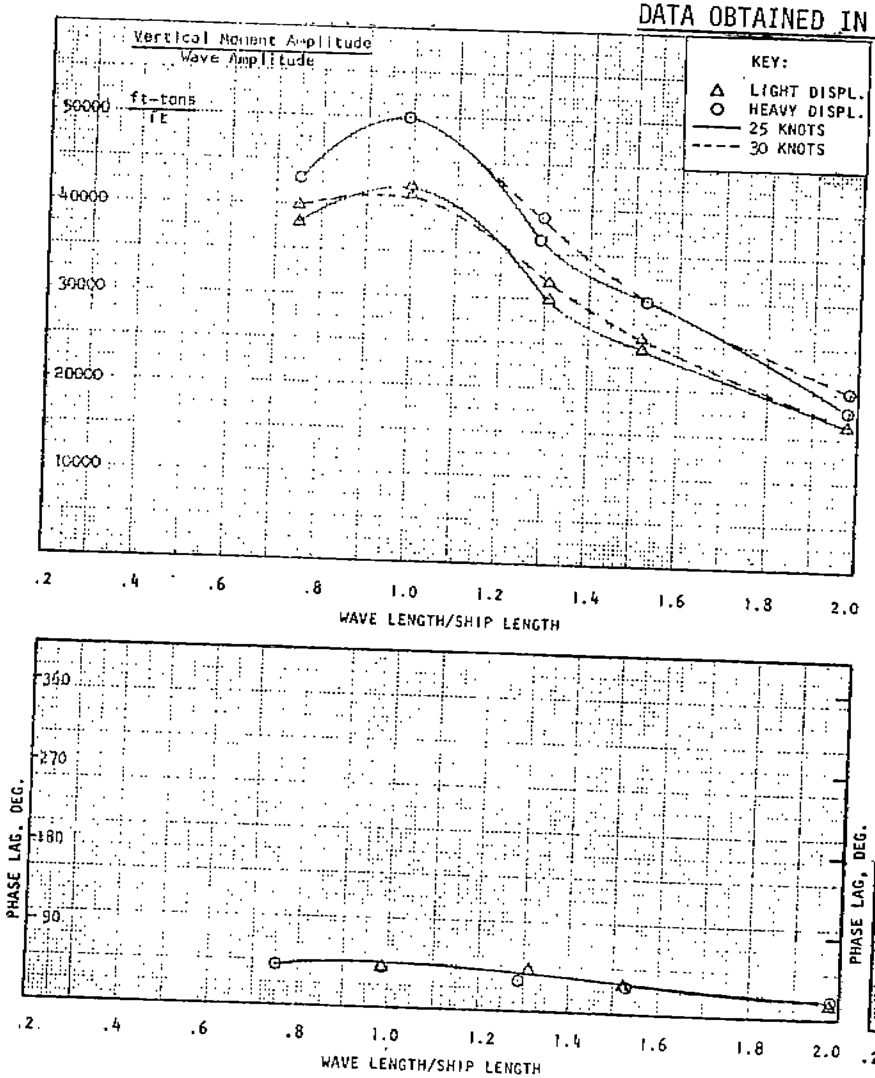


FIGURE A-1 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 0° HEADING

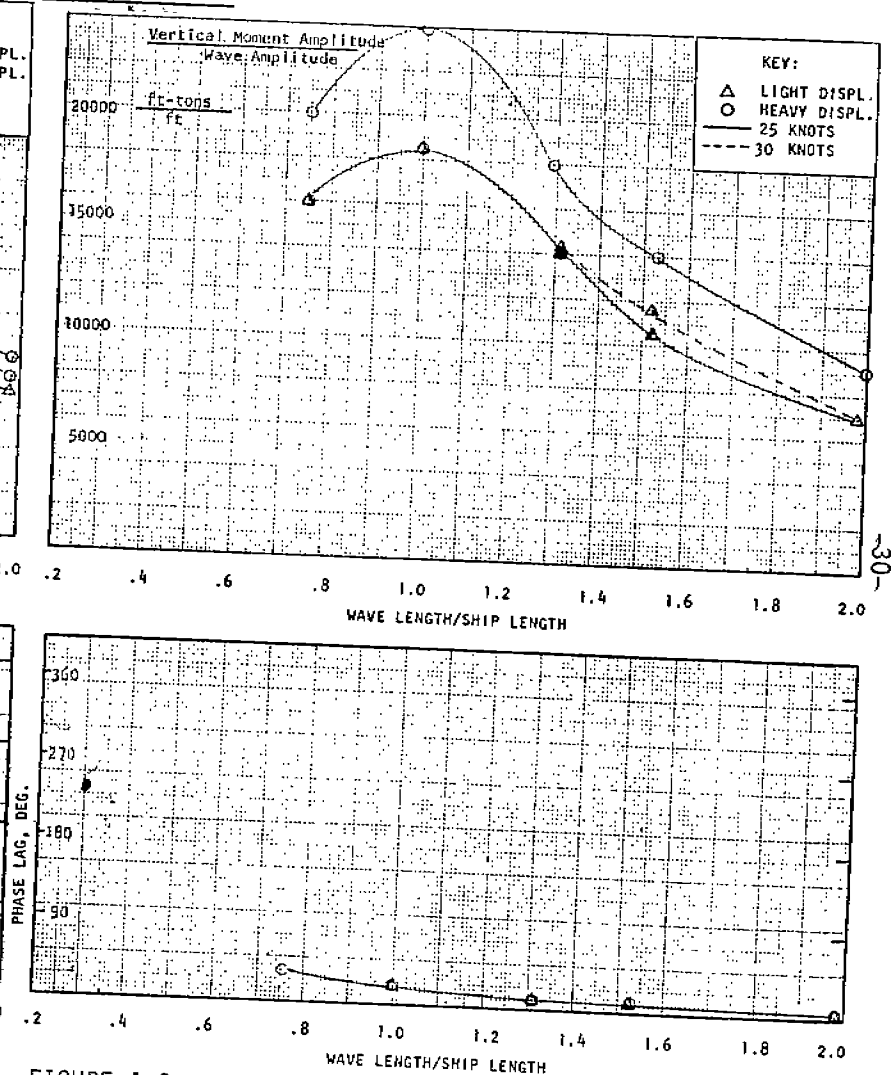


FIGURE A-2 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 0° HEADING

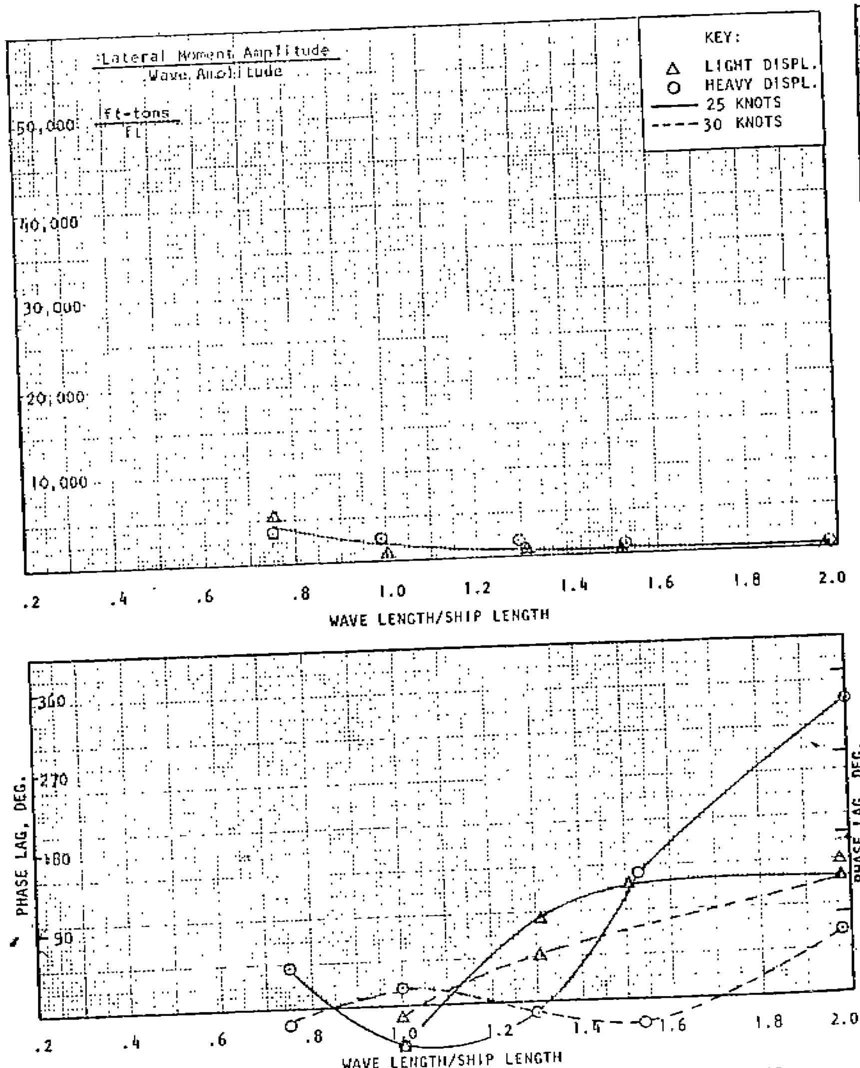


FIGURE A-3 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 0° HEADING

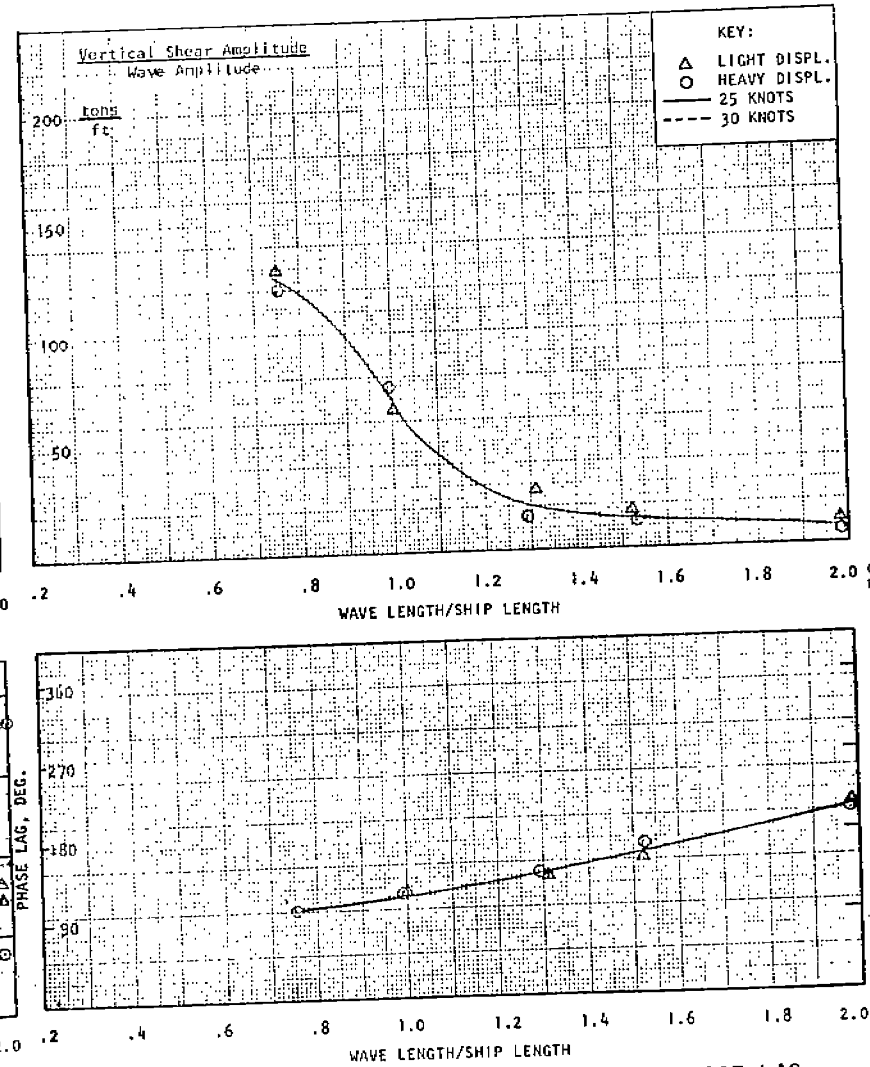


FIGURE A-4 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 0° HEADING

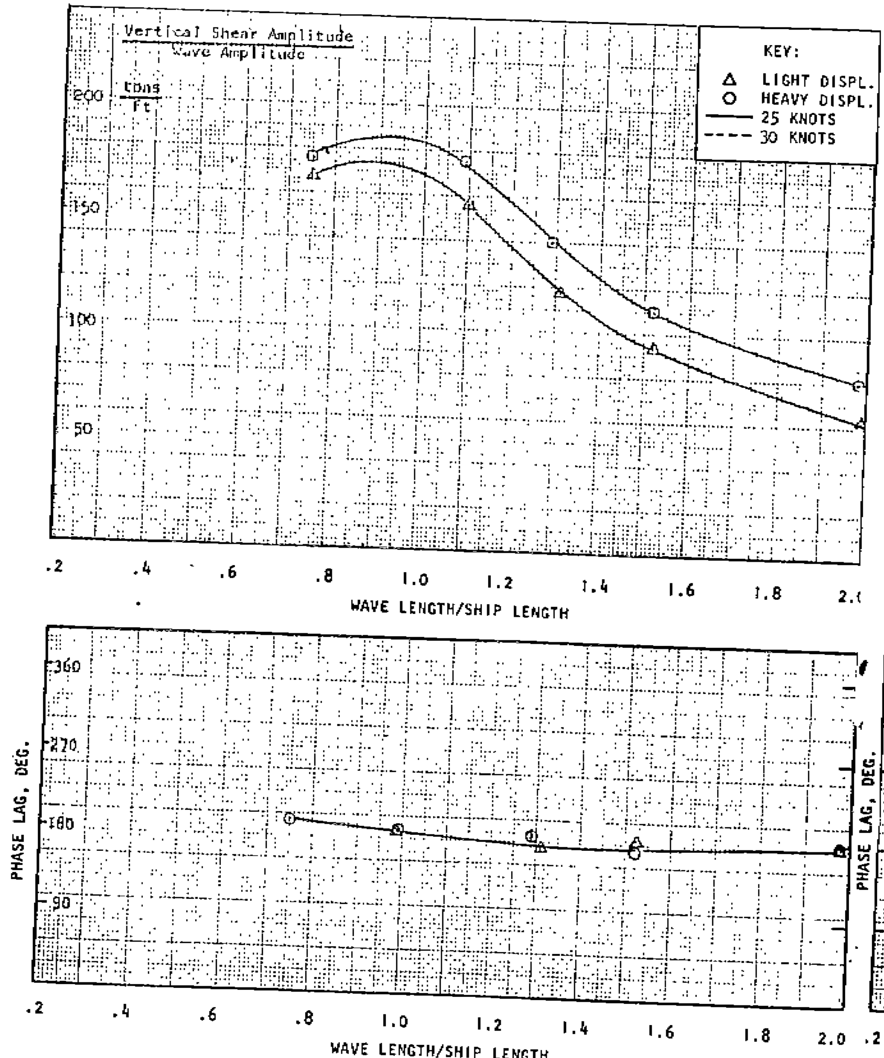


FIGURE A-5 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 0^{0} HEADING

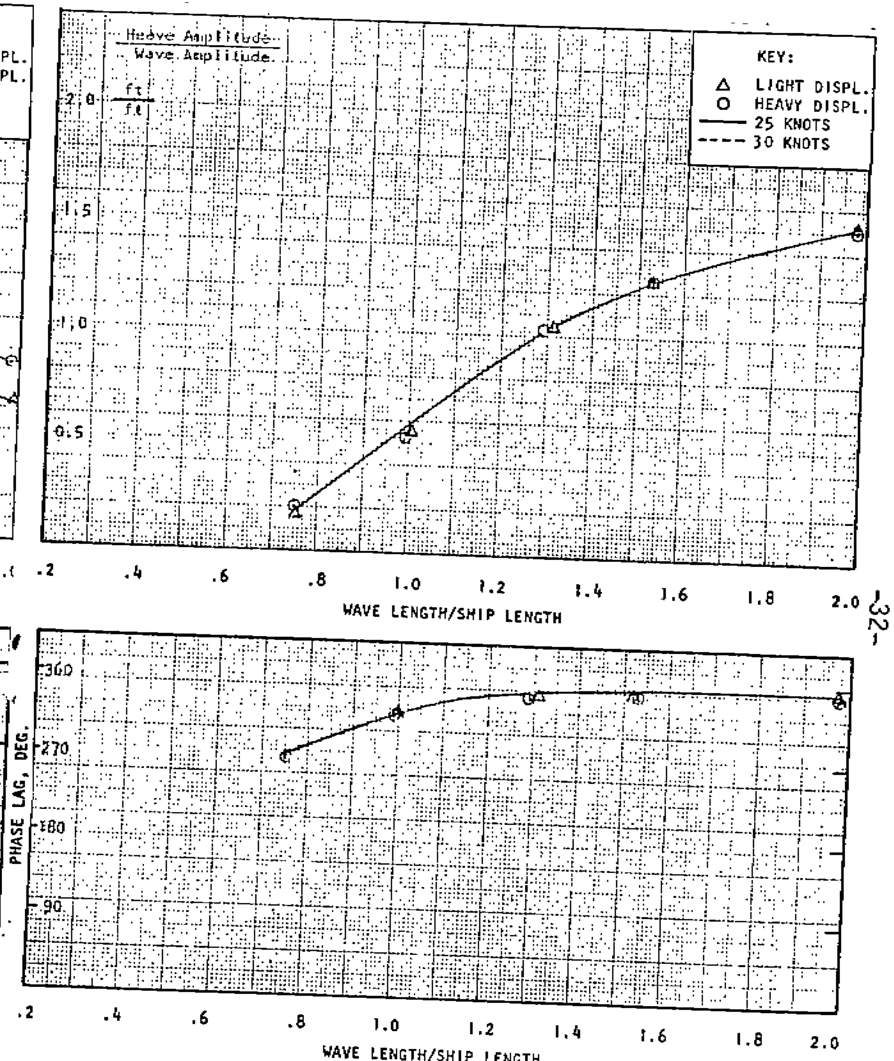


FIGURE A-6 - FRAME 124 HEAVE AND PHASE LAG, 0^{0} HEADING

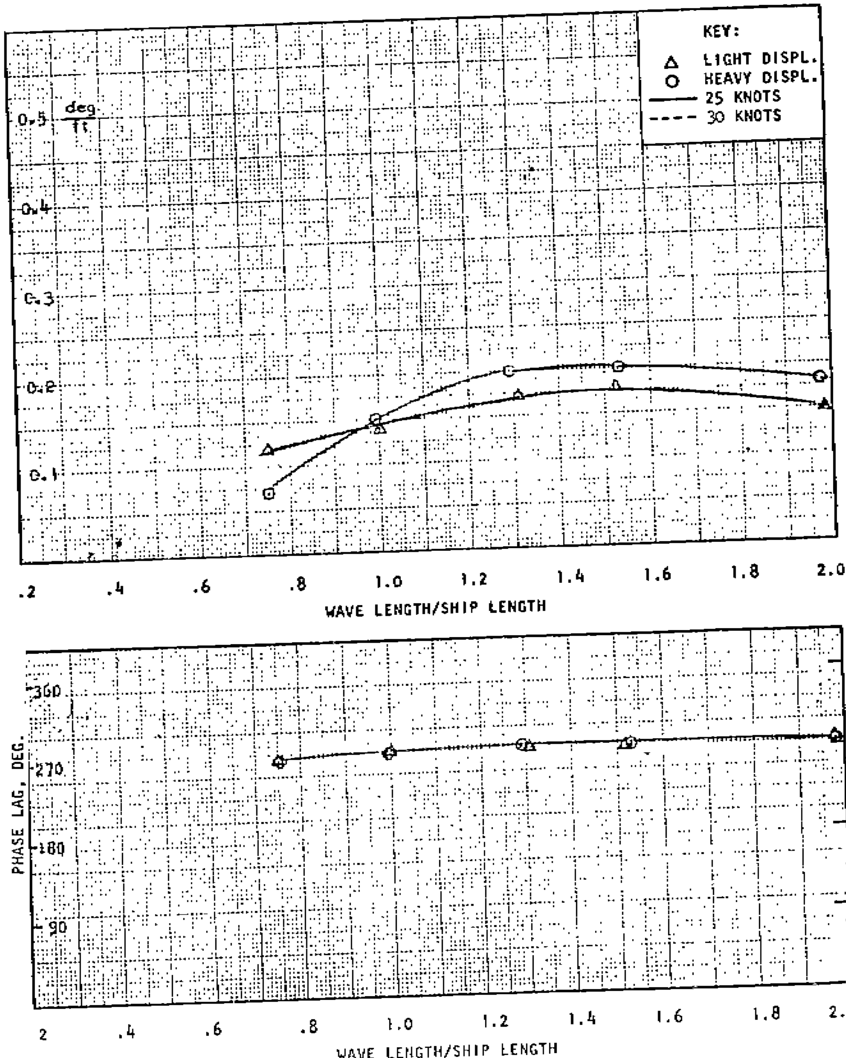


FIGURE A-7 - PITCH AND PHASE LAG, 0° HEADING

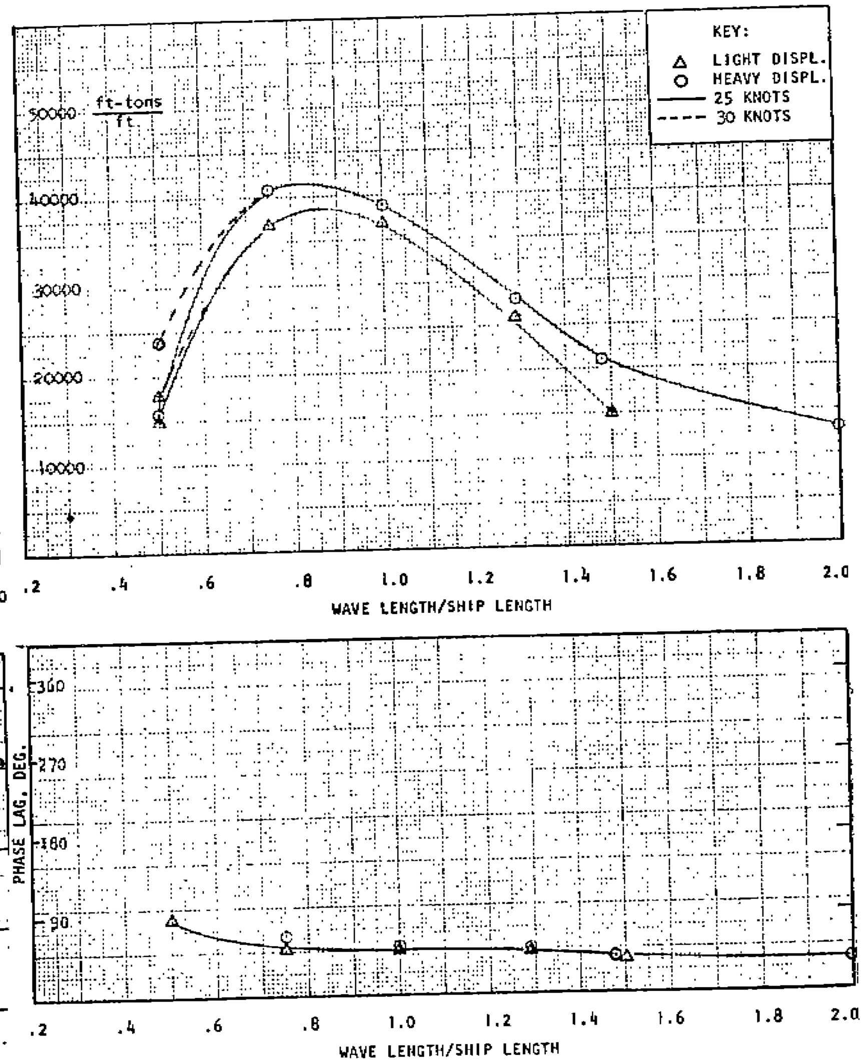


FIGURE A-8 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 30° HEADING

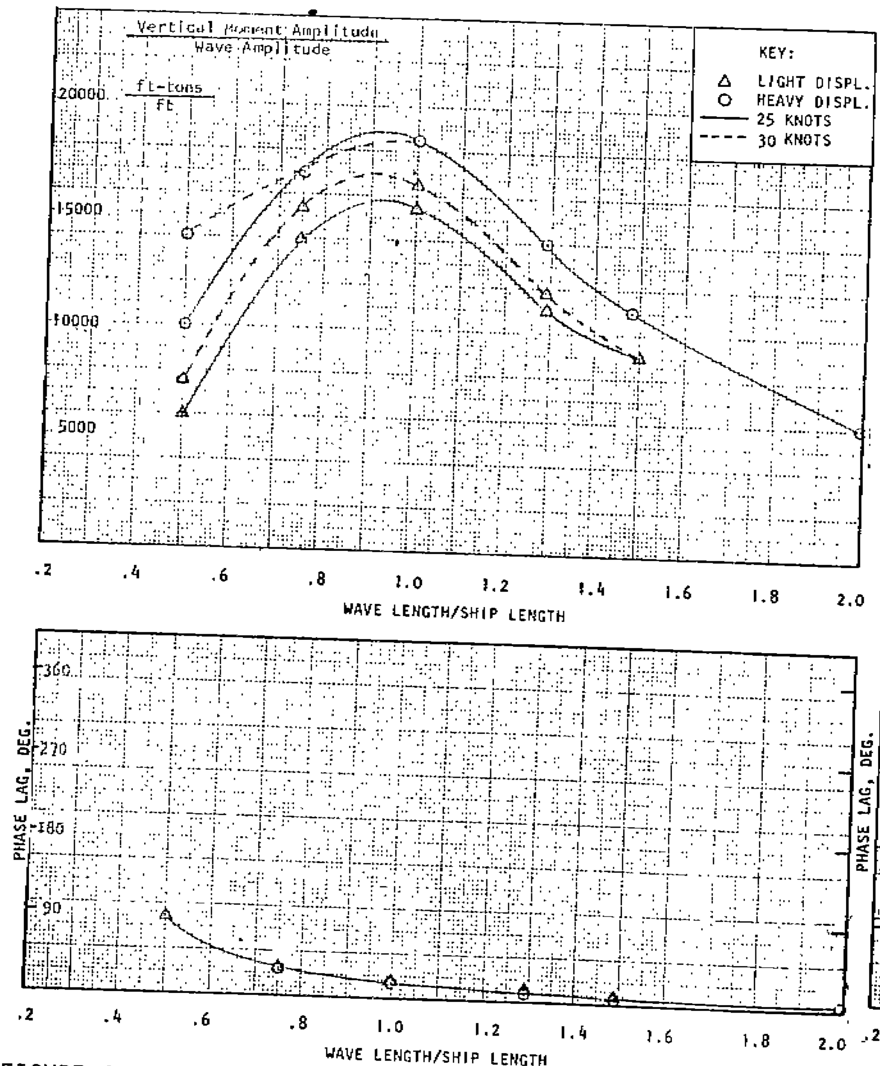


FIGURE A-9 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 30° HEADING

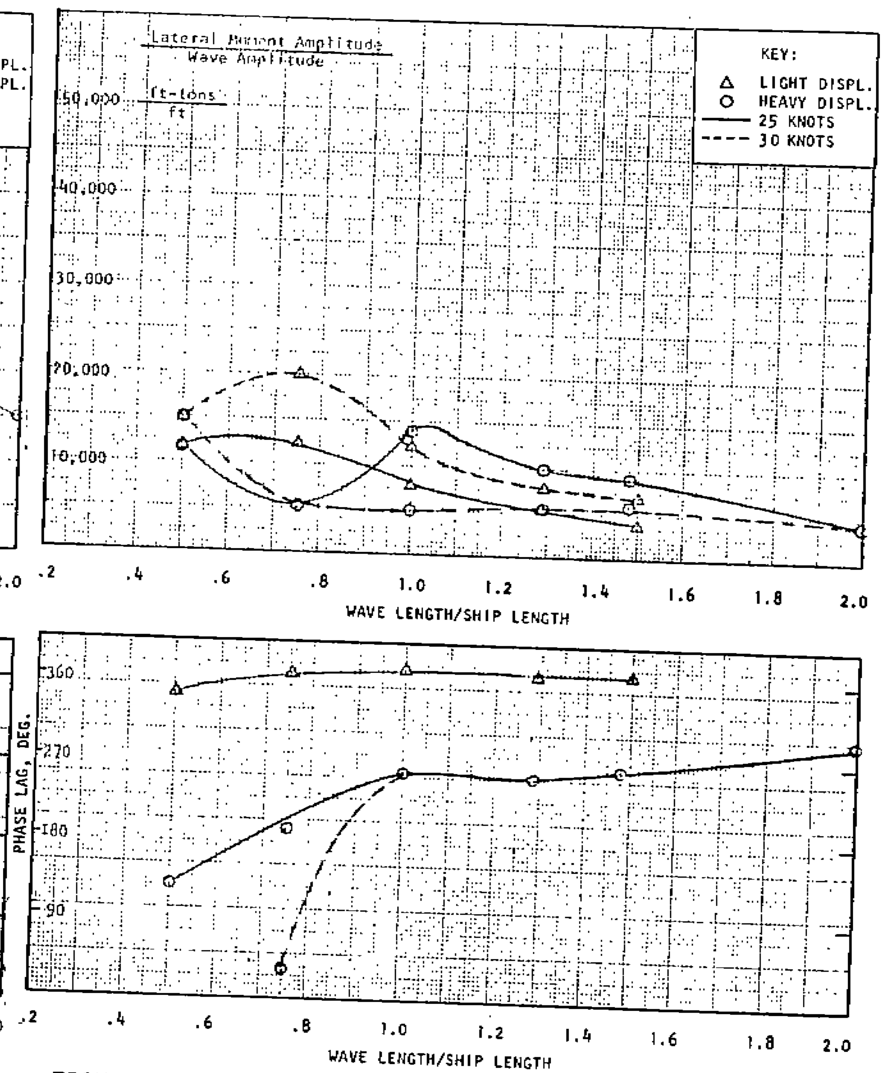


FIGURE A-10 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 30° HEADING

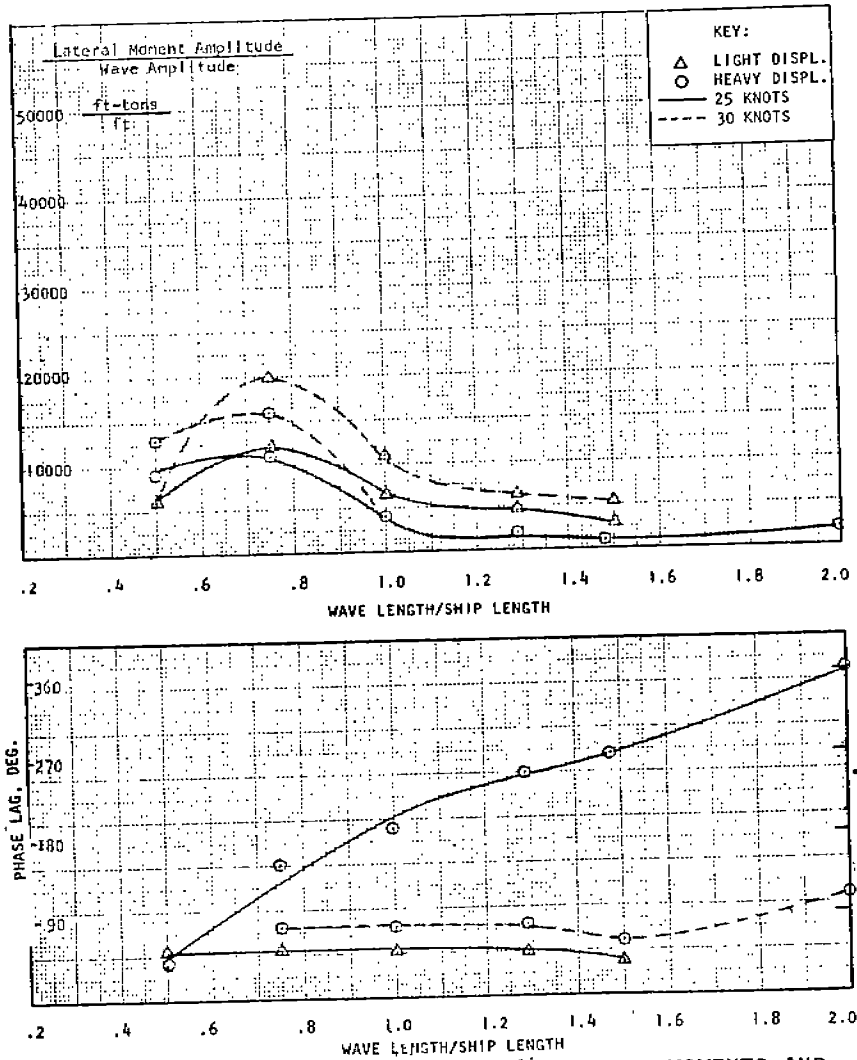


FIGURE A-11 - FRAME 258 LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 30° HEADING

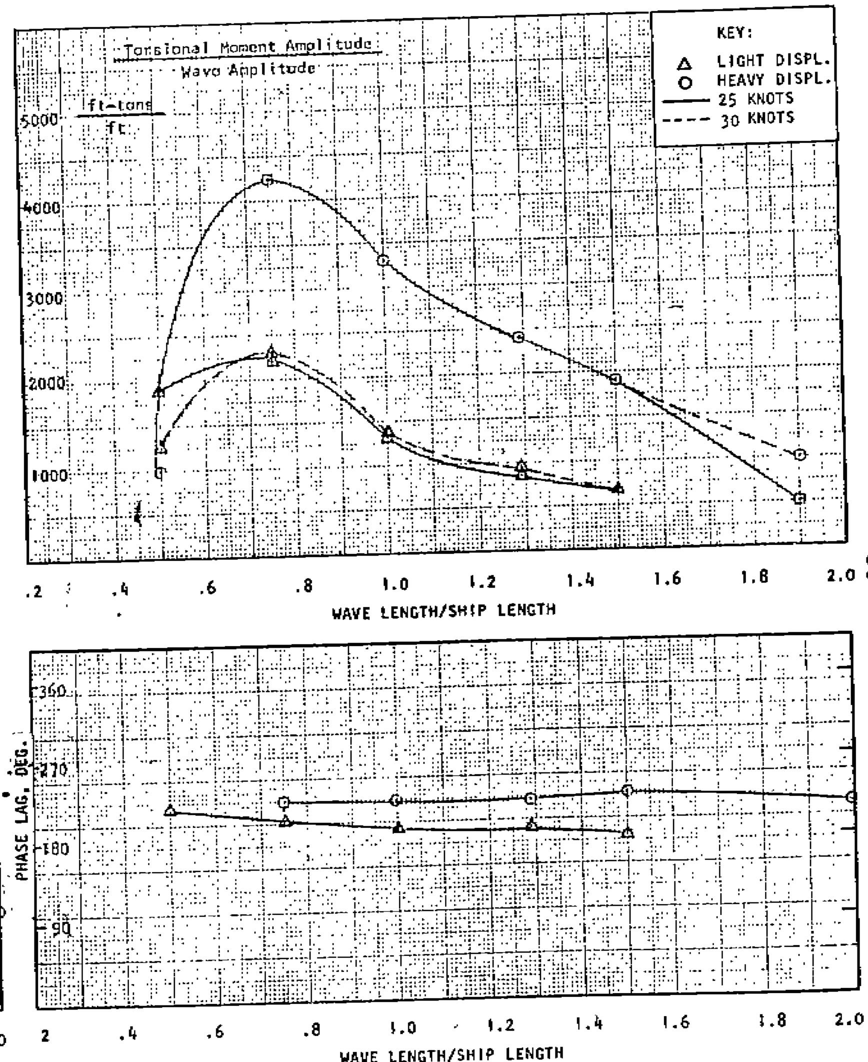


FIGURE A-12 - MIDSHIP TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 30° HEADING

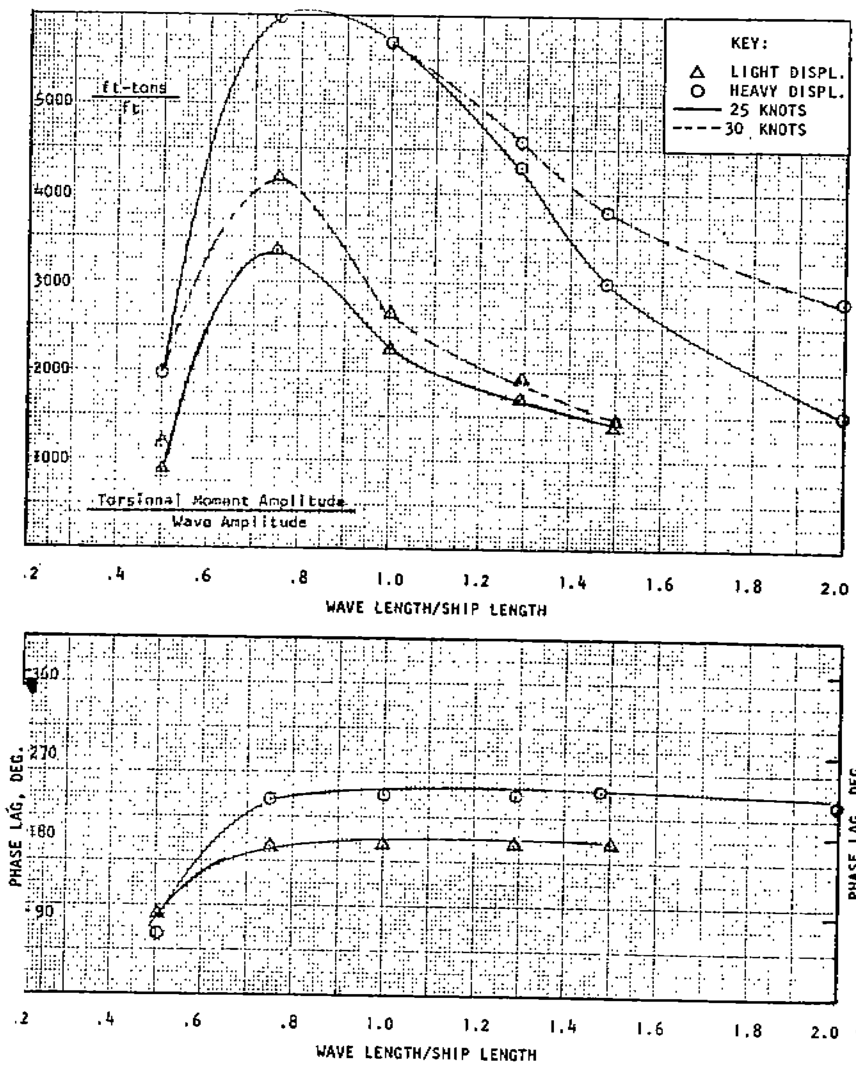


FIGURE A-13 - FRAME 258 TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 30^{0} HEADING

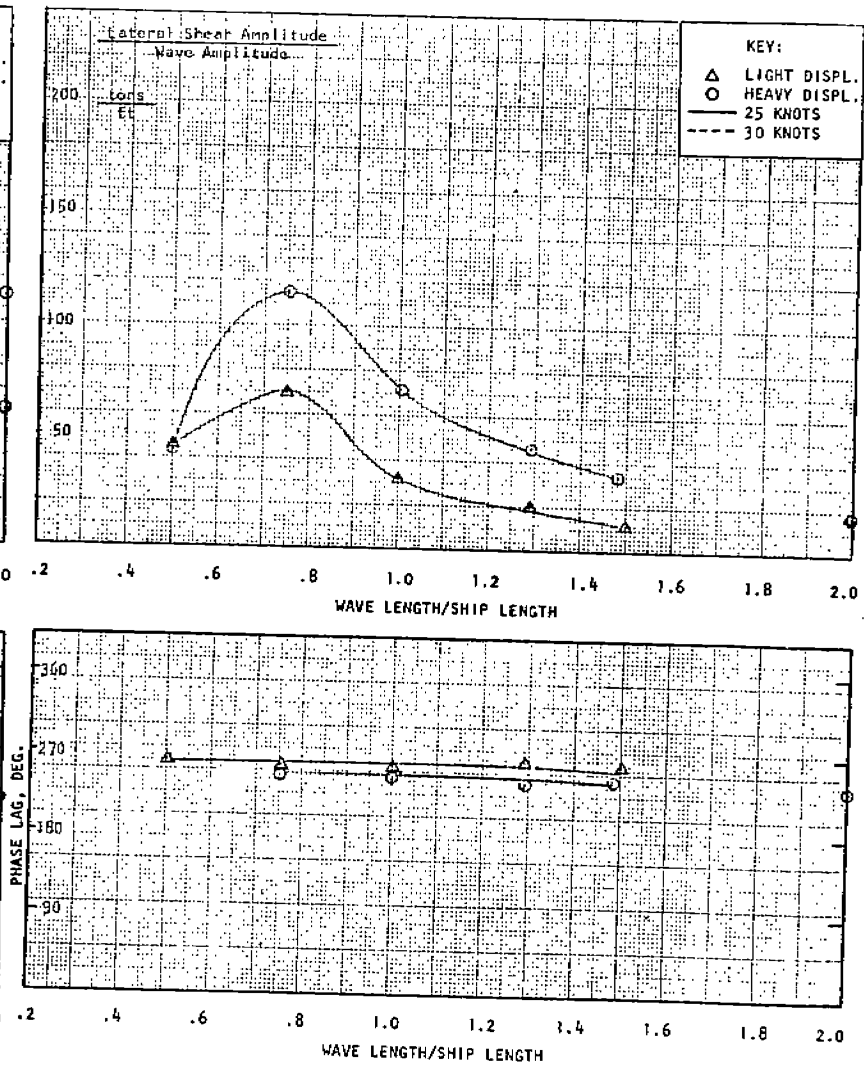


FIGURE A-14 - MIDSHIP LATERAL SHEAR AND PHASE LAG, 30^{0} HEADING

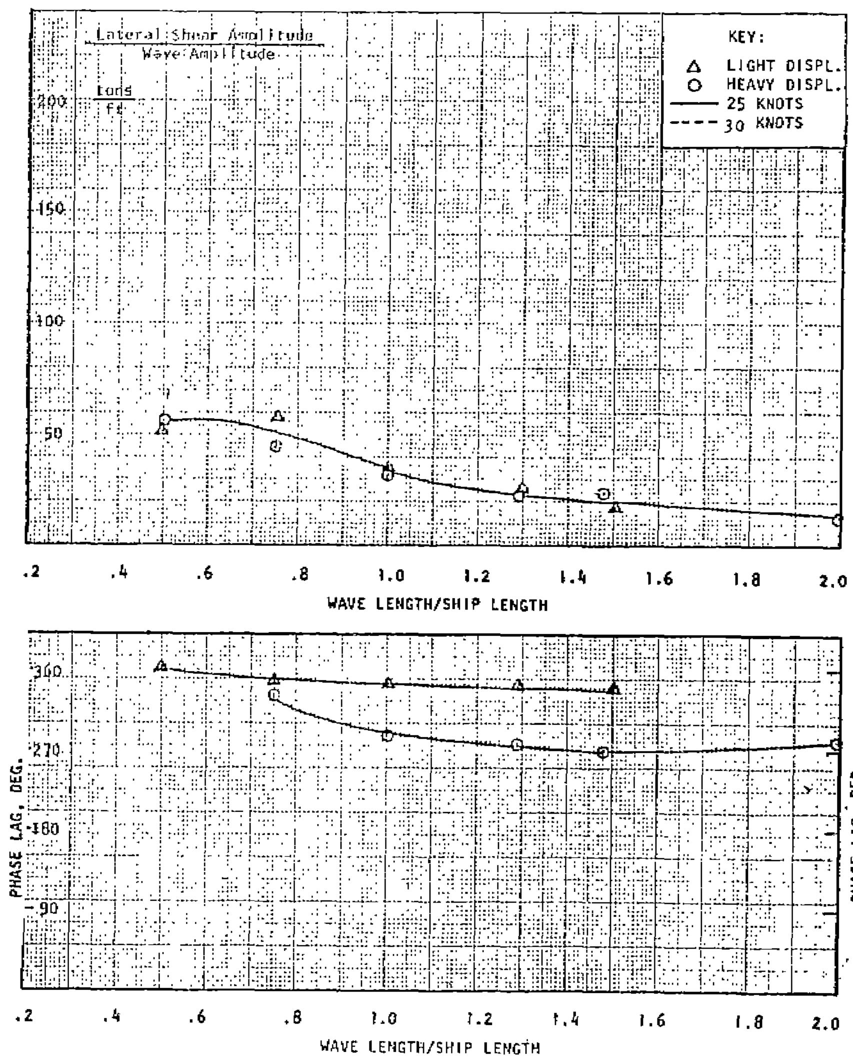


FIGURE A-15 - FRAME 258 LATERAL SHEAR AND PHASE LAG, 30° HEADING

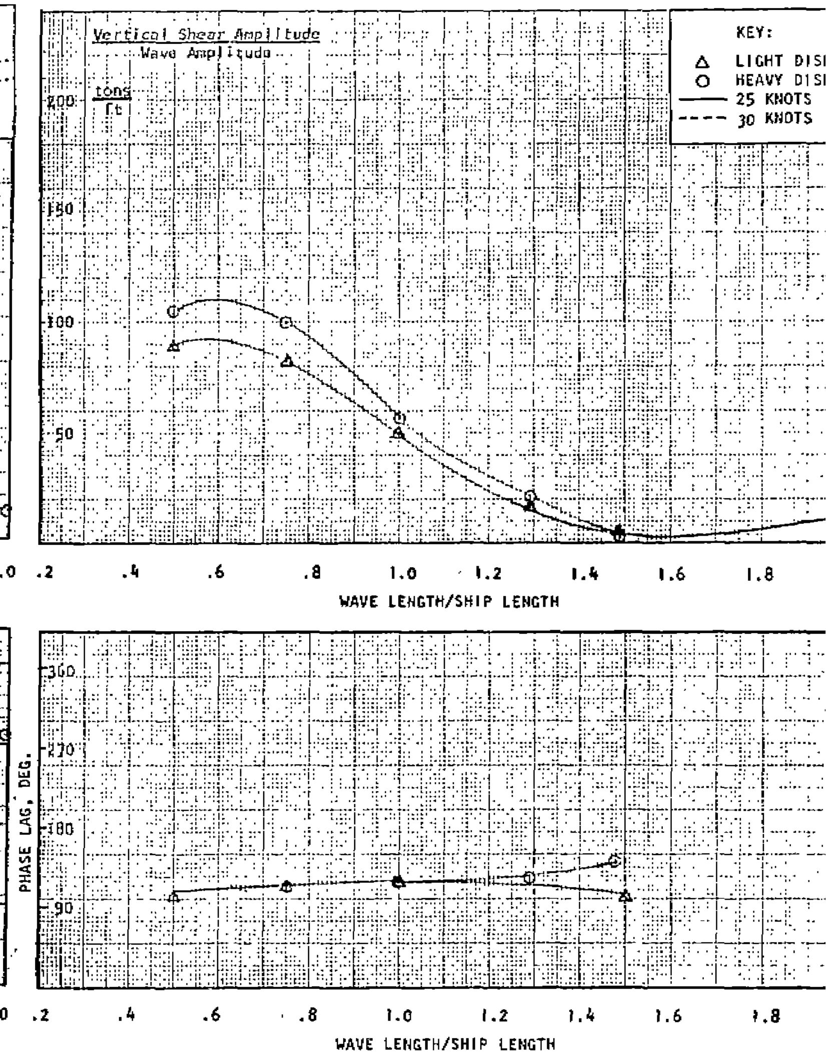


FIGURE A-16 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 30° HEADING

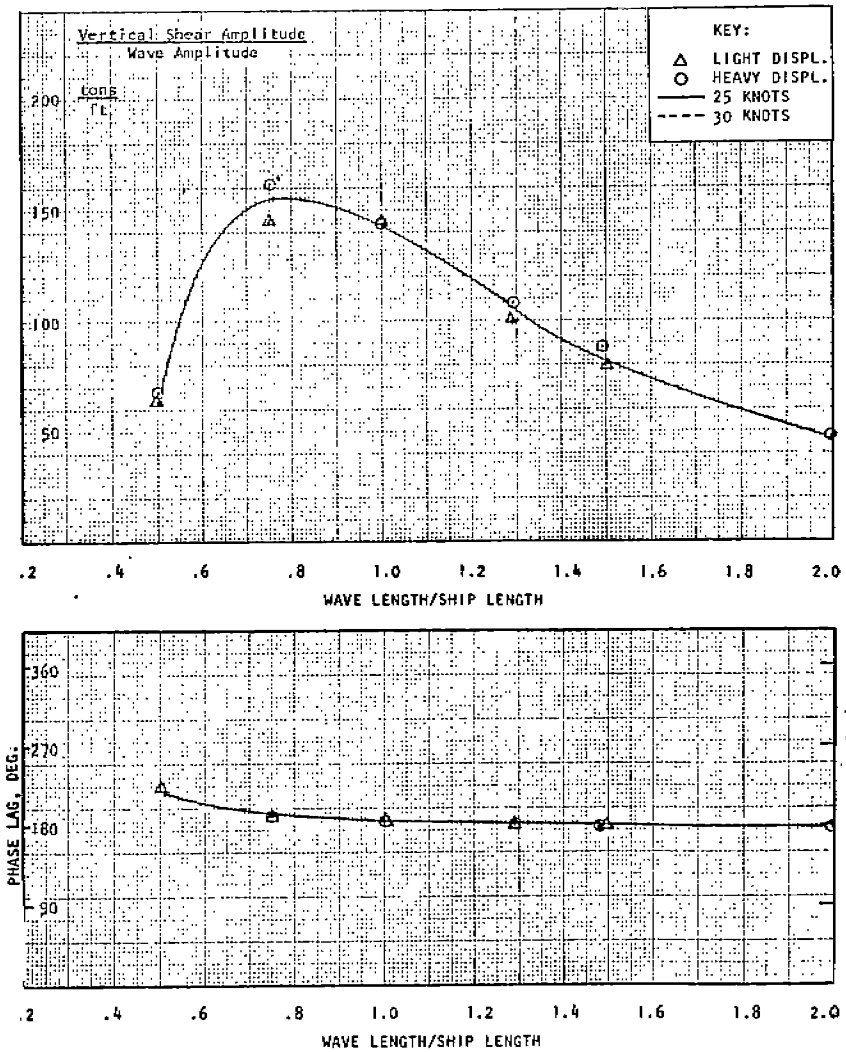


FIGURE A-17 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 30° HEADING

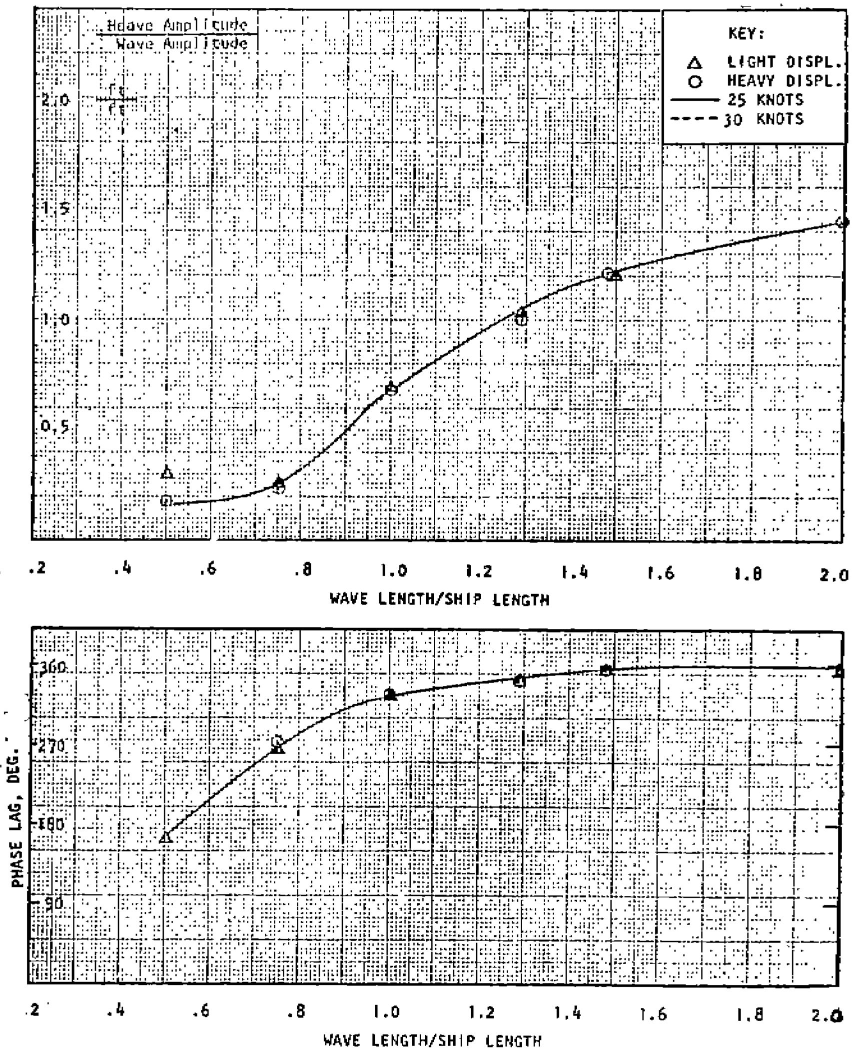


FIGURE A-18 - FRAME 124 HEAVE AND PHASE LAG, 30° HEADING

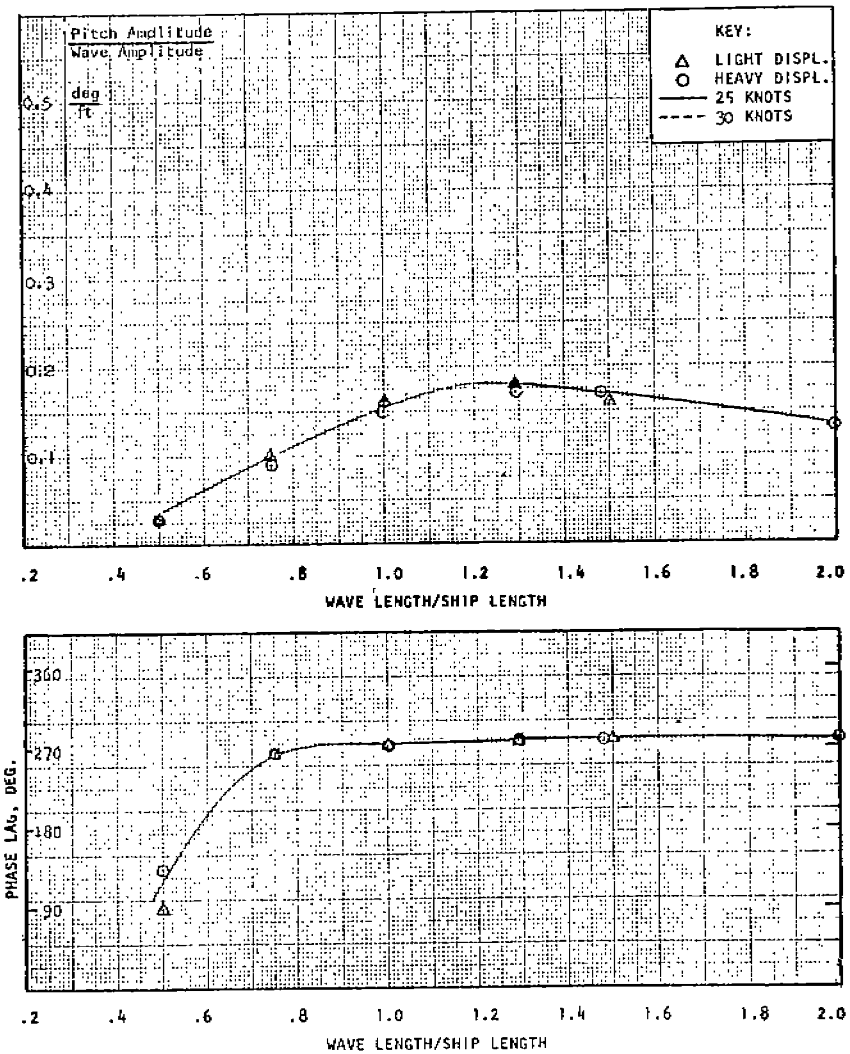


FIGURE A-19 - PITCH AND PHASE LAG, 30^{0} HEADING

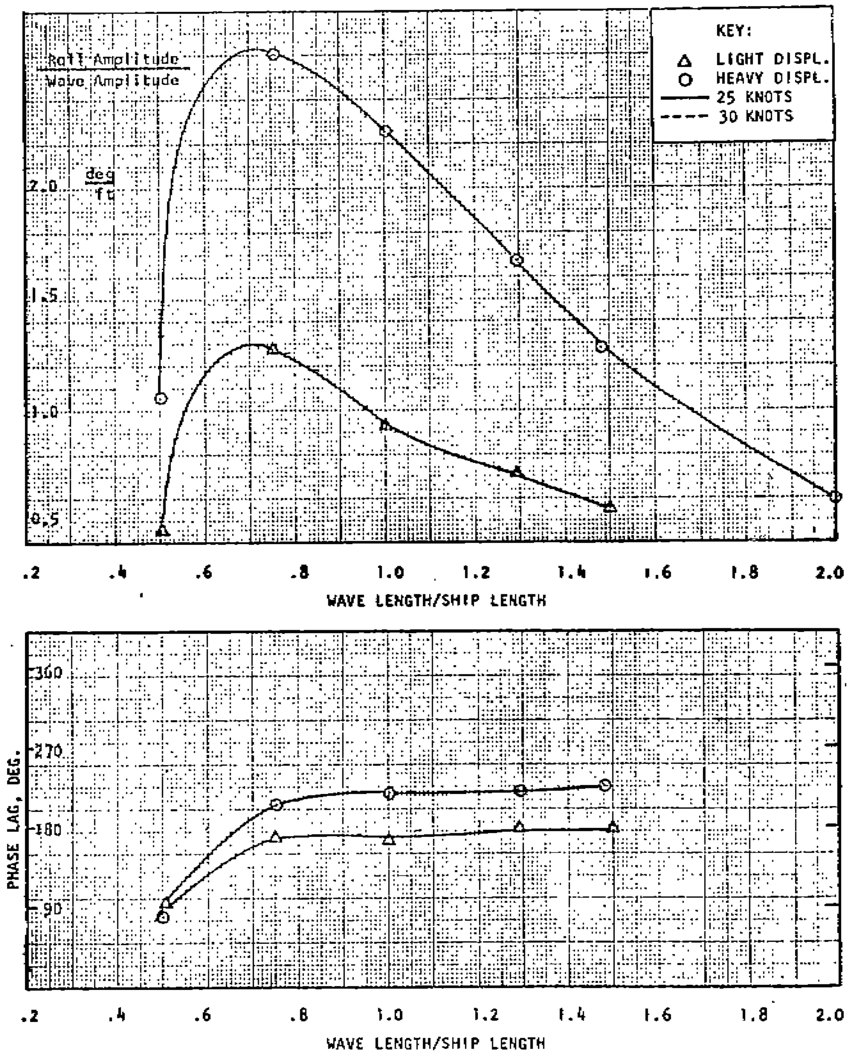


FIGURE A-20 - ROLL AND PHASE LAG, 30^{0} HEADING

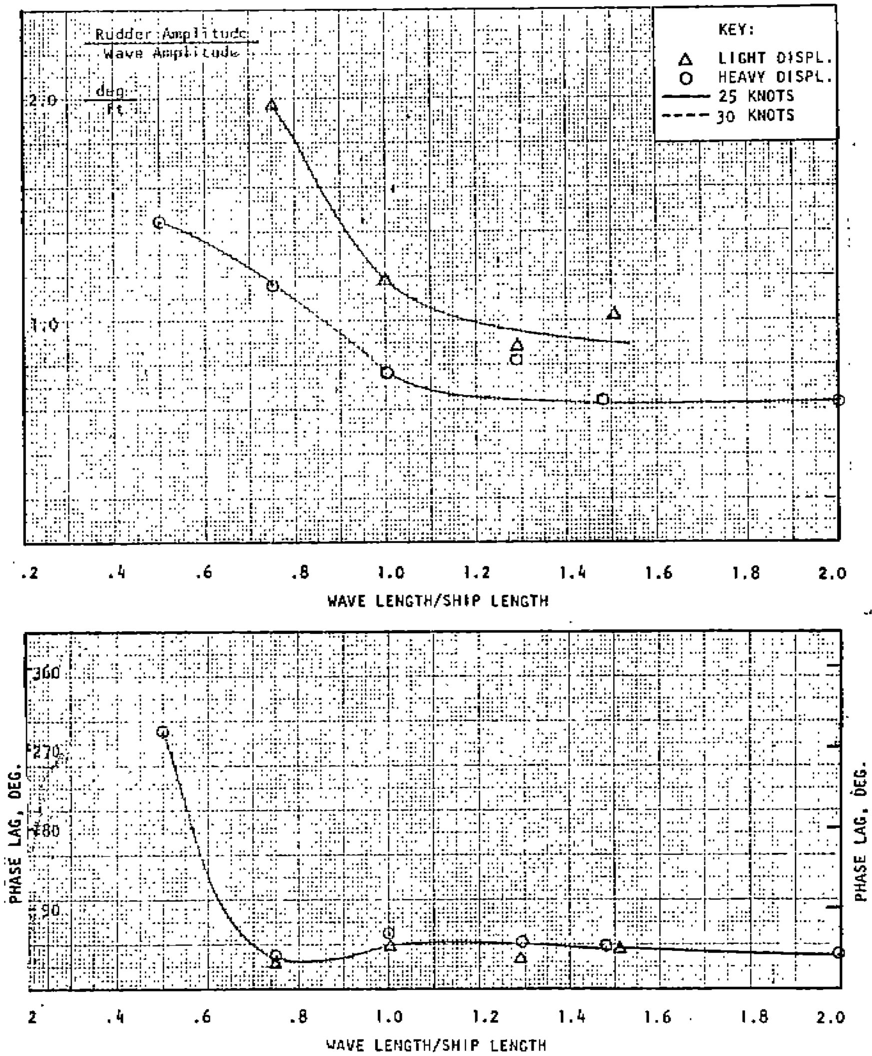


FIGURE A-21 - RUDDER AND PHASE LAG, 30° HEADING

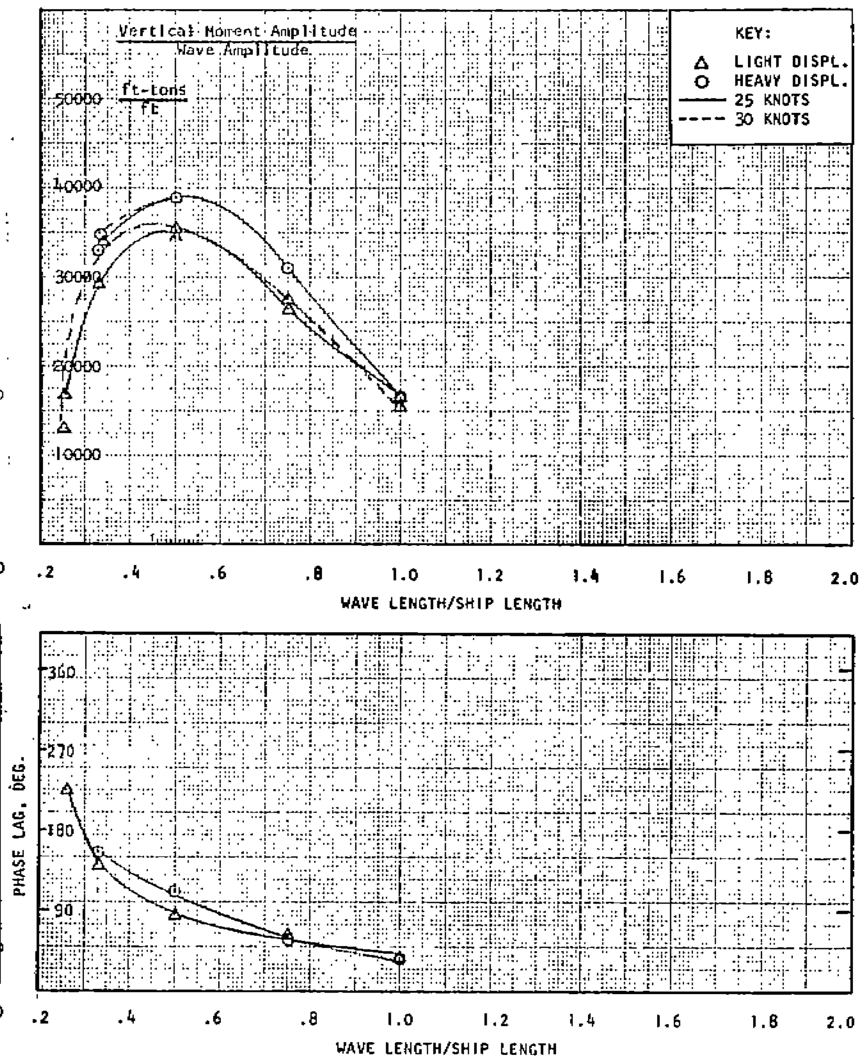


FIGURE A-22 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 60° HEADING

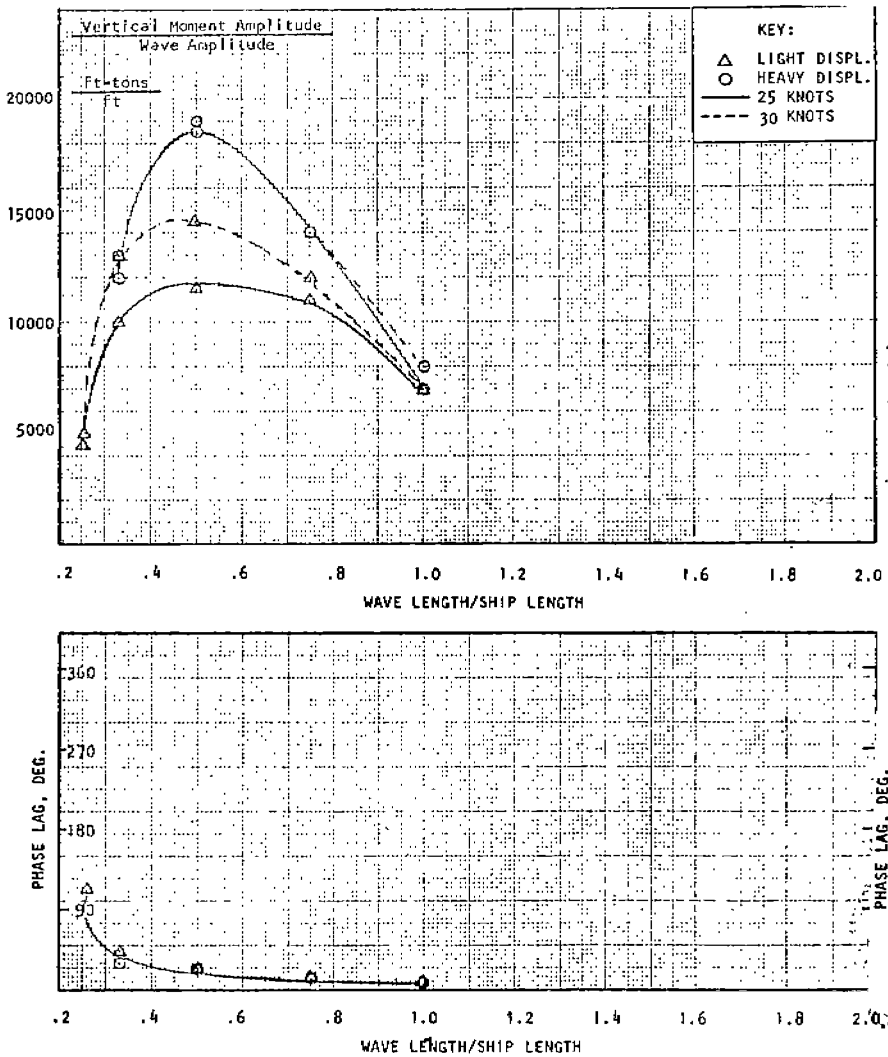


FIGURE A-23 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 60° HEADING

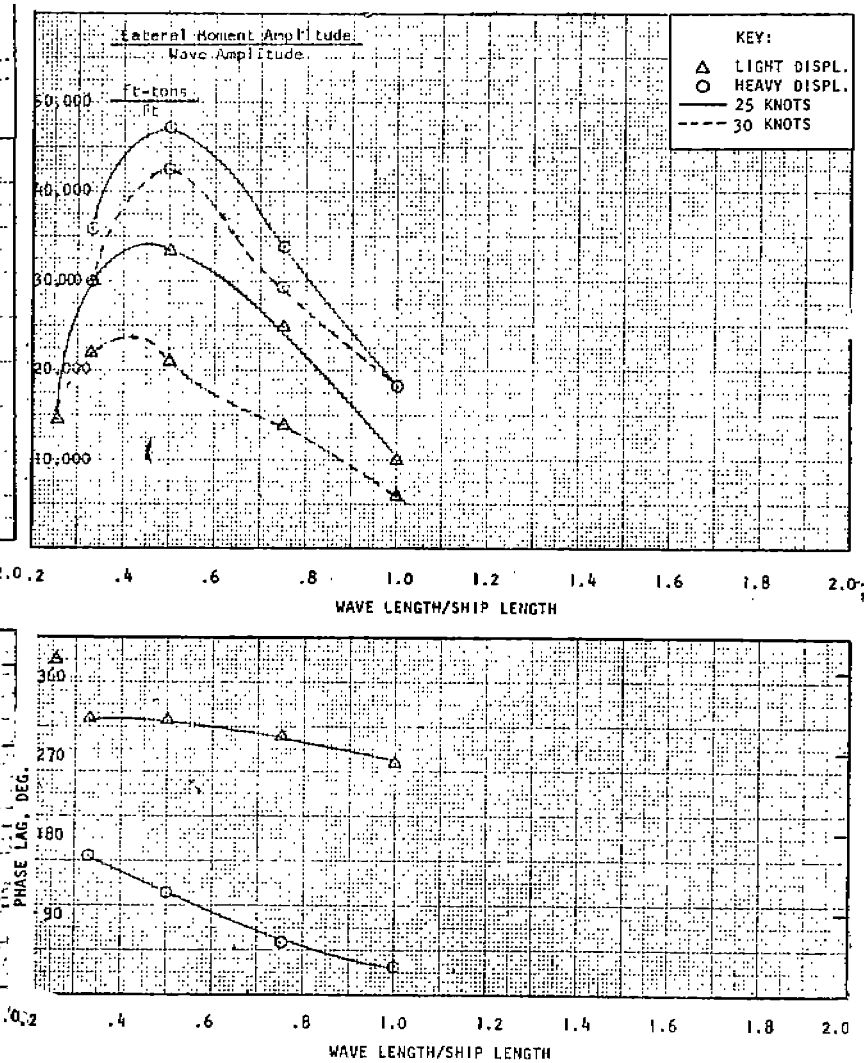


FIGURE A-24 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 60° HEADING

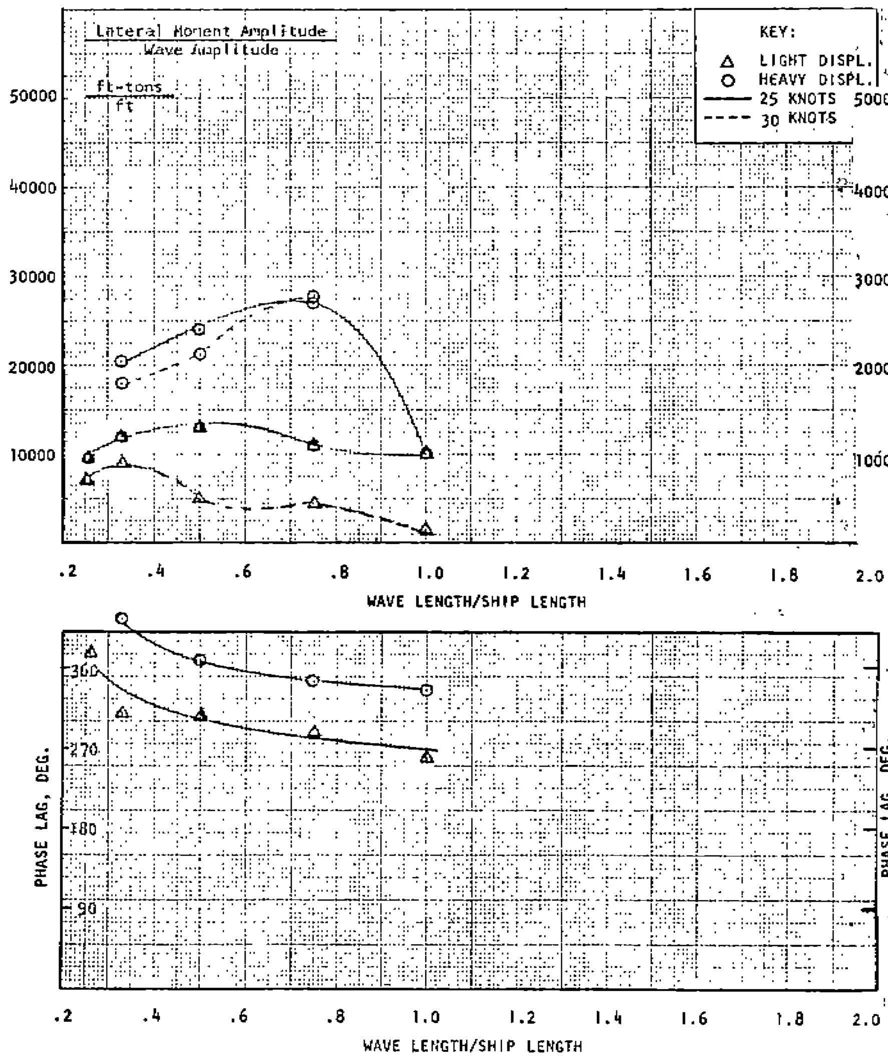


FIGURE A-25 - FRAME 258 LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 60° HEADING

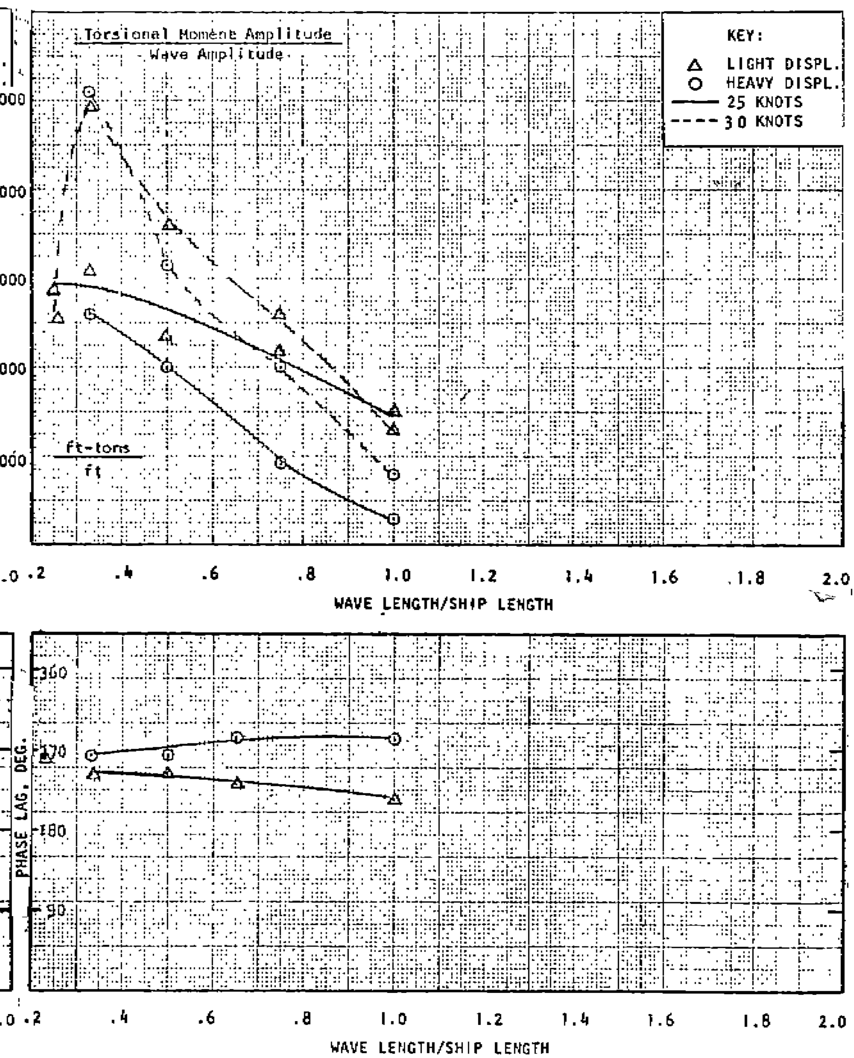


FIGURE A-26 - MIDSHIP TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 60° HEADING

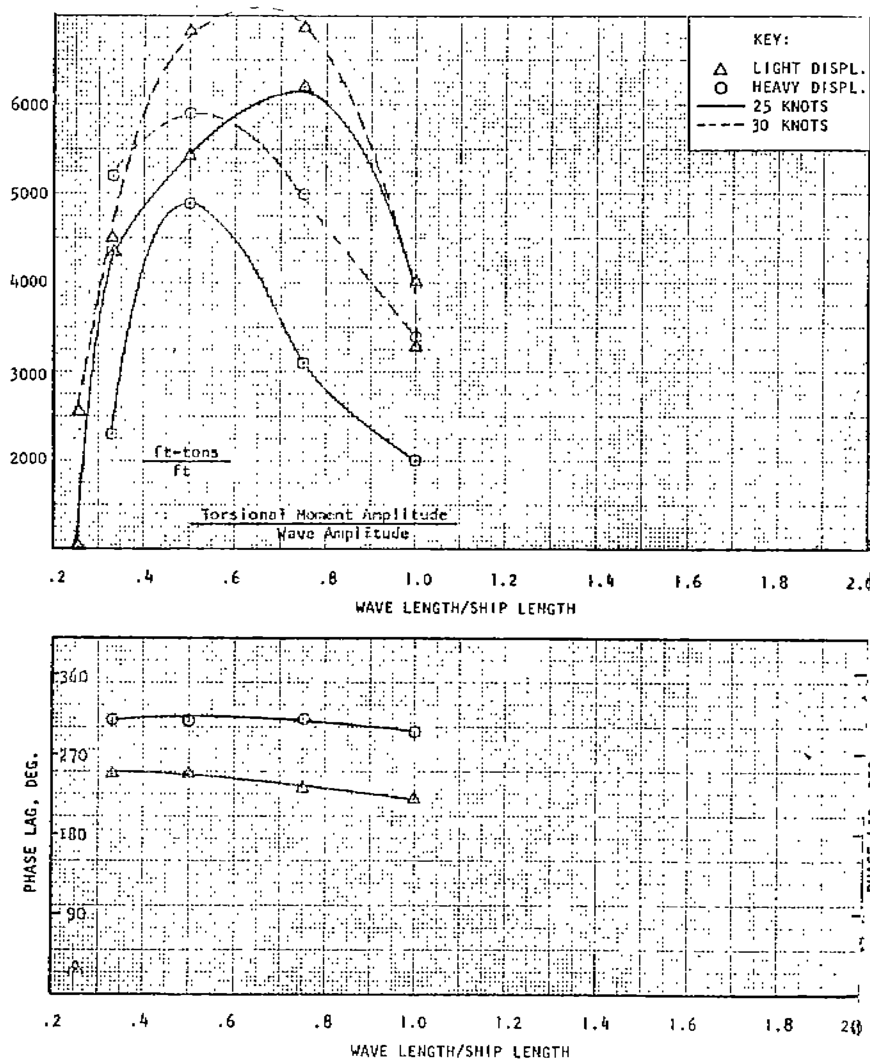


FIGURE A-27 - FRAME 258 TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 60^{0} HEADING

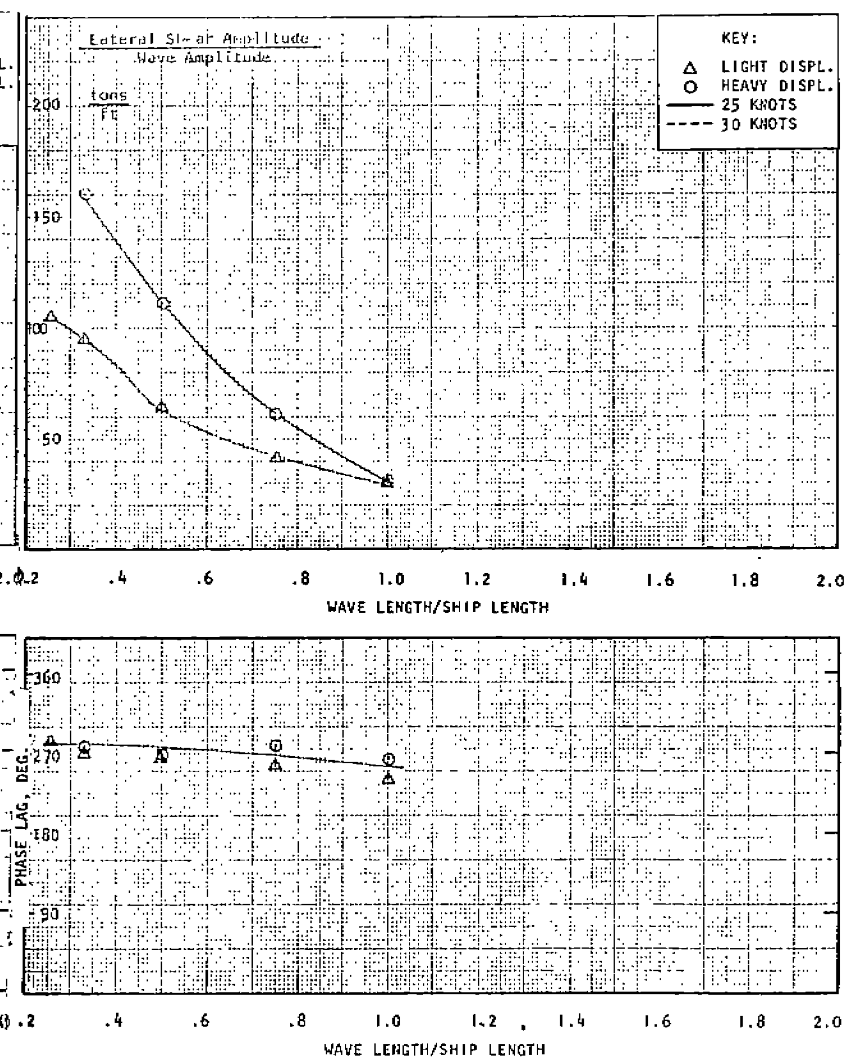


FIGURE A-28 - MIDSHIP LATERAL SHEAR AND PHASE LAG, 60^{0} HEADING

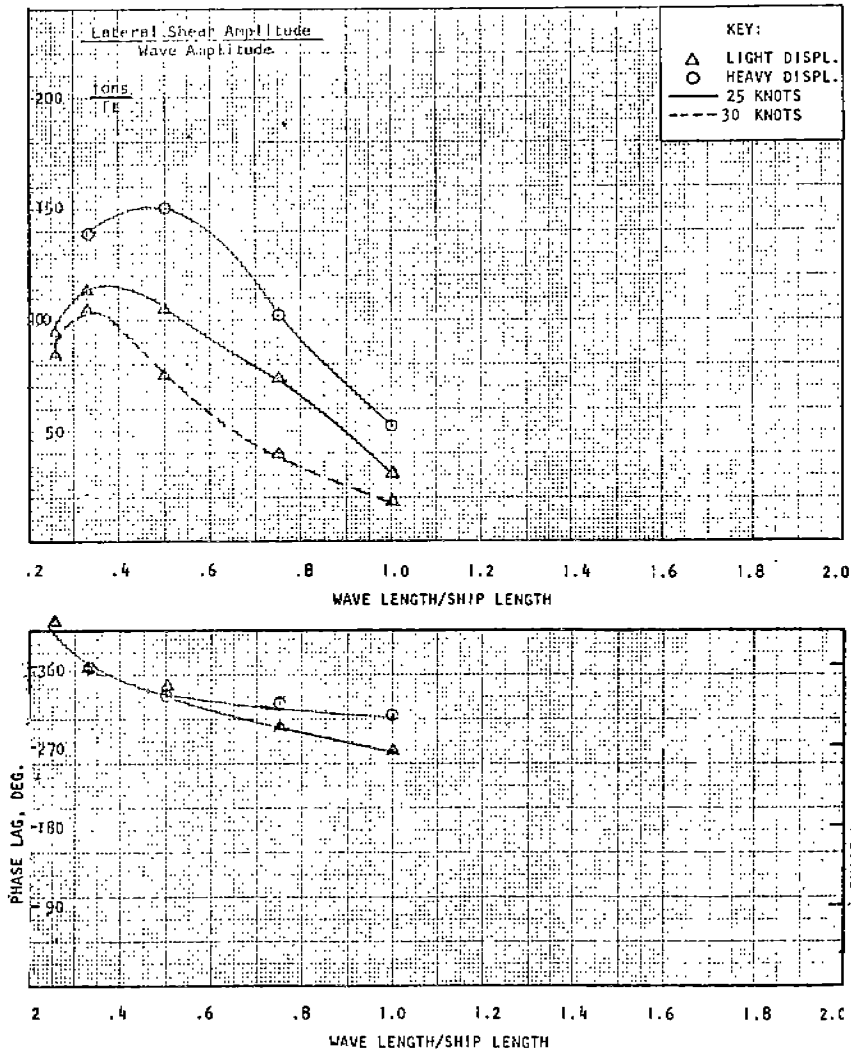


FIGURE A-29 - FRAME 258 LATERAL SHEAR AND PHASE LAG, 60° HEADING

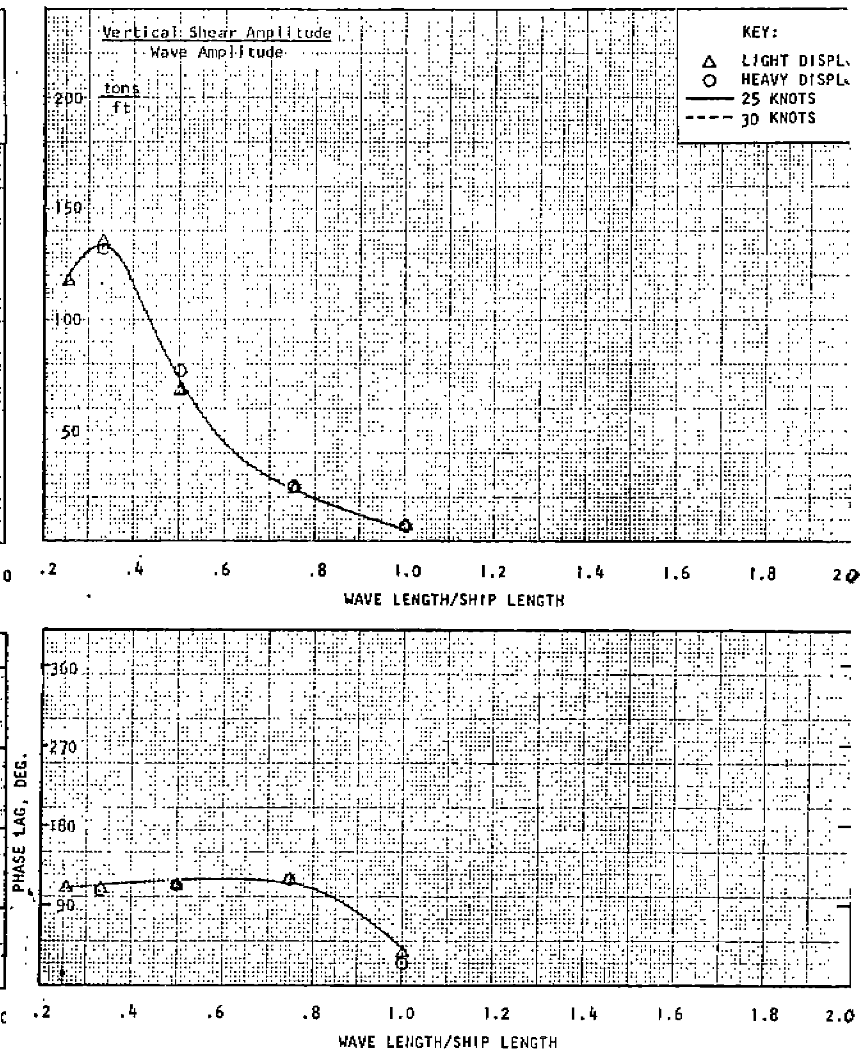


FIGURE A-30 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 60° HEADING

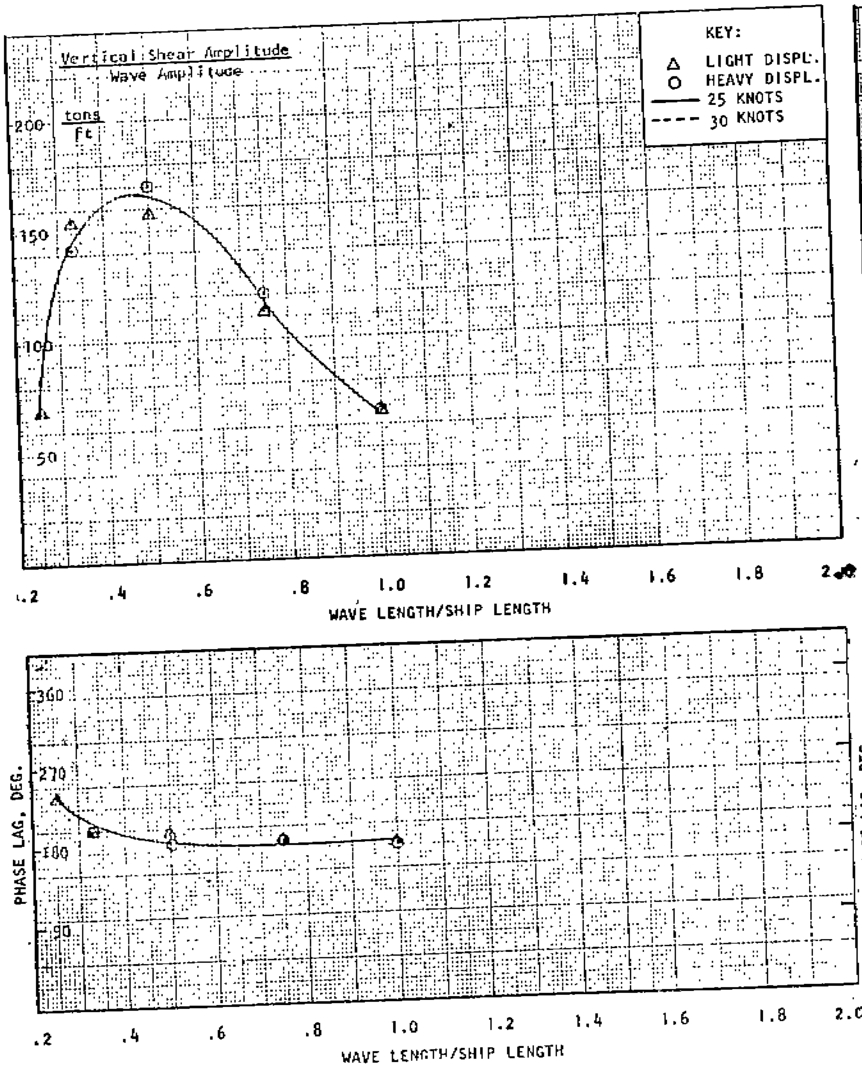


FIGURE A-31 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 60^{o} HEADING

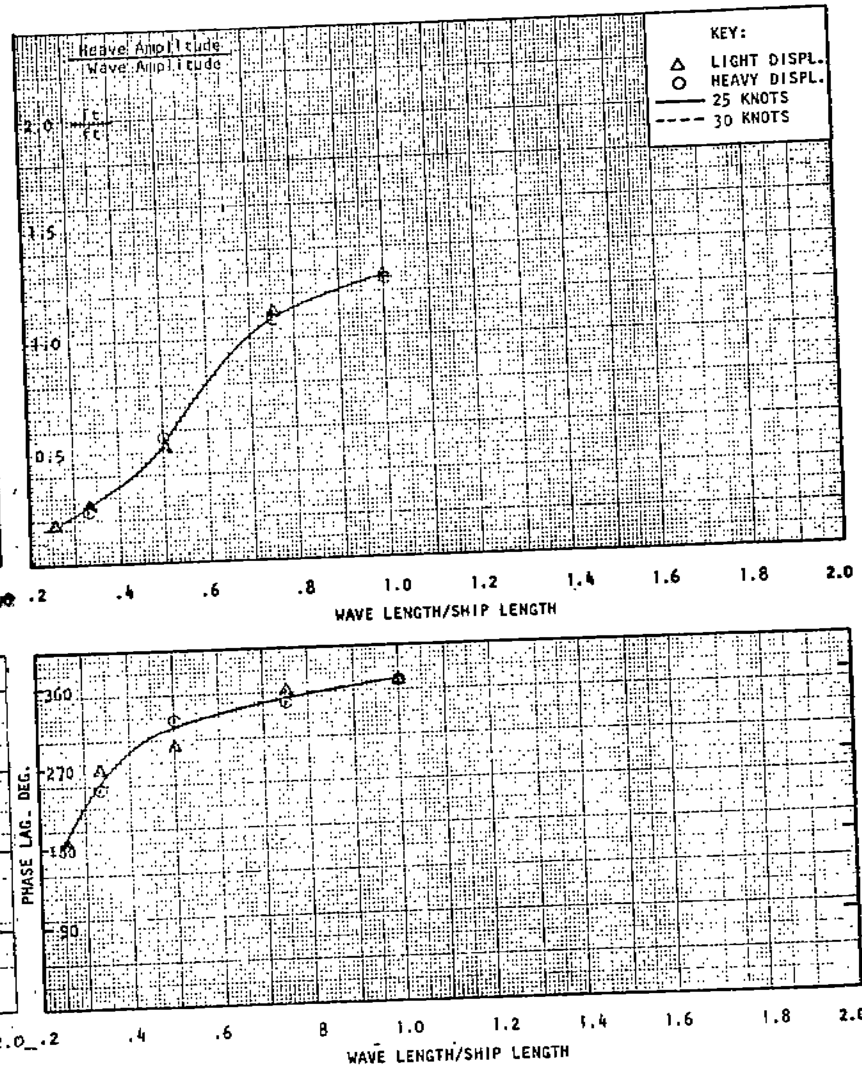


FIGURE A-32 - FRAME 124 HEAVE AND PHASE LAG, 60^{o} HEADING

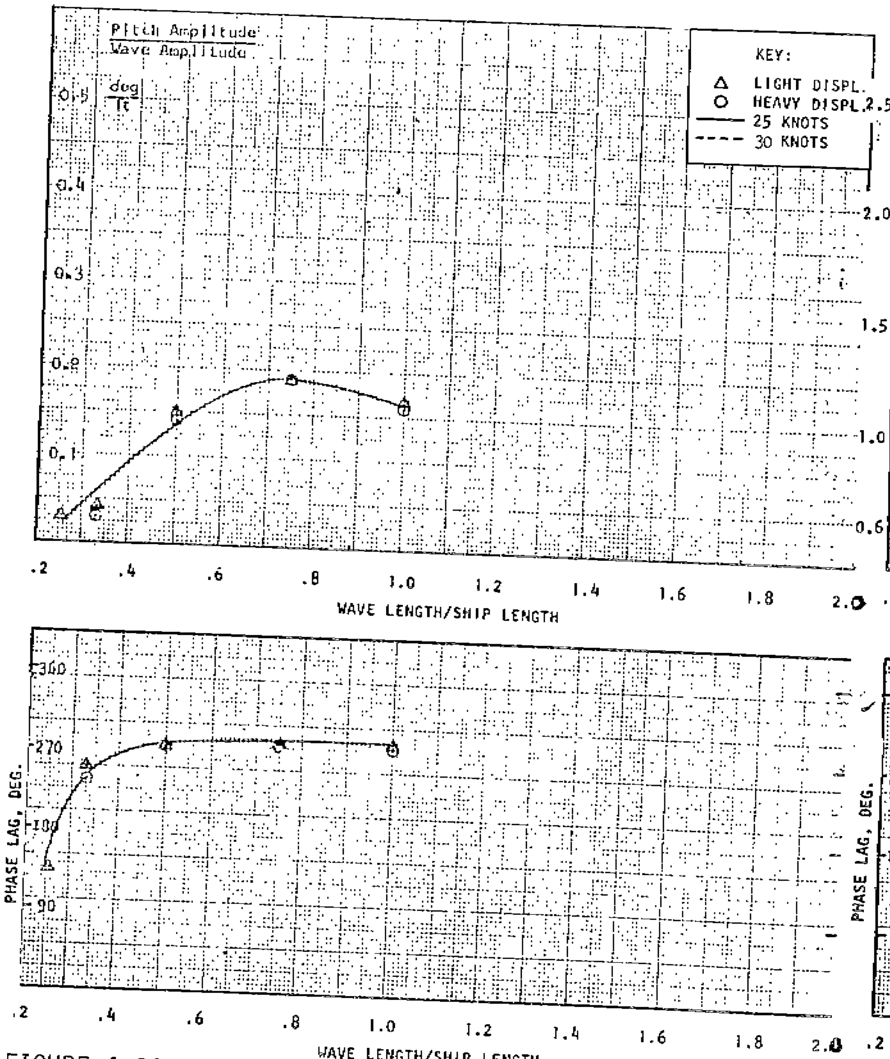


FIGURE A-33 - PITCH AND PHASE LAG, 60^{0} HEADING

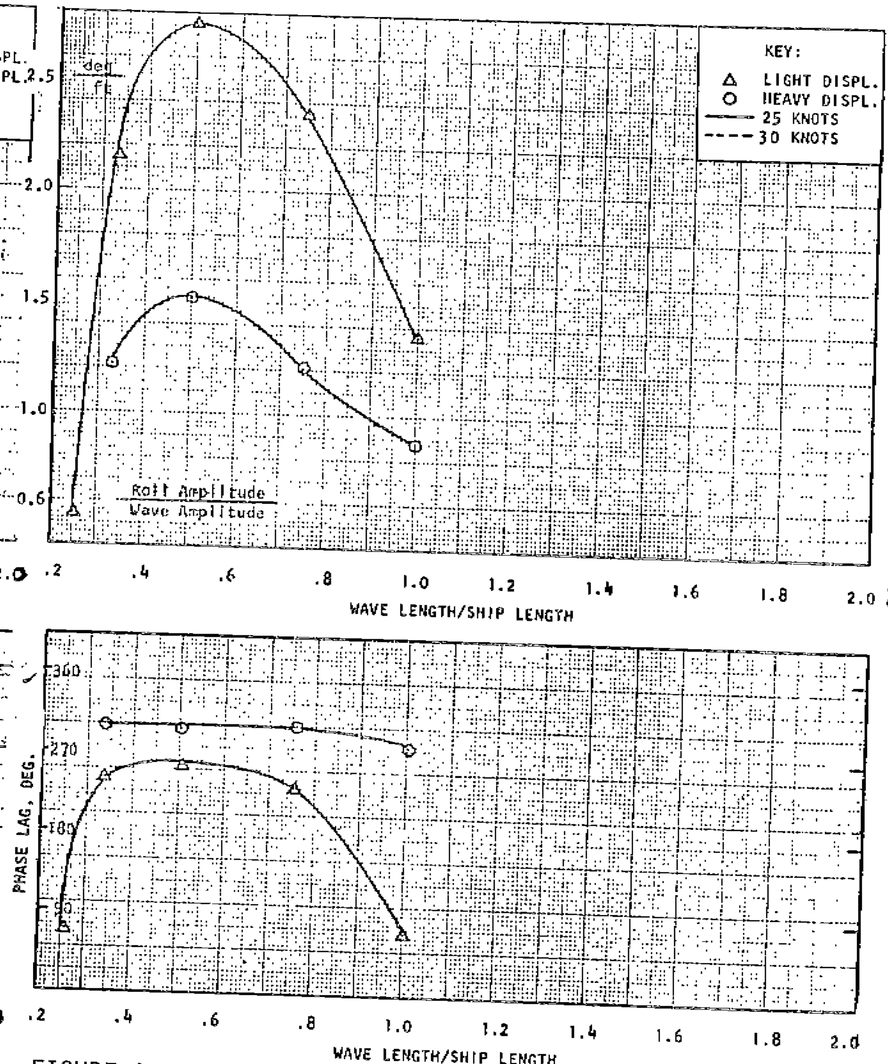


FIGURE A-34 - ROLL AND PHASE LAG, 60^{0} HEADING

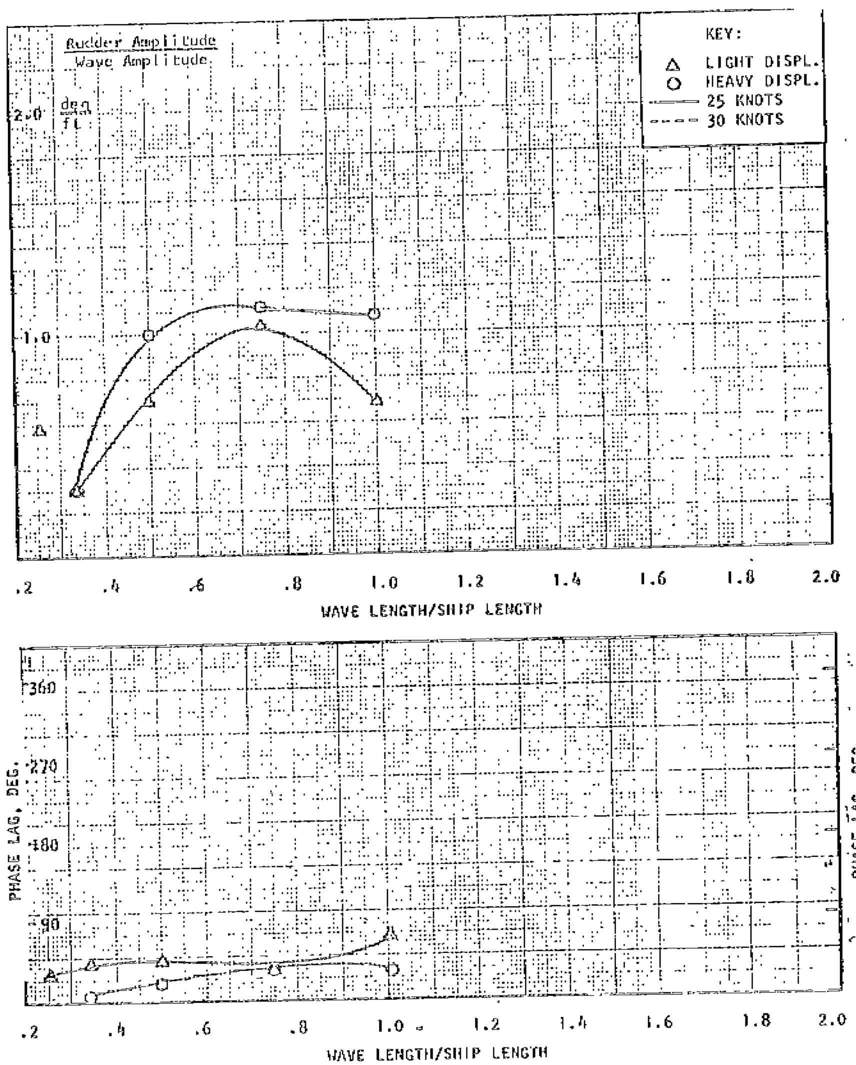


FIGURE A-35 - RUDDER AND PHASE LAG, 60^{0} HEADING

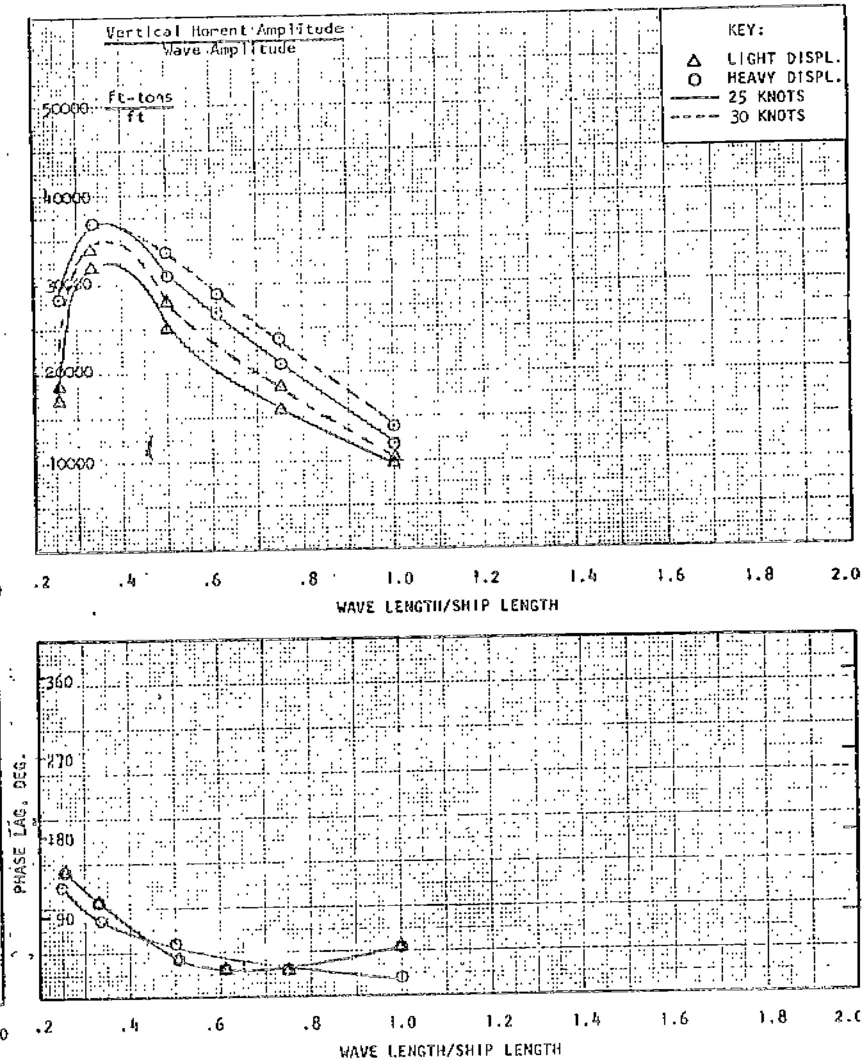


FIGURE A-36 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 240^{0} HEADING

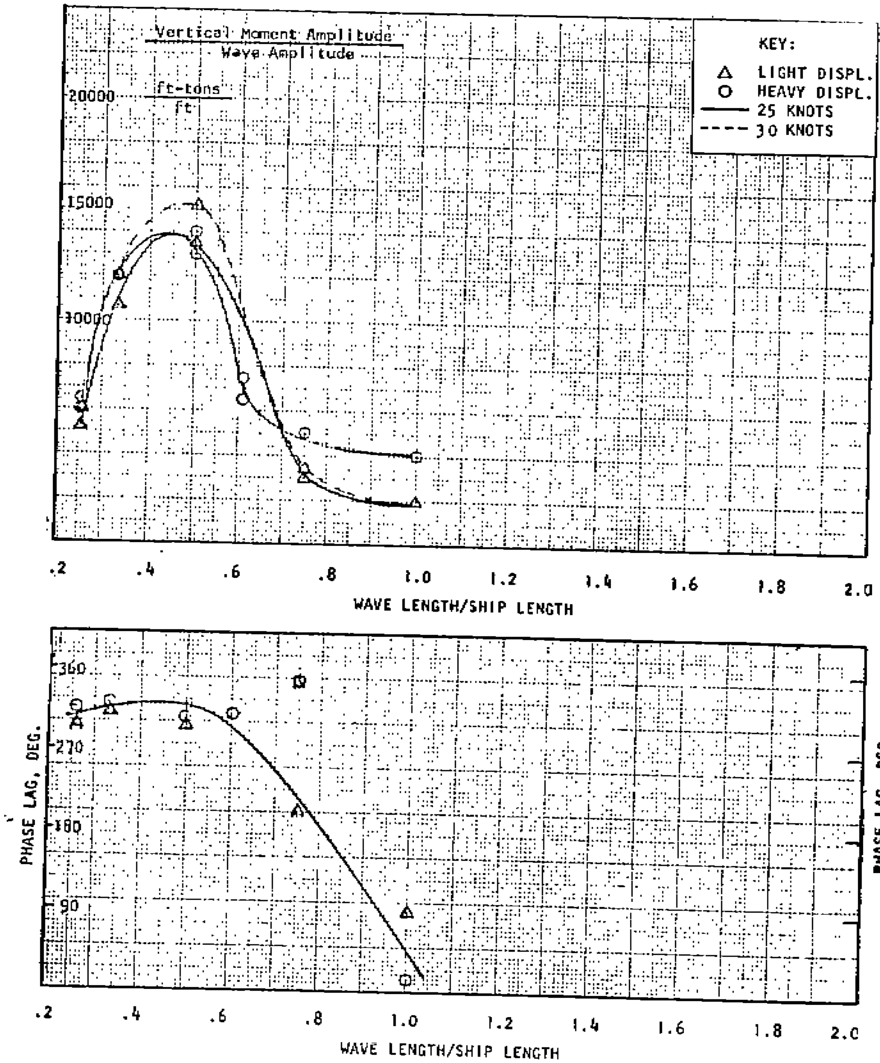


FIGURE A-37 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 240^{0} HEADING

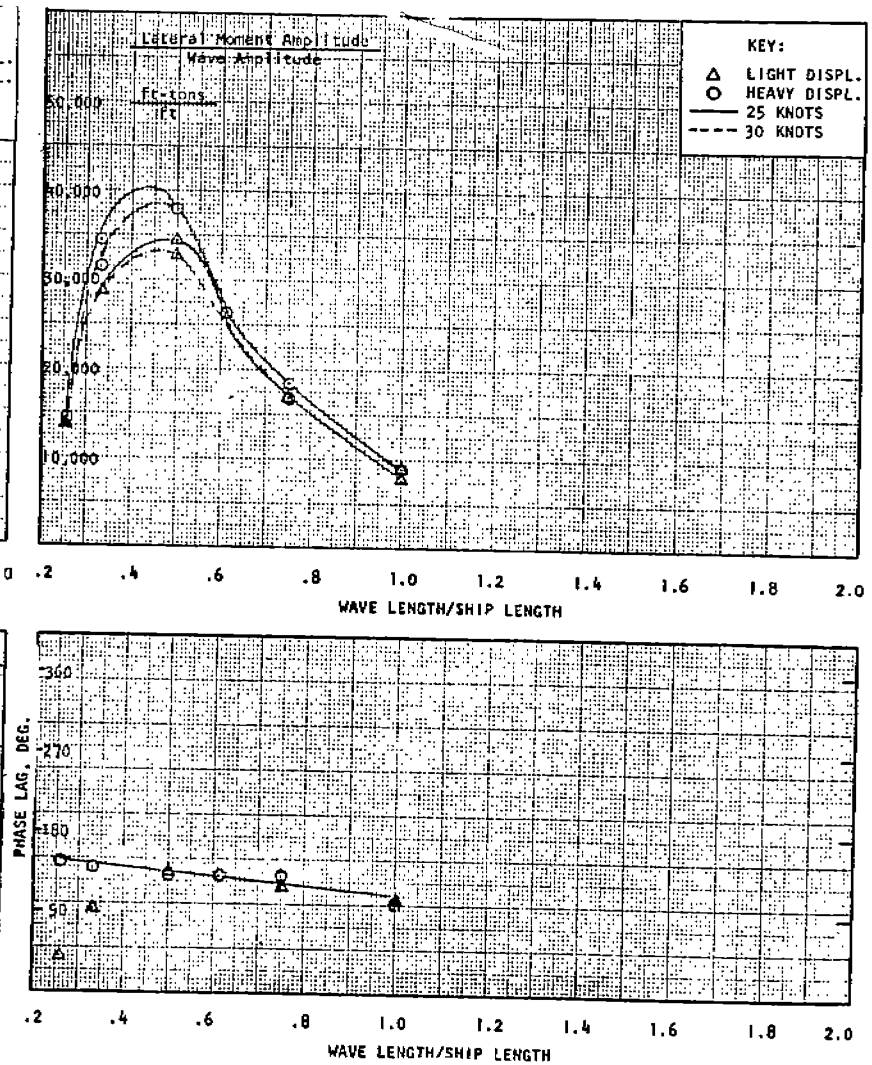


FIGURE A-38 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 240^{0} HEADING

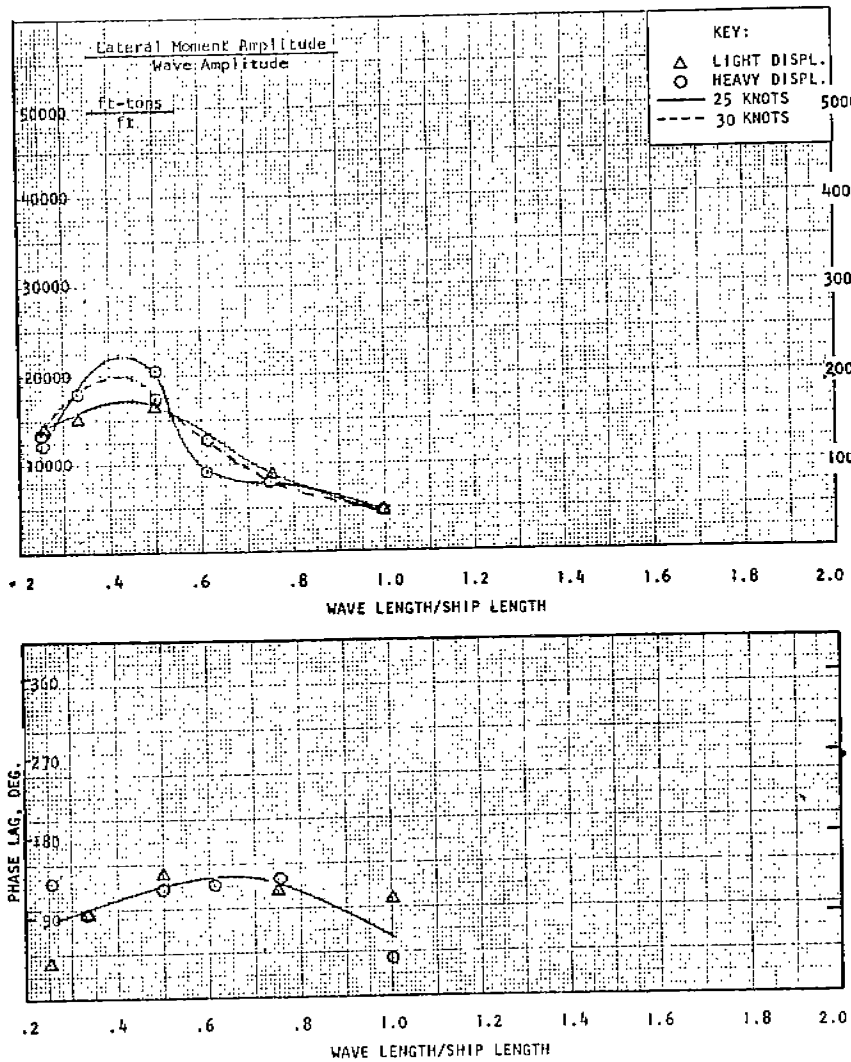


FIGURE A-39 - FRAME 258 LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 240° HEADING

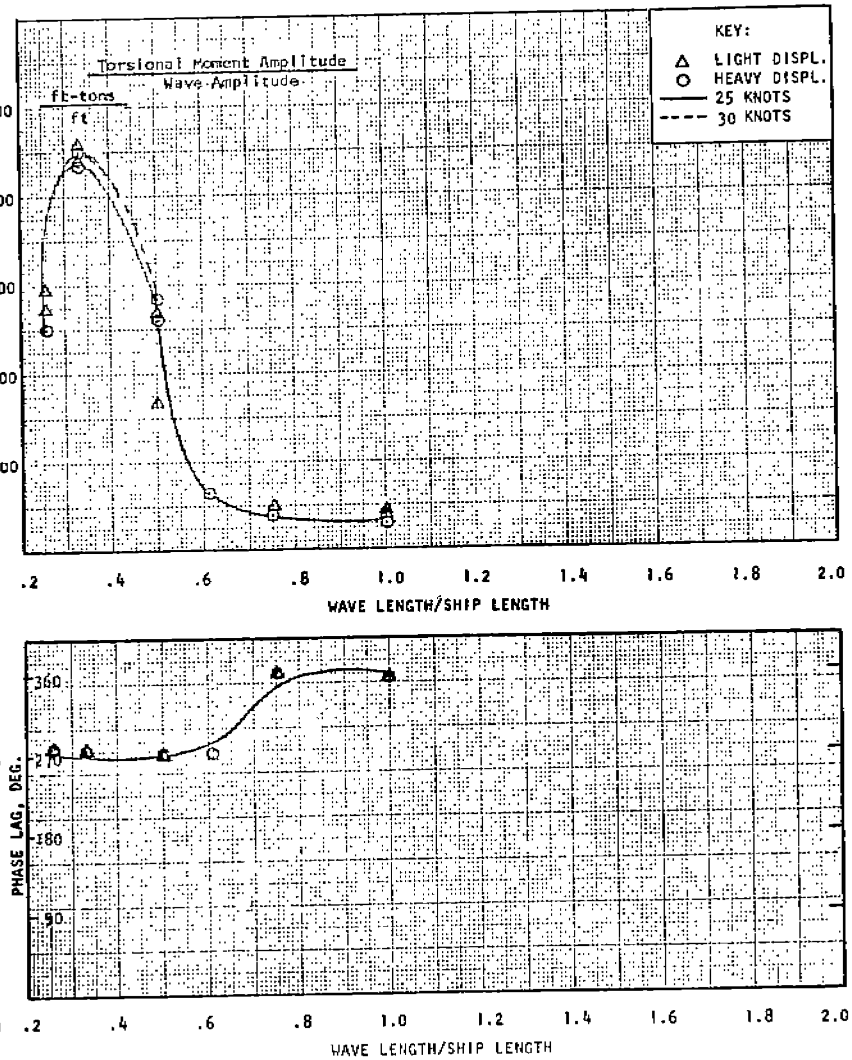


FIGURE A-40 - MIDSHIP TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 240° HEADING

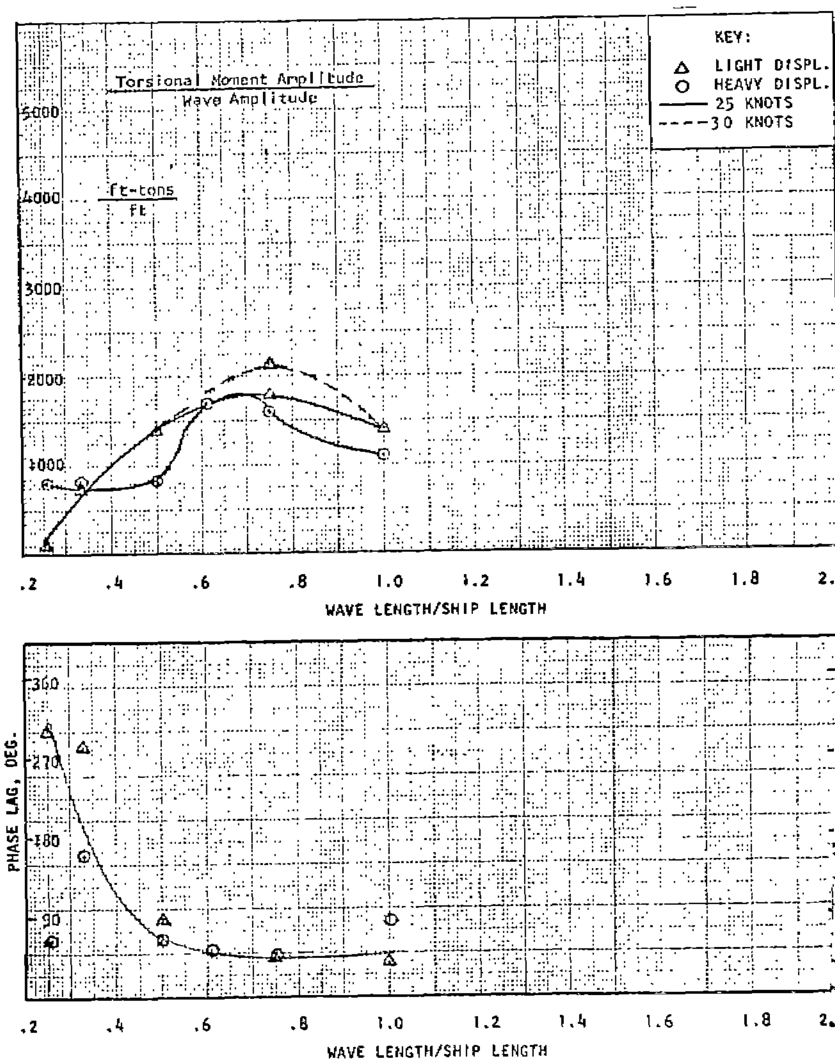


FIGURE A-41 - FRAME 258 TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 240° HEADING

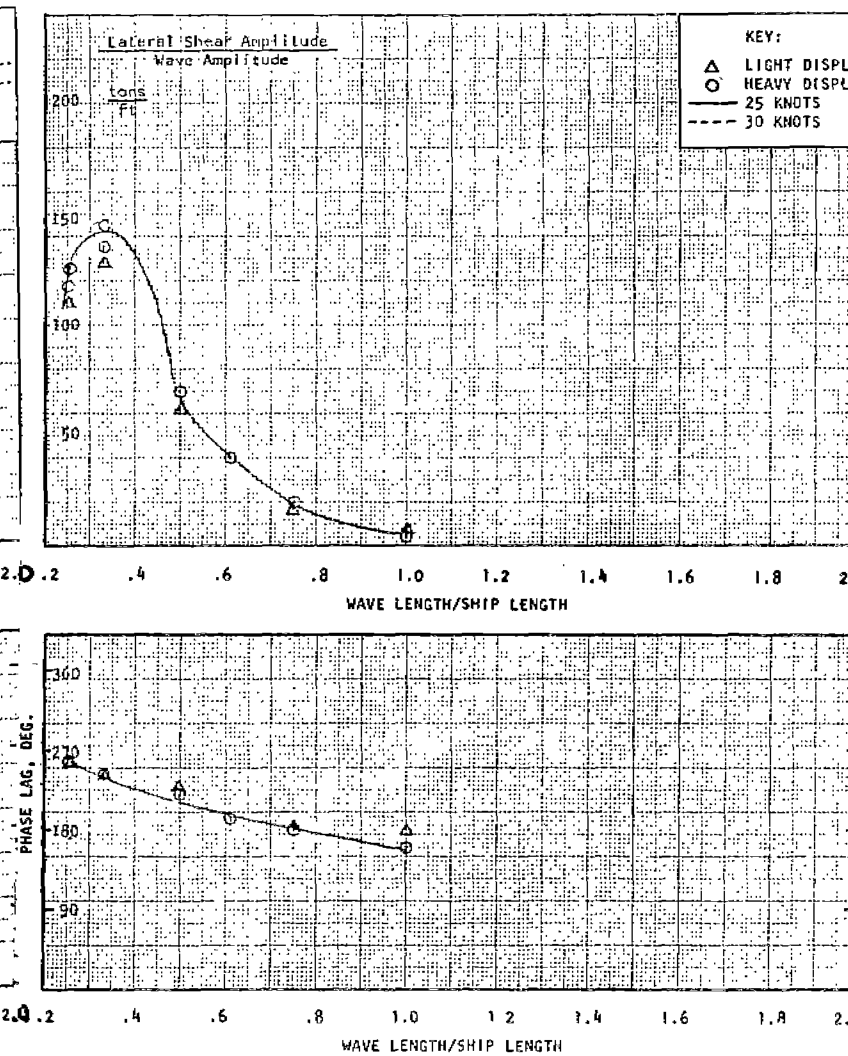


FIGURE A-42 - MIDSHIP LATERAL SHEAR AND PHASE LAG, 240° HEADING

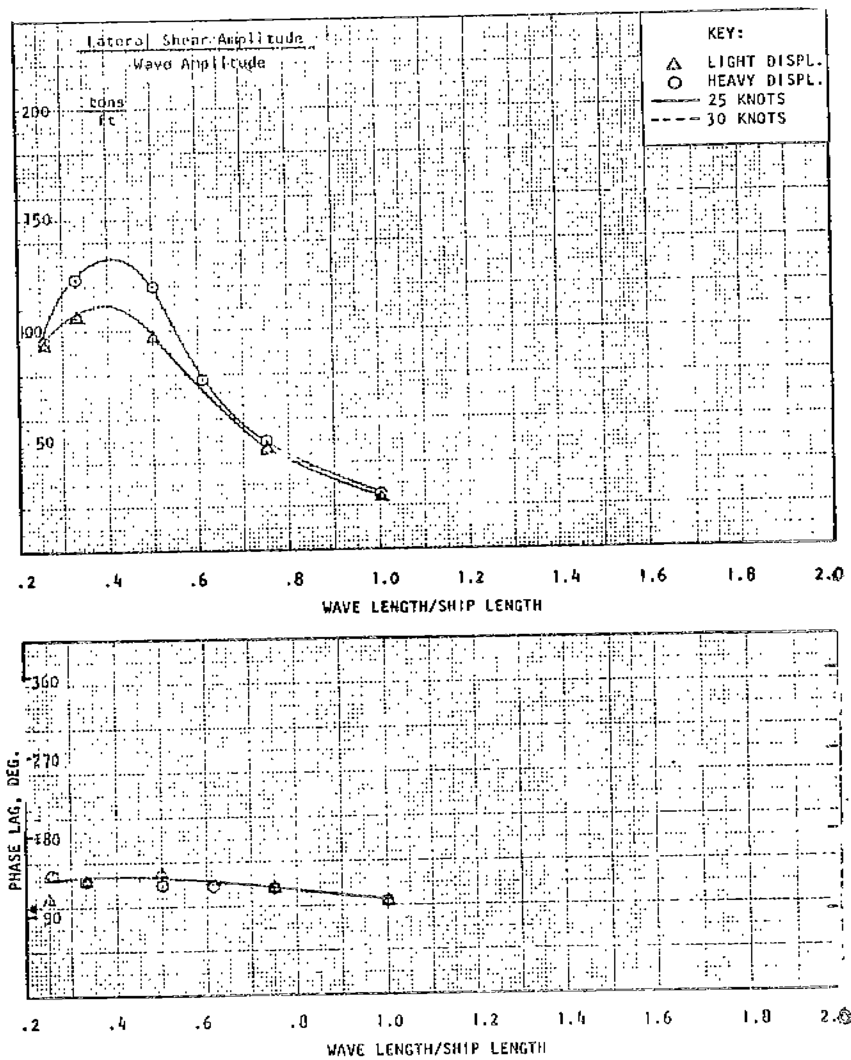


FIGURE A-43 - FRAME 258 LATERAL SHEAR AND PHASE LAG, 240° HEADING

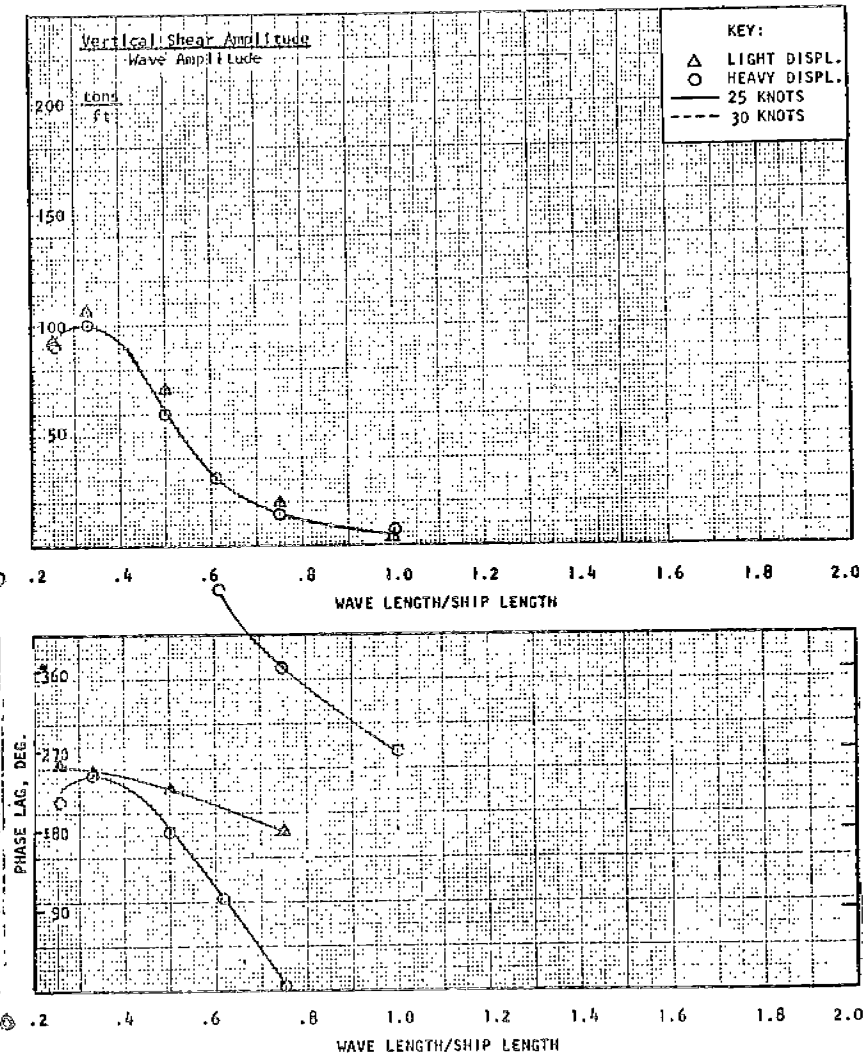


FIGURE A-44 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 240° HEADING

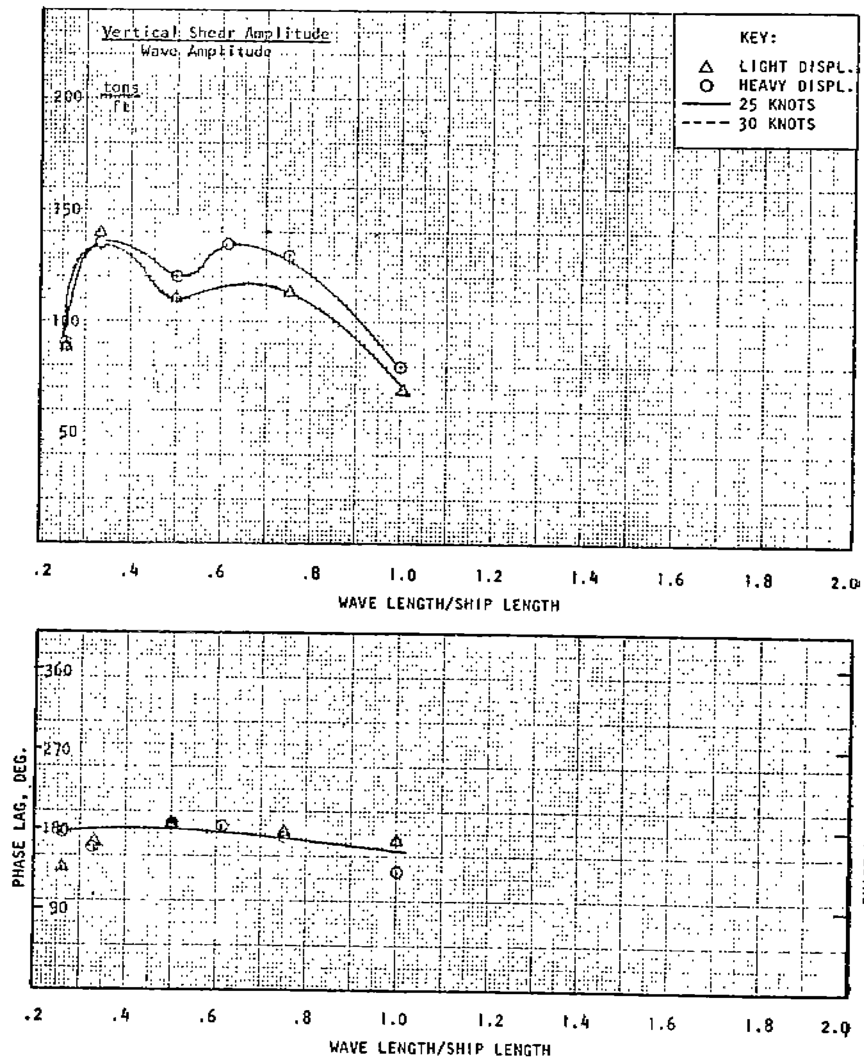


FIGURE A-45 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 240° HEADING

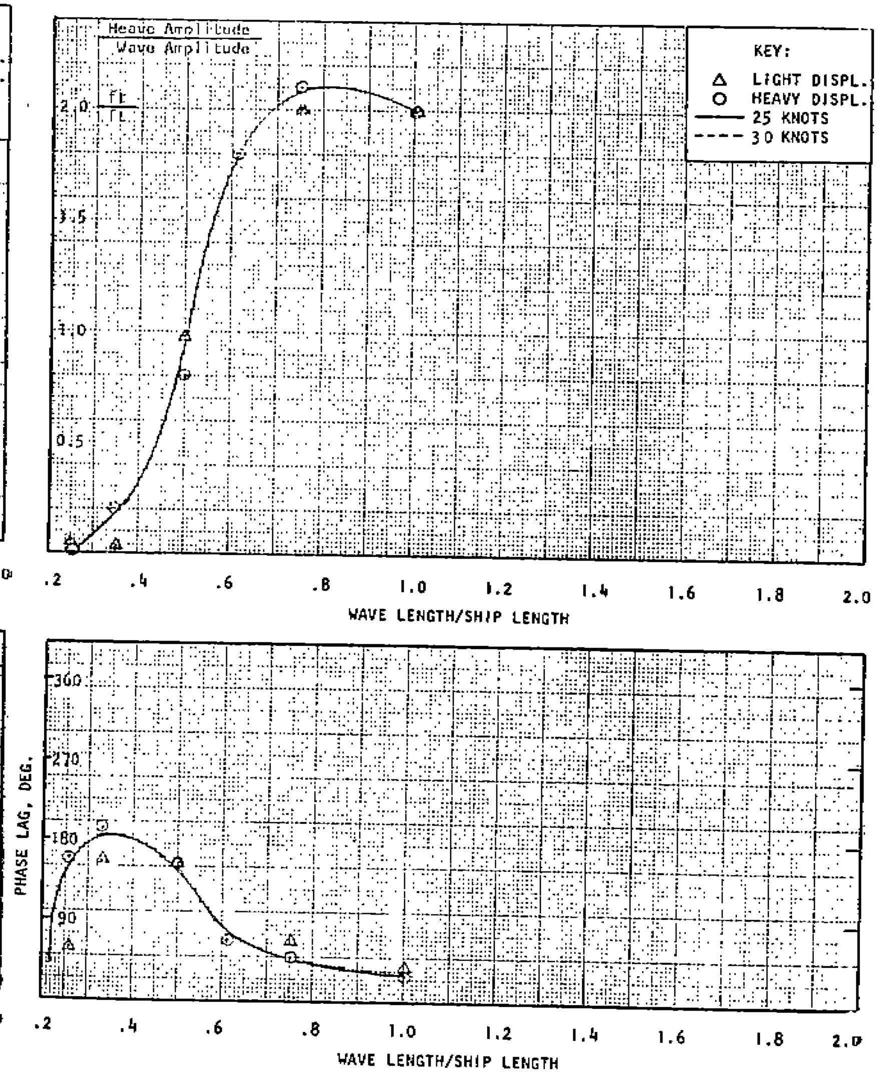


FIGURE A-46 - FRAME 124 HEAVE AND PHASE LAG, 240° HEADING

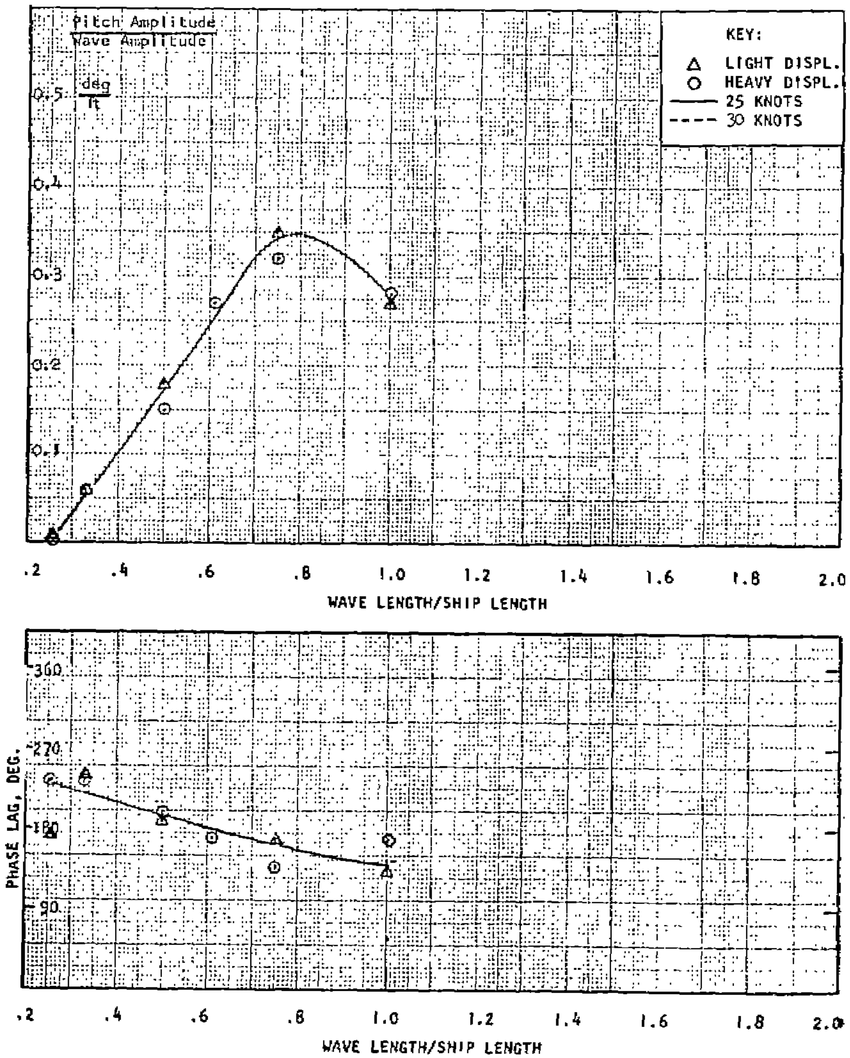


FIGURE A-47 - PITCH AND PHASE LAG, 240^{0} HEADING

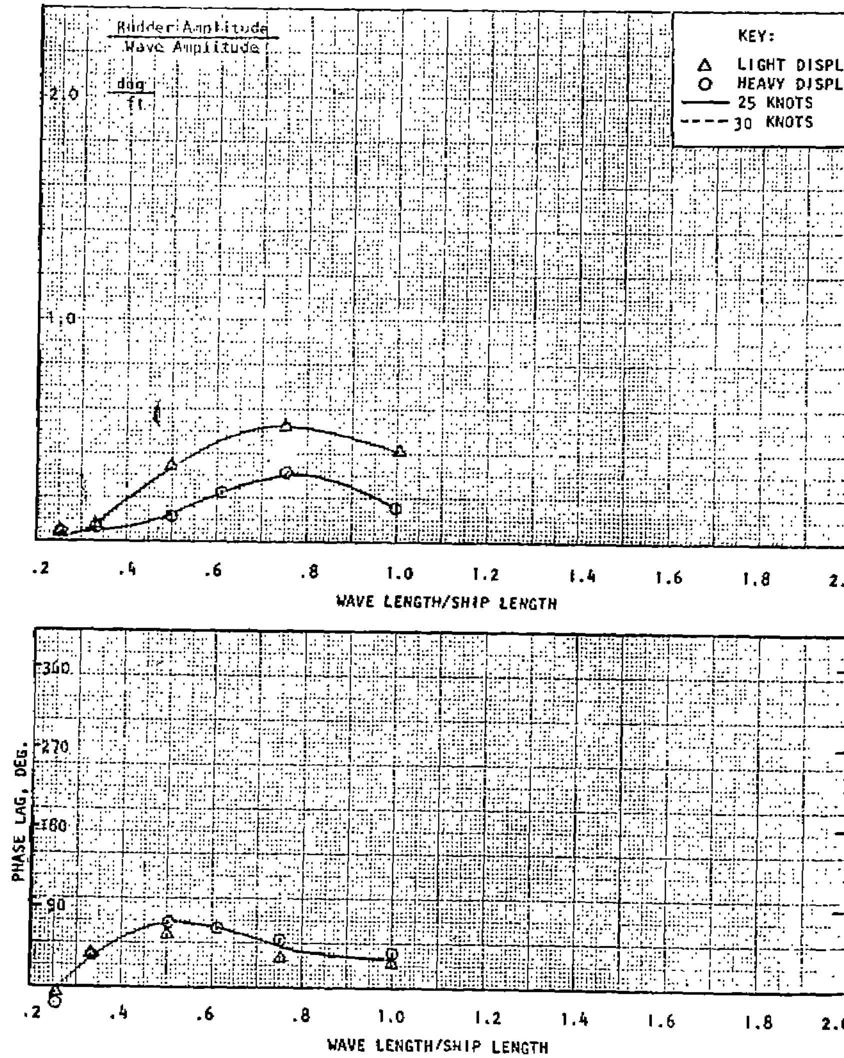


FIGURE A-48 - RUDDER AND PHASE LAG, 240^{0} HEADING

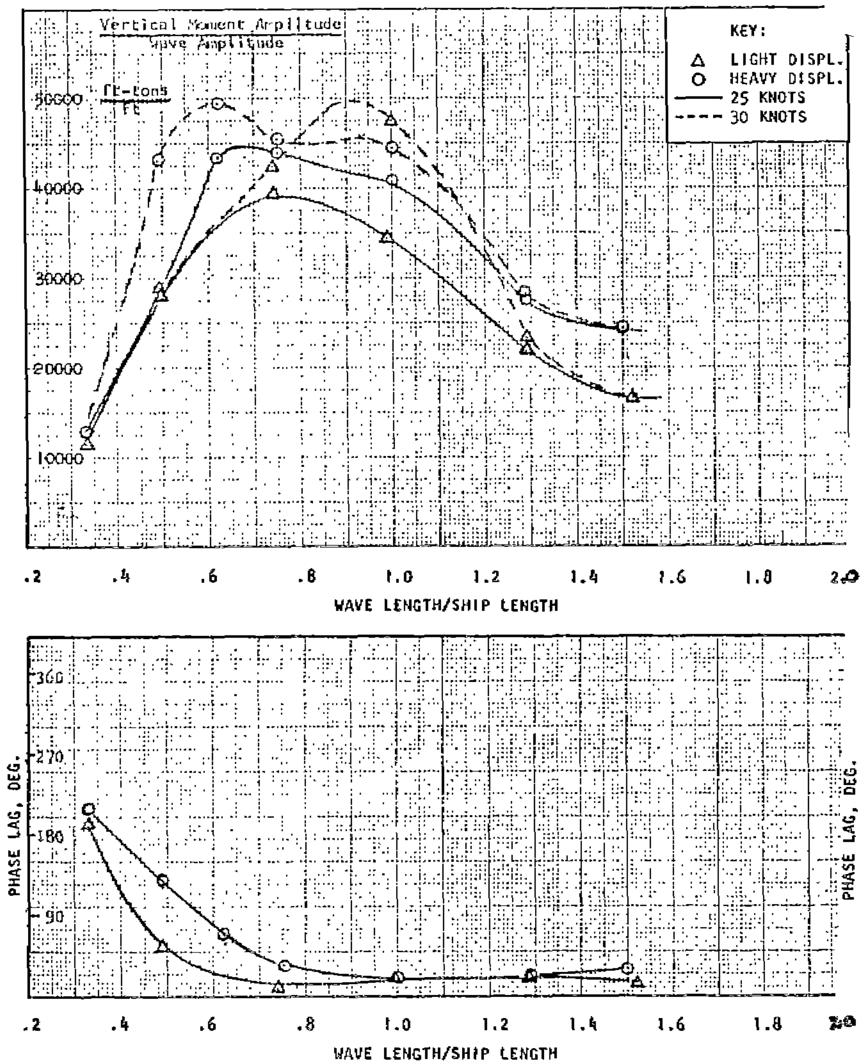


FIGURE A-49 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 210° HEADING

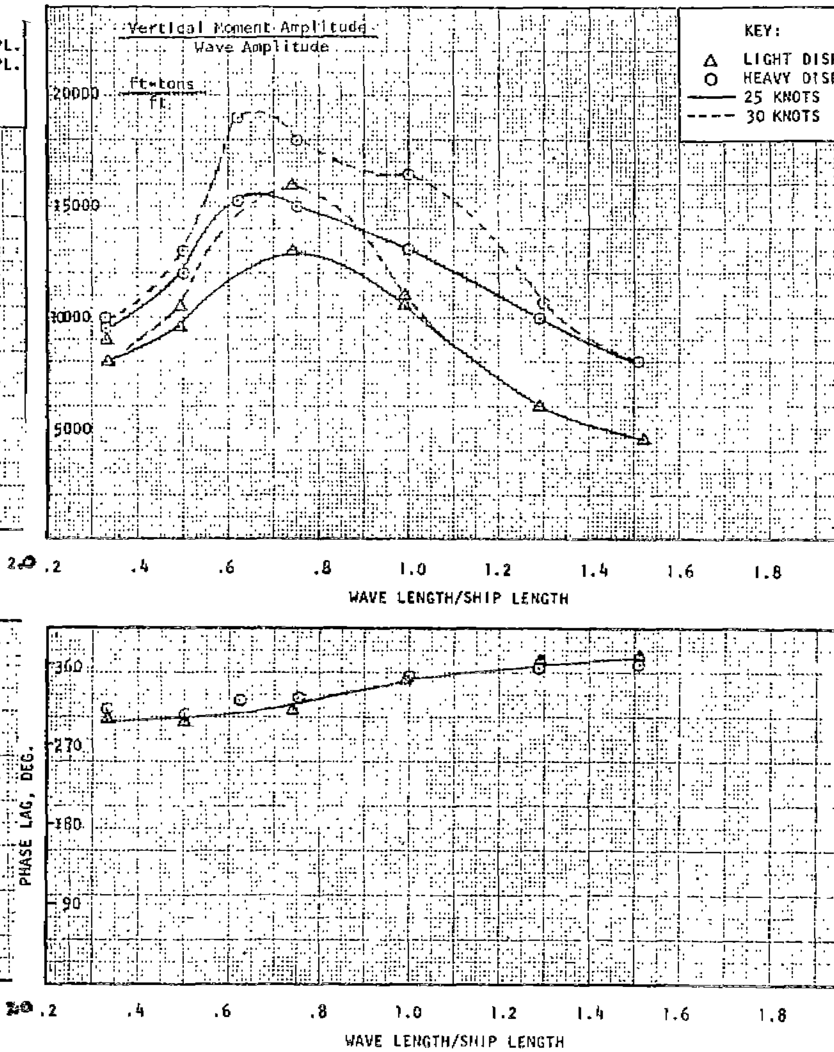


FIGURE A-50 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 210° HEADING

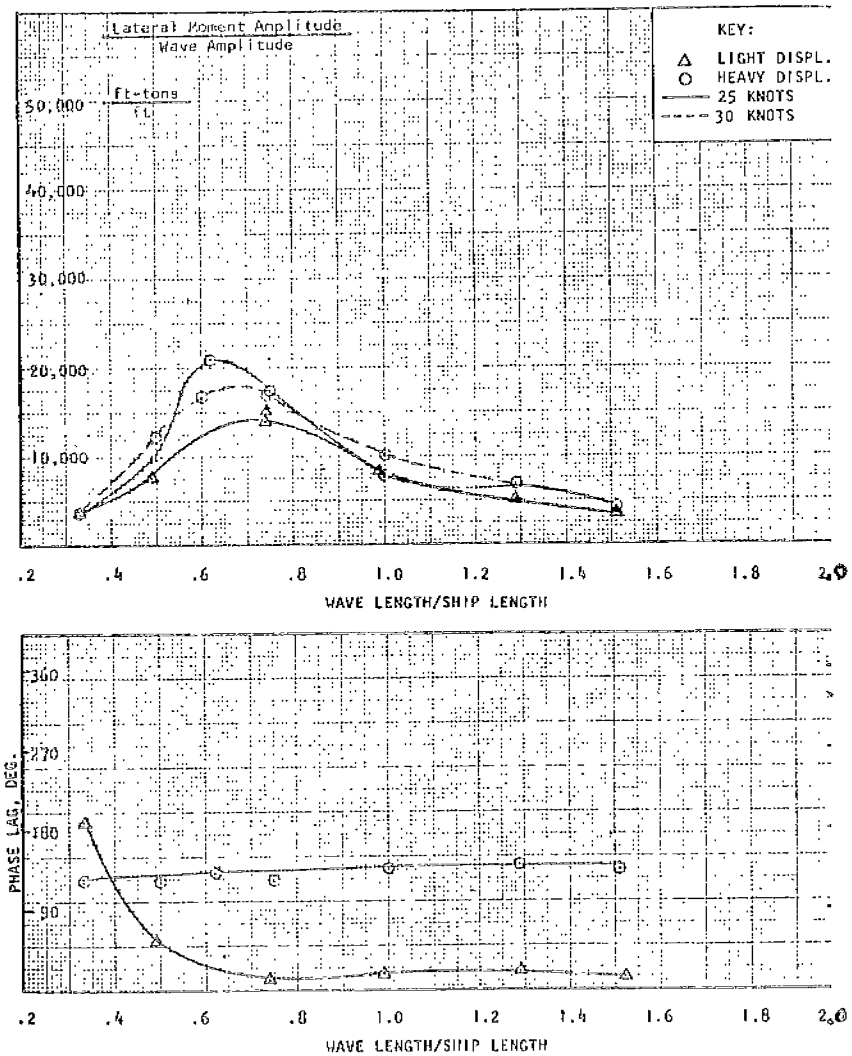


FIGURE A-51 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 210^{0} HEADING

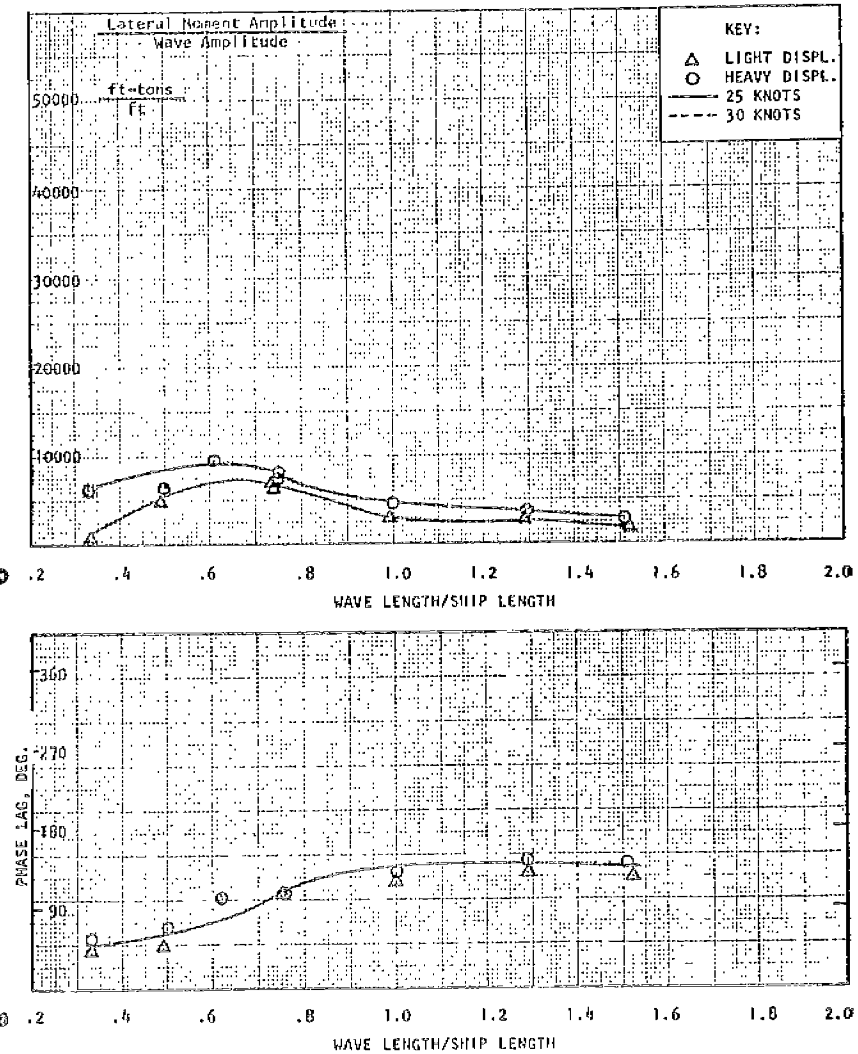


FIGURE A-52 - FRAME 258 LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 210^{0} HEADING

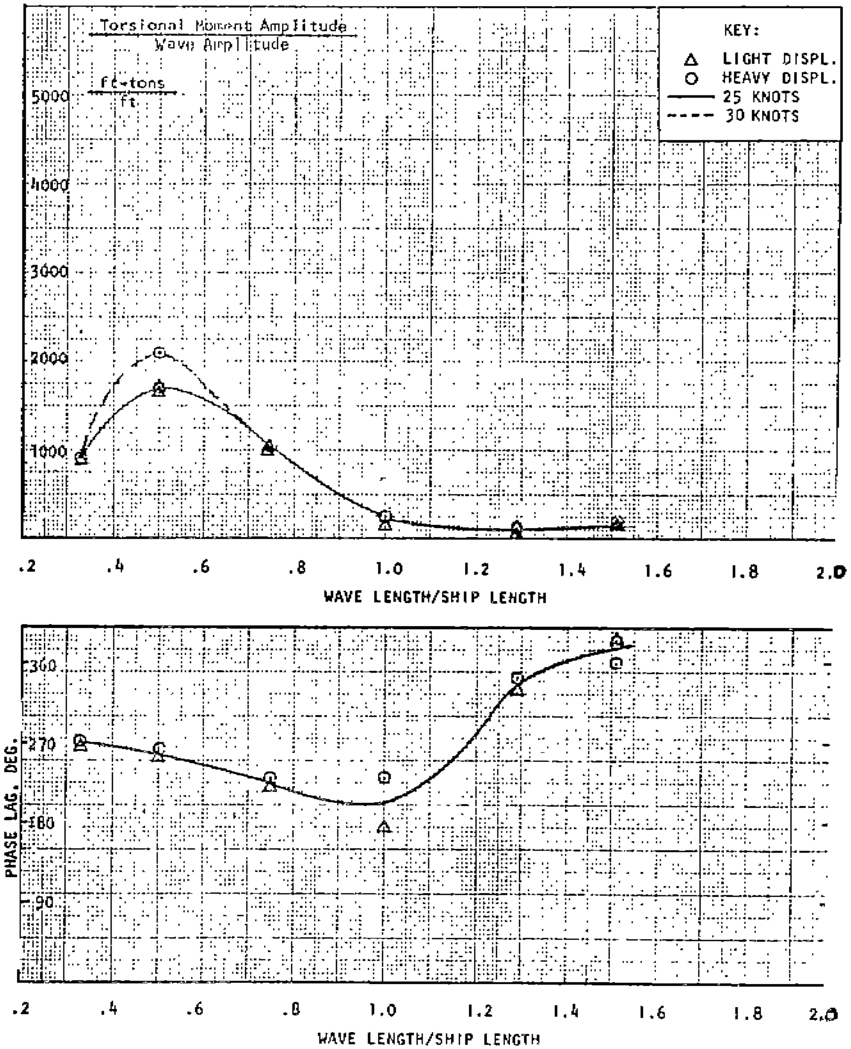


FIGURE A-53 - MIDSHIP TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 210° HEADING

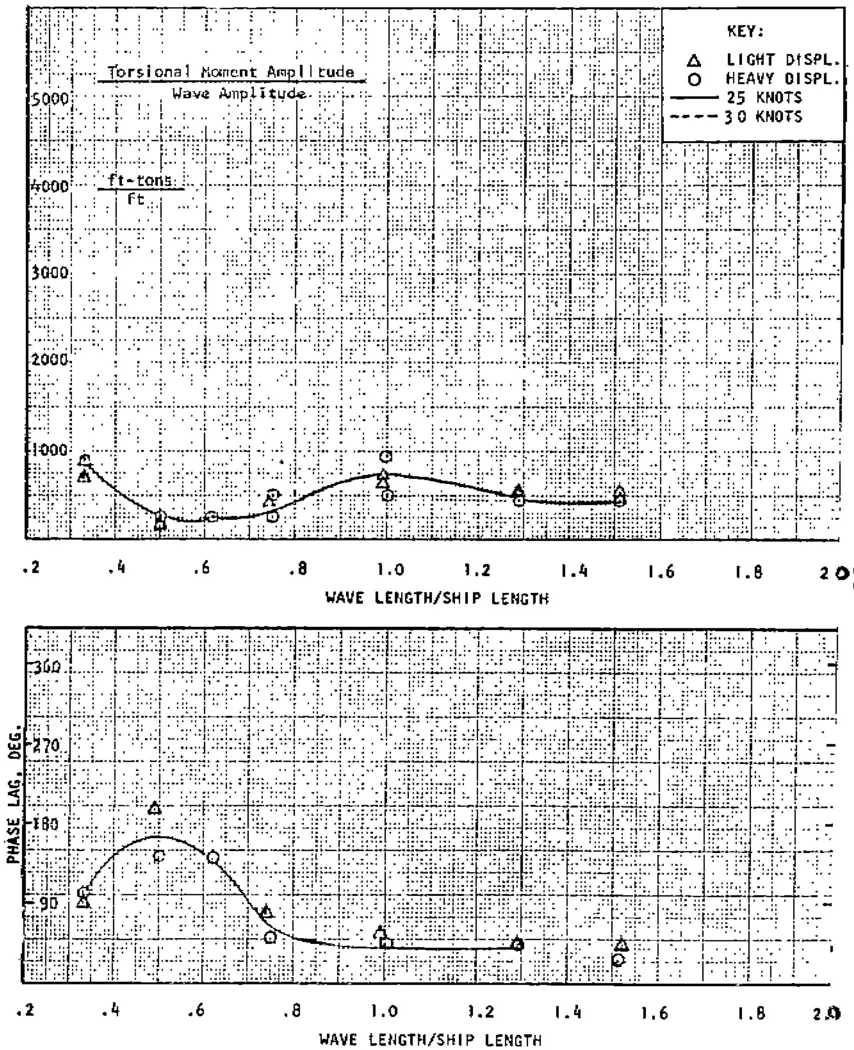


FIGURE A-54 - FRAME 258 TORSIONAL WAVE BENDING MOMENTS AND PHASE LAG, 210° HEADING

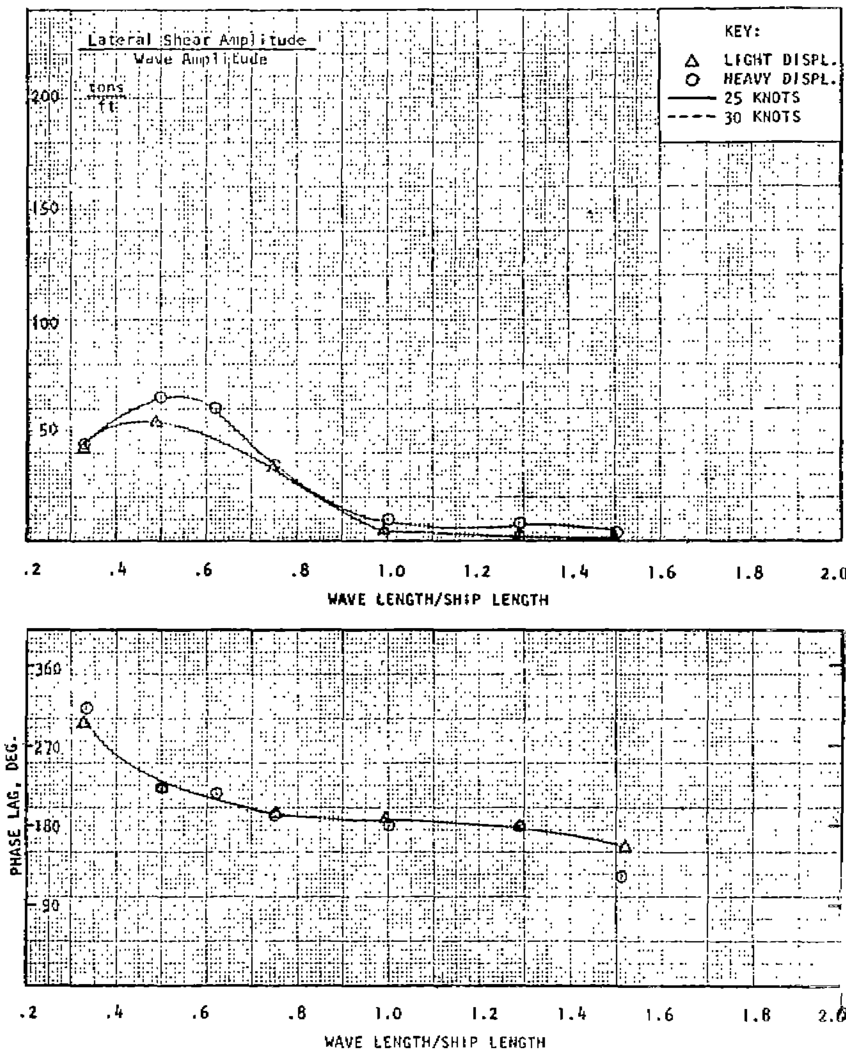


FIGURE A-55 - MIDSHIP LATERAL SHEAR AND PHASE LAG, 210° HEADING

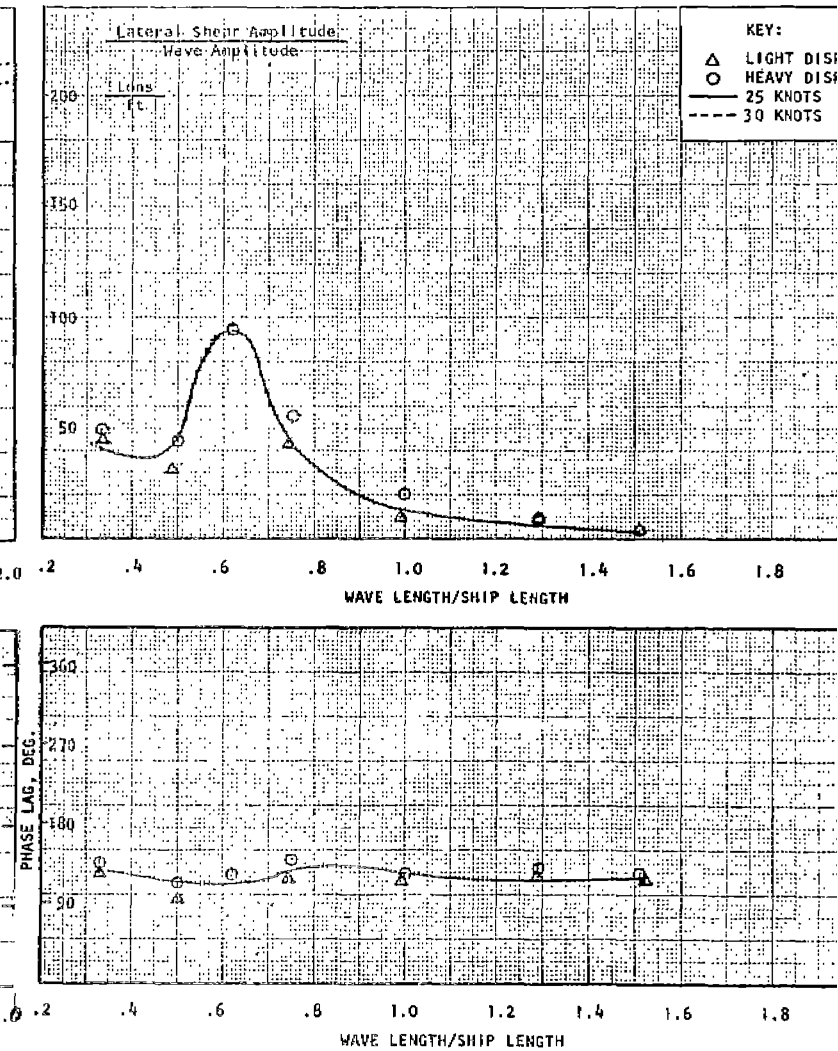


FIGURE A-56 - FRAME 258 LATERAL SHEAR AND PHASE LAG, 210° HEADING

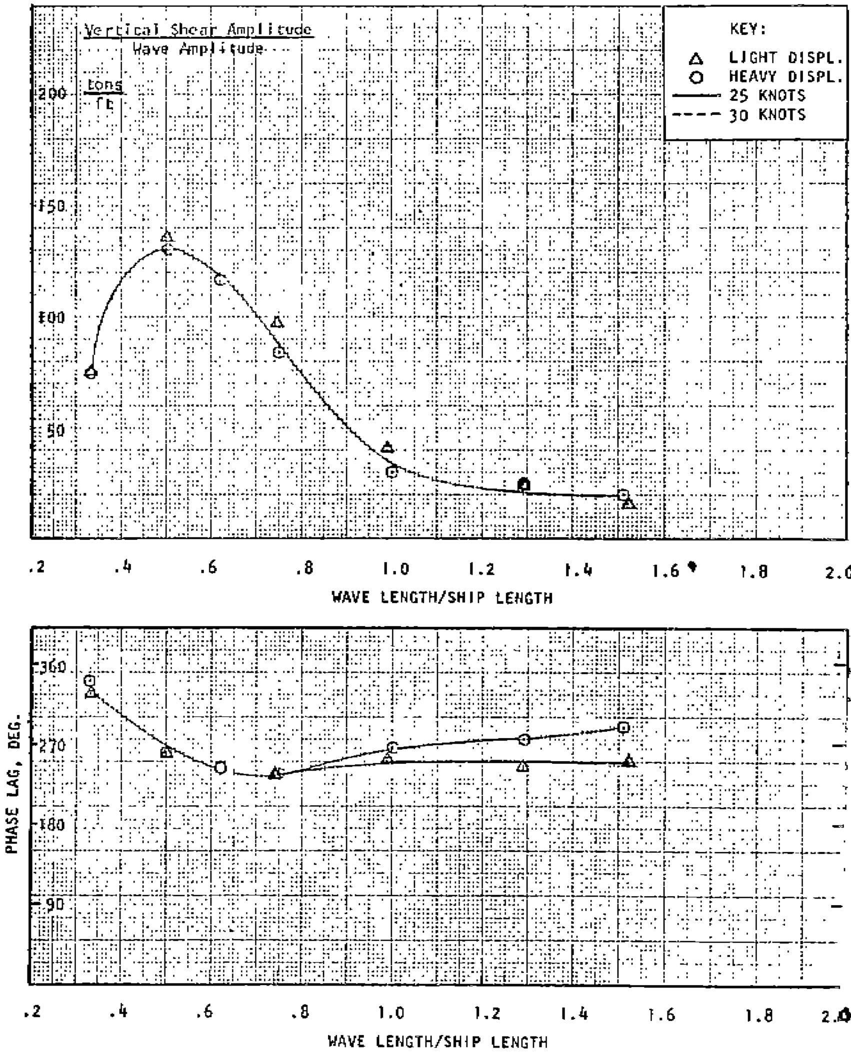


FIGURE A-57 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 210° HEADING

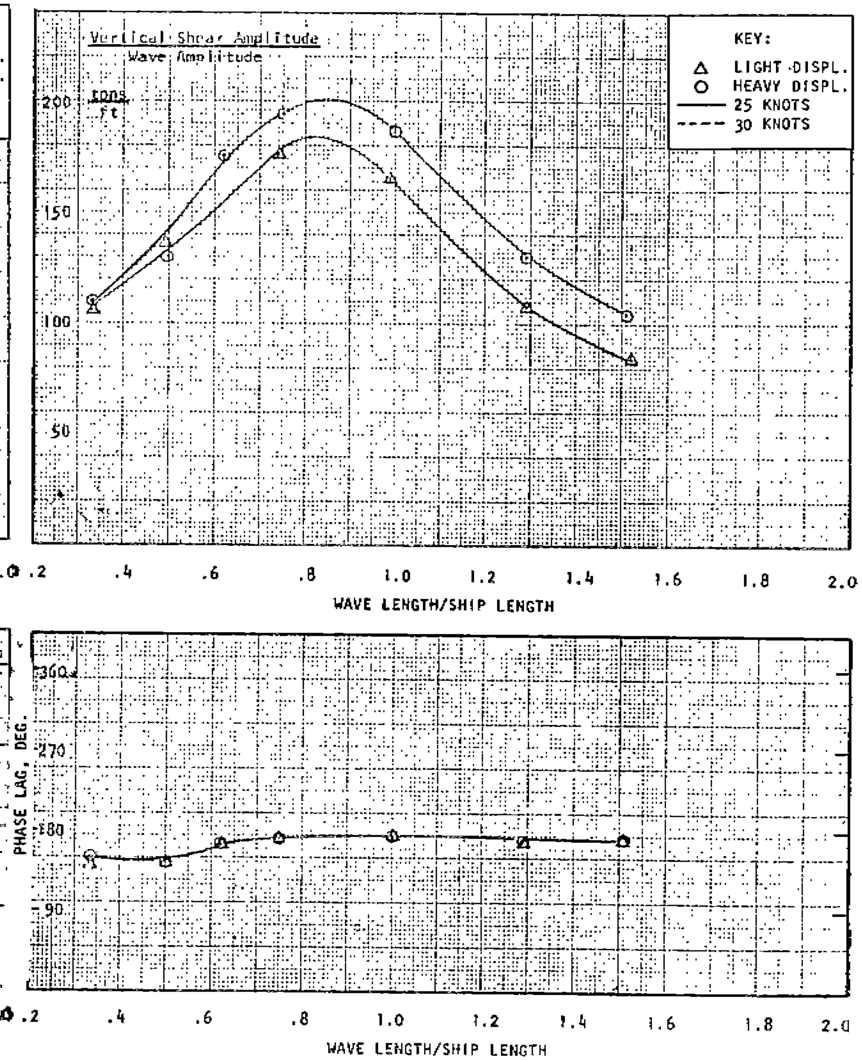


FIGURE A-58 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 210° HEADING

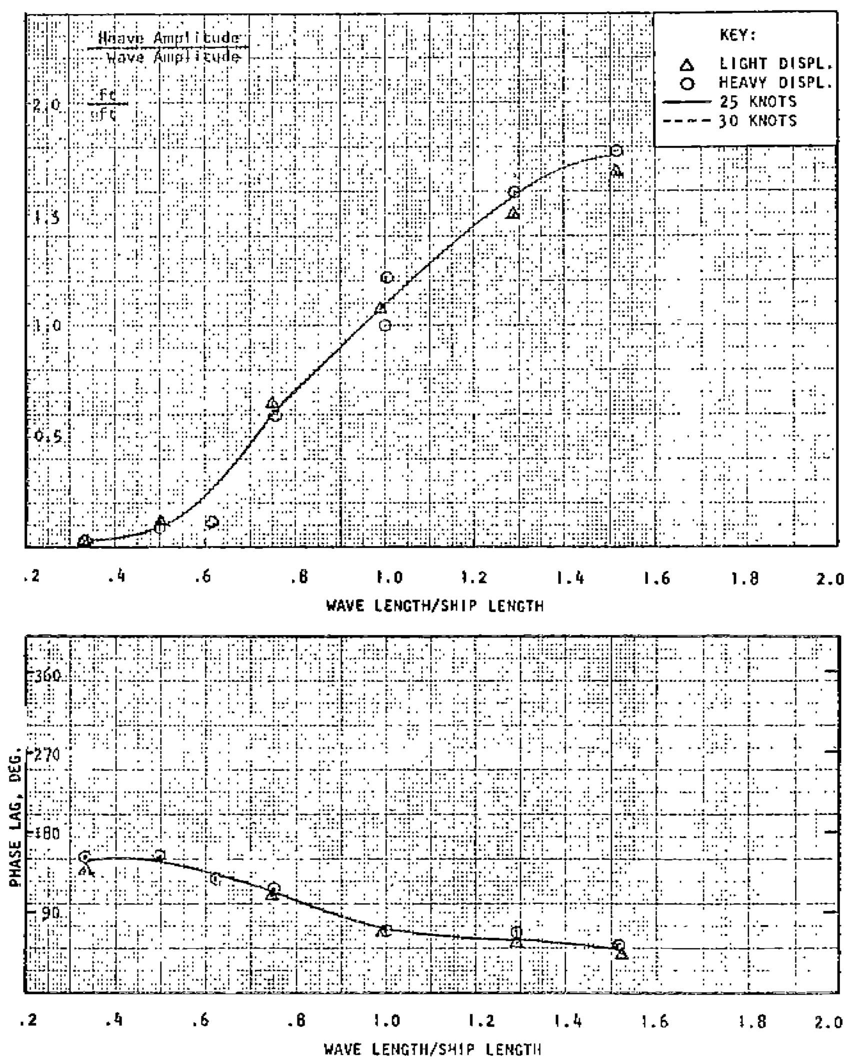


FIGURE A-59 - FRAME 124 HEAVE AND PHASE LAG, 210° HEADING

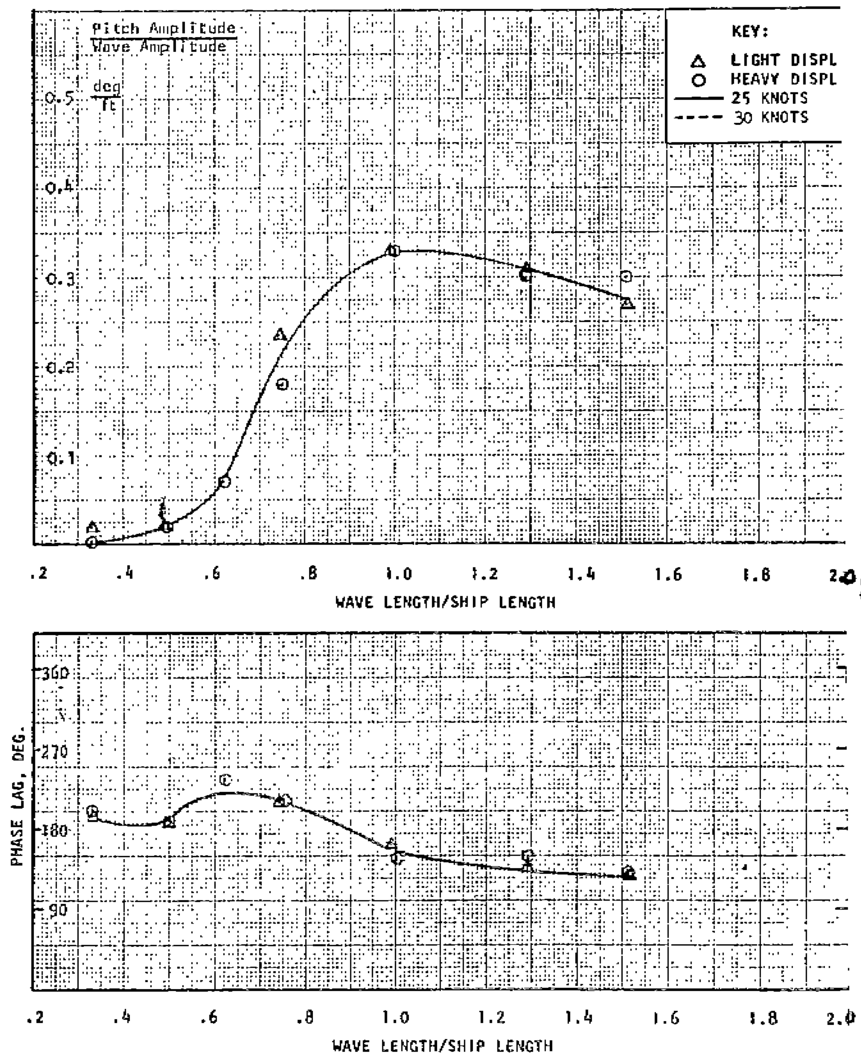


FIGURE A-60 - PITCH AND PHASE LAG, 210° HEADING

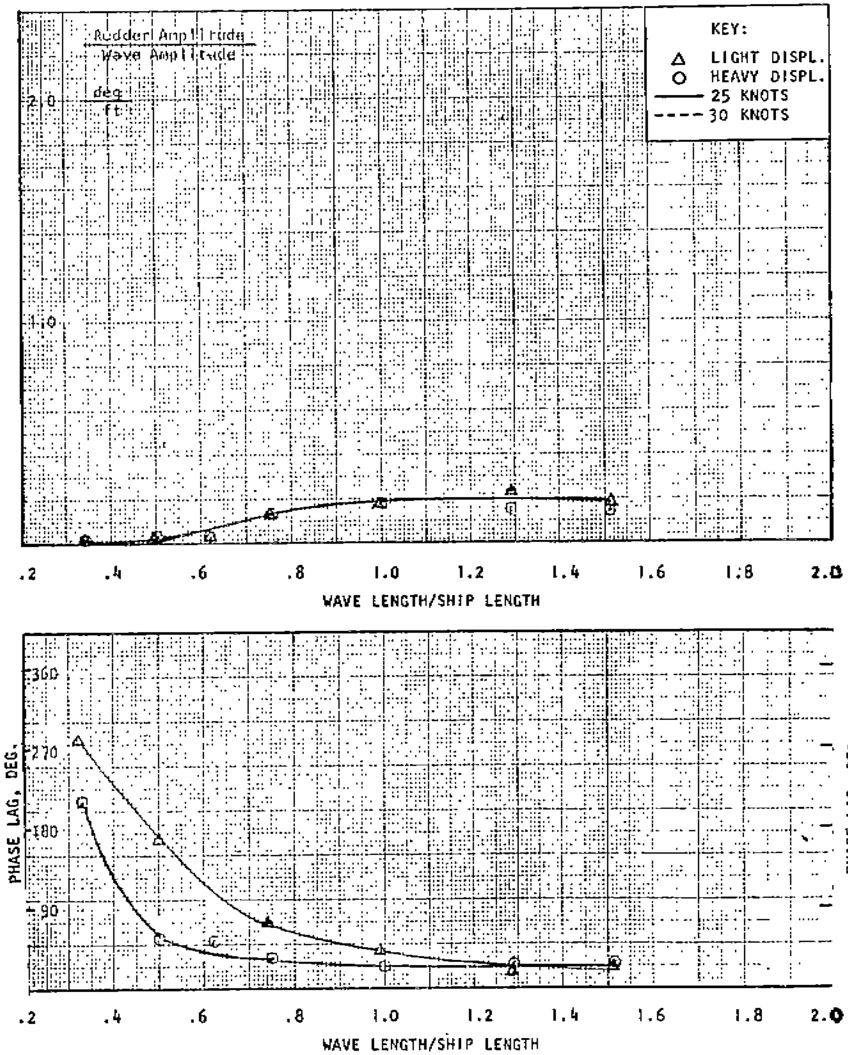


FIGURE A-61 - RUDDER AND PHASE LAG, 210^{o} HEADING

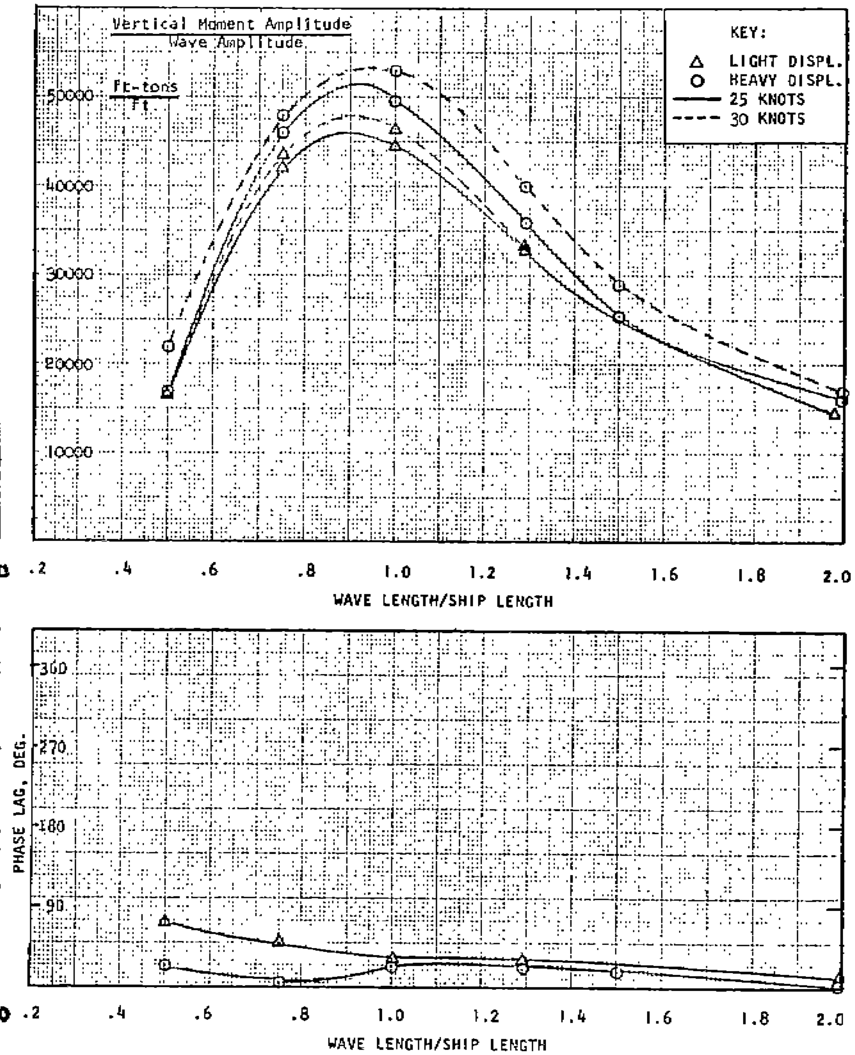


FIGURE A-62 - MIDSHIP VERTICAL WAVE BENDING MOMENTS AND WAVE PHASE LAG, 180^{o} HEADING

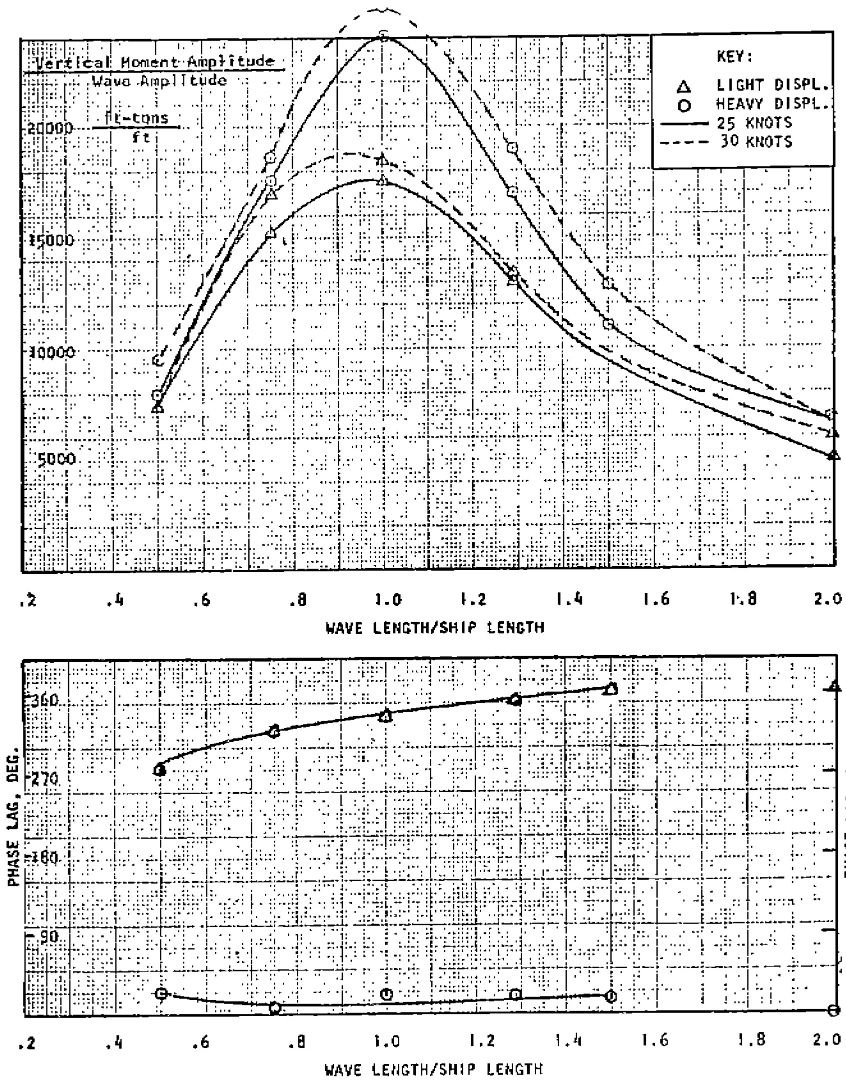
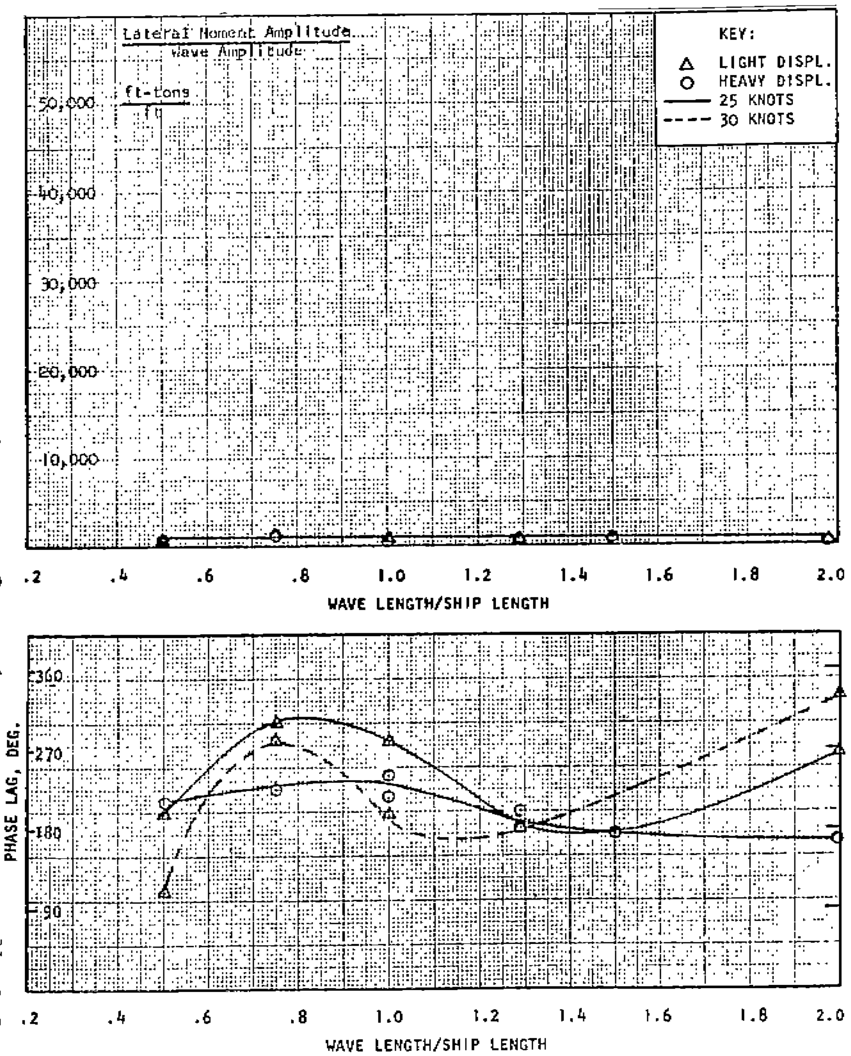


FIGURE A-63 - FRAME 258 VERTICAL WAVE BENDING MOMENTS AND PHASE LAG, 180° HEADING



FIGIRE A-64 - MIDSHIP LATERAL WAVE BENDING MOMENTS AND PHASE LAG, 180° HEADING

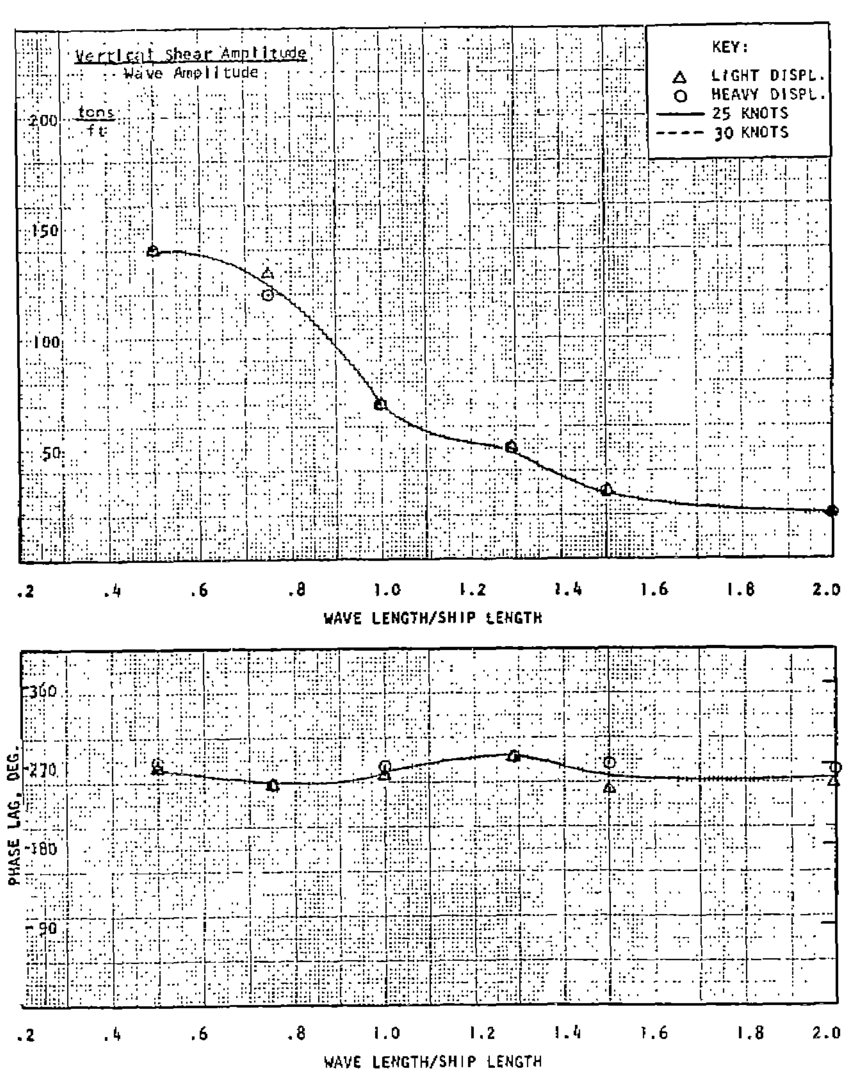


FIGURE A-65 - MIDSHIP VERTICAL SHEAR AND PHASE LAG, 180° HEADING

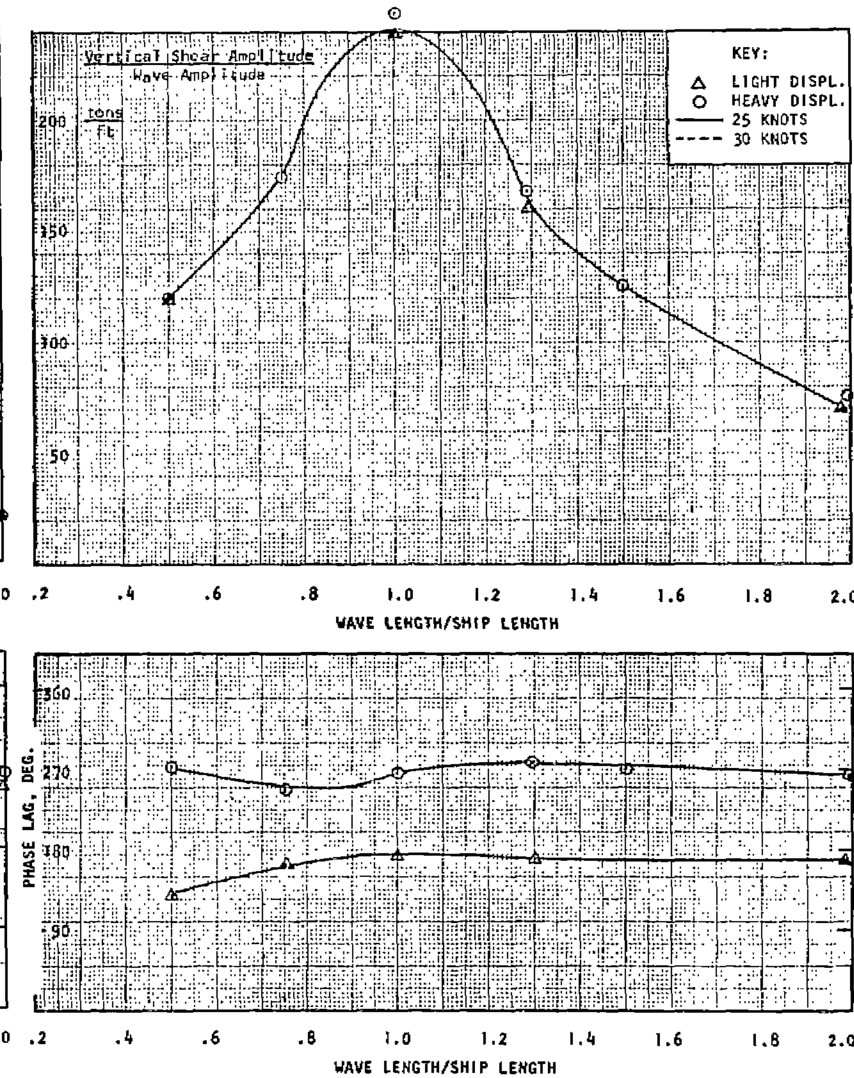


FIGURE A-66 - FRAME 258 VERTICAL SHEAR AND PHASE LAG, 180° HEADING

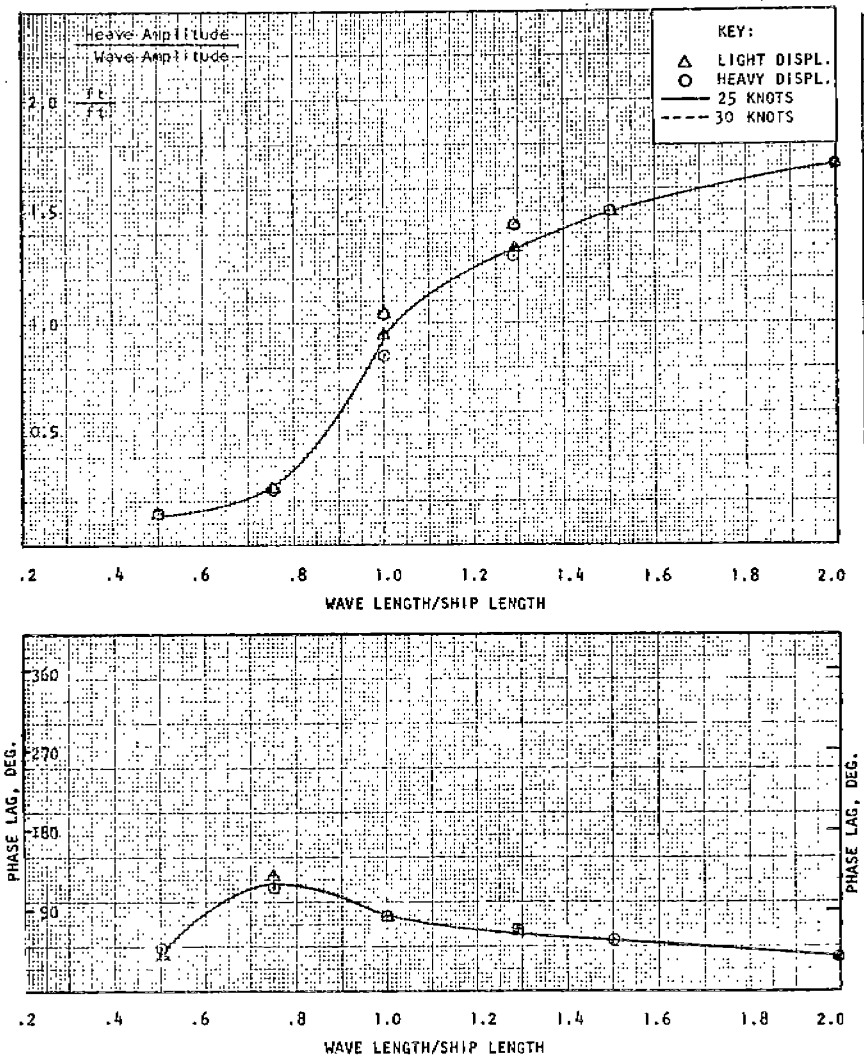


FIGURE A-67 - FRAME 124 HEAVE AND PHASE LAG, 180° HEADING

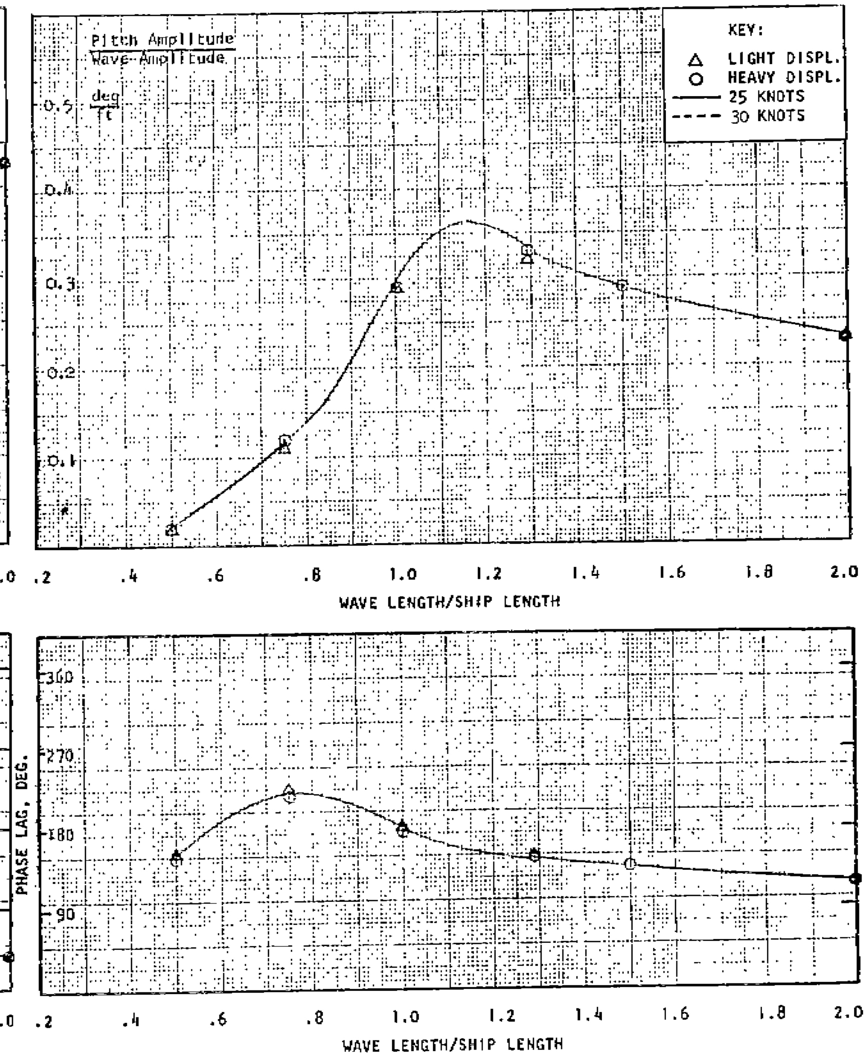


FIGURE A-68 - PITCH AND PHASE LAG, 180° HEADING

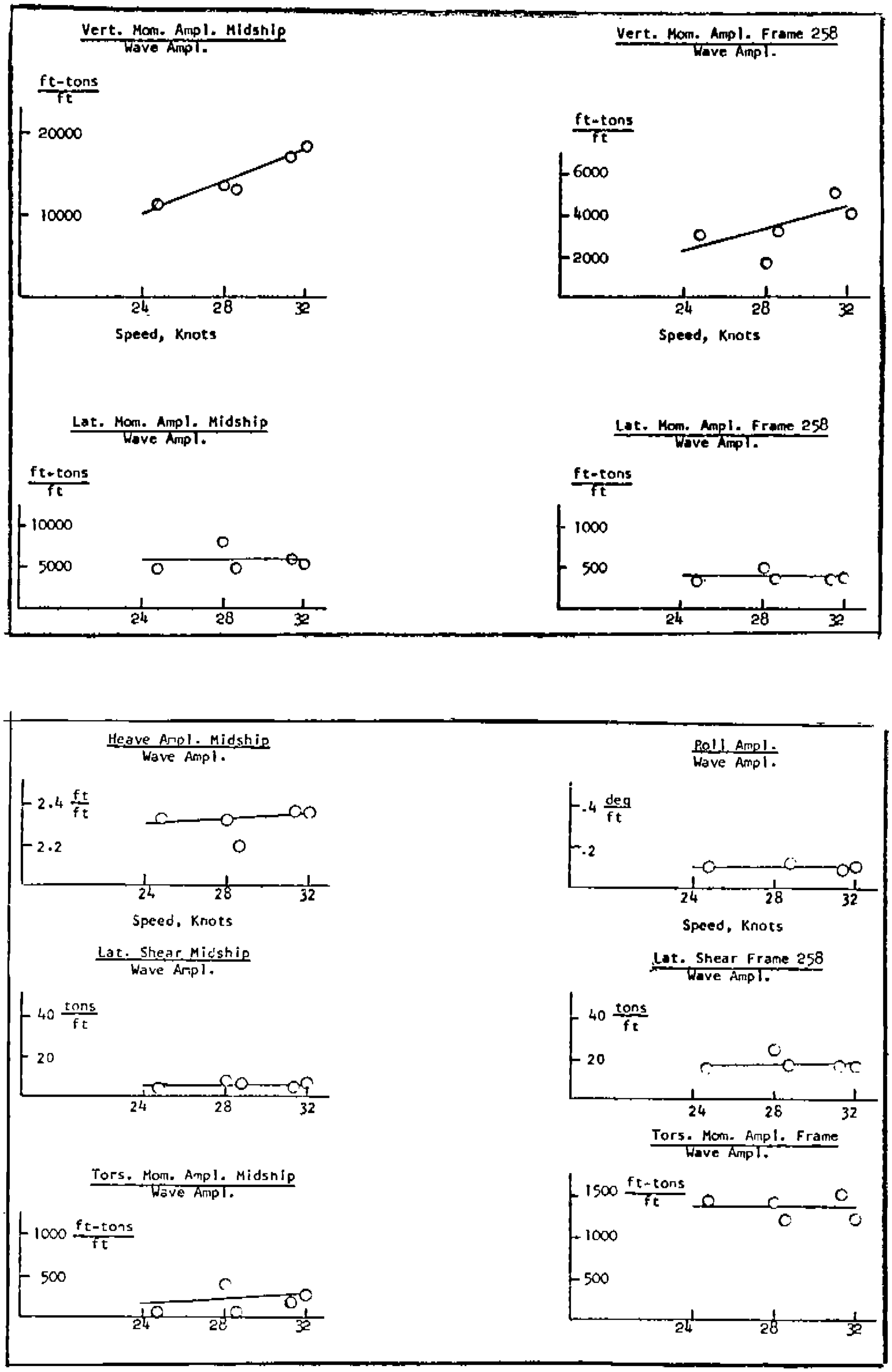


FIGURE A-69 - CROSSPLOTS: DATA FOR 270^{o} HEADING WAVE LENGTH/SHIP LENGTH = 0.33 HEAVY DISPLACEMENT

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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13. ABSTRACT

Vertical, lateral and torsional wave bending moments, and vertical and lateral shears were measured at two sections of a 1/140-scale model of the SL-7 containership. The model was self-propelled through a ship speed range of 24 and 32 knots at seven headings to regular waves of lengths between 0.25 and 2.0 times the length between perpendiculars. Motions were also measured. Two ship conditions: light and full load were covered. Results are presented in charts of load or motions amplitude/wave amplitude vs. wave length and phase lag vs. wave length, with heading, ship speed and loading condition as parameters.

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Torsional Wave Bending Moments						
Wave Shearing Forces						
Model Tests						

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SHIP STRUCTURE COMMITTEE PUBLICATIONS

These documents are distributed by the National Technical Information Service, Springfield, Va. 22151. These documents have been announced in the Clearinghouse journal U.S. Government Research & Development Reports (USGRDR) under the indicated AD numbers.

SSC-230, *Program SCORES - Ship Structural Response in Waves* by A. I. Raff, 1972. AD 752468.

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SL-7 PUBLICATIONS TO DATE

SL-7-1, (SSC-238) - *Design and Installation of a Ship Response Instrumentation System Aboard the SL-7 Class Containership S.S. SEA-LAND McLEAN* by R. A. Fain. 1974.

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