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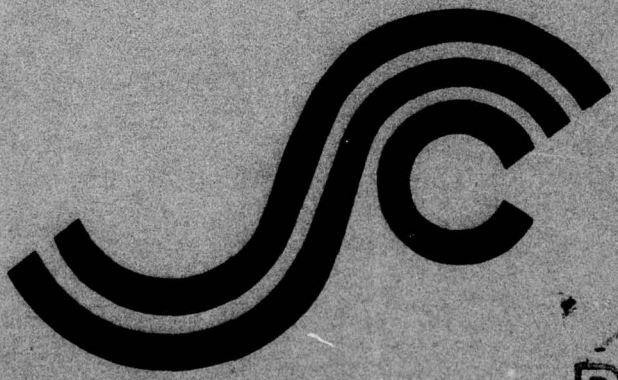


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SSC-271
(SL-7-12)

A CORRELATION STUDY OF SL-7 CONTAINERSHIP LOADS AND MOTIONS - MODEL TESTS AND COMPUTER SIMULATION

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SR-230

1 DEC 1977

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 has been 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 contains the results and discussions of the loads and motions correlation between model test and computer simulation results.

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SSC-271

(SL-7-12)

Final Technical Report

on

Project SR-230, "SL-7 Data Correlation"

A CORRELATION STUDY OF SL-7 CONTAINERSHIP LOADS AND MOTIONS - MODEL TESTS AND COMPUTER SIMULATION

by

Paul Kaplan, T. P. Sargent and Mark Silbert

OCEANICS, INC.

under

Department of the Navy
Naval Sea Systems Command
Contract No. N00024-75-C-4285

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ABSTRACT

A correlation study is carried out [for the SL-7 container ship]by means of comparison of results for structural loads and motions in waves obtained from model tests and computer calculations. The different aspects that could affect computer predictions are examined via further computations and analyses in order to determine their influence on the output data. Similarly an examination of the possible effects that influence the model test data are also examined. The main objective of this study is to determine the capabilities of both test methods for prediction purposes.

Comparisons are also made between theoretical predictions and results for other related ship models for which test data are available. Consistency of various results obtained is used as a basis for assessing the degree of validity of any particular method, as well as determining the exact difference in results due to various mechanisms that influence both the theory and experiments. Improvements in the theoretical model leading to an extended SCORES theory are described, together with the comparison with a range of available data for the SL-7 and other ships. The particular type of output information, as well as the regions wherein such data are found to differ significantly from the theory are described together with suggested reasons for such lack of agreement. Recommendations for additional tests and further computations for comparison purposes are also provided, with an interim conclusion that the computer program (extended SCORES theory) is presently a suitable tool for prediction purposes.

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NOMENCLATURE

a = wave amplitude

a', b, c', d, e, g' = coefficients in vertical (heave) equation of motion

$a_{11}, a_{12}, a_{17}, a_{18}$ = coefficients in surge equation of motion

a_{31}, a_{32} = coefficients in pitch equation of motion coupling surge

A, B, C, D, E, G' = coefficients in vertical plane (pitch) equation of motion

A'_{33} = sectional vertical added mass

B^* = local waterline beam

BM_z = vertical bending moment

c = wave speed (celerity)

$\frac{df_z}{dx}$ = total local vertical loading on ship

$\frac{dK}{dx}$ = sectional hydrodynamic moment, about x axis, on ship

$\frac{dX}{dx}$ = sectional longitudinal hydrodynamic force on ship

$\frac{dY}{dx}$ = sectional lateral hydrodynamic force on ship

$\frac{dZ}{dx}$ = sectional vertical hydrodynamic and hydrostatic force on ship

F_{rs} = sectional lateral added mass due to roll motion

g = acceleration of gravity

$\overline{GB}$ = vertical distance between center of gravity and center of buoyancy of ship

$\overline{GM}$ = initial metacentric height of ship

$\bar{h}$ = mean section draft

H = sectional draft

k = wave number

k_1 = longitudinal added mass coefficient

K_w = wave excitation moment, about x axis, on ship

m = mass of ship

M_s = sectional lateral added mass

$M_{s\phi}$ = sectional added mass moment of inertia due to lateral motion

M_w = wave excitation moment, about y axis, on ship

N_{rs} = sectional lateral damping force coefficient due to roll motion

N_s = sectional lateral damping force coefficient

$N_{s\phi}$ = sectional damping moment coefficient due to lateral motion

N'_x = sectional longitudinal damping force coefficient

N'_z = sectional vertical damping force coefficient

$\overline{OG}$ = vertical distance between waterline and center of gravity, positive up

R_T = total resistance (drag) of ship

S = local section area

t = time

v_w = lateral orbital wave velocity

V = ship forward speed

x = horizontal axis in direction of forward motion of ship (along length of ship); surge

x_o = location along ship length at which moments are determined

x_s, x_b = x coordinates at stern and bow ends of ship, respectively

X_w = longitudinal wave excitation force on ship

y = horizontal axis directed to starboard; sway

Y_w = lateral wave excitation force on ship

z = vertical axis directed downwards; heave

$\bar{z}$ = sectional center of buoyancy, from waterline

Z_w = vertical wave excitation force on ship

α = linear roll damping coefficient

α_e = equivalent linear roll damping coefficient for quadratic nonlinear system

β = angle between wave propagation direction and ship forward motion; quadratic roll damping coefficient

Δ = change or additional terms in indicated quantity

δm = local mass

ζ_ϕ = fraction of critical roll damping

ζ_{ϕ_e} = equivalent fraction of critical roll damping for quadratic nonlinear system

η = surface wave elevation, positive upwards from undisturbed water surface

θ = pitch angle, positive bow-up

λ = wave length

ρ = density of water

ϕ = roll angle, positive starboard-down

ϕ_w = velocity potential for incident surface waves

ψ = yaw angle, positive bow-starboard

ω = circular wave frequency

ω_e = circular frequency of wave encounter

ω_ϕ = natural roll frequency

Subscripts

h = hydrodynamic

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INTRODUCTION

In order to determine the capabilities of model testing and computer response calculations for predicting ship loads and motions in waves, particularly for the SL-7 fast container ship, a correlation study of the results obtained by both techniques should be carried out. The objectives of such a study are:

1. To develop a procedure for comparing results of previous investigations that have provided model test data and computer calculations.
2. To carry out the data comparison, using the available information as well as related data, techniques, etc.
3. To analyze the results of the correlation, with the ultimate aim to determine the relative capabilities of both test methods (i.e. model tests and computer calculations) as a means of ship structural load prediction.

The basic sources of data for this study are two reports ([1] and [2]), which provide the results of a model test study of the SL-7 ship response in regular waves [1] as well as the results of computer calculations for (mathematically simulated) similar conditions [2]. The model test technique was essentially an extension of previous experimental studies (e.g. [3], [4]) at the same laboratory (i.e. Davidson Laboratory, Stevens Inst. of Tech.), with an increase in the number of variables being measured. This was due to the importance of torsion and lateral shear for a container ship, as well as an increase in the number of stations being instrumented for measurement, thereby requiring more detailed evaluation of instrument channel coupling and a digital computer for data analysis. However there were some problems encountered in regard to "controlling" the craft under certain heading conditions (e.g. stern-quartering and beam seas) as well as limitations in wave characteristics (wavelength and wave amplitude) at such headings. In addition there was also an indication of a possible error in instrumentation settings for one mode of ship motion (i.e. heave motion) that was reported in [1].

The technique used for the computer calculations in [2] was based on the theory described in [5], using the SCORES program [6] developed from that theory. This particular program has been shown (in [5] and subsequent applications) to provide good agreement between computed values of ship motions and loads and those measured in model tests. Most of the comparisons have been made for head sea operation, with an extensive amount also carried out for oblique wave headings as well. However, no previous applications of the program were made for following seas or stern-quartering seas for a fast ship, which results in low encounter frequencies for which the theory in [5] (as well as other generally available ship theory analyses) was not considered to be precisely applicable. Certain other theories,

e.g. [7], are not applied to this range of conditions since these conditions are known to limit the applicability of such theory.

Under these circumstances, the investigation report in [2] exhibited a number of conditions where there was a lack of agreement between the theory and the model test data. The regions where such differences appeared were associated with the heading conditions with low encounter frequencies (following and stern-quartering seas), as well as some conditions where roll motion was significant but not properly predicted by theory due to the influence of possible nonlinear roll damping in regions near the roll resonance frequency. Since means of overcoming these basic difficulties of the theory were discussed (and illustrated to a small degree) in [2], it is recognized that still other effects may have to be considered in order to reconcile the state of agreement between the theory and the model test data. The results of comparison between theory and experiment shown in [2] were only part of the overall comparison effect devoted to that task, with other remaining test conditions evaluated but not exhibited in that report (i.e. [2]). This was due to all of the effort devoted to explaining the causes of the lack of agreement; the changes and modifications of parts of the computer program in order to "correct" the computed results for certain conditions (e.g. in following seas); and the limited extent of that investigation which did not anticipate the extent of disagreement between theory and experiment that arose because of the range of conditions covered, thereby necessitating extended analytical and computational efforts.

As a result of the work in [2], further investigations, analyses and computer programming efforts were applied by Oceanics, Inc. in the course of additional work on ship motions and loads (primarily for commercial clients) in order to overcome some of the difficulties and/or limitations of the computer analysis that were indicated in [2]. Particular procedures have been developed which allow for and correct some of the deficiencies of theory exhibited in [2], while other approaches that can be applied for that purpose have also been evolved in other applications. However none of these recent developments have been documented or published, since they have only been applied to particular problems of commercial clients, where the results obtained in the specific investigations were of major interest and there was no requirement of detailed development, reporting, documentation, etc. All such methods can be considered as extensions of the basic SCORES program, allowing application to a number of problems beyond the limits of the program and theory described in [5] and [6].

It is intended to apply these extended techniques to determine whether it is possible to obtain better agreement between theory and model experiment, as well as to determine the "sensitivity" of computed results to certain changes in input data, theoretical

models for hydrodynamic forces, etc. The results will provide a measure of the range of magnitudes possible from theoretical (and computer simulated) mathematical models, thereby establishing a measure of deviation or reliability of computer predictions of ship motions and loads. The possible deviation of experimental data will be determined via the use of error bands indicated by the experimental reliability limits provided in [1], together with estimates of other possible extraneous effects associated with the measuring instruments, data processing procedures, experimental restraints imposed on the model, etc. A method of establishing the differences between theory and experiment will evolve from this type of analysis, together with an evaluation of the effect of such differences in predicting statistical measures of ship loads in an irregular seaway. The details and description of the procedures that are employed, as well as the results obtained, in this comparison and correlation effort are provided in the following sections of this report.

GENERAL OUTLINE OF TECHNIQUES USED IN STUDY

The particular items that are considered and analyzed for both the computer prediction procedure as well as the experimental measurements via model tests are described below. These varied elements are examined in detail in the present study, with their results contributing to a more complete assessment of data correlation for the two methods of ship load prediction.

1. Computer Prediction Analysis

In evaluating the capability of computer predictions of ship motions and loads, the influence of a number of phenomena and procedures that could modify the results is directly determined. It is important to ascertain the "sensitivity" of computer results to different computational techniques, input data, theoretical models of hydrodynamic forces, effect of other degrees of freedom, nonlinearities, etc., in order to determine the influence on the resulting output data. A description of some of these different elements that could influence the computer results is given by the following discussion.

a) Input Data

One possible influence on the results for the wave-induced loads is the effect of the various mass and inertial properties distributed over the ship sections. In order to correlate model tests and computer predictions, these mass and inertial values used in the computer simulation should correspond exactly to those used in the model tests. An outline of the procedure used to obtain this equivalence was given in [2], where the overall characteristics for the 3 model segments were satisfied, using a distribution of mass (and inertia) that would yield the desired equivalence. However it is known that the particular distribution

is not unique, and other possible mass distributions that could still satisfy the overall mass and inertia properties of the model segments can also be established. This is done for another similar mass distribution (other than that used in the work reported in [2]), which still satisfies the overall mass-inertial properties of the ship model, in order to evaluate the influence on the resulting ship loads. This will verify whether the requirements of the overall mass-inertial properties is sufficient, or if more extensive detailed mass input information must be used whenever attempting to obtain a more precise estimate of wave-induced ship loads.

b) Hydrodynamic Theory for Sectional Forces

The techniques used in [5] for evaluating the two-dimensional sectional added mass and damping is based on the use of the Lewis form mapping procedure [8]. While the general shape of the ship sections for the SL-7 does not seem to deviate from the general ship forms for which this procedure is applicable, it should be determined whether a different hydrodynamic representation for the sectional added mass and damping could influence the final results obtained from computer prediction methods. The present study also makes use of the Frank Close-Fit technique [9] as the method for the hydrodynamic coefficients used in the program of [6], replacing the use of the Lewis form technique. Results are obtained using the basic theory and program, with this alternate method of representing the sectional hydrodynamic forces. These results are then compared for a number of cases, using both procedures for these hydrodynamic terms, in order to evaluate possible differences in the final output values for motions and loads, thereby providing a measure of the dependence of the output from a computer prediction technique on the nature of the detailed hydrodynamics.

c) Illustration of Results for Similar Ships

In order to provide further validity of the computer prediction technique, results obtained for other ship forms by Oceanics, Inc. in the course of certain applications for commercial clients will also be presented. The comparison between theoretical values obtained from the computer program in [6] with model test data for these cases is presented as a means of providing further validation for the procedure. The particular craft chosen for this purpose are ship forms that are generally similar to that of the SL-7 i.e. high-speed fine shape hulls.

d) Effect of Neglected Coefficients in Equation System

The mathematical theory presented in [5] differs somewhat from that given in [7], mainly due to certain speed-dependent terms that enter into the definition of some of the coefficients. Some consideration of the influence of these terms was given in [2], although the results of the computations with and without

these terms were not presented in detail in that report (only the conclusions mentioned). A detailed comparison of the influence of these additional terms, as part of an extended strip theory modification of the basic SCORES analysis [5], is provided for a larger number of cases in order to judge the dependence of the computer results on such differences in coefficient definition.

e) Presentation of Complete Test Condition Results

While all of the test conditions reported in [1] were evaluated by means of computer simulation in the work of [2], not all of the results were reported in graphical form in [2]. The present study will provide the computational results for all test conditions (together with comparison with model data), thereby providing a larger data base for use of the correlation study.

f) Influence of Rudder Deflection

The effects of rudder deflection on various lateral loads and ship roll motion were exhibited in [1], and computations to remove the influence of the rudder from the measured results were made in the course of the work reported in [2]. This would then allow a direct comparison between theory and computer evaluation and the model test results since the basic theory did not incorporate the influence of the rudder. More extensive information on the exact measurements, phase relations, etc. that were obtained at the Davidson Laboratory work have been provided, beyond the information given in [1], so that a more precise evaluation can be made of the influence of the rudder in the comparison and correlation work.

g) Effect of Surge Motion

While the steady state surge displacement has been considered in the evaluation of the output data reported in [1], it must also be recognized that there is an oscillatory response of surge that is induced by waves. Inclusion of the surge degree of freedom in regard to its coupling with the vertical plane motions of heave and pitch, as well as the influence of this additional degree of freedom on the vertical plane loads, must also be determined. Oceanics has developed an extension of the SCORES program that includes this additional degree of freedom in surge, and an evaluation of its influence on the results obtained in the SL-7 investigation is made as part of the present study. This will serve to illustrate the influence of the response due to this degree of freedom, which as been previously neglected in most ship motion theoretical analyses.

h) Effect of Low Encounter Frequency

One of the major areas of disagreement indicated in [2] was in following and stern-quartering seas, where low encounter frequency occurred. In [2] some discussion was presented that indicated an improper influence of the vertical added mass terms on the structural load responses. A more detailed analysis of the various contributory terms entering into the evaluation of vertical shear and vertical bending moments is necessary, for a number of cases where this low-frequency influence is manifested by the original theory. This provides a basis for judging where the major terms arise, and whether there is a consistent influence expected in accordance with basic principles of hydrodynamics and mechanics. The results discussed in [2] were not illustrated in that report, but are provided in the present report. Analyses and proposed theoretical approaches are presented, together with results of computations, in order to provide a more valid representation of the low-frequency range associated with following and stern-quartering seas.

i) Nonlinear Roll Effect

The analysis in [2] indicated that the calm water roll decay of the SL-7 ship model was represented by a damping that had both a linear and nonlinear (i.e. quadratic) term. However an assumed constant linear damping value was used throughout the computations in [2] for both loading conditions, since that was the state of the art for the SCORES program (see [5] and [6]). Techniques have been developed by Oceanics, Inc. in order to calculate the response in roll (as well as those coupled with roll) when nonlinear damping of this type is present for both regular waves, where the responses are then dependent on the amplitudes of the particular waves, as well as in the case of irregular seas in determining statistical responses (rms, etc.) in different sea states (see [10]-[12]).

Applications are made with this method in order to determine the roll response, as well as the related lateral plane loads, for the particular ship damping characteristics presented in [1]. In addition, computations to determine the sensitivity of computed results to values of roll damping are also presented.

2. Model Test Data

A number of possible effects on the model data have been indicated in [1]. The range of precision of the data presented in [1] is indicated in that report, so that a basis of assessing the extent of agreement between theory and experiment can be related to that information. The particular elements affecting the model test data, that can affect the correlation, are described below.

a) Measurement Precision

As indicated above, and in [1], the estimates of measurement precision can be used to establish a possible "band" of values on both sides of the data presented in [1]. This "spread" of values can be used as a basis of judgment of the degree of correlation between theory and experiment, as an initial step.

In addition consideration of the effects of certain measurement errors, based on the magnitude of the "ideal" measured value of test input condition such as the wave characteristics, is also presented.

b) Rudder Influence

A discussion of the rudder influence on the test data has been given in [1], and procedures for extracting that influence from the overall measured values have been indicated in [1], [2] and also in the discussion of item(1f) in this section of the report. The method of allowing for the rudder effects is directly applied to the data, resulting in a set of results that are used for direct comparison of the "pure ship" responses, as obtained from theory and model test.

c) Effect of Leeway Angle

The influence of this angular difference between desired and attained heading angle relative to the waves (i.e. leeway angle) cannot be directly discussed from the measured data. However, an estimate of the effects of such a difference on the various motion and load responses is obtained via theoretical computations in order to illustrate the possible extent of the leeway angle influence.

d) Effect of Roll Constraint and Model Directional Stability

One of the problems indicated in [1] that affect the behavior of the SL-7 model was the difficulty in maintaining proper control of the ship heading and the resulting heel orientation. Such problems were present throughout the test program reported in [1], and the effects of such control problems on the measured data is examined in order to evaluate the resulting influence on the range of measured data presented there.

3. Data Correlation Analysis

The various possible influences of the elements described above, for both the computer evaluation and the model test method, indicate the extent of variation possible in each procedure due to each of the separate items. It is generally expected that the aim is to find as much consistent agreement between both procedures as possible in order to validate the theory as a

prediction tool. The possible differences between model and full-scale responses are assessed in the light of what possible effect should then be introduced in the computer model and theory in order to achieve prediction of full-scale values by that method. This is evolved in the course of the analysis when determining the effects of the various elements outlined above.

In regard to the correlation of the results themselves, the relative error between values obtained by both procedures must be determined and compared to the possible precision error bands. The important measure of any frequency response data, whether from model test or computer calculations, is the evaluation of response statistics. Thus evaluation of such rms responses are made for a series of known wave spectra, using ship response characteristics obtained from computer results and those from model test data. These results are compared, and also compared to the values obtained from the model test data when considering the extremes of data indicated by the error bands. The relative differences in this case are used as a means of assessing the prediction capabilities of either method for estimation of ship loads. The particular level of deviation that can be tolerated under such conditions will ultimately have to be evaluated from the results of relative levels of deviation indicated by full-scale measurements of ships at sea, including possible full-scale SL-7 data also, for different conditions.

The results obtained from such an analysis will indicate the capabilities of the two methods as possible means of prediction of full-scale ship loads, with some measure of a deviation allowance that can be tolerated in practice for such predictions, with such predictions, with such final conclusions based upon consideration of extensive full-scale data as well. In addition, another result of the present study is an extension of the SCORES computer program that will allow for various phenomena not considered previously in its initial development, and which can overcome the deficiencies of that program in a number of conditions that have been indicated to require such extension in modifications, as illustrated for example in the results of [2]. The utility of such a tool will probably increase as faster and longer ships evolve, which require evaluation of more extensive operating conditions, required load responses important for particular designs, etc.

SHIP CHARACTERISTICS USED IN STUDY

The basic SL-7 ship has certain loading specifications that apply to its operation, which are described as the "heavy" and "light" loading conditions. These basic characteristics are described below in Table 1. Using the data provided in [1] the distribution of loading over the 20 stations representing the ship was established in order to apply the basic computer program of [6]. These values, which are the same as those used in [2], are given for the two load conditions in Tables 2 and 3. They

correspond to the full-scale equivalents of the model tested in [1], in order to reproduce the "achieved characteristics indicated for the model in [1].

TABLE 1

SHIP CHARACTERISTICS

Length:	Overall	946.6 ft. (288.518 m.)
Length:	Between Perpendiculars	880.5 ft. (268.376 m.)
Breadth:	Maximum	105.5 ft. (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.(9.95m.)	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.)

TABLE 2

Weight Properties of the
SL-7 (Heavy) used in the Computer Program

Station	Weight,[1] (long tons)	Vertical center[2] of gravity, ft.	K_{xx}, ft.
0(FP)	435.19	- 2.0116	23.8
1	900.40	9.0734	25.3
2	1110.55	9.0884	24.9
3	1304.96	-15.5416	35.5
4	1625.78	-10.3496	32.9
5	1973.79	- 5.5316	33.7
6	2323.47	- 4.5676	35.0
7	2709.73	3.3524	35.4
8	3024.64	4.2684	39.0
9	3420.21	5.0194	39.9
10	3421.71	7.4784	38.7
11	3206.49	10.8954	39.7
12	3776.005	7.8594	40.7
13	3526.57	- 2.5356	45.6
14	2837.96	- 2.0016	42.5
15	2893.305	- 1.8436	39.3
16	2491.125	- 5.7896	37.2
17	2056.03	- 7.9736	34.3
18	1758.175	- 8.8426	33.5
19	1888.51	- 7.6116	32.5
20(AP)	1075.395	- 6.8986	23.61

[1] The ship is divided into 20 segments of 44.025 ft. lengths. The weight at each station is assumed to be uniformly distributed over the segment and centered at the station.

[2] The vertical center of gravity of each element is measured, positive downward, with respect to the ship's overall VCG.

TABLE 3

Weight Properties of the
SL-7 (Light) used in the Computer Program

Station	Weight,[1] (long tons)	Vertical Center of gravity,[2] ft.	K_{xx}, ft.
0	358.465	- 3.2944	24.90
1	866.42	6.3056	25.26
2	1072.305	7.2256	25.30
3	1229.20	- 9.8944	35.40
4	1273.11	-10.5944	33.50
5	1561.22	- 8.2844	33.20
6	1931.51	- 6.5944	33.60
7	2298.655	5.3056	32.92
8	2613.37	4.5056	35.09
9	2827.715	5.9056	36.33
10	2804.37	7.1056	36.84
11	2671.77	8.6056	37.00
12	3479.65	5.3056	38.65
13	3462.25	- 4.5944	45.50
14	2830.20	- 2.9944	42.57
15	2811.80	- 1.7944	37.90
16	2117.15	- 4.5944	36.98
17	1467.80	- 6.7944	35.64
18	1158.815	- 2.1544	34.10
19	1514.62	- .7944	32.00
20	1072.505	- 9.2944	23.00

[1] The ship is divided into 20 segments of 44.025 ft. lengths. The weight at each station is assumed to be uniformly distributed over the segment and centered at the station.

[2] The vertical center of gravity of each element is measured, positive downward, with respect to the ship's overall VCG.

RESULTS OF COMPUTATIONS WITH SCORES PROGRAM

A number of computations were carried out using the original SCORES program of [6] in order to determine the effects of various phenomena, computation techniques, etc., that were listed and discussed previously. The results of these computations are described in the following sections.

1. Effect of Weight Distribution

The particular weight distributions established for the present study are listed in Tables 2 and 3, and a number of small variations and their effects were evaluated as well, with the general conclusions presented here. It was found that the effect of the weight distribution used, as long as it was fairly close to the achieved conditions in the model test, produced negligible differences in the computed magnitudes of ship loads and motions. The only significant difference found was that very small changes in the final distribution given in Tables 2 and 3, primarily for the vertical center of gravity of each element, resulted in a more satisfactory "closure condition" check for the torsional bending moment, i.e. the requirement of a zero (or very close to zero) value of torsion at the ship ends. Otherwise the values for all of the loads, including torsions, were negligibly affected.

2. Effect of Sectional Force Representation

As mentioned previously, the method of representing the hydrodynamic forces, i.e. sectional added mass and damping, used in [6] was based upon the Lewis form method. Computations were then carried out with the basic program, but utilizing the hydrodynamic coefficients obtained from the Frank Close-Fit technique of [9], which evaluates the added mass and damping of two-dimensional ship sections due to heave, sway, and roll motions of the section. These expressions were used in determining the resultant coefficients of the equations of motion as well as in the wave excitation terms, as required by the method of [5] and [6], leading to the resulting values of ship motions and loads. Comparison of these results with the results obtained in [2], which made use of the Lewis form sectional forces, showed differences of the order of 1-2% at most for all cases. Thus, there does not appear to be any significant difference in the results, for this particular ship, when using the alternative method of representing sectional hydrodynamic forces in conjunction with the basic program of [6].

3. Effect of Surge Motion

The effect of surge motion has been neglected in the analysis of [5], and is also not treated in the work of [7]. However, the model tests in [1] were carried out with the model free to surge, so it is necessary to evaluate the possible influence of this additional degree of freedom on the ship motions and the resulting wave loads.

Surge motion is coupled to the vertical plane equations of heave and pitch, following closely the approach taken in [13], by the equations

$$a_{11}\ddot{x} + a_{12}\dot{x} + a_{17}\ddot{\theta} + a_{18}\dot{\theta} = X_w \tag{1}$$

$$a'\ddot{z} + b\dot{z} + c'z - d\ddot{\theta} - e\dot{\theta} - g'\theta = Z_w \tag{2}$$

$$a_{31}\ddot{x} + z_{32}\dot{x} + (A + a_{31}\overline{GB})\ddot{\theta} + (B + a_{32}\overline{GB})\dot{\theta} + C\theta - D\ddot{z} - E\dot{z} - G'z = M_w + \int_{x_s}^{x_b} \left(\frac{dX_w}{dx}\right)(z + \overline{OG})\,dx \tag{3}$$

where x is surge, positive forward, and a_{11}, a_{12}, a_{17}, a_{18}, a_{31}, a_{32}, X_w, etc. are new terms (defined below) as compared to the original SCORES theory derived in [5]. The surge motion does not couple into the heave equation and, by symmetry, does not couple into the lateral motions. There is only coupling between roll and sway in the lateral plane. The new coefficients in Equations (1) and (3) are as follows:

$$\begin{aligned} a_{11} &= m\,(1+k_1) \\ a_{12} &= \left(\frac{dR_T}{dV}\right)_{V=V_o} + \int_{x_s}^{x_b} N'_x\,dx \\ a_{17} &= k_1 m\,\overline{GB} \\ a_{18} &= a_{12}\,\overline{GB} \\ a_{31} &= a_{17} \\ a_{32} &= a_{18} \end{aligned} \tag{4}$$

where k_1 = longitudinal added mass coefficient

N'_x = local sectional longitudinal damping coefficient

$\overline{GB} = \overline{KG} - \overline{KB}$

$\left(\frac{dR_T}{dV}\right)_{V=V_o}$ = total resistance variation at speed V_o (mean ship speed)

The longitudinal wave excitation is defined as follows:

$$X_w = \int_{x_s}^{x_b} \frac{dX_w}{dx}\, dx \qquad (5)$$

where

$$\frac{dX_w}{dx} = -\rho\, S(x)\, \frac{D}{Dt}\left(\frac{\partial \phi_w}{\partial x}\right)$$

$$\frac{D}{Dt} = \left(\frac{\partial}{\partial t} - V\frac{\partial}{\partial x}\right)$$

S = local sectional area

$$\phi_w = -\,ace^{-k\bar{h}}\cos[k(-x\cos\beta + y\sin\beta) + \omega_e t]$$

which leads to

$$\frac{dX_w}{dx} = -\,\rho akge^{-k\bar{h}}\cos\beta\; S(x)\cos(-kx\cos\beta + \omega_e t) \qquad (6)$$

The longitudinal added inertia coefficient is estimated from hydrodynamic potential flow theory (e.g. [14] in terms of the ship dimensions (length and beam). The term $\left(\frac{dR_T}{dV}\right)_{V=V_o}$ represents the total resistance variation evaluated at the ship speed V_o, which is the derivative with respect to speed of the total ship resistance curve and thus contributes to surge damping.

The surge damping term a_{12} includes the small axial wave damping contribution in addition to the total resistance variation. It is derived on the basis of an "expanding" two-dimensional section, where the expansion is proportional to dB*/dx, the longitudinal rate of change of the ship local beam. The two-dimensional section damping form used is that derived in [15], which is based on thin-ship theory. The local damping term is

$$N'_x = \rho\omega_e\left(\frac{dB^*}{dx}\right)^2\int_0^H F(\xi)\, e^{-\omega_e^2\xi/g}\, d\xi \qquad (7)$$

where H = local sectional draft

$F(\xi)$ = equivalent Haskind form = $1 - \frac{\xi}{H}^{n}$

and n is determined so that the Haskind form has the same area coefficient as the local section.

The terms in the heave and pitch equations of motion, which are derived in [5], are given below as:

$$a' = m + \int A'_{33}dx, \quad b = \int N'_z dx - V \int d(A'_{33})$$

$$c' = \rho g \int B^* dx, \quad d = D = \int A'_{33} x dx$$

$$e = \int N'_z x dx - 2V \int A'_{33}dx - V \int x d(A'_{33})$$

$$g' = \rho g \int B^* x dx - Vb, \quad A = I_y + \int A'_{33} x^2 dx$$

$$B = \int N'_z x^2 dx - 2V \int A'_{33} x dx - V \int x^2 d(A'_{33})$$

$$C = \rho g \int B^* x dx - VE, \quad E = \int N'_z x dx - V \int x d(A'_{33})$$

$$G' = \rho g \int B^* x dx$$

where all the indicated integrations are over the length of the ship. The wave-excitation terms, the right hand sides of Eq. (2) and (3), are given by:

$$Z_w = \int_{x_s}^{x_b} \frac{dZ_w}{dx} dx \tag{8}$$

$$M_w = \int_{x_s}^{x_b} \frac{dZ_w}{dx} x dx \tag{9}$$

where the local sectional vertical wave force acting on the ship section is represented by

$$\frac{dZ_w}{dx} = -\left[\rho g B^* \eta + \left(N' - V \frac{dA'_{33}}{dx} \right) \dot{\eta} + A'_{33} \ddot{\eta} \right] e^{-k\bar{h}} \tag{10}$$

where $\bar{h}$ = mean section draft and $\eta(x,t)$ is the wave surface elevations at the CG reference location.

The various hydrodynamic and related terms entering these equations are defined by

ρ = density of water

A'_{33} = local sectional vertical added mass

N'_z = local sectional vertical damping force coefficient

B^* = local waterline beam

The wave-induced vertical bending moment at the position x_o along the ship, including the effects of surge, is given by

$$BM_z(x_o) = \left[\int_{x_s}^{x_o} \text{ or } \int_{x_o}^{x_b}\right]\left\{(x-x_o)\frac{df_z}{dx} - (\bar{z} + \overline{OG})\right.$$
$$\left. - \delta m \cdot \ddot{x} + \left[\frac{dX_h}{dx} + \frac{dX_w}{dx}\right]\right\} dx \qquad (11)$$

in terms of the local vertical loading $\frac{df_z}{dx}$ defined in [5]. The quantity $\frac{dX_h}{dx}$ is the differential hydrodynamic surge force determined from the terms defined in Eq. (1) and (4).

Computations were carried out to determine the motions and loads of the SL-7 with the linear surge equation (and its contribution to loads) included in the mathematical model. The results obtained from these calculations, over a range of different operating conditions, showed negligible differences from the results obtained with surge neglected (at most only about 1-2% difference). Thus the influence of surge is not a significant factor on the magnitude of the resulting ship loads, reinforcing the method of [5] which does not include that degree of freedom while still exhibiting good agreement with model test data.

4. Effect of Rudder Deflection

Since there is presently no representation of rudder forces (and their effect) per se in the SCORES program, no direct evaluation of the effect of rudder deflection can be provided from computer calculations. It would also be necessary to know the actual rudder deflections (which are provided in the model test results of [1]) for any full-scale estimation by computational means, as well as a method of representing the actual model forces properly. However the model test data indicated in [1], as well as the analysis of the special tests conducted in [1] for evaluating rudder influence, indicated an influence of the order of 20% of the peak lateral and torsional moment and lateral shears that may be attributed to rudder action. The significance of this level of influence, which is also associated with the rolling motion of the ship, will be considered in a later section of the report.

5. Investigation of Wave-Excitation Forces

While it has been shown previously that there is no influence on the SL-7 motions and loads due to the different representations of the sectional hydrodynamic forces, which represent the dynamical coefficients of the different state variables (i.e. motion displacements, velocities, etc.) in the motion equations, the question of the adequate representation of the wave-excitation forces by the theoretical methods in [5] and [6] was also considered. For the case of head seas the basic method used for determining the vertical force and pitch moment due to waves for a restrained model of a Series 60 form had been previously compared with model test data in [16]. In that case good agreement was shown, lending validity to the basic approach used in the SCORES program. However a number of other operating conditions corresponding to different headings relative to the waves, and also considering other wave-excitation forces besides the vertical force and pitching moment, were investigated in the present study in order to determine the utility of the methods used in the SCORES program [6].

Computations were carried out for a Series 60, C_B = 0.60 model at various headings with respect to the waves, which considered the wave-excitation forces in all modes of motion, and comparison was made with model test data. For the case of zero speed the results of the comparison with the data of [17] were quite good, with close agreement for all cases analyzed over the range of headings. However, there were some differences that occurred when the models had forward speed (when comparing with the data of [18]), even for the case of vertical force and pitch moment which were analyzed exactly in the same way as the head-sea case but using the appropriate wave properties corresponding to the particular ship heading. The extent of the lack of agreement was not significant, and was primarily for short wavelengths, considering the difficulties inherent in making such measurements for restrained models when running at forward speed and covering larger frequencies of encounter. Nevertheless this comparison indicated a sufficiently consistent method of calculating the various wave-excitation forces required for conventional hydrodynamic ship motion analysis. The successful correlation for a Series 60 model, in regard to loads (and motions) in [5], covering a range of headings and modes of response, also tends to support that conclusion.

EXTENDED SCORES THEORY AND RESULTS OF COMPARISON WITH MODEL DATA

As indicated in [2], and also known in various articles concerned with ship motion theories, the equations in [7] differ somewhat from those used in [5] by virtue of certain speed-dependent coefficient terms that reflect aspects of symmetry between coefficients which are dictated by the theoretical results of [19]. In a number of cases considered in the past, primarily for ships of Series 60 form, the results of the theories of [5]

and [7] showed good agreement with model experimental data. However, due to the high speed for the present SL-7 ship, the effects of forward speed in modifying the coefficients may be significant and could possibly account for some of the differences between theory and experiment. In addition the form of the wave-excitation forces expressed in [7] is also somewhat different from that used in [5], reflecting the influence of forward speed primarily, so that an extended theoretical model that could include some of these effects was considered necessary for purposes of computation and comparison with the SL-7 data. A description of this extended theory, as well as the results of computations and comparison with the SL-7 model data of [1], are given in the following sections.

1. Theoretical Model

Some consideration of an extended theoretical ship motion model has been given in the work of [20], with specific application to a large high-speed container ship, as well as the case of a general representation of hydrodynamic forces (in the vertical plane) in [21] for purposes of comparison with coefficients in the equations of motion obtained from forced oscillation tests.

The basic form of the equations in [5] was based upon an application of slender body theory which was given in [22], where major consideration was given to the inertial hydrodynamic force on a ship section. To this result was added the representation of a damping force, accounting for free surface wave dissipation, in terms of the relative velocity. For the case of vertical plane motion (heave and pitch), the basic equation for the sectional vertical force which includes the hydrodynamic inertial and damping effects, was given in [5] by

$$\frac{dZ_h}{dx} = -\frac{D}{Dt}\left[A'_{33}(\dot{z} - x\dot{\theta} + V\theta)\right] - N'_z(\dot{z} - x\dot{\theta} + V\theta) \quad (12)$$

where A'_{33} = local sectional vertical added mass

N'_z = local sectional vertical damping force coefficient

and the hydrostatic force representation is deleted.

The extended theory accounts for the fluid momentum effects of both inertial and damping nature by the expression

$$\frac{dZ_h}{dx} = -\frac{D}{Dt}\left[\left(A'_{33} + \frac{N'_z}{i\omega_e}\right)(\dot{z} - x\dot{\theta} + V\theta)\right] \quad (13)$$

where it is assumed that all motions are of the form $e^{i\omega_e t}$, with ω_e the frequency of encounter. This expression yields the same results as the original SCORES theory development in [5], together with additional terms (for dZ/dx) which are

$$V\frac{dN'_z}{dx}\left(z - x\theta - \frac{V}{\omega_e{}^2}\dot{\theta}\right) - N'_z V\theta \tag{14}$$

These terms can also be expressed in a different manner, e.g.

$$V\frac{dN'_x}{dx}\,z \;=\; -\frac{V}{\omega_e{}^2}\frac{dN'_x}{dx}\ddot{z} \tag{15}$$

so that the equivalence between the resulting expressions in this extended theory and those in [7] can be seen.

In a similar manner the vertical wave-excitation force on a section is obtained, by use of the relative motion concept relating wave motion and ship-motion characteristics, in the form

$$\frac{dZ_w}{dx} \;=\; -\frac{D}{Dt}\left[\left(A'_{33} + \frac{N'_z}{i\omega_e}\right)\dot{\eta}\right]e^{-k\bar{h}} - \rho g B^* \eta e^{-k\bar{h}} \tag{16}$$

This expression for wave-excitation force then becomes

$$\frac{dZ_w}{dx} \;=\; -\left[\left(\rho g B^* - \frac{\omega}{\omega_e}V\frac{dN'_z}{dx}\right)\eta + \left(N'_z\frac{\omega}{\omega_e} - V\frac{dA'_{33}}{dx}\right)\dot{\eta} + A'_{33}\ddot{\eta}\right]e^{-k\bar{h}} \tag{17}$$

where ω is the wave frequency (rad./sec.). Thus it can be seen that there are some modifications to the wave-excitation forces also in the extended theory representation, with all results (for both wave-excitation and hydrodynamic coefficients) being the same for zero forward speed (V=0). The major differences in approach in the various theories are due to forward speed, with greater effects anticipated for larger speed conditions, which are present for the SL-7 ship.

For the case of lateral plane motions, there are similar type additional terms, and further simplifications have been found due to the equivalence of certain two-dimensional hydrodynamic coefficients. The coefficient relations, in terms of the notation of [5], are

$$F_{rs} = M_{s\phi} \ , \quad N_{rs} = N_{s\phi} \tag{18}$$

which relate roll and sway added mass and damping coupling coefficients. The additional terms in the lateral sectional hydrodynamic force are given by

$$\Delta \frac{dY}{dx} = N_s V\psi - V \frac{dN_{rs}}{dx} \phi + V \frac{dN_s}{dx} (y + x\psi + \frac{V}{\omega_e^2} \dot{\psi}) \tag{19}$$

For the sectional roll moment, the additional terms are

$$\Delta \frac{dK}{dx} = V \frac{dN_r}{dx} \phi - N_{rs} V\psi - V \frac{dN_{rs}}{dx} (y + x\psi + \frac{V}{\omega_e^2} \dot{\psi}) - \overline{OG} \, (\Delta \frac{dY}{dx}) \tag{20}$$

By the same procedures there are also changes in the local sectional wave-excitation forces, which are given by

$$\frac{dY_w}{dx} = \left[(\rho S + M_s) \frac{Dv_w}{Dt} - V v_w \frac{dM_s}{dx} + k - F_{rs} \frac{Dv_w}{Dt} + V \frac{dF_{rs}}{dx} v_w \right.$$

$$\left. + \frac{\omega}{\omega_e} N_s v_w + \frac{V}{\omega \omega_e} \frac{dN_s}{dx} \frac{Dv_w}{Dt} \right] \frac{\sin(\frac{\pi B^*}{\lambda} \sin\beta)}{\frac{\pi B^*}{\lambda} \sin\beta} \tag{21}$$

for the lateral sectional wave force, and by

$$\frac{dK_w}{dx} = \left[- \frac{D}{Dt} (F_{rs} v_w) + \rho (\frac{B^{*3}}{12} - S\bar{z}) \frac{Dv_w}{Dt} - \frac{\omega}{\omega_e} N_{rs} v_w \right.$$

$$\left. - \frac{V}{\omega \omega_e} \frac{dN_{rs}}{dx} \frac{Dv_w}{Dt} \right] \frac{\sin(\frac{\pi B^*}{\lambda} \sin\beta)}{\frac{\pi B^*}{\lambda} \sin\beta} - \overline{OG} \frac{dY_w}{dx} \tag{22}$$

for the sectional wave roll moment, where v_w is the lateral wave orbital velocity.

All of the above expressions are combined with the previous expressions in [5], for the hydrodynamic forces due to motions, in order to establish the new coefficients in the equations of motion by integration, with sectional pitch and yaw moments given by

$$\frac{dM}{dx} = -x\frac{dZ}{dx} \quad , \quad \frac{dN}{dx} = x\frac{dY}{dx} \qquad (23)$$

The new expressions for sectional wave-excitation forces, and the pitch and yaw wave moments obtained by similar expressions as in Eq. (23), are integrated to obtain the total wave-excitation forces and moments for the equations of motion. The new sectional forces are used in determining the loads (shears and bending moments) in the same manner as in [5].

2. Results of Computations and Comparisons for SL-7

The comparisons between the model test data of [1] and the calculated results, using the extended SCORES theory described above, are made on the basis of the sign conventions used in [1]. In that case the transfer functions, in the form of amplitude and phase, are given with the amplitude of a particular response referred to the tested wave amplitude (i.e. response per unit wave amplitude) and the phases are all referred to that of the midship vertical bending moment. The midship vertical bending moment per se has its phase referred to the wave elevation at the ship CG location, so that all relations between phases were reconciled in this manner.

The computations were initially carried out with estimated values of the critical damping ratio ζ_ϕ, where $\zeta_\phi = 0.10$ for the light displacement configuration and $\zeta_\phi = 0.09$ for the heavy displacement configuration. These values were assumed to be applicable over the entire speed range of the SL-7, and are the same as those used in the original theoretical study of [2]. Further consideration of the influence of roll damping on various responses is discussed in later sections of this report.

The particular variables that are compared and considered separately for the vertical plane responses and lateral plane responses are listed below. The vertical plane responses are the pitch motion; the vertical shear and vertical bending moment at midship; and the vertical shear and vertical bending moment at Frame 258. For the lateral plane the variables responses compared are the roll angle; lateral shear and lateral bending moment at midship; lateral shear and lateral bending moment at Frame 258; the torsional moment at midship; and the torsional moment at Frame 258. The comparisons are given for all of these responses (if model test data are available) for the entire range of headings tested in [1], extending from head through following seas. Separate presentation and discussions are given for the vertical and lateral plane responses in the following, in accordance with the procedures described here.

2.1 Vertical Plane Responses

The comparison between theory and experiment is presented for each heading, with the responses arranged in the form of pitch motion, vertical bending moment and vertical shear for each heading. Data and computational results for both the heavy and light displacement conditions are shown together on the same

graph for the same operating speed and heading conditions. The heading angles are 180° (head seas); 210° and 240° (bow seas); 60° and 30° (quartering seas); and 0° (following seas). No model test data were obtained for beam seas (90° heading) because the wave heights to be generated were considered too small for reliability of data, so no comparison is presented for that heading. The comparison for the vertical plane responses, as given in Figures 1-30, shows a significant improvement relative to those given in [2]. The pitch motion comparison is quite good, which is similar to the case in [2], while the agreement between theory and experiment for the vertical bending moment and shears shows a decided improvement relative to the results of [2].

The midship vertical bending moment for the head-sea case shows differences of the order of 10-15% in the region of the largest magnitudes, while the most significant improvement between theory and experiment for the vertical bending moment (relative to that shown in [2]) is shown by the results for following seas (0° heading). Any significant deviation for vertical bending moment, for the case of head and bow seas, seems to occur for shorter wavelengths, and in general the degree of agreement between theory and experiment for this range of headings may be considered to be almost as good as that exhibited in [5], which was the basis for demonstration of the utility of the original SCORES program.

The loads comparison in following seas is still not as good as what may be desired for verification of a theory, although the results for the quartering-sea cases are fairly acceptable. As mentioned previously in this report, and also in [2], the effects of low frequency of encounter, which represent the conditions for following seas and also some of the quartering-sea cases, may possibly influence the degree of comparison due to the limits of applicability of the basic strip theory used in the present computations. Some further discussion of these effects, and possible ways of overcoming them, are given in a later section of this report.

2.2 Lateral Plane Responses

For the lateral plane responses, the comparison between theory and experiment is also presented for each heading, with the responses arranged in the form of roll angle, lateral bending moment, lateral shear, and torsional moment. Since the theory indicates zero response for pure-head and following seas and the model data are invalid because of heel and roll restraint, no consideration is given to those headings, and similarily for the beam-sea case since no model data were obtained for that condition.

For the case of bow seas (headings of 210° and 240°) the agreement between theory and experiment for the various loads (since no roll response data were presented) shown in Figures 31-42 is generally good for lateral bending moment and shear. The

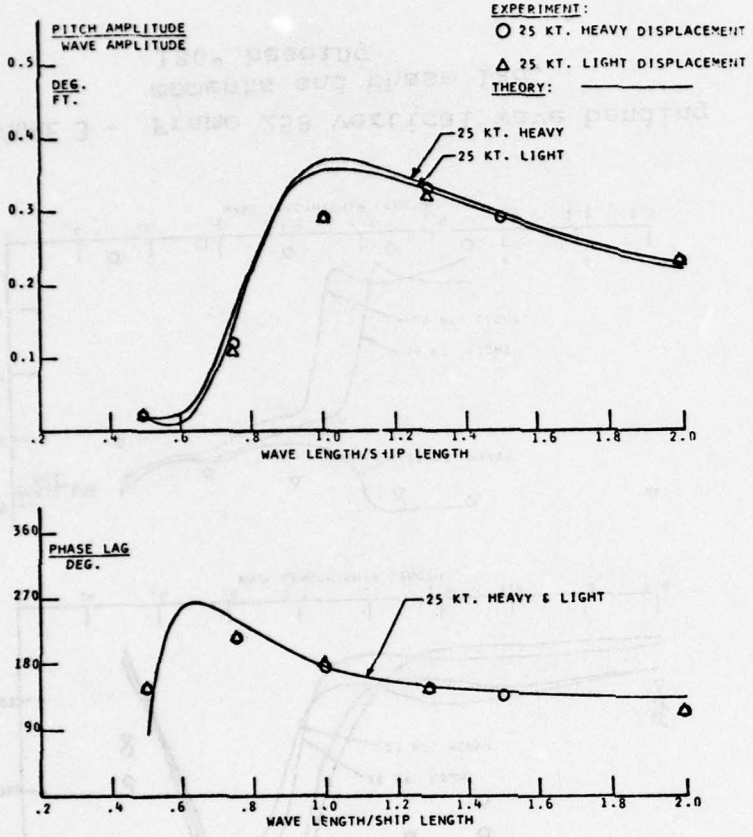


FIGURE 1 - Pitch and phase lag, 180° heading

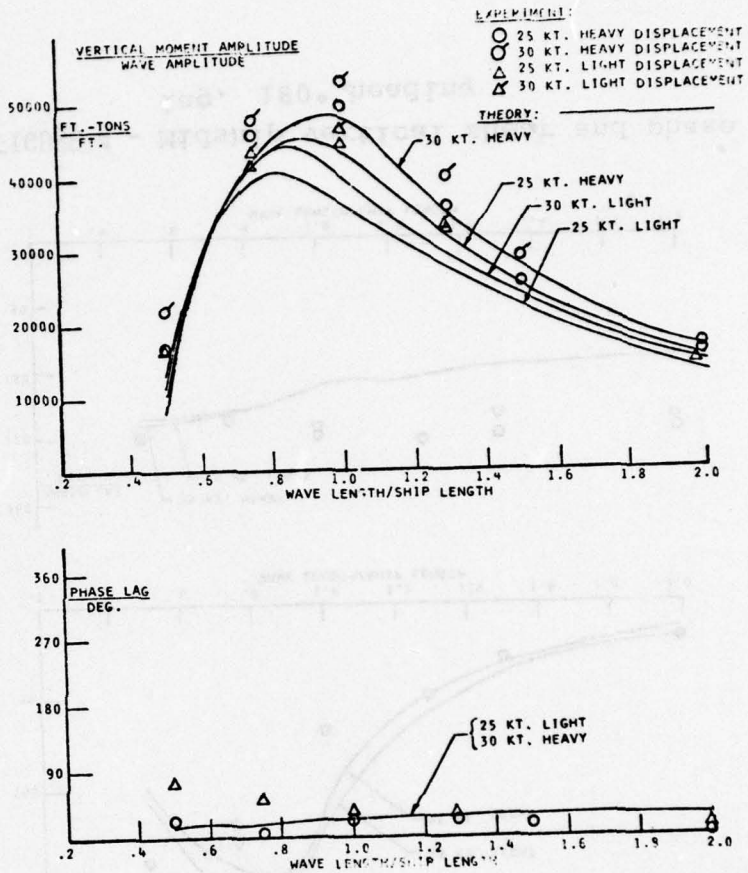


FIGURE 2 - Midship vertical wave bending moments and phase lag, 180° heading

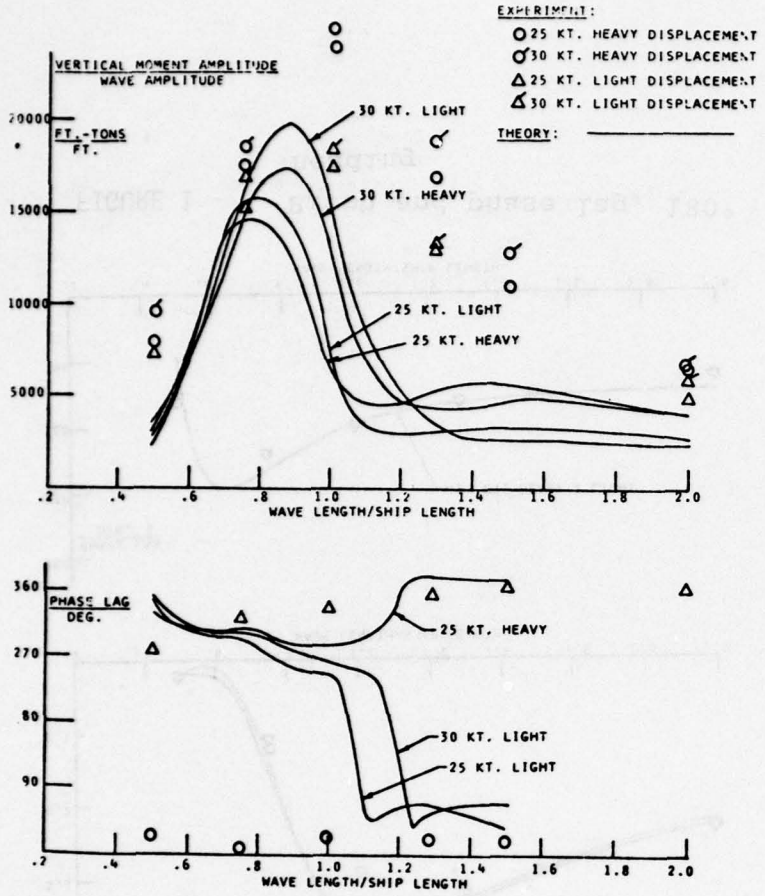


FIGURE 3 - Frame 258 vertical wave bending moments and phase lag, 180° heading

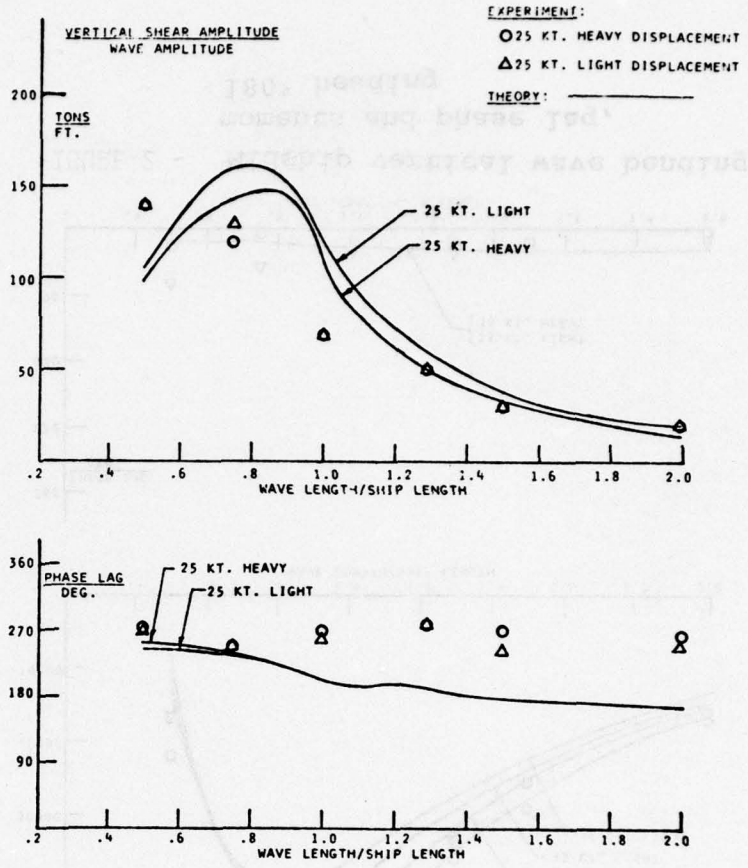


FIGURE 4 - Midship vertical shear and phase lag, 180° heading

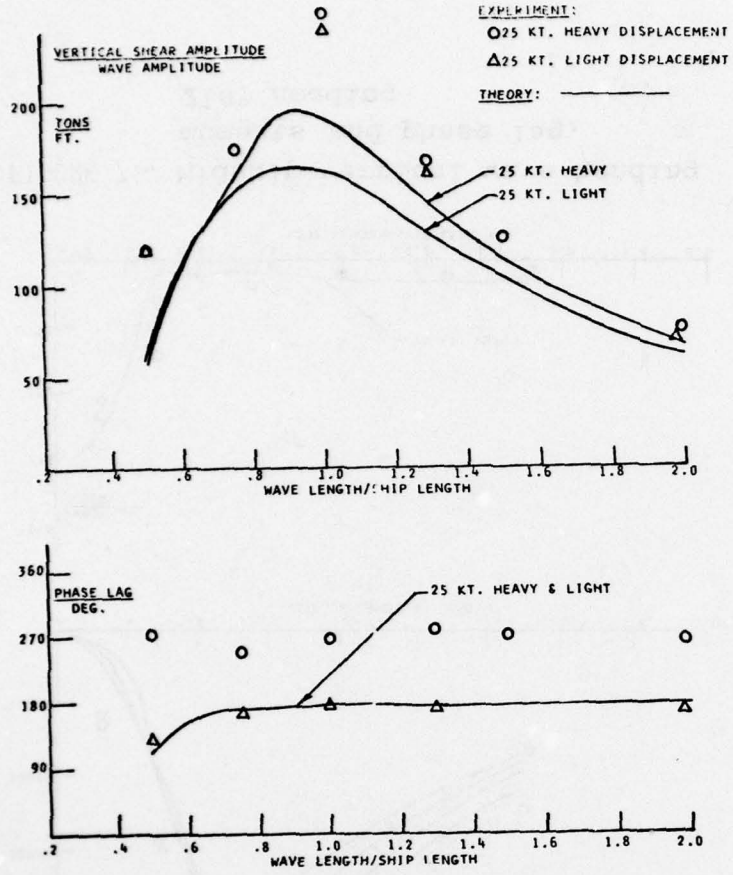


FIGURE 5 - Frame 258 vertical shear and lag, 180° heading

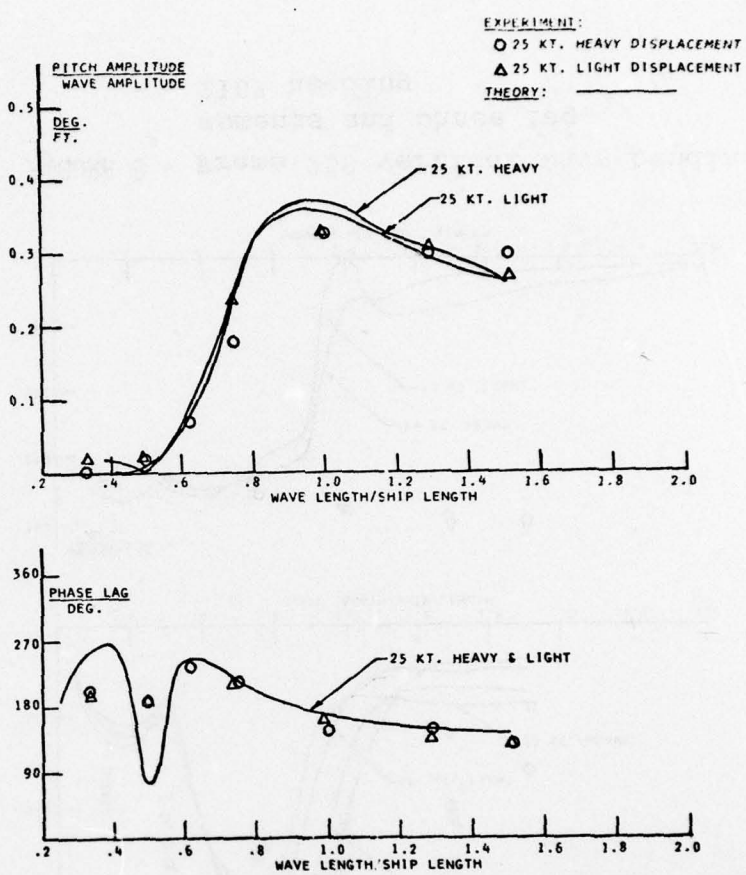


FIGURE 6 - Pitch and phase lag, 210° heading

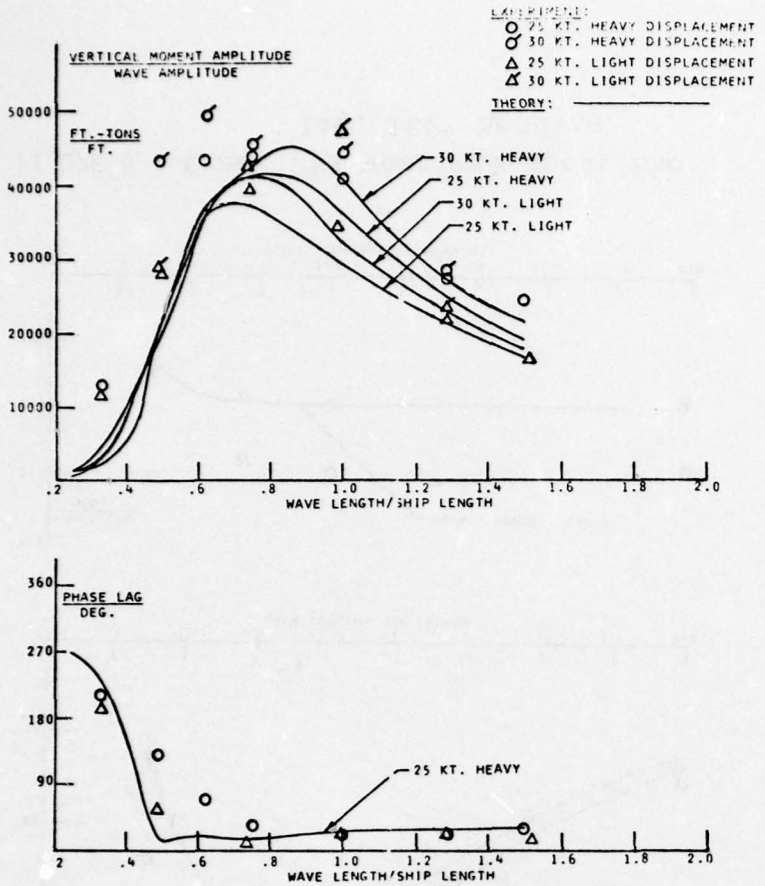


FIGURE 7 - Midship vertical wave bending moments and phase lag, 210° heading

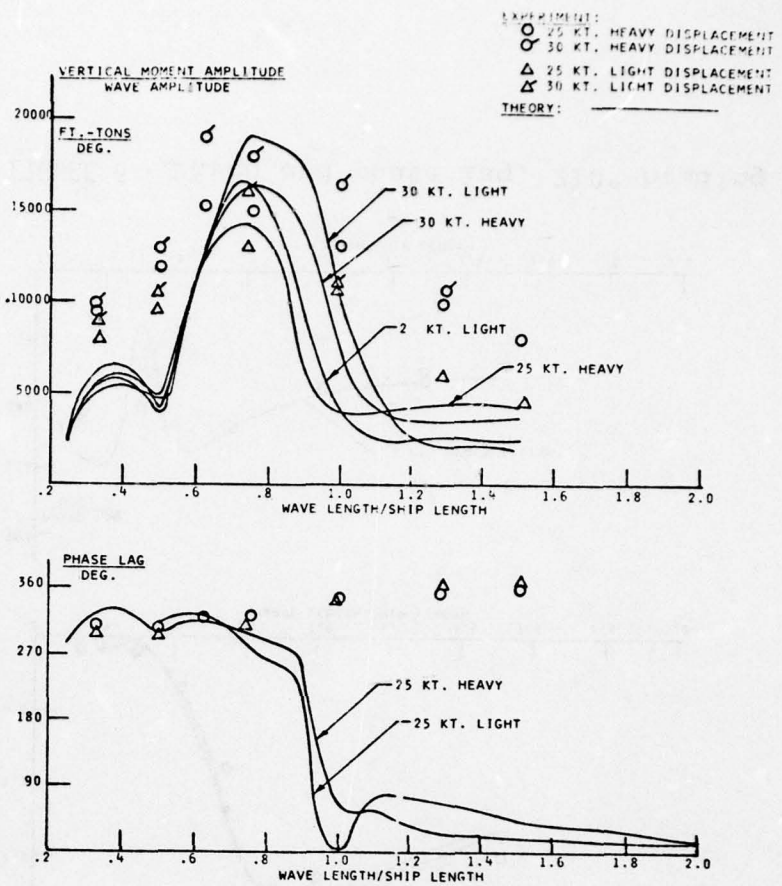


FIGURE 8 - Frame 258 vertical wave bending moments and phase lag, 210° heading

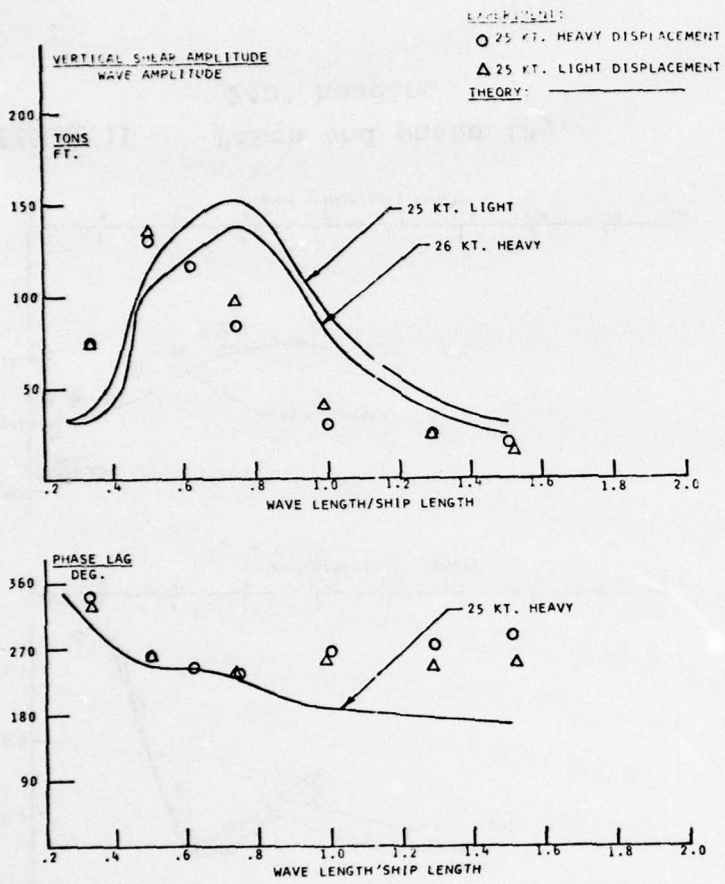


FIGURE 9 - Midship vertical shear and phase lag, 210° heading

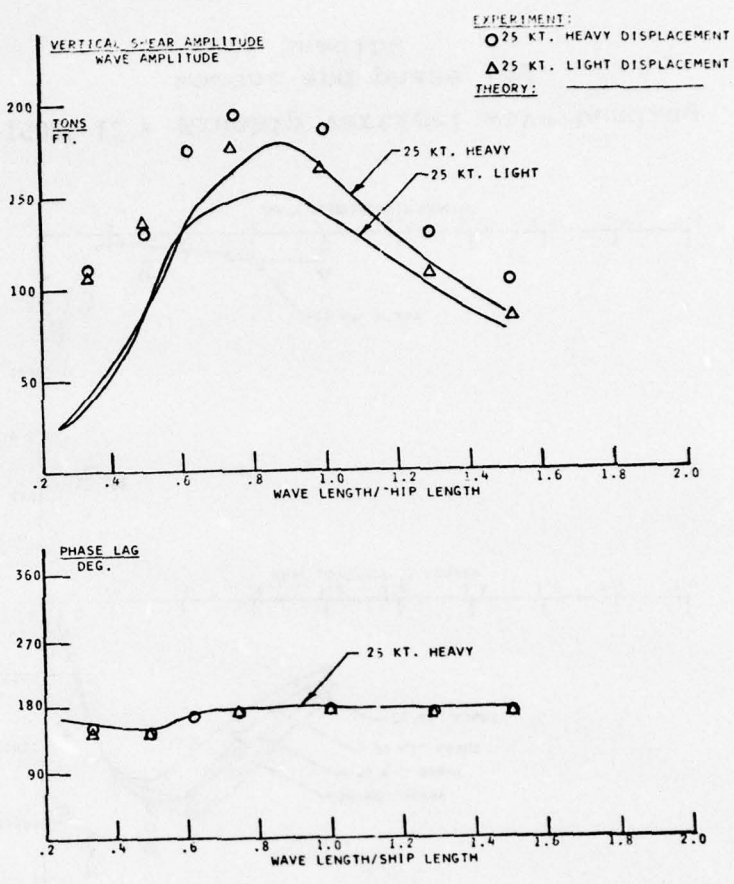


FIGURE 10 Frame 258 vertical shear and phase lag, 210° heading

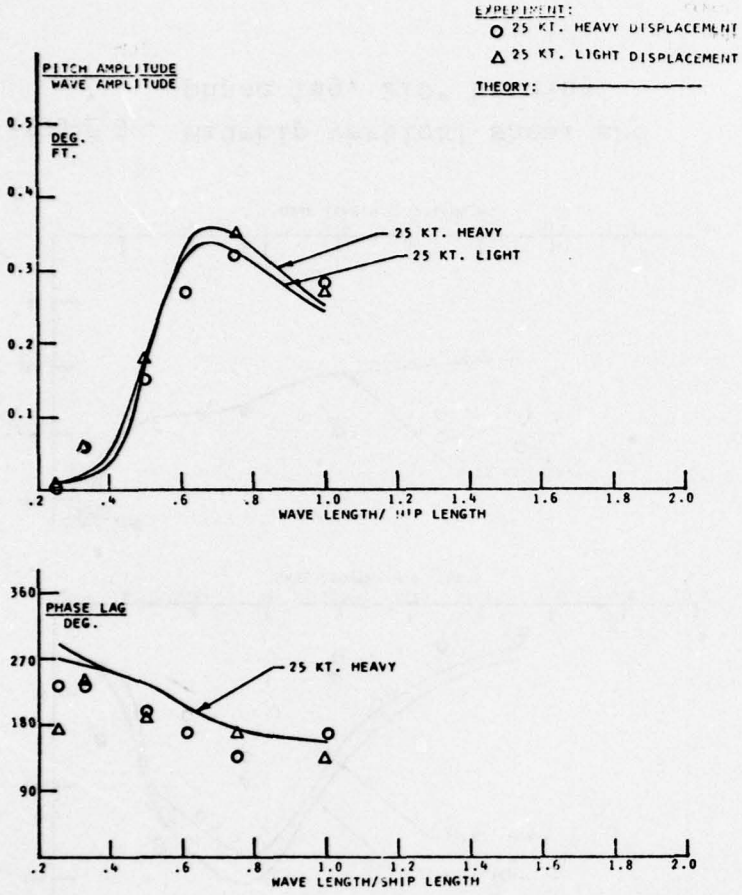


FIGURE 11 - Pitch and phase lag, 240° heading

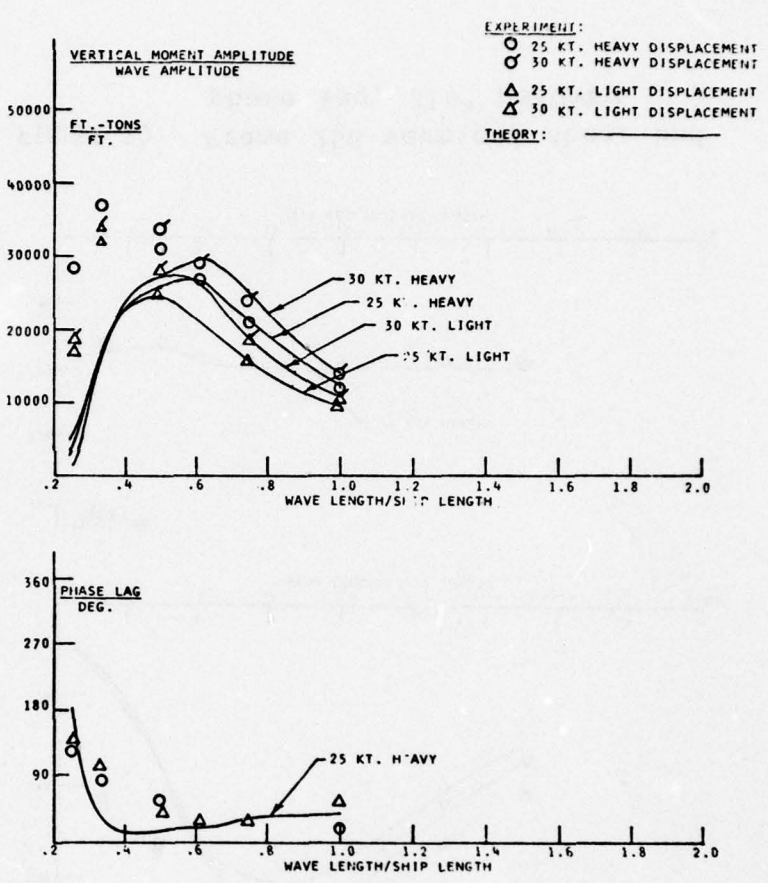


FIGURE 12 - Midship vertical wave bending moment and phase lag, 240° heading

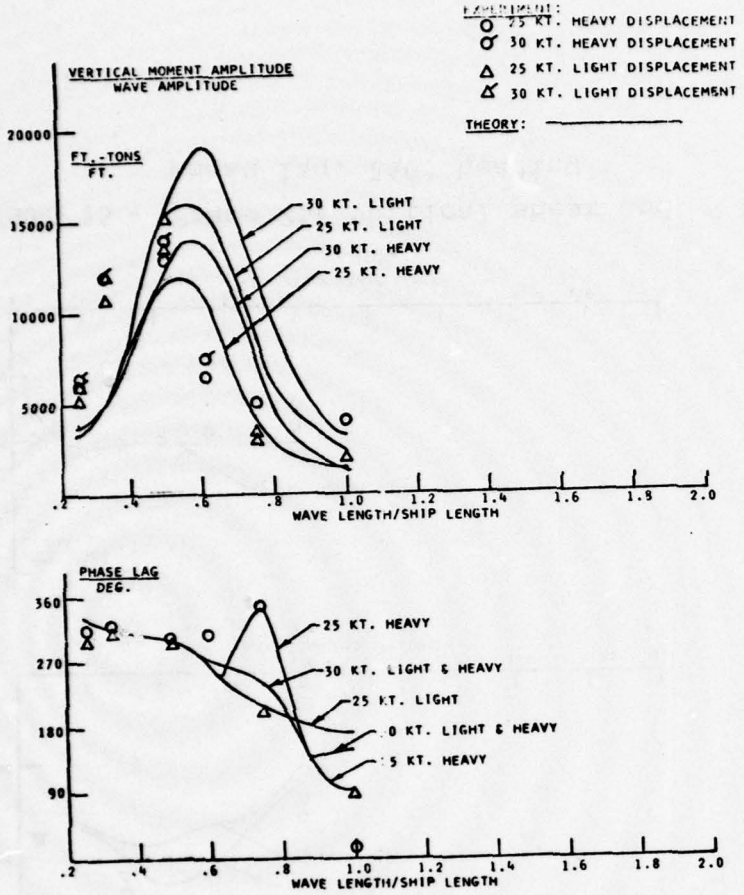


FIGURE 13 - Frame 258 vertical wave bending moment and phase lag, 240° heading

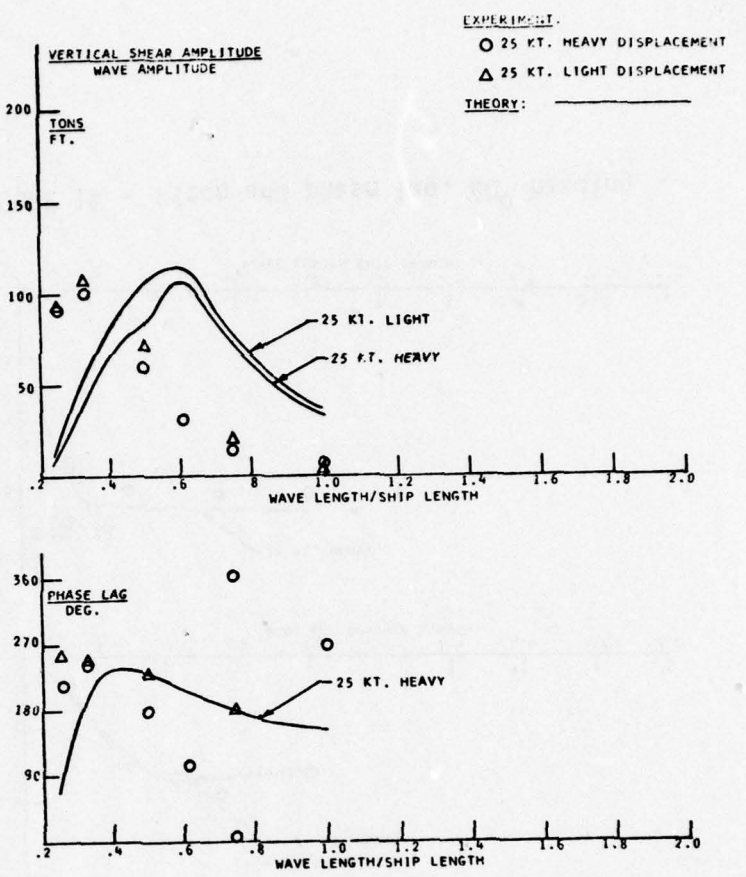


FIGURE 14 - Midship vertical shear and phase lag, 240° heading

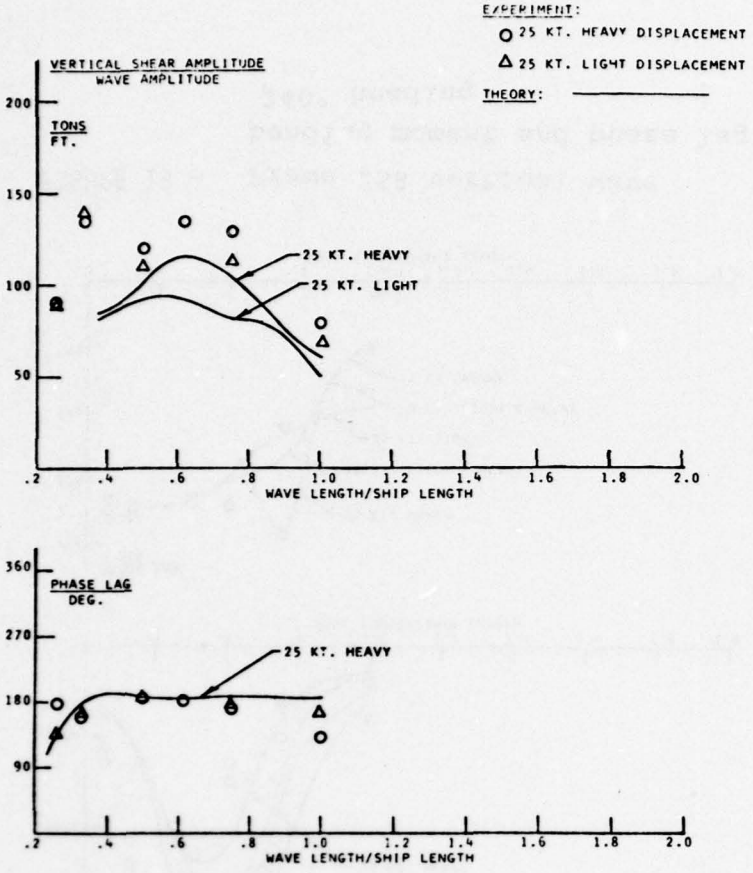


FIGURE 15 - Frame 258 vertical shear and phase lag, 240° heading

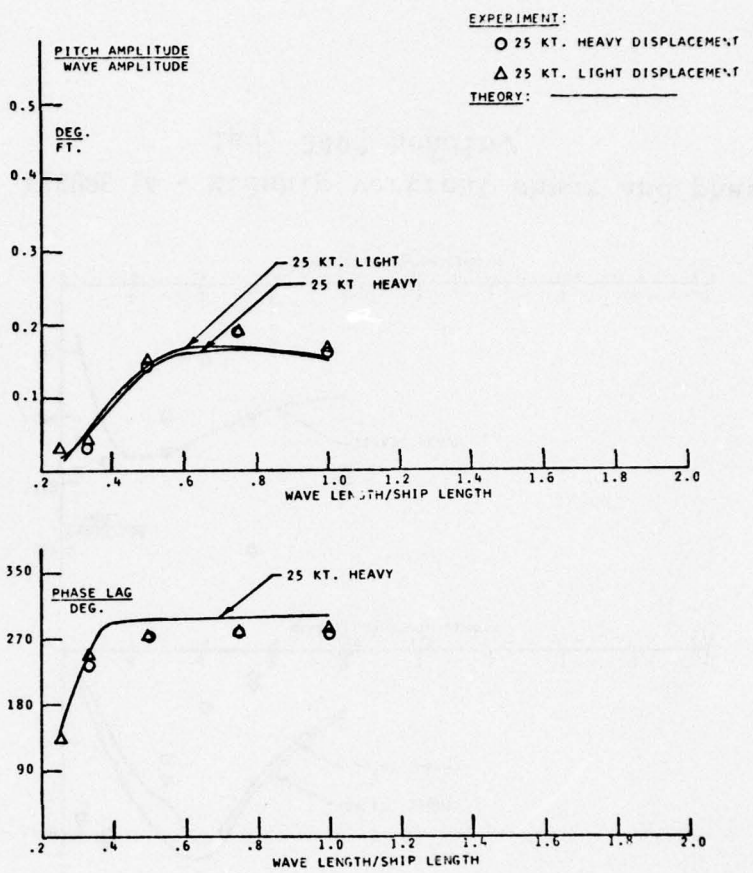


FIGURE 16 - Pitch and phase lag, 60° heading

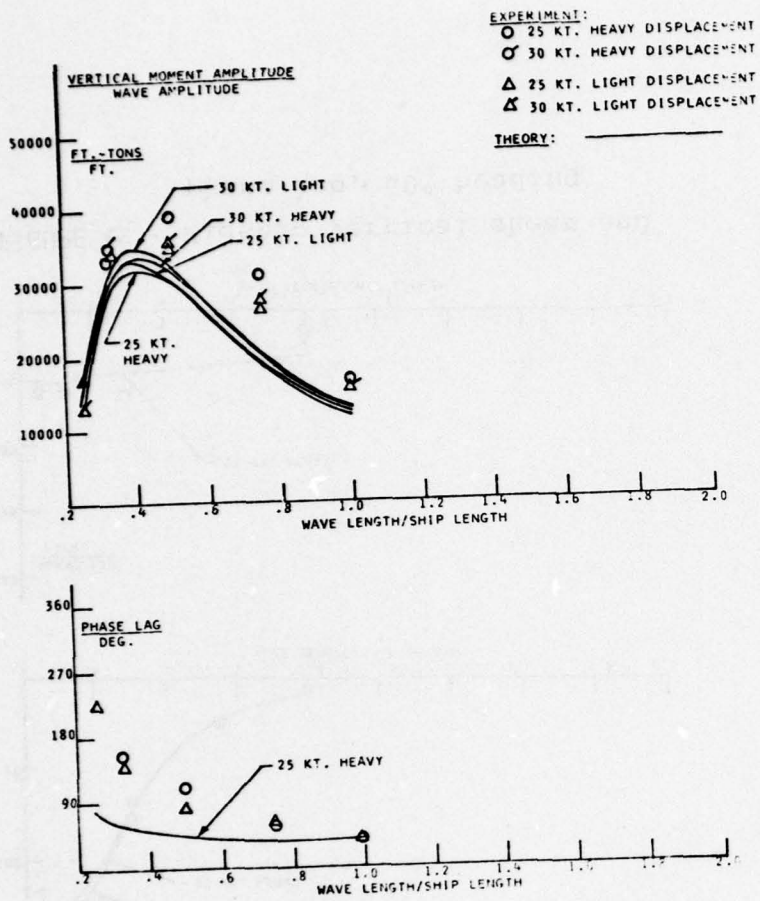


FIGURE 17 - Midship vertical wave bending moments and phase lag, 60° heading

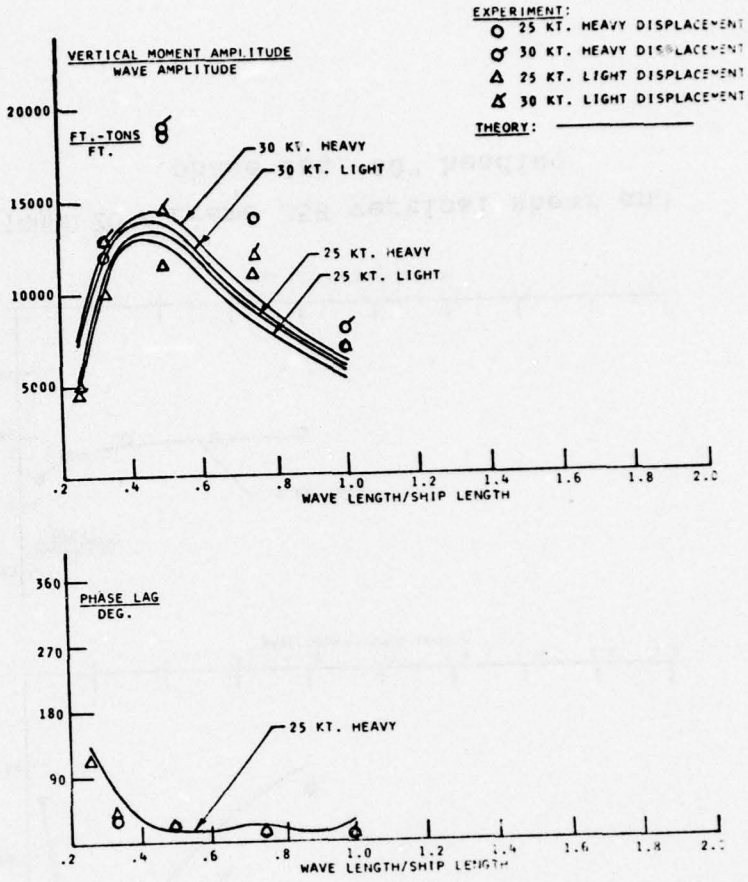


FIGURE 18 - Frame 258 vertical wave bending moments and phase lag, 60° heading

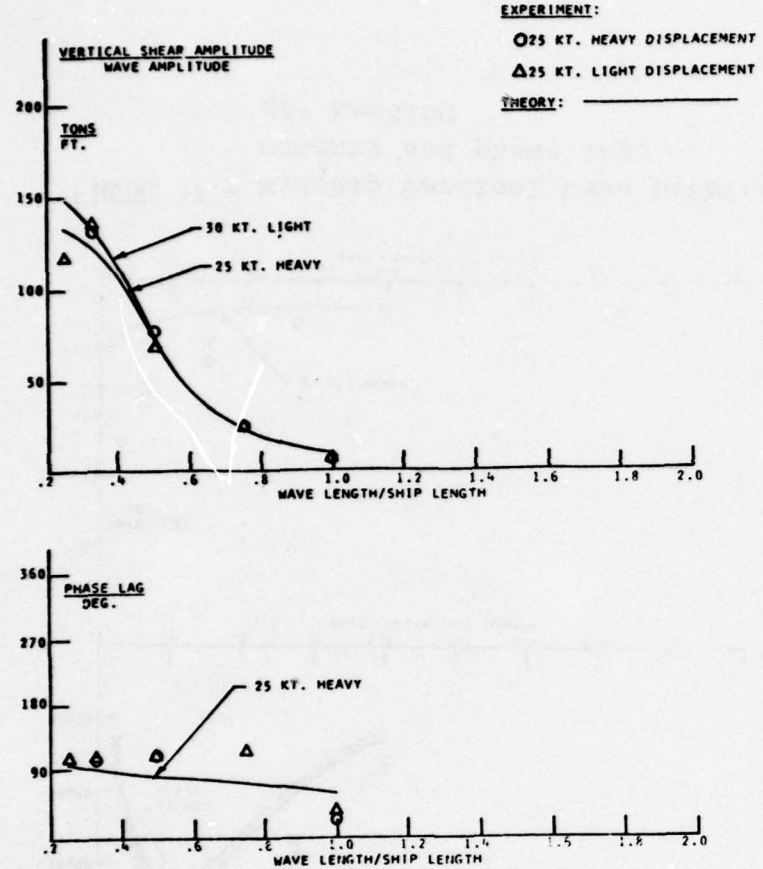


FIGURE 19 - Midship vertical shear and phase lag, 60° heading

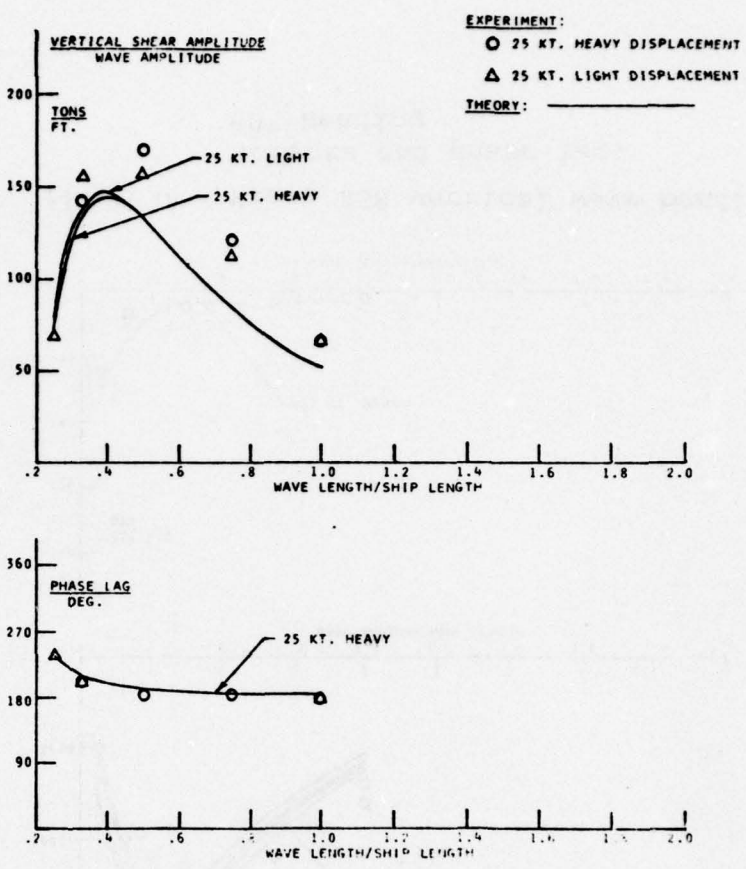


FIGURE 20 - Frame 258 vertical shear and phase lag, 60° heading

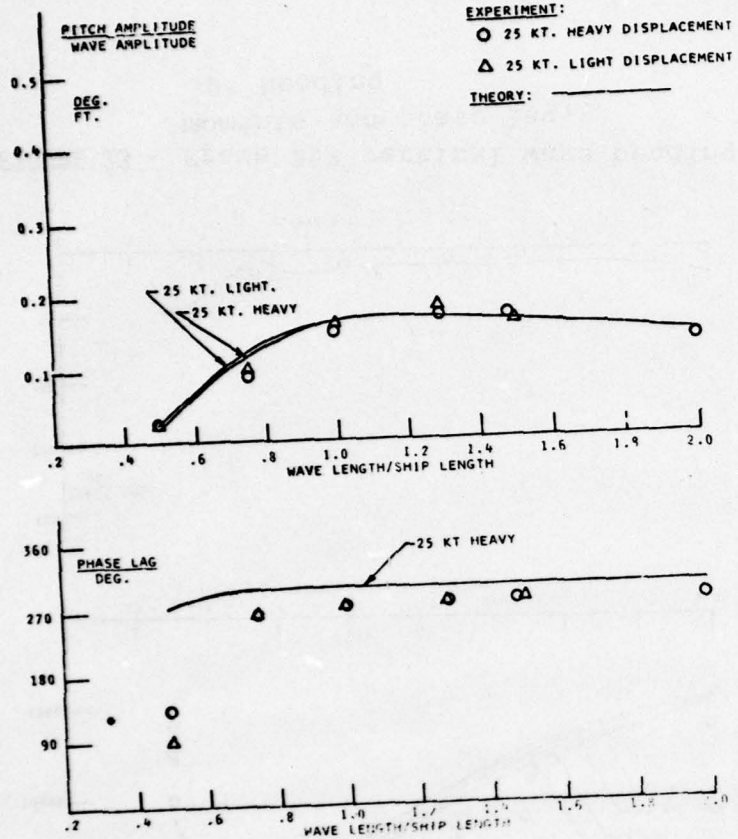


FIGURE 21 - Pitch and phase lag, 30° heading

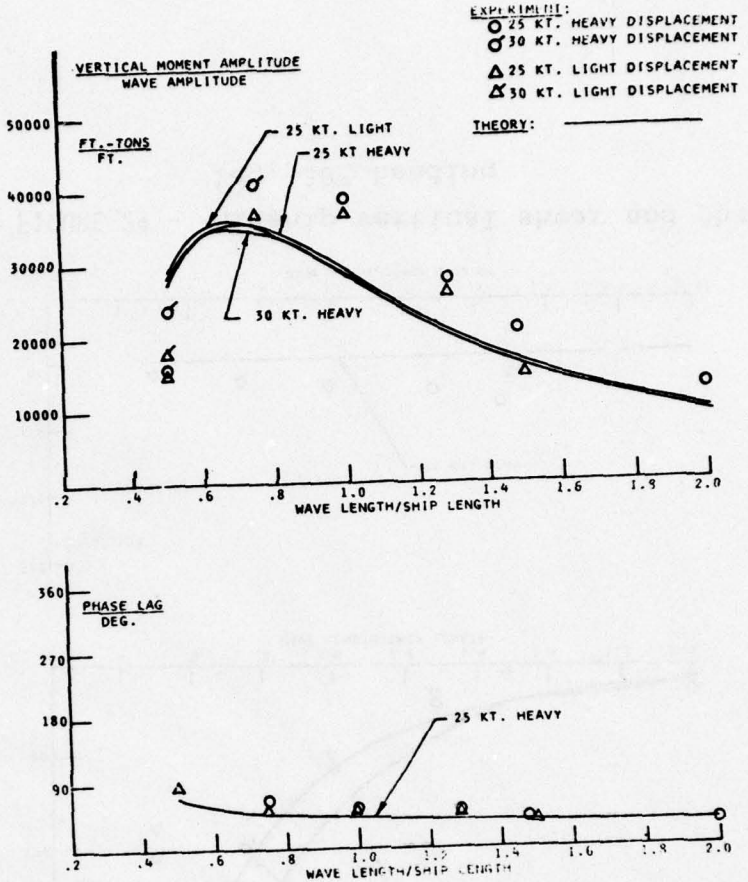


FIGURE 22 - Midship vertical wave bending moments and phase lag, 30° heading

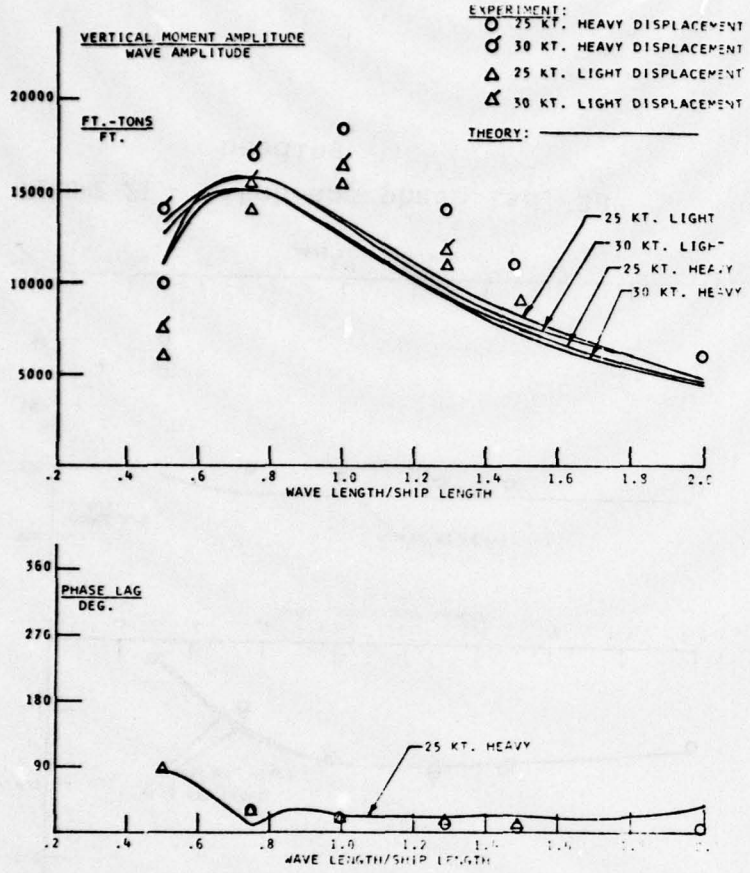


FIGURE 23 - Frame 258 vertical wave bending moments and phase lag, 30° heading

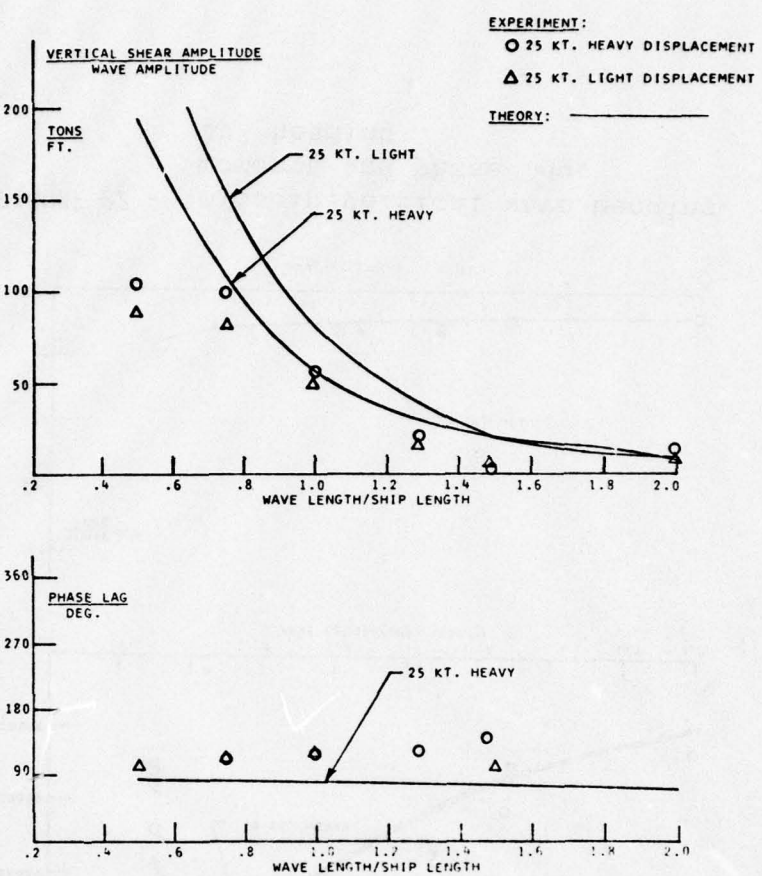


FIGURE 24 - Midship vertical shear and phase lag, 30° heading

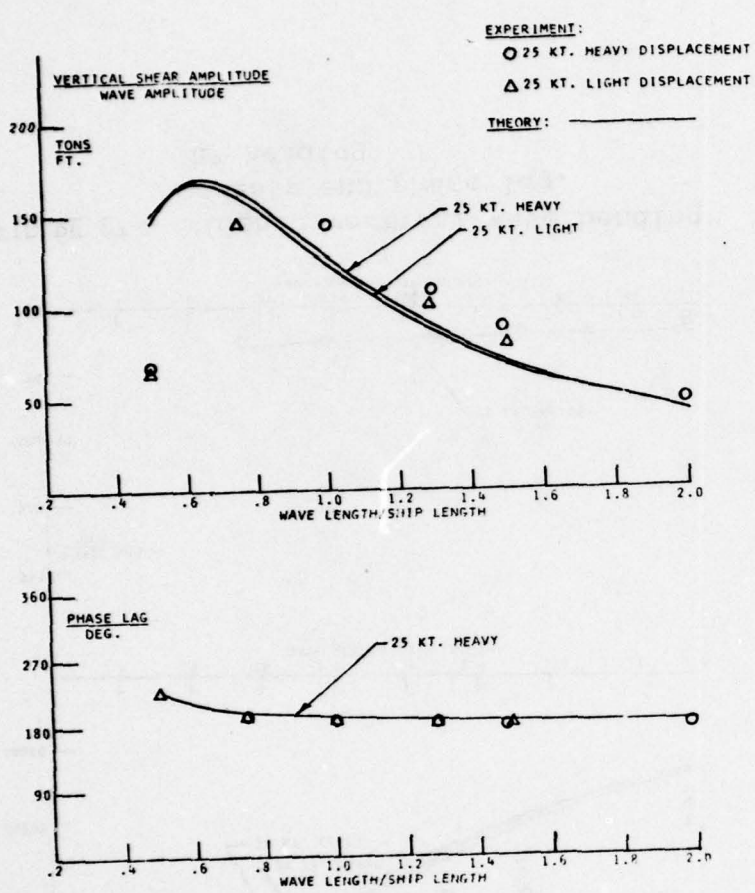


FIGURE 25 - Frame 258 vertical shear and phase lag, 30° heading

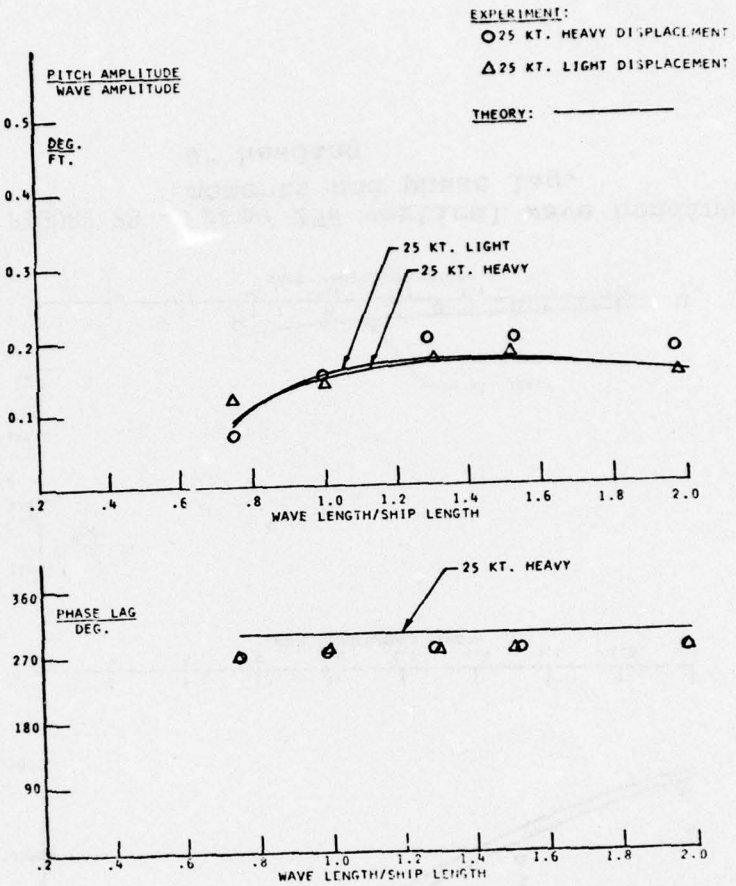


FIGURE 26 - Pitch and phase lag, 0° heading

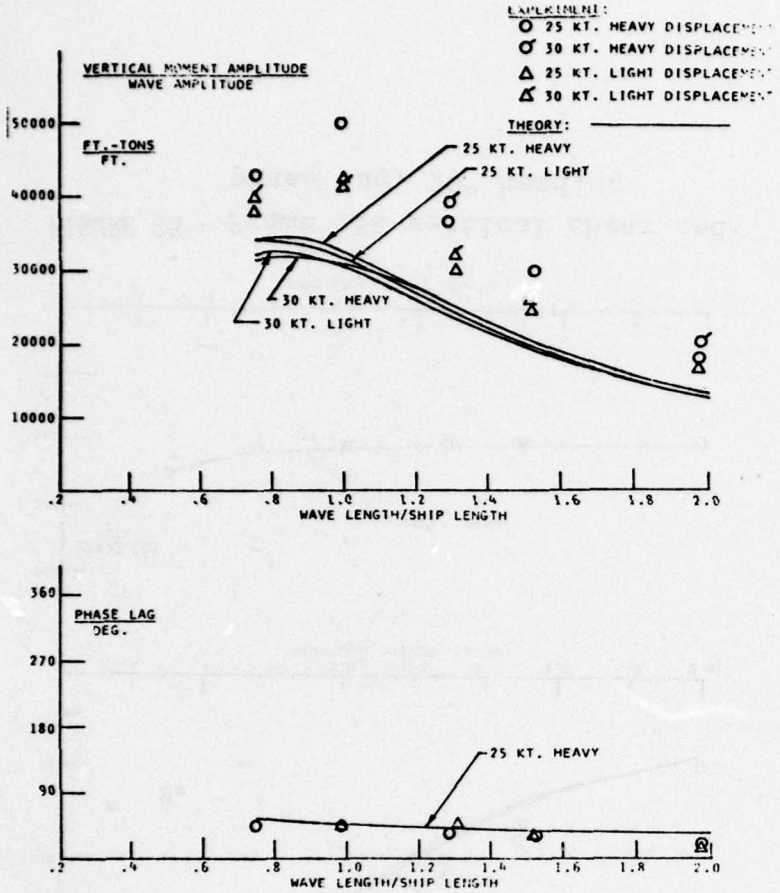


FIGURE 27 - Midship vertical wave bending moments and phase lag, 0° heading

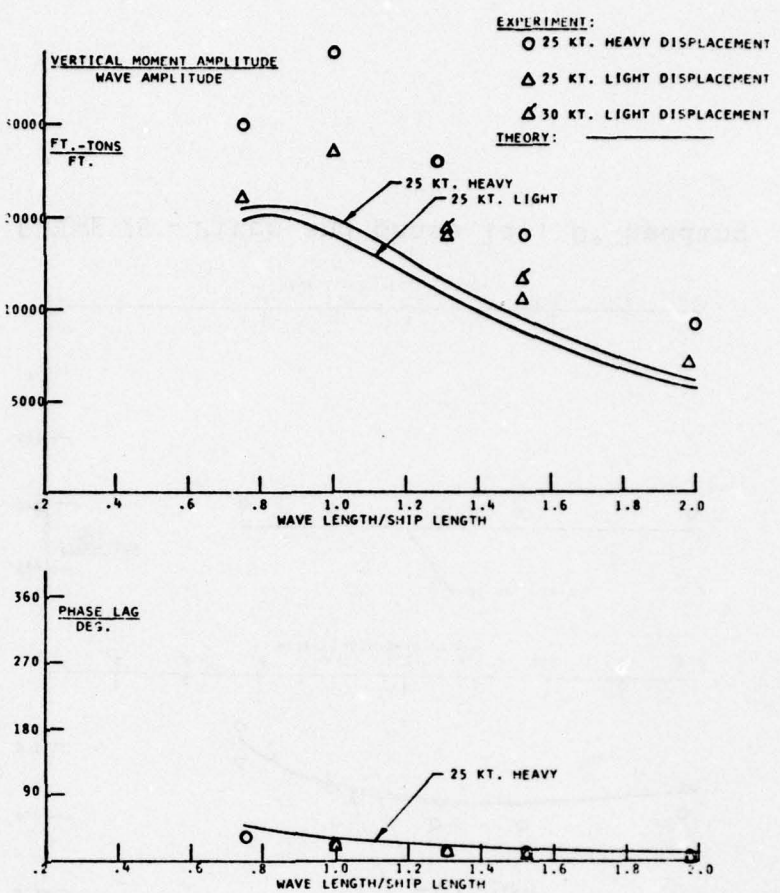


FIGURE 28 - Frame 258 vertical wave bending moments and phase lag, 0° heading

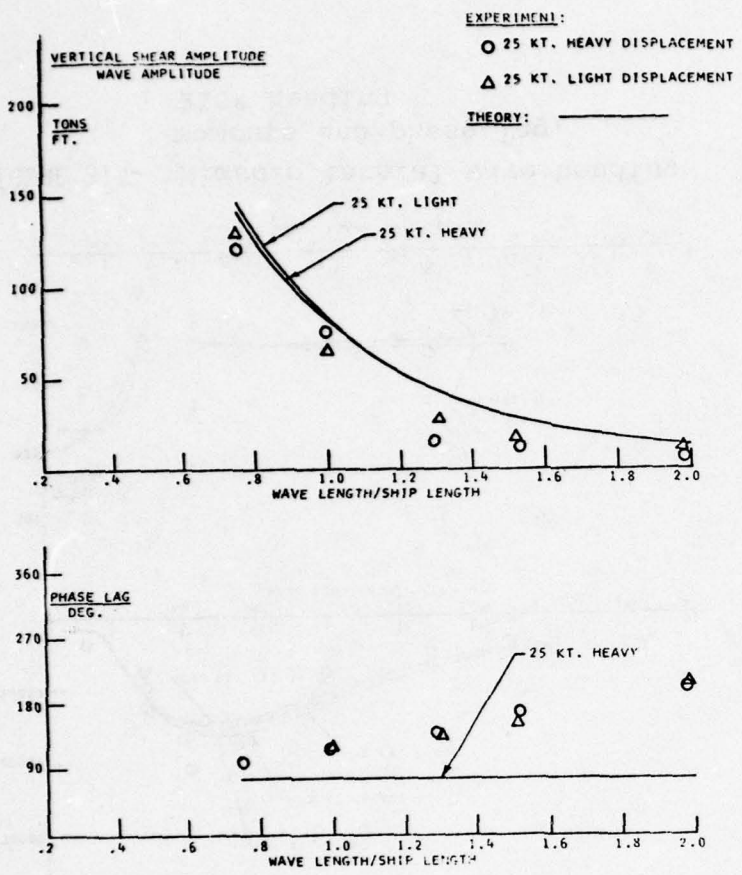


FIGURE 29 - Midship vertical shear and phase lag, 0° heading

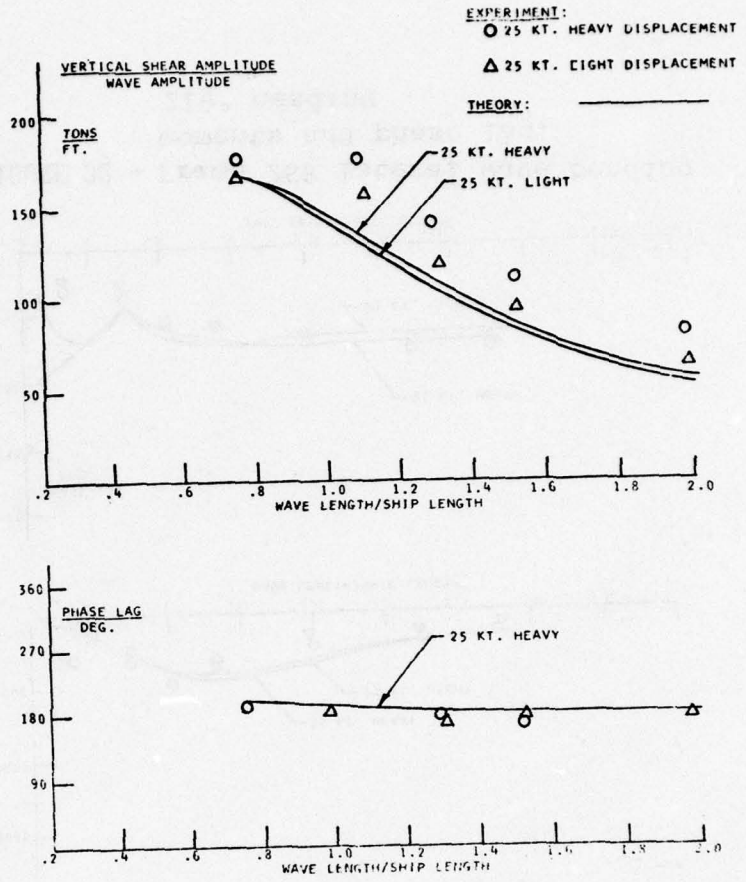


FIGURE 30 -Frame 258 vertical shear and phase lag, 0° heading

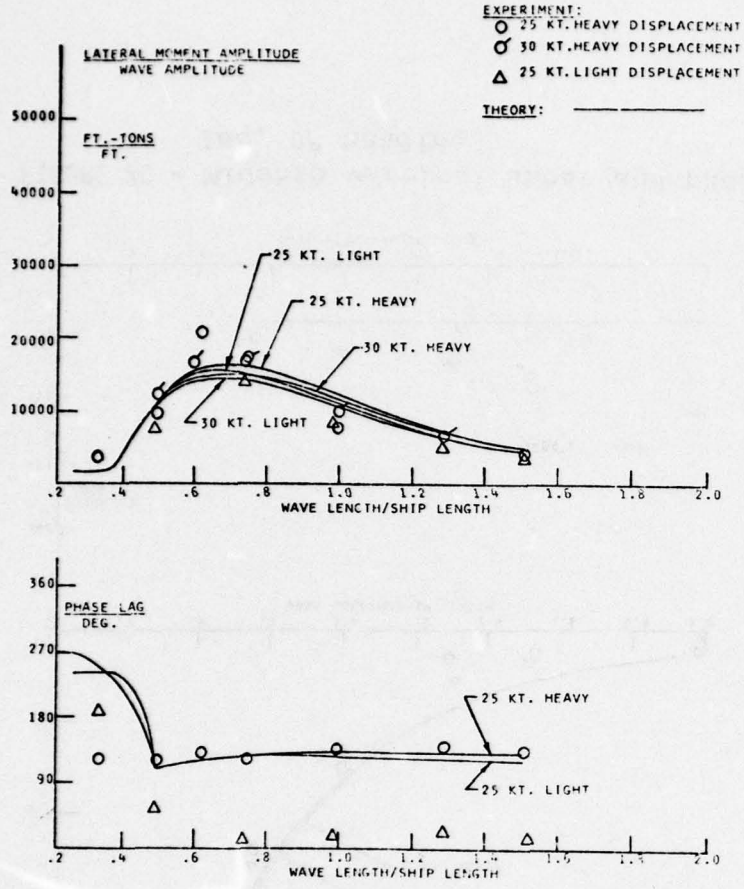


FIGURE 31 - Midship lateral wave bending moments and phase lag, 210° heading

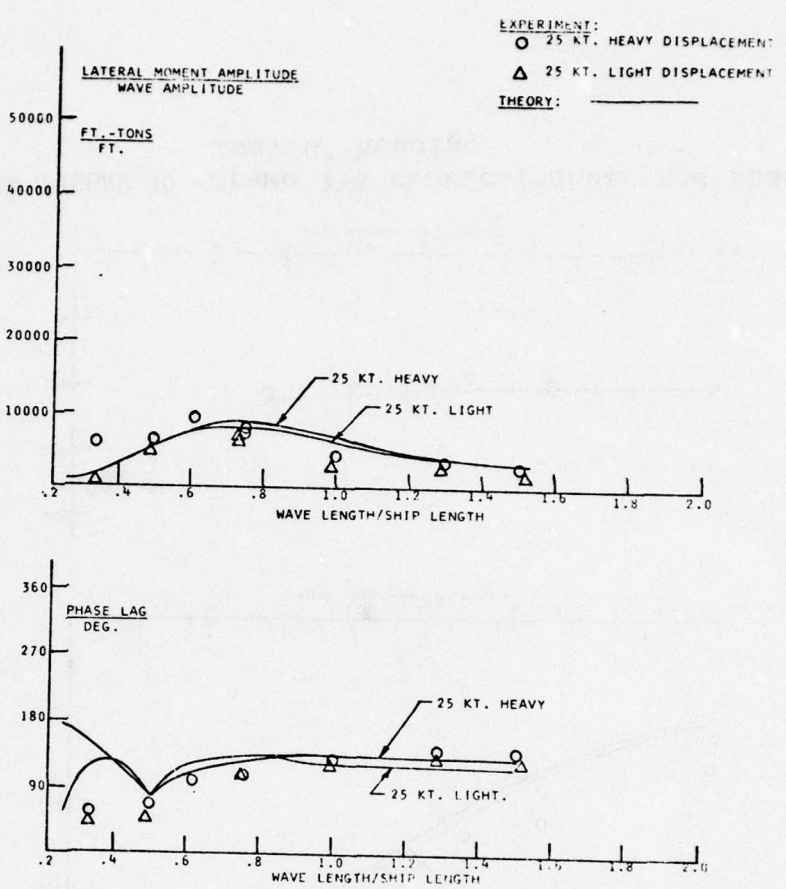


FIGURE 32 - Frame 258 lateral wave bending moments and phase lag, 210° heading

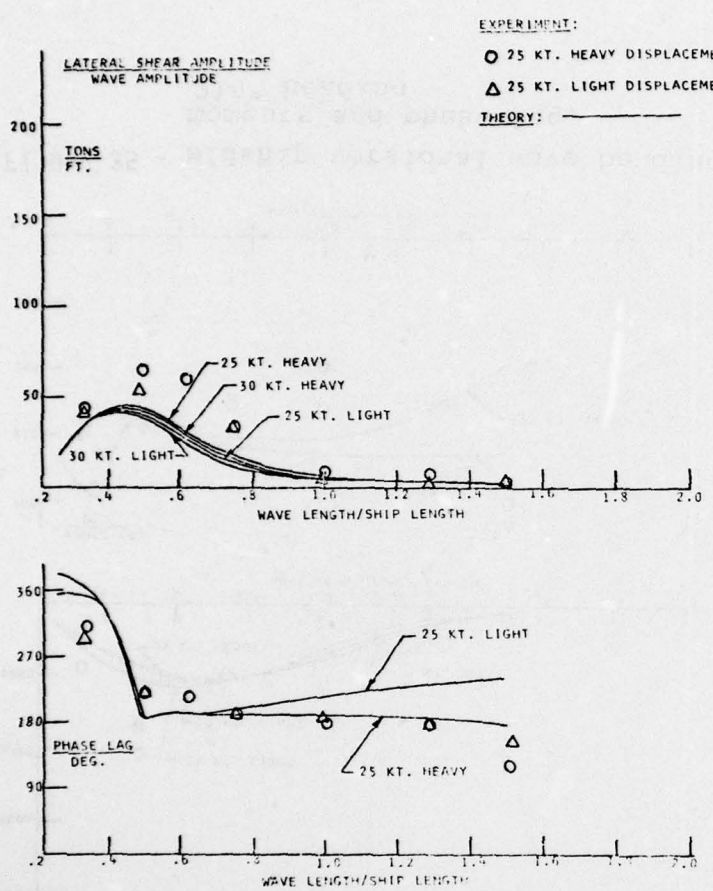


FIGURE 33 - Midship lateral shear and phase lag, 210° heading

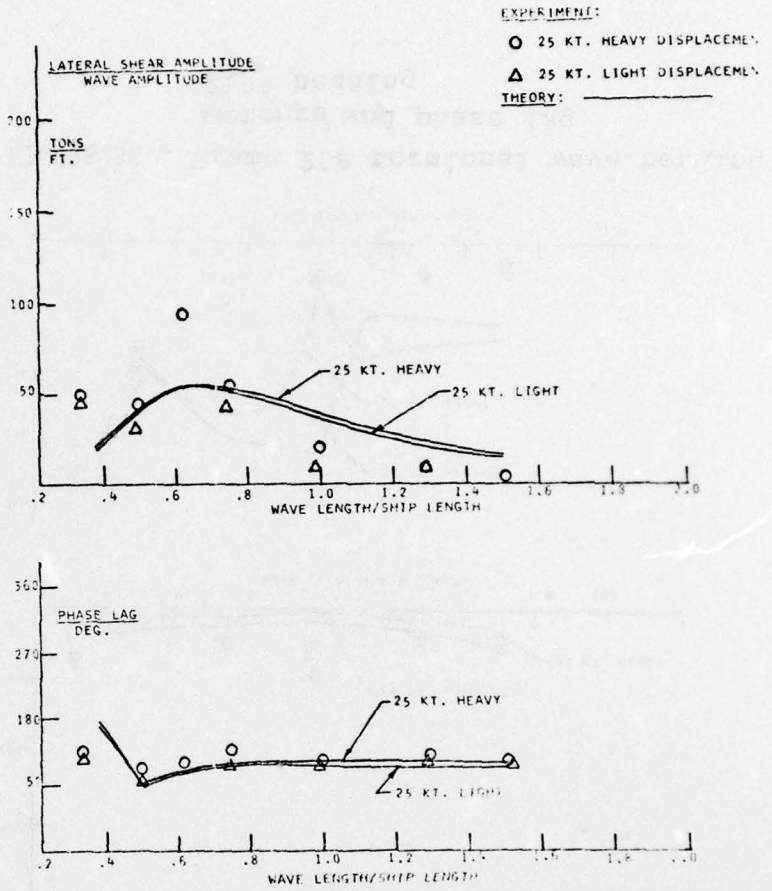


FIGURE 34 - Frame 258 lateral shear and phase lag, 210° heading

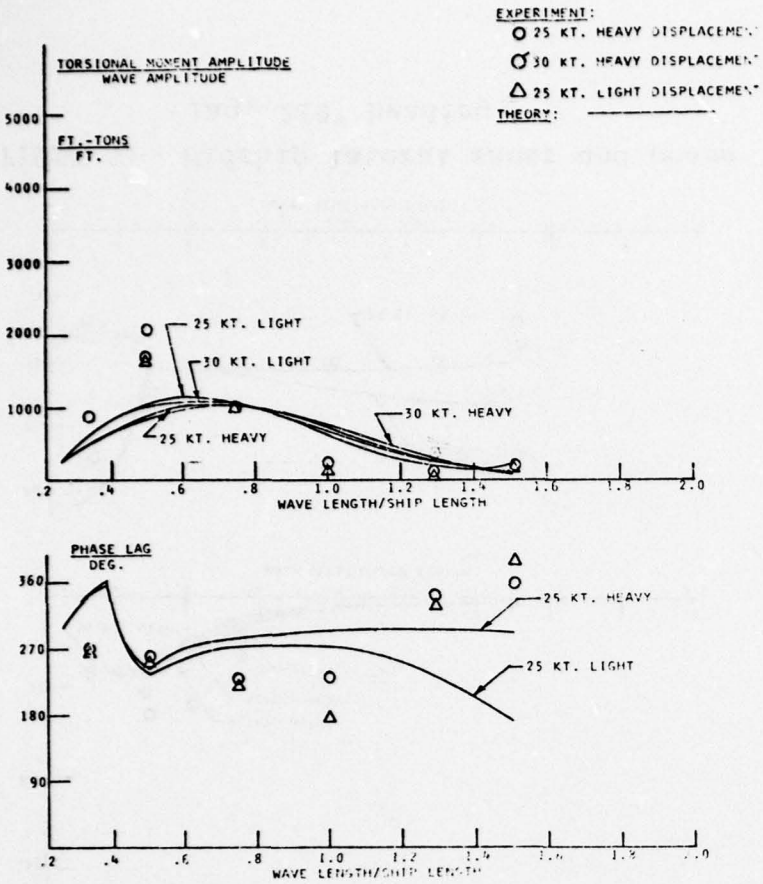


FIGURE 35 - Midship torsional wave bending moments and phase lag, 210° heading

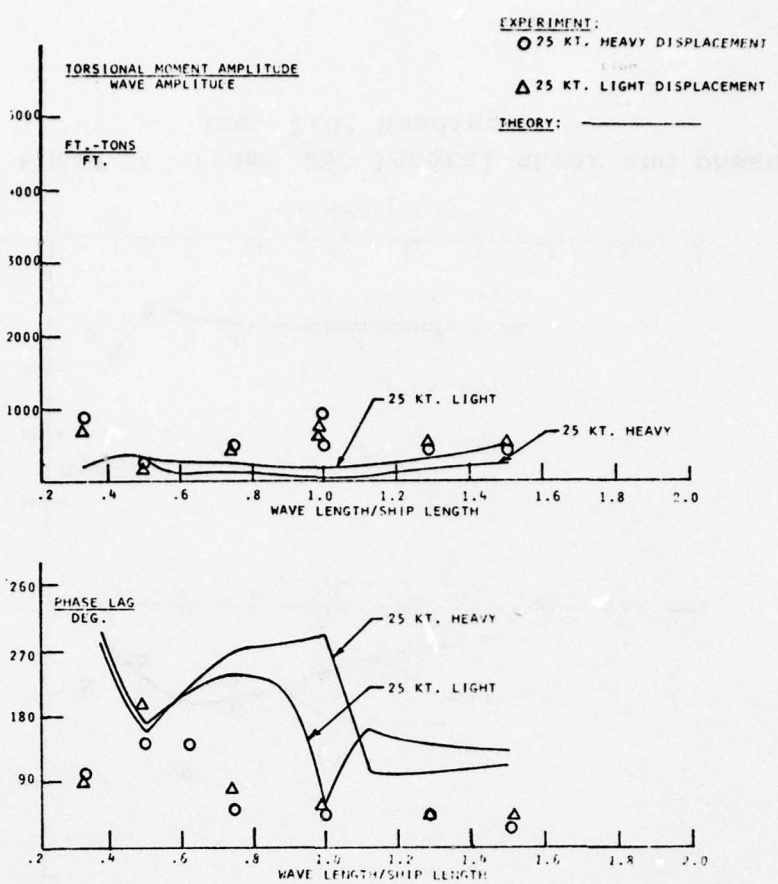


FIGURE 36 - Frame 258 torsional wave bending moments and phase lag, 210° heading

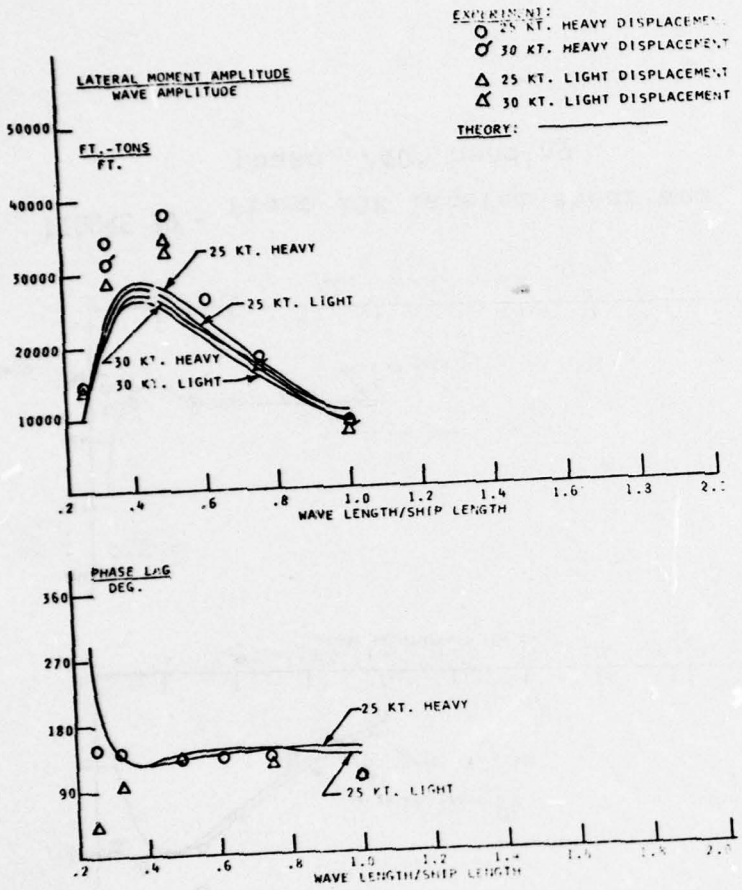


FIGURE 37 - Midship lateral wave bending moments and phase lag, 240° heading

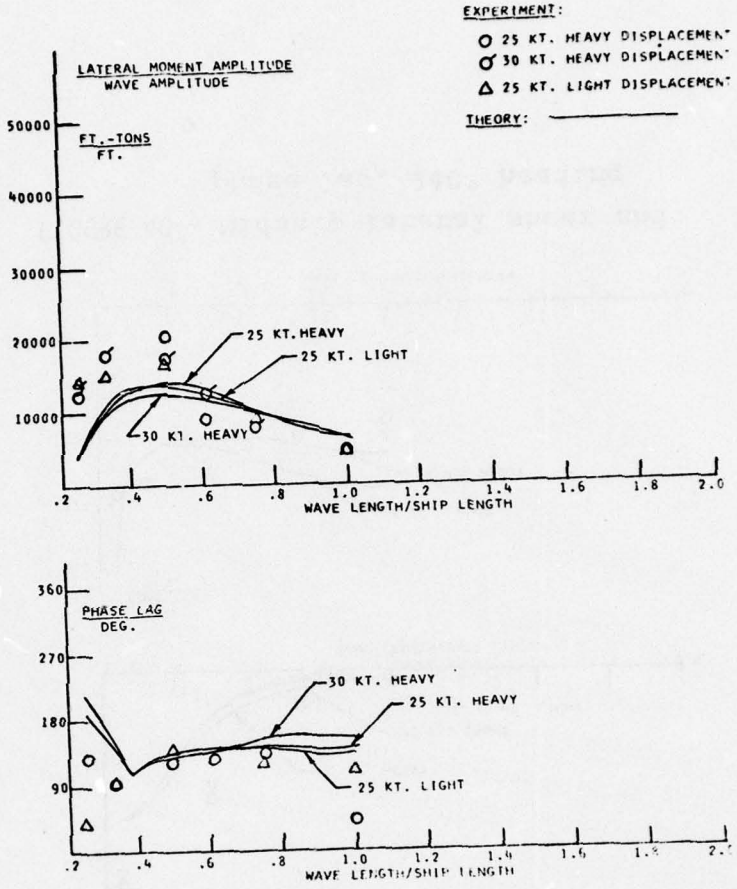


FIGURE 38 - Frame 258 lateral wave bending moments and phase lag, 240° heading

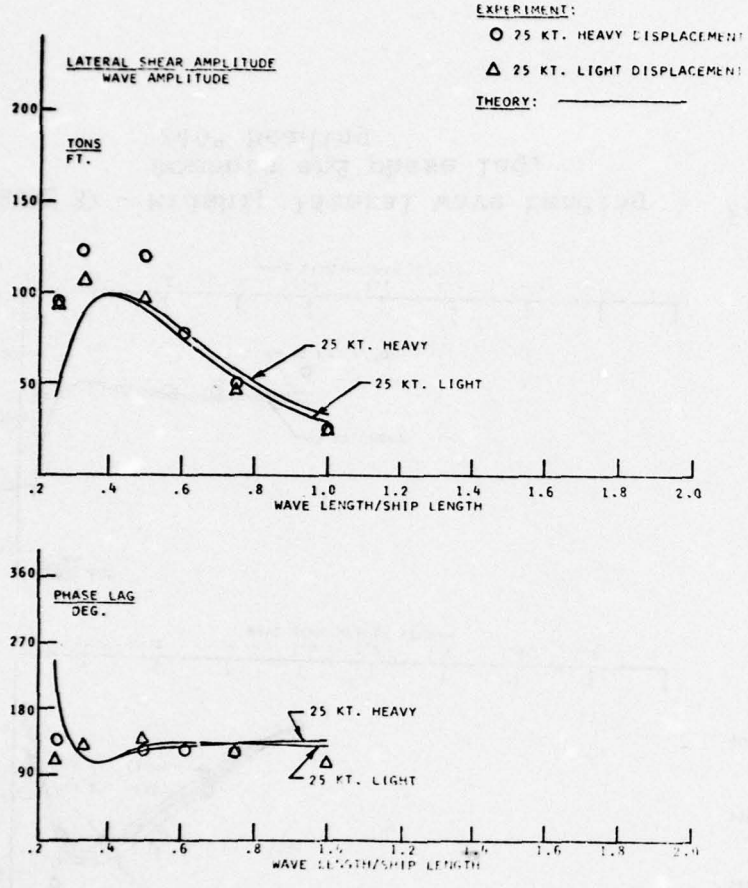


FIGURE 39 - Frame 258 lateral shear and phase, 240° heading

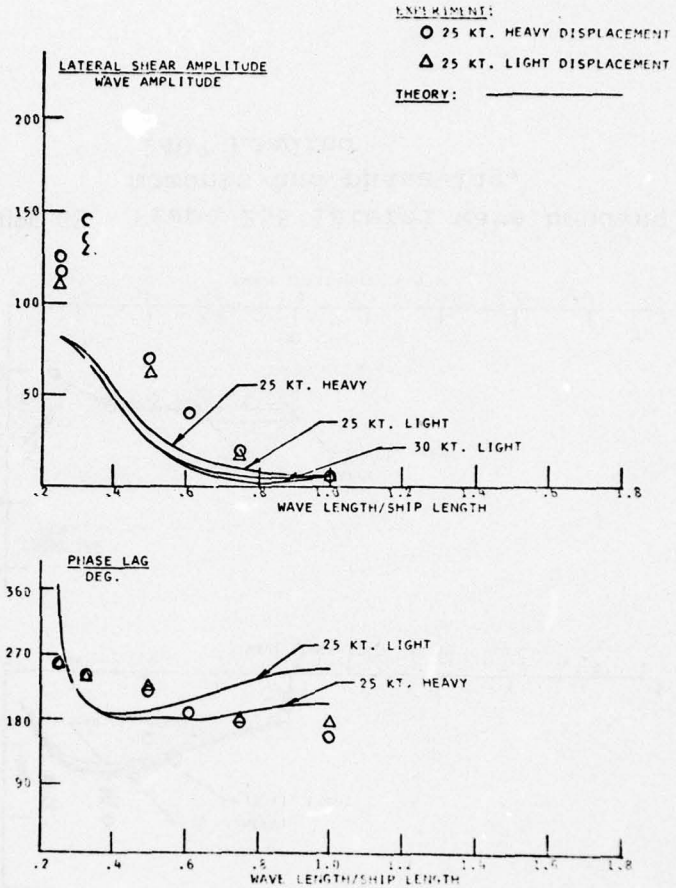


FIGURE 40 - Midship lateral shear and phase lag, 240° heading

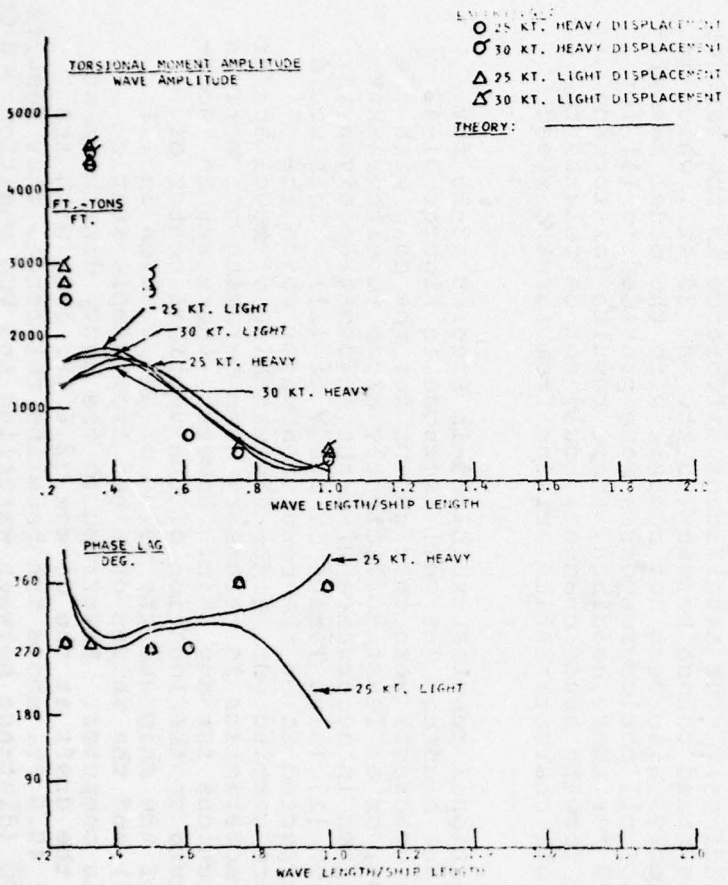


FIGURE 41 - Midship torsional wave bending moments and phase lag, 240° heading

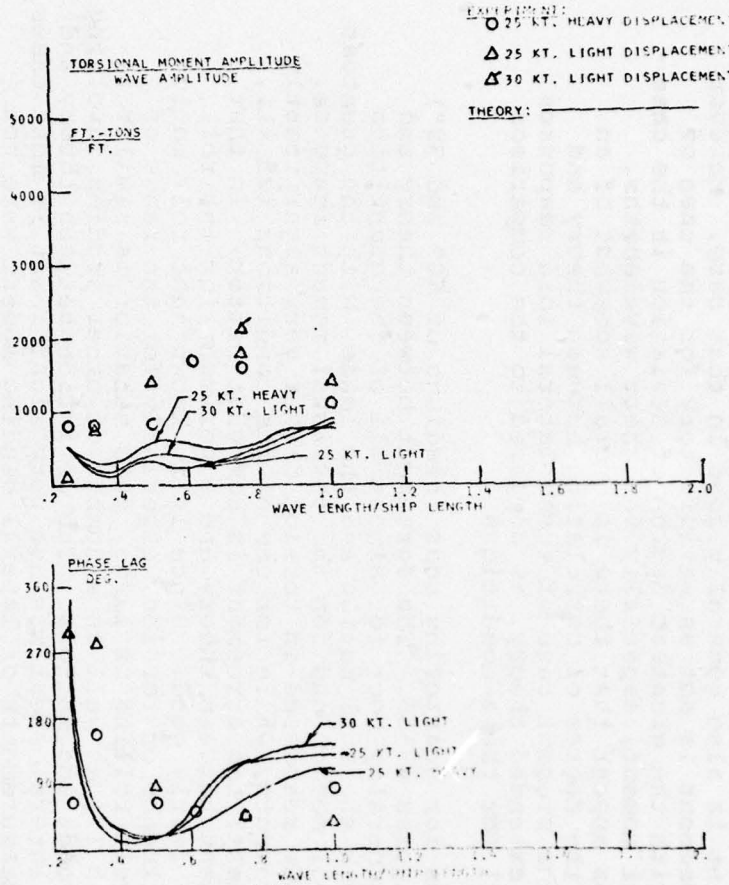


FIGURE 42 - Frame 258 torsional wave bending moments and phase lag, 240° heading

torsional response is small for the case of the 210° heading, and the agreement is also generally good in that case. However the overall agreement is not as satisfactory for the case of 240° heading, with the greatest degree of deviation in the case of the torsional moment, especially for short wavelengths. However, it does appear that there is overall somewhat of an improvement in the degree of correlation between theory and experiment in the present case of these lateral load responses when using the extended theory, as compared to the comparison presented in [2] for these conditions.

The results for quartering seas (headings of 60° and 30°) are shown in Figures 43-56. The agreement between theory and experiment is generally poor for almost all of the quantities compared for both the roll motion and the loads, with the greatest deviation in roll motion and for the torsional moment response. In most cases the responses in torsion differ very significantly from the measurements, while for one of the conditions (25 kt., heavy displacement) the agreement is somewhat better. In that case the agreement between theory and experiment for the roll motion was also fairly good. Since it is known that roll motion has a large influence on torsion, especially for the range of conditions wherein rolling is large, this behavior is similar to that obtained in [2] as well as a number of other studies involving lateral plane loads and motions. The deviation between theory and experiment for lateral shear was not very significant in most cases, but the model measurements of lateral bending moment were not predicted well by the theory for these particular test conditions (30° and 60° headings). The significant difference in the torsion response for the speed change between 25 kt. and 30 kt., which is predicted by theory, also does not compare with the model measurements. Since no roll motion responses were provided in [1] for the 30 kt. speed for these headings, these results for torsion changes (due to forward speed changes) could not be related to any change in roll characteristics arising from forward speed changes.

The computational results exhibited in Figures 43-56 for the quartering-sea headings (as well as those in Figures 31-42 for the bow-sea headings) were carried out for the ship with the correct GM value, or at least sufficiently close to either that desired or obtained in accordance with the information given in Tables 5 and 6 of [1] (also Tables IV and V of [2]). This would ordinarily be expected to be the condition under which the computations were carried out, since the matching of model and/or full-scale characteristics is necessary when carrying out motions and loads predictions for any ship. However, there was an inconsistency in regard to the location of the vertical center of gravity (VCG) of the ship and the value of GM as given in [1] (Tables 5 and 6) and the values obtained from simple static computations via computer. Referring to the heavy displacement configuration, the draft at the CG was 32.6 ft. and, with the achieved VCG as 40.6 ft. above the baseline reference, that results in a value of $\overline{OG}$ (distance between waterline and VCG position) = 8 ft.

With that position of the VCG, and the ship orientation within the water at the desired draft conditions, the resulting GM value would then be 4.55 ft. Similarly in the case of the light displacement configuration, with a CG draft of 29.8 ft., the value of $\overline{OG}$ was 9.5 ft. in order to match the achieved VCG position in the model. In that case for the light displacement the GM value would then be 8.9 ft. For each of these conditions the GM value would be significantly different from that desired or achieved in the model representation, which was 2.6 ft. for the heavy displacement and 5.32 ft. for the light displacement (these values were the ones used for the present computation).

The value of GM obtained from the computer for each condition depends on the position of the metacenter M, which is determined from the geometry of the submerged portion of the ship. The displacement and related hydrostatic conditions determined from the computer appear to satisfy the requirements for the model, since the calculated displacements differ by less than 1% from those indicated in [1] and the trim conditions are in equilibrium, with the proper longitudinal center of buoyancy and longitudinal CG positions which also agree with that for the model. Thus there is a fundamental question as to the relation between the GM values and $\overline{OG}$ values determined via computation as compared to those reported for the model in [1].

The choice for computation would be either to have the correct GM value and an incorrect $\overline{OG}$ values, or the correct $\overline{OG}$ value and an incorrect GM value. The choice made for the computation, where the results of motion and load responses are shown in Figures 43-56 (and also Figures 31-42) was that of a correct GM value, which was thought to be a more important parameter. Since there is a significant contribution to the torsional moment due to rolling motion, with an important contribution arising from the value of $\overline{OG}$ (see [5] and [6]), there is certainly the prospect of error if all of these quantities are not consistently related to each other, especially for the quartering-sea headings where roll was large. Computations were also made for the conditions with correct $\overline{OG}$ value but incorrect GM (results of calculations not shown), with no improvement in the correlation with experiment and no discernible pattern in the results either. Thus the question of the roll characteristics of the SL-7 model, even for the static considerations, appears to introduce some external influence on the computation results and the resulting comparison between theory and model experiment. In addition to the static considerations there are other aspects of rolling motion and its influence on the lateral plane loads which must also be considered, and some discussion of these effects is given in the following section.

3. Effect of Roll Damping

As mentioned previously the smooth-water roll-decay characteristics of the SL-7 model, as shown in Figure 4 of [1], indicated that the roll damping was nonlinear for the forward-speed conditions exhibited there. Assuming that the roll motion had a combined

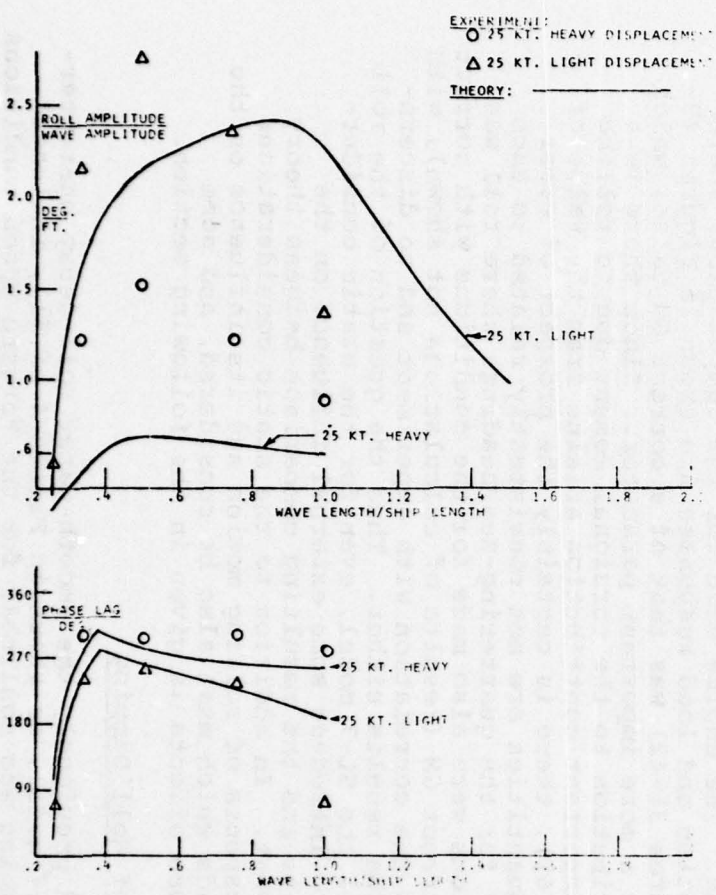


FIGURE 43 - Roll and phase lag, 60° heading

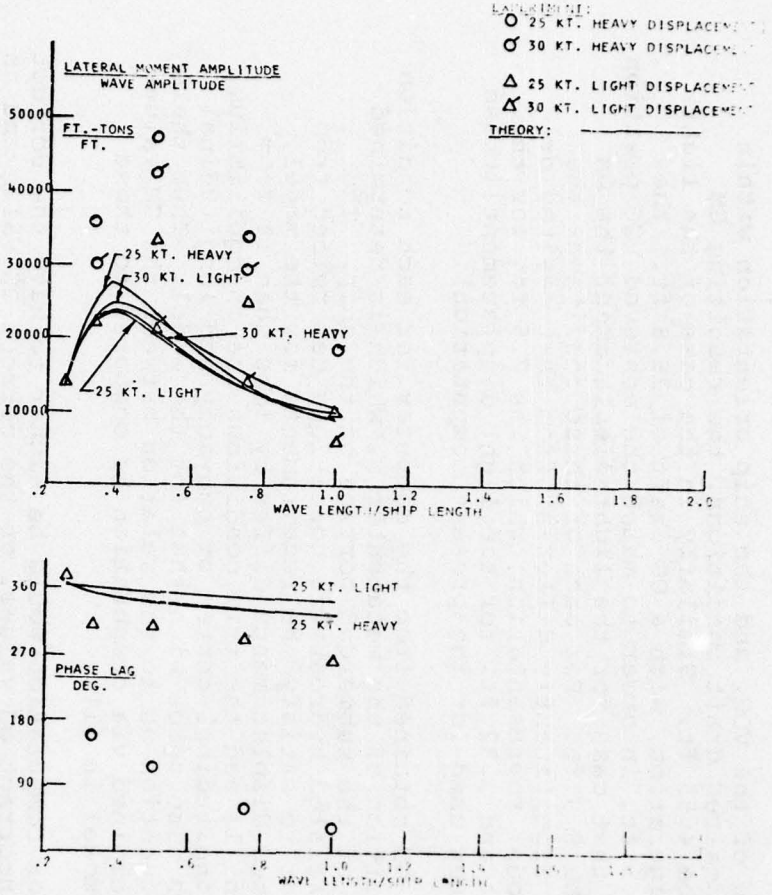


FIGURE 44 - Midship lateral wave bending moments and phase lag, 60° heading

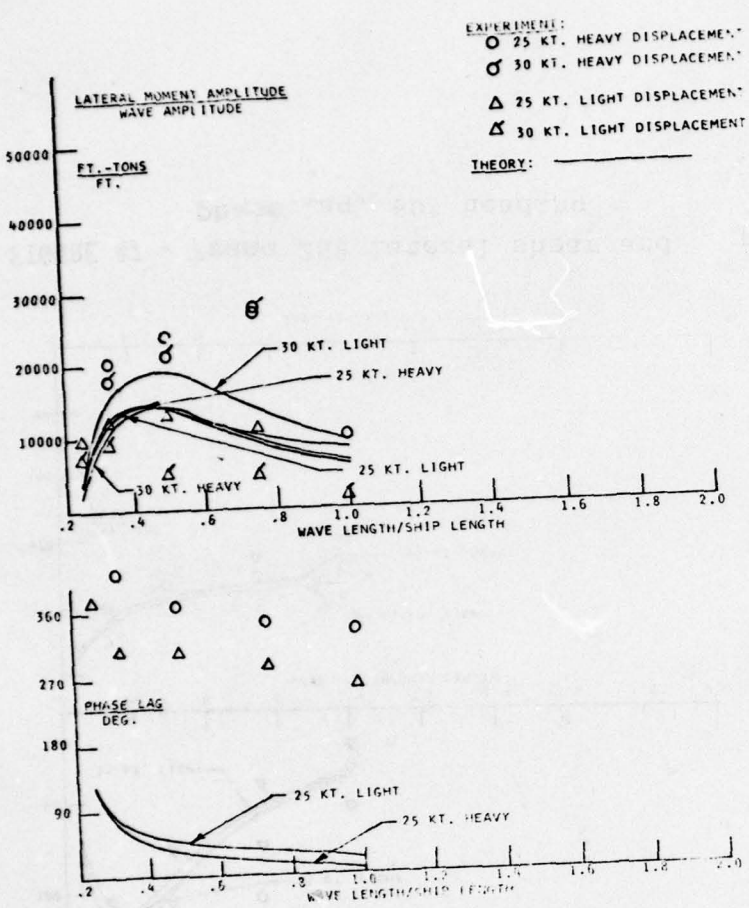


FIGURE 45 - Frame 258 lateral wave bending moments and phase lag, 60° heading

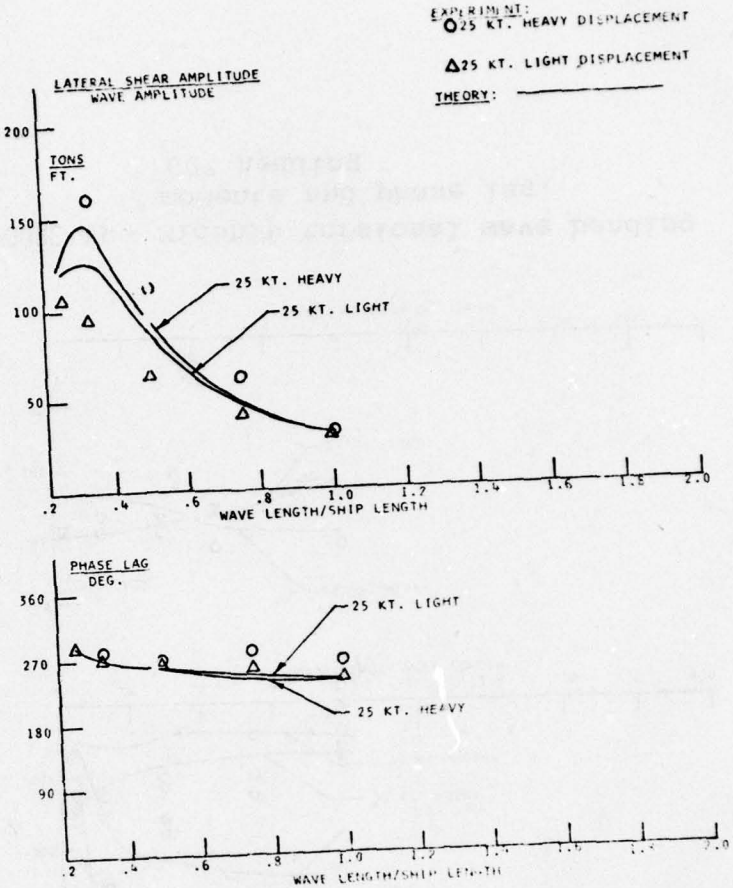


FIGURE 46 - Midship lateral shear and phase lag, 60° heading

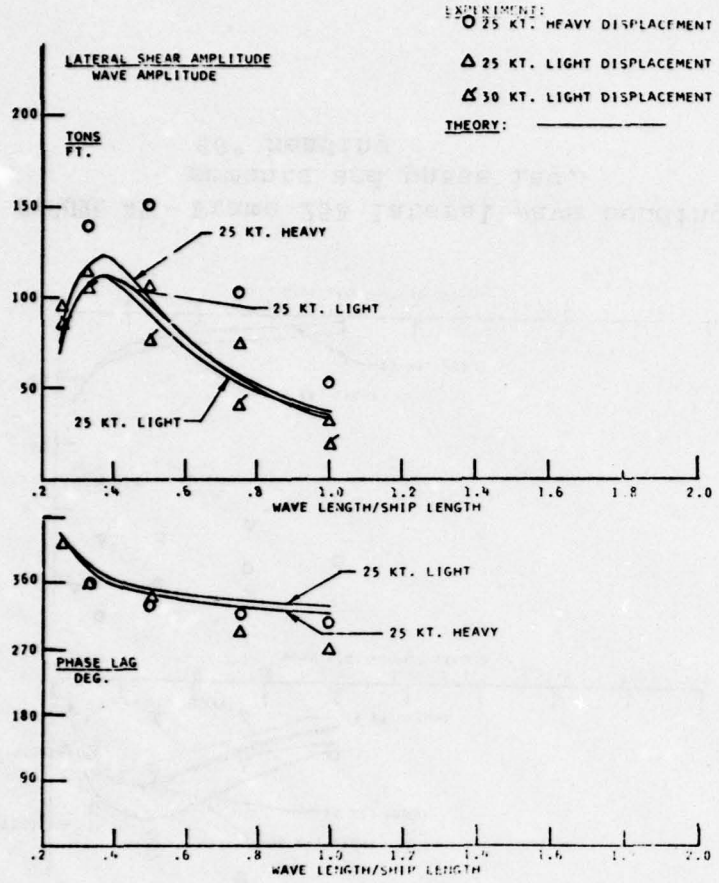


FIGURE 47 - Frame 258 lateral shear and phase lag, 60° heading

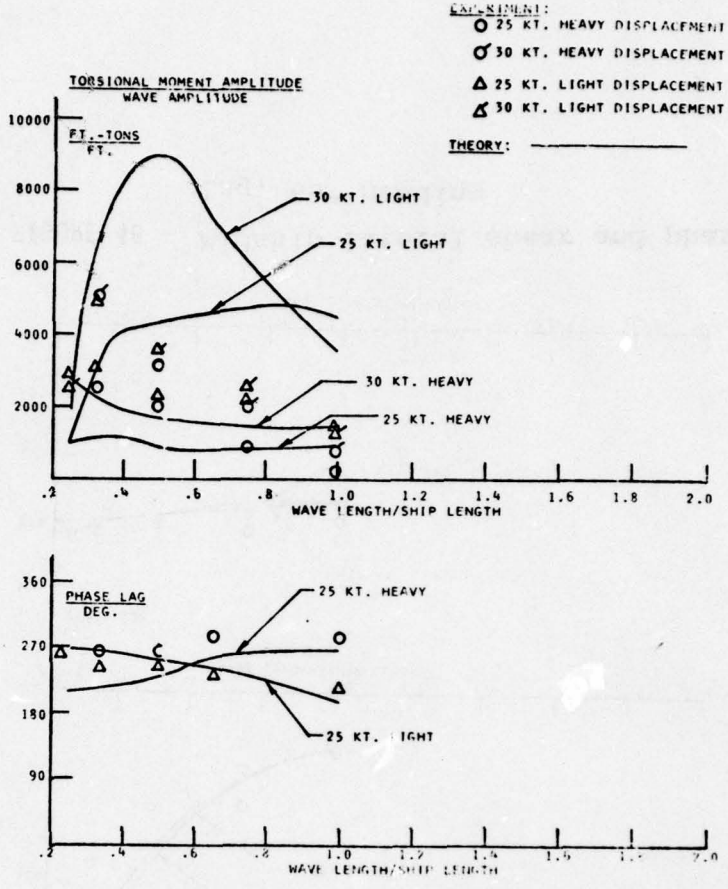


FIGURE 48 - Midship torsional wave bending moments and phase lag, 60° heading

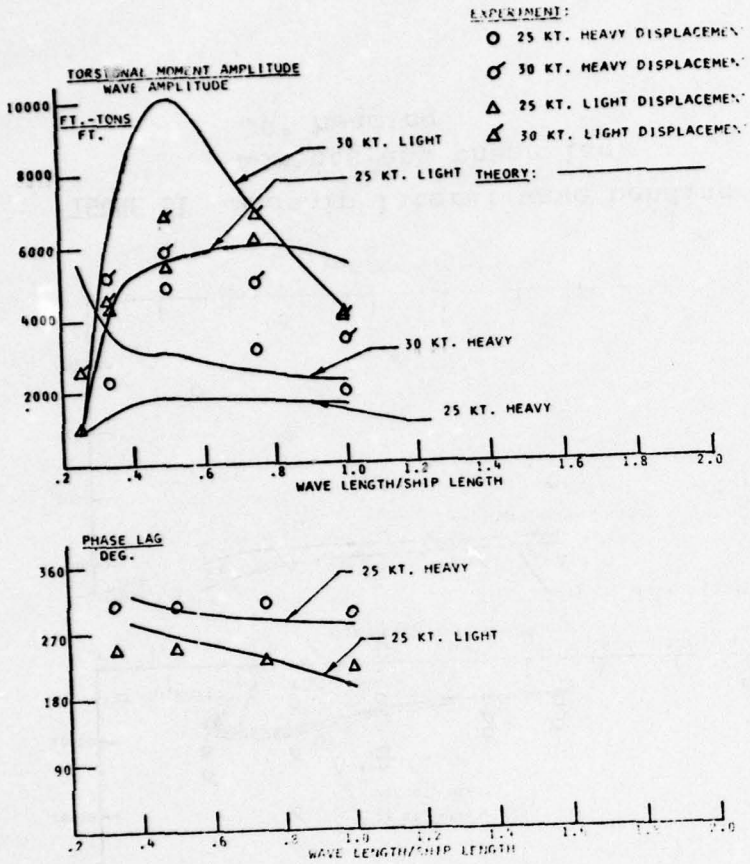


FIGURE 49 - Frame 258 torsional wave bending moments and phase lag, 60° heading

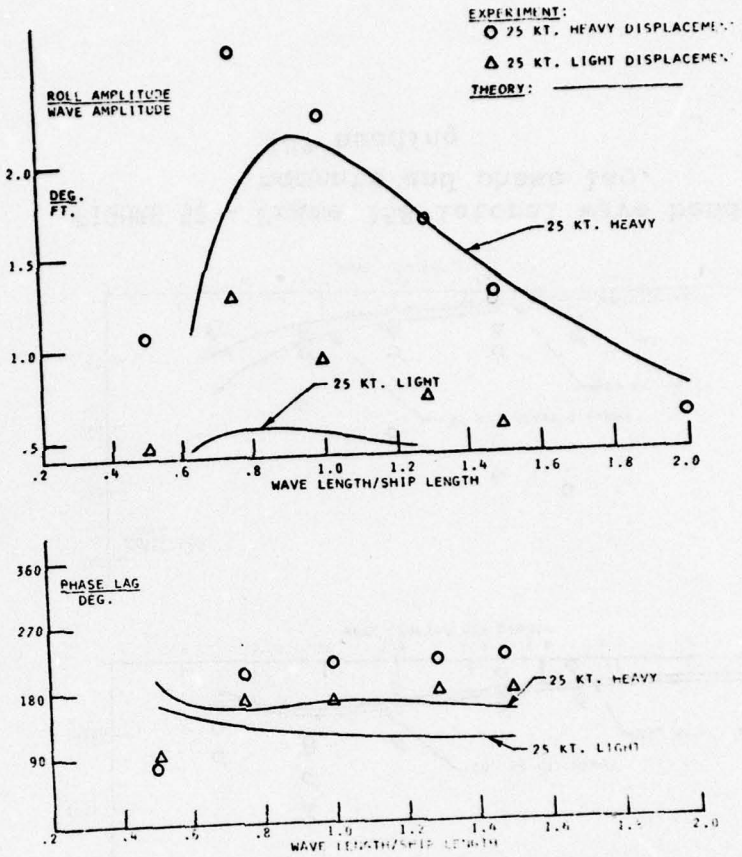


FIGURE 50 - Roll and phase lag, 30° heading.

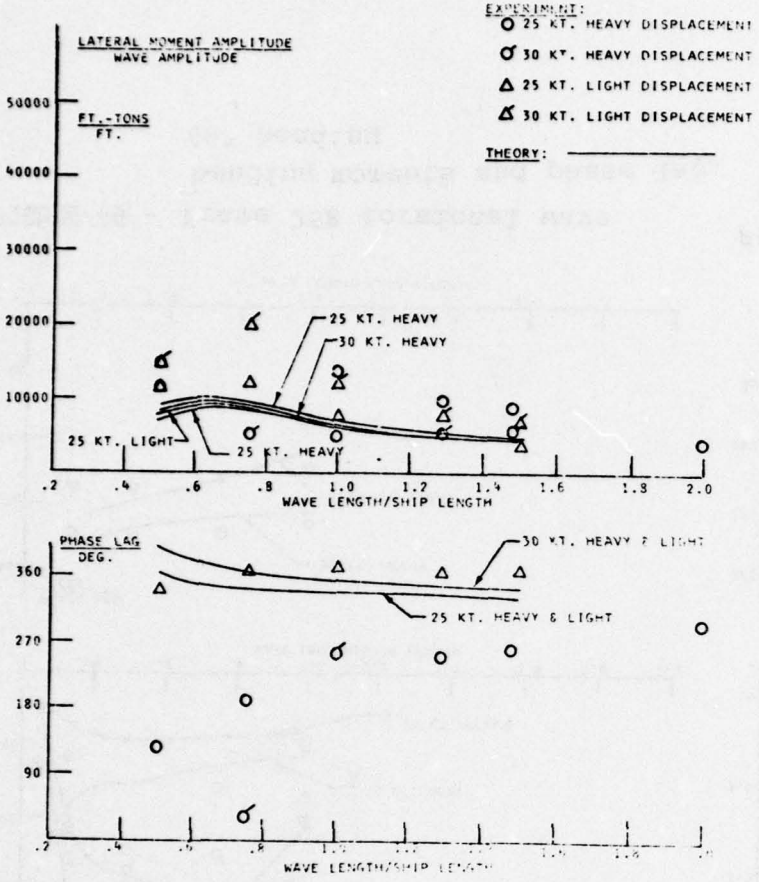


FIGURE 51 - Midship lateral wave bending moments and phase lag, 30° heading

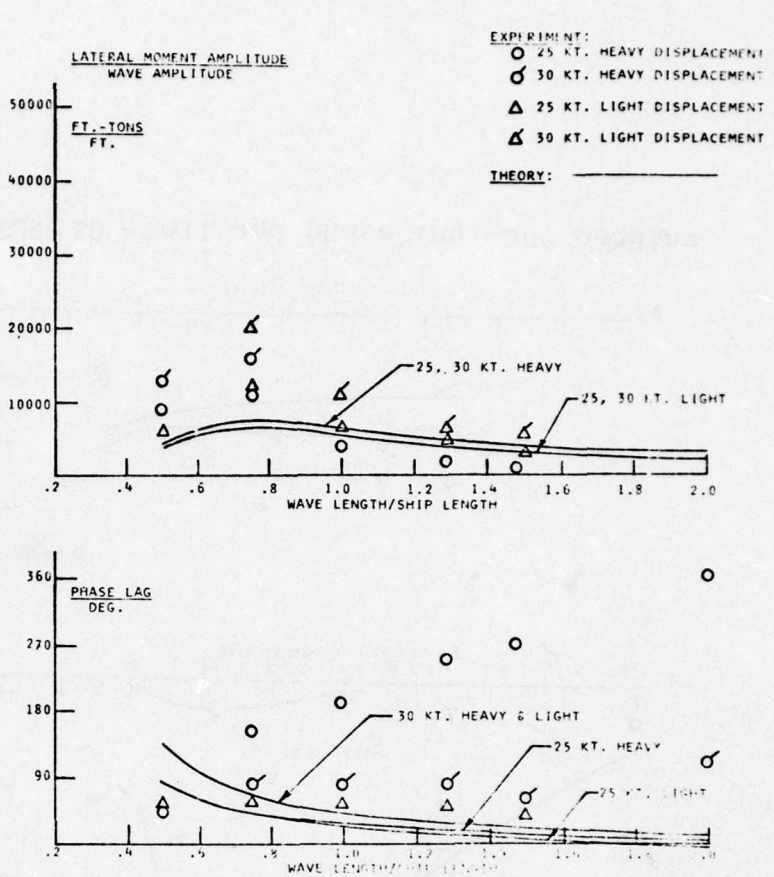


FIGURE 52 - Frame 258 lateral wave bending moments and phase lag, 30° heading

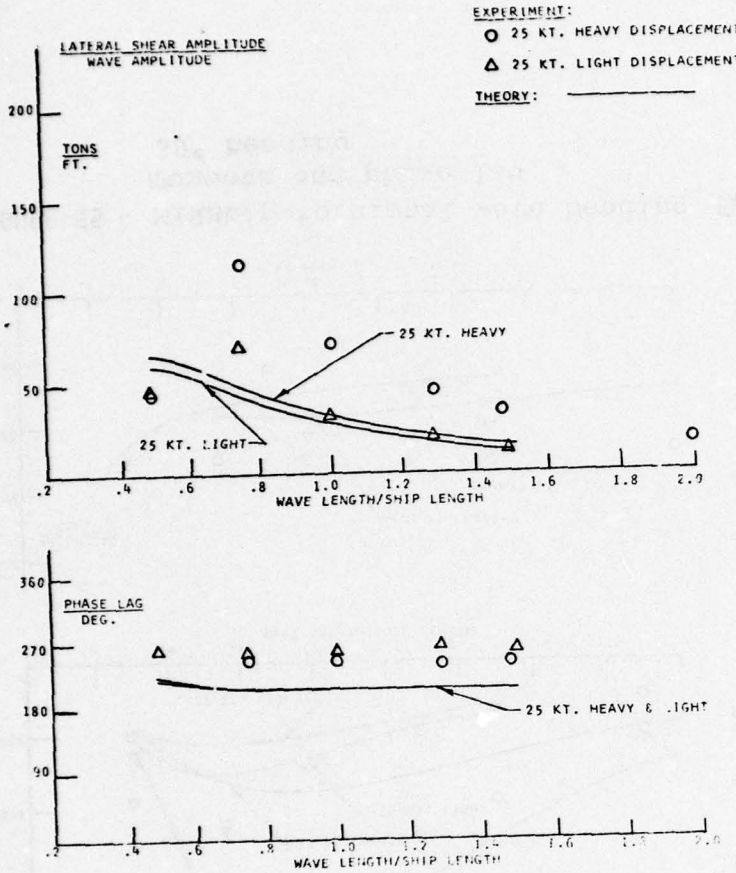


FIGURE 53 - Midship lateral shear and phase lag, 30° heading

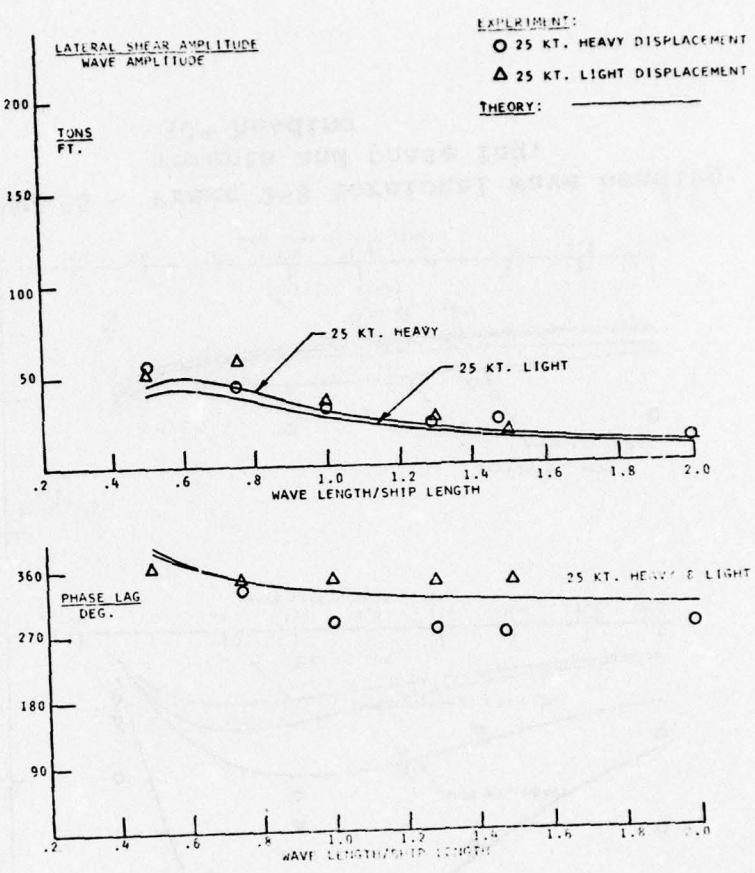


FIGURE 54 - Frame 258 lateral shear and phase lag, 30° heading

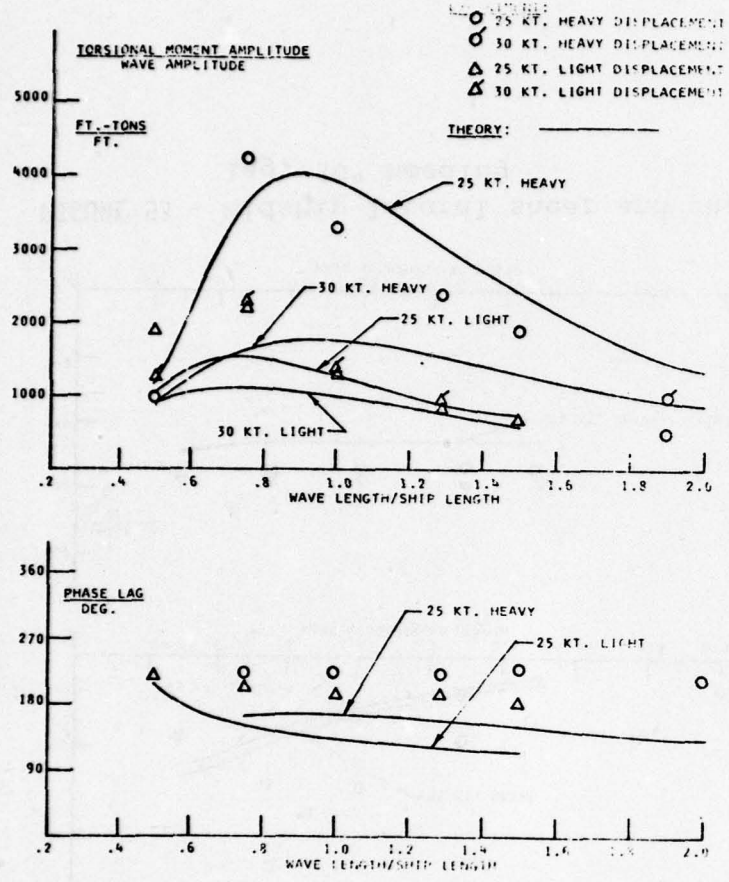


FIGURE 55 - Midship torsional wave bending moments and phase lag, 30° heading

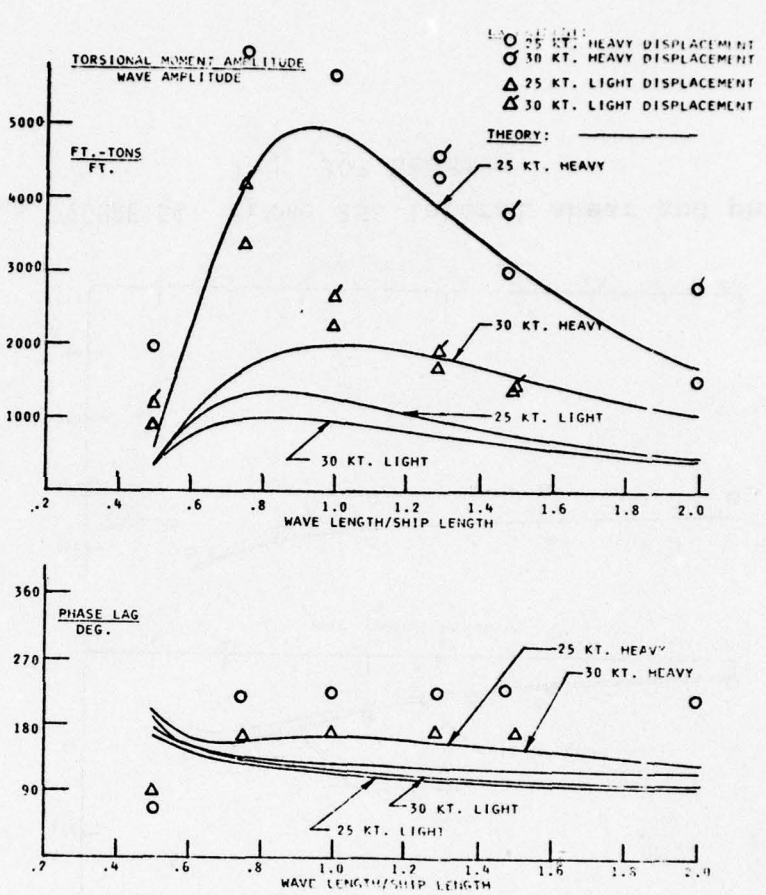


FIGURE 56 - Frame 258 torsional wave bending moments and phase lag, 30° heading

linear and quadratic damping, as represented by the free oscillation equation

$$\ddot{\phi} + \alpha\dot{\phi} + \beta\dot{\phi}|\dot{\phi}| + \omega_\phi^2\phi = 0 \qquad (24)$$

the roll decay from an initial value was analyzed via nonlinear oscillation theory [23] in order to determine the values of α and β (since ω_ϕ is known for the two displacement conditions).

The results of the mathematical solution fit with the parameter values are shown relative to the measured decay data in Figures 57 and 58, where the parameter values for the light displacement configuration are $\alpha = 0.06$ sec.$^{-1}$ and $\beta = 1.787$, and the values for the heavy displacement configuration are $\alpha = 0.0108$ sec.$^{-1}$ and $\beta = 12.665$ (using radian measure for the angles). The match of the amplitudes of oscillatory decay is quite good, indicating proper values for the parameters in this model.

According to the method of equivalent linearization used for frequency response analysis in [12], the effective value of linear damping is represented by

$$\alpha_e = \alpha + \frac{8}{3\pi}\beta\omega_\phi|\phi| \qquad (25)$$

where $|\phi|$ represented the amplitude of roll in an oscillatory forced response. The equivalent roll damping ratio $\zeta_{\phi_e} = 2\omega_o\alpha_e$ is then

$$\zeta_{\phi_e} = \frac{\alpha}{2\omega_o} + \frac{4}{3\pi}\beta|\phi| \qquad (26)$$

and this value is then used in an iterative manner in connection with the extended SCORES theory to determine a final value of ζ_{ϕ_e} that agrees with the resultant value of roll angle at the roll resonant frequency. This method was used in [12] with success in treating the nonlinear damped roll responses in model tests.

In the present case of the SL-7 this method was applied, considering resonant roll responses, and it was found that the resulting effective damping ratio ζ_{ϕ_e} that converged with the calculated resonant roll angle was much larger than would be logically expected, i.e. an effective damping ratio $\zeta_{\phi_e} = 0.162$ for the light displacement configuration and $\zeta_{\phi_e} = 0.3$ for the heavy displacement configuration. The agreement between theory and model experiment for the torsion response was also not

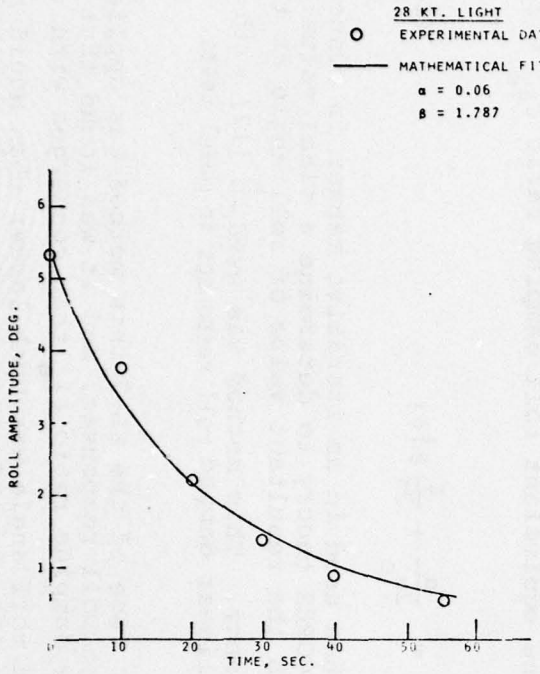


FIGURE 57 - Roll extinctions.

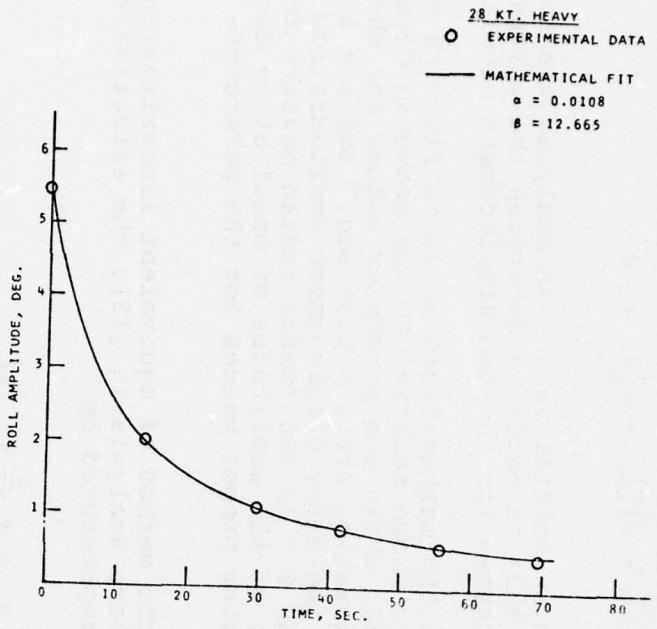


FIGURE 58 - Roll extinctions.

satisfactory when using these large values of effective roll damping, thereby providing another reason for their lack of credibility.

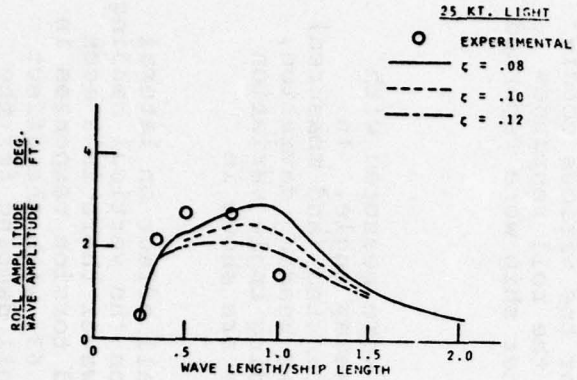
Some further illustrations of the influence of the magnitude of the roll damping coefficient ζ_ϕ are shown by the results in Figure 59 and 60. Both of these figures show roll response and torsion response for different values of ζ_ϕ, approximately ±0.02 about the average values assumed in [2] and also the calculations used in the present study ($\zeta_\phi = 0.1$ for the light displacement configuration and $\zeta_\phi = 0.09$ for the heavy displacement configuration). The effect of such small changes in ζ_ϕ is seen to be relatively large in some cases, especially for torsion for the light displacement configuration (Figure 59), while fairly satisfactory agreement is obtained for the roll motion in that case. The lack of agreement with torsion model data using any of the roll damping values was discussed in the preceding section of the report.

Another feature of the comparison between theory and model experiment was an inconsistent agreement regarding the roll resonance condition. While there was some indication of a resonant response for the heavy displacement configuration, at 25 kt. speed and 30° heading, which agreed with experiment, the same was not true for the light displacement configuration (25 kt., 60° heading). The experimental roll response for both configurations over the range of wavelengths, for the 25 kt. speed and the two headings (as shown in Figures 43 and 50) thus indicates a lack of agreement relative to resonance for the various conditions tested. Similar effects in regard to the roll responses in quartering seas for another large container ship were reported in [20].

4. Effect of Leeway Angle

As reported in [1], the heading angles were measured with a variation up to ±4° due to the observed leeway angle. In order to determine the sensitivity of the computed (and measured) results to this possible magnitude of angular heading deviation, some computations were carried out with heading angle variation of ±4° about the nominal value. The results are shown in Figures 61-65.

It can be seen that there is only a small effect on lateral bending moment, with a much smaller effect on the vertical bending moment due to the small heading change. However there is a much larger relative effect on the roll angle and torsion responses in quartering seas, as shown in Figures 62 and 63, with the effect being somewhat larger than the changes in roll damping for the same conditions indicated in Figures 59 and 60. Thus it appears that some of the results in the lateral plane responses are quite sensitive to heading angle derivatives, at least for the order of ±4° changes (which may not be the average leeway deviation in each case).



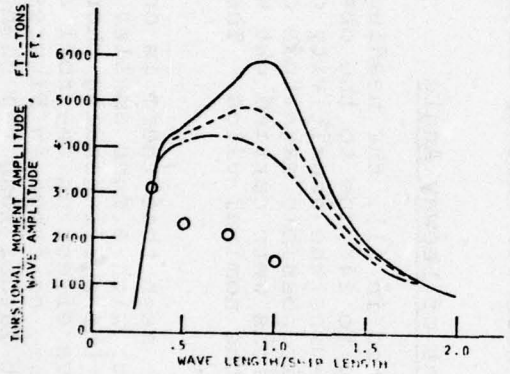
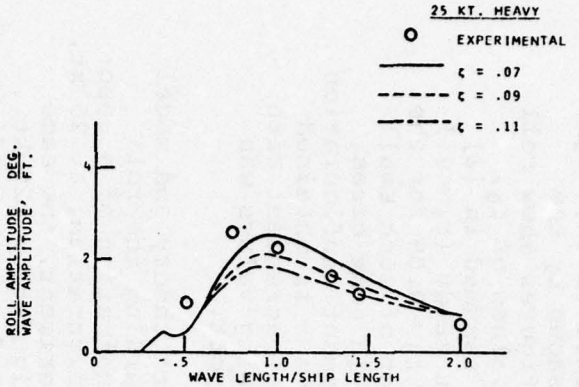


FIGURE 59 - Effect of critical roll damping, 60° heading



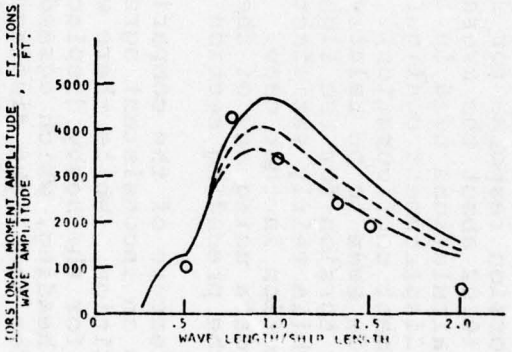


FIGURE 60 - Effect of critical roll damping, 30° heading

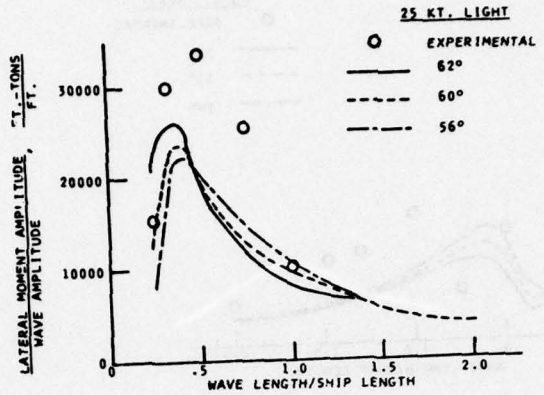


FIGURE 61 - Effect of leeway, 60° heading

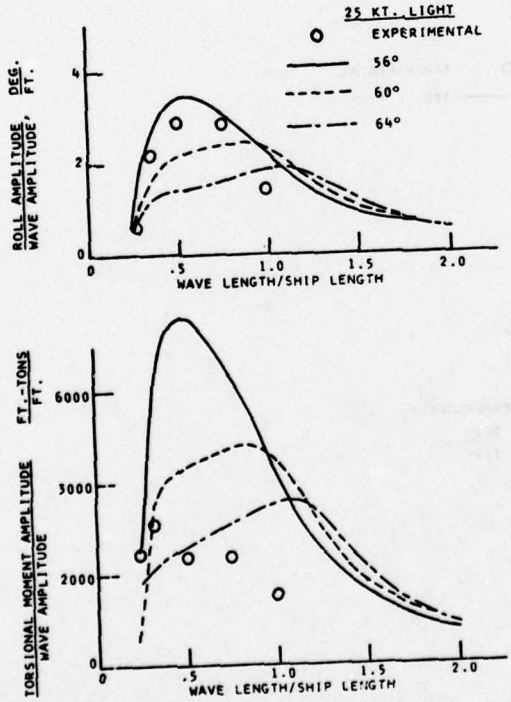


FIGURE 62 - Effect of leeway, 60° heading

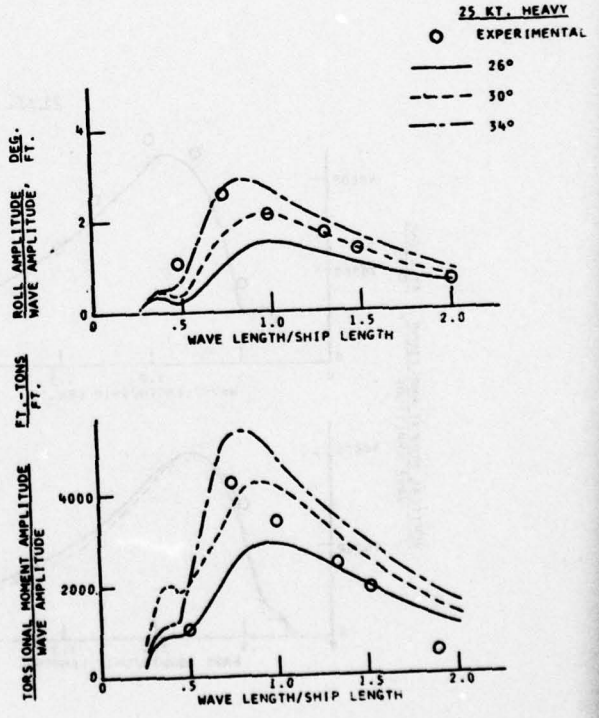


FIGURE 63 - Effect of leeway, 30° heading

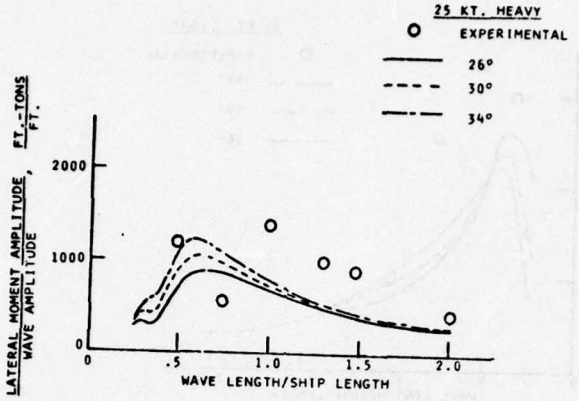


FIGURE 64 - Effect of leeway, 30° heading

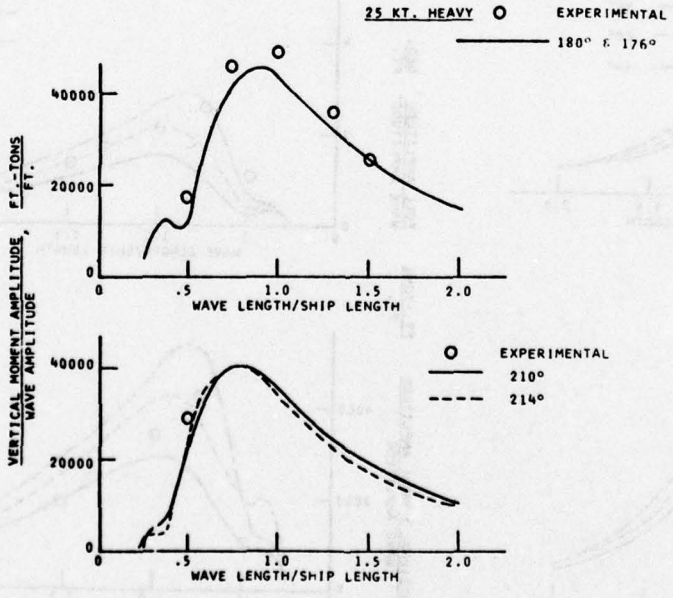


FIGURE 65 - Effect of leeway, 180° and 210° heading

5. Results of Computations for Dutch Container Ship

A similar type of large fast container ship model was tested in Holland at NSMB in oblique regular waves [23], with measurements of the same basic motions and wave loads. The model was a 1:55 scale of a full-scale ship of 270 m. length (LBP) with a displacement of 56,097 m. tons, so that the model size was significantly larger than that of the SL-7 model in [1]. In addition the model wave height in the tests was kept constant regardless of the wavelength, and corresponded to 4.4 m. full scale. A full description of the model characteristics, test conditions, procedures and results is presented in [23].

Since this ship is similar to the SL-7, and the test measurements were of the same general type as in [1], a comparison of the experimental data in [23] with the calculated results from the present extended SCORES theory would be a further test of the validity of the computer method for wave-load prediction. Some previous computations of these ship responses had been carried out ([24]) using the original SCORES program of [6], and the results for wave loads were sufficiently close to the model data, or followed the proper pattern of the model-load data, to represent a useful tool although the degree of agreement was not as good as the various cases illustrated in [5]. Representative results of computations with the extended SCORES program are shown here, compared to the model-test data of [23], and discussed in the following.

The results for heave and pitch motions, midship VBM and vertical shear for the ship in head seas (180° heading) are shown in Figures 66-69 for the forward speed corresponding to a Froude number $F_n = 0.245$. The agreement between theory and experiment in this case, for both amplitude and phase (relative to the wave elevation at the ship CG), is very good. Similar results were found for the case of bow seas (referred to as 225° heading), and an indication of the results for a lateral-plane response for this condition is the midship-torsion response shown in Figure 70. In that case the results of the original SCORES theory is also shown, with generally good agreement between theory and experiment from both theories for this particular response and condition.

The comparison for the case of quartering seas at 65° heading showed good agreement for heave and pitch motion and the midship vertical bending moment and vertical shear (representative results for VBM are shown in Figure 71). The roll-motion comparison was fair (Figure 72), with good agreement for midship lateral bending moment and lateral shear for this condition (see Figures 73 and 74). The midship torsion response in Figure 75 showed a much lesser degree of agreement.

For the case of 45° heading the comparison for the vertical-plane responses was good, and the midship lateral bending

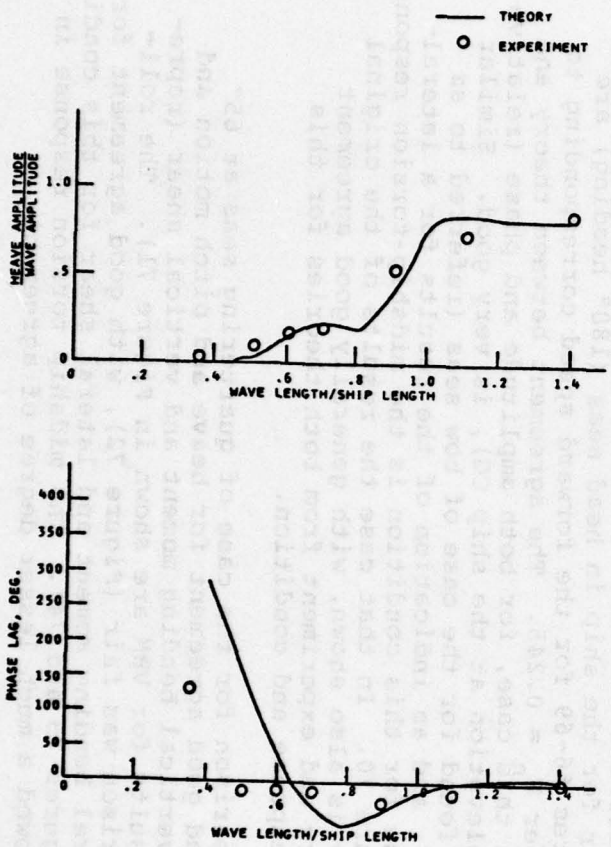


FIGURE 66 - Dutch container ship, F_n = .245, heading = 180°

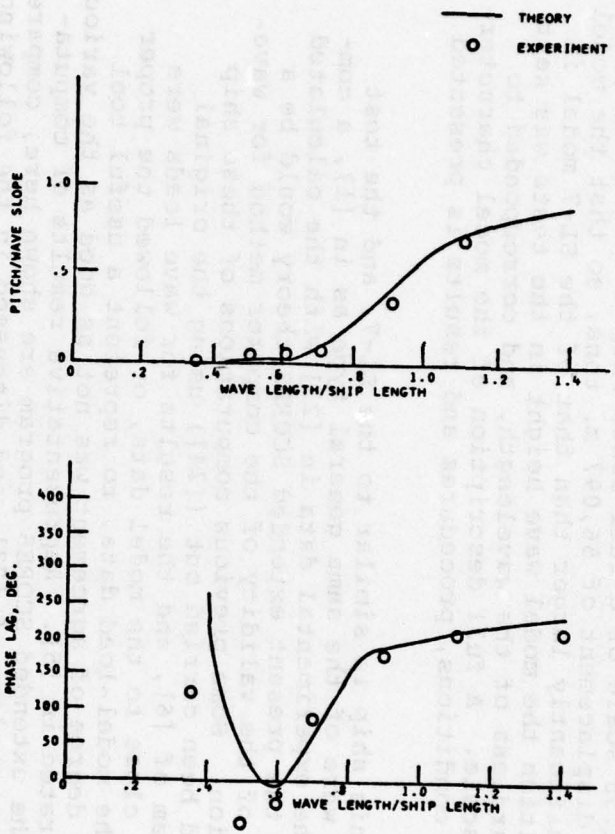


FIGURE 67 - Dutch container ship, F_n = .245, heading = 180°

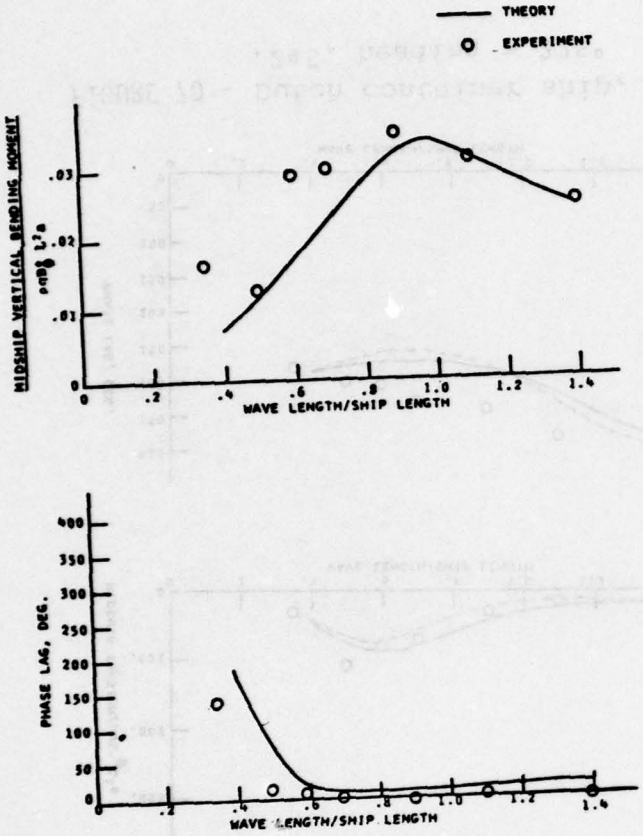


FIGURE 68 - Dutch container ship, F_n = .245, heading = 180°

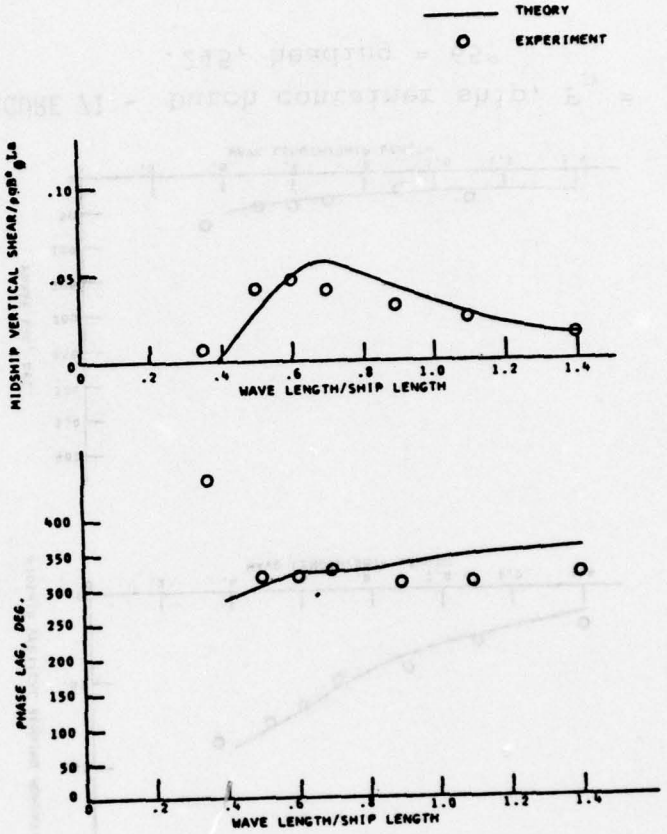


FIGURE 69 - Dutch container ship, F_n = .245, heading = 180°

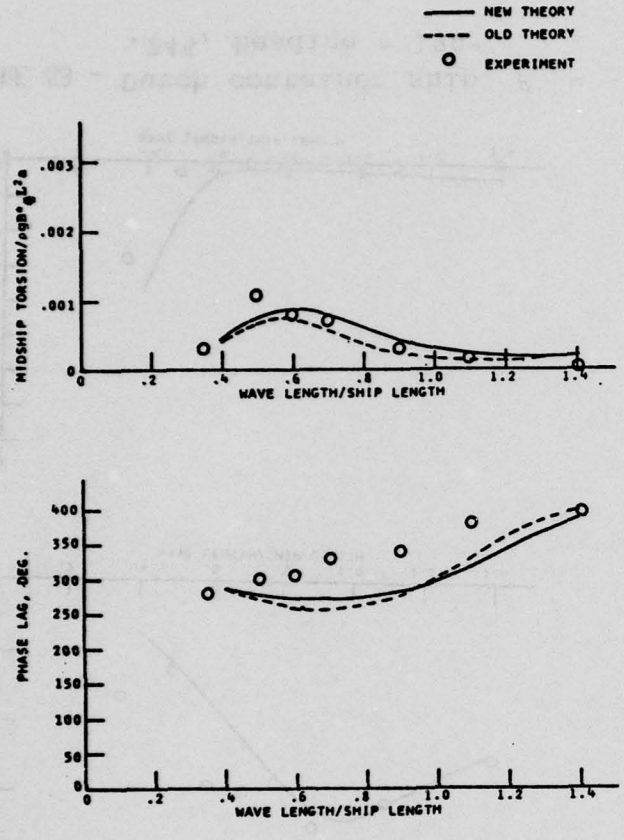


FIGURE 70 - Dutch container ship, F_n = .245, heading = 225°

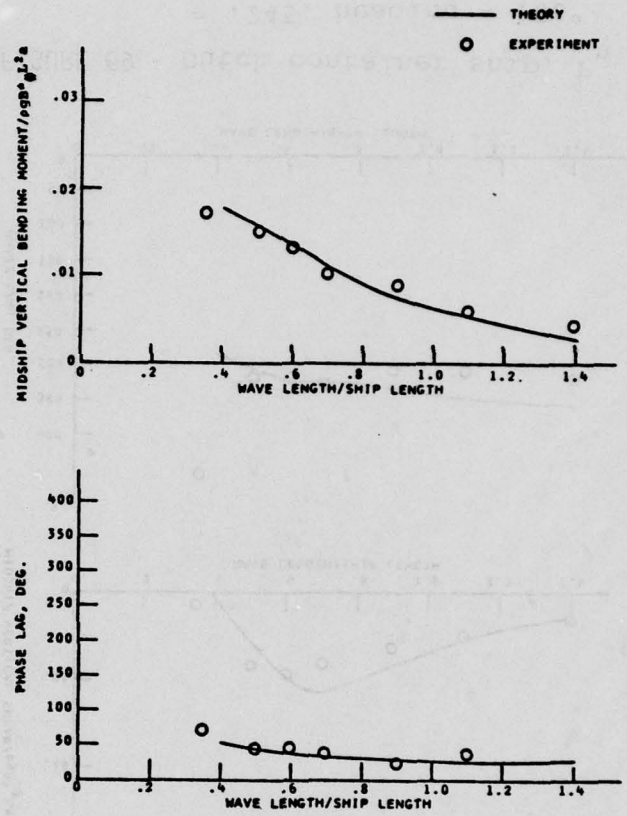


FIGURE 71 - Dutch container ship, F_n = .245, heading = 65°

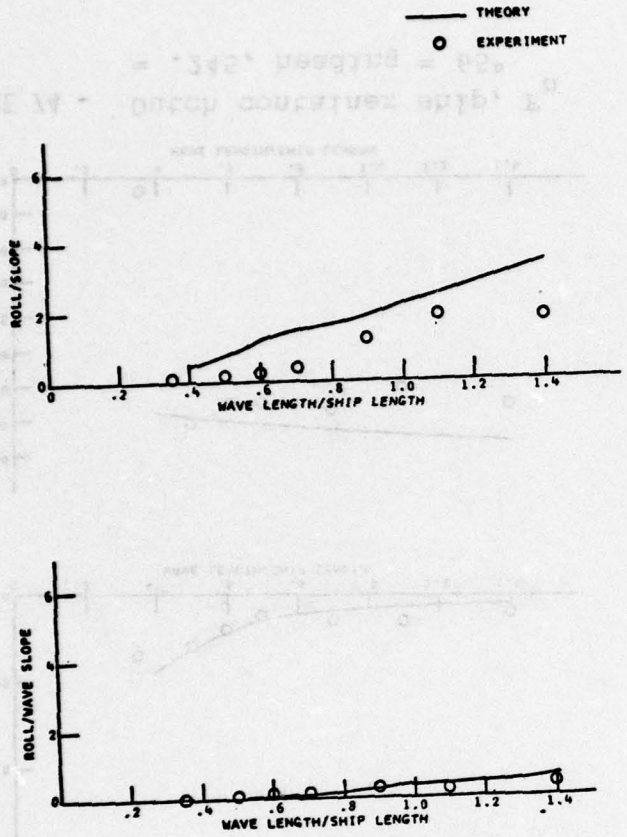


FIGURE 72 - Dutch container ship, F_n = .245

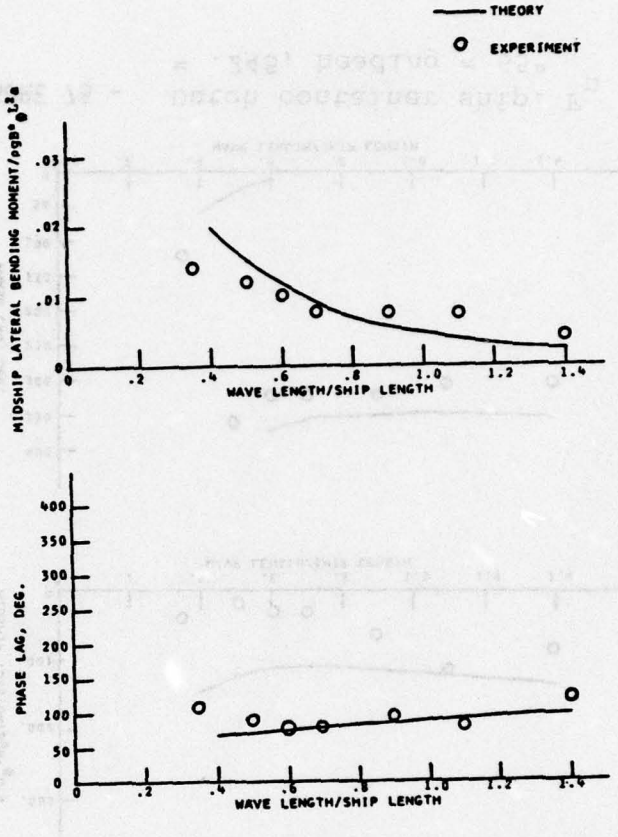


FIGURE 73 - Dutch container ship, F_n = .245, heading = 65°

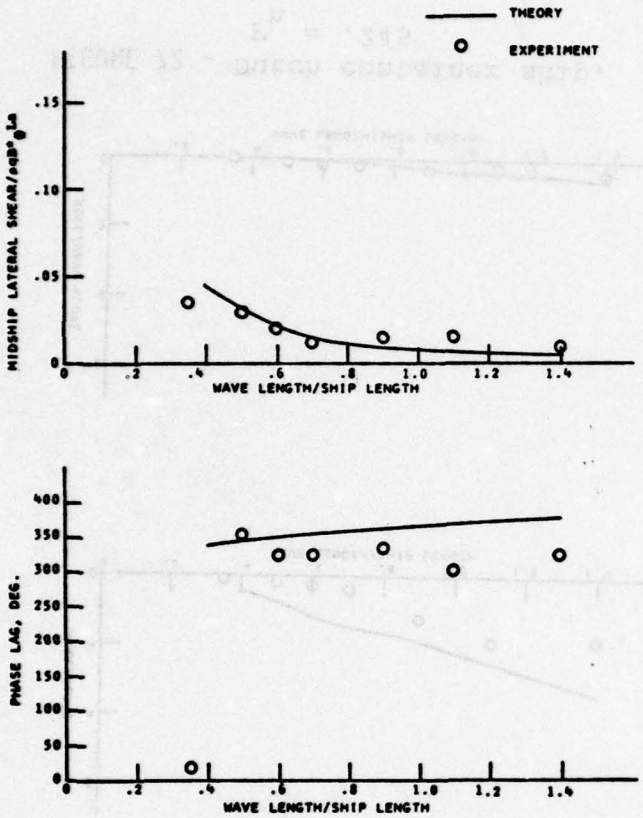


FIGURE 74 - Dutch container ship, F_n = .245, heading = 65°

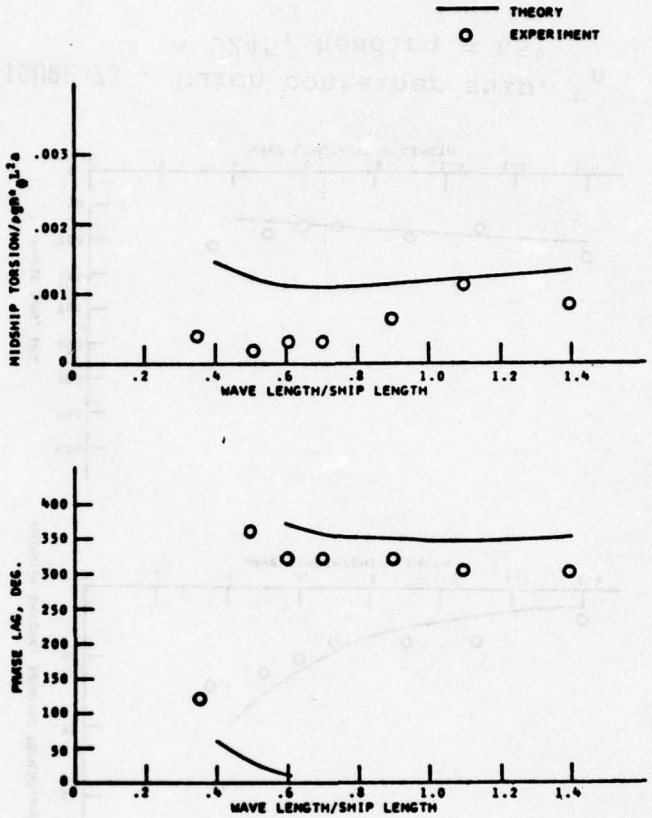


FIGURE 75 - Dutch container ship, F_n = .245, heading = 65°

comparison in Figure 76 was also quite good. However the torsion-response comparison was not satisfactory, as shown in Figure 77, although there was an improvement of the theory result relative to the original SCORES computations. This could possibly be related to the roll-motion results for this case, which are shown together with the results for the 25° heading case in Figure 78. The lack of adequate roll prediction for the 25° heading nevertheless did not lead to poor torsion response for this heading, as shown in Figure 79. Good agreement for the 25° heading was also found for both midship lateral bending moment and lateral shear, and similarly for the vertical-plane responses at this heading.

The comparisons between the model experiments of [23] and the present extended SCORES theory for this large fast container ship show generally good agreement between theory and experiment, with significant differences found in the roll motion and torsion responses for only a part of the conditions compared. It thus appears that the theory presented herein (i.e. the extended SCORES theory) has received further verification of its utility as a wave-load prediction tool as a result of these comparisons with data for a similar type ship under similar operational conditions.

6. Results of Computations for Series 60 Ship

Since the extended SCORES theory computed results have shown improved correlation with model experiments for the SL-7 (except for conditions where roll behavior and characteristics were anomalous), and have also improved the correlation for the Dutch container ship tested in [23], the question of its utility for other ships arises. This is due to the fact that many conventional ships have shown agreement of model-test data with the original SCORES theory computations (e.g. see [5]), and it is possible that the extended SCORES theory results could alter the degree of agreement between theory and experiment. For the large fast container ships the influence of forward speed is expected to be significant, especially in view of the fact that the theory modifications (i.e. additional terms) required to produce the extended SCORES theory are proportional to the forward speed.

In order to determine the effect of the extended SCORES theory modifications on the correlation of computer results with model-test data, some computations were carried out for the same Series 60 ship that was studied in [5], viz. the model with $C_B = 0.80$ that was tested in [25]. Representative results for the wave loadings, i.e. vertical and lateral bending moments and the torsional moment (all at midship), at different headings for the speed $F_n = 0.15$ are shown in Figures 80-84. These figures show the model-test data, the computed results using the original SCORES theory (old) and those using the present extended SCORES theory (new). It can be seen from these figures that the differences between the two theoretical results are not very large, with a generally better agreement with the experimental data in most cases (but not in all) for the extended SCORES theory.

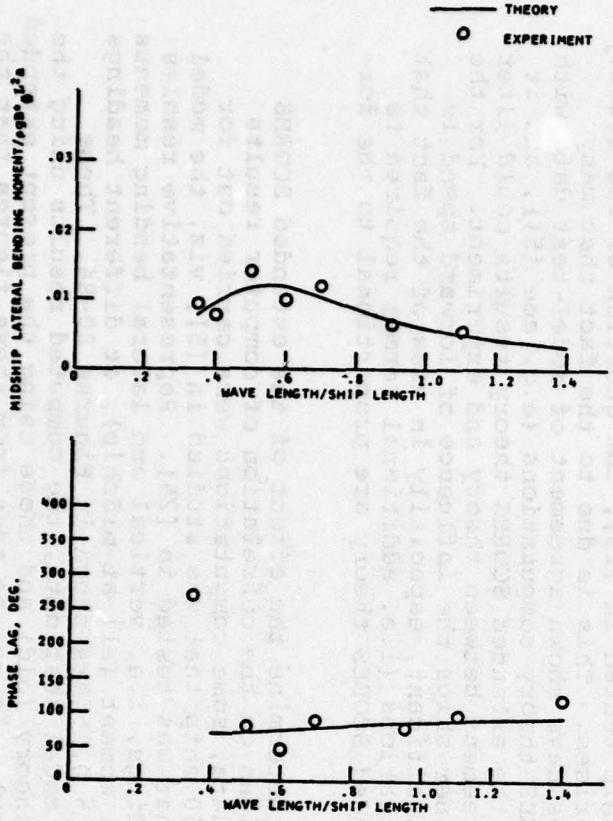


FIGURE 76 - Dutch container ship, F_n = .245, heading = 45°

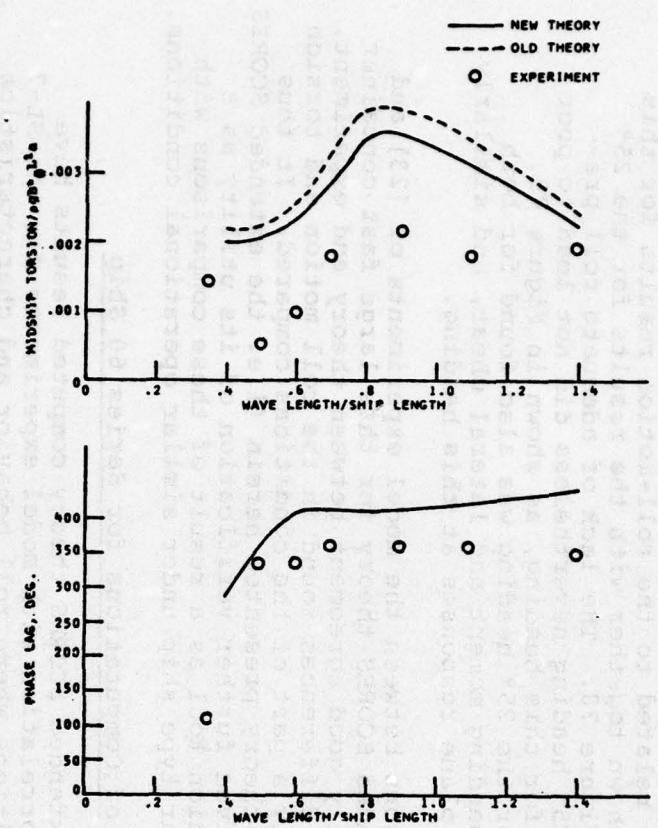


FIGURE 77 - Dutch container ship, F_n = .245, heading = 45°

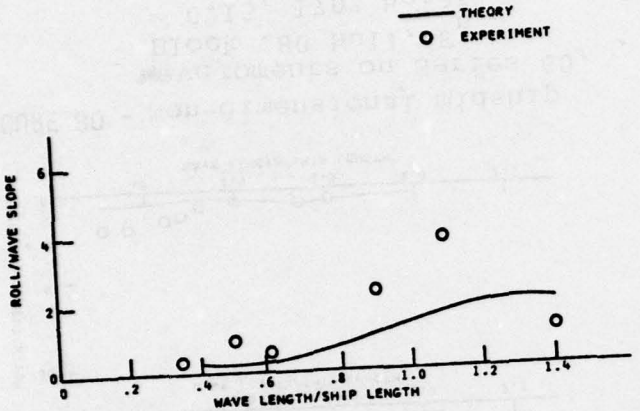
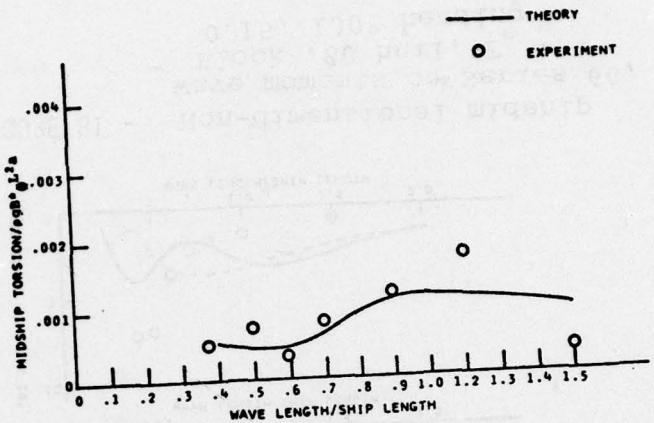
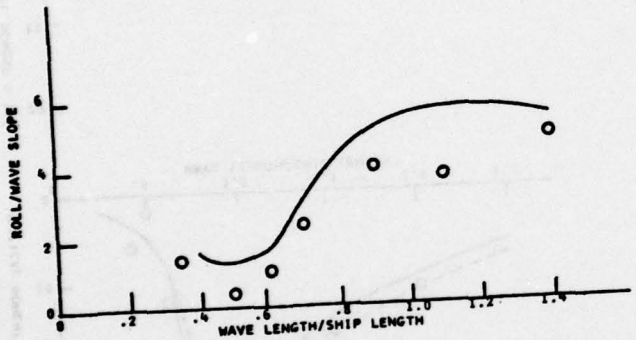


FIGURE 78 - Dutch container ship, F_n = .245, heading = 25°





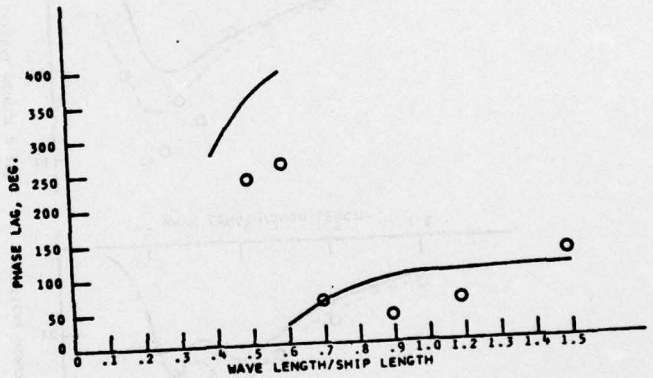


FIGURE 79 - Dutch container ship, F_n = .245, heading = 25°

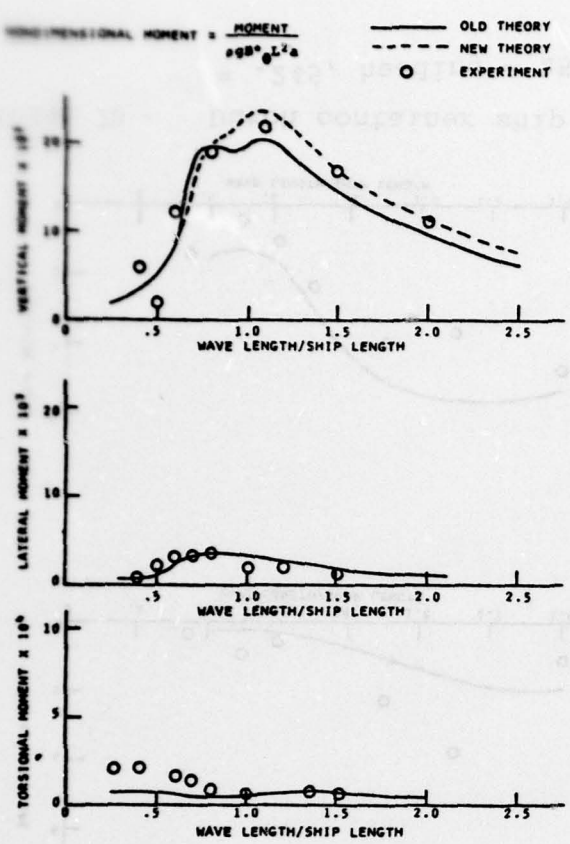


FIGURE 80 - Non-dimensional midship wave moments on Series 60, Block .80 hull, F_n = 0.15, 170° heading

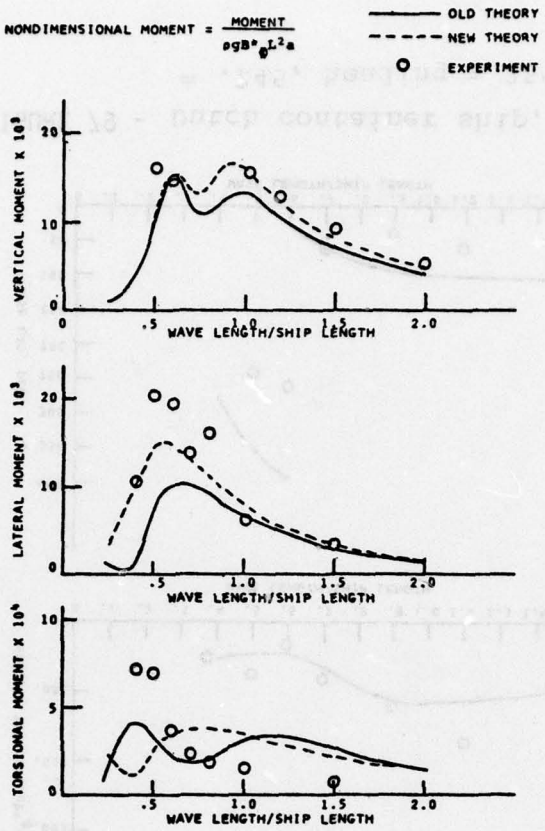


FIGURE 81 - Non-dimensional midship wave moments on Series 60, Block .80 hull, F_n = 0.15, 130° heading

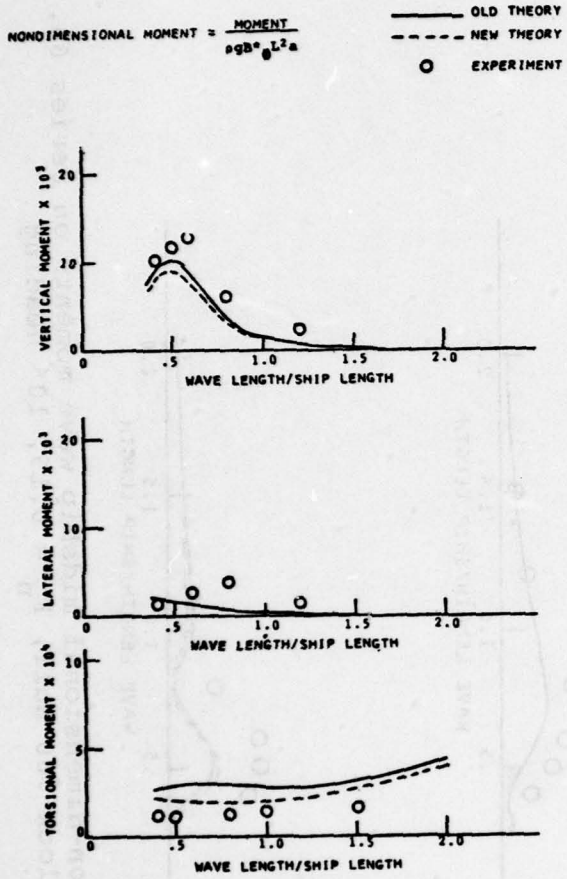


FIGURE 82 - Non-dimensional midship wave moments on Series 60, Block .80 hull, F_n = 0.15, 90° heading

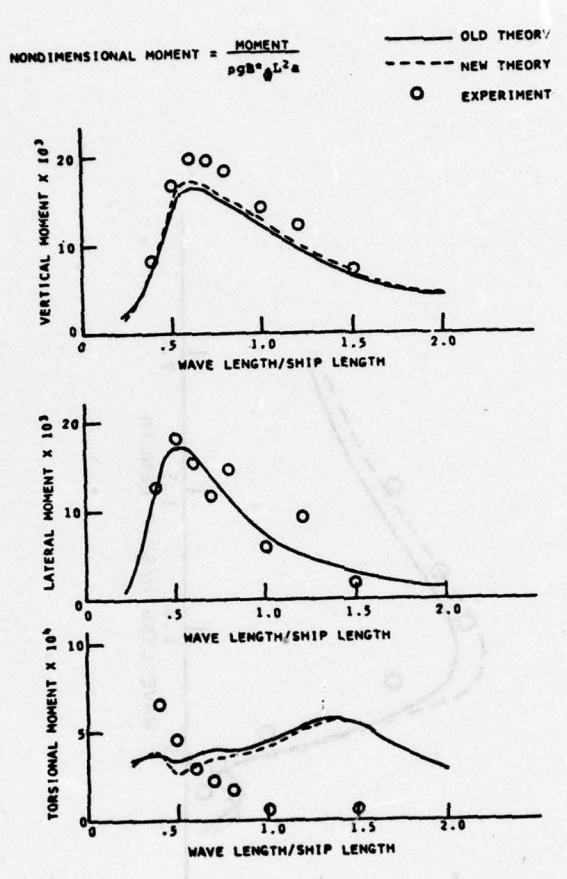


FIGURE 83 - Non-dimensional midship wave moments on Series 60, Block .80 hull, F_n = 0.15, 50° heading

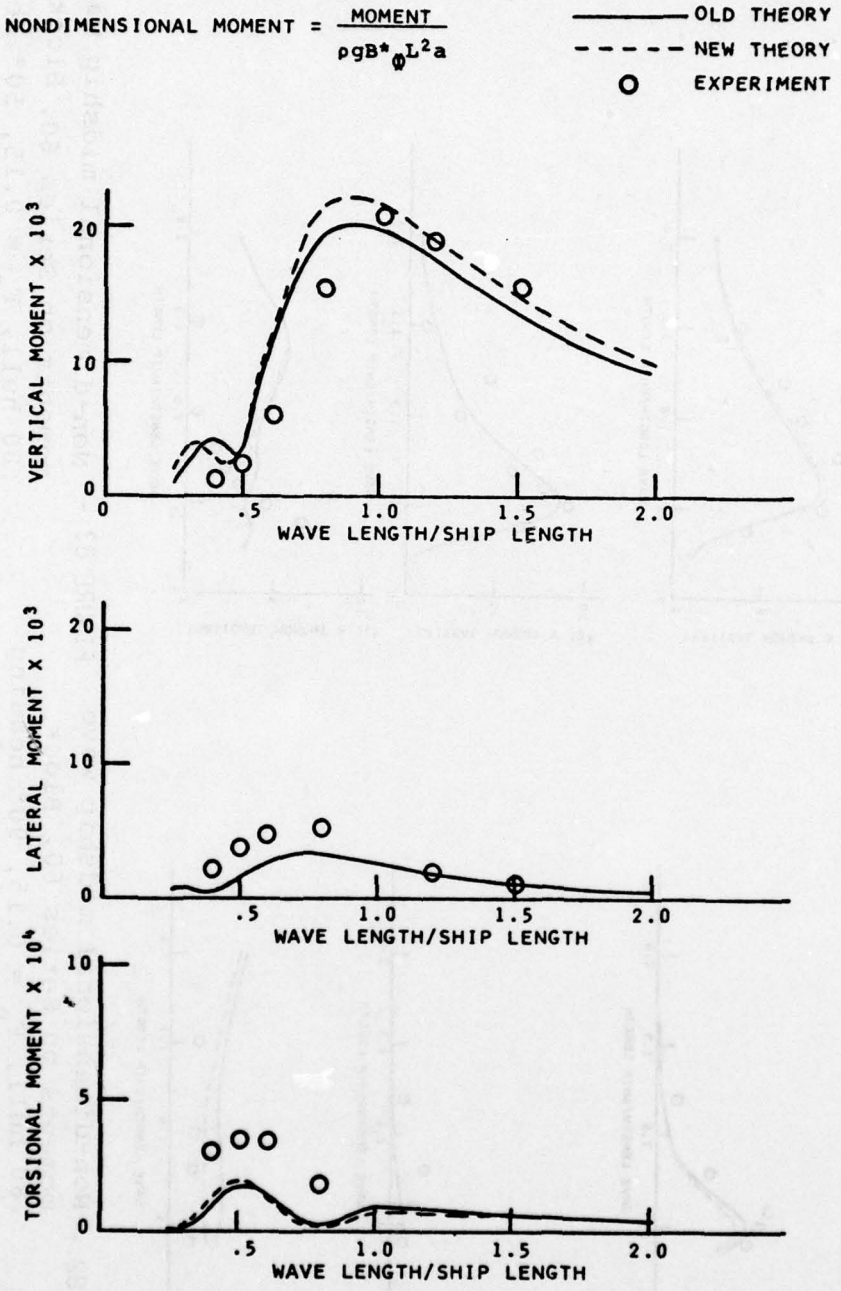


FIGURE 84 - Non-dimensional midship wave moments on Series 60, Block .80 hull, F_n = 0.15, 10° heading

The difficulty in adequate prediction of torsion is still present using either theoretical approach for some of the conditions, which may probably be due to the same reasons as discussed in [5]. Thus it can be seen that the extended SCORES theory is valid for conventional ships and is thus a useful prediction tool for ship wave loads.

ANALYSIS AND COMPUTATIONS FOR LOW ENCOUNTER FREQUENCY

In following and quartering-sea heading conditions for the SL-7 model, the encounter frequencies were found to be relatively low. In view of the logarithmic behavior at low frequency of the vertical sectional added mass (A'_{33}), it was thought during the work reported in [2] that this behavior could possibly have an unduly large effect that could influence the computed results for this ship in that range of operation. Some computations were carried out in [2] with this added-mass term set equal to zero throughout the entire wavelength range in following and quartering seas, with results that showed significantly improved agreement of this particular modified theory with the model-test data, primarily for the vertical bending moment and vertical shear at midships. While such an improvement did occur for these cases, as shown in [2], the use of this procedure would not be generally applicable to all headings; would not necessarily be appropriate for ships other than the SL-7 (based upon this single set of results); and the selection of particular conditions for the encounter frequency wherein the computational technique would "shift" to include the constraint with $A'_{33} = 0$ could not be easily established for general use.

While the results of the present extended SCORES theory for the SL-7 have produced significant improvement in the correlation of the calculated results for the vertical-plane wave loads with those obtained from model tests, there are still basic questions as to the general validity of any type of strip theory for conditions with low encounter frequency. This is due to the basic requirement of strip theory being valid for high frequencies (or short wavelengths), but which has been successfully applied to longer wave conditions (see [26] for a general discussion of assumptions used in various ship-motion theories). Since the various vertical-plane hydrodynamic terms derived from strip theory may not have validity for some of the low-frequency conditions of the SL-7 in following and quartering seas, a theoretical approach was considered wherein these terms would be neglected, i.e., $A'_{33} = N'_{33} = 0$. The resulting theory would then include hydrostatic forces, as well as wave-excitation forces due to the Froude-Krylov effect and the pressure gradient variation with depth, together with the ship inertia forces. For the vertical plane this would involve solution of a second-order differential equation for both heave and pitch, which are coupled only hydrostatically, in order to obtain those motion responses. The local loading would then be found in terms of the ship inertial loads and the distributed hydrostatic and wave-force

terms, in the same manner as indicated in [5] but without any hydrodynamic terms due to the added mass and damping, i.e. $A_{33}^{1} = N_{33}^{1} = 0$ throughout the computations. Since the encounter-frequency conditions for the use of this method do not include the resonant heave and pitch natural frequencies, no difficulty should arise due to the lack of a damping mechanism for these conditions.

The results of the computations for the SL-7 heave and pitch motions, using this approach that neglects hydrodynamic forces due to motions, shows generally small differences from the motion responses obtained from the extended SCORES theory. A typical illustration of the comparison of the theoretical predictions of heave and pitch motions, for the case of following seas (0° heading), is given in Figure 85. Since the motions are generally well predicted by either the original or extended SCORES theories, the model data is essentially bracketted by the curves shown in Figure 85 and this method, neglecting hydrodynamic forces, is also an adequate procedure for determining ship motions.

Calculations of the midship bending moment for the SL-7 at headings of 0°, 30°, and 60° were also made using this method, and the comparison between theory and experiment is shown in Figures 86-88. There is generally an improvement in the correlation of the VBM amplitudes relative to that obtained from the extended SCORES theory, except for the shorter wavelengths. However the phase angles show large errors, of the order of 45° -150°, which tends to cast some doubt on the basic utility of this method for wave-load prediction at low encounter frequencies. Somewhat similar type results were found when applying this theoretical model to the Dutch container ship tested in [23], with fairly close agreement between the amplitudes from this special theory and the results of the extended SCORES theory. The close agreement with experimental amplitudes for motion and loads in the vertical plane is useful, but the same is true for the results of the extended SCORES theory. The lack of phase agreement provides further basis for use of the extended SCORES theory as a prediction tool rather than the application of special methods (i.e. involving neglect of hydrodynamic added mass and damping in the vertical plane) for the case of low encounter frequencies.

DISCUSSION OF SL-7 MODEL TEST DATA

In order to judge the general validity of the model-test data results for the SL-7 that were obtained in [1], a comparison of some nondimensional wave loads from that investigation was made with those obtained from a similar ship, viz. the Dutch container ship tested in [23]. The main item of interest was the midship vertical bending moment, which is the largest moment

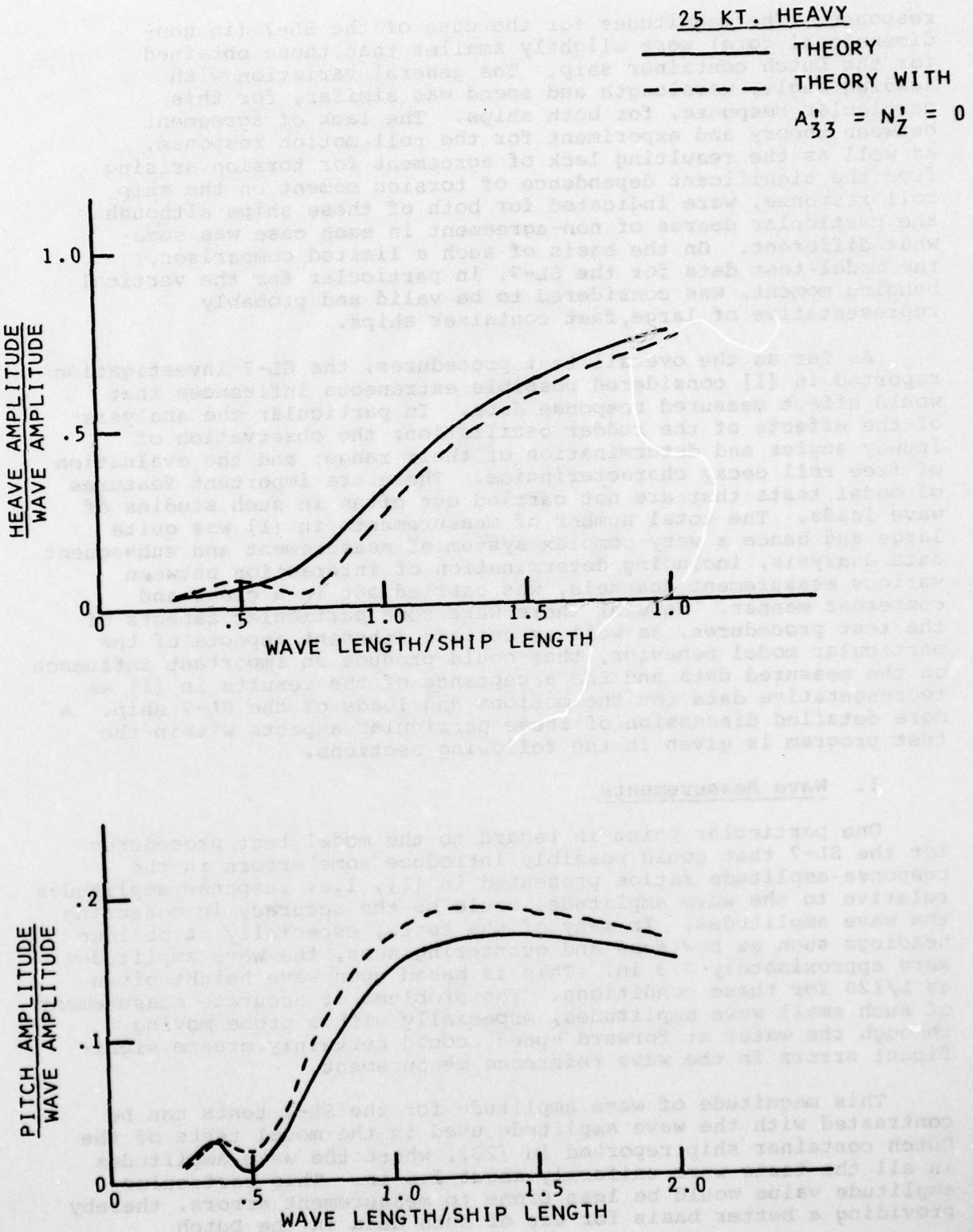


FIGURE 85 - Heave and pitch, 0° heading

response. The magnitudes for the case of the SL-7 (in non-dimensional form) were slightly smaller than those obtained for the Dutch container ship. The general variation with heading angle, wavelength and speed was similar, for this particular response, for both ships. The lack of agreement between theory and experiment for the roll-motion response, as well as the resulting lack of agreement for torsion arising from the significant dependence of torsion moment on the ship roll response, were indicated for both of these ships although the particular degree of non-agreement in each case was somewhat different. On the basis of such a limited comparison, the model-test data for the SL-7, in particular for the vertical bending moment, was considered to be valid and probably representative of large, fast container ships.

As far as the overall test procedures, the SL-7 investigation reported in [1] considered possible extraneous influences that would affect measured response data. In particular the analysis of the effects of the rudder oscillation; the observation of leeway angles and determination of their range; and the evaluation of free roll decay characteristics. These are important features of model tests that are not carried out often in such studies of wave loads. The total number of measurements in [1] was quite large and hence a very complex system of measurement and subsequent data analysis, including determination of interaction between various measurement channels, was carried out in a clear and competent manner. However there were some particular aspects of the test procedures, as well as certain inherent aspects of the particular model behavior, that could produce an important influence on the measured data and the acceptance of the results in [1] as representative data for the motions and loads of the SL-7 ship. A more detailed discussion of these particular aspects within the test program is given in the following sections.

1. Wave Measurements

One particular point in regard to the model-test procedures for the SL-7 that could possibly introduce some errors in the response-amplitude ratios presented in [1], i.e. response amplitudes relative to the wave amplitude, could be the accuracy in measuring the wave amplitudes. In many of the tests, especially at oblique headings such as bow seas and quartering seas, the wave amplitudes were approximately 0.3 in. This is based upon wave height given as L/120 for these conditions. The problems of accurate measurement of such small wave amplitudes, especially with a probe moving through the water at forward speed, could certainly create significant errors in the wave reference measurement.

This magnitude of wave amplitude for the SL-7 tests can be contrasted with the wave amplitude used in the model tests of the Dutch container ship reported in [23], where the wave amplitudes in all the tests were uniformly about 1.6 in. This particular amplitude value would be less prone to measurement errors, thereby providing a better basis for use of such data in the Dutch

investigation. Since no detailed indication of error level magnitudes in wave amplitude per se were provided in the SL-7 report (i.e. [1]), the only judgment as to the accuracy of the wave-amplitude measurements in that case is based upon the generally small magnitude used and the prospect of possible larger errors in that case.

2. Roll-Decay Characteristics

As indicated previously, the special smooth-water roll-extinction tests that provided the roll-decay time histories were a useful addition to the direct model-test measurements of the SL-7 motions and loads in waves. This information could then be used to obtain proper numerical values of the coefficients in the roll-damping representation, as well as indicate the nature of the roll-damping characteristics. For zero speed the roll-decay curve was obtained after releasing the model from an initial roll-angle displacement, and the resulting decay curve indicated linear roll damping. For the conditions when the model was running at a speed equivalent to 28 kt. (full scale), the decay curves represented the response obtained after a steady resonant roll was introduced via the rudder oscillation, with the decay record obtained after the rudder oscillation was stopped.

The method of analysis used to determine the linear and nonlinear coefficients that are present in the representation of roll motion given in Eq. (24) is based upon the decay from an initial displacement, and assumes that the roll angular velocity is initially zero at that instant as well. It is possible that the test method used with the model running at speed did not satisfy that particular requirement, but there is no detailed discussion of the procedures used given in [1]. If there was a non-zero roll angular velocity present, then the solution method used to obtain the values of the parameters α and β in Eq. (24) would not be applicable, so that any values found would not be the proper parameter values. Perhaps that is the reason why the particular values found for α and β from these runs at speed provided too large a value of effective roll damping, which was the result indicated in a preceding section that considered the question of the influence of nonlinear roll damping.

3. Roll Static and Inertial Characteristics

A discussion was given previously, when considering lateral-plane motion and load responses, of an inconsistency between the values of the transverse metacentric height GM and the location of the VCG relative to the waterline at the LCG position, i.e. the distance known as $\overline{OG}$ in [5]. The hydrostatic characteristics of the waterplane, as well as the location of the VCB, determine the location of the metacentre M. Since the ship model was oriented in accordance with the data presented in [1], all of these hydrostatic properties obtained from calculation should be proper values for the ship. The value of VCG given in [1] would then not be

consistent with the GM value in accordance with the computations. Since the computations produced proper displacement, LCB and LCG location, etc. the question arises as to whether some error was present in the model or the model-test procedures. The possible magnitude of difference in GM obtained from the computed values (using the indicated VCG in [1]) would exceed significantly any change in GM due to free-surface effects, so that there appears to be some fundamental problem in reconciling the relations between GM and the VCG location given in [1]. The extent of this possible error in the quantities could then contribute significantly to the lack of correlation between theory and experiment in lateral-plane responses for quartering seas, since the influence of roll motion on lateral-plane loads is significant in that region.

4. Directional Control and Influence on Lateral-Plane Responses

One of the problems in conducting the model tests, which was reported in [1], was due to certain difficulties in maintaining control of the ship heading. In some cases the model developed large heel and yaw angles, and only the runs wherein such effects did not occur were reported as the source of data presented in [1]. Due to the influence of different starting-up transients in the carriage system, it is possible that a particular run would not necessarily be representative of the actual conditions which would be experienced when running at a particular heading and speed in a wave system. The only way to really determine the validity of such data obtained from any run would be to have check runs for the same basic condition, and as a result of the various control difficulties such repeat runs may not have been made or in some instances could not be obtained. This behavior could possibly be responsible for some error in the obtained ship motions and loads, and the effect of this aspect has not been presented in any specific quantitative form in [1].

The sensitivity of some of the lateral-plane responses to changes in heading, as manifested by the leeway angle, were shown to be possibly significant in magnitude according to computations exhibited in Figures 61-64. The control difficulty experienced in [1] could have resulted in a variation of heading manifested by a leeway angle of such a magnitude ($\sim 4°$) that differences in the responses could arise due to that effect, as well as the problem of repeatability discussed above. All of these effects are specific problems that were experienced with this particular model, at the scale it was tested, when using the apparatus and techniques available at the testing organization. Possible modifications in the equipment and test technique for such tender high-speed ships might have resulted in different response magnitudes in the lateral plane, but the extent of such differences cannot be precisely established as a means of assessing the utility of the present test data.

5. Effect of Rudder and Data-Measurement Precision

As indicated in [1] the effect of rudder oscillation on lateral-plane responses is most significant for those cases where roll motion was largest, viz. in quartering seas. The magnitude of this effect on the lateral responses is indicated to be about 20% in [1], but according to some more detailed assessments based on the information in [1] the effect could be somewhat larger for certain cases. On that basis it appears that there is a fairly substantial allowable "band" about the model-test data which could allow an improved degree of correlation with any theoretical results sufficiently close to lie in that band. However the comparison between theory and experiment for quartering-sea lateral-plane responses shows larger differences than that, especially for the torsion responses. The lack of good correlation with roll motion, and its influence on such results, has been discussed previously and that is probably the major factor rather than consideration of rudder effects.

The general level of measurement accuracy for all of the model-data responses given in [1] has been stated as 5-10% (in that report) or as a fixed threshold, whichever is greater. These levels allow a wider band around the model data generally, for both vertical and lateral-plane responses, thereby allowing for an improvement in the correlation between theory and experiment when viewed in this manner. However this general statement as to measurement accuracy bounds does not relieve the prospect of other errors that may be present in the data due to other distinct effects that have been isolated and discussed previously in the present report.

CORRELATION BETWEEN THEORY AND EXPERIMENT

All of the preceding information and discussion regarding theory and experiment is aimed at evaluating the degree of correlation between these two approaches for predicting full-scale ship loads, with particular application to the SL-7 ship. This particular step is important since an entire program of investigation, including structural modeling, finite-element analyses, full-scale loads and motions measurement, wave measurements on the full-scale ship, etc. is being carried out under the Ship Structure Committee with support of other organizations as well. The entire investigation provides an excellent opportunity to determine the structural loads (and subsequent ship stresses) in many environmental situations, so that methods of analysis and prediction can be better assessed as to their utility for design purposes. A complete description of the entire SL-7 program is provided in [27].

The present correlation study is aimed at determining the relative capabilities of model tests and computer calculations as a means of predicting ship structural loads in waves. Previous

studies, e.g. [5], have shown the utility of computation by means of comparison between the theory results and model-test data, where good agreement between the two approaches provided a validation of the computer method. Since computation methods are much more efficient then model tests, from both the economic and time of performance points of view, the use of this method was enhanced by such a successful correlation.

However, in the case of the SL-7, the degree of correlation between theory calculations and model-test data shown in [2] was relatively poor. This particular class of ship, viz. a large, fast container ship, introduced special conditions due to its high speed coupled with test conditions for short waves that were not experienced in any prior studies using the theory and computer program of [5] and [6]. The additional analyses carried out in the present study shows that the most significant aspect of the theory which improved the degree of correlation between theory and experiment was the inclusion of additional terms in the equations, resulting in the extended SCORES theory. These additional terms are proportional to forward speed and have their largest influence at high speed, which is consistent with the results for this case.

Computations with the extended SCORES theory were applied to another large, fast container ship with good agreement between theory and experiment, as shown in Figures 66-79. The conditions there were essentially the same as for the SL-7, with similar high speed (and Froude number) and covering headings down to quartering seas. The same theory was applied to a conventional Series 60 ship model, for which the original SCORES theory showed fairly good agreement with model-test data in [5], and the degree of agreement was somewhat improved by this extended-theory method. Thus there is no degradation of the good results obtained in [5], while agreement for the case of large, fast container ships at all headings is also found by use of the extended SCORES theory. The agreement was generally good for both vertical plane and lateral-plane responses, with a reduced agreement in the lateral plane. This is probably due to use of an estimated linear roll-damping value, lack of information on detailed distribution of roll-inertial properties along model hull, and other factors related to roll-motion influence that have been discussed herein as well as other references (e.g. [5], [20]).

In the case of the SL-7, the agreement between the extended-theory calculations and model-test data for vertical-plane responses was generally good, with a significant improvement relative to the results obtained in [2]. This was found over the entire heading range, from head through following seas. The differences between theory and experiment for vertical-plane loads were about 10-15%, while the general precision of data measurement is given in [1] as 5-10%. This type of agreement is certainly satisfactory, and is consistent with the results obtained in [5] as well as being representative of the present state of the art in computer prediction of ship motions and loads. Application

of the extended SCORES theory directly gave these results, and it was not necessary to use any altered equation system for different frequency ranges, as was done for some low-frequency cases (only as an illustration of an approach) and shown in Figures 86-88.

For the lateral-plane response of SL-7, the agreement was still poor, especially for quartering seas. An improvement relative to the results of [2] was obtained for bow-sea headings, with fairly good agreement for some responses, but the conditions in quartering seas are more important since larger lateral-plane responses are experienced there, primarily due to the influence of large roll motions. The significance of roll motion in this regard, where poor roll-response correlation results also in poor lateral-load-response correlation, is an important feature of the whole problem. In bow seas, with very small roll motion and hence small effect on lateral-load responses, the correlation between theory and model experiment was generally good. Thus concern is directed toward the roll characteristics of the SL-7 model in the tests reported in [1].

A number of items related to the roll motion of the SL-7 model were discussed in preceding sections of this report. The sensitivity of calculated load results to the roll-damping value and also the general level of roll-motion response has been amply illustrated. A number of features of the model roll characteristics have been shown to be questionable, such as the static roll and inertial characteristics that relate GM and $\overline{OG}$, as well as the directional control problem of the particular model in [1] that certainly had an influence on the rolling responses. Questions as to repeatability of certain data runs, wave-measurement accuracy, the effect of heading deviations, sufficient length of run at low frequency of encounter, etc. are all present for just the range of conditions where difficulty in correlation between theory and experiment is found for this SL-7 model.

Another aspect of rolling, viz. the determination of roll-damping-decay curves when running at forward speed, did not provide enough information as to details of conditions that would allow proper evaluation of the linear and nonlinear damping parameters as has been done for cases at zero speed in other applications. However that aspect can be viewed as secondary until the questions concerning the proper static and inertial roll properties is reconciled, as well as the influence of directional control difficulty on roll and lateral-plane load responses.

On the basis of all of these questions and unknown features, it appears that the model tests, at least in quartering seas, should be run again with more detailed concern as to repeatability, etc. Necessary model-apparatus modifications, or use of facilities that have appropriate test equipment for tender, fast, surface ships, should be insured to eliminate the difficulties experienced in [1]. Perhaps the use of a larger model, with larger wave heights in the tests, would be a more suitable procedure for repeat tests in this

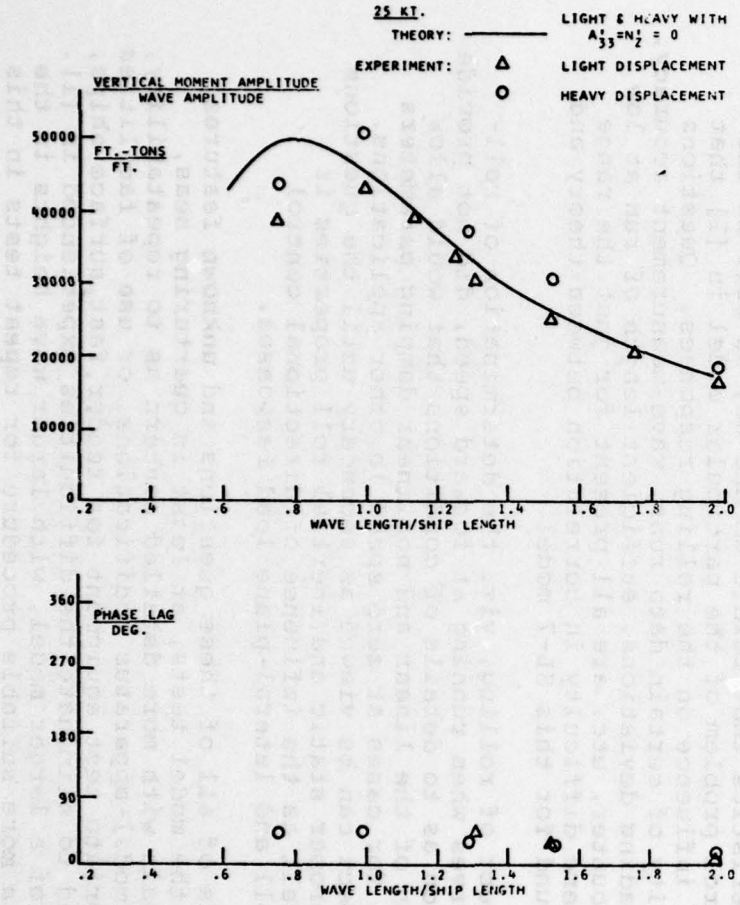


FIGURE 86 - Midship vertical wave bending moments and wave phase lag, 0° heading

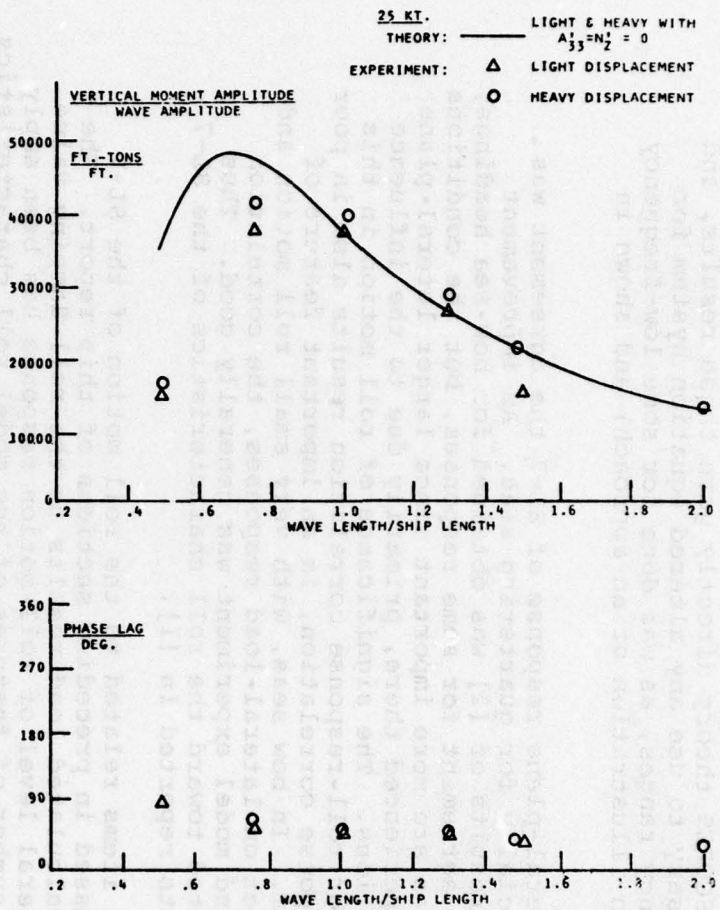


FIGURE 87 - Midship vertical wave bending moments and wave phase lag, 30° heading

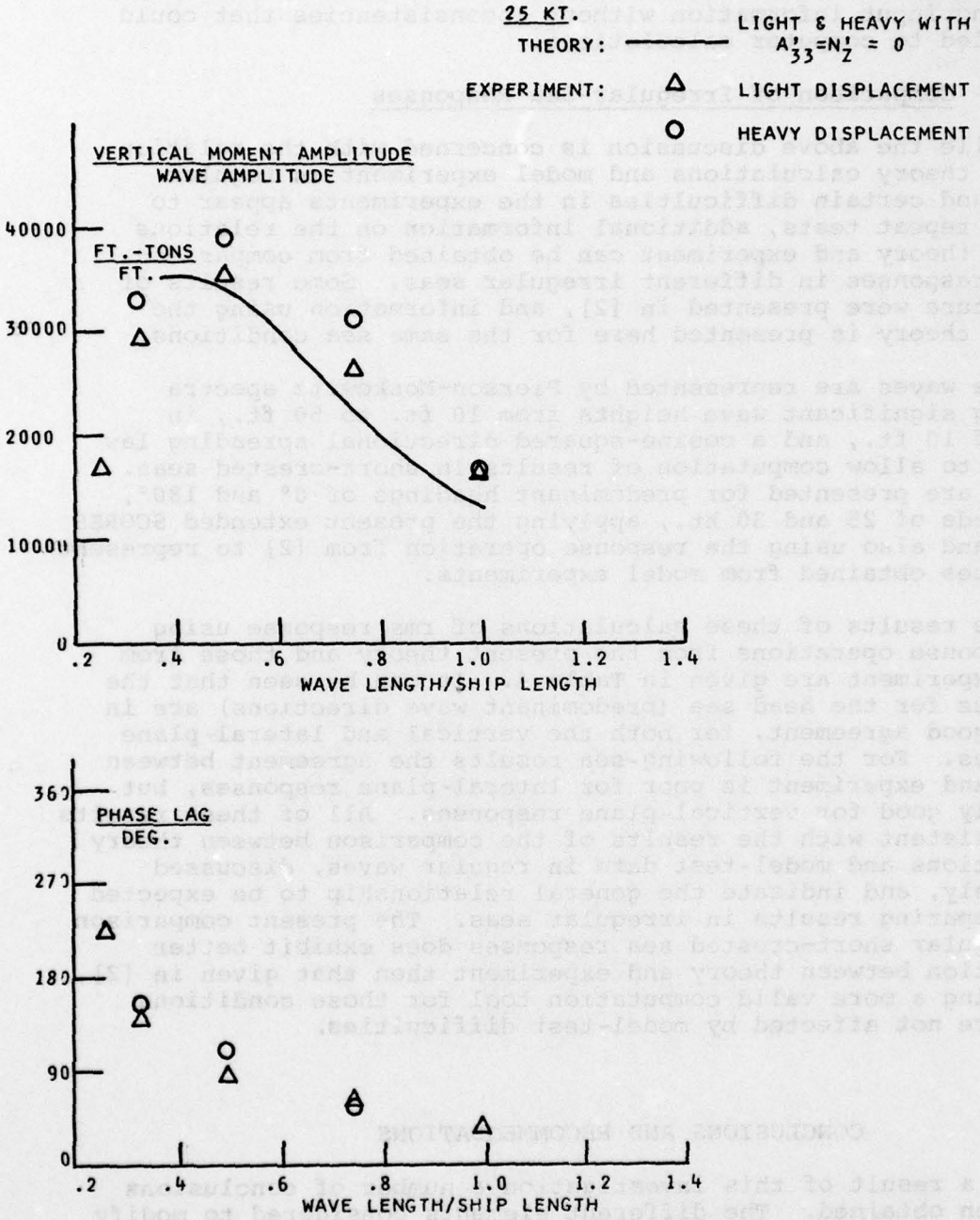


FIGURE 88 - Midship vertical wave bending moments and wave phase lag, 60° heading

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A CORRELATION STUDY OF SL-7 CONTAINERSHIP LOADS AND MOTIONS - M--ETC(U)
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area. Similarly the larger model would allow more accurate determination of roll static and inertial properties, thereby providing input information without inconsistencies that could be applied to computer calculations.

1. Comparison of Irregular-Sea Responses

While the above discussion is concerned with the relation between theory calculations and model experiment in regular waves, and certain difficulties in the experiments appear to warrant repeat tests, additional information on the relations between theory and experiment can be obtained from comparison of rms responses in different irregular seas. Some results of this nature were presented in [2], and information using the present theory is presented here for the same sea conditions.

The waves are represented by Pierson-Moskowitz spectra covering significant wave heights from 10 ft. to 50 ft., in steps of 10 ft., and a cosine-squared directional spreading law is used to allow computation of results in short-crested seas. Results are presented for predominant headings of 0° and 180°, for speeds of 25 and 30 kt., applying the present extended SCORES theory and also using the response operation from [2] to represent the values obtained from model experiments.

The results of these calculations of rms response using the response operations from the present theory and those from model experiment are given in Table 4. It can be seen that the responses for the head sea (predominant wave directions) are in fairly good agreement, for both the vertical and lateral-plane responses. For the following-sea results the agreement between theory and experiment is poor for lateral-plane responses, but generally good for vertical-plane responses. All of these results are consistent with the results of the comparison between theory calculations and model-test data in regular waves, discussed previously, and indicate the general relationship to be expected when comparing results in irregular seas. The present comparison of irregular short-crested sea responses does exhibit better correlation between theory and experiment then that given in [2], indicating a more valid computation tool for those conditions which are not affected by model-test difficulties.

CONCLUSIONS AND RECOMMENDATIONS

As a result of this investigation a number of conclusions have been obtained. The different elements considered to modify the basic theory have been shown to have negligible effect, except for the addition of certain speed-dependent terms in the equations of motion that result in the extended SCORES theory. This theoretical model has shown good correlation with model-test data for conventional ships, another large, fast container ship similar to SL-7, and also for the SL-7 vertical-plane responses. The extended SCORES theory can be used over the entire range of

TABLE 4

Comparison Between Theoretical and Experimental R.M.S. Responses in Short-Crested Seas

Heading = 0°
Speed = 25 kt.

	Significant Wave Height, ft.				
	10	20	30	40	50
			Pitch - Deg.		
Theory (Heavy)	.117	.536	.970	1.34	1.64
(Light)	.126	.557	.996	1.37	1.67
Experiment (Heavy)	.1164	.556	.9926	1.284	1.464
(Light)	.1254	.5594	.9668	1.237	1.403
			Vertical Bending Moment (midship)-ft. tons		
Theory (Heavy)	4.91E4	1.29E5	1.79E5	2.10E5	2.30E5
(Light)	5.21E4	1.31E5	1.79E5	2.09E5	2.27E5
Experiment (Heavy)	4.2742E4	1.501E5	2.216E5	2.623E5	2.860E5
(Light)	4.511E4	1.399E5	1.998E5	2.324E5	2.51E5
			Lateral Bending Moment (midship)-ft. tons		
Theory (Heavy)	2.24E4	4.34E4	5.42E4	6.06E4	6.48E4
(Light)	1.98E4	3.93E4	4.99E4	5.63E4	6.07E4
Experiment (Heavy)	3.451E4	7.094E4	8.846E4	9.778E4	1.031E5
(Light)	2.685E4	5.567E4	6.737E4	7.264E4	7.537E4
			Lateral Shear (midship) - tons		
Theory (Heavy)	1.31E2	2.24E2	2.65E2	2.86E2	2.99E2
(Light)	1.22E2	2.07E2	2.44E2	2.62E2	2.74E2
Experiment (Heavy)	1.312E2	3.057E2	3.945E2	4.398E2	4.650E2
(Light)	7.707E1	1.794E2	2.248E2	2.455E2	2.563E2
			Vertical Shear (midship) - tons		
Theory (Heavy)	4.46E2	7.27E2	8.30E2	8.78E2	9.02E2
(Light)	4.97×10^2	7.96×10^2	9.03×10^2	9.49E2	9.78E2
Experiment (Heavy)	1.893E2	4.145E2	5.054E2	5.467E2	5.677E2
(Light)	1.814E2	3.893E2	4.729E2	5.101E2	5.243E2
			Roll - Deg.		
Theory (Heavy)	1.21	5.01	7.95	9.86	11.1
(Light)	1.75	4.32	5.92	6.83	7.39
Experiment (Heavy)	2.201	7.027	9.902	11.468	12.359
(Light)	2.221	5.118	6.470	7.111	7.450
			Torsion (about c.g., midship)-ft. tons		
Theory (Heavy)	2.58E3	9.81E3	15.2E3	1.85E4	2.08E4
(Light)	3.79E3	9.13E3	12.3E3	1.41E4	1.51E4
Experiment (Heavy)	1.834E3	6.495E3	9.373E3	1.091E4	1.178E4
(Light)	2.056E3	5.266E3	6.793E3	7.519E3	7.902E3

TABLE 4
(Continued)

Comparison Between Theoretical and Experimental
R.M.S. Responses in Short-Crested Seas

Heading = 0°
Speed = 30 kt.

	Significant Wave Height, ft.				
	10	20	30	40	50
	Vertical Bending Moment (midship)-ft. tons				
Theory (Heavy)	4.85E4	1.27E5	1.76E5	2.06E5	2.26E5
(Light)	5.20E4	1.31E5	1.79E5	2.08E5	2.27E5
Experiment (Heavy)	4.401E4	1.520E5	2.240E5	2.648E5	2.890E5
(Light)	5.094E4	1.452E5	2.045E5	2.372E5	2.557E5
	Lateral Bending Moment (midship) ft. tons				
Theory (Heavy)	1.96E4	3.99E4	5.13E4	5.85E4	6.35E4
(Light)	2.00E4	4.06E4	5.20E4	5.91E4	6.39E4
Experiment (Heavy)	3.428E4	6.537E4	7.767E4	8.372E4	8.71E4
(Light)	2.247E4	5.486E4	6.990E4	7.703E4	8.080E4
	Torsion (about c.g., midship) - ft. tons				
Theory (Heavy)	2.62E3	5.92E3	8.83E3	1.11E4	1.28E4
(Light)	6.19E3	1.24E4	1.52E4	1.65E4	1.73E4
Experiment (Heavy)	2.288E3	6.860E3	9.766E3	1.139E4	1.232E4
(Light)	2.791E3	6.127E3	7.704E3	8.455E3	8.852E3

TABLE 4
(Continued)

Comparison Between Theoretical and Experimental
R.M.S. Responses in Short-Crested Seas

Heading = 180°
Speed = 25 kt.

	Significant Wave Height, ft.				
	10	20	30	40	50
	Pitch - Deg.				
Theory (Heavy)	.199	1.09	1.85	2.39	2.79
(Light)	.204	1.07	1.81	2.34	2.74
Experiment (Heavy)	.1904	1.007	1.714	2.157	2.423
(Light)	.1904	1.007	1.714	2.157	2.423
	Vertical Bending Moment (midship)-ft. tons				
Theory (Heavy)	4.11×10^4	1.40×10^5	2.05×10^5	2.43×10^5	2.66×10^5
(Light)	3.99×10^4	1.27×10^5	1.81×10^5	2.14×10^5	2.34×10^5
Experiment (Heavy)	5.166×10^4	1.590×10^5	2.255×10^5	2.613×10^5	2.814×10^5
(Light)	4.617×10^4	1.416×10^5	2.002×10^5	2.316×10^5	2.493×10^5
	Lateral Bending Moment (midship)-ft. tons				
Theory (Heavy)	2.48×10^4	5.57×10^4	7.13×10^4	7.94×10^4	8.41×10^4
(Light)	2.41×10^4	5.28×10^4	6.67×10^4	7.38×10^4	7.78×10^4
Experiment (Heavy)	3.175×10^4	6.388×10^4	7.646×10^4	8.207×10^4	8.496×10^4
(Light)	2.639×10^4	5.325×10^4	6.411×10^4	6.898×10^4	7.150×10^4
	Lateral Shear (midship) - tons				
Theory (Heavy)	.755E2	1.16E2	1.30E2	1.35E2	1.38E2
(Light)	.728E2	1.08E2	1.19E2	1.24E2	1.26E2
Experiment (Heavy)	1.075E2	1.807E2	2.033E2	2.124E2	2.169E2
(Light)	1.024E2	1.666E2	1.858E2	1.935E2	1.972E2
	Vertical Shear (midship) - tons				
Theory (Heavy)	1.63E2	4.51E2	5.90E2	6.57E2	1.38E2
(Light)	1.83E2	5.03E2	6.58E2	7.35E2	7.77E2
Experiment (Heavy)	2.055E2	4.240E2	5.131E2	5.548E2	5.770E2
(Light)	2.055E2	4.240E2	5.131E2	5.548E2	5.770E2
	Torsion (about c.g., midship) - ft. tons				
Theory (Heavy)	1.69E3	3.45E3	4.26E3	4.75E3	5.16E3
(Light)	1.91E3	3.68E3	4.75E3	6.03E3	7.62E3
Experiment (Heavy)	1.970E3	3.351E3	3.795E3	3.982E3	4.077E3
(Light)	2.062E3	3.515E3	3.972E3	4.161E3	4.255E3

TABLE 4
(Continued)

Comparison Between Theoretical and Experimental
R.M.S. Responses in Short-Crested Seas

Heading = 180°
Speed = 30 kt.

	Significant Wave Height, ft.				
	10	20	30	40	50
	Vertical Bending Moment (midship)-ft. tons				
Theory (Heavy)	4.09E4	1.37E5	2.00E5	2.38E5	2.61E5
(Light)	4.11E4	1.36E5	1.96E5	2.31E5	2.53E5
Experiment (Heavy)	6.052E4	1.777E5	2.501E5	2.890E5	3.109E5
(Light)	4.882E4	1.572E5	2.242E5	2.595E5	2.791E5
	Lateral Bending Moment (midship)-ft. tons				
Theory (Heavy)	2.69E4	5.68E4	7.15E4	7.92E4	8.37E4
(Light)	2.28E4	4.99E4	6.34E4	7.03E4	7.42E4
Experiment (Heavy)	3.043E4	6.196E4	7.507E4	8.108E4	8.421E4
(Light)	2.571E4	5.225E4	6.308E4	6.795E4	7.047E4
	Torsion (about c.g., midship)-ft. tons				
Theory (Heavy)	2.07E3	3.93E3	4.87E3	5.51E3	6.10E3
(Light)	1.86E3	3.62E3	4.66E3	5.83E3	7.33E3
Experiment (Heavy)	2.196E3	3.714E3	4.185E3	4.381E3	4.480E3
(Light)	2.150E3	3.635E3	4.097E3	4.287E3	4.381E3

conditions, with sufficient accuracy at low encounter frequencies, and does not require special treatment of hydrodynamic forces just for that region in order to provide adequate vertical-plane load predictions.

The major problem for correlation of the SL-7 lateral-plane responses occurs in quartering-sea conditions where large roll motion occurs. While the problem of proper roll-motion prediction generally exists in this case as well as for other ships, there appear to be problems in the model experiments and determination of model characteristics related to roll that raise questions as to the validity of the present SL-7 model-test data for these operating conditions. This is considered to be due to inconsistent values of roll static and inertial properties, lack of repeatable test results due to the model directional control behavior, etc.

At this time it appears that the use of computer calculations for load prediction of ships, including the SL-7 type of container ship, is a suitable tool for further use as long as adequate input data on the ship characteristics are provided. The benefits of calculation methods in regard to time and cost factors are evident, and the overall agreement between theory and experiment has had sufficient verification to allow its utility for this purpose.

The present study points out a number of recommendations for further work in this area of SL-7 data correlation, which are listed below:

1. Further model tests should be carried out in the quartering-sea range, preferably with a larger model and/or special test apparatus that would be more suitable to such tender ship models with directional control problems.

2. A more detailed determination should be made of the model roll static and inertial properties prior to the tests to insure consistency of the resulting values.

3. The roll-decay tests should be made with more information on time histories of motion presented, thereby allowing more precise analysis to evaluate damping parameters (linear and nonlinear), as well as using more than one method of initial roll disturbance as a means of checking repeatability of decay characteristics.

4. The correlation analysis associated with the data obtained from the tests described above can be carried out using the present extended SCORES theory, with input data pertinent to the model that is being re-tested. Such a comparison will provide a more definitive answer concerning the relation of theory and model tests for predictive purposes when considering lateral-plane responses in quartering seas.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

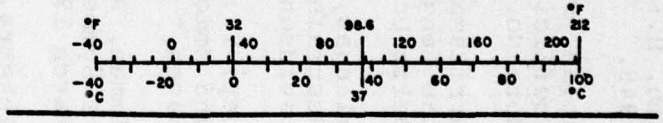
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SSC-271	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

COMPUTERS, MATHEMATICAL MODELS, SHIP HULLS, STRUCTURAL ANALYSIS, WAVES, CONTAINER SHIP

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A correlation study is carried out (for the SL-7 container ship) by means of comparison of results for structural loads and motions in waves obtained from model tests and computer calculations. The different aspects that could affect computer predictions are examined via further computations and analyses in order to determine their influence on the output data. Similarly an examination of the possible effects that influence the model test data are

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also examined. The main objective of this study is to determine the capabilities of both test methods for prediction purposes.

Comparisons are also made between theoretical predictions and results for other related ship models for which test data is available. Consistency of various results obtained is used as a basis of assessing the degree of validity of any particular method, as well as determining the exact difference in results due to various mechanisms that influence both the theory and experiments. Improvements in the theoretical model leading to an extended SCORES theory are described, together with the comparison with a range of avaiable data for the SL-7 and other ships. The particular type of output information, as well as the regions wherein such data are found to differ significantly from the theory are described together with suggested reasons for such lack of agreement. Recommendations for additional tests and further computations for comparison purposes are also provided, with an interim conclusion that the computer program (extended SCORES theory) is presently a suitable tool for prediction purposes.