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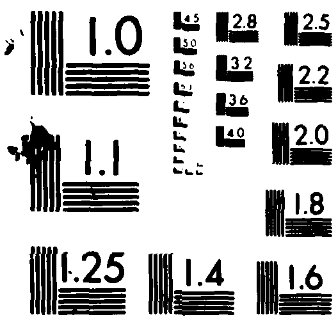

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Response Amplitude Operators (RAOs) are predicted by two ship motion computer models for four container vessels, two discharge lighters, and two barges. The response of each vessel in surge, heave, sway, pitch, roll, and yaw is computed as a function of wave exciting frequency for head, quartering, and beam seas. Computations were carried out for both heavy and light loading conditions of the containerships while the discharge lighters and barges were lightly loaded. Differences in the mathematical models for the ship motions

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programs are discussed and compared. The primary objective of the report was to make RAO data available for the vessels considered in this study.

FOREWORD

DoD planning for the logistics support to sustain major contingency operations, including amphibious assault operations and Logistics-Over-the-Shore (LOTS) evolutions, relies extensively on the use of US Flag commercial shipping. Since the mid-1960s commercial shipping has been steadily shifting towards containerships, Roll-On/Roll-Off (RO-RO) ships, and barge ships; e.g., LASH and SEABEE. By 1985 as much as 85 percent of US Flag sealift capacity may be in container-capable ships; i.e., mainly non-selfsustaining (NSS) containerships. Such ships cannot operate without extensive port facilities. Amphibious assault and LOTS operations are usually conducted over undeveloped beaches, and expeditious response times preclude conventional port development. Handling of containers in this environment presents a serious problem. The problem defined above is addressed in the overall DoD Over-the-Shore Discharge of Cargo (OSDOC) efforts involving development by the Army, Navy, and Marine Corps. Guiding policy is documented in the "DoD Project Master Plan for Surface Container Supported Distribution System" and the OASD I&L system definition paper, "Over-the-Shore Discharge of Cargo (OSDOC) System."

In response to the DoD Master Plan, Navy Operational Requirement (OR-YSL03) has been prepared for an integrated Container Offloading and Transfer System (COTS) for discharging container-capable ships in the absence of port facilities. The COTS Navy Development Concept (NDCP) No. YSL03 was promulgated in July 1975 and assigned to the Navy Material Command to develop the concept. The Naval Facilities Engineering Command has been assigned as Principal Development Activity (PDA) with the Naval Sea Systems Command assisting.

The COTS advanced development program includes the ship unloading subsystem, the ship-to-shore subsystem and common system elements. The ship unloading subsystem includes:

1. The development of Temporary Container Discharge Facilities (TCDF) using merchant ships and barges with add-on cranes and support equipment to offload non-selfsustaining (NSS) containerships alongside;

2. The development of Crane-on-Deck (COD) techniques and equipment for direct placement of cranes on the decks of NSS containerships to render them selfsustaining in an expedient manner;

3. The development of equipment and techniques to offload RO-RO ships offshore;

4. The development of interface equipment and techniques to enable ship discharge by helicopters (either existing or projected in other development programs).

The ship-to-shore subsystem includes the development of elevated causeways to allow cargo handling over the surf-line and development of self-propelled causeways to transport cargo from ships to the shoreside interface. The commonality subsystem includes:

1. The development of wave attenuating Tethered Float Breakwaters (TFB) to provide protection to COTS operating elements;

2. The development of special cranes and crane systems to compensate for container motion experienced during afloat handling;

3. The development of transportability interface items to enable essential outsize COTS equipment transport on merchant ships, particularly barge ships;

4. The development of system integration components such as moorings, fendering, communications, and services.

Response amplitude operators (RAOs) for four containerships, two lighter craft, and two barge configurations are presented with a discussion of the theoretical ship motion programs used to predict them.

TABLE OF CONTENTS

	Page No.
INTRODUCTION	1
COMPARISON OF SHIP MOTION MODELS	3
MODEL ASSUMPTION	3
STRIP THEORY DEVELOPMENT	5
VISCOSITY EFFECTS	5
RELATIVE MOTION BETWEEN SHIPS	6
CONCLUSIONS	6
RESPONSE AMPLITUDE OPERATORS	7
INPUT DATA	7
DISCUSSION OF RESULTS	7
SUMMARY	29

LIST OF ILLUSTRATIONS

Figure No.		Page No.
1	Definition of Wave Incident Angle Relative to Ship	7
2	Comparison of Ship Motion RAOs for a C4S1A in a Light and Heavy Loading Condition for Head Seas	9
3	Comparison of Ship Motion RAOs for a C4S1A in a Light and Heavy Loading Condition for Quartering Seas	10

LIST OF ILLUSTRATIONS
(continued)

Figure No.		Page No.
4	Comparison of Ship Motion RAOs for a C4S1A in a Light and Heavy Loading Condition for Beam Seas	11
5	Comparison of Ship Motion RAOs for C5S73B in a Light and Heavy Loading Condition for Head Seas	12
6	Comparison of Ship Motion RAOs for a C5S73B in a Light and Heavy Loading Condition for Quartering Seas	13
7	Comparison of Ship Motion RAOs for a C5S73B in a Light and Heavy Loading Condition for Beam Seas	14
8	Comparison of Ship Motion RAOs for a C6S85A in a Light and Heavy Loading Condition for Head Seas	15
9	Comparison of Ship Motion RAOs for a C6S85A in a Light and Heavy Loading Condition for Quartering Seas	16
10	Comparison of Ship Motion RAOs for a C6S85A in a Light and Heavy Loading Condition for Beam Seas	17
11	Comparison of Ship Motion RAOs for a C7S88A in a Light and Heavy Loading Condition for Head Seas	18
12	Comparison of Ship Motion RAOs for a C7S88A in a Light and Heavy Loading Condition for Quartering Seas	19
13	Comparison of Ship Motion RAOs for a C7S88A in a Light and Heavy Loading Condition for Beam Seas	20
14	Comparison of Ship Motion RAOs for an LCU-1610 and an LCM-8 in a Light Loading Condition for Head Seas	21
15	Comparison of Ship Motion RAOs for an LCU-1610 and an LCM-8 in a Light Loading Condition for Quartering Seas	22
16	Comparison of Ship Motion RAOs for an LCU-1610 and an LCM-8 in a Light Loading Condition for Beam Seas	23
17	Comparison of Ship Motion RAOs for a Pontoon Barge and a Delong-A Barge in a Light Loading Condition for Head Seas	24

LIST OF ILLUSTRATIONS
(continued)

Figure No.		Page No.
18	Comparison of Ship Motion RAOs for a Pontoon Barge and a Delong-A Barge in a Light Loading Condition for Quartering Seas	25
19	Comparison of Ship Motion RAOs for a Pontoon Barge and a Delong-A Barge in a Light Loading Condition for Beam Seas	26

LIST OF TABLES

Table No.		Page No.
1	Vessels Considered in COTS Study	2
2	Modes of Motion Predicted by Programs	4
3	Matrix of Runs Included in Study	8
4	Comparison of RAOs for MIT 5-D Seakeeping and RELMO Programs	28

INTRODUCTION

The purpose of this report is to present analytically predicted response amplitude operators (RAOs) for four container vessels, two discharge lighters, and two barges. The data were produced to support the design and analysis of a motion-compensated crane for the Container Offloading Transfer System (COTS) at NCSC. RAOs for surge, heave, sway, pitch, roll, and yaw motions are included for head, quartering, and beam seas. A secondary objective is to compare the response amplitude operators predicted by two available ship motion computer models. The data are presented in graphical form with motion response for each degree of freedom plotted versus exciting frequency. Motions were computed for all vessels in a lightly loaded configuration while the containership motions were also computed for a heavily loaded condition.

The COTS project addressed the design, engineering trade-off, and performance study for a shipboard motion compensated crane. The crane must be capable of safely transferring a 40-ton (36,287.39 kg) container from a containership to the deck of a tethered discharge lighter in a sea state 3 [$H_{1/3}$ = 5.0 ft (1.52 m)]. This requirement can be defined in terms of the maximum allowable vertical relative velocity between the container and the discharge lighter. It follows that the amount of motion compensation required depends on the relative motion between the crane boom tip and the lighter deck. A search of the literature showed that the required relative motion data for the vessels of interest were not available. Further study revealed that while some motion data are available in the literature[1] [2] for individual vessels, the data were not directly applicable to the vessels of interest in the COTS study. The container vessels, discharge lighters, and barges of interest are listed in Table 1.

Since the desired motion data were not available, a state-of-the-art ship motion computer model was needed to produce the required data. A

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[1]Naval Civil Engineering Center Technical Note N-1371, "The Motion of Floating Advanced Base Components in Shoal Water--A Comparison Between Theory and Field Test Data," by D. A. Davis and H. S. Zwibel, January 1975.

[2]Loukakis, T. A. and Chryssostomidis, C., "Seakeeping Standard Series for Cruiser-Stern Ships," The Society of Naval Architects and Marine Engineers, paper presented at the Annual Meeting, New York, New York, November 13-15, 1975.

TABLE 1

VESSELS CONSIDERED IN COTS STUDY

Vessel	Length* (ft)(m)	Beam (ft)(m)	Draft (ft)(m)	Displacement (long tons)(metric tons)
C4S1A#	528.00 (160.9)	75.70 (23.0)	17.96 (5.40)	10,000 (10,160.48)
C4S1A+	528.00 (160.9)	75.70 (23.0)	29.75 (9.10)	20,580 (20,910.27)
C5S73B+	581.83 (177.3)	78.00 (23.7)	29.62 (9.00)	24,655 (25,050.67)
C5S73B#	552.74 (159.3)	78.00 (23.7)	19.08 (5.80)	14,766 (15,002.97)
C6S85A+	625.00 (190.5)	90.00 (27.4)	31.42 (9.50)	28,520 (28,977.69)
C6S85A#	593.75 (180.9)	90.00 (27.4)	21.51 (6.50)	17,697 (17,981.00)
C7S88A+	677.00 (206.3)	95.00 (28.9)	33.72 (10.20)	38,256 (38,869.94)
C7S88A#	643.15 (196.0)	95.00 (28.9)	23.70 (7.20)	23,510 (23,887.29)
LCM-8	57.17 (17.1)	20.98 (6.4)	2.31 (0.70)	50 (50.80)
LCU-1610	124.95 (36.1)	29.00 (8.8)	2.90 (0.88)	185 (187.97)
3x15 Pontoon Causeway	90.00 (27.4)	21.00 (6.4)	1.40 (0.43)	55 (55.88)
DeLong-A Barge	296.00 (90.2)	80.00 (24.3)	26.49 (8.00)	17 (17.48)

*Load water line length

+Heavy condition

#Light condition

review of available ship motion programs revealed that three models had the potential of producing the required motion data. These models are discussed and compared in a latter section of this report with particular attention focused on the assumptions made in deriving the mathematical model, the degrees of freedom for motion computation, and the accuracy of the results. The theoretical comparison showed that two of the models were the same, for all practical purposes, thus yielding only two programs to be compared with actual executions of similar data sets. This comparison for several data sets generated the RAO data presented in this report.

COMPARISON OF SHIP MOTION MODELS

A review of the literature for the prediction of the response of a ship to a seaway produced three state-of-the-art models: (1) the 5-D Seakeeping Program, Massachusetts Institute of Technology;[3] [4] (2) the RELMO, Ship Motions Program, Civil Engineering Laboratory;[1] and (3) the NSRDC Ship Motion and Sea Load Computer Program,[5] David W. Taylor Naval Ship Research and Development Center (DTNSRDC). The remainder of this section will discuss the theory used in each program.

MODEL ASSUMPTION

The ship motion models of all three programs are based on strip theory. Both the MIT and NSRDC programs use the formalized theory developed by Salvensen, et al.[6] The RELMO program, based on the work of Kaplan and Putz,[7] is somewhat simpler because forward velocity of the

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[1]ibid.

[3]Massachusetts Institute of Technology Preliminary Draft, "5-D Seakeeping Program User's Manual," by A. Stein, to be published.

[4]Massachusetts Institute of Technology, Department of Naval Architecture and Marine Engineering Report Number 70-3, "Computed Aided Prediction of Seakeeping Performance in Ship Design," by T. A. Loukakis, August 1970.

[5]Naval Ship Research and Development Center Report 3289, "The Frank Close-Fit Ship Motion Computer Program," by W. Frank and N. Salvesen, June 1970.

[6]Salvesen, E. O. Tuck and Faltinsen, D., "Ship Motions and Sea Loads," Transaction of the Society of Naval Architects and Marine Engineers, Vol. 78, 1970.

[7]Naval Civil Engineering Laboratory Contract Report CR-62-8, "The Motions of a Moored Construction Type Barge in Irregular Waves and Their Influence on Construction Operation," by P. Kaplan and R. R. Putz, August 1962.

ship is not included. The following assumptions were made in the development of the formal strip theory:

1. All modes of motion (ship responses to the wave forces and moments) are small, linear, and harmonic.

2. The ship has lateral symmetry.

3. The ship has a long, slender hull form.

4. For heave and pitch motions, fluid viscous effects can be disregarded.

5. The wave resistance, perturbation potential, and all its derivatives are small enough to be ignored in formulating the linear motion problem.

6. The frequency of ship oscillation is relatively high so that the length of waves generated is on the order of ship beam rather than ship length.

7. Viscosity effects on roll motions can be accounted for by including a viscous damping term in the roll equation of motion.

8. Water depth is infinite.

Although the equations of ship motion in all three programs are based on strip theories, results can vary because of the different methods used to compute the various hydrodynamic coefficients and the wave exciting forces and moments. Another source of difference in the program stems from the manner in which the viscosity effects on roll are evaluated. Table 2 gives the modes of ship motion predicted by each program. Then some of the differences observed among the programs are discussed.

TABLE 2

MODES OF MOTION PREDICTED BY PROGRAMS

	Surge	Sway	Heave	Roll	Pitch	Yaw	Rel*	Vel+
MIT		√	√	√	√	√	√	√
RELMO	√	√	√	√	√	√	√	
NSRDC	√	√	√	√	√	√		√

*Relative motion capability

+Forward velocity capability

The MIT program does not account for surge motion which might be important in some cases. It has been modified to compute relative vertical and transverse motions between two ships. The RELMO program is designed to predict all six modes of relative motion between two ships but does not provide for forward velocity effects. All six modes of motion are predicted by the NSRDC program, but relative motions between two ships are not computed. At present, RELMO is the only program that solves the entire problem of relative motion between two ships. In principle, an available surge motion model could be added easily to the MIT program; and the NSRDC program could be expanded in a straightforward manner to predict relative motions.

STRIP THEORY DEVELOPMENT

In the strip theory approach the hull is divided into approximately 20 transverse sections, and the coefficients are determined for each section for a two-dimensional cylinder having the same cross-sectional shape. In the RELMO program, correction factors are applied to compensate for the three-dimensional effects of damping on heave and pitch (these factors are usually set equal to unity if the ship hull can be considered slender as was the case in the present study). In the MIT and NSRDC programs, correction factors are not applied to compensate for interaction between sections in any mode of motion.

RELMO uses the Lewis-form conformal mapping technique exclusively, changing section shape where necessary to avoid bulbous bow-type cross sections. The NSRDC program uses the Frank close-fit technique to compute added mass and damping coefficients and is considered more accurate than the Lewis-form technique. The Frank close-fit technique involves the distribution of pulsating sources of constant strength along straight-line segments between adjacent points which define the section's shape. The velocity potential for this entire distribution of source singularities over the perimeter of the section is determined. The strength of the source segment is calculated to satisfy the boundary condition on the hull. Pressures over the surface are than obtained from the velocity potential using Bernoulli's equation. Finally, the hydrodynamic force and moment are obtained by integration of the pressure over the hull. The added mass is that part of the force in phase with acceleration of the oscillatory motion. Damping is proportional to the velocity associated with the motion. The close-fit method should yield more accurate wave and force moment results since the vertical variation of the wave pressure is included. In the Lewis-form technique used by RELMO, the wave force and moment on the hull are only approximations; e.g., in some integrations the pressure at half the draft is used.

VISCOSITY EFFECTS

In all three programs, viscosity is neglected in all modes of motion except roll. RELMO accounts for the roll effect by modifying the coefficient of roll moment due to section damping force in roll and by specifying an experimental determined value of roll period. The value of roll damping is selected as a function of the shape of the hull (0.04 for a round hull and 0.08 for vessels with flat-bottom hulls). The NSRDC and MIT programs account for viscosity effects by the introduction of a non-linear viscous roll damping term. At the present time, the manner in which viscosity effects are introduced into the roll equations has not been adequately verified by comparison with experimental data. All three programs contain a viscous damping term to improve roll motion predictions. In all three cases, the viscous damping correction term reflects the effect of hull and bilge keel geometry and eddy generation. In RELMO, these effects are not introduced directly but are reflected by the observed roll period of the ship. The correction is more analytical in the other two programs where hull and bilge keel geometry are used directly to compute the viscosity contributions.

RELATIVE MOTION BETWEEN SHIPS

When two closely spaced floating bodies experience forced oscillation, each radiates surface waves that affect the motion of the other. The RELMO program computes relative longitudinal transverse and vertical motions while the MIT program predicts only relative vertical motion. Neither of these programs includes the wave effects of one ship on the other. The MIT program includes a sheltering coefficient which attenuates the wave impinging on the leeward ship; the RELMO program does not consider the attenuation problem. At present, the NSRDC program cannot predict relative motion between ships. Even in the absence of a free surface, the relative motion between two bodies creates hydrodynamic forces and moments that affect the motion of each. Such interacting forces are neglected in all three programs.

CONCLUSIONS

Due to the similarity of both the theoretical development and the solution technique, the MIT and NSRDC programs should yield essentially the same results except that surge is neglected in the MIT program and relative motions are not computed in the NSRDC program.

Since the MIT program was already installed on the NCSC B5700 computer, the NSRDC program was eliminated from further comparison considerations. Due to differences in the application of strip theory solution techniques, further comparison of the RELMO and MIT models must be carried out by examining the RAO prediction and computational efficiency of the two programs. While the degree of accuracy is the most important comparative factor, it should be mentioned that the MIT program requires four times the execution time of RELMO for the same ship configuration.

RESPONSE AMPLITUDE OPERATORS

INPUT DATA

The ship parameter portion of the input data for the ship motion programs can be generated for a given vessel from the trim and stability booklet, the lines drawing, and the curves of displacement and form. Although the maritime administration (MARAD) is a depository for all three types of data for Government subsidized vessels, it is often considered proprietary and therefore not available. MARAD supplied ship data for the four container vessels considered in this study. The data for the lighter vessels of interest were obtained from the Naval Ship Engineering Center (NAVSEC), Washington, DC, while the barge data were obtained from the Civil Engineering Laboatory (CEL), Naval Construction Battalion Center, Port Hueneme, California.

Although sufficient data were obtained[8] for the analysis of each of the vessels of interest, it should be noted that compiling the data was an extremely difficult task since no single source could supply all the information required to completely describe each vessel.

DISCUSSION OF RESULTS

Using the ship geometric data described above in the RELMO and MIT computer programs, RAOs were computed for the four containerships, two *discharge lighters,* and two barges (Table 1). The RAOs of surge, heave, sway, pitch, roll, and yaw for each vessel were computed for head, quartering, and beam seas corresponding to wave incident angles (β) of 180, 135, and 90 degrees (Figure 1). Table 3 describes the basic motions of configurations investigated as well as cross reference of loading condition versus figure number where the RAO data are plotted. Figures 2 through 19 present the RAO data for each of the vessels as predicted by

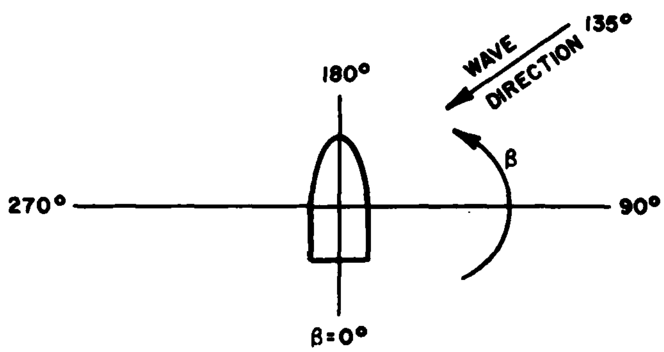

FIGURE 1. DEFINITION OF WAVE INCIDENT ANGLE RELATIVE TO SHIP

[8]Naval Coastal Systems Center Technical Note TN 415, "Preparation of Input Data for COTS Ship Motion Study," by D. C. Summey and T. C. Watson, April 1977.

TABLE 3

MATRIX OF RUNS INCLUDED IN STUDY

Ship	Loading Condition	Wave Incidence	Program	Figure Number
C4S1A	Light	Head Quartering Beam	RELMO	2 3 4
	Heavy	Head Quartering Beam	RELMO/MIT	2 3 4
C5S73B	Light	Head Quartering Beam	RELMO/MIT	5 6 7
	Heavy	Head Quartering Beam	RELMO/MIT	5 6 7
C6S85A	Light	Head Quartering Beam	RELMO/MIT	8 9 10
	Heavy	Head Quartering Beam	RELMO/MIT	8 9 10
C7S88A	Light	Head Quartering Beam	RELMO/MIT	11 12 13
	Heavy	Head Quartering Beam	RELMO/MIT	11 12 13
LCU-1610	Light	Head Quartering Beam	RELMO/MIT	14 15 16
LCM-8	Light	Head Quartering Beam	RELMO/MIT	14 15 16
Pontoon Barge	Light	Head Quartering Beam	RELMO/MIT	17 18 19
DeLong-A Barge	Light	Head Quartering Beam	RELMO/MIT	17 18 19

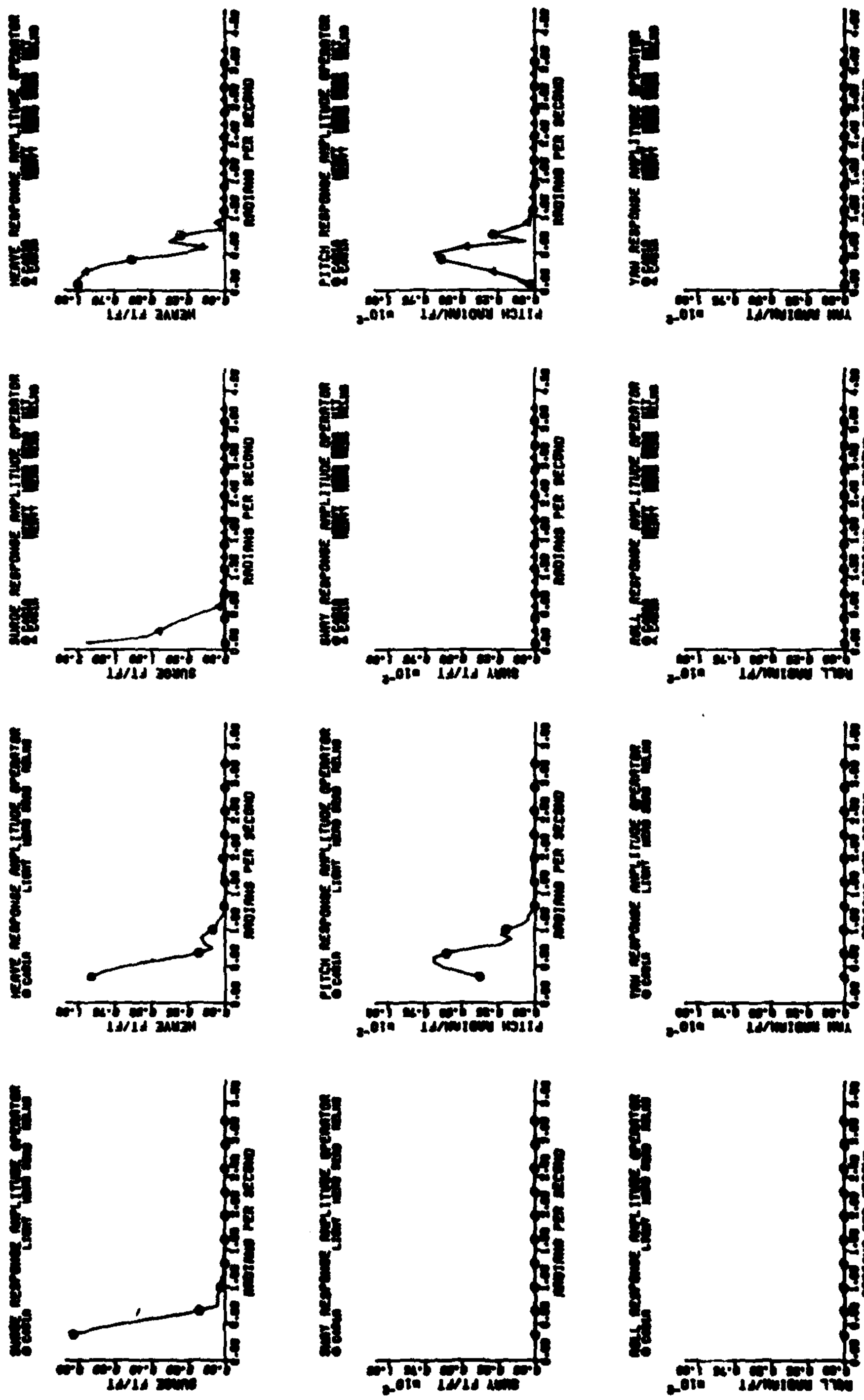

FIGURE 2. COMPARISON OF SHIP MOTION RAOs FOR A C4S1A IN A LIGHT AND HEAVY LOADING CONDITION FOR HEAD SEAS

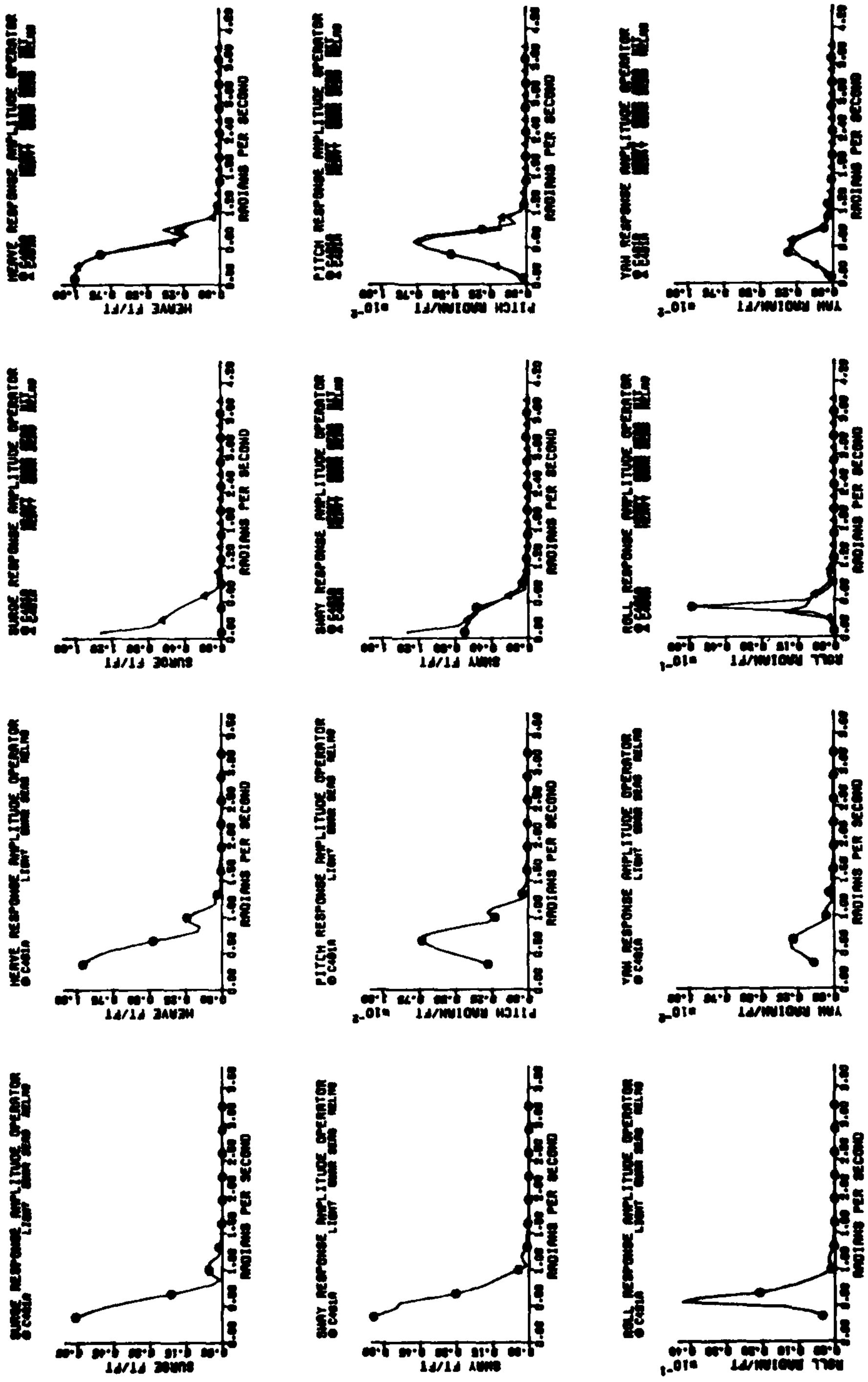

FIGURE 3. COMPARISON OF SHIP MOTION RAOs FOR A C4S1A IN A LIGHT AND HEAVY LOADING CONDITION FOR QUARTERING SEAS

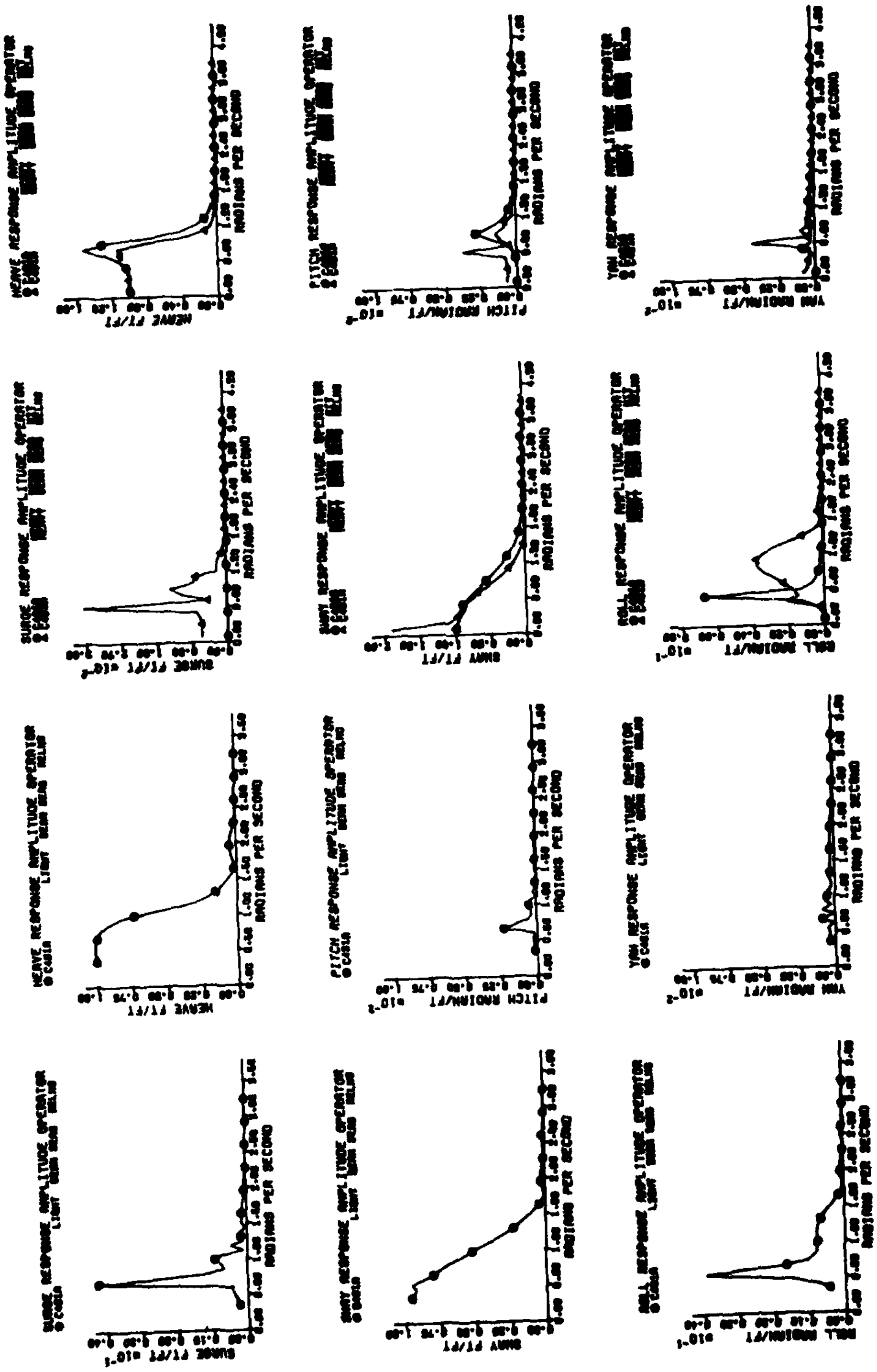

FIGURE 4. COMPARISON OF SHIP MOTION RAOs FOR A C4S1A IN A LIGHT AND HEAVY LOADING CONDITION FOR BEAM SEAS

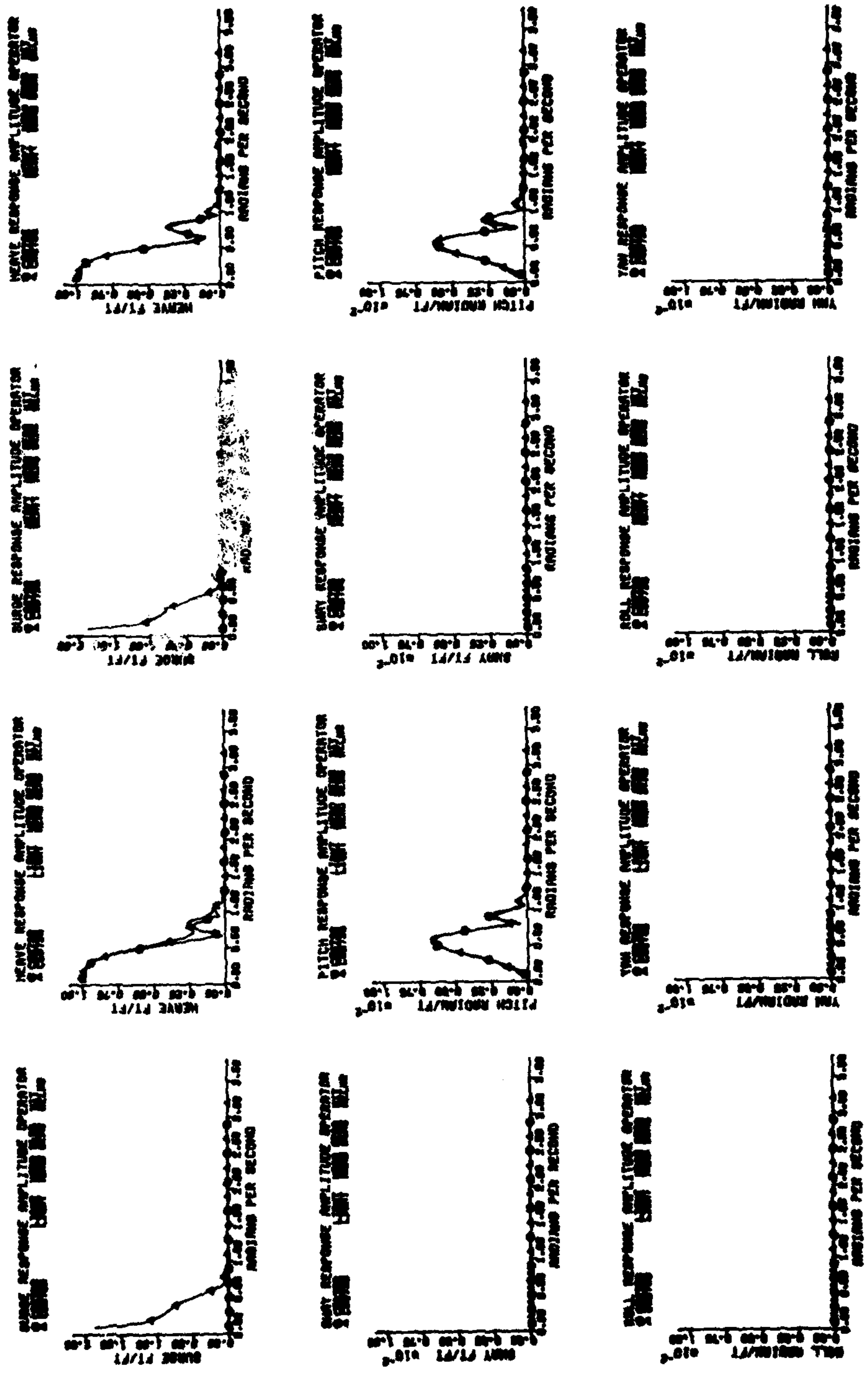

FIGURE 5. COMPARISON OF SHIP MOTION RAOs FOR A C5S73B IN A LIGHT AND HEAVY LOADING CONDITION FOR HEAD SEAS

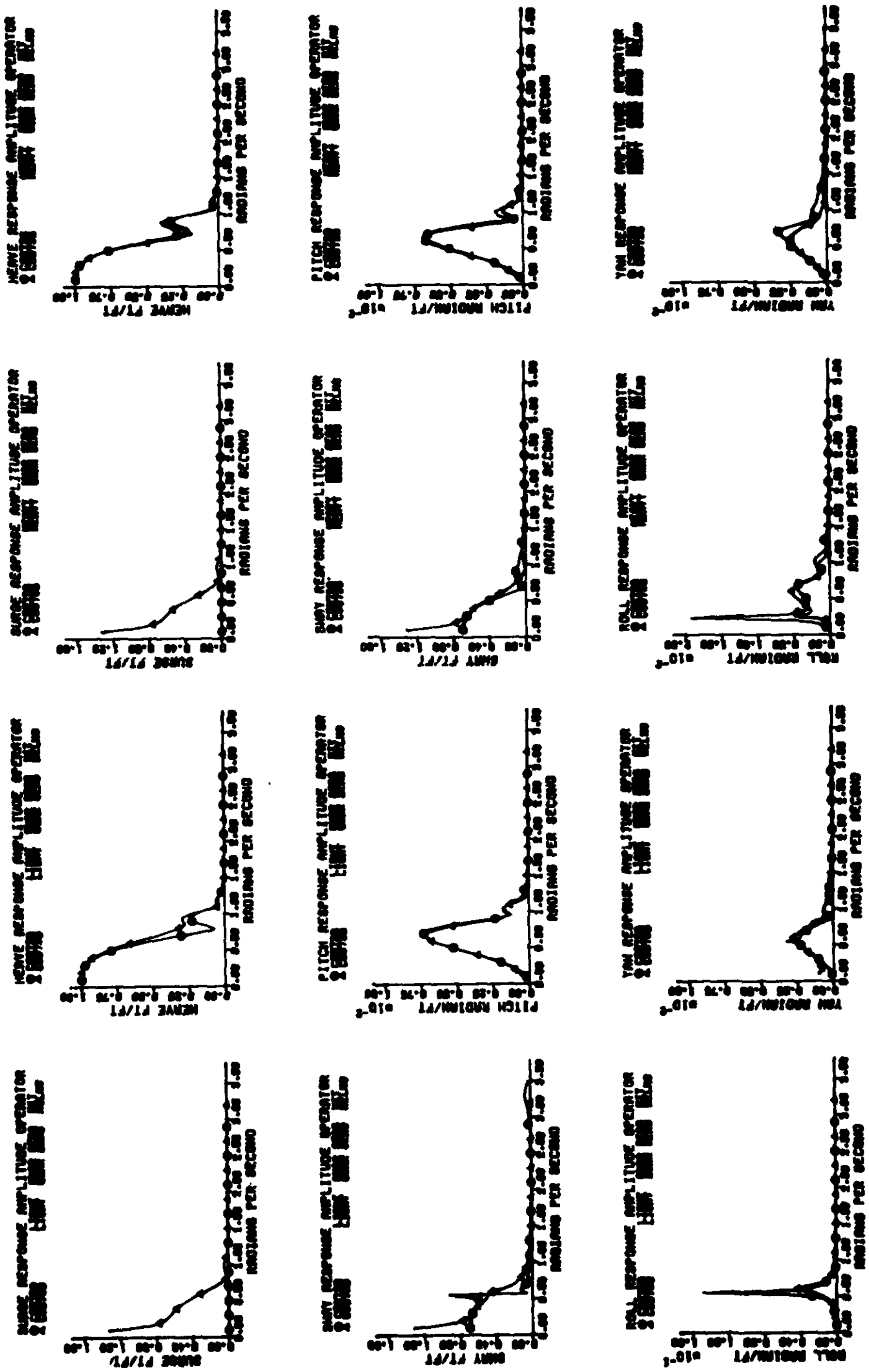

FIGURE 6. COMPARISON OF SHIP MOTION RAOs FOR A C5S73B IN A LIGHT AND HEAVY LOADING CONDITION FOR QUARTERING SEAS

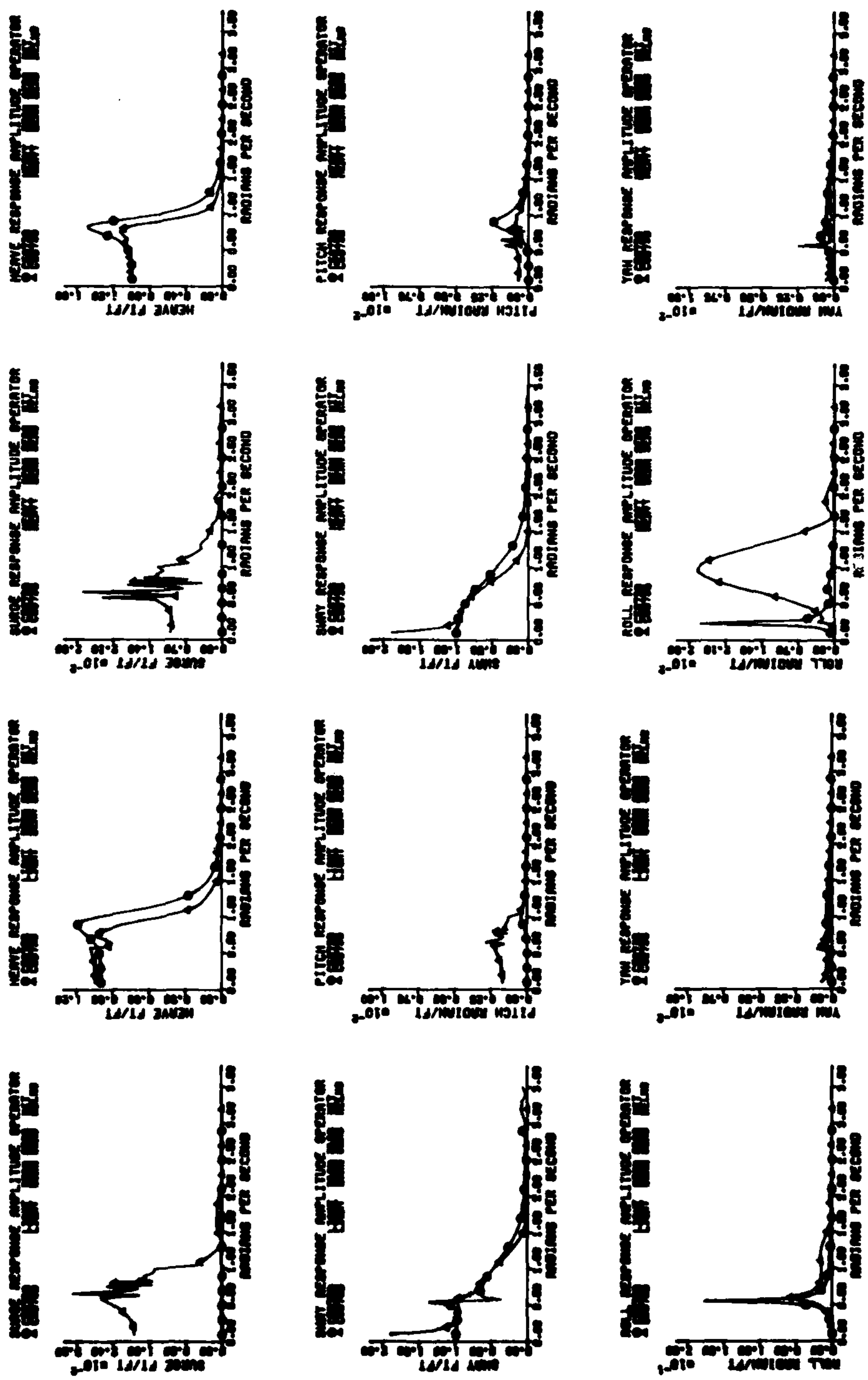

FIGURE 7. COMPARISON OF SHIP MOTION RAOs FOR A C5S73B IN A LIGHT AND HEAVY LOADING CONDITION FOR BEAM SEAS

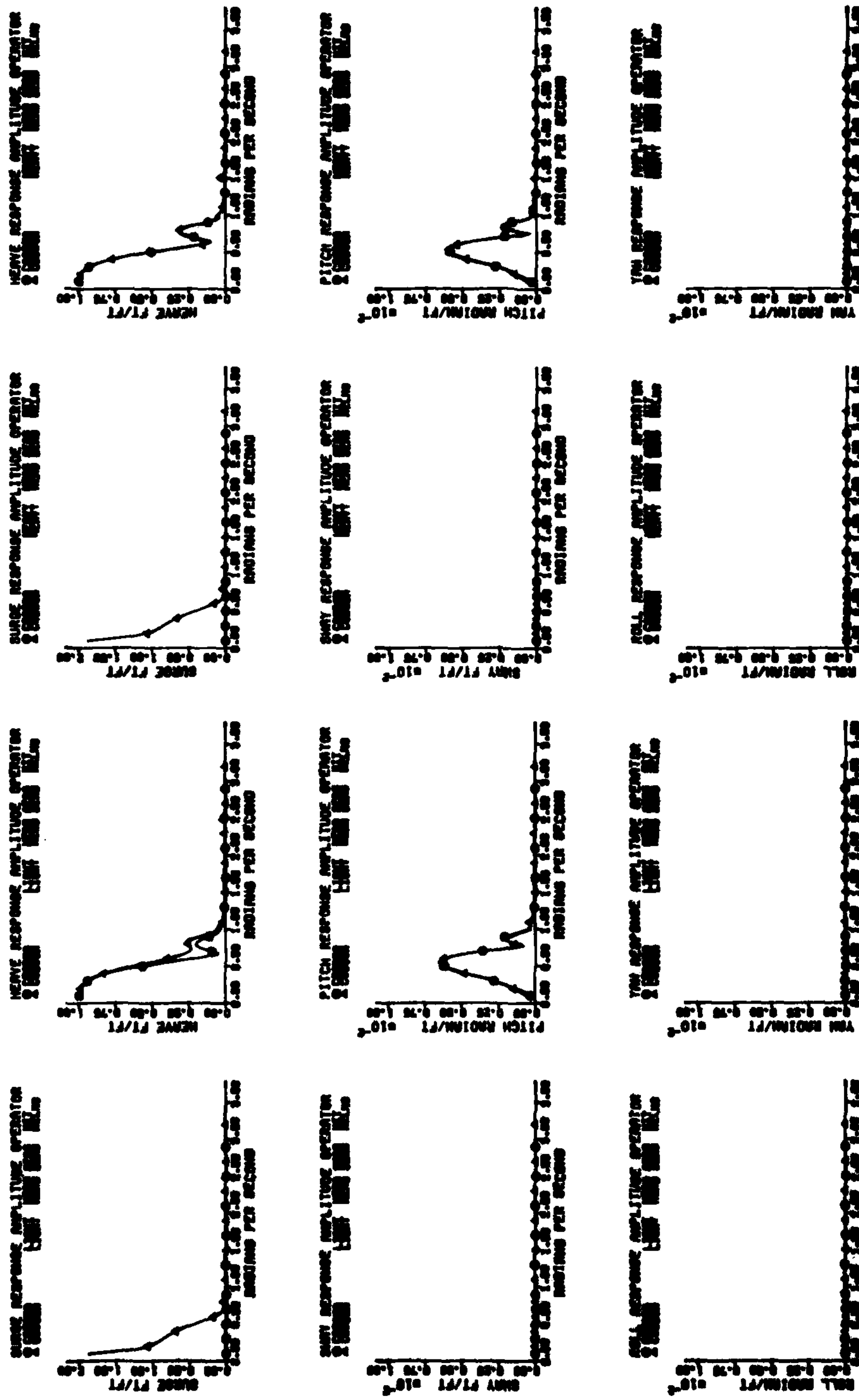

FIGURE 8. COMPARISON OF SHIP MOTION RAOs FOR A C6S85A IN A LIGHT AND HEAVY LOADING CONDITION FOR HEAD SEAS

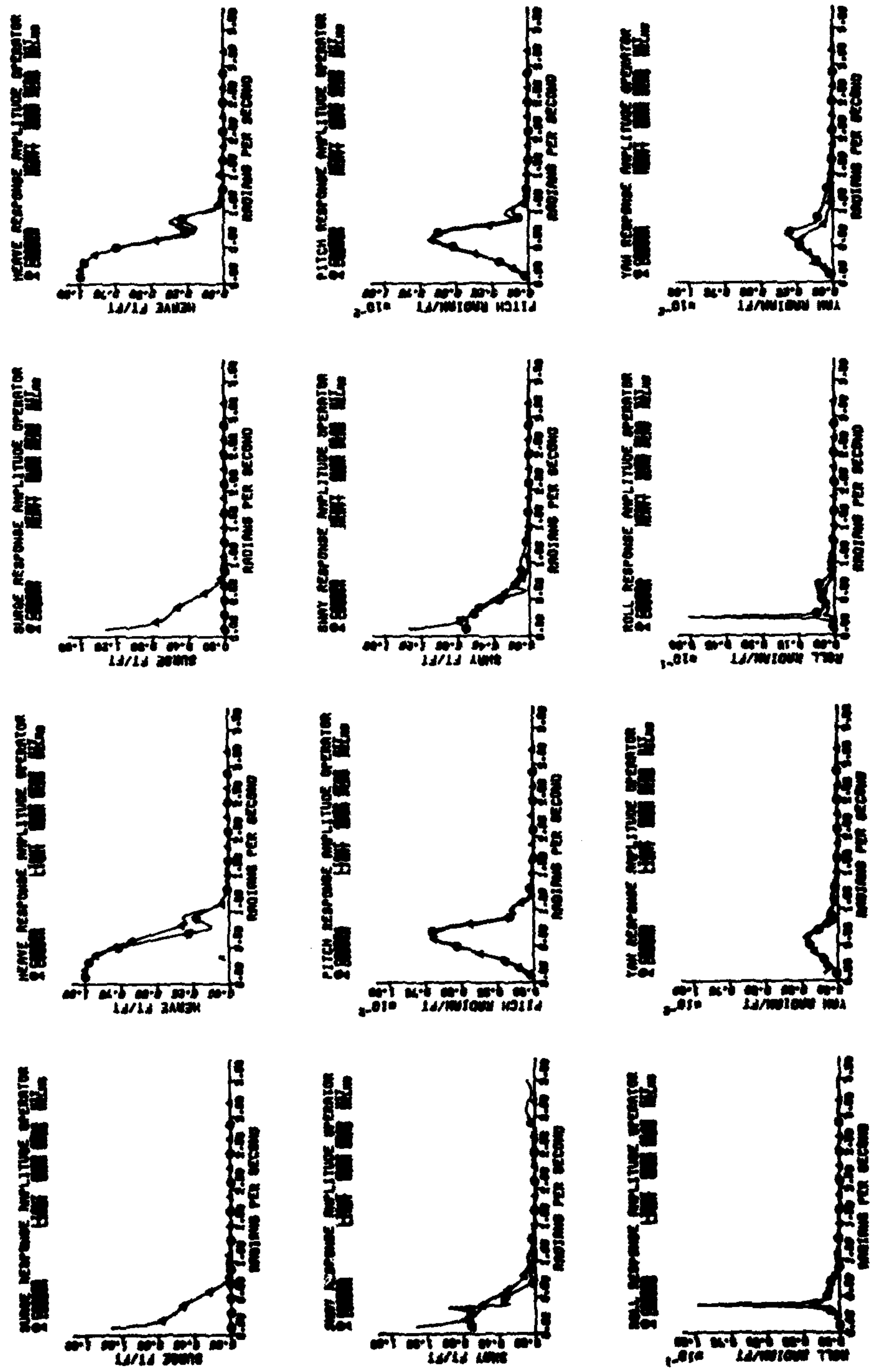

FIGURE 9. COMPARISON OF SHIP MOTION RAOs FOR A C6S85A IN A LIGHT AND HEAVY LOADING CONDITION FOR QUARTERING SEAS

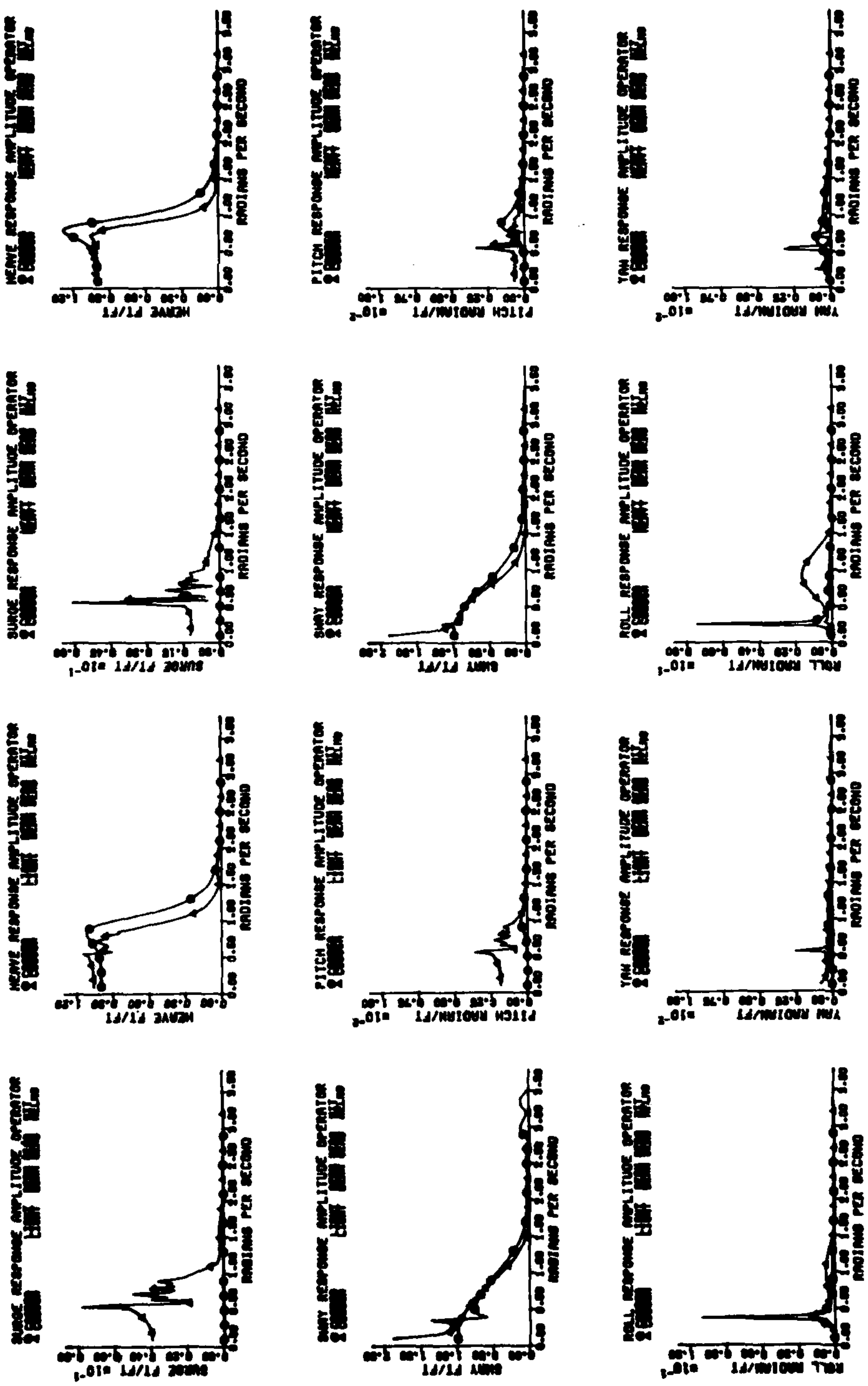

FIGURE 10. COMPARISON OF SHIP MOTION RAOs FOR A C6S85A IN A LIGHT AND HEAVY LOADING CONDITION FOR BEAM SEAS

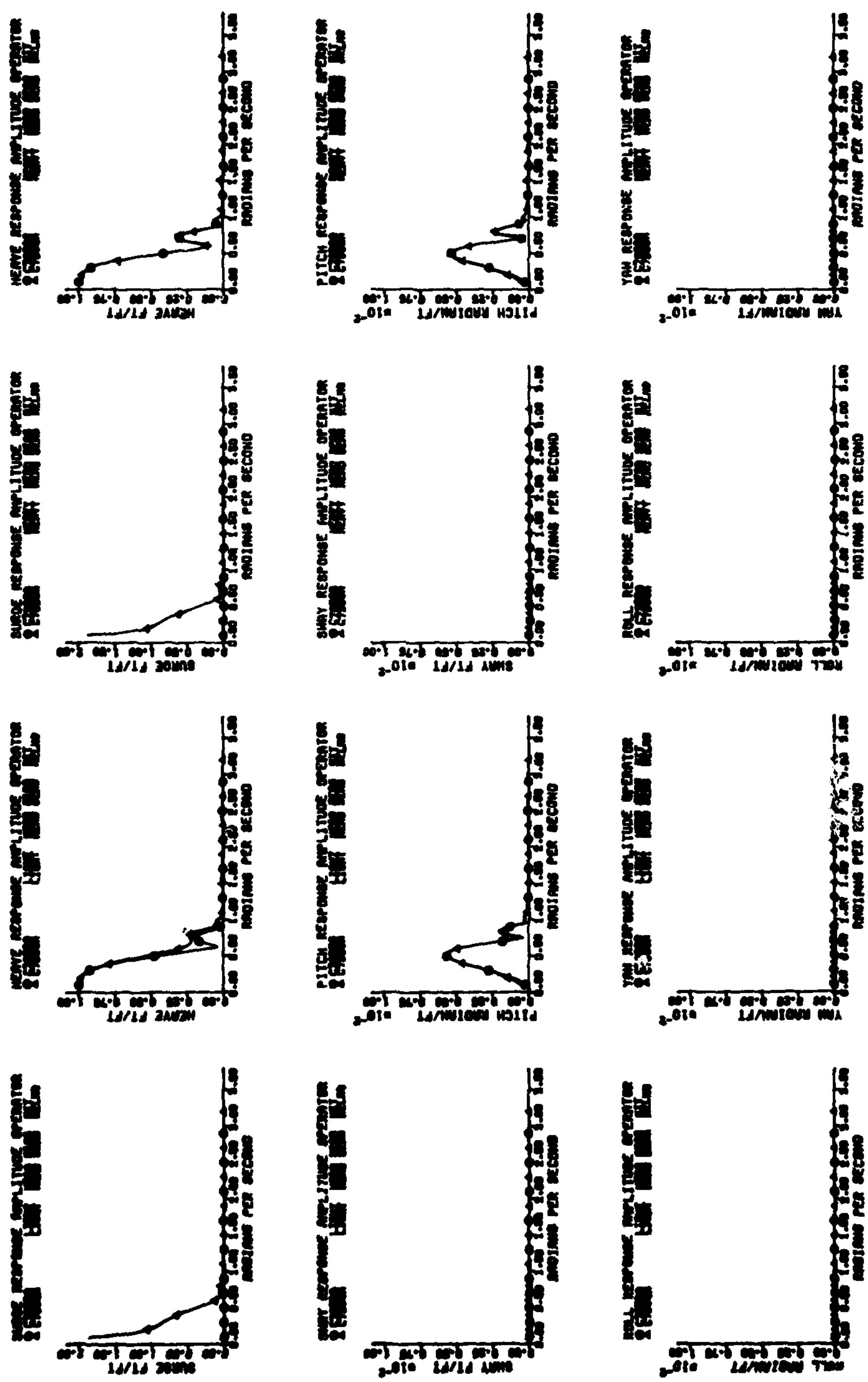

FIGURE 11. COMPARISON OF SHIP MOTION RAOs FOR A C7S88A IN A LIGHT AND HEAVY LOADING CONDITION FOR HEAD SEAS

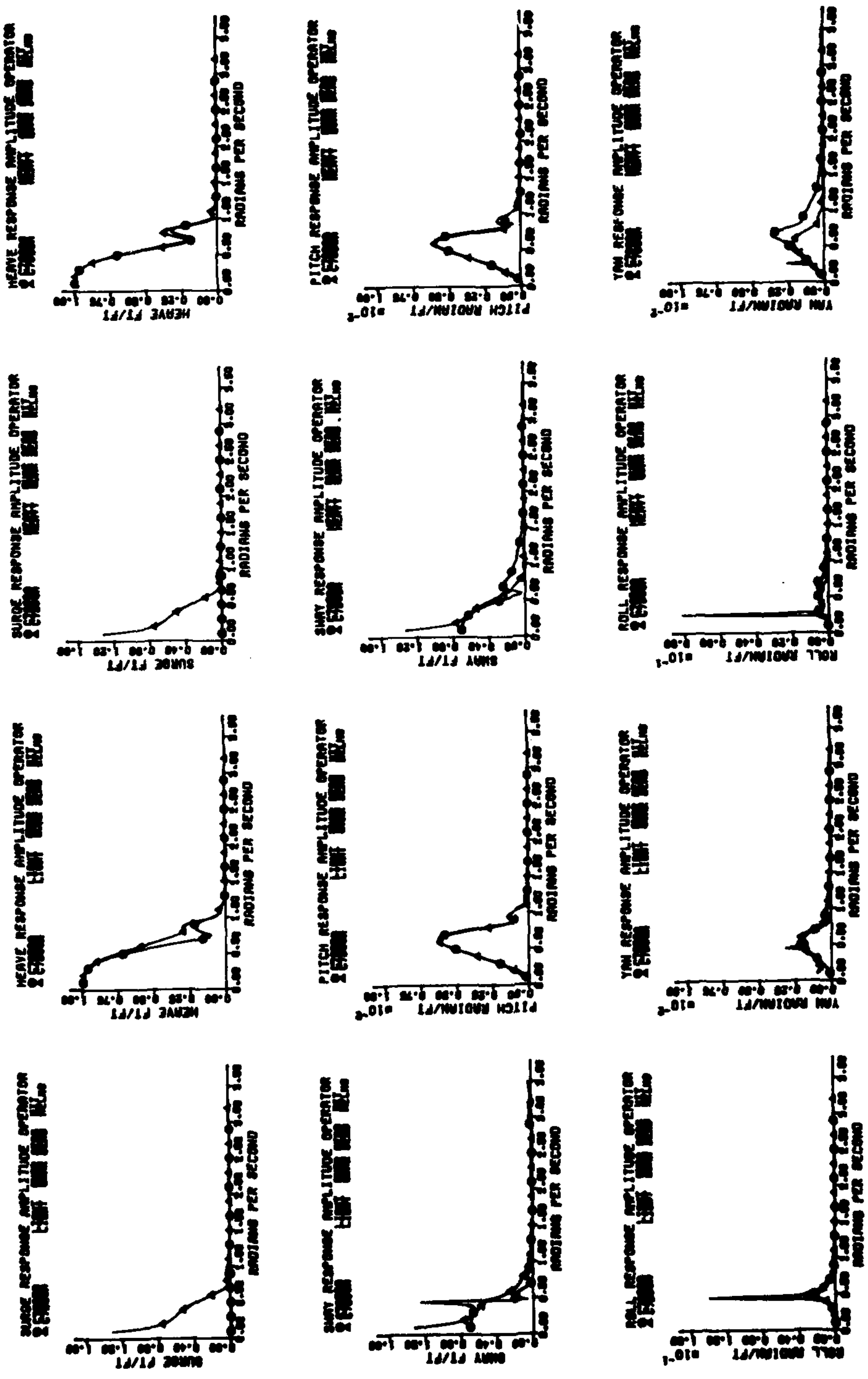

FIGURE 12. COMPARISON OF SHIP MOTION RAOs FOR A C7S88A IN A LIGHT AND HEAVY LOADING CONDITION FOR QUARTERING SEAS

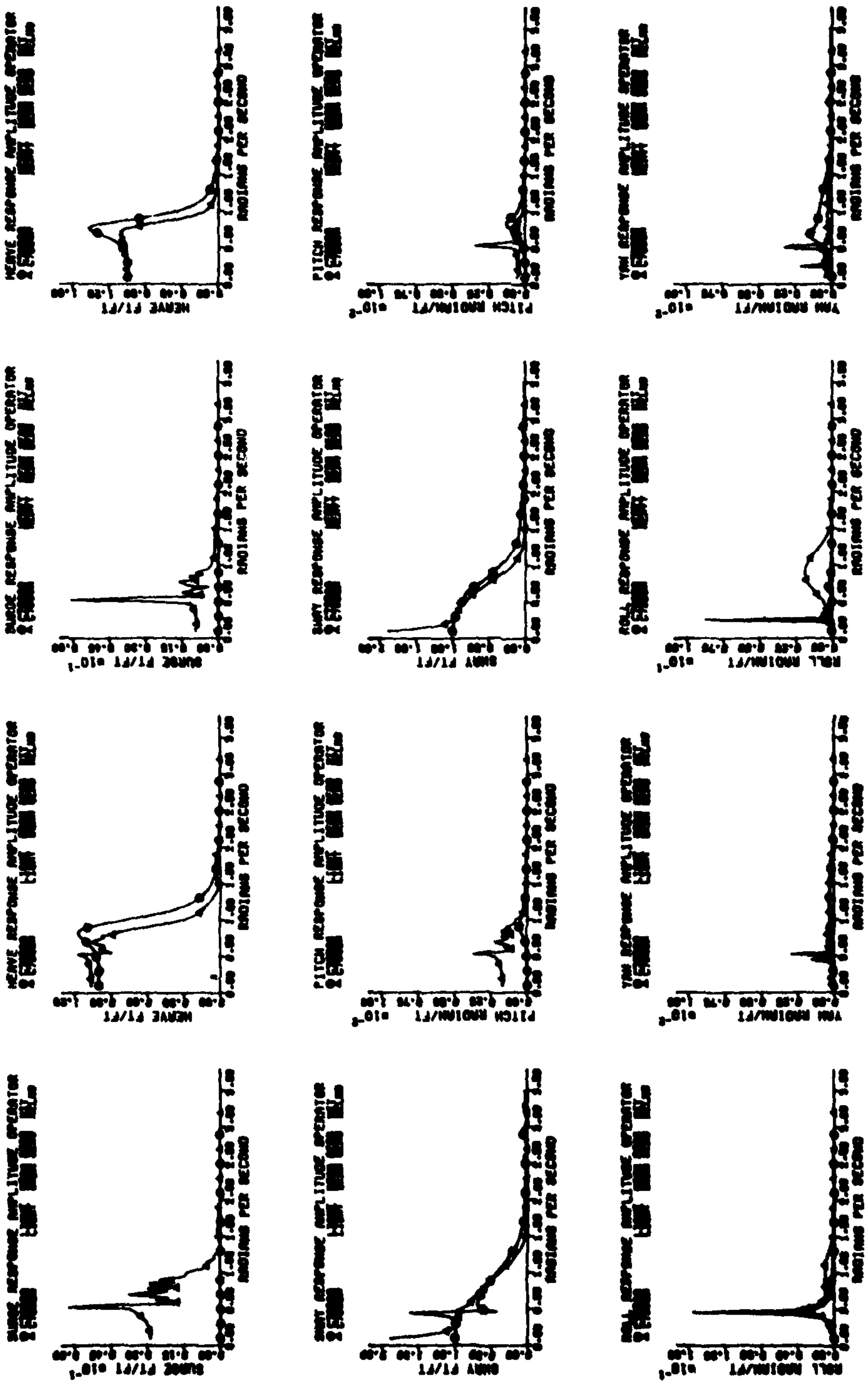

FIGURE 13. COMPARISON OF SHIP MOTION RAOs FOR A C7S88A IN A LIGHT AND HEAVY LOADING CONDITION FOR BEAM SEAS

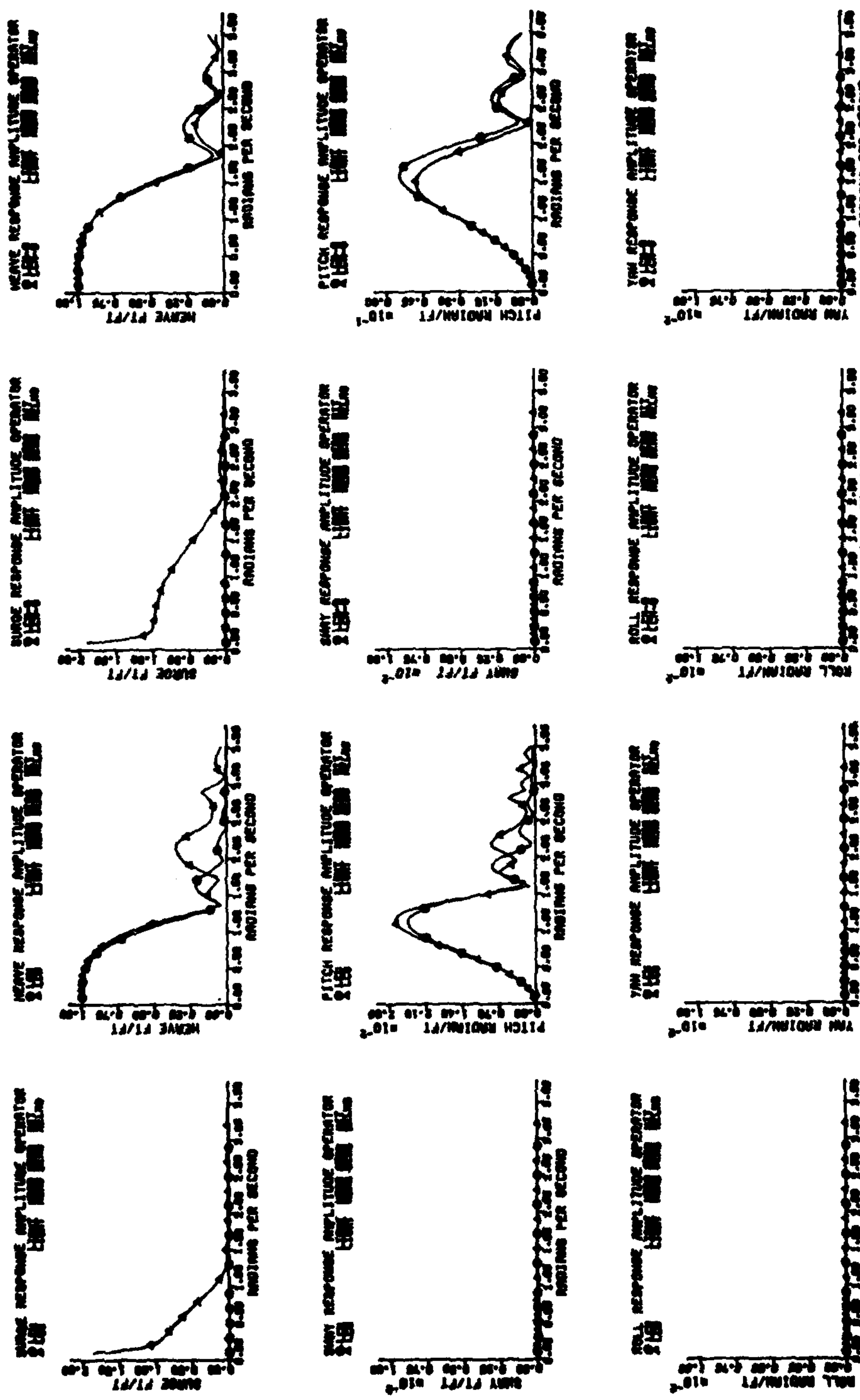

FIGURE 14. COMPARISON OF SHIP MOTION RAOs FOR AN LCU-1610 AND AN LCM-8 IN A LIGHT LOADING CONDITION FOR HEAD SEAS

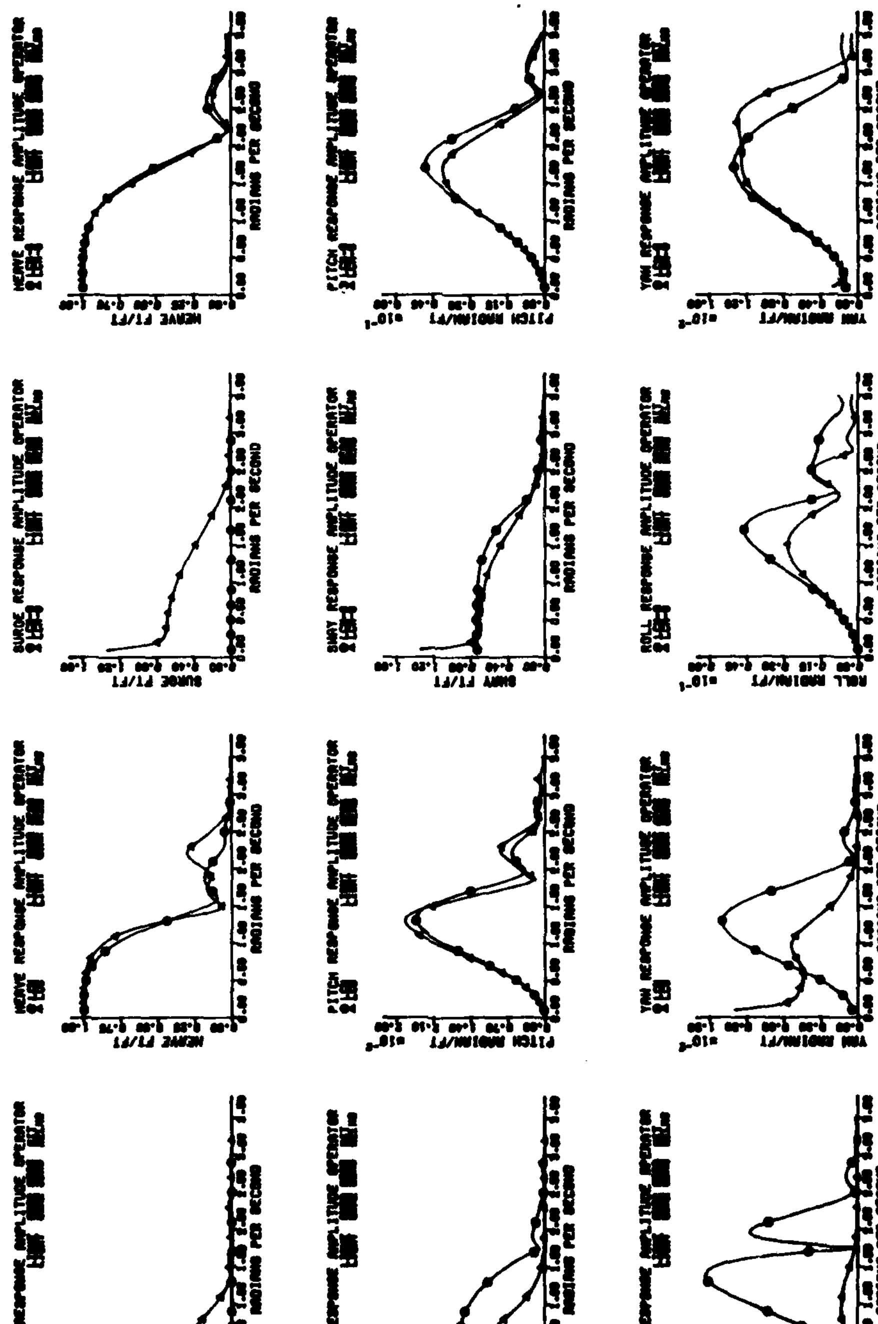

FIGURE 15. COMPARISON OF SHIP MOTION RAOs FOR AN LCU-1610 AND AN LCM-8 IN A LIGHT LOADING CONDITION FOR QUARTERING SEAS

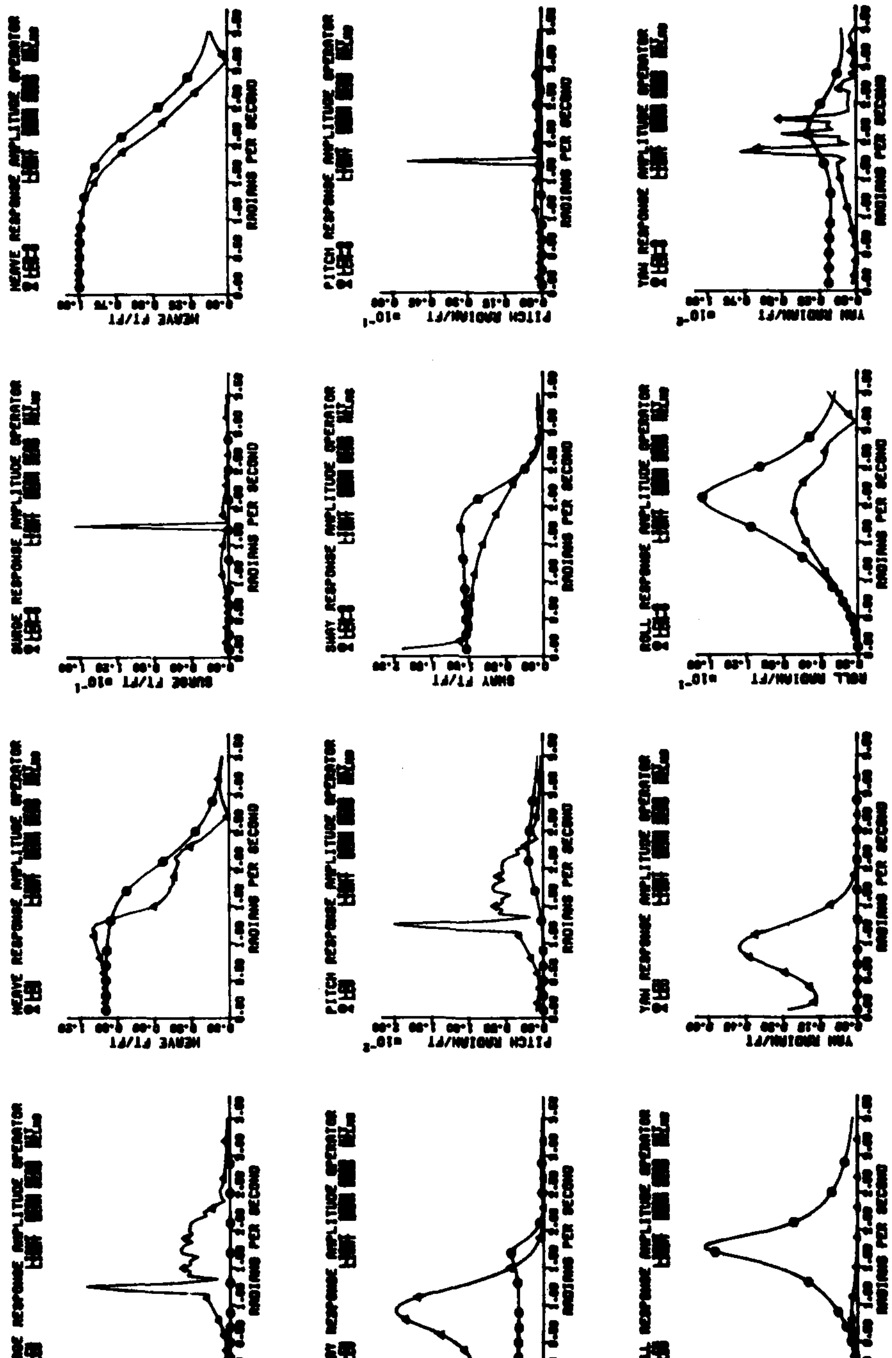

FIGURE 16. COMPARISON OF SHIP MOTION RAOs FOR AN LCU-1610 AND AN LCM-8 IN A LIGHT LOADING CONDITION FOR BEAM SEAS

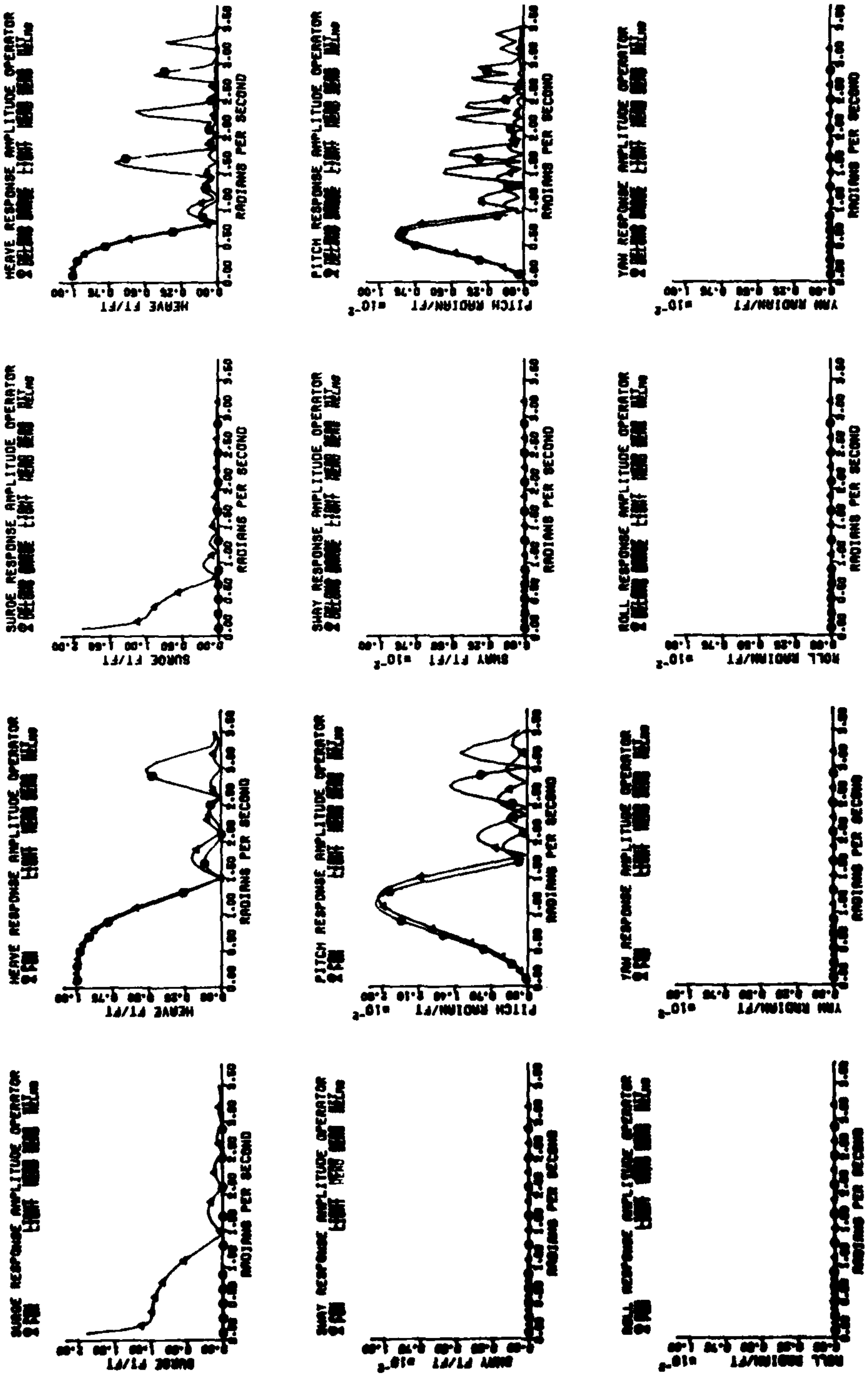

FIGURE 17. COMPARISON OF SHIP MOTION RAOs FOR A PONTOON BARGE AND A DELONG-A BARGE IN A LIGHT LOADING CONDITION FOR HEAD SEAS

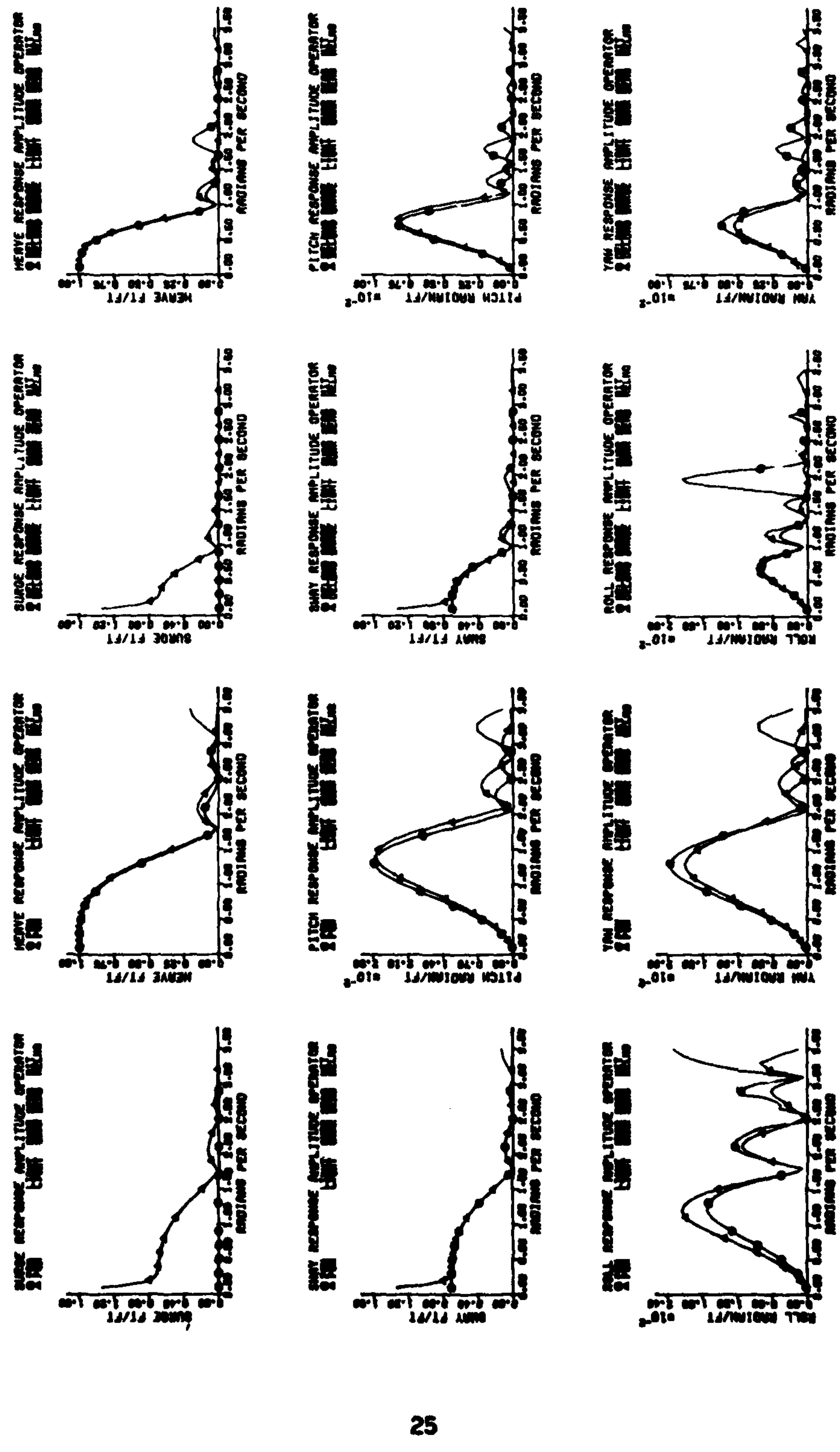

FIGURE 18. COMPARISON OF SHIP MOTION RAOs FOR A PONTOON BARGE AND A DELONG-A BARGE IN A LIGHT LOADING CONDITION FOR QUARTERING SEAS

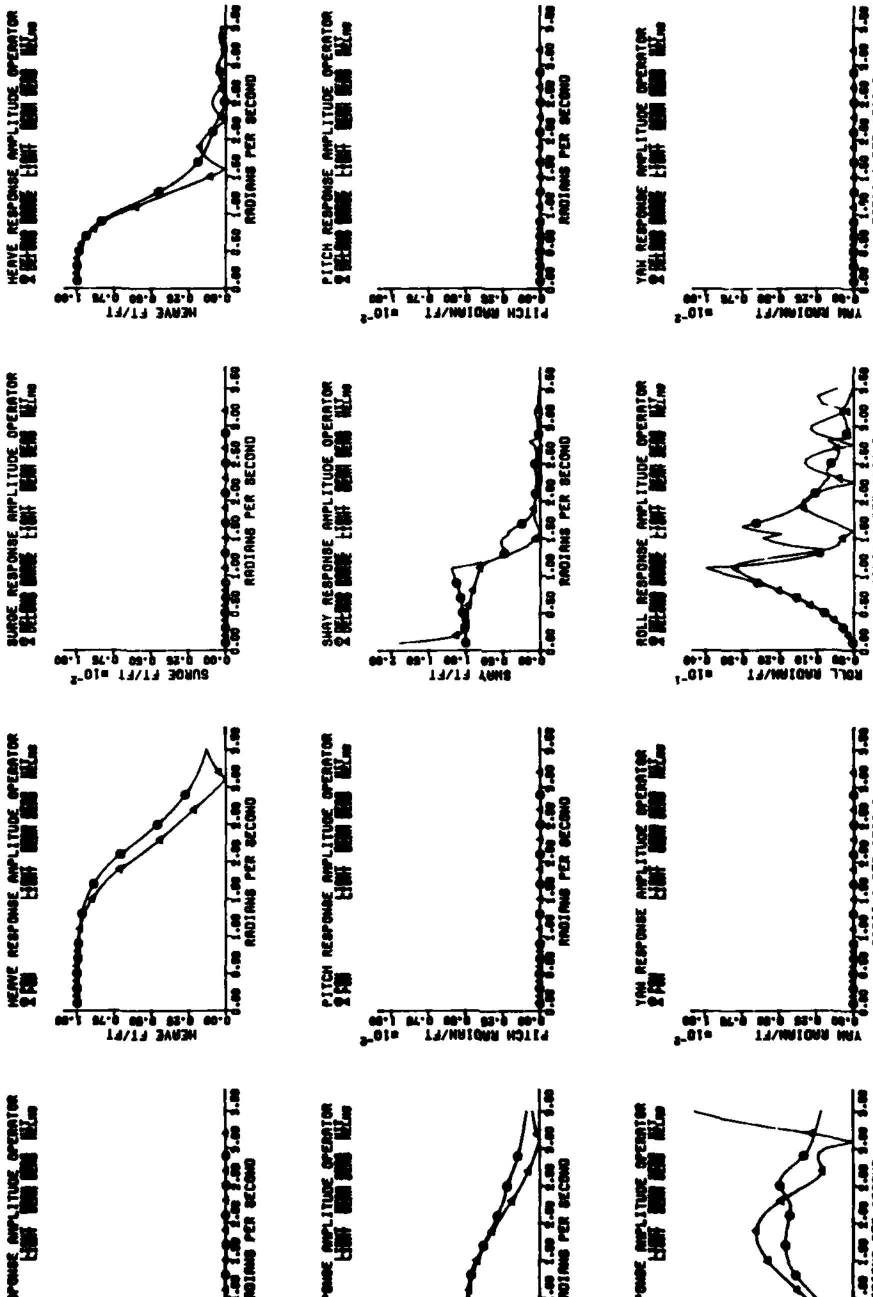

FIGURE 19. COMPARISON OF SHIP MOTION RAOs FOR A PONTOON BARGE AND A DELONG-A BARGE IN A LIGHT LOADING CONDITION FOR BEAM SEAS

both computer models at a single wave heading. For the containerships, both the light and heavy data are presented in the same figure; for the lighters and barges a single figure depicts two different vessels at a single heading.

Some general observations can be made about the RAO data presented in Figures 2 through 19. In those cases where the RAOs should be small due to ship symmetry, i.e., sway in head seas, surge in beam seas, roll in head seas, the predicted values for both programs are indeed small. As expected theoretically, the predicted heave RAOs for all vessels approach unity as wave frequency decreases to small values regardless of ship heading or wave incident angle. In many cases, the surge and sway RAOs generated by the RELMO program show an unrealistic increase at low frequencies for head, quartering, and beam seas. MIT sway RAOs approach unity in a realsitic manner at low frequencies for quartering and beam seas. Sway RAOs generated by the MIT program show an unexpected discontinuity at a frequency near the roll RAO peak frequency for many cases of quartering and beam seas. As expected, the best overall agreement between the two programs is observed for heave and pitch RAOs for head and quartering seas. In all cases, the pitch RAO predicted by both programs tends to zero as the wave frequency decreases. The most consistent discrepancy noted between the programs appears in the prediction of the roll RAOs; those calculated by the MIT program have noticeably larger peak values in most cases. For quartering seas the roll resonance peak frequencies predicted by the two programs compare well; however, for beam seas the RELMO program predicted unreasonable peak frequencies for the heavily loaded containerships.

Although most of the RAOs for all vessels investigated appear reasonable, there are some anomalies in the data presented. For the container ship class of vessels there are no glaring discrepancies; however, this is not the case for the lighter and barge data. In the beam sea condition the RELMO predictions for both the LCU-1610 and LCM-8 exhibit unreasonable peaks for pitch and surge RAOs at essentially the same frequency. A similar problem is noted for the MIT prediction of roll for both the pontoon and DeLong-B barges in the beam sea condition. Even though these anomalies exist, the reason for their appearance has not been determined. The reader should note that even though these anomalies are present they are easily recognized and are the exception rather than the rule.

Table 4 is included to assist the reader in accessing the degree of agreement in the RAO comparisons. For the three classes of vessels considered in this study, the RAO comparisons are rated as good, fair, or poor depending upon the authors' assessment of the degree of agreement between the MIT and RELMO programs.

TABLE 4

COMPARISON OF RAOs FOR MIT 5-D SEAKEEPING AND RELMO PROGRAMS

	HEAD SEAS ($\beta = 180°$)				QUARTERING SEAS ($\beta = 135°$)				BEAM SEAS ($\beta = 90°$)			
	CONTAINER SHIP	DISCHARGE LIGHTER	BARGE	COMMENTS	CONTAINER SHIP	DISCHARGE LIGHTER	BARGE	COMMENTS	CONTAINER SHIP	DISCHARGE LIGHTER	BARGE	COMMENTS
SURGE	N/A	N/A	N/A	Surge not predicted by MIT program.	N/A	N/A	N/A	Surge RAO not predicted in MIT program.	N/A	N/A	N/A	Surge RAO not predicted by MIT program.
HEAVE	Good	Good	Good	Agreement good for both amplitude and peak frequency.	Good	Good	Good	Agreement especially good for heavy container ships. Very good agreement for heave RAO for lighters and barges.	Fair	Fair	Good	RELMO heave RAOs for container ships consistently smaller than MIT values.
SWAY	Good	Good	Good	Small sway RAO values predicted for head seas.	Fair	Fair	Fair	Agreement good except for unrealistic increase at low frequencies for RELMO and discontinuity for MIT.	Fair	Poor	Fair	Good agreement for container ship RAOs except at very low frequencies and at discontinuity in MIT data for light condition. Agreement for barges good except at very low frequencies where RELMO data increases unrealistically.
PITCH	Good	Good	Fair	Barge pitch RAO agreement good at lower frequencies; poor at higher frequencies.	Good	Good	Fair	Very good agreement for barge RAOs at low frequencies; poor at higher frequencies.	Good	Poor	Good	Small values predicted for container ship and barge pitch for beam seas.
ROLL	Good	Good	Good	Small roll RAO values predicted for head seas.	Poor	Poor	Fair	Fair agreement for quartering sea peak frequency for container ships; amplitudes are widely different.	Poor	Poor	Fair	Fair peak frequency agreement for lighter container ships and very poor for heavy container ships. Barge roll RAOs agree well at lower frequencies.
YAW	Good	Good	Good	Small yaw RAO values predicted for head seas.	Good	Poor	Good	Yaw RAOs for one lighter (LCU-8) are in good agreement at lower frequencies.	Good	Poor	Good	Container ship and barge yaw RAOs are very small for beam seas.

SUMMARY

Response amplitude operators are predicted by two digital ship motion computer models for four container vessels, two discharge lighters, and two barges. The response of each vessel in surge, heave, sway, pitch, roll, and yaw is computed as a function of wave exciting frequency for head, quartering, and beam seas. The containership RAOs were computed for both heavy and light loading conditions while only the light loading condition was investigated for the lighters and barges. Differences in the mathematical models for the ship motions programs are discussed and compared. The primary objective of this study has been fulfilled by the presentation of the RAO for the variety of vessels considered.

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