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PRELIMINARY ROLL AND PITCH PREDICTIONS FOR TWO CANDIDATE HULL FORMS OF T-AGS

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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20034

PRELIMINARY ROLL AND PITCH PREDICTIONS FOR TWO CANDIDATE HULL FORMS OF T-AGS

by

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SHIP PERFORMANCE DEPARTMENT

August 1974 SPD-576-01

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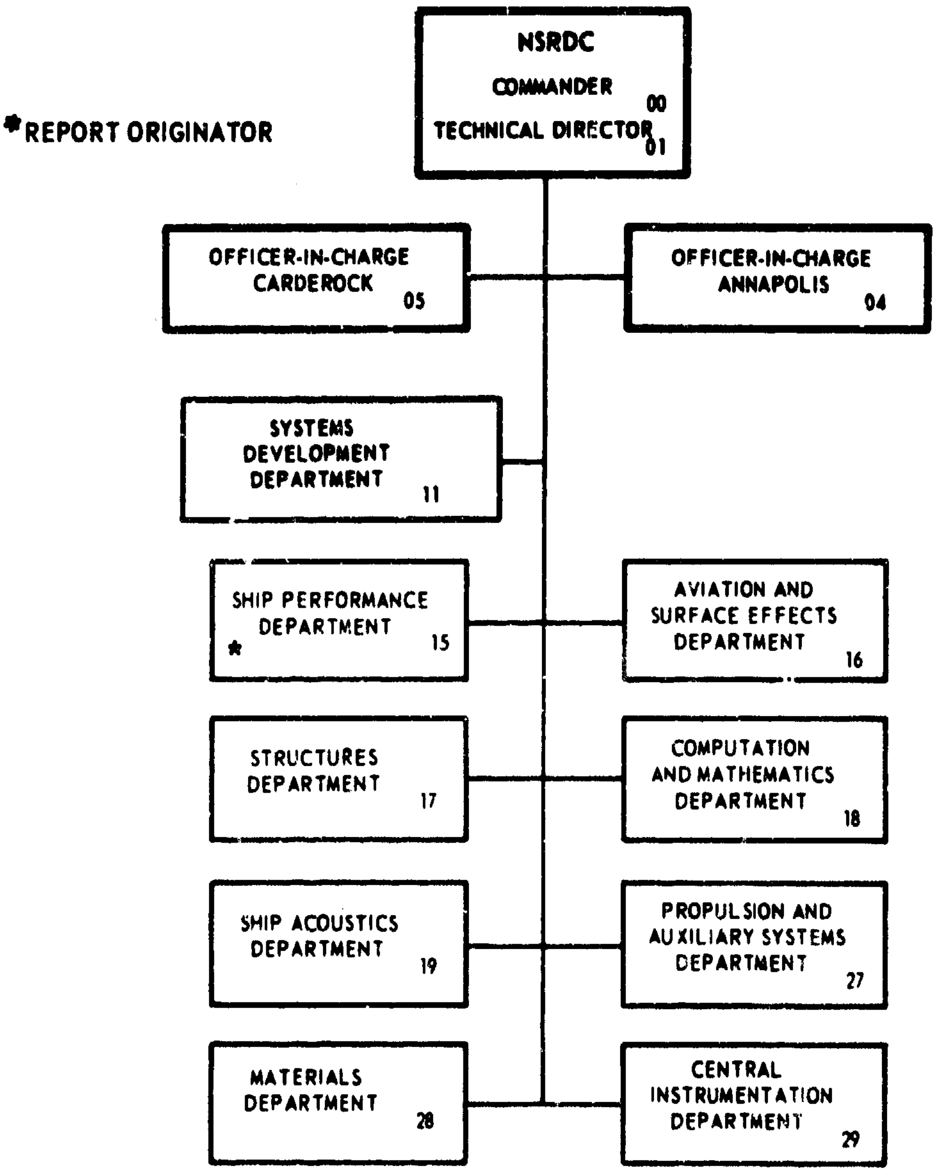

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ship speed, three sea states, and four ship headings relative to waves. Comparisons between the two hull forms, on the basis of these predictions, indicate that the hard chined hull rolls and pitches less than the conventional hull form. However, it is not considered possible to infer from these limited results that one hull is a more seaworthy one than the other.

TABLE OF CONTENTS

	Page
ABSTRACT	1
ADMINISTRATIVE INFORMATION	1
INTRODUCTION	1
PREDICTION PROCEDURE	2
OVERVIEW OF PROCEDURE	2
SHIP AND PREDICTION PARTICULARS	3
DISCUSSION OF SEA REPRESENTATION	4
CALCULATION OF ROLL IN STEEP WAVES	6
CRITERIA FOR ACCEPTABLE SHIP RESPONSE LEVELS	7
RESULTS	9
DISCUSSION OF RESULTS AND CONCLUSIONS	10
RECOMMENDATION	11
APPENDIX - COMMENTS ON PREDICTION VALIDITY	12
REFERENCES	14

LIST OF FIGURES

Figure 1 - Computer Fit to Underwater Body Plan of ATF	16
Figure 2 - Computer Fit to Underwater Body Plan of OSB	17
Figure 3 - Theoretical Wave Spectra Used to Represent Sea Conditions	18
Figure 4 - Length and Sea Condition Influence on Most Probable Extreme Roll and Pitch Amplitudes in 200 Motion Amplitudes	19

LIST OF TABLES

Page

Table 1 - ATF Particulars 20

Table 2 - OSB Particulars 21

Table 3 - Constants for Single Amplitude Statistics and Definition of Sea State 22

Table 4 - Most Probable Extreme Roll and Pitch Amplitudes in 200 Motion Amplitudes for ATF 23

Table 5 - Most Probable Extreme Roll and Pitch Amplitudes in 200 Motion Amplitudes for OSB 24

Table 6 - Percentage Difference in Roll and Pitch Motion Levels of the ATF and OSB Hull Forms 25

ABSTRACT

The purpose of this investigation is to make abbreviated ship motion predictions to assist in the preliminary selection of an acceptable hull form for a Military Sealift Command general survey ship identified as T-AGS. General seakeeping characteristics such as deck wetness, bow/stern slamming and associated accelerations are not considered. Only pitch and roll motion predictions are made for two candidate hull forms, one having a conventional hull form and the other a hard chined form. Each of the candidate hulls is expanded into a series of four specific ship geosims. Predictions are presented for one ship speed, three sea states, and four ship headings relative to waves. Comparisons between the two hull forms, on the basis of these predictions, indicate that the hard chined hull rolls and pitches less than the conventional hull form. However, it is not considered possible to infer from these limited results that one hull is more seaworthy than the other.

ADMINISTRATIVE INFORMATION

This investigation was performed at the Naval Ship Research and Development Center (NSRDC) and authorized by Naval Ship Engineering (NAVSEC) Work Request N-65197-75-WR5. It is identified as Work Unit Number 1-1568-841.

INTRODUCTION

To assess the relative merit of two candidate hull forms for a Military Sealift Command survey ship identified as T, Auxiliary, General Survey, i.e., T-AGS, roll and pitch motion predictions were made for these hulls in irregular long crested seas. Predictions were made by using several procedures and undocumented NSRDC computer programs. Three aspects of these procedures are somewhat unusual for this type of motion prediction investigation. The first is the simple use of geosims to investigate the influence of relatively minor changes in hull size on the ship responses. The second is the use of a series of four individual wave spectra to represent sea conditions at a specific sea state or wave height level. The third is the use of specific motion level criteria to define acceptable ship roll and pitch motions. All three aspects are discussed at some length in the following sections of this report.

PREDICTION PROCEDURE

OVERVIEW OF PROCEDURE

The ship response predictions were made in five distinct steps. These steps consist of the generation of response amplitude operators, RAO's; the generation of irregular long crested sea root mean square, RMS, responses; the calculation of suitable response statistics or limiting motion levels; the tabulation of results, and the generation of a graph which summarizes the results. The first step was performed primarily by the Naval Ship Engineering Center (NAVSEC), whereas the other steps were performed by the NSRDC Ship Performance Department.

The NAVSEC data decks were used as input to the NSRDC version of the Ship Motion and Sea Load Computer Program, see Reference 1,* rather than the NAVSEC version. This latter version had not yet been optimized for production calculations. The RAO's thus obtained were used as input to existing undocumented NSRDC ship motion computer programs in order to calculate RMS responses in irregular long crested seas, which in turn were then used to compute response statistics that should not be exceeded for the satisfactory performance of the ships, e.g., most probable extreme response in 200 motion amplitudes. These statistics were then tabulated as well as plotted to summarize the response predictions. Response levels which exceeded either 10 degrees pitch amplitude or 15 degrees roll amplitude are denoted by ** in the data tables. The 10 and 15 degree criteria were designated as design parameters by NAVSEC Code 6114.

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* References are listed on pages 14-15.

SHIP AND PREDICTION PARTICULARS

Predictions were made for geosim hull forms based on the ATF, i.e., Auxiliary Tug Fleet, and the OSB, i.e., Offshore Supply Boat. They are for a ship speed of 12 knots in head (180°), bow (120°), beam (90°), and quartering (60°) long crested waves for sea states 4, 5, and 6 represented by significant wave heights of 7, 10, and 18 feet. Each sea state is defined in terms of four distinct Bretschneider wave spectra. Responses were thus computed for 12 different wave spectra, i.e., 3 heights, 4 modal wave periods. A discussion of the sea state representation follows in the next section.

In order to examine the effect of relatively minor changes in hull size on ship roll and pitch, four specific ship lengths were considered for each of the two ships: 174 feet, 194 feet, 214 feet, and 234 feet. The use of geosims to study minor changes in hull dimensions is a simple procedure because once hull geometry and load specifications such as the vertical center of gravity, and the gyradii are known for the base hull, they are also known for the other geosims. The use of geosims implies that all hull characteristics are Froude scaled, i.e., dimensions are scaled by the length or scale ratio, displacement is scaled by the cube of the scale ratio, and time is scaled by the square root of the scale ratio. The scale ratio is, by definition, the ratio of the length of a particular geosim to the length of the base hull. Thus, geosims larger than the base hull have proportionately much larger displacements. For example, a 20 percent increase in length over the base hull length results in a geosim displacement approximately 75 percent greater than the base hull displacement. A 10 percent increase in length over the base hull, on the other hand, results in a more acceptable and realistic displacement increase of 33 percent above the base hull displacement. Thus, it appears from practical design considerations that the use of geosims to investigate the effects of changes in hull size on ship motions should be restricted to length increases or decreases of 10 percent or less.

The computer fits of the body plans of the two ships are shown in Figures 1 and 2 and the particulars are given in Tables 1 and 2. It should be noted that the ATF was fitted with bilge keels for purposes of these calculations. In addition, it should be pointed out that the load characteristics of these ships are not entirely realistic. Tables 1 and 2 indicate that both hulls have the same nondimensional roll gyradii. It is expected that the OSB would have a somewhat larger roll gyradii than the ATF because a relatively large, as compared to ATF, amount of the total hull weight of the OSB is at or near the extreme local beam of the ship sections. The result of this factor is that the OSB would have a somewhat larger roll period when compared to the ATF than is evident from the present predictions.

DISCUSSION OF SEA REPRESENTATION

The inadequacy of the one parameter* Pierson-Moskowitz wave spectrum, see Reference 2, as a model of the sea for ship response predictions has been demonstrated repeatedly in the past year, see References 3, 4, 5, 6, and 7. Briefly, misleading motion response predictions will result when such a spectrum for a particular wave height is used to represent a general sea state, such as a sea state 4, 5, or 6. It should be noted that sea state is defined in terms of the wave height and generally the significant wave height is used as this defining wave height. The significant wave height is defined to be equal to the average of the third highest waves. The reason why misleading motion predictions occur when the single parameter Pierson-Moskowitz spectrum is used for the sea state model is that this spectrum represents only a single type of sea condition, i.e., a fully developed wind generated sea. In the open ocean, however, swell corrupted seas and even pure wind generated seas at various stages of sea development occur far more frequently than the rather rare fully developed type of sea condition. The more common sea conditions have substantially different harmonic contents or wave spectra compared to those for fully developed seas and therefore result in different ship responses.

Both visually observed, see References 8, 9, and 10, and measured, see References 11 and 12, wave data have indicated that a wave spectrum

* Significant wave height.

with a particular modal period and significant wave height cannot adequately represent the rather wide range of sea conditions that can and do occur with the same general wave height. In other words, the modal (peak) period or frequency content (shape) of the spectrum can vary considerably for a given significant wave height.

At present, there are two basic schools of thought about how to improve the accuracy and realism of the sea description for ship response prediction purposes. One school of thought, see References 4 and 6, favors some type of idealized spectral family and the other, see References 3 and 5, favors use of a weighted set of real, measured spectra. The equivalence of these two approaches is demonstrated in Reference 13 for large ships in extreme seas. As a result, it was considered that the most convenient of the two approaches could be employed in this present investigation because it also considers ship responses in extreme seas (relative to the small size of the hull forms under consideration).

For the reasons discussed above, the seas were analytically represented by two parameter (significant wave height and modal period) wave spectra of the form developed by Bretschneider, see Reference 14. Here modal wave period represents the period corresponding to the peak of the wave spectrum. Table 3 presents sea states defined in terms of significant wave heights as well as the statistical constants* which relate various amplitude statistics to the RMS wave height or ship responses. For this investigation, sea state 4 is represented by a 7 foot significant wave height with four different wave spectra, i.e., Bretschneider spectra with modal wave periods of 6, 8, 10, and 14 seconds. Sea States 5 and 6 are similarly represented by these same 6, 8, 10, and 14 second spectra at significant wave height levels of 10 and 18 feet. Examples of the Bretschneider wave spectra used to represent the sea conditions are shown in Figure 3 for a one foot significant wave height to demonstrate the range of sea conditions considered.

It is important to note here that the same modal period spectrum represents different sea conditions in sea states 4, 5, and 6 when the

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* All constants derived on the assumption that wave heights follow a Rayleigh amplitude distribution.

spectrum is appropriately scaled to the 7, 10, and 18 foot significant wave heights. The different sea conditions consist of pure wind generated seas, a mixture of wind generated seas and swell, and seas where swells predominate. The 6 second seas, for example, represent partially developed, fetch limited wind generated seas. Specifically at the 7 foot significant wave height level, these seas represent common open ocean sea conditions which occur shortly after a hurricane moves into a particular area. At the 10 and 18 foot significant wave height levels, however, these 6 second seas represent rare, fetch limited hurricane seas which have been observed in the Great Lakes, see Reference 8, but not in the open ocean. The 8 second seas represent common open ocean partially developed wind generated seas at both the 7 and 10 foot significant wave height levels. At the 18 foot wave height level these 8 second seas again represent rare, fetch limited hurricane seas noted in the Great Lakes. The 10 second seas represent common open ocean, partially developed storm seas at the 18 foot significant wave height level. At the lower significant wave height levels these 10 second seas represent mixed wind and swell seas, with the 7 foot, 10 second seas representing seas where swell waves rather than wind waves predominate. Finally, the 14 second seas represent mixed wind and swell sea conditions at all three levels of wave height.

CALCULATION OF ROLL IN STEEP WAVES

Recent NSRDC ship motion and acceleration prediction work for the U. S. Coast Guard has indicated the inadequacy of current NSRDC roll prediction procedures in extreme seas. It has become apparent that roll nonlinearities cannot be ignored when roll predictions in extreme seas are made. Extreme seas are defined, for these purposes, as seas which have wavelength* to significant wave height ratios of 1/40 or less. As a result, revisions to the prediction procedure to account for roll nonlinearities are currently underway. The roll motion predictions for the ATF and OSB both fall in the above category of roll prediction in extreme seas. The urgency of the present ATF/OSB work does not allow the complete application

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* Wavelength corresponding to the modal wave period.

of the procedure developed for the Liquid Natural Gas, LNG, work for the U. S. Coast Guard. Therefore, the roll nonlinearity correction factors developed for the LNG roll predictions are applied directly to the ATF/OSB ship roll values. It is to be noted that these corrections are approximately applicable since the Froude speed of the LNG ships and the ATF/OSB ships are quite similar. The correction factors were applied to roll in beam (90°) and quartering (60°) seas. A description or documentation of the roll nonlinearity correction procedure is currently being written for the U. S. Coast Guard.

CRITERIA FOR ACCEPTABLE SHIP RESPONSE LEVELS

The performance of ships from the ship motion point of view can best be determined by considering the amount of time certain undesirable response levels are exceeded and the consequences that result when these levels are exceeded.

The question as to which response criterion or statistic to choose for the limiting, or acceptance level of ship response must, of necessity, depend either on the functional characteristic of the system to be installed on the ship, or on the ship's mission. Further, it is considered that the selection of the motion limiting statistic or criterion is best determined by the designer of the system to be installed on the ship. This practice was followed in recent work at NSRDC wherein gunfire control machinery was not able to accept even rare instances of exceeding prescribed ship motion levels. In that investigation, it was concluded that a suitably rare event for the gunfire control system would be the highest observed response within a 15 minute time period. This motion level corresponded to the highest expected value of pitch and roll amplitude within 1000 occurrences. This most probable extreme value of ship motion is related by a factor of 3.72 to the RMS ship motion.

In the absence of specific knowledge about the consequence of exceeding the motion limit, a less stringent limiting motion level criterion--the highest expected value of ship motion amplitude within 200 occurrences has been selected in the present case. This value is related by a factor of

3.25 to the RMS ship motions. Results given in Tables 4 and 5 and Figure 4 are based on this limiting criteria.

A still less severe limiting criterion can be found by considering the average of the 1/10 highest ship motion amplitudes, $R_{1/10}$. It can be shown that only one motion amplitude in approximately 26 can be expected to exceed the $R_{1/10}$ motion level.

The first and third limiting motion levels discussed above are presented to allow or suggest alternative limiting motion levels to the one selected. If the criterion employed in establishing the limiting motion is regarded as too lax, it can be made more stringent simply by multiplying the values in Tables 4 and 5 by 1.15, i.e., by (3.72/3.25), see Table 3. Similarly, if the limiting motion statistic is regarded as being too stringent, it can be relaxed by multiplying the values in Tables 4 and 5 by 0.78, i.e., 2.55/3.25.

Table 3 gives these statistical constants, as well as others, for both single and double amplitude ship responses and wave heights. Again, it should be noted that the data presented in Tables 4 and 5 and Figure 4 are all single amplitudes for the case of the most probable extreme motion in 200. It is important to note, however, that the highest expected (or most probable) value in N amplitudes of ship motion is calculated on the assumption that wave and motion amplitudes are distributed according to the Rayleigh distribution. Repeated model and full scale experiments have demonstrated that this basic assumption is sufficiently accurate for engineering purposes. Both full scale experiments and simulations thereof have demonstrated that the occurrence of swell in the seas will produce departures in the amplitude distribution from the theoretical Rayleigh* distribution. These departures from the Rayleigh distribution in swell and wind generated seas have generally resulted in overpredictions (up to 40 percent) of the highest expected values in N motion amplitudes. These overpredictions increase with N. Therefore, to provide reasonably accurate predictions, N should be as small as practicable. All of the above reasons led to the selection of extreme motion predictions for 200 rather than 1000 motion amplitudes.

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* See Reference 15.

RESULTS

The results of the predictions are presented in Tables 4, 5, and 6 as well as in Figure 4. Tables 4 and 5 present the most probable extreme roll and pitch amplitudes that are likely to occur in 200 motion amplitudes for the two ships. This limiting motion level criterion was selected on the basis of both the expected number of motion amplitudes in 15 minutes in quartering seas, and the fact that the largest angular motions occur in quartering seas. A somewhat more thorough discussion on the selection of this limiting motion level criterion, as well as methods for adjusting this level, is presented in the Criteria for Acceptable Ship Response Levels Section.

Tables 4 and 5 present the roll and pitch results for four headings, four modal wave periods, three wave heights and four ship lengths (associated with four geometrically scaled ships). The four data columns represent the modal wave periods. Each column contains the responses at the three levels of significant wave height. Each data row represents a specific ship heading with the responses arranged in order of increasing ship length. This ordering of the basic ship response data easily illustrates the influence on the limiting motion responses of sea conditions (modal period and height), as well as heading and ship length on size. However, since the base hull length is 194 feet and geosims which varied by more than 10 percent of the base hull length are regarded as unrealistic, the roll and pitch results for the 234 foot ship length are equally unrealistic.

Table 6 presents the percentage difference between the roll and pitch responses of the ATF and the OSB on the basis of OSB responses. Positive percentages denote the cases when the ATF responses are greater than the corresponding OSB responses, and negative percentages denote ATF responses lower than corresponding OSB responses.

The numerical values in Tables 4, 5, and 6 are all rounded to three significant digits before printing. It should be noted that the Table 6 results were computed using the true (unrounded) values corresponding to the rounded values found in Tables 4 and 5.

Figure 4 was prepared to illustrate graphically, for both ships, the influence of ship size (length), the effect of variations in sea conditions in sea state 5 (significant wave height 10 feet), and the effect of variations in heading on ship responses. The heading effect on roll and pitch is shown by connecting the maximum and minimum ship responses in the various ship headings with a vertical line. There is, of course, one such bar type symbol (I) for each of the four sea conditions, i.e., 6, 8, 10, and 14 second modal wave periods. Thus, the effect of ship heading is shown by the height of the response symbol (I) for all four sea conditions clustered about the appropriate ship size (length).

DISCUSSION OF RESULTS AND CONCLUSIONS

The results of the motion predictions indicate clearly that the pitch and roll amplitude responses of the conventional rounded bottom ATF are substantially greater* than for the hard chined OSB. In head seas, for example, (heading for maximum pitch) the ATF appears to pitch from 25 to 69 percent more than the OSB, see Table 6. In quartering seas, the corresponding difference in pitch is from about 16 to 27 percent. Roll in head seas is, of course, zero when long crested seas are considered, as in this investigation. In bow seas, the ATF roll responses are from 50 to 89 percent greater than the OSB roll responses. Differences between ATF and OSB roll responses are, as was the case for pitch, less in quartering seas (32 to 45 percent) than in bow seas (50 to 89 percent).

As expected, increasing the ship size always decreases the ship responses for both ships, see Tables 4 and 5. These benefits in ship response reductions with increasing size were essentially the same for both ships although again the hard chined OSB achieved slightly larger motion reductions with size than the ATF. Motion reductions with increase in size were also larger in head or bow seas than in quartering seas for both ships. Benefits in ship response reductions with increasing ship size are substantially less pronounced in seas with swell, i.e., 10 and 14 second seas, than in the shorter seas, i.e., 6 and 8 second modal periods. Motion

* Except for pitch in beam seas, which is of negligible magnitudes for both hulls.

reductions with size varied a great deal, with about one half of the calculation conditions resulting in motion reductions of 25 percent or greater. This percentage is based on the responses for the ships at a 234 foot length.

In examining the results of Tables 4 and 5, it may be noted that the ATF fails to meet the limiting roll motion criteria about three times as frequently as the OSB. Neither boat ever fails to meet the pitch criteria.* In addition, it may be noted that by far the greatest number of failures to meet the roll motion limits occur in quartering seas rather than in beam or bow seas. It would appear that if the ships do not necessarily have to perform their mission in quartering seas, then neither ship requires roll stabilization to reduce roll.

In summary, it appears on the basis of the roll and pitch predictions that the OSB rather than the ATF hull is a more suitable candidate hull for the T-AGS ship. However, it should be strongly emphasized that the clear superiority of the OSB ship from the roll and pitch response viewpoint is no guarantee that the OSB hull will have better general seakeeping qualities than the ATF. For example, it is apparent from a review of the stern lines of both vessels (see Figures 1 and 2) that the consequences of stern emergence which may be expected in sea state 4 are likely to result in far higher vertical stern accelerations due to impacts on the OSB than on the ATF. Similarly, since relative bow and stern motions were not considered as part of this investigation, an unequivocal choice cannot be made on the basis of present predictions.

RECOMMENDATION

If preliminary design alternatives require alterations in major hull parameters such as length, beam, or draft of more than 10 percent, geosims should not be used. It is recommended instead that these alterations be made on the basis of constant or rationally increasing hull displacement. Separate computer programs to carry out these hull alterations should be developed.

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* Except for five head sea cases for the ATF.

APPENDIX

COMMENTS ON PREDICTION VALIDITY

The NSRDC Ship Motion and Sea Loads Computer Program, see Reference 1, commonly referred to as the Six Degree of Freedom Program, calculates ship responses in sinusoidal waves. Ship responses in irregular seas are then calculated by use of the linear superposition principal in the as yet undocumented NSRDC Irregular Sea Response Prediction Program. Experimental verification for the above ship motion prediction programs has been performed to date primarily with model scale experiments of U.S. Navy ships. The verification incudes air capable ships (LPH-9, Sea Control Ship), destroyers (DAVIDSON A, DE 1006), cargo vessels (MARINER, AOE), as well as a large commercial LNG tanker. Additional experimental verification of the programs has been done by a foreign classification society. Both regular and irregular wave verification experiments have been performed.

It should be noted, however, that none of the verification experiments were performed on hull forms which have sharp chines such as the ones of the OSB. It is considered, therefore, that without experimental verification, the accuracy of the predicted roll and pitch motions is not known. Additional comments about expected magnitudes of prediction inaccuracies are made in the remainder of this section to assist in the interpretation of the results.

The hard chined OSB hull is expected to have significantly greater viscous damping (roll, pitch and heave) than the more conventional ATF hull. However, these damping differences are not expected to result in large pitch and heave motion differences.

It is further expected that neither pitch nor heave will be seriously affected by the chine for small ship motions. Small motions in this context denote motions which do not cause the bow or stern of the OSB to emerge from the water. Once bow or stern emergence occurs, it is expected that the pitch and heave responses will become very nonlinear. Very little is known about the effect of these motion nonlinearities on the accuracy of motion predictions made with the present programs. It is expected, but not verified experimentally, that these motion nonlinearities would tend to limit pitch and heave. Thus, the motions predicted by the use of linear ship motion theory, as in the present case, are expected to be conservative, i.e., greater than the true ship pitch and heave motions.

Some experimental data (bilge keel, roll, roll damping) suggest that the NSRDC programs may tend to underpredict roll damping values for ships with sharp chines. The predicted OSB roll values are therefore expected to be somewhat higher than roll values that would be experienced by the ship.

It is concluded from the above discussion of the prediction accuracies that the basic conclusion regarding the relative magnitudes of the ATF/OSB roll and pitch responses is correct.

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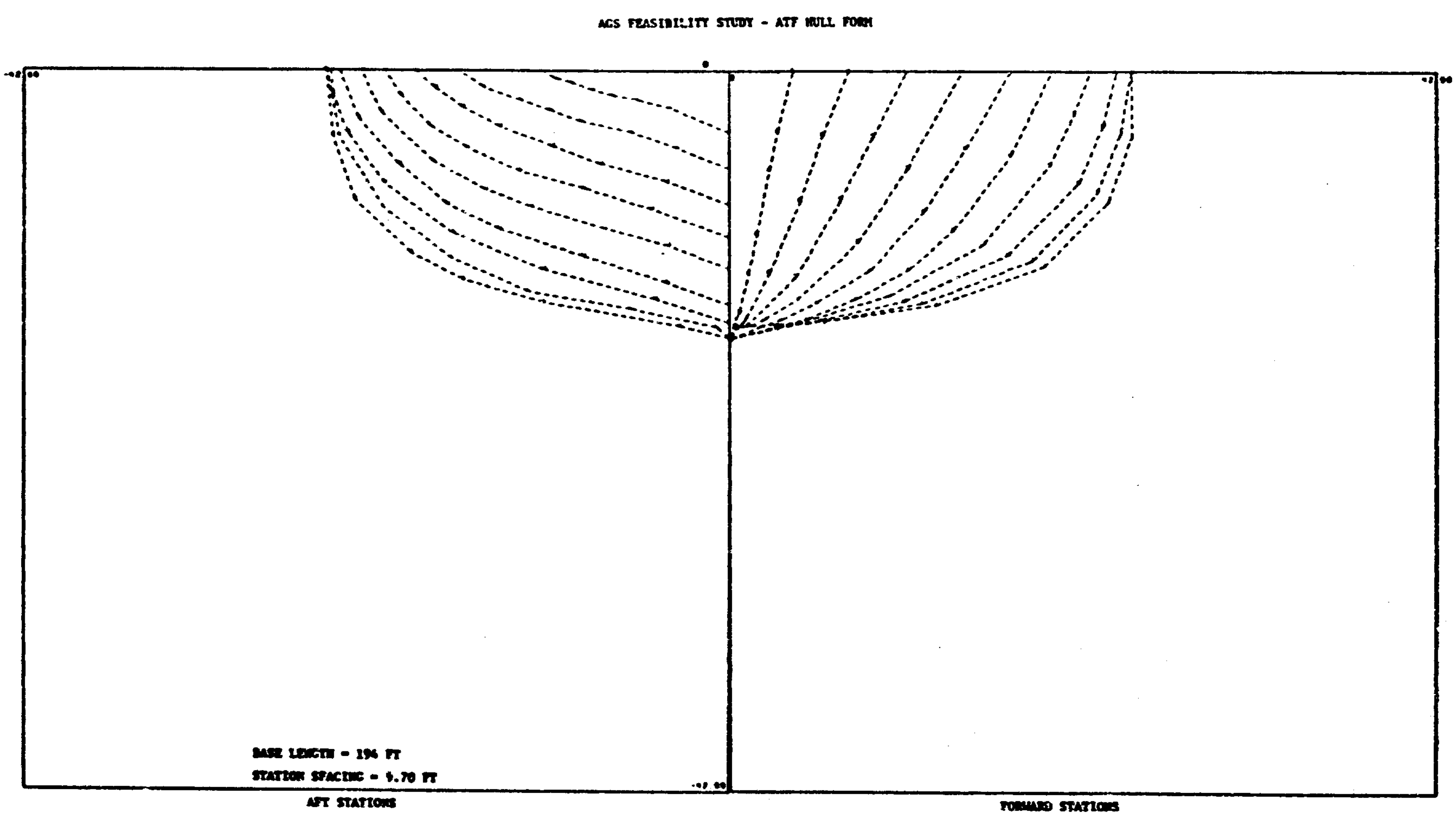

Figure 1 - Computer Fit to Underwater Body Plan of ATF

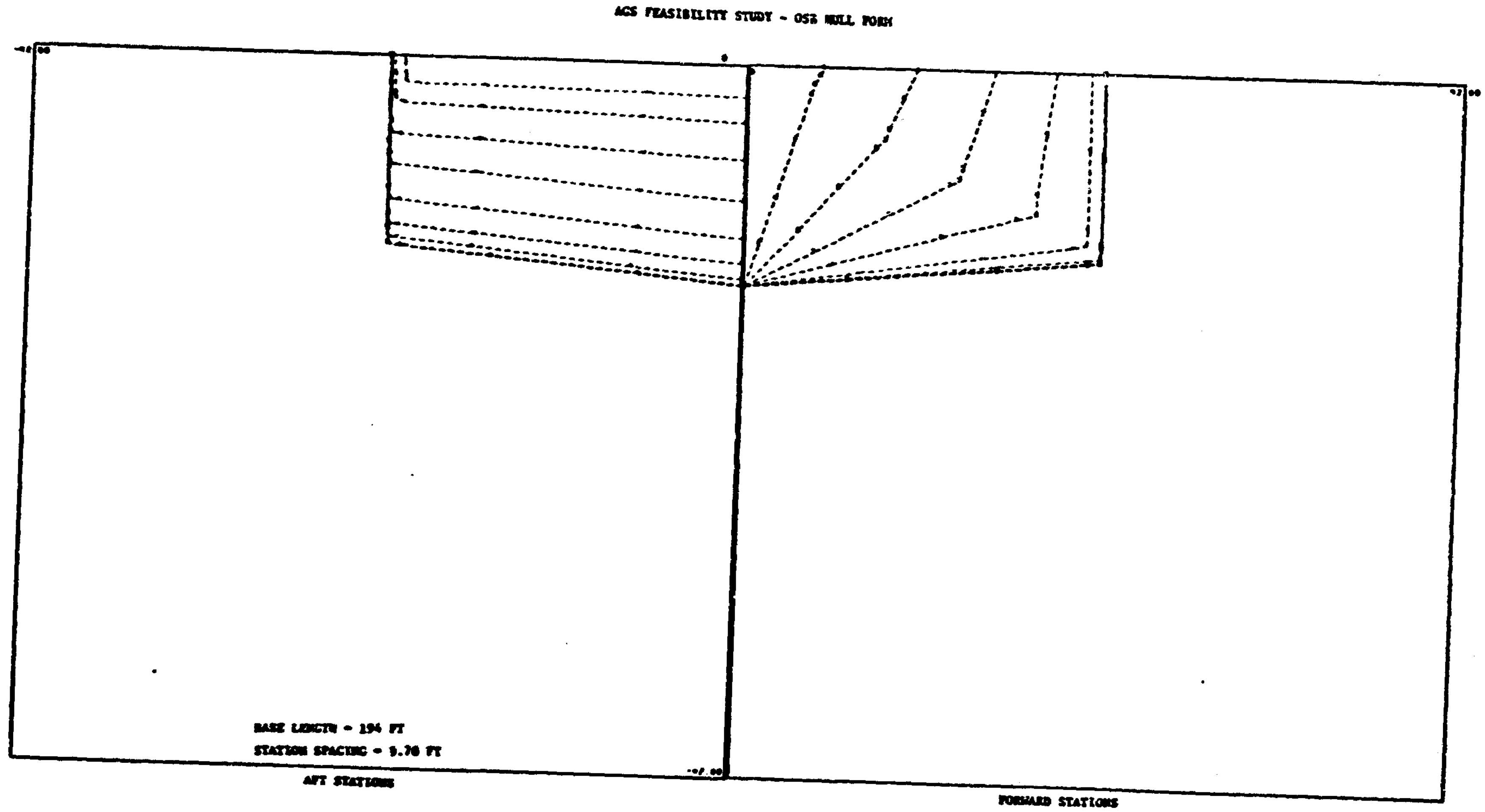

Figure 2 - Computer Fit to Underwater Body Plan of OSB

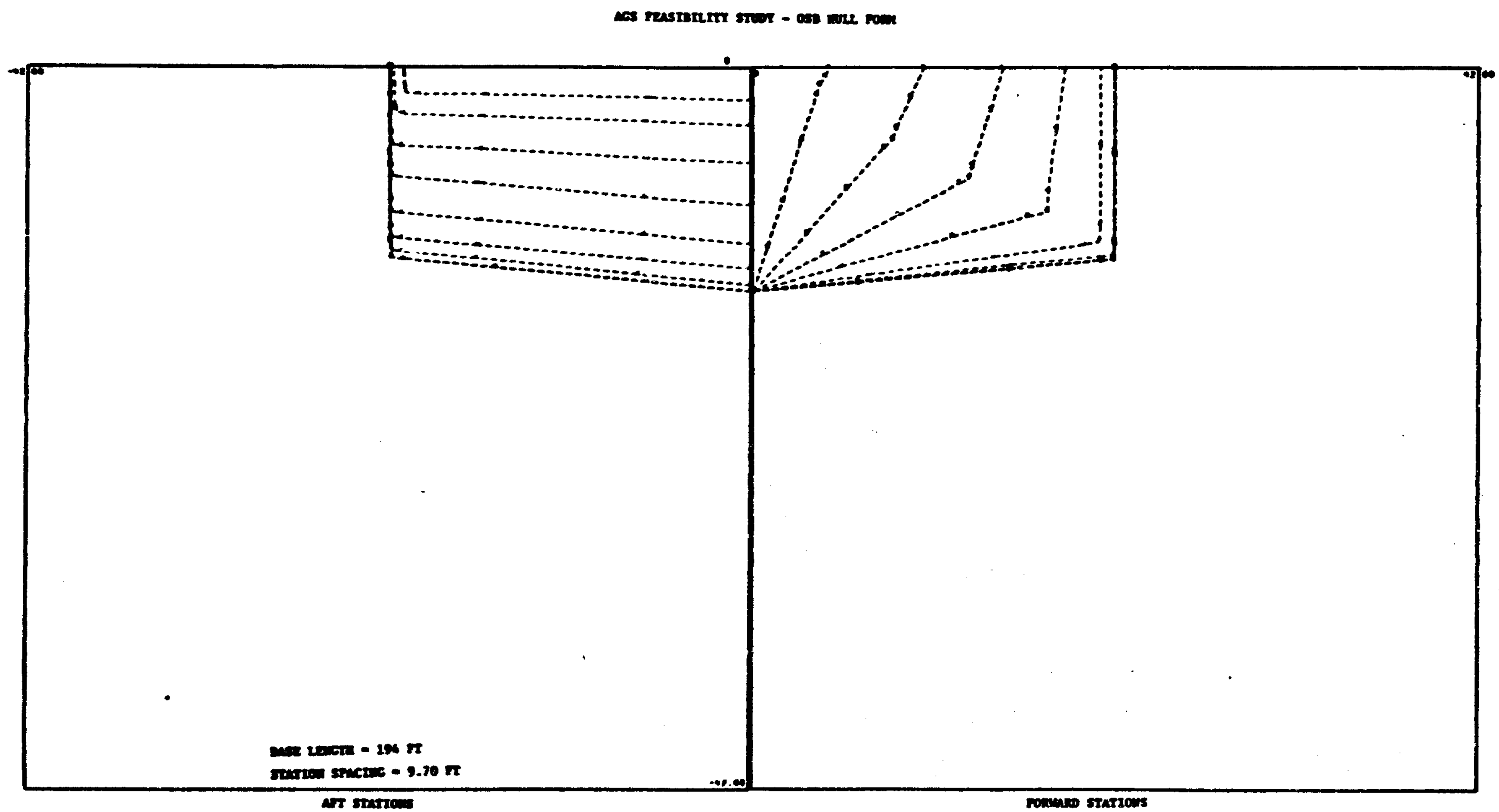

Figure 2 - Computer Fit to Underwater Body Plan of OSB

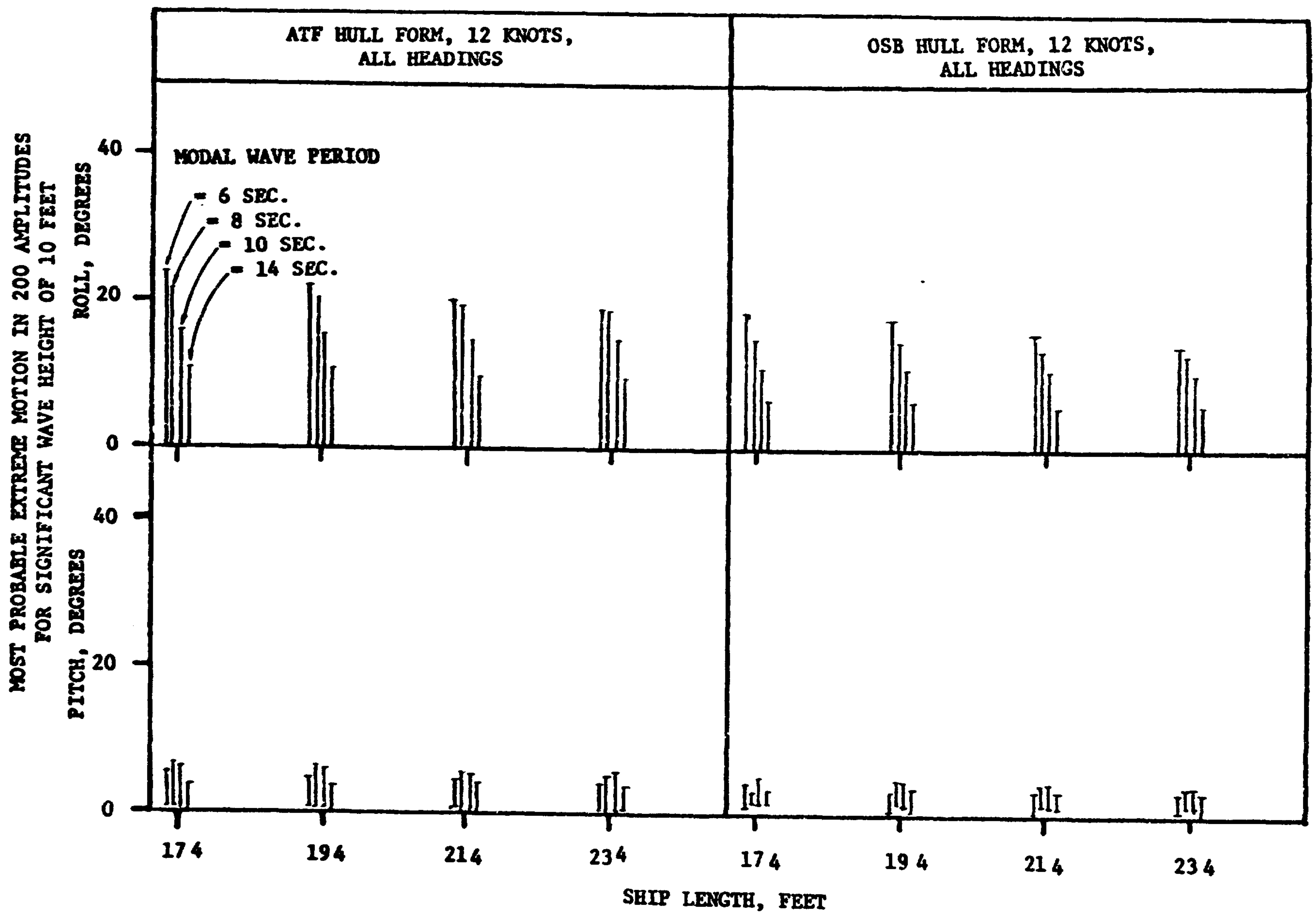

Figure 4 - Length and Sea Condition Influence on Most Probable Extreme Roll and Pitch Amplitudes in 200 Motion Amplitudes

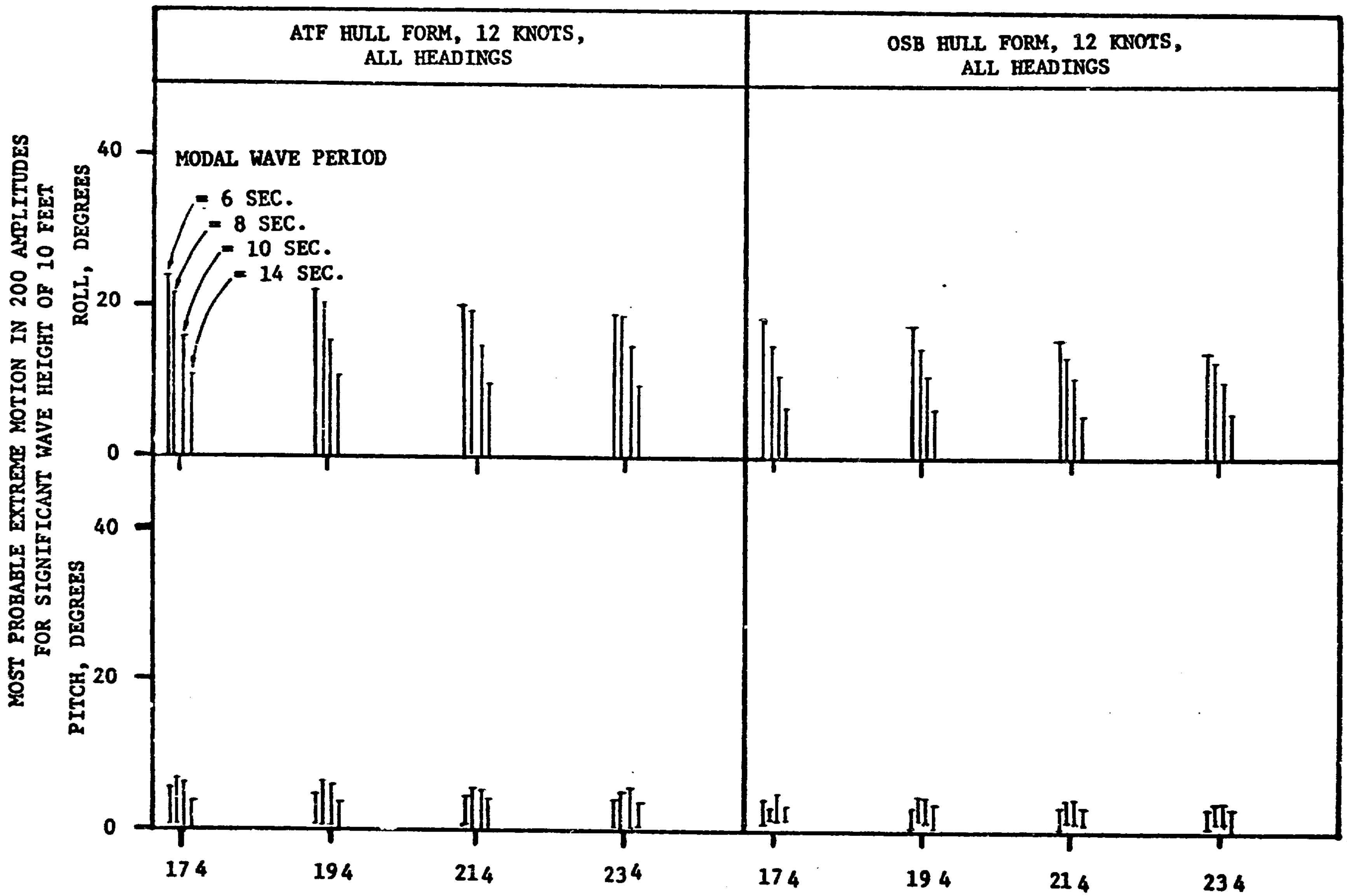

Figure 4 - Length and Sea Condition Influence on Most Probable Extreme Roll and Pitch Amplitudes in 200 Motion Amplitudes

TABLE 2 - OSB PARTICULARS

AGS FEASIBILITY STUDY - OSB HULL FORM
TABLE OF SHIP PARTICULARS

SHIP LENGTH(LBP)	L	194.00 FEET	LENGTH/BEAM	4.619
MAXIMUM BEAM*	B	42.00 FEET	BEAM/DRAFT	3.231
MAXIMUM DRAFT*	T	13.00 FEET	DRAFT/BEAM	.310
DISPLACEMENT	W	1910 TONS,SW	W/(.01L)**3	261.688
DESIGN SPEED	V	11.98 KNOTS	FROUDE NUMBER	.256
VERTICAL CG	KG	16.00 FEET	KG/BEAM	.381
METACENTRIC HT.	GM	5.84 FEET	GM/BEAM	.139
LONGITUD. CG**	LCG	-1.90 FEET	LCG/LENGTH	-.020
ROLL GYRADIUS	RRG	16.80 FEET	RRG/BEAM	.400
PITCH GYRADIUS	PRG	48.50 FEET	PRG/LENGTH	.250
YAW GYRADIUS	YRG	48.50 FEET	YRG/LENGTH	.250
EST. ROLL PERIOD		7.70 SECS	ROLL FREQ.(RAD)	.816
TRANSOM WIDTH	TW	40.50 FEET	TW/BEAM	.964
WATERPLANE AREA	AWP	7030 SQ. FEET	AWP/(LB)	.863
WETTED SURFACE	WS	10179 SQ. FEET	WS/(2LT+2BT+LB)	.713
LONGITUD. CB**	LCB	-1.90 FEET	LCB/LENGTH	-.020
LONGITUD. CF**	LCF	-.10 FEET	LCF/LENGTH	-.001
VERTICAL CB	KB	7.59 FEET	KB/BEAM	.181
METACENTER	KM	21.84 FEET	KM/BEAM	.520
BLOCK COEFF.	CB	.63		
SECTION COEFF.	CX	.93		
PRISMATIC COEFF.	CP	.68		

* AT STA. 7.00 ** AFT OF MIDSHIPS

NOTE: BY FROUDE SCALING, VARIATIONS ON THE BASE HULL FORM, L = 194 FEET, ARE

	L FEET	B FEET	DISPLACEMENT TONS, S.W.	EST. ROLL PERIOD SEC.
	174	37.7	1378	7.29
(BASE)	194	42.0	1910	7.70
	214	46.3	2563	8.09
	234	50.6	3352	8.46

TABLE 3 - CONSTANTS FOR SINGLE AMPLITUDE STATISTICS AND DEFINITION OF SEA STATE

Single Amplitude Statistics		Sea States in Terms of Significant Wave Height
Root mean square value, RMS	$= \sigma$	Sea State 2 Range 1.92 to 4.13 Ft
Average amplitude	$= 1.25\ \sigma$	Sea State 3 Range 4.13 to 5.66 Ft
Average of highest 1/3 amplitudes, significant	$= 2.00\ \sigma$	Sea State 4 Range 5.66 to 7.36 Ft
Highest expected amplitude in 10	$= 2.15\ \sigma$	Sea State 5 Range 7.36 to 13.04 Ft
Average of highest 1/10 amplitudes	$= 2.55\ \sigma$	Sea State 6 Range 13.04 to 20.80 Ft
Highest expected amplitude in 30	$= 2.61\ \sigma$	Sea State 7 Range 20.80 to 40.32 Ft
Highest expected amplitude in 50	$= 2.80\ \sigma$	Sea State 8 Range 40.32 to 61.58 Ft
Highest expected amplitude in 100	$= 3.03\ \sigma$	
Highest expected amplitude in 200	$= 3.25\ \sigma$	
Highest expected amplitude in 1000	$= 3.72\ \sigma$	

Definitions

σ^2 = Statistical variance of time history

N = Number of amplitudes

CONSTANT = $\sqrt{2}\ (\ell n\ N)^{1}/_{2}$, where CONSTANT relates σ to the highest expected amplitude in N amplitudes.

NOTES:

1) The highest expected amplitude in N amplitudes is the most probable extreme value in N amplitudes. This value may be exceeded 63% of the time.

2) To obtain wave height or double amplitude statistics from RMS values, mulitply single amplitude constants by 2.0.

TABLE 4 - MOST PROBABLE EXTREME ROLL AND PITCH AMPLITUDES IN 200 MOTION AMPLITUDES FOR ATF

ATF HULL FORM
MOST PROBABLE EXTREME ROLL IN 200 MOTION CYCLES
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.*	18.*	TO = 8. SWH = 7.	10.	18.*	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	194.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	214.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	234.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120.	174.	2.6	3.7	6.6	6.9	9.9	17.9**	8.7	12.4	22.3**	7.3	10.4	18.8**
	194.	1.9	2.7	4.9	5.4	7.7	13.9	7.7	11.0	19.8**	7.1	10.2	18.3**
	214.	1.5	2.1	3.8	4.2	6.0	10.8	6.8	9.7	17.4**	6.9	9.8	17.7**
	234.	1.2	1.7	3.1	3.3	4.7	8.6	5.9	8.4	15.2**	6.6	9.5	17.1**
90.	174.	3.9	5.5	9.9	7.7	11.0	19.7**	7.6	10.9	19.6**	5.0	7.1	12.7
	194.	2.8	4.0	7.2	6.5	9.3	16.7**	7.1	10.1	18.1**	4.8	6.9	12.5
	214.	2.1	3.0	5.3	5.4	7.8	14.0	6.5	9.3	16.7**	4.7	6.8	12.2
	234.	1.6	2.3	4.1	4.5	6.4	11.6	5.9	8.5	15.2**	4.6	6.6	11.9
60.	174.	18.4**	26.3**	47.4**	14.9	21.3**	38.3**	10.8	15.4**	27.7**	5.9	8.4	15.2**
	194.	16.5**	23.5**	42.3**	14.2	20.3**	36.6**	10.5	15.0**	27.1**	5.9	8.4	15.1**
	214.	14.6	20.9**	37.5**	13.6	19.4**	34.8**	10.3	14.7	26.5**	5.8	8.3	15.0
	234.	12.9	18.4**	33.1**	12.9	18.4**	33.1**	10.0	14.3	25.8**	5.8	8.2	14.8

NOTE - ** DENOTES LIMIT OF 15.0 DEGREES IS EXCEEDED.

ATF HULL FORM
MOST PROBABLE EXTREME PITCH IN 200 MOTION CYCLES
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.*	18.*	TO = 8. SWH = 7.	10.	18.*	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	3.6	5.2	9.3	5.0	7.1	12.8**	4.5	6.4	11.5**	2.8	4.0	7.2
	194.	2.8	4.0	7.3	4.4	6.3	11.3**	4.2	6.0	10.8**	2.7	3.9	7.0
	214.	2.2	3.1	5.6	3.9	5.5	10.0	3.9	5.6	10.1**	2.7	3.8	6.9
	234.	1.7	2.4	4.3	3.4	4.9	8.8	3.7	5.2	9.4	2.6	3.7	6.7
120.	174.	3.6	5.2	9.4	3.6	5.2	9.4	2.9	4.2	7.6	1.7	2.5	4.5
	194.	3.1	4.5	8.0	3.4	4.8	8.6	2.8	4.0	7.2	1.7	2.5	4.4
	214.	2.7	3.8	6.8	3.1	4.4	7.9	2.7	3.8	6.9	1.7	2.4	4.4
	234.	2.3	3.2	5.8	2.8	4.1	7.3	2.6	3.7	6.6	1.7	2.4	4.3
90.	174.	.8	1.2	2.1	.7	1.0	1.7	.5	.8	1.4	.3	.5	.9
	194.	.7	1.1	1.9	.6	.9	1.6	.5	.7	1.3	.3	.5	.9
	214.	.7	1.0	1.8	.6	.8	1.5	.5	.7	1.3	.3	.5	.8
	234.	.6	.9	1.6	.6	.8	1.4	.5	.7	1.2	.3	.5	.8
60.	174.	3.5	4.9	8.9	3.0	4.4	7.8	2.4	3.4	6.2	1.4	2.0	3.6
	194.	3.1	4.4	8.0	2.8	4.1	7.3	2.3	3.3	5.9	1.4	2.0	3.6
	214.	2.8	4.0	7.1	2.7	3.8	6.8	2.2	3.2	5.7	1.4	2.0	3.5
	234.	2.5	3.6	6.4	2.5	3.6	6.4	2.1	3.0	5.5	1.3	1.9	[illegible]

NOTE - ** DENOTES LIMIT OF 10.0 DEGREES IS EXCEEDED.
TO IS MODAL WAVE PERIOD IN SECONDS.
SWH IS SIGNIFICANT WAVE HEIGHT IN FEET.

* CONSIDERED RARE WAVE HEIGHT FOR THIS MODAL WAVE PERIOD.

TABLE 5 - MOST PROBABLE EXTREME ROLL AND PITCH AMPLITUDES IN 200 MOTION AMPLITUDES FOR OSB

USH HULL FORM
MOST PROBABLE EXTREME ROLL IN 200 MOTION CYCLES
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.*	18.*	TO = 8. SWH = 7.	10.	18.*	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	194.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	214.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	234.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120.	174.	1.4	2.0	3.6	4.5	6.5	11.7	5.8	8.3	14.9	4.3	6.2	11.1
	194.	1.0	1.5	2.6	3.5	5.0	9.0	5.1	7.3	13.2	4.2	6.0	10.7
	214.	.8	1.1	2.0	2.6	3.8	6.8	4.5	6.4	11.6	4.0	5.8	10.4
	234.	.6	.9	1.7	2.0	2.9	5.1	3.9	5.6	10.0	3.9	5.5	10.0
90.	174.	2.7	3.9	7.0	5.7	8.1	14.6	5.6	8.1	14.5	3.7	5.2	9.4
	194.	1.9	2.7	4.9	4.8	6.9	12.4	5.2	7.5	13.4	3.6	5.1	9.2
	214.	1.3	1.9	3.4	4.0	5.7	10.3	4.8	6.9	12.4	3.5	5.0	9.0
	234.	.9	1.4	2.4	3.3	4.7	8.5	4.4	6.3	11.3	3.4	4.9	8.8
60.	174.	13.2	18.9**	33.9**	10.3	14.7	26.5**	7.4	10.6	19.1**	4.1	5.8	10.5
	194.	12.0	17.1**	30.5**	9.9	14.1	25.4**	7.3	10.4	18.7**	4.1	5.8	10.4
	214.	10.8	15.5**	27.9**	9.4	13.5	24.2**	7.1	10.1	18.3**	4.0	5.8	10.4
	234.	9.8	14.0	25.2**	9.0	12.8	23.1**	6.9	9.9	17.8**	4.0	5.7	10.3

NOTE - ** DENOTES LIMIT OF 15.0 DEGREES IS EXCEEDED.

USH HULL FORM
MOST PROBABLE EXTREME PITCH IN 200 MOTION CYCLES
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.*	18.*	TO = 8. SWH = 7.	10.	18.*	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	2.3	3.3	6.0	3.6	5.1	9.2	3.4	4.8	8.6	2.2	3.2	5.7
	194.	1.9	2.5	4.5	3.1	4.5	8.0	3.1	4.5	8.1	2.2	3.1	5.6
	214.	1.3	1.9	3.4	2.7	3.9	7.0	2.9	4.2	7.5	2.1	2.9	5.3
	234.	1.0	1.4	2.5	2.3	3.3	6.0	2.7	3.8	6.9	2.0	2.9	5.2
120.	174.	2.5	3.5	6.3	2.7	3.9	7.0	2.3	3.3	6.0	1.5	2.1	3.7
	194.	2.0	2.9	5.3	2.5	3.5	6.3	2.2	3.1	5.7	1.4	2.0	3.7
	214.	1.7	2.4	4.4	2.2	3.2	5.7	2.1	3.0	5.3	1.4	2.0	3.6
	234.	1.4	2.0	3.7	2.0	2.9	5.2	2.0	2.8	5.0	1.4	2.0	3.5
90.	174.	1.3	1.8	3.3	1.2	1.7	3.1	1.0	1.4	2.6	.6	.9	1.6
	194.	1.1	1.6	2.9	1.1	1.6	2.9	1.0	1.4	2.5	.6	.9	1.6
	214.	1.0	1.5	2.6	1.0	1.5	2.6	.9	1.3	2.3	.6	.9	1.6
	234.	.9	1.3	2.4	.9	1.4	2.4	.9	1.2	2.2	.6	.9	1.5
60.	174.	2.8	4.0	7.2	2.5	3.6	6.5	2.0	2.9	5.2	1.2	1.7	3.1
	194.	2.5	3.5	6.4	2.4	3.4	6.1	1.9	2.6	5.0	1.2	1.7	3.0
	214.	2.2	3.2	5.7	2.2	3.1	5.6	1.9	2.7	4.6	1.2	1.7	3.0
	234.	2.0	2.8	5.0	2.0	2.9	5.3	1.8	2.5	4.6	1.1	1.6	2.9

NOTE - ** DENOTES LIMIT OF 10.0 DEGREES IS EXCEEDED.
TO IS MODAL WAVE PERIOD IN SECONDS.
SWH IS SIGNIFICANT WAVE HEIGHT IN FEET.
* CONSIDERED RARE WAVE HEIGHT
FOR THIS MODAL WAVE PERIOD.

TABLE 6 - PERCENTAGE DIFFERENCE IN ROLL AND PITCH MOTION LEVELS OF THE ATF AND OSB HULL FORMS

(ATF - OSB)/OSB * 100 PERCENT
ROLL
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.	18.	TO = 8. SWH = 7.	10.	18.	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	194.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	214.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	234.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120.	174.	83.3	83.3	83.3	52.9	52.9	52.9	49.5	49.5	49.5	69.3	69.3	69.3
	194.	88.4	88.4	88.4	55.3	55.3	55.3	49.9	49.9	49.9	70.1	70.1	70.1
	214.	88.5	88.5	88.5	58.5	58.5	58.5	50.4	50.4	50.4	70.7	70.7	70.7
	234.	84.9	84.9	84.9	62.9	62.9	62.9	51.1	51.1	51.1	71.3	71.3	71.3
90.	174.	41.0	41.0	41.0	34.8	34.8	34.8	35.1	35.1	35.1	35.4	35.4	35.4
	194.	47.3	47.3	47.3	34.8	34.8	34.8	35.0	35.0	35.0	35.4	35.4	35.4
	214.	56.6	56.6	56.6	35.0	35.0	35.0	34.9	34.9	34.9	35.3	35.3	35.3
	234.	68.6	68.6	68.6	35.4	35.4	35.4	34.9	34.9	34.9	35.3	35.3	35.3
60.	174.	39.7	39.7	39.7	44.6	44.6	44.6	44.8	44.8	44.8	44.4	44.4	44.4
	194.	37.4	37.4	37.4	44.2	44.2	44.2	44.8	44.8	44.8	44.4	44.4	44.4
	214.	34.7	34.7	34.7	43.8	43.8	43.8	44.8	44.8	44.8	44.5	44.5	44.5
	234.	31.6	31.6	31.6	43.2	43.2	43.2	44.8	44.8	44.8	44.5	44.5	44.5

(ATF - OSB)/OSB * 100 PERCENT
PITCH
SHIPSPEED = 12.0 KNOTS

HEADING DEG	SHIP LENGTH FT	TO = 6. SWH = 7.	10.	18.	TO = 8. SWH = 7.	10.	18.	TO = 10. SWH = 7.	10.	18.	TO = 14. SWH = 7.	10.	18.
180.	174.	55.9	55.9	55.9	38.8	38.8	38.8	32.5	32.5	32.5	25.4	25.4	25.4
	194.	60.4	60.4	60.4	41.2	41.2	41.2	33.6	33.6	33.6	25.7	25.7	25.7
	214.	64.9	64.9	64.9	43.6	43.6	43.6	34.8	34.8	34.8	29.8	29.8	29.8
	234.	69.4	69.4	69.4	46.2	46.2	46.2	36.1	36.1	36.1	30.2	30.2	30.2
120.	174.	48.8	48.8	48.8	33.7	33.7	33.7	26.7	26.7	26.7	19.7	19.7	19.7
	194.	52.0	52.0	52.0	36.2	36.2	36.2	28.0	28.0	28.0	20.0	20.0	20.0
	214.	54.9	54.9	54.9	38.6	38.6	38.6	29.4	29.4	29.4	20.4	20.4	20.4
	234.	57.6	57.6	57.6	40.9	40.9	40.9	30.8	30.8	30.8	20.9	20.9	20.9
90.	174.	-37.2	-37.2	-37.2	-43.8	-43.8	-43.8	-45.6	-45.6	-45.6	-46.5	-46.5	-46.5
	194.	-35.1	-35.1	-35.1	-43.0	-43.0	-43.0	-45.3	-45.3	-45.3	-46.4	-46.4	-46.4
	214.	-32.8	-32.8	-32.8	-42.1	-42.1	-42.1	-45.0	-45.0	-45.0	-46.4	-46.4	-46.4
	234.	-30.5	-30.5	-30.5	-41.2	-41.2	-41.2	-44.6	-44.6	-44.6	-46.3	-46.3	-46.3
60.	174.	23.8	23.8	23.8	20.0	20.0	20.0	18.4	18.4	18.4	15.5	15.5	15.5
	194.	24.7	24.7	24.7	20.5	20.5	20.5	18.7	18.7	18.7	17.5	17.5	17.5
	214.	25.7	25.7	25.7	21.1	21.1	21.1	19.0	19.0	19.0	17.6	17.6	17.6
	234.	26.7	25.7	26.7	21.7	21.7	21.7	19.3	19.3	19.3	17.7	17.7	17.7

NOTE - TO IS MODAL WAVE PERIOD IN SECONDS.
SWH IS SIGNIFICANT WAVE HEIGHT IN FEET.