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SLAMMING AND DECK WETNESS CHARACTERISTICS OF A UNITED STATES COAST GUARD MEDIUM ENDURANCE CUTTER (WMEC) IN LONG-CRESTED, HEAD SEAS

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SLAMMING AND DECK WETNESS CHARACTERISTICS OF A UNITED STATES COAST GUARD MEDIUM ENDURANCE CUTTER (WMEC) IN LONG-CRESTED, HEAD SEAS

by

N. K. Bales

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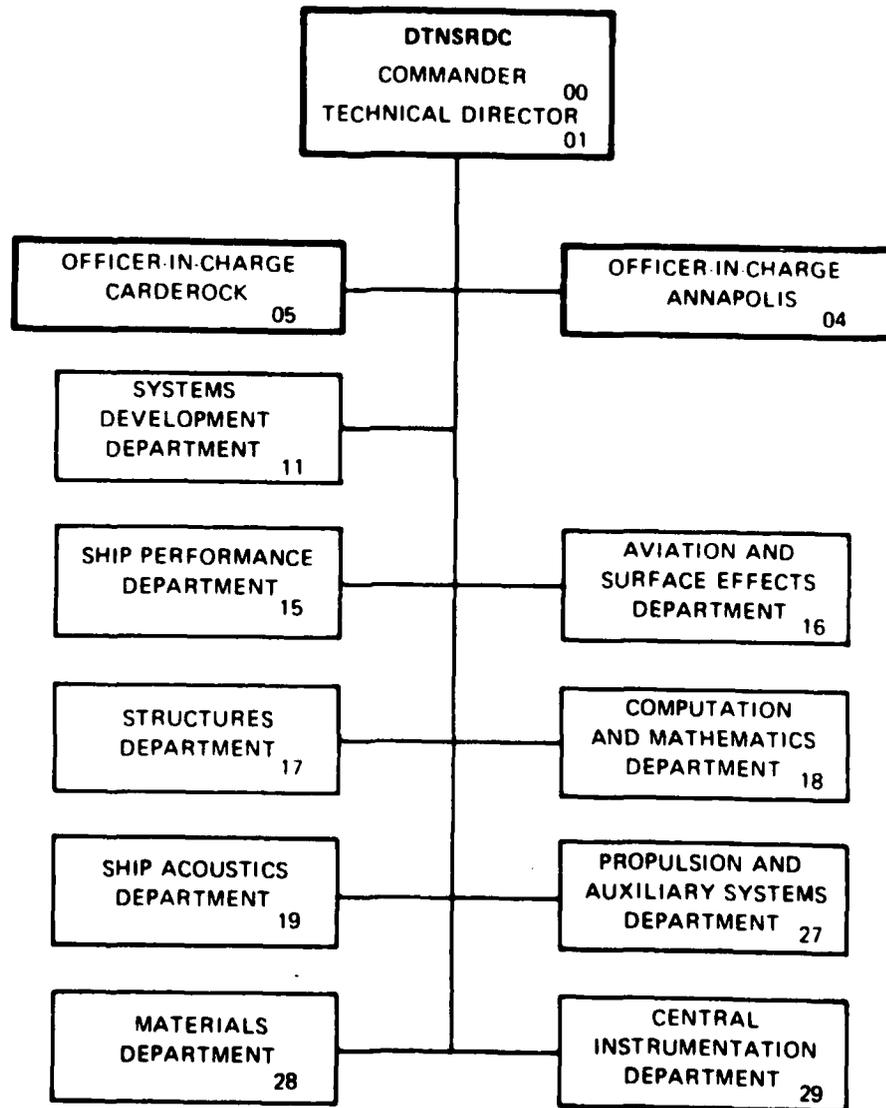
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NOTATION

H_{OBS}	Observed wave height
L	Ship length
r_A	Amplitude of relative motion
\ddot{s}_A	Amplitude of acceleration
T_o	Modal wave period
T_{OBS}	Observed wave period
z_A	Amplitude of heave
ζ_A	Wave amplitude
$(\bar{\zeta}_w)_{1/3}$	Significant wave height
θ_A	Amplitude of pitch
λ	Wavelength
ω_e	Encounter frequency

ABSTRACT

The use of analytical results to characterize the bottom slamming and deck wetness of a United States Coast Guard Medium Endurance Cutter (WMEC) in head seas is justified on the basis of correlation with a prior experiment and of a hypothesis to the effect that dynamic swell-up and incident wave distortion can be neglected for purposes of computing slamming probabilities. Slamming and deck wetness are then analyzed in the context of the wave environment for two WMEC operational regions. This analysis indicates that the WMEC will be limited by slamming in wave conditions which are expected to occur at least one percent of the time in both regions considered. It also shows that the operation of the ship may be limited by deck wetness at low speeds in rarely-occurring long waves.

ADMINISTRATIVE INFORMATION

The investigation reported herein was sponsored by the United States Coast Guard (USCG). Military Interdepartmental Purchase Request Z-70099-6-62370 provided the required funding. At the David W. Taylor Naval Ship Research and Development Center (DTNSRDC), where the work was performed, it was identified by Work Unit Number 1-1568-022.

INTRODUCTION

The seakeeping characteristics of a USCG Medium Endurance Cutter (WMEC) were determined experimentally at DTNSRDC during the summer of 1976. The results of this investigation are reported in reference 1*. Reference 1 includes a discussion of the possibility of the WMEC experiencing bottom slamming and severe deck wetness. These phenomena did not occur during the

*References are listed on page 13.

WMEC experiment, but it was hypothesized that they could occur in sea conditions which could not be reproduced at the scale of the model employed for the experiment. Further, it was noted that these critical wave conditions could reasonably be expected to occur in the real environment.

To explore these matters in depth, the USCG authorized a follow-on investigation of the WMEC. This investigation was to consist of two basic elements. First, the responses of the WMEC were to be computed and compared with those measured during the experiment. Given reasonable correlation between the analytical and experimental responses, the analysis was to be extended to include computation of the slamming and deck wetness characteristics of the WMEC in the context of its operational environment. This work has been performed, and the results are reported hereinafter.

ANALYTICAL/EXPERIMENTAL COMPARISONS

DTNSRDC's Frank Close Fit Ship Motion Computer Program, reference 2, was used to determine the responses of the WMEC analytically. The mathematical model of hull geometry used for these computations is shown in Figure 1. Table 1 compares some of the major characteristics of this mathematical model with those used for the WMEC experiment. (The latter characteristics are abstracted from reference 1.)

Figures 2 through 16 compare the computed response amplitude operators and phase angles with the corresponding measurements reported in reference 1. An additional comparison is presented in Table 2. This table compares the measured response statistics reported in reference 1 with corresponding statistics derived from the computed response amplitude operators and measured wave spectra. Derivation of the latter response statistics was based upon linear superposition as described in reference 3.

The comparisons in Table 2 and in Figures 2 through 16 all refer to Sea State 3 and Sea State 5 conditions. As noted in reference 1, Sea State 3 was represented by a wave spectrum with a significant height of approximately 1.5 metres (5 feet) and a modal period of 5.5 seconds while Sea State 5 was represented by a wave spectrum with a significant height of approximately 3.0 metres

(10 feet) and a modal period of 10.5 seconds. Reference 1 also includes figures which define the shapes of these wave spectra.

The pitch and heave results presented compare favorably in all cases except that of the 15-knot heave response amplitude operator (Figure 7). In this case, the computed response amplitude operator exhibits a resonant peak which is not evident from inspection of the experimental data. The correlation exhibited by the relative motion results is fairly good in all cases. Some discrepancies must be expected because the relative motion computations do not account for dynamic swell-up (reference 4) or incident wave distortion (reference 5). These phenomena are, however, minimized for locations near the stem (at least in head waves).

Correlation is rather poor for vertical acceleration at Station 14. Figures 11 through 13 show that the response amplitude operators for this variable are frequently over-predicted. Table 2 indicates that the resultant response statistics can be significantly over-predicted.

To summarize, the results presented indicate that viable predictions of WMEC pitch, heave, and Station 0 relative motion in head waves can be obtained analytically; but that predictions of the ship's vertical acceleration at Station 14 are likely to be high.

ANALYSIS OF SLAMMING AND WETNESS

Relative motion is the response which determines the slamming and wetness characteristics of a ship. In the preceding section of this report, it was shown that viable predictions of WMEC relative motion at Station 0 could be obtained by analytical means. However, it was noted that selection of Station 0 was fortuitous in this respect because the location minimized the influence of dynamic swell-up and incident wave distortion.

Relative motion at Station 0 provides a reasonable basis for an analysis of severe deck wetness. (Here "severe" implies shipping of green water as opposed to spray and/or bow wave profile overtopping.) However, a location further aft must be chosen for a realistic analysis of slamming. Slamming will influence operations only when it produces hull girder vibrations which are evident to

personnel aboard the ship. This indicates that it must be evaluated at a location where the hull has a sufficiently large bottom area to transmit large forces to the hull girder.

It follows that dynamic swell-up and incident wave distortion will influence relative motion at locations of concern with respect to slamming. There is, however, a mitigating circumstance. Both phenomena occur as a result of ship-wave interactions, and keel emergence is a prerequisite for slamming. Hence, it appears reasonable to assume that these phenomena can be neglected to a first approximation in an analysis of slamming. Under this assumption, analytical relative motion response amplitude operators can be used to analyze slamming. The only restriction is that the pitch, heave and phase angle results from which these response amplitude operators are computed be reasonably accurate; and this has been shown to be true for the WMEC.

In view of the foregoing considerations, it was felt that the slamming and wetness characteristics of the WMEC in head seas could be determined on the basis of its computed relative motion response amplitude operators. Prior to performing these computations, it is desirable to define the wave environment in which the ship will operate. This matter is addressed in the immediately following section. The actual slamming and wetness computations are described in the subsequent section.

DEFINITION OF THE WAVE ENVIRONMENT

Two WMEC operational regions were specified by the USCG: one off the northeast coast of the continental United States and one in the Gulf of Alaska. The Summary of Synoptic Meteorological Observations (SSMO) for North American Coastal Marine Areas, references 6 and 7, was found to include wave height and period data applicable to each of these regions. Data were, in fact, available for a number of SSMO Areas in each region. Hence, it was necessary to select particular SSMO Areas for analysis.

The USCG limited the selection to two SSMO Areas in each region. The selected areas in the Gulf of Alaska were SSMO Area 4, extending from 57 degrees north latitude to the coast and from 140 to 146 degrees west longitude; and SSMO Area

5 which extends from 57 degrees north latitude to the coast and from 146 to 151 degrees west longitude. Off the northeast coast, the USCG selections were SSMO Area 13, extending from 40 to 42 degrees north latitude and from 69 to 72 degrees west longitude (excluding land masses); and SSMO Area 15 which extends from 38 to 40 degrees north latitude and from 70 to 75 degrees west longitude (again excluding land masses). In each region, the more severe of the two selected areas (from the viewpoint of WMEC operability) was to be analyzed.

It was decided to select the "more severe" areas on the basis of average and maximum observed wave heights in the wave period range thought to be critical for operation of the WMEC. Reference 1 indicates a critical period range of 7 to 8 seconds, and this finding is supported by the analytical results reported here. The closest bracket for this period range in the SSMO tabulations is in terms of observed wave periods from 6 to 7 and from 8 to 9 seconds. Table 3 exhibits the relevant statistics for the SSMO Areas under consideration. From inspection of this table, it is evident that SSMO Area 5 is more severe than SSMO Area 4 in terms of both average and maximum wave height given critical wave periods. Similarly, SSMO Area 15 is more severe than SSMO Area 13. It was, accordingly, decided to analyze SSMO Areas 5 and 15 in detail.

The SSMO data for the chosen areas was used to define the wave environment in terms of modal wave periods, T_0 , and significant wave heights, $(\bar{z}_w)_{1/3}$, using the calibrations given in reference 8. Details of the procedure followed are described in the appendix to this report, and the ultimate results are shown in Figure 17. Figure 17 also shows the significant wave height to modal wave period relationship associated with the Pierson-Moskowitz wave spectral family (defined in reference 9) and identifies the wave conditions modeled during the WMEC experiment described in reference 1.

Some notes concerning the interpretation of Figure 17 are in order. The probability of occurrence of given combinations of significant wave height and modal wave period is constant along each of the contours shown, e.g., conditions along the "1.0% Wave Contour" for SSMO Area 5 are expected to occur one percent of the time in this area. Conditions inside the cited contour are expected to

occur more than one percent of the time. Probability of occurrence is maximized along the "Most Probable Waves" line.

From the foregoing discussion, it should be evident that Figure 17 characterizes the wave environment which the WMEC is expected to encounter through probabilities of occurrence down to 0.001 (0.1 percent). This degree of definition is adequate for establishing ship operability and habitability. Survival conditions can, of course, occur outside the 0.1 percent contours; but such conditions are not within the scope of this investigation.

SLAMMING AND WETNESS LIMITS

It is assumed that, at a given modal wave period and ship speed, voluntary changes in course or speed which arise from operability and/or habitability considerations will limit ship operation to the lower of two significant wave heights:

1. That at which the probability of bottom slamming at Station 3 reaches 0.03, or
2. That at which the probability of severe deck wetness at Station 0 reaches 0.07.

These criteria are based on references 10 and 11. The same or similar limits are used in most state-of-the-investigations of slamming and deck wetness which are in the open literature.

The computed relative motion response amplitude operators displayed earlier were used for the deck wetness calculations. Relative motion response amplitude operators for Station 3 of the WMEC were computed in an identical manner, and used for the slamming computations. Under linear superposition (reference 3, as previously cited) these response amplitude operators were used to determine response statistics for the wave conditions defined by Figure 17. The two-parameter, Bretschneider wave spectral family, reference 12, was employed. (Using the Pierson-Moskowitz wave spectral family would have defined response statistics only in wave conditions lying along the Pierson-Moskowitz line in Figure 17. This would obviously have been inadequate in the context of the real environment defined by the figure.)

The response statistics determined by the procedure just outlined were used in accord with reference 13 to compute slamming and wetness probabilities. Freeboard and draft were corrected for trim and sinkage using data from reference 14. The results of this process are exhibited by Figures 18, 19, and 20. Each of these figures superimposes the slamming and wetness limits associated with a particular ship speed on the environmental characteristics shown in Figure 17.

Along the "Slamming Limit" lines in Figures 18 through 20, the probability of the WMEC experiencing bottom slamming at Station 3 is equal to 0.03. Along the "Wetness Limit" lines in the same figures, the probability of the WMEC experiencing severe deck wetness at Station 0 is equal to 0.07. So, in accord with the assumption cited at the beginning of this section, the lower of these two lines in any of the figures defines the WMEC's operational limit at the ship speed to which the figure is applicable. For instance, Figure 18 shows that, at a speed of 6 knots, the WMEC is limited by slamming in waves with modal periods of up to 9.5 seconds; and by deck wetness in longer waves. Further, this figure shows that the most restrictive limit at six knots occurs in waves with a modal period of just over seven seconds. Then slamming will restrict operation to waves of 4.8 metres significant height.

The operational limits are, of course, easily interpreted in the context of the wave environment by inspection of Figures 18, 19, and 20. In the 6-knot case (Figure 18) just discussed, the limit due to slamming falls within the 1.0 percent wave contours for both SSMO areas of concern, but does not closely approach the most probable wave line for either area. The limit due to wetness occurs within the 0.1 percent wave contours for both areas, but not within the 1.0 percent contours. It follows that slamming will limit the operations of the WMEC at 6 knots more frequently than wetness, but that neither phenomenon is likely to impose restrictions in waves which occur much more than 1.0 percent of the time.

As ship speed increases, the slamming limit becomes increasingly dominant. The minimum limiting wave height (always associated with slamming) drops from the 4.8 metre level at 6 knots to 4.1 metres at 15 knots, but remains more than a metre above the most probable wave lines. And, as would be expected from

resonance considerations, the modal period which produces the minimum limiting wave height increases with ship speed.

It is of interest to compare the results just described with those which would have been obtained from an analysis based on the Pierson-Moskowitz wave spectral family. This can be done by inspection of Figures 18 through 20. The intersections of the slamming limit and wetness limit lines with the Pierson-Moskowitz line define operational limits in Pierson-Moskowitz spectra. At 6 knots, a Pierson-Moskowitz analysis would have found no limits to exist in waves of up to 10-metre significant height. At 10 knots, the WMEC would have been found to be limited by wetness to Pierson-Moskowitz waves of 7.8 metre significant height. Pierson-Moskowitz waves of 5.2 metres significant height would have produced a limit due to slamming at 15 knots. The logical fallacy of employing a fixed relationship of wave height to wave period should be evident. Even conditions along the most probable waves line (which differs more radically from the Pierson-Moskowitz line for the coastal areas considered here than is usually the case for open-ocean data) rarely occur more than 10 percent of the time.

It appears that the wave environment in SSMO Area 15 (east coast operational region) will restrict WMEC operations more frequently than that in SSMO Area 5 (Gulf of Alaska operational region). This is due to three factors:

1. The 1.0 percent wave contour for Area 15 encompasses greater wave heights than that in Area 5 for the range of wave periods most critical for slamming,
2. The 0.1 percent wave contour for Area 15 encompasses greater ranges of wave height and period which can impose limitations due to wetness, and,
3. The most probable waves in Area 15 are of greater height than those in Area 5 for all wave periods.

However, the differences between the two areas are not dramatic.

CONCLUSIONS

Analytical predictions of the pitch, heave and Station 0 relative motion of the WMEC in head waves agree reasonably well with model-scale measurements of these variables. On the other hand, absolute vertical acceleration at Station 14 is generally over-predicted. The agreement found for Station 0 relative motion, and a hypothesis to the effect that dynamic swell-up and incident wave distortion are negligible with respect to bottom slamming justify the use of analytical results in analyzing the slamming and deck wetness characteristics of the WMEC in head seas.

The slamming and wetness analysis indicates that the WMEC will usually be slam-limited in long-crested head seas, but may be limited by deck wetness in long waves. In the context of the wave environment in SSMO Areas 5 (Gulf of Alaska) and 15 (off the northeast coast of the continental United States) the WMEC can reach its operational limit in waves which occur more than 1.0 percent of the time at all speeds considered (6 through 15 knots). However, the limits are never closely approached in the most probable waves.

The results of the slamming and wetness analysis confirm the hypothesis put forth in reference 1 (on the basis of the WMEC model experiment) as to the possibility of the WMEC experiencing bottom slamming and severe deck wetness. The critical conditions for these phenomena are, as hypothesized, in severe, partially-developed seas, i.e., in conditions to the left of the Pierson-Moskowitz line in Figures 17 through 20. Minimum limiting significant wave heights of 4 to 5 metres occur at modal wave periods of 7 to 8 seconds. For these periods, Pierson-Moskowitz wave spectra have significant heights of only 2.0 to 2.5 metres. However, 4 to 5 metre significant heights occur at these periods within the 1.0 percent wave contours for both WMEC operational areas evaluated.

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APPENDIX
DERIVATION OF WAVE ENVIRONMENT CHARACTERISTICS

Table A1 exhibits the wave height and period data taken from reference 6 of the text for SSMO Area 5 in the Gulf of Alaska. These data were compiled from visual observations made in the subject area between 1963 and 1970. As can be seen, a total of 4,143 observations were used. An asterisk indicates that the corresponding combination of wave height and period was observed to occur in at most 0.05 percent of the total number of observations.

This appendix will demonstrate the manner in which the Table A1 data were transformed to obtain the wave environment definition given by Figure 17 of the text.

The initial step in this transformation is to retabulate the subject data in such a manner that waves of indeterminate period are eliminated and the "asterisk conditions" are quantified to the extent possible. Table A2 illustrates the results of this retabulation of the Table A1 data. The waves of indeterminate period have been combined with those most likely to occur in each wave height range. When, as is the case here for 12-foot (3.7 metre) waves, the "most likely" is not unequivocally defined, the waves of indeterminate period are combined with the candidate period range which appears most reasonable in the context of the other data. Further, it can be seen that the asterisks were simply taken at face-value, i.e., as being less than or equal to 0.05. More elaborate treatments of these matters are possible, but cannot be justified in the contexts of initial data quality and/or other approximations which are required by the subsequent steps in the transformation process.

Data for each period range in Table A2 were plotted as exemplified by Figure A1; and curves, also illustrated by Figure A1, were faired through the plotted data. (The fairing was generally biased to high waves.) Wave heights corresponding to the maximum, 1.0 and 0.1 percentage occurrence levels were read from the faired curves. It should be noted that wave height can be double-valued at the 1.0 and/or 0.1 levels. In Figure A1, for instance, wave heights of both 2 feet (0.6 metres) and 27 feet (8.2 metres) occur at the 0.1 percentage level.

Next, the wave height data read from the fixed-period curves were plotted and faired as shown in Figure A2. The double-valued nature of the 1.0 and 0.1 level data has been interpreted in the sense of closed contours. The fairing of these contours is, again, biased to high waves. The faired contours are shown as broken lines for periods of less than 6 seconds and more than 13 seconds because the fairing process is purely subjective in these ranges.

At this point, the data are in the basic form desired. The closed curves are the 1.0 and 0.1 percent wave contours, and the curve faired through the maximum values defines the most probable waves. However, the results remain in terms of observed values; and must be converted to physically meaningful statistics before they can be used with an analytical wave spectral family. The calibrations given by Nordenstrom in reference 8 of the text were used to make this conversion. These calibrations were derived by comparing measured and observed data. They indicate that observed wave periods are very nearly equal to modal wave periods, but that observed wave heights tend to exceed significant height in severe seas and be less than significant height in mild seas. Explicitly, the calibrations can be written as:

$$(\bar{\zeta}_w)_{1/3} = 1.68 (H_{OBS})^{0.75} \quad [A1]$$

and

$$T_o = 1.146 (T_{OBS})^{0.96} \quad [A2]$$

in units of metres for equation [A1] and of seconds for equation [A2].

These calibrations were applied to data read from the faired contours and most probable line in Figure A2. This produced the wave environment characterization of SSMO Area 5 which is shown by Figure 17 of the text. SSMO Area 15 data, taken from reference 7 of the text, were treated in an identical manner to obtain the characterization thereof which is also shown by Figure 17. It can be noted that the Area 15 data consisted of 5,295 observations taken between 1949 and 1970.

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TABLE 1 - COMPARISON OF WMEC HULL CHARACTERISTICS

Prototype Parameter	Physical Model	Mathematical Model
Ship Length (metres/feet)	77.72/255.0	77.72/255.0
Draft Amidships (metres/feet)	4.11/13.5	4.11/13.5
Displacement (tonnes/long tons)	1762/1734	1749/1721
Pitch Gyradius (metres/feet)	18.65/61.2	18.65/61.2

TABLE 2 - COMPARISON OF MEASURED AND COMPUTED WMEC RESPONSE STATISTICS

Significant Single Amplitude of	Sea State	Ship Speed (knots)	Measured Value	Computed Value
Pitch (degrees)	3*	6	1.3	1.2
		10	1.4	1.3
		15	1.5	1.4
	5**	6	2.7	2.6
		10	3.1	3.0
		15	3.2	3.1
Heave (metres/feet)	3	6	0.34/1.1	0.34/1.1
		10	0.40/1.3	0.40/1.3
		15	0.46/1.5	0.49/1.6
	5	6	1.07/3.5	1.04/3.4
		10	1.19/3.9	1.16/3.8
		15	1.25/4.1	1.28/4.2
Acceleration at Station 14 (metres/sec ² & feet/sec ²)	3	6	0.30/1.0	0.37/1.2
		10	0.37/1.2	0.40/1.3
		15	0.55/1.8	0.64/2.1
	5	6	0.64/2.1	0.67/2.2
		10	0.82/2.7	0.82/2.7
		15	1.10/3.6	1.22/4.0
Relative Motion at Station 0 (metres/feet)	3	6	1.46/4.8	1.34/4.4
		10	1.55/5.1	1.46/4.8
		15	1.77/5.8	1.62/5.3
	5	6	2.38/7.8	2.13/7.0
		10	2.44/8.0	2.65/8.7
		15	2.83/9.3	2.83/9.3

* $(\bar{\zeta}_w)_{1/3} = 1.5 \text{ m}, T_0 = 5.5 \text{ sec}$

** $(\bar{\zeta}_w)_{1/3} = 3.0 \text{ m}, T_0 = 10.5 \text{ sec}$

TABLE 3 - WAVE HEIGHT STATISTICS FOR WAVE PERIODS CRITICAL TO WMEC OPERATIONS IN SELECTED SSMO AREAS

Operational Region	SSMO Area	Observed Wave Period (seconds)	Average Observed Wave Height (metres/feet)	Maximum Observed Wave Height (metres/feet)
Gulf of Alaska	4	6-7	1.8/6	7.0-7.6/23-25
		8-9	2.1/7	7.0-7.6/23-25
Gulf of Alaska	5	6-7	1.8/6	7.0-7.6/23-25
		8-9	2.4/8	7.9-9.8/26-32
East Coast	13	6-7	1.8/6	7.0-7.6/23-25
		8-9	2.4/8	7.9-9.8/26-32
East Coast	15	6-7	1.8/6	7.9-9.8/26-32
		8-9	2.7/9	7.9-9.8/26-32

TABLE A1 - SSMO AREA 5 WAVE HEIGHT AND PERIOD DATA

Period (sec)	PERCENT FREQUENCY OF WAVE HEIGHT (FT*) VS WAVE PERIOD (SECONDS)												Total	Mean Hgt	
	<1	1-2	3-4	5-6	7	8-9	10-11	12	13-16	17-19	20-22	23-25			26-32
<6	2.0	7.9	13.4	8.1	3.2	1.8	1.1	.8	.3	.2	.0	.0	.0	1603	4
6-7	.2	1.4	5.8	7.0	4.7	3.4	2.0	.9	1.4	.3	.3	.1	.0	1140	6
8-9	.1	.3	1.7	2.8	2.9	2.2	1.6	.9	1.1	.4	.2	.1	.2	601	8
10-11	.0	.2	.4	.8	1.1	1.2	1.0	.6	.7	.3	.3	.2	*	286	9
12-13	.0	*	.1	.3	.2	.7	.5	.1	.3	.1	*	.1	*	112	9
>13	.0	.0	.0	.1	.3	.4	.4	.3	.5	*	.2	.1	*	96	11
INDET	5.7	.1	.1	.3	.2	.2	.2	.1	.3	.1	*	*	.0	305	2
TOTAL	332	409	891	808	523	412	278	156	189	61	46	27	11	4143	5
PCT	8.0	9.9	21.5	19.5	12.6	9.9	6.7	3.8	4.6	1.5	1.1	.7	.3	100.0	

* 0.3048 metres per foot

TABLE A2 - REVISED WAVE HEIGHT AND PERIOD DATA FOR SSMO AREA 5

Observed Height (feet*)	Observed Period (seconds)					
	<6	6-7	8-9	10-11	12-13	>13
<1	7.7 [†]	0.2	0.1	0	0	0
1-2	8.0 [†]	1.4	0.3	0.2	≤0.05	0
3-4	13.5 [†]	5.8	1.7	0.4	0.1	0
5-6	8.4 [†]	7.0	2.8	0.8	0.3	0.1
7	3.2	4.9 [†]	2.9	1.1	0.2	0.3
8-9	1.8	3.6 [†]	2.2	1.2	0.7	0.4
10-11	1.1	2.2 [†]	1.6	1.0	0.5	0.4
12	0.8	1.0 [†]	0.9	0.6	0.1	0.3
13-16	0.3	1.7 [†]	1.1	0.7	0.3	0.5
17-19	0.2	0.3	0.5 [†]	0.3	0.1	≤0.05
20-22	0	0.3	0.2	≤0.35 [†]	≤0.05	0.2
23-25	0	0.1	0.1	≤0.25 [†]	0.1	0.1
26-32	0	0	0.2	≤0.05	≤0.05	≤0.05

*0.3048 metres per foot

[†]Waves of indeterminate period added

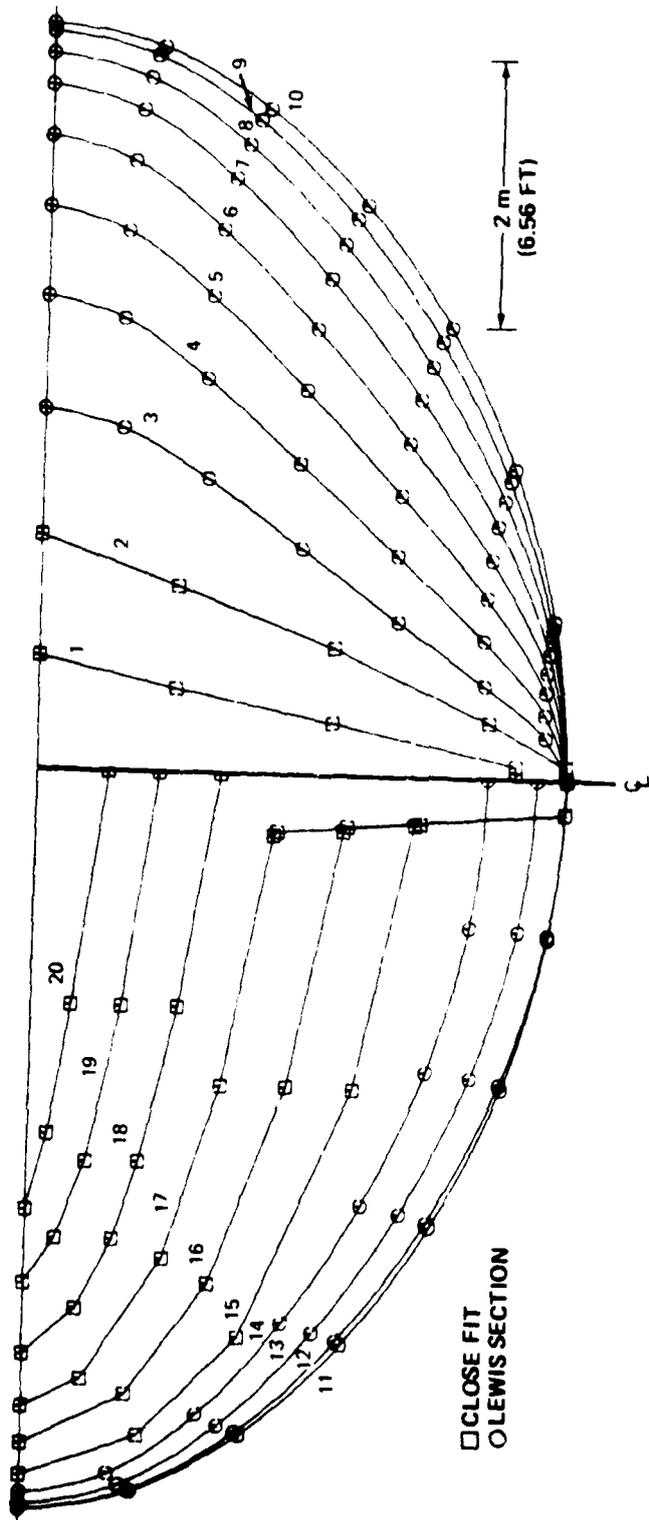


Figure 1 - Mathematical Model of WMEC Hull Geometry

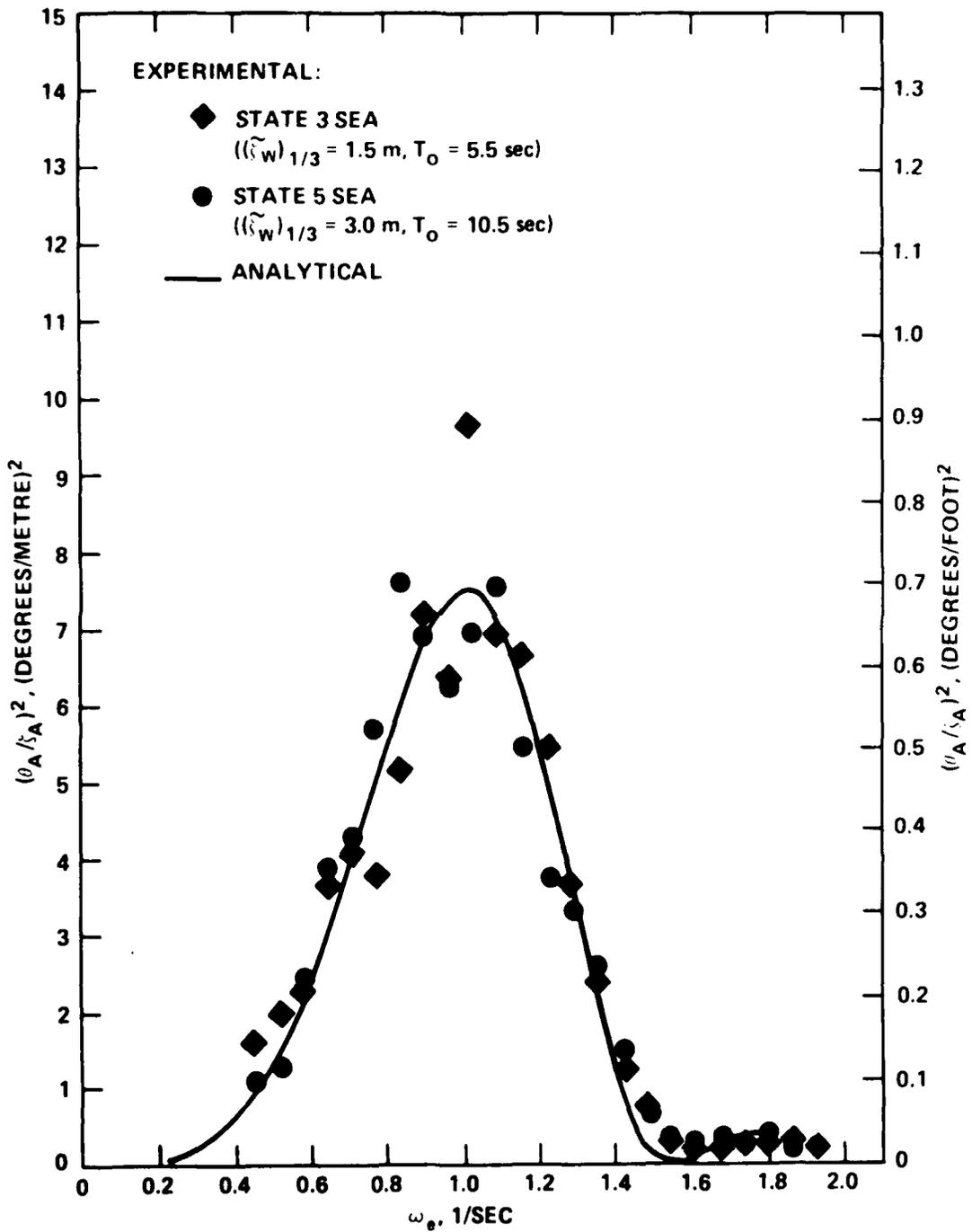


Figure 2 - WMEC Pitch Response Amplitude Operator Comparisons at 6 knots

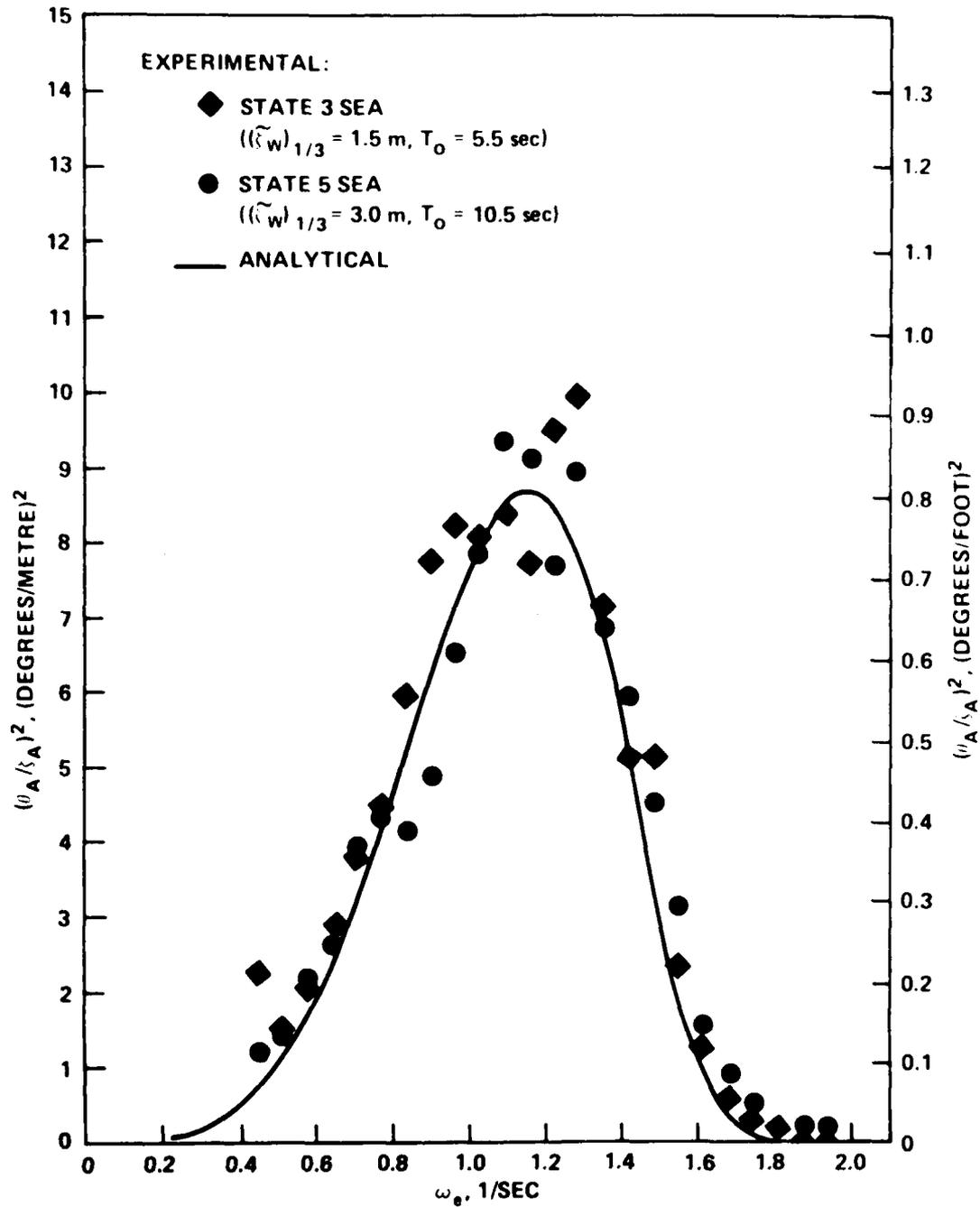


Figure 3 - WMEC Pitch Response Amplitude Operator Comparison at 10 knots

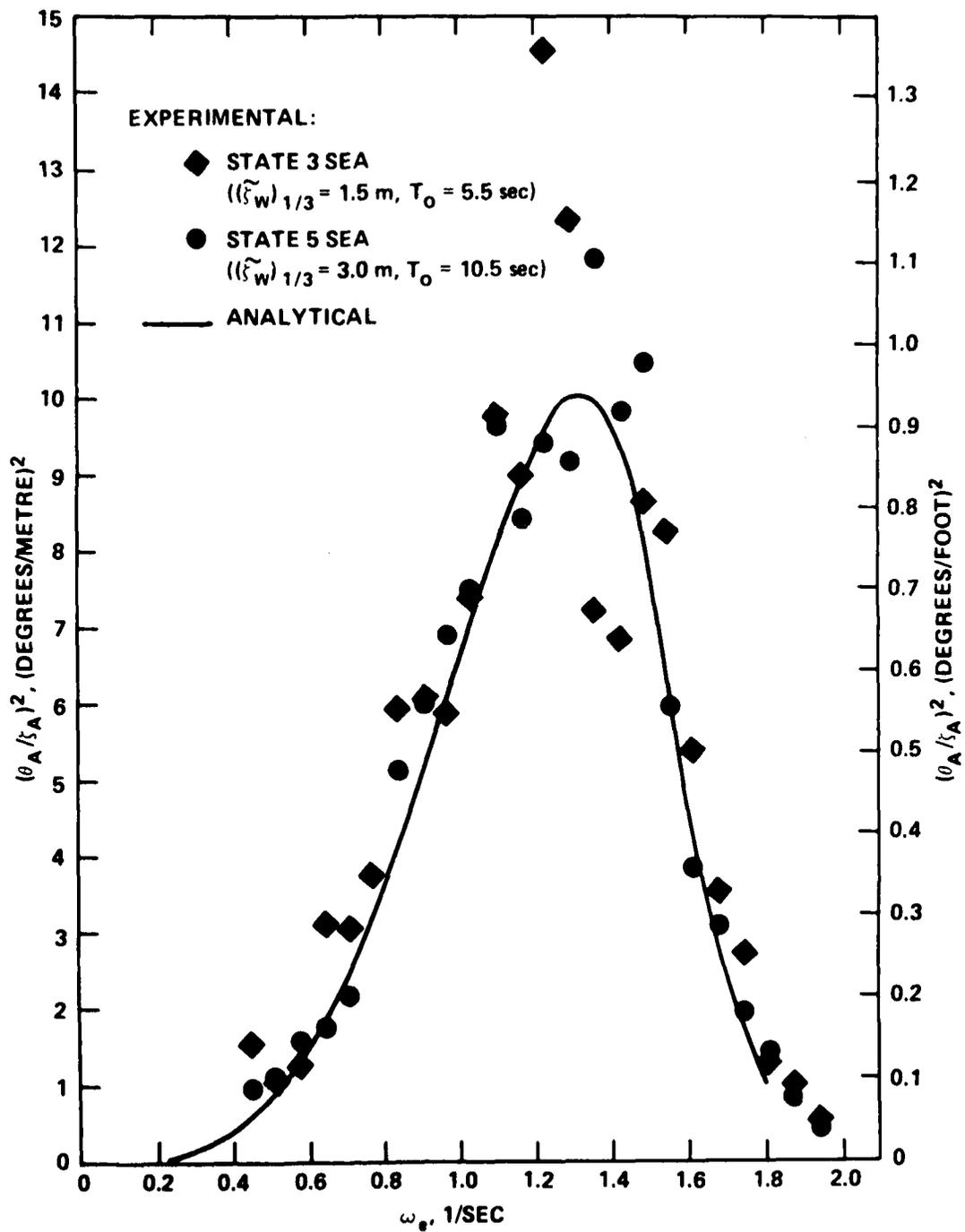


Figure 4 - WMEC Pitch Response Amplitude Operator Comparison at 15 knots

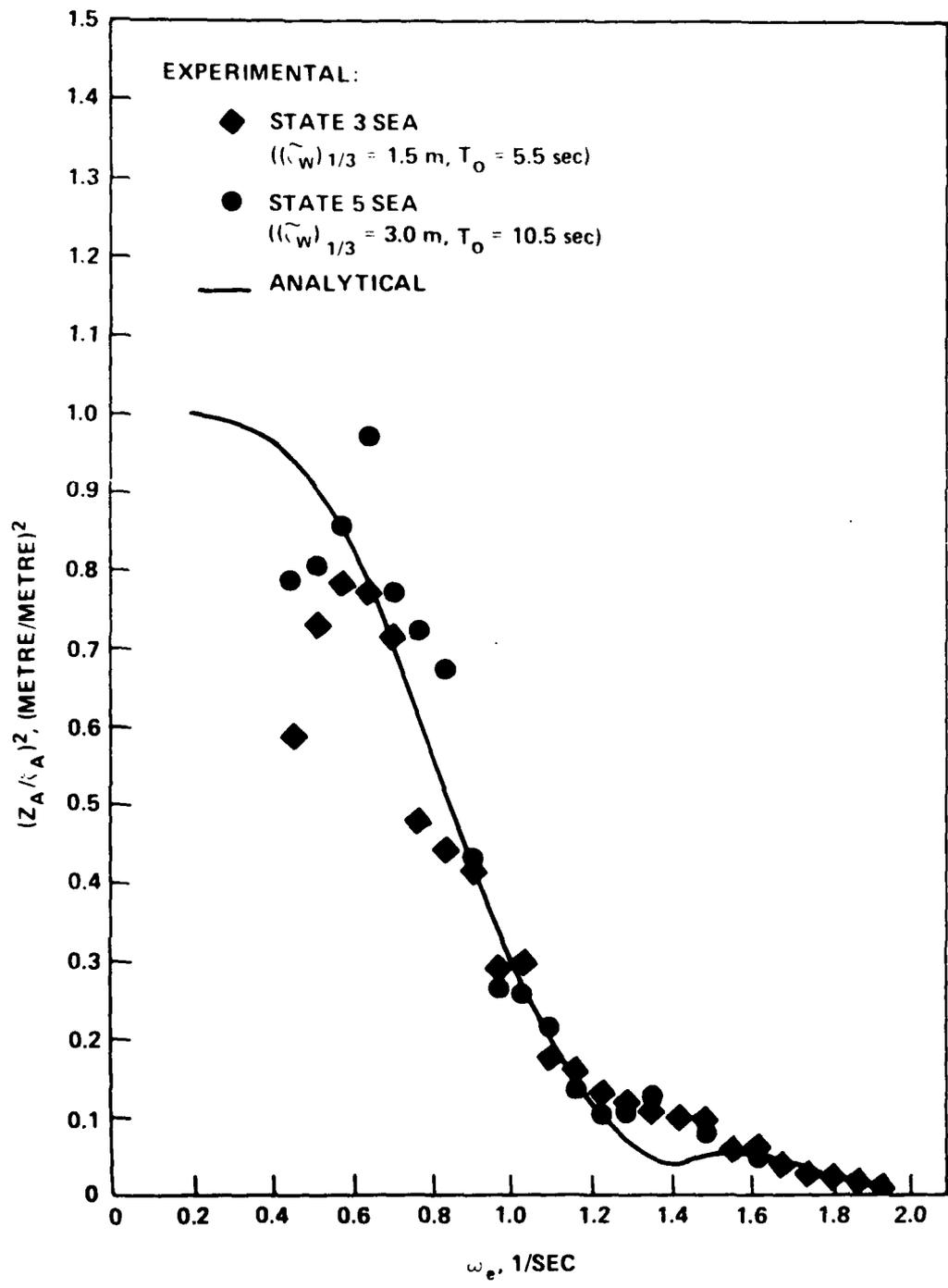


Figure 5 - WMEC Heave Response Amplitude Operator Comparison at 6 knots

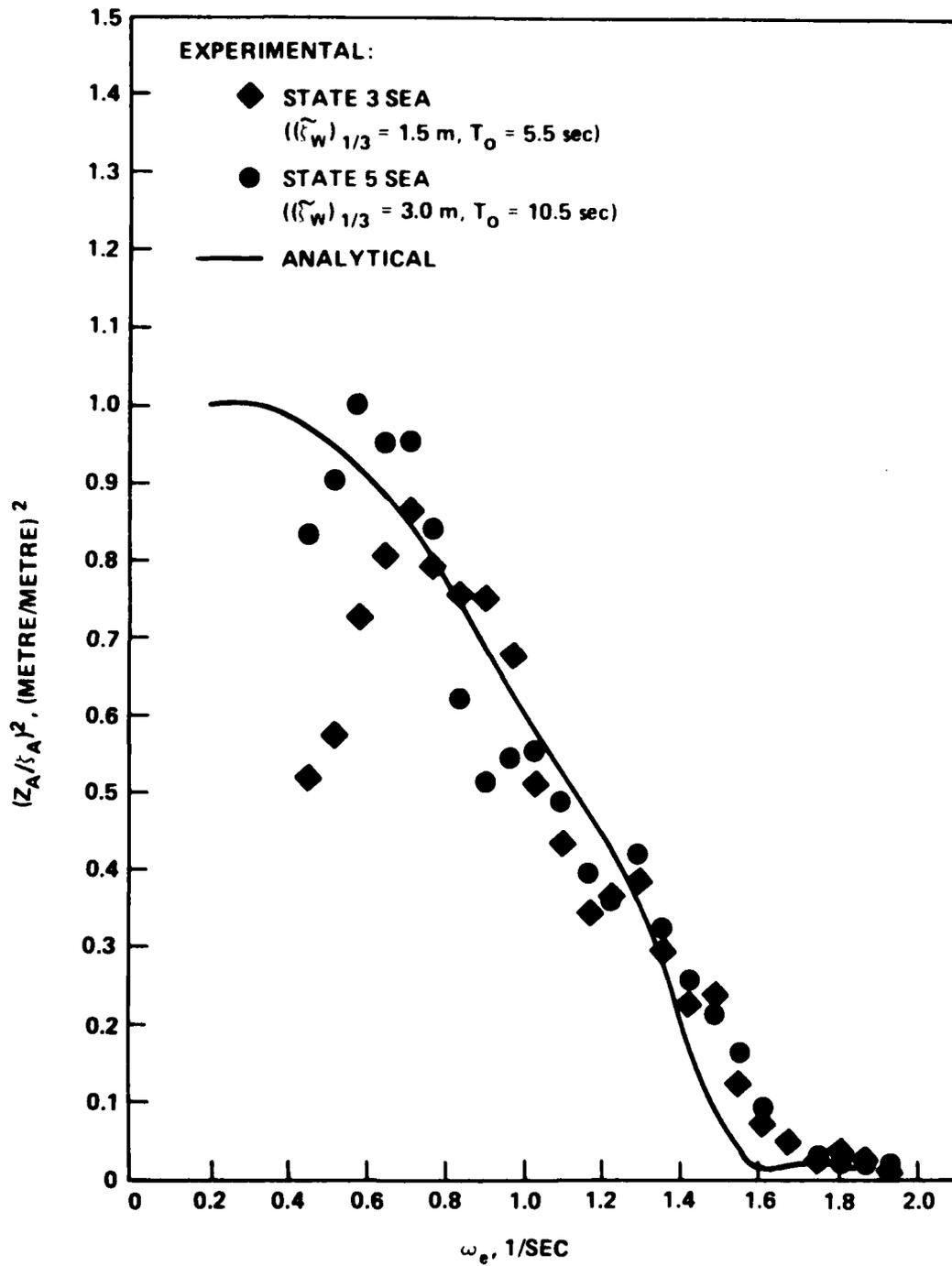


Figure 6 - WMEC Heave Response Amplitude Operator Comparison at 10 knots

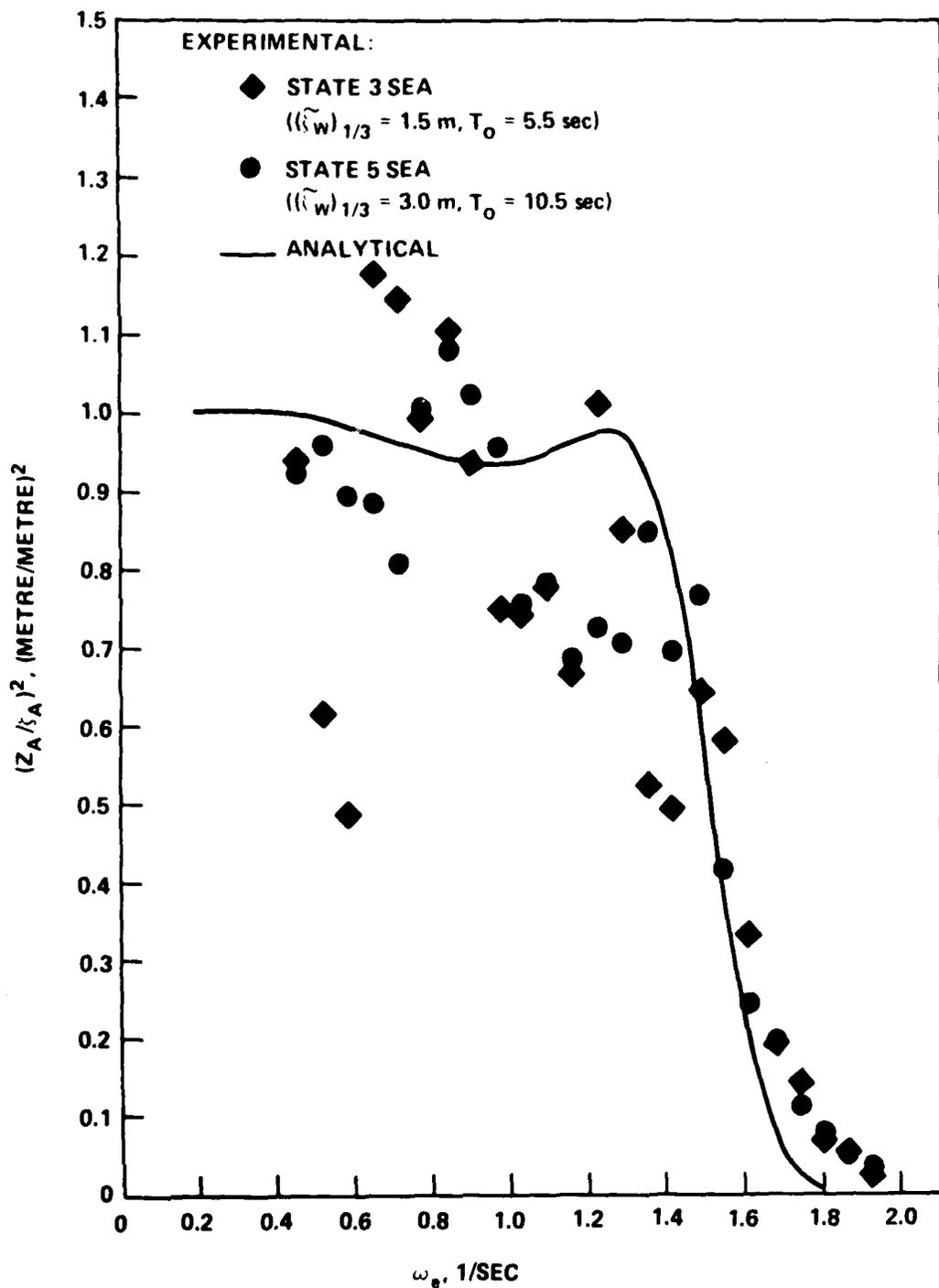


Figure 7 - WMEC Heave Response Amplitude Operator Comparison at 15 knots

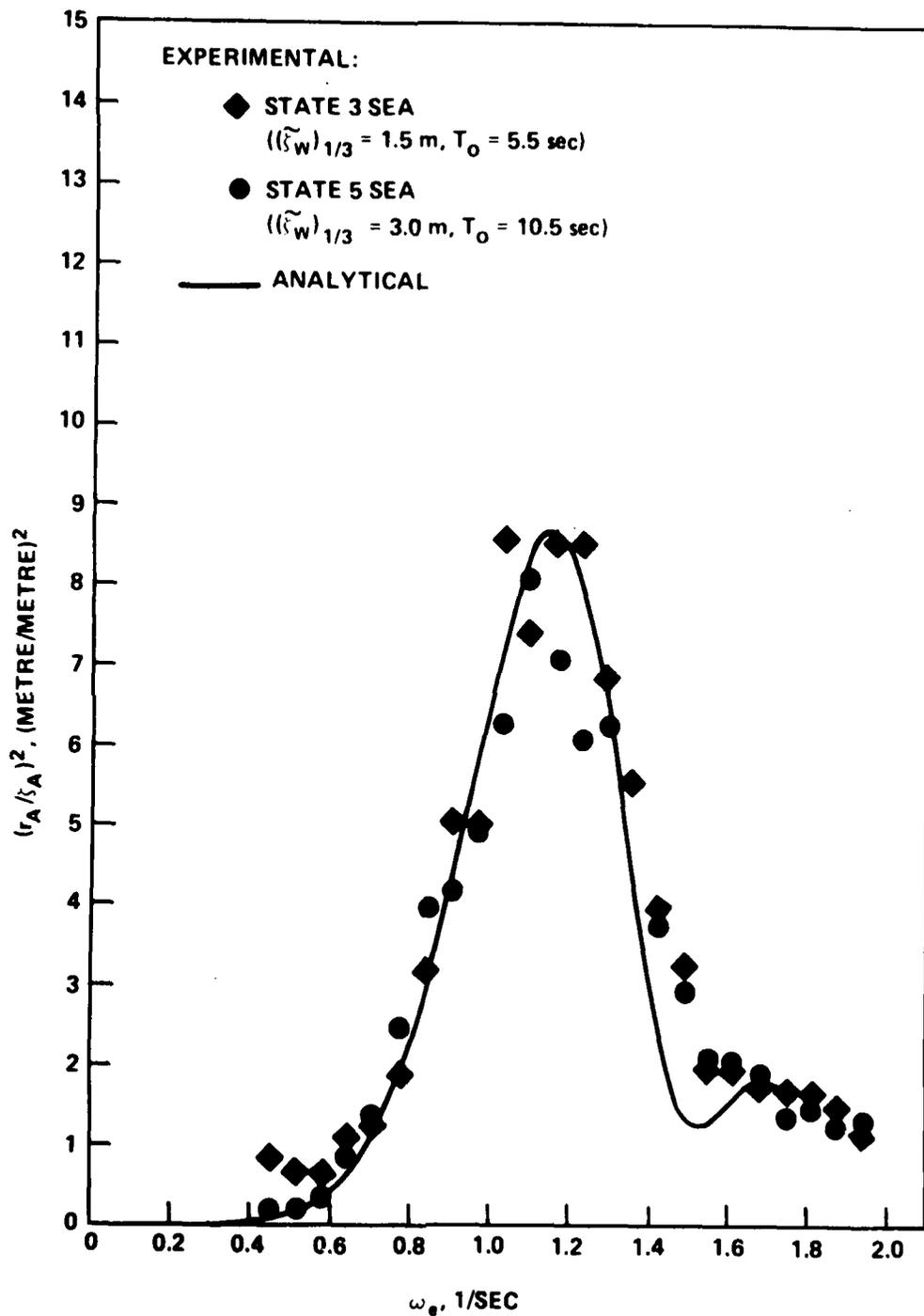


Figure 8 - WMEC Station 0 Relative Motion Response Amplitude Operator Comparison at 6 knots

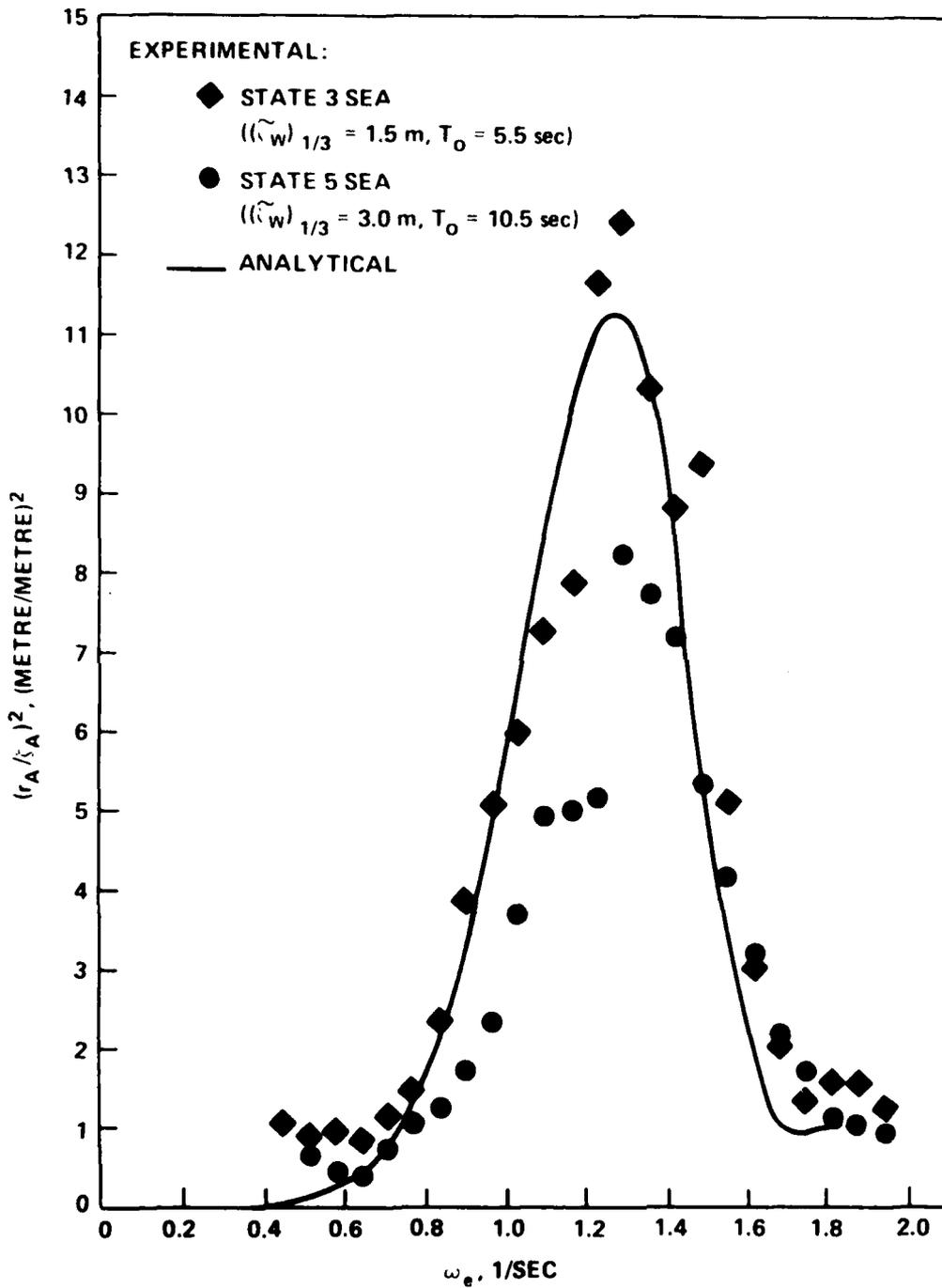


Figure 9 - WMEC Station 0 Relative Motion Response Amplitude Operator Comparison at 10 knots

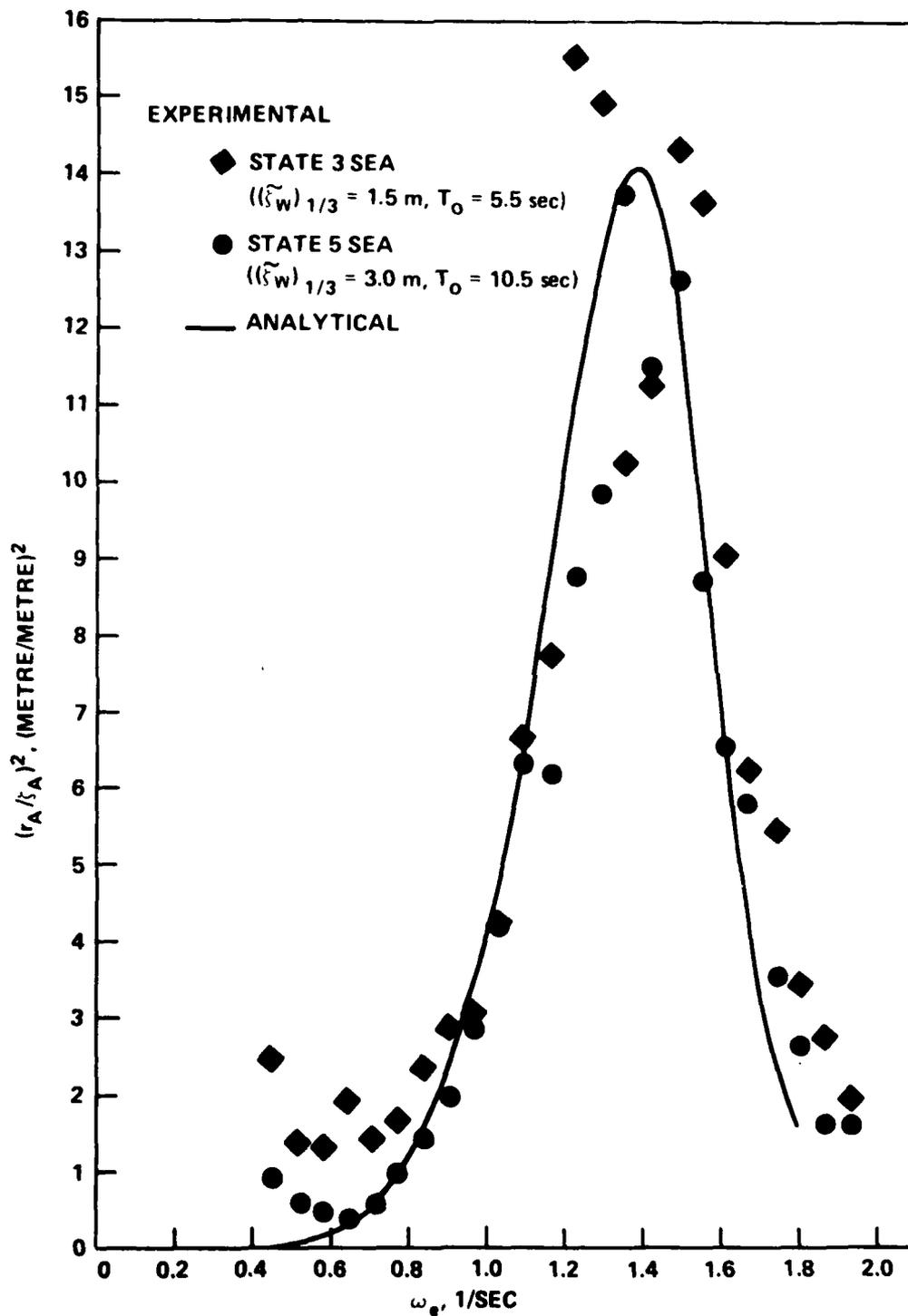


Figure 10 - WMEC Station 0 Relative Motion Response Amplitude Operator Comparisons at 15 knots

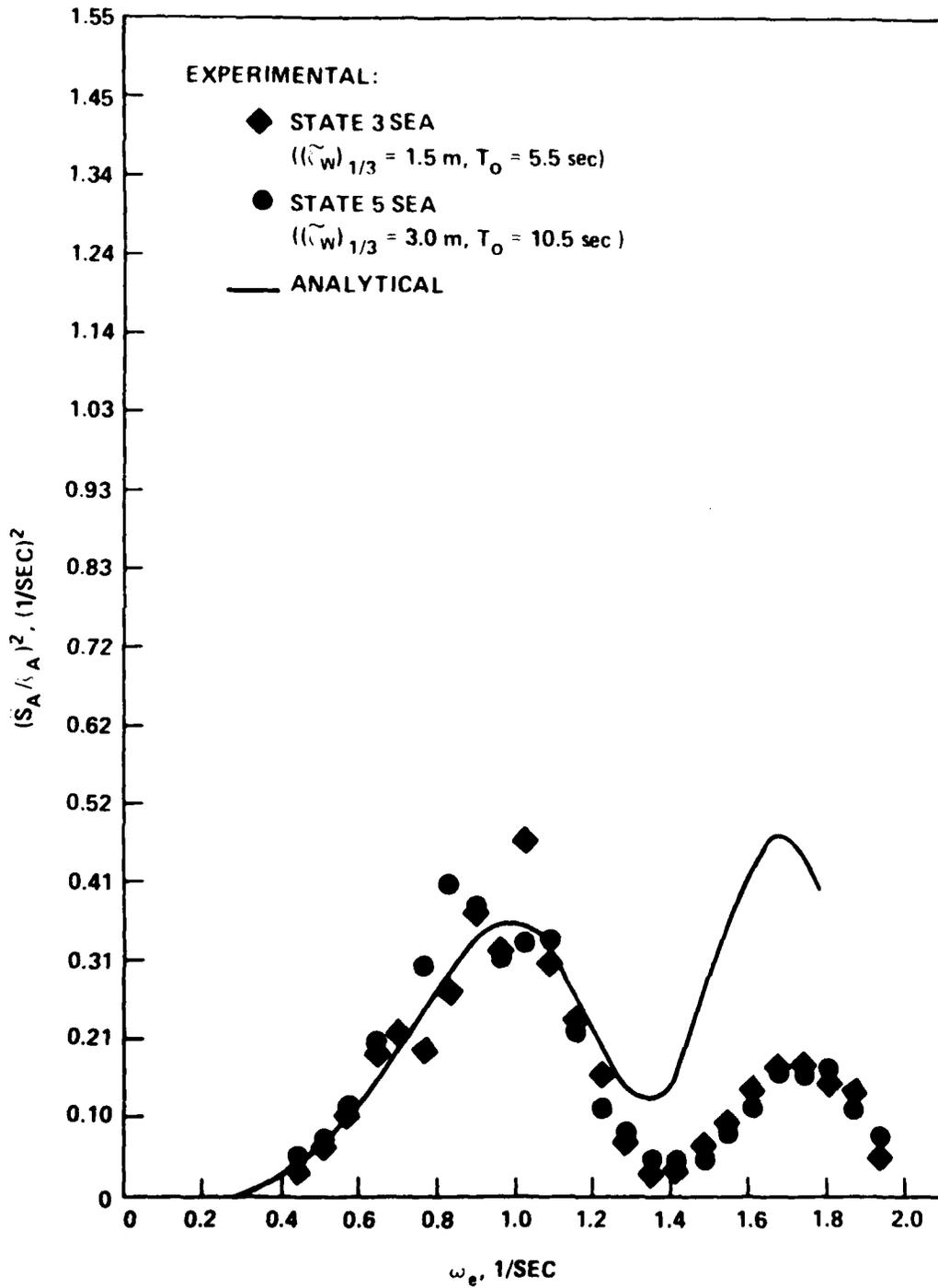


Figure 11 - WMEC Station 14 Vertical Acceleration Response Amplitude Operator Comparison at 6 knots

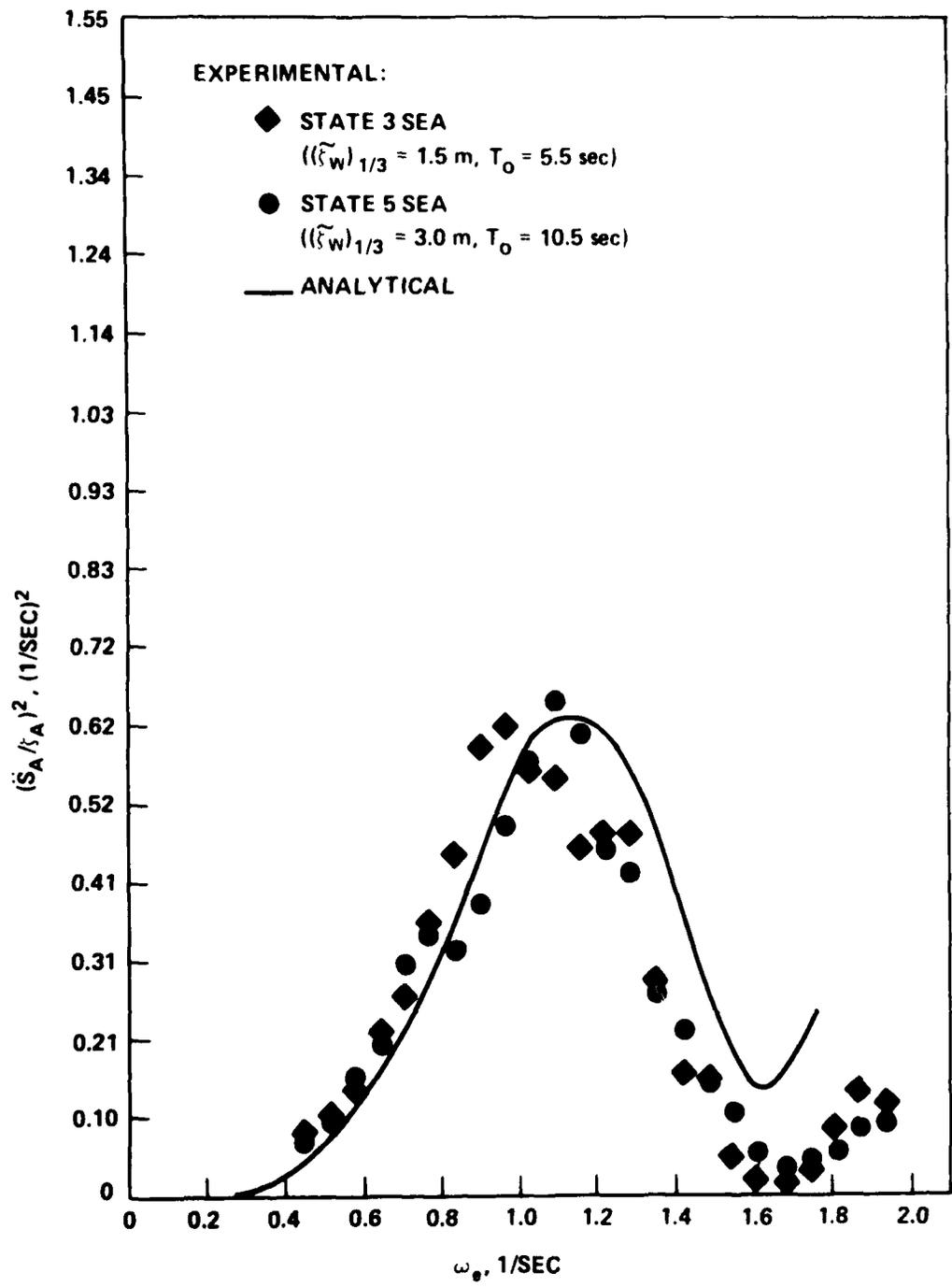


Figure 12 - WMEC Station 14 Vertical Acceleration Response Amplitude Operator Comparison at 10 knots

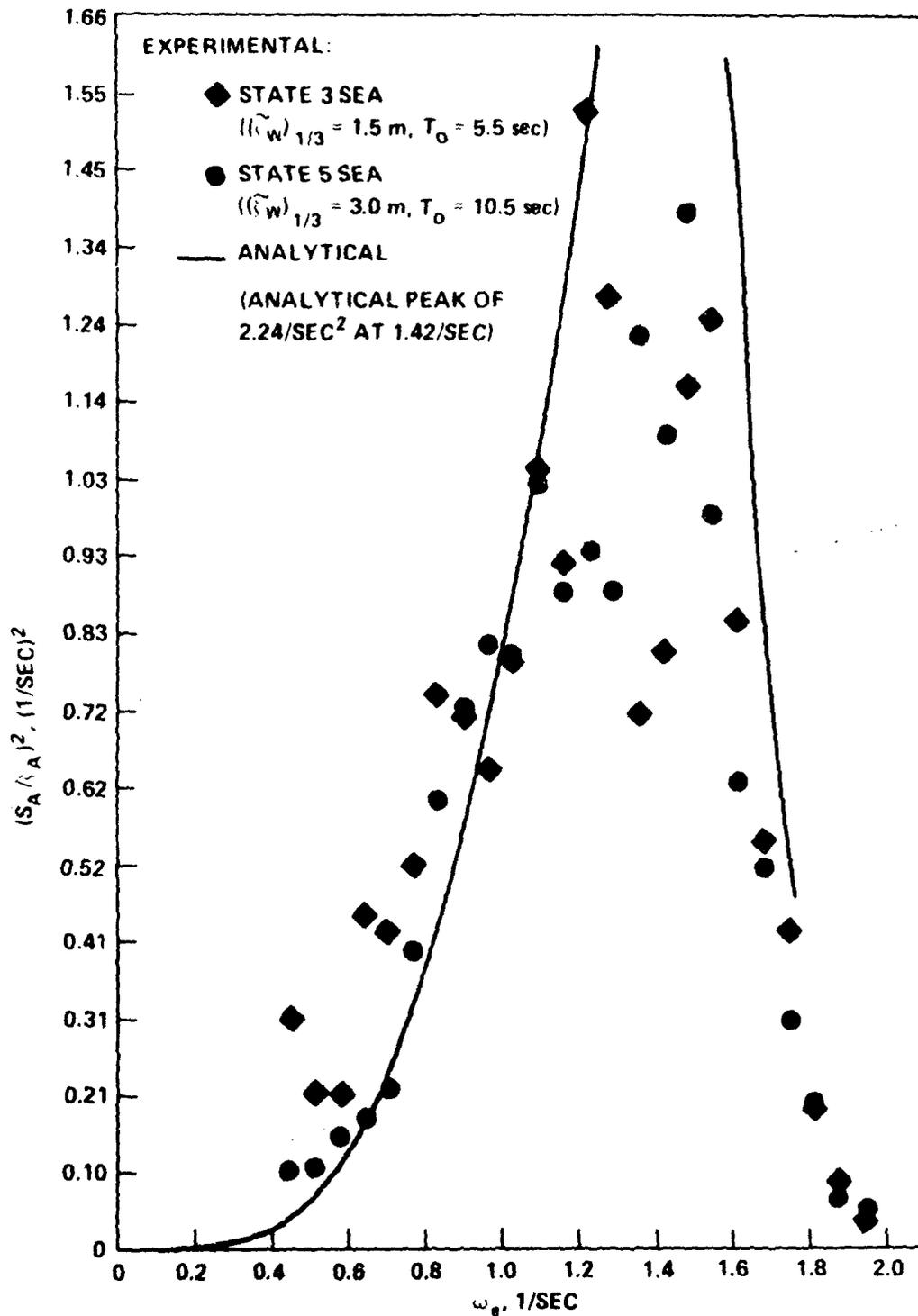


Figure 13 - WMEC Station 14 Vertical Acceleration Response Amplitude Operator Comparison at 15 knots

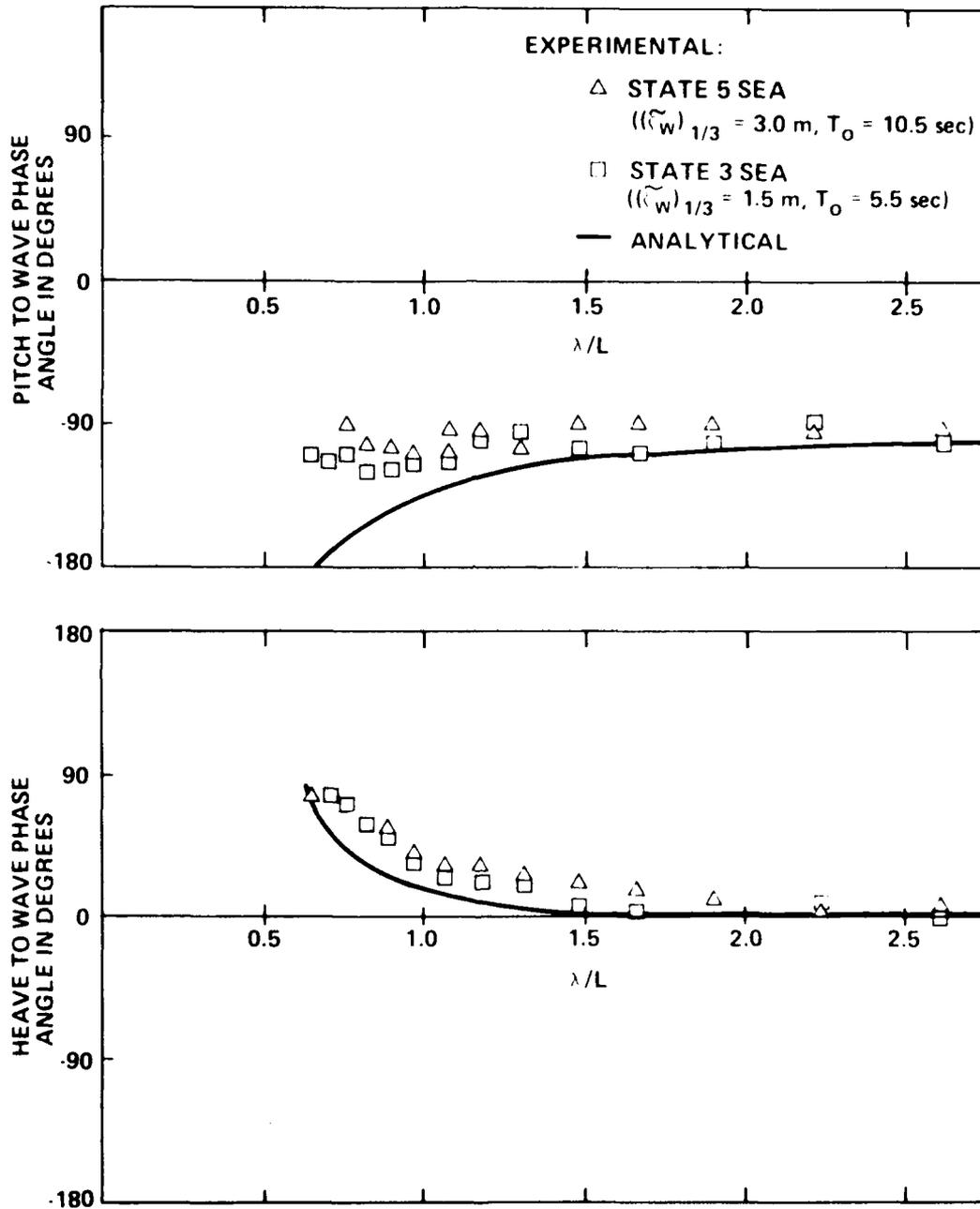


Figure 14 - WMEC Pitch to Wave and Heave to Wave Phase Angle Comparisons at 6 Knots

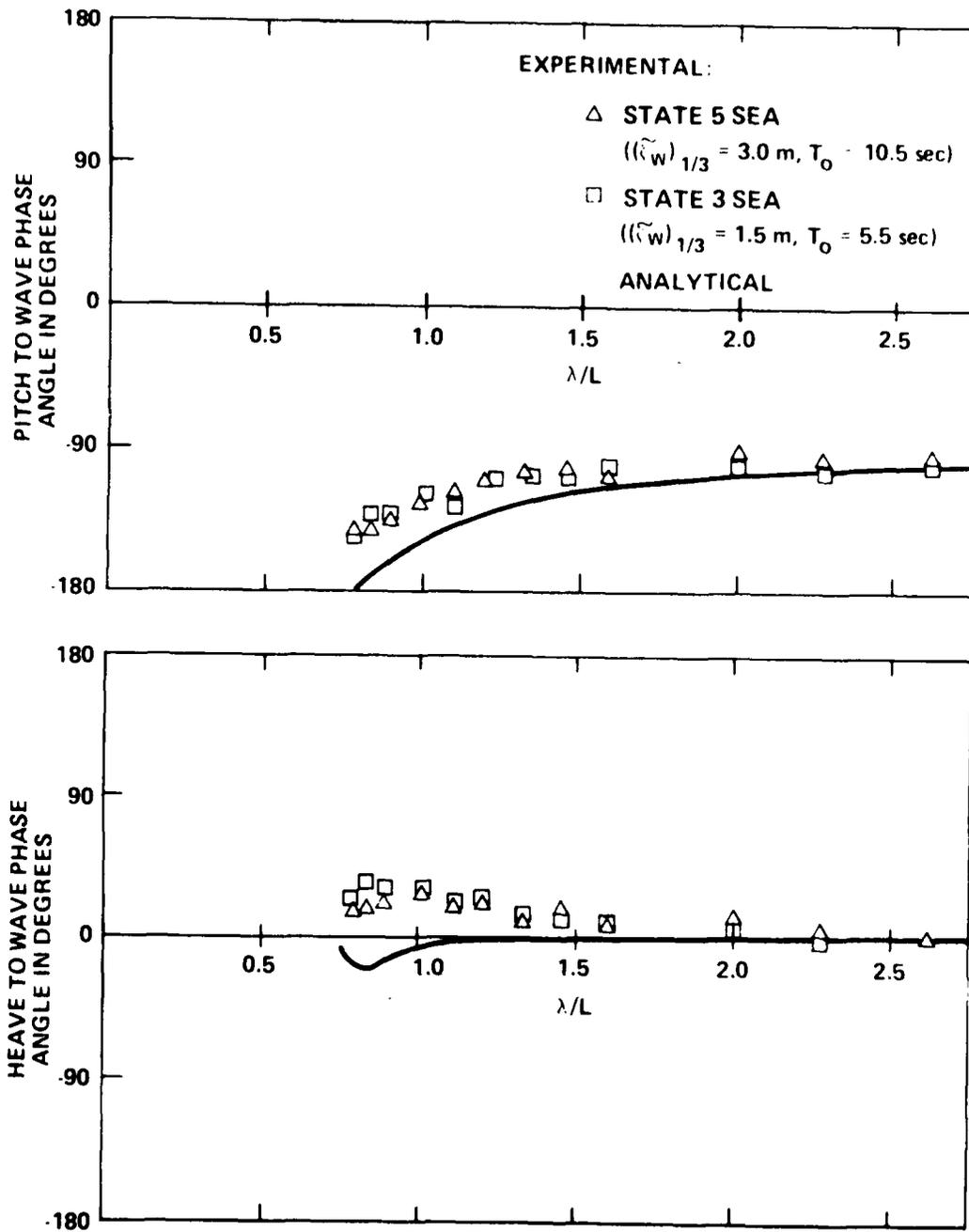


Figure 15 - WMEC Pitch to Wave and Heave to Wave Phase Angle Comparisons at 10 knots

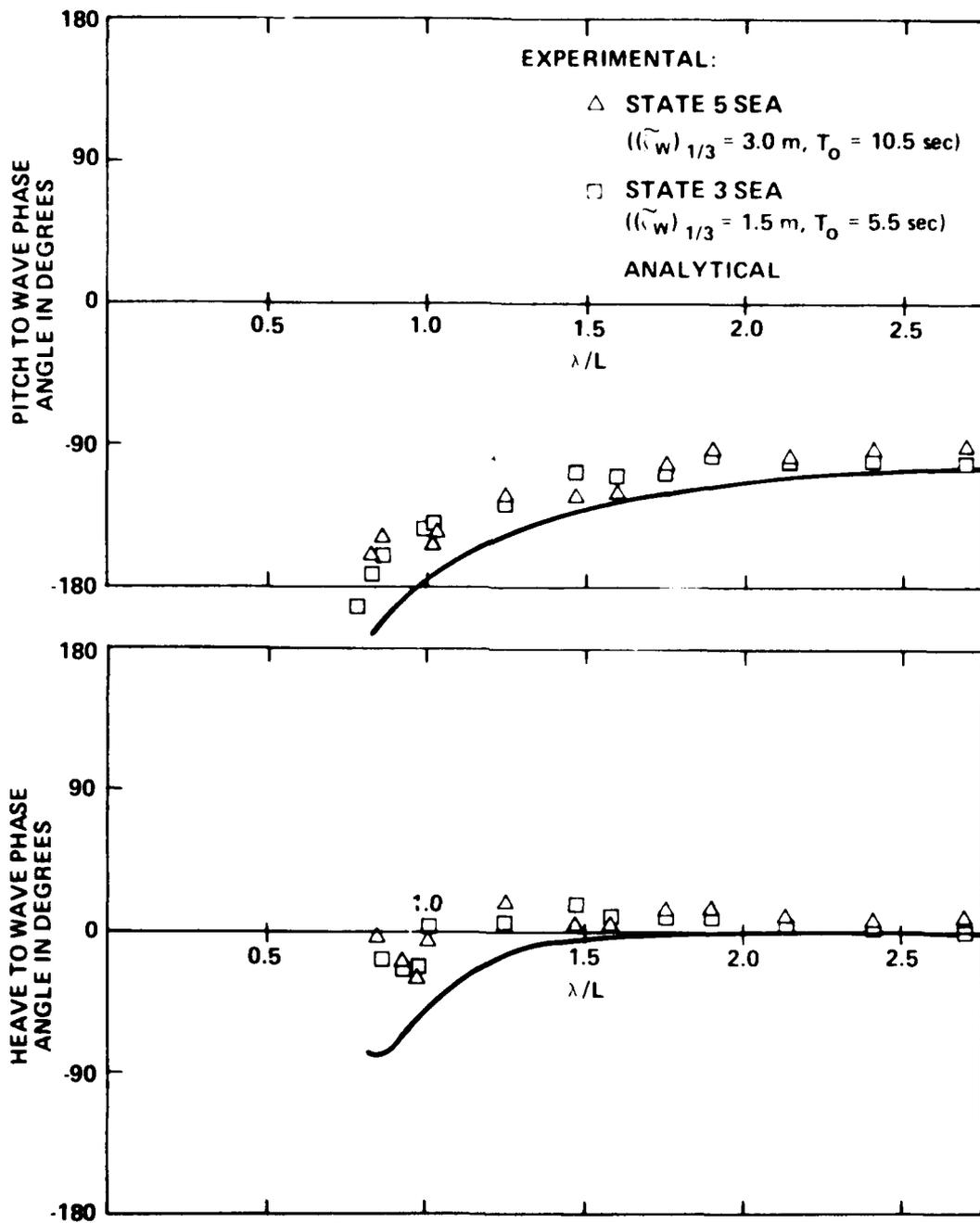


Figure 16 WMEC Pitch to Wave and Heave to Wave Phase Angle Comparisons at 15 knots

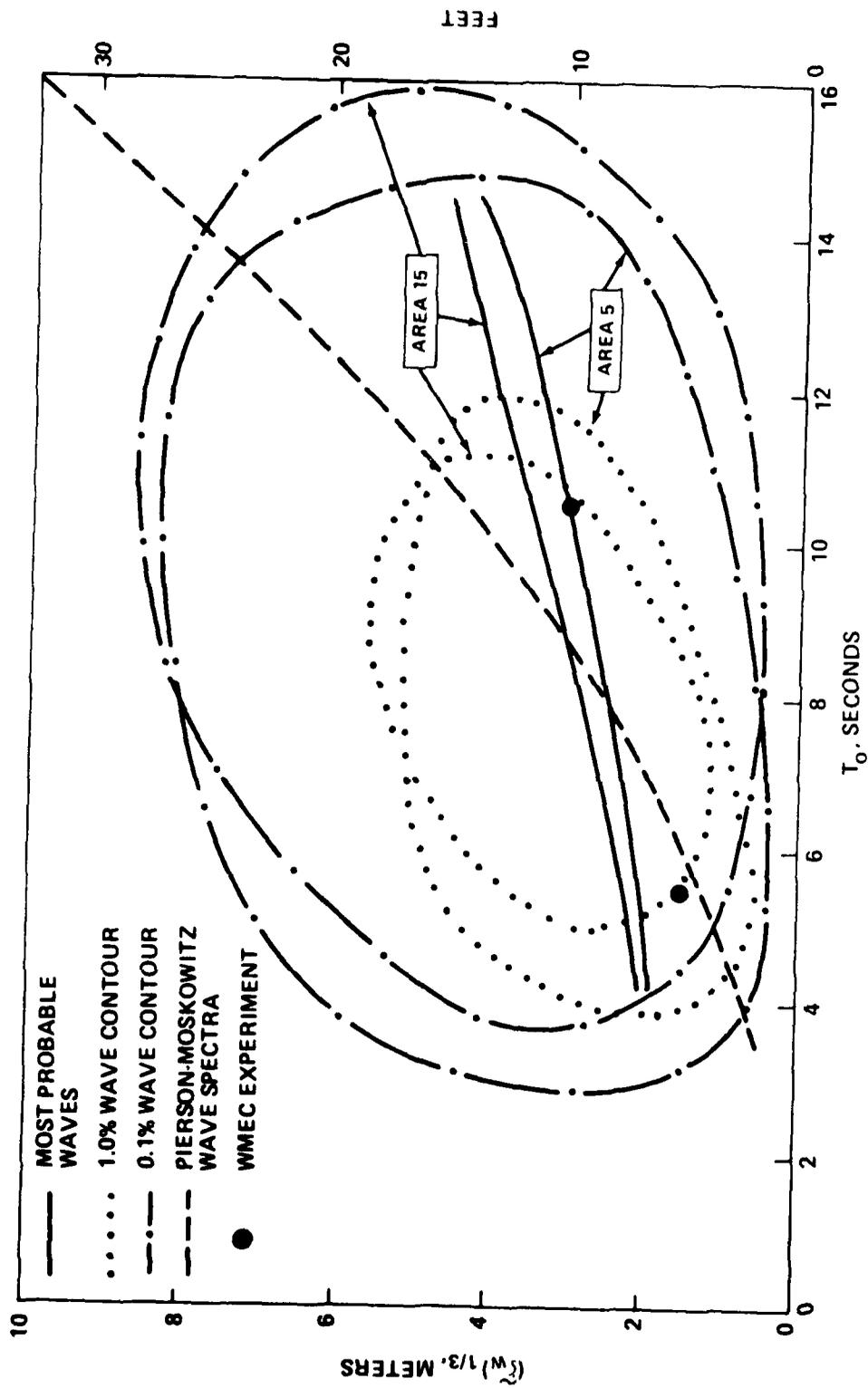


Figure 17 - Definition of the Wave Environment for SSMO Areas 5 and 15

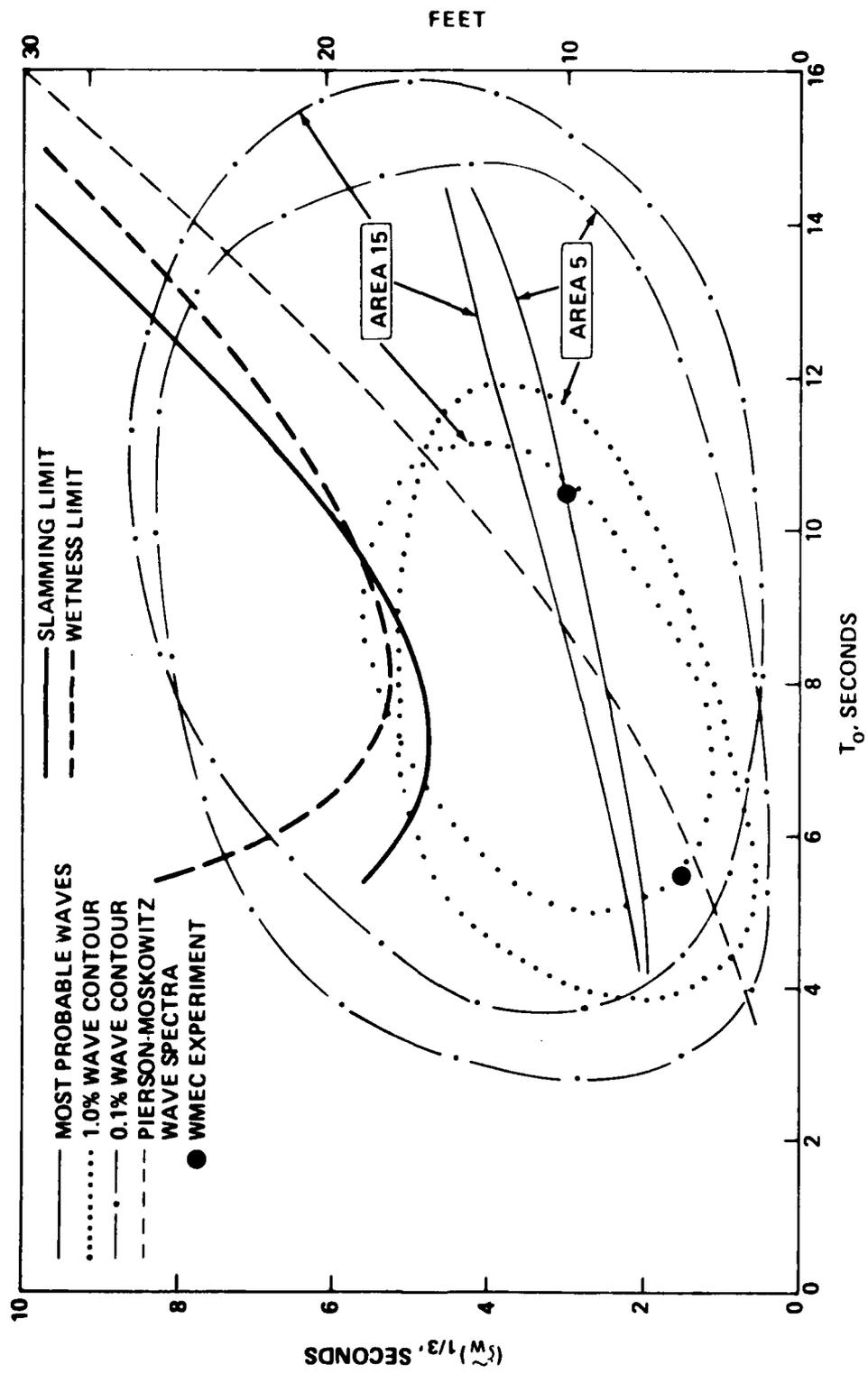


Figure 18 - WMEC Operational Limits at 6 knots in the Context of the Wave Environment

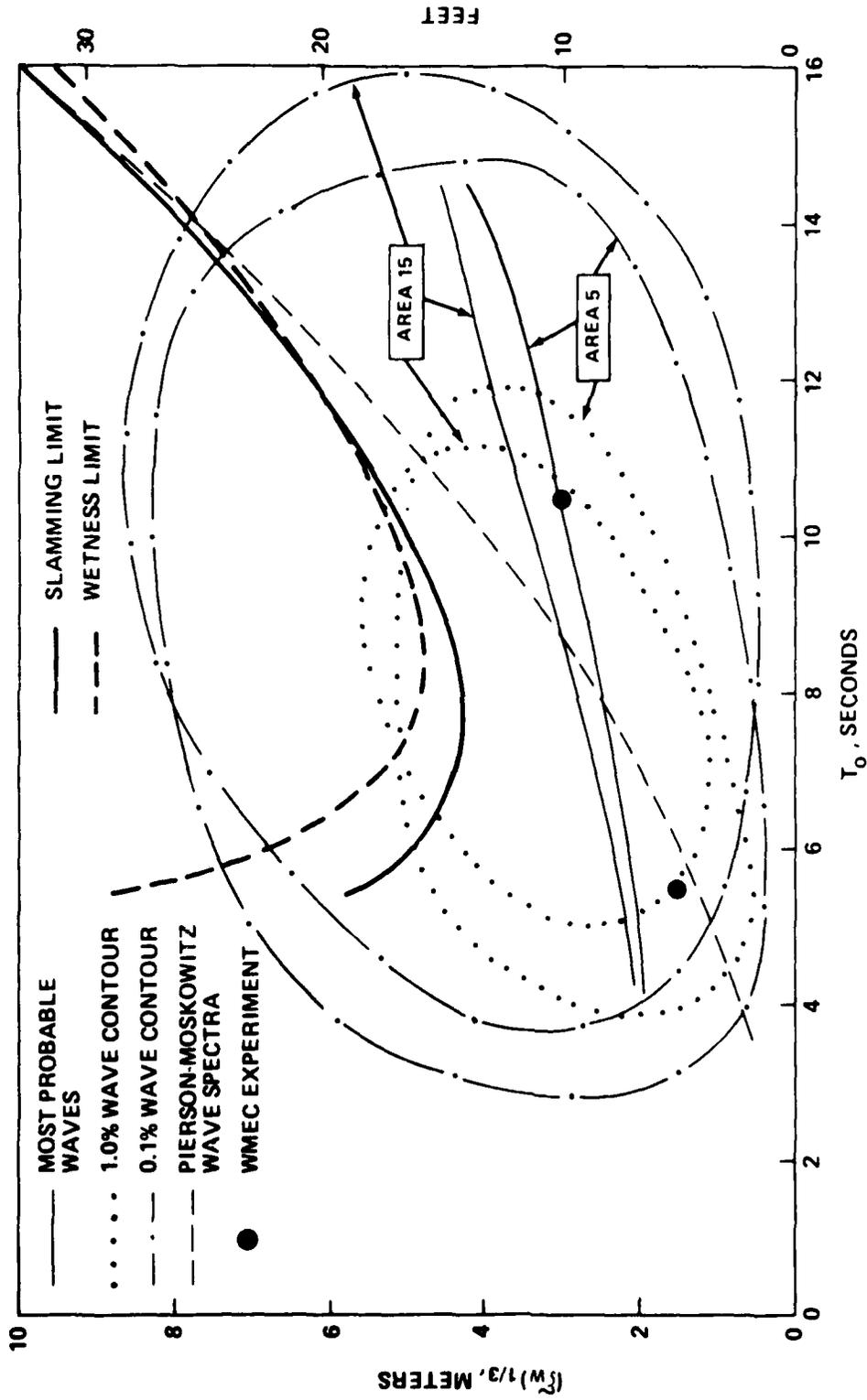


Figure 19 - WMEC Operational Limits at 10 Knots in the Context of the Wave Environment

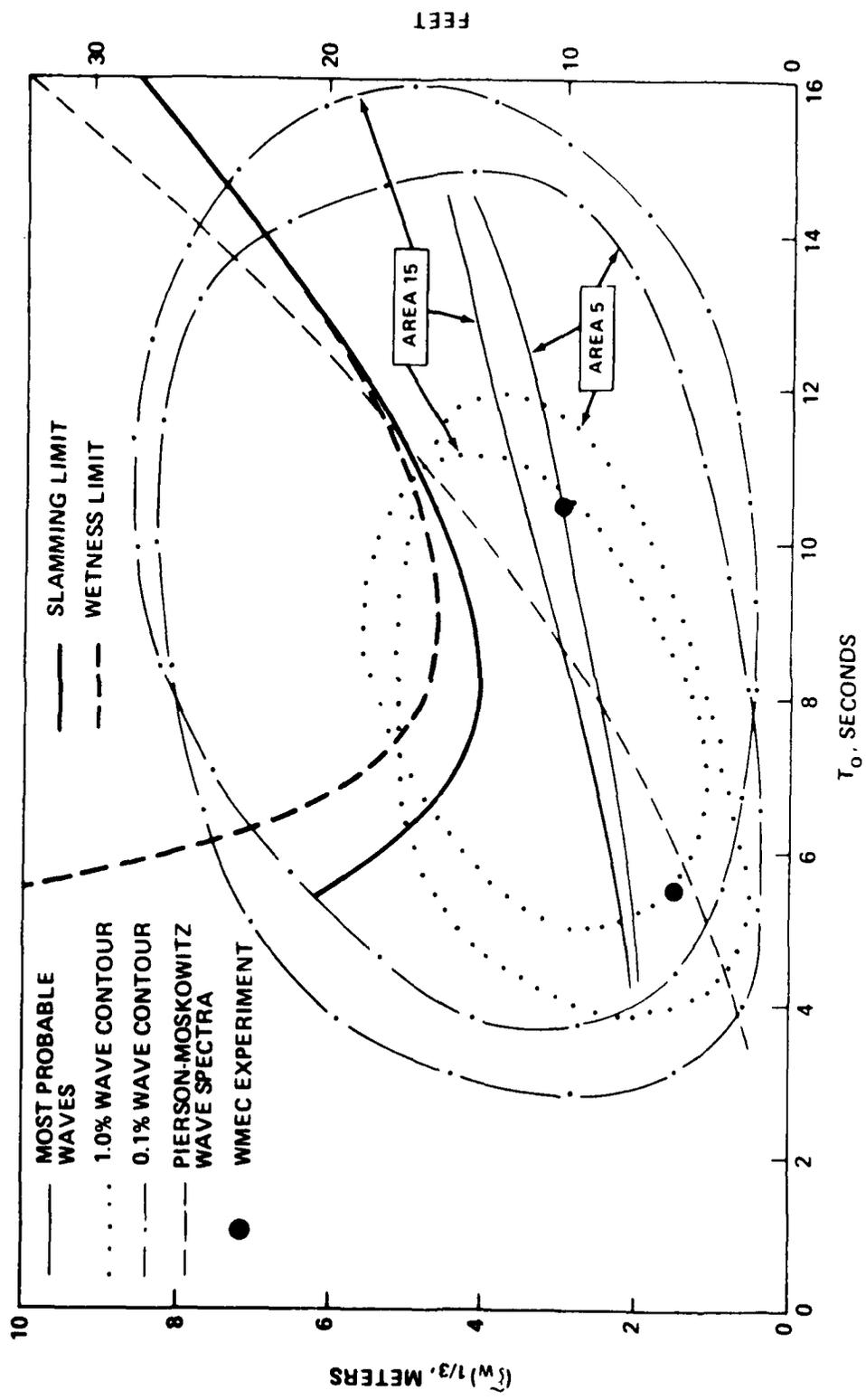


Figure 20 - WMEC Operational Limits at 15 Knots in the Context of the Wave Environment

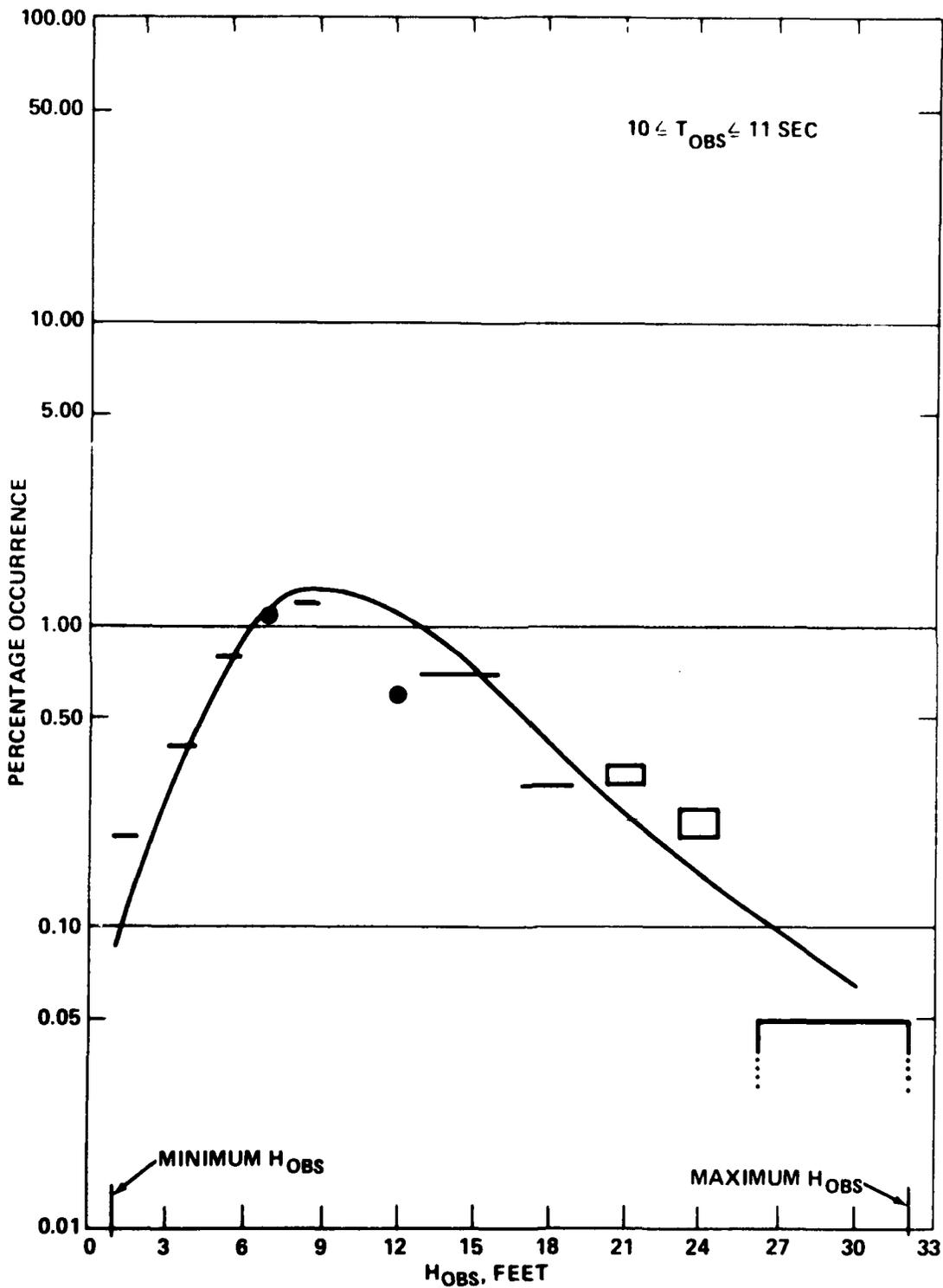


Figure A1 - Sample Plot and Fairing of SSMO Area 5 Data for Fixed Period

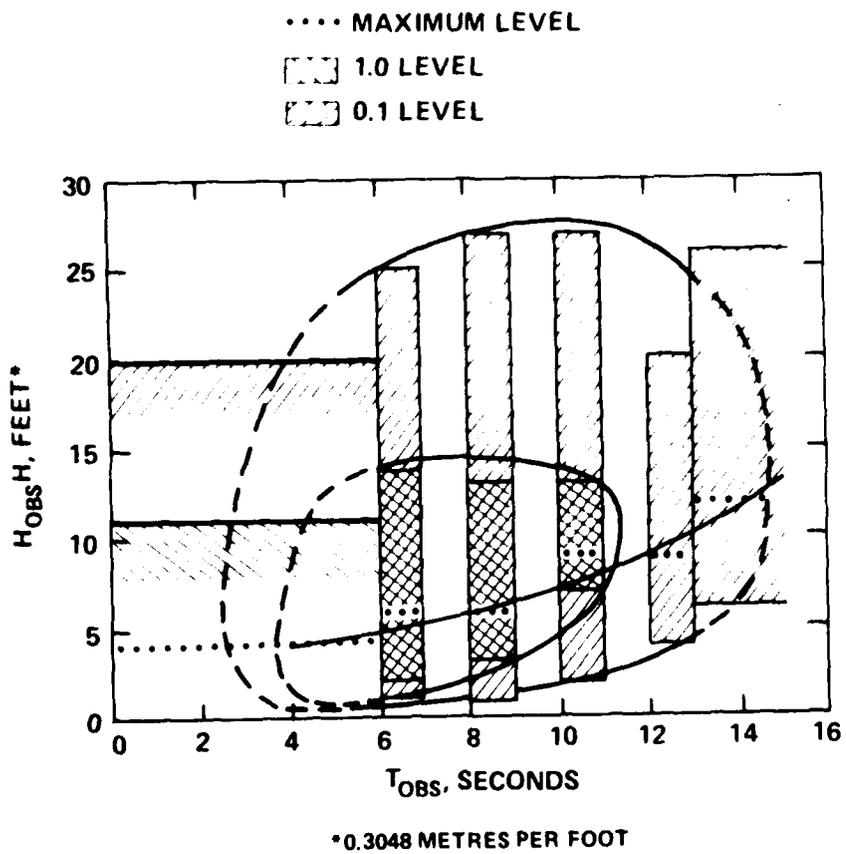


Figure A2 - Plot and Fairing of SSMO Area 5 Data over Period

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