

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER



Bethesda, Md. 20084

SEAGOING BOX SCORES AND SEAKEEPING CRITERIA FOR MONOHULL, SWATH, PLANING, HYDROFOIL, SURFACE EFFECT SHIPS, AND AIR CUSHION VEHICLES

by

Philip Mandel

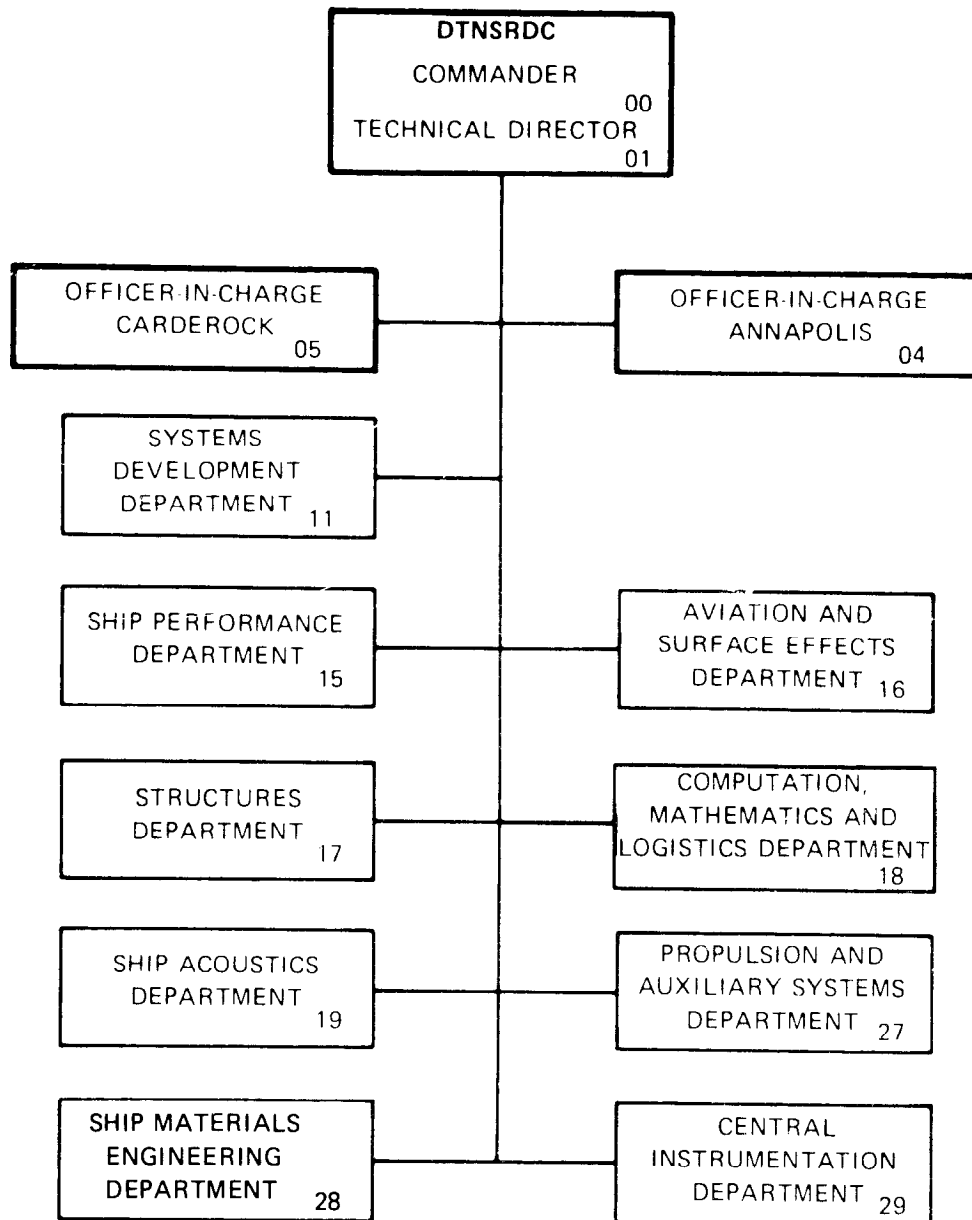
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This work brings together prescribed values of 18 seakeeping criteria for monohulls, small-waterplane-area twin-hull (SWATH) ships, planing craft, surface effect ships, and air cushion vehicles from sources indicated in the report. The nature of each criterion is discussed and the prescribed values of these 18 criteria for each vehicle type are compared and discussed. Although some of the prescribed values of these 18 criteria are not reconcilable, other values, obtained from independent sources, show remarkable agreement. At least one new criterion not included in Table 2 is needed for monohulls.

Appendixes A, B, and C contain a useful summary of important results of Olson's massive work in a form not presented in his work.

The usefulness and limitations of the frequency and time domain ship motion data bases developed for monohulls are described in Appendix D. The existence of these two data bases makes it possible to calculate the values of several of the criteria of Table 2 by two completely independent means.

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NOTATION

A	Nondimensional coefficients
a	Regular wave amplitude
B	Ship beam
e	Exponential $e = 2.7183$
g	Gravity acceleration
Hz	Hertz, unit of frequency (1 hertz = $1/2\pi$ radians per sec = 1 cycle per second)
$K(\omega)$	Nondimensional coefficient of added drag in regular waves, function of ω
k	Any positive integer value greater than 0
L	Ship length
LC	Long-crested seas
MSI	Motion sickness incidence = $f(t_1, \omega, \ddot{z})$
m	Meter
N_s	Number of events per unit time
PSEPR	Positive signal excess ping return
RAO	Response amplitude operator
$RAO_z(\omega)$	RAO of the heave response as a function of ω
$RAO_\eta(\omega_e)$	RAO of one of the η responses as a function of ω_e
$RAO_\theta(\omega)$	RAO of the pitch response as a function of ω
RMS	Root mean square value of a response
RMS_{ζ_z}	RMS value of the relative vertical displacement between a point on the vehicle and a point on the surface of the ocean immediately below (or above) the first point

$RMS_{\zeta z}$	RMS value of the relative vertical velocity between the same two points
$r(t)$	Response as a function of time
SC	Short-crested seas
$S_{\zeta}(\omega)$	Ordinate of the wave spectrum as a function of ω
$S_{\zeta}(\omega_e)$	Ordinate of the wave spectrum as a function of ω_e
$S_{\eta}(\omega_e)$	Ordinate of one of the response spectra as a function of ω_e
T	Ship draft at location near bow; ship freeboard; vertical distance between a point on the vehicle and the smooth ocean surface
TOE	Encounter period of maximum response
T_o	Spectral modal period, $T_o = 2\pi/\omega_o$ (corresponds to the period of the component wave contributing the most energy to the spectrum)
t	Sonar dome submergence period; also time
* t	Specified time interval between two successive slams
t_1	Motion exposure time interval
V	Vehicle velocity
* v	Threshold relative vertical between vehicle and water surface
x,y,z	Earth axes coordinate system,* also displacements in x, y, and z directions, also surge, sway and heave
x_o, y_o, z_o	Vehicle axes coordinate system,* also displacement in $x_o, y_o,$ and z_o directions

*With the origin located at the intersection of the plane of symmetry of the vehicle, its calm water waterplane, and the transverse plane at the longitudinal location of the center of gravity of the vehicle.

γ_k	Random phase angle between each of k sine waves
$\gamma_{\zeta z}$	Phase angle between wave excitation and heave
$\gamma_{\zeta \theta}$	Phase angle between wave excitation and pitch
ΔR	Added drag in regular waves
$\Delta \omega$	Very narrow band of frequencies
ζ	Significant wave height (average of 1/3 highest waves); sea surface elevation; wave height
η	One of the responses
θ	Pitch angle; rotation of a vehicle about the earth y axis
λ	Wave length = $2\pi g/\omega^2$
μ	Angle between vehicle velocity and wave direction
ρ	Fluid mass density
ϕ	Roll angle; rotation of a vehicle about the earth x axis
ψ	Yaw angle; rotation of a vehicle about the earth z axis
ω	Wave circular frequency = 2π Hz
ω_e	Encounter circular frequency
ω_k	Center frequency of narrow band of frequencies
ω_o	Spectral modal frequency

ABSTRACT

Three seagoing box scores applicable to any vehicle operating on the surface of the ocean are defined and assessed. One of the box scores is directly useful for calculating the operational worth and the technical seagoing merit of vehicles performing ocean surveillance-like functions. The second box score is similarly useful for the ordinary transportation function of vehicles. The third box score is useful for measuring the technical seagoing merit of vehicles performing any function.

This work brings together prescribed values of 18 seakeeping criteria for monohulls, small-waterplane-area twin-hull (SWATH) ships, planing craft, surface effect ships, and air cushion vehicles from sources indicated in the report. The nature of each criterion is discussed and the prescribed values of these 18 criteria for each vehicle type are compared and discussed. Although some of the prescribed values of these 18 criteria are not reconcilable, other values, obtained from independent sources, show remarkable agreement. At least one new criterion not included in Table 2 is needed for monohulls.

Appendixes A, B, and C contain a useful summary of important results of Olson's massive work in a form not presented in his work.

The usefulness and limitations of the frequency and time domain ship motion data bases developed for monohulls are described in Appendix D. The existence of these two data bases makes it possible to calculate the values of several of the criteria of Table 2 by two completely independent means.

ADMINISTRATIVE INFORMATION

The work reported herein and performed by the David W. Taylor Naval Ship Research and Development Center (DTNSRDC) was authorized and supported by the Naval Sea Systems Command (SEA 0323) under the Block Program for Ship Feasibility Studies. The funding identification for this work is as follows: Program Element 62543N, Task Area SF 43-411-291, Code 1170, Work Unit Number 1100-001 titled Advanced Vehicle Comparison.

INTRODUCTION

This report accepts as axiomatic two premises:

1. Evaluation of the operational worth of proposed naval ships and advanced vehicles in the design stage is essential if wise decisions concerning naval vehicle procurement are to be made.

2. Being able to assess the seagoing* performance of a naval vehicle in the design stage is at least as important in determining its ultimate operational worth as being able to assess its speed and endurance in smooth water.

Three comprehensive box scores, discussed in this report, offer a way of assessing the seagoing performance of competitive vehicle types operating on the ocean surface. However, all three of these box scores depend on a host of seakeeping criteria, whose nature and whose prescribed values have been devised by individual investigators dealing with an individual vehicle type. These criteria and their prescribed values, therefore, not only lack the benefit of cross-fertilization but are one of the weakest of the three essential elements** needed to calculate the box scores.

Further development of seakeeping criteria and their prescribed values is, therefore, imperative if the thrust of the second axiomatic premise is to be fulfilled. In accord with this need, this report clarifies the philosophy that underlies the concept of seagoing criteria and the vital distinction that must be made between the actual and the prescribed values of these criteria. It also assembles the seagoing criteria currently proposed for hydrofoils and monohulls and compares and discusses the prescribed values of these criteria proposed in various sources for these two vehicle types plus small-waterplane-area, twin-hull (SWATH) ships, planing craft, surface effect ships (SES), and air cushion vehicles (ACV). As such this report represents a part of the needed research concerning seakeeping

*In this report the word "seagoing" should be exclusively interpreted in the narrow sense implied by the less common word "wavegoing." This report deals only with the issue of the effect of rough seas on vehicle performance. It does not deal with other issues that may be implied in the term "seagoing."

**The two other essential elements are described subsequently.

criteria. However, it does not address the vital issue of what approach should be taken in future research on seakeeping criteria. Some work is underway in the U.S. utilizing the questionnaire approach with which the British have had some favorable experience. There are other approaches. This is an issue that remains to be addressed.

The other two essential elements needed to calculate the three box scores are also discussed in this report. They are:

1. The quantitative definition of the seaway including its statistics.
2. The prediction of vehicle responses including vehicle speed as a function of sea state severity.

THREE SEAGOING BOX SCORES

Box Score 1 was postulated and calculated by Olson^{1*} for four combatant monohull ships and a SWATH (see Appendixes A, B, and C). Box Score 2, which is applicable to any ship, military or commercial, engaged in conventional transportation or military protection of shipping functions was postulated but not calculated by Mandel et al.² Box Score 3 was postulated by Comstock et al.³ and is currently used by the Naval Ship Engineering Center to assess the seagoing performance of naval ships.

The definitions of these three box scores are as follows:

Box Score 1: The percent of time that a given vehicle in a given condition of loading can perform its function in a specified ocean area in a given season at a specified speed without the actual value of any one of x applicable seakeeping criteria ever exceeding the prescribed value of that criterion.

Box Score 2: The time that a vehicle needs to transit between two specified locations in calm water in a given season divided by the time that the vehicle would require to travel between the same two locations in rough water in that season without the actual value of any one of the x applicable criteria of Box Score 1 ever exceeding its prescribed value.

*A complete listing of references is given on page 85.

Box Score 3: The area under the curve shown in Figure 1 (called the Stratified Measure of Merit by Comstock³) whose abscissa is significant wave height and whose ordinate is the product of the following two parameters, both of which are direct functions of significant wave height:

(a) The probability of occurrence of each value of significant wave height in the ocean area and in the season during which the vehicle is to operate (see the last column of Table 1).

(b) The area on the seakeeping speed polar diagram shown in Figure 2 (called the Measure of Merit by Comstock³). On this figure the magnitude of the vehicle speed at each heading is limited either by the prescribed value of one of the x applicable seakeeping criteria of Box Score 1 (identified as Criteria A, B, and C in Figure 2), or by the added drag and altered propulsive efficiency of the vehicle in the seas defined by the set of values of significant wave heights of (a) (whichever is more speed constraining).

These three box scores share a common strength. Provided the criteria, the prescribed values of the criteria, and the predicted motions are all correct, each box score is a valid, quantifiable technical measure of the seagoing merit of any present or foreseeable vehicle operating at the interface. Box Scores 1 and 2 also have a second strength that Box Score 3 does not possess. Both Box Scores 1 and 2 are ratios between performance in rough water and in calm water. As such they are directly connected with the probability that the vehicle's desired operational function will be successfully accomplished, which is an essential ingredient of the operational worth of the vehicle. Box Score 3 was not expressed by Comstock et al.³ as a ratio between performance in rough and calm seas. Therefore, Box Score 3 as defined cannot be directly used in calculating the operational worth of vehicles. It is, however, very useful as a measure of technical seagoing worth independent of mission.*

*In practice, seakeeping criteria associated with accomplishing particular operational functions are used in calculating Box Score 3. When this is done, the value of Box Score 3 still reflects only the technical seagoing worth of the vehicle in performing that function, and its value has no relation to the probability that the operation will be successfully accomplished.

Percent Time Each Value of Significant Wave Height is Encountered X Measure
of Merit from Seakeeping Speed Polar Diagram. (See Fig. 2)

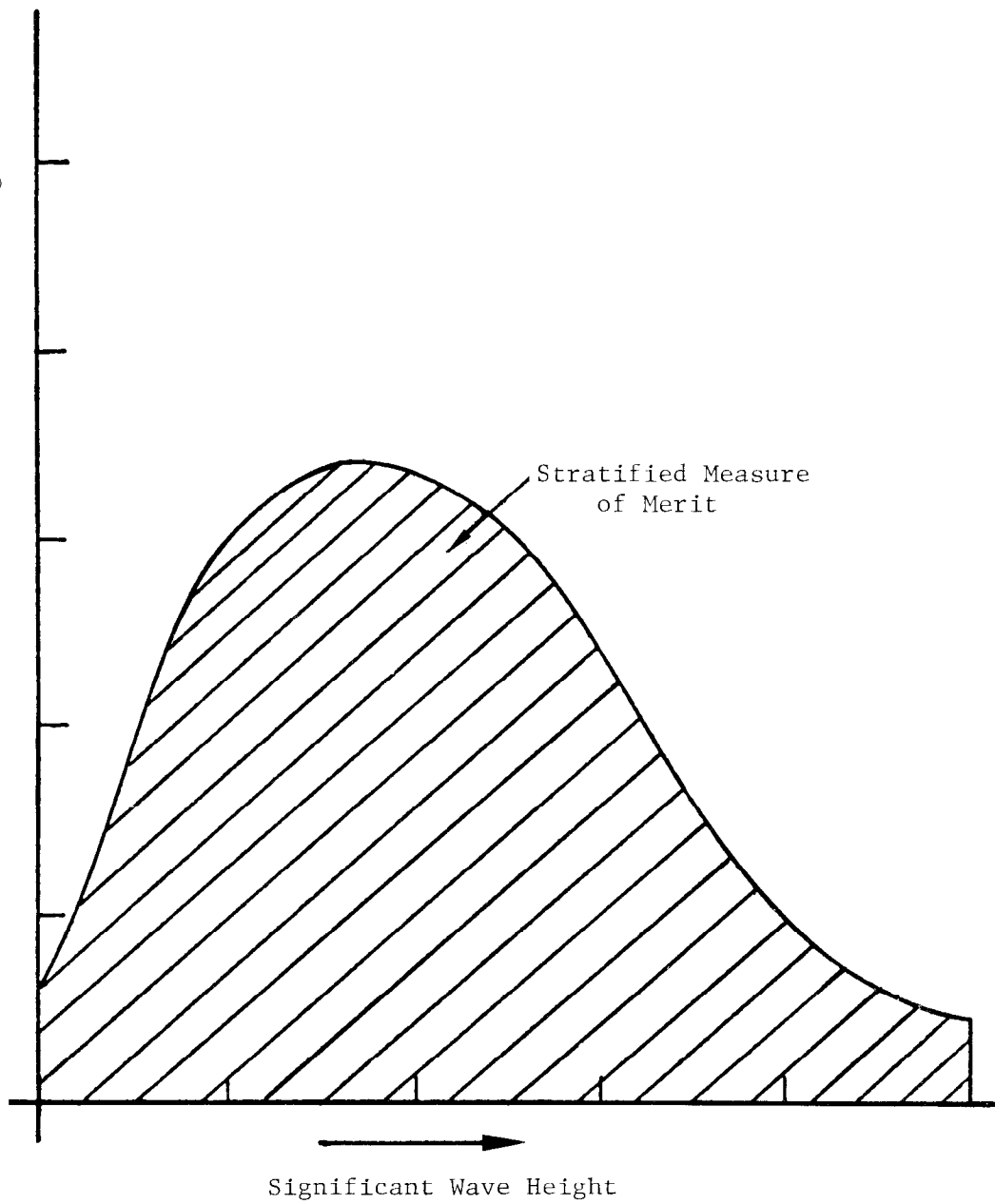


Figure 1 - Stratified Measure of Merit
(Source: Reference 3)

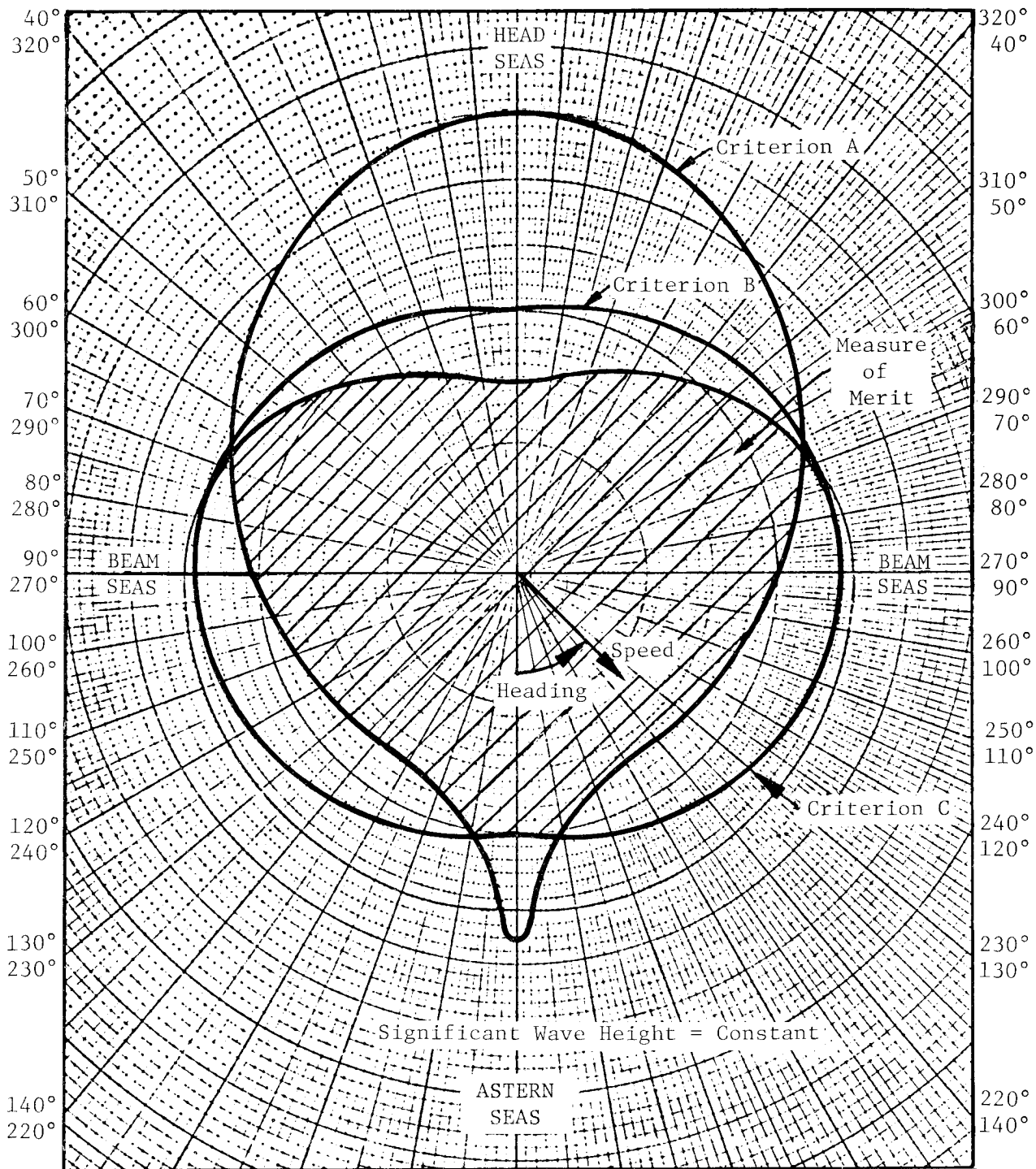


Figure 2 - Example of a Seakeeping Speed Polar Diagram

Box Score 1 is directly useful in calculating the operational worth of Navy and Coast Guard vehicles engaged in an ocean surveillance mission or a force defense operation about a stationary position. These missions are usually conducted at an essentially fixed speed and any heading direction between 0 and 360 degrees is equally probable. Box Score 1 is also directly useful for other ship functions where the heading of the ship may be more constrained. For example, ships launching or recovering aircraft proceed in a direction such that the wind over the deck is parallel to the centerplane of the ship. Box Score 1 can be calculated for this function by restricting the ship-wave heading angle to values that yield this condition.

Assuming that a correct set of seakeeping criteria and their prescribed values is available for a particular vehicle function and that the wave conditions in the desired ocean area and over the desired season are known in the statistical sense depicted in Table 1, 100 minus Box Score 1 is the percent of time that function cannot be performed at the prespecified speed because of seakeeping considerations. It is this value that is used directly in calculating the operational worth of a vehicle. There may be reasons other than seakeeping for not carrying out the function, but Box Score 1 quantifies the seakeeping reason that is ignored in many current assessments of the operational worth of vehicles.

Because of its restriction to an essentially fixed vehicle speed, Box Score 1 is not useful in calculating the operational worth of vehicles engaged in the transportation or shipping protection functions. For these functions, Box Score 2 is useful. It is one of the key factors by which the specified design speed of a vehicle must be multiplied to obtain the speed made good on a particular route in a particular season. The latter is an essential ingredient in calculating the operational worth of transportation vehicles. Other key factors are involved in calculating speed-made-good, but they are not included in Box Score 2 because they are not directly associated with vehicle performance in rough seas. These key factors are associated with ocean currents, wind drag, fouling, visibility

TABLE 1 - JOINT PROBABILITIES OF OCCURRENCE OF SIGNIFICANT WAVE HEIGHT AND MODAL PERIOD
IN SELECTED NORTH ATLANTIC AREA IN DECEMBER-FEBRUARY

(All wave directions included) Source: Reference 9

Significant Wave Height, ζ		Modal Period (sec)											Totals
ft	m	Inde- terminate	<5.38	6.41- 7.43	8.45- 9.46	10.47- 11.47	12.47- 13.47	14.48- 15.45	16.44- 17.43	18.41- 19.39	20.37- 21.34	>21.34	
1.95	0.59	0.00667	0.00986	0.00055	0.00037	0.00023	0.00014	0.00006	0.00001	0.00002	0.00012	0.00015	0.01818
3.28	1.00	0.00107	0.02567	0.00324	0.00101	0.00045	0.00011	0.00011	0.00006	0.00004	0.00002	0.00130	0.03308
5.51	1.68	0.00340	0.05361	0.02756	0.00578	0.00253	0.00113	0.00028	0.00016	0.00008	0.00012	0.00071	0.09536
7.47	2.28	0.00509	0.03533	0.06912	0.02543	0.00696	0.00288	0.00118	0.00034	0.00019	0.00001	0.00034	0.14687
9.27	2.83	0.00652	0.01332	0.05616	0.04383	0.01531	0.00447	0.00137	0.00041	0.00010	0.00000	0.00005	0.14154
10.96	3.34	0.00638	0.00677	0.03992	0.04713	0.02375	0.00768	0.00261	0.00054	0.00013	0.00002	0.00002	0.13495
12.56	3.83	0.00605	0.00282	0.02111	0.03788	0.02534	0.01019	0.00223	0.00065	0.00032	0.00000	0.00001	0.10660
14.10	4.30	0.00400	0.00209	0.01411	0.02975	0.02414	0.01134	0.00420	0.00092	0.00027	0.00000	0.00004	0.09086
15.59	4.75	0.00327	0.00121	0.00757	0.01808	0.01666	0.00895	0.00329	0.00128	0.00045	0.00007	0.00000	0.06083
17.03	5.19	0.00335	0.00105	0.00706	0.01814	0.01769	0.00964	0.00476	0.00244	0.00045	0.00005	0.00010	0.06473
18.43	5.62	0.00066	0.00019	0.00099	0.00232	0.00303	0.00173	0.00061	0.00034	0.00002	0.00004	0.00003	0.00996
19.80	6.03	0.00050	0.00013	0.00134	0.00232	0.00311	0.00242	0.00130	0.00042	0.00000	0.00003	0.00000	0.01157
21.13	6.44	0.00037	0.00041	0.00185	0.00522	0.00572	0.00327	0.00158	0.00079	0.00001	0.00001	0.00002	0.01925
22.44	6.84	0.00042	0.00018	0.00195	0.00477	0.00575	0.00401	0.00202	0.00055	0.00003	0.00004	0.00000	0.01974
23.72	7.23	0.00017	0.00020	0.00034	0.00168	0.00241	0.00165	0.00085	0.00030	0.00015	0.00000	0.00001	0.00776
24.98	7.61	0.00058	0.00003	0.00075	0.00163	0.00328	0.00264	0.00086	0.00034	0.00014	0.00001	0.00012	0.01038
26.22	7.99	0.00051	0.00014	0.00043	0.00145	0.00268	0.00226	0.00072	0.00050	0.00002	0.00002	0.00013	0.00886
27.44	8.36	0.00018	0.00000	0.00026	0.00090	0.00163	0.00148	0.00067	0.00030	0.00000	0.00003	0.00001	0.00545
28.64	8.73	0.00008	0.00000	0.00018	0.00066	0.00148	0.00099	0.00039	0.00023	0.00009	0.00000	0.00002	0.00412
29.83	9.09	0.00038	0.00002	0.00033	0.00130	0.00187	0.00257	0.00120	0.00084	0.00062	0.00018	0.00014	0.00945
31.00	9.45	0.00000	0.00000	0.00005	0.00002	0.00015	0.00019	0.00000	0.00000	0.00003	0.00001	0.00000	0.00045
Totals		0.04965	0.15303	0.25488	0.24969	0.16418	0.07971	0.03028	0.01141	0.00319	0.00078	0.00320	1.00000

8

conditions, deterioration of power output, etc. It should be noted that, just as Box Score 1 is not useful for the transportation function, Box Score 2 is not useful for the vehicle missions for which Box Score 1 is useful.

The unique feature of Box Score 1 is that it measures the seagoing merit of a vehicle operating at an approximate specified speed but not on a specified route. The unique feature of Box Score 2 is that it measures seagoing merit on a specified route. Both of these features are combined in Box Score 3. However, unlike Box Scores 1 and 2, Box Score 3 has no direct relation to operational worth. It may nevertheless be more useful than either Box Scores 1 or 2 in assessing the overall technical seagoing merit of competitive vehicles.

QUANTITATIVE DEFINITION OF THE SEAWAY AND ITS STATISTICS

The definition of the seaway and its statistics is the most basic element common to all seagoing box scores. This element has three parts:

1. Specification of the input parameters and their values needed to characterize sea state severity.
2. Specification of a representative spectral formulation incorporating these input parameters.
3. Specification of the joint probabilities of occurrence of the values of the input parameters of the spectrum.

The commonly accepted prime parameter defining sea state severity is the significant wave height. In addition, another seaway parameter, modal period,* T_o , is currently used as a supplement to define the sea state. Development of spectral formulations representing the ocean surface has culminated in a six-parameter spectral formulation by Ochi et al.⁴ that can simultaneously represent both storm seas and swell. Ochi and Bales have also examined the impact of different spectral formulations on ship responses.⁵ Since the current ocean wave statistical base^{6,7} yields values of only two seaway parameters (significant wave height and modal period),

*Modal period is the period of that component wave of the wave spectrum that contributes the most energy to the spectrum.

use of Ochi's six-parameter formulation is not currently justified and the two parameter Bretschneider⁸ spectral formulation is used in current work. This formulation is:

$$S_{\zeta}(\omega) = 0.3125 \frac{\omega_o^4}{\omega^5} \zeta^2 e^{-1.25(\omega_o/\omega)^4} \quad (1)$$

where ω = wave frequency

ω_o = modal frequency

ζ = significant wave height

e = exponential $e = 2.7183$

It is evident from Equation (1) that the ordinate of the wave spectrum $S_{\zeta}(\omega)$ has dimensions of length² × time. This means that the area under the wave spectral formulation has the dimensions of wave height squared which is directly proportional to the wave energy contained in the spectrum. This concept is used in developing Equation (D.2) in Appendix D.

The statistics of the seaway are currently receiving more attention than spectral formulations. A program is now available⁹ based on work reported by Chryssostomidis¹⁰ that predicts the joint and conditional probabilities of occurrence of 22 different values of significant wave height between 0 and 10 meters and 10 different intervals of modal period (<5, 6-7, 8-9, 10-11, 12-13, 14-15, 16-17, 18-19, 20-21, and >21 sec) for the ocean areas and for the seasons covered by Hogben and Lumb⁶ and by the U.S. Navy Climatic Atlas.⁷ Table 1 is a sample result of that program for the winter North Atlantic. A joint project is now underway between Fleet Numerical Weather Control (FNWC) and the David W. Taylor Naval Ship R & D Center to provide an extensive climatology of wave parameters derived from a twenty-year data set of directional wave spectra. These were hindcast for over 2000 locations in the northern hemisphere at intervals of six hours. One extraordinary result from this project, reported by Bales¹¹, is that very large modal periods, in excess of 19 sec, coexist with very large

significant wave heights, in excess of 50 ft (15.2m), in the North Pacific in the winter (see Table 1 for older data for the North Atlantic).

VEHICLE RESPONSES

Analytical approaches for predicting the actual values of the responses to specified seaways of monohulls, SWATH ships, and hydrofoils in the foil-borne condition are fairly well developed for ahead seas and fairly accurate as long as certain tight constraints are observed. Although these same approaches are used for seas from other than the ahead direction, the prediction of roll, sway, and yaw responses in bow quartering, beam, and stern quartering seas for monohulls and SWATH's is far less accurate than for pitch and heave in ahead seas. Furthermore, the analytical approaches used for monohulls, SWATH's, and hydrofoils are not applicable to planing craft, SES, and ACVs. The analytical approaches that are used for predicting the motions of these latter vehicles are less well substantiated than for the former.

The experimental model approach is of course available and utilized for all vehicle types. So too is the full scale approach. However, because of the enormous amount of information that must be known to assess the seagoing qualities of a vehicle and because of the high cost of model and full scale tests, economics severely constrain the use of these two approaches.

Economics also constrain the way in which the analytical approach is utilized. Because of the high cost of acquiring predicted responses, they were presented in a seakeeping standard series format by Loukakis and Chryssostomidis.¹² At the Center, ship motion data bases have been established for several combatant and merchant ship classes. At present, these data bases include those for the DD-963, CG-26, FF-1052, FFG-7, and FF-1040 classes of naval combatant ships reported by Baitis et al.;¹³ for the C3, C4, C5, and LASH classes of commercial ships;¹⁴ and for several liquid natural gas (LNG) tankers.¹⁵ These ship motion data bases exist only for the specified monohulls. None exist for the other vehicle types of this report.

Baitis¹³ divided motion data for monohulls into three parts as follows:

1. Frequency Domain, Unit Response Amplitude Operator (RAO) Data.
2. Root Mean Square (RMS)/Modal Period of Encounter (TOE)* Data.
3. Time Domain Data.

Each of these parts is discussed in Appendix D.

Although very large amounts of ship motion data can be stored most compactly in the RMS/TOE form, those data are not adequate to determine the actual values of some of the seakeeping criteria that are now or may in the future be imposed on ship motions. For these criteria, ship motion data in the time domain are needed. The disadvantage of the time domain data base is that it requires about 1800 times** as many data points as need to be stored in the RMS/TOE data base to cover the same number of choices of values of input parameters. The number of data points in the RMS/TOE and in the time domain data bases of Baitis' report¹³ are compared in Appendix D. The classes of criteria that can be accurately treated only with ship motion data in the time domain are also described in Appendix D.

In addition to the three parts of the motion data base for monohulls included by Baitis,¹³ a complete motion data base would include a fourth part:

Added Drag and Altered Propulsive Efficiency in a Seaway.

This part of the responses for all of the vehicle types of this report is also discussed in Appendix D.

SEAKEEPING CRITERIA AND THEIR VALUES

The added drag and altered propulsive efficiency in a seaway act to restrict achievable vehicle speeds in moderate sea states. This speed reduction is entirely involuntary involving no voluntary action on the part of the vehicle operator. In more severe seas, one of the vehicle

*TOE is the modal period of encounter whereas $T_o = (2\pi/\omega_o)$ used in Table 1 is the modal wave period.

**A half-hour time record with data points recorded every half second involves 3600 data points, whereas in the RMS/TOE data base only two values, RMS and TOE, are used to characterize the entire spectrum (see Appendix D).

responses or one of the seakeeping events* may induce the vehicle operator voluntarily to reduce speed below that which the vehicle can achieve considering its added drag in a seaway and its altered propulsive efficiency. Figure 3 illustrates the involuntary speed reduction in ahead seas caused by added drag and reduced propulsive efficiency and the voluntary speed reduction caused by two seakeeping events, slamming and deck wetness, for a monohull in two different conditions of loading. Figure 3 also lists all the vehicle and environmental factors that constrain the calm water speed of all interface vehicles.

Both the involuntary and voluntary speed reduction of Figure 3 must be taken account of in calculating the values of Box Scores 2 and 3. This is not true in the case of Box Score 1. Because Box Score 1 is evaluated at a fixed speed (usually well below the maximum speed), the involuntary speed reduction has no influence on its value; only the voluntary speed reduction of Figure 3 is essential because it determines the allowable value of significant wave height for the value of vehicle speed specified for Box Score 1.

In order to determine the magnitude of the voluntary speed reductions for all of the box scores, a host of seakeeping criteria are employed. These criteria comprise certain vehicle responses, certain seakeeping events, and the frequencies at which some of these responses and events occur. The seakeeping criteria discussed in this report are listed in Table 2. For a given vehicle, in a given condition of loading, the prescribed value of only one criterion from this list** will most constrain vehicle heading and speed in a sea of fixed significant wave height and modal period, or will most constrain the allowable significant wave height

*A seakeeping event usually involves the relative motion between the vehicle and the sea surface. It therefore involves both response(s) of the vehicle relative to the earth axes and the sea surface elevation relative to the earth axes. Slamming, deck wetness, propeller emergence, and sonar dome emergence are examples of this type of seakeeping event.

**By coincidence the prescribed value of more than one criterion may simultaneously most constrain the allowable significant wave height to the same value for a fixed value of T_0 . If this occurs, each of these criteria is a governing criterion.

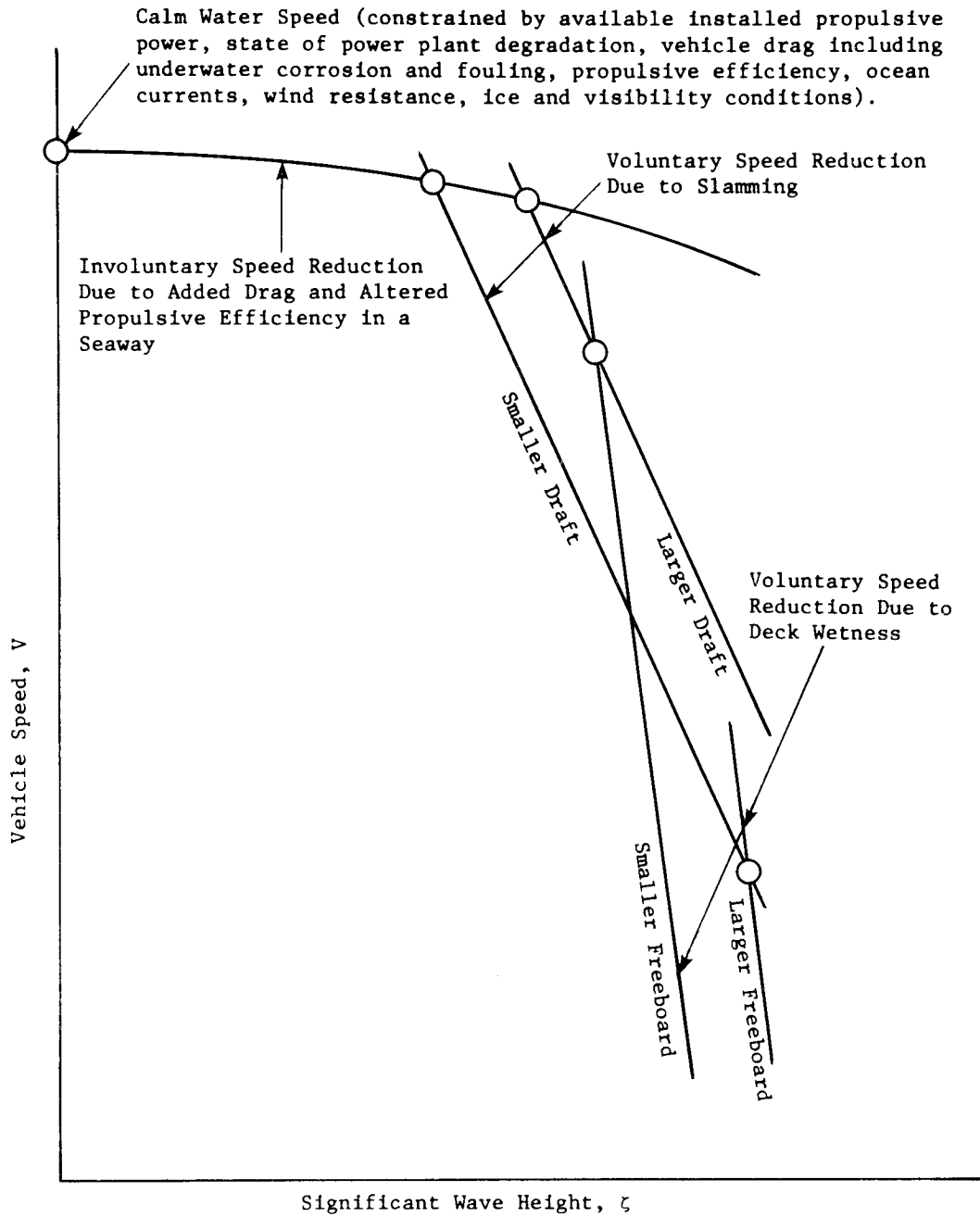


Figure 3 - Involuntary and Voluntary Speed Reduction from Calm Water Speed for a Monohull in Ahead Seas at One Value of Spectral Modal Period

TABLE 2 - SEAKEEPING CRITERIA AND THEIR PRESCRIBED VALUES* FOR VARIOUS VEHICLES AND VEHICLE FUNCTIONS

Source		Olson ¹		Savitsky**	Stark ^{16,17}		Fee**	Wachnik//	Vehicle Function
Column Number	Vehicle	1	2	3	4 Hydrofoil	5	6	7	
		Monohull	SWATH	Planing	Hullborne	Foilborne	SES	ACV	
Criterion Number	Olson ¹ and/or Stark ¹⁶ Criteria	A. VALUES FOR TASK PROFICIENCY AND VEHICLE SUBSYSTEM CRITERIA							
1	Roll Angle ϕ , deg	9.6	9.6	+	3/	1.25/	1.5	3.4/	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
2	Pitch Angle θ , deg	2.4	2.4	+	3/	1.5/	1.5	1.6/	
3	Roll Rate $\dot{\phi}$, deg/sec	+	+	+	2/	2/	+	4.4/	
4	Pitch Rate $\dot{\theta}$, deg/sec	+	+	+	2/	2/	+	2.5/	
5	Yaw Rate $\dot{\psi}$, deg/sec	+	+	+	2/	+	+	+	
B. VALUES FOR LINEAR RIDE QUALITY CRITERIA									
6	Vertical Acceleration \ddot{z}	+	+	+	+	0.11 g***	0.10 g	0.11 g/	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
7	Lateral Acceleration \ddot{y}	+	+	+	+	0.06 g***	0.10 g	+	
8	Motion Sickness Incidence (MSI)	20% of unacclimated males vomit in 2 hours		+	+	10% of unacclimated males vomit in 4 hr		+	
C. VALUES FOR NONLINEAR RIDE QUALITY AND VEHICLE SEAKEEPING CRITERIA									
9	Vertical Acceleration \ddot{z}	0.2 g RMS deceleration	+	0.3 g RMS// deceleration	+	0.5 g peak deceleration	0.6 g peak deceleration	+	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
10	Lateral and Longitudinal Acceleration \ddot{y} and \ddot{x}	+	+	+	+	0.25 g peak deceleration	+	+	
11	Slamming/Wave Contact Frequency	1 slam/2-5 minutes	1 wave contact/2-5 minutes	+	+	1 peak deceleration/minute	1 peak deceleration/minute	+	
D. VALUES FOR MISCELLANEOUS VEHICLE SEAKEEPING CRITERIA									
12	Propeller Emergence	+	RMS displacement to the free surface ≤ 6.4 ft ††	+	+	+	+	+	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
13	Deck Wetness Frequency	1 wetness/2 minutes	+	+	+	+	+	+	
E. VALUES FOR HELICOPTER OPERATIONS SEAKEEPING CRITERIA									
14	Flight Deck Vertical Displacement	2.1 ft (0.61m)	2.1 ft (0.61m)	+	+	+	+	+	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
15	Flight Deck Vertical Velocity	3.5 ft/sec (1.07 m/s)	3.5 ft/sec (1.07 m/s)	+	+	+	+	+	
16	Roll Angle ϕ , deg	3.2	3.2	+	+	+	+	+	
F. VALUES FOR SONAR SEARCH SEAKEEPING CRITERIA									
17	PSEPR'S/Ping ⁺⁺⁺	3/5	3/5	+	+	+	+	+	TRANSIT ALONE TRANSIT PLUS HELICOPTER OPERATIONS TRANSIT PLUS HELICOPTER OPERATIONS PLUS SONAR SEARCH
18	Sonar Dome Submergence	At least 30 seconds		+	+	+	+	+	

*Unless otherwise noted, all values given are single amplitude, RMS values.
 **Reported informally by D. Savitsky on 7/20/78 and J.J. Fee on 3/31/78.
 ***These are frequency weighted values which are not to be exceeded for 90 percent of the operating year (see Table 7).
 †This criterion was not treated for the indicated vehicle in the indicated work.
 ††This dimensional value applies to the 3408 tonne SWATH frigate only¹ (6.4 ft = 1.95 m).
 †††Positive Signal Excess Ping Return.
 //These are not prescribed values. The text discusses these values.
 //DTNSRDC Report in preparation: "SR.N4 Motions" by Z.G. Wachnik and R.D. Pierce.
 //For a mission duration of 4 hours.

for a given modal period* and for a given vehicle speed and heading. This criterion is called the governing criterion. The governing criterion may change as speed, heading, or vehicle function are altered for a single vehicle in a fixed load condition for a fixed modal period. Or it may change with modal period for a fixed vehicle speed, heading, and function. Insuring that the governing criteria are identified for each of these conditions and functions requires individual consideration of the applicable seakeeping criteria. Appendix A, summarizing data from Olson's work,¹ identifies the governing criteria for four monohulls and a SWATH for three different vehicle functions. Appendix B identifies the governing criteria as a function of vehicle speed for three values of vehicle-wave heading angle and four values of modal period for two of the monohulls and the SWATH.

The governing criterion for a given vehicle function, speed, and heading may be different for different vehicles of the same general type and may even be different for the same vehicle in different conditions of loading. The latter point is demonstrated in Figure 3. In a light condition of loading (shallow draft and large freeboard) the governing criterion for a monohull performing the transit function is the slamming criterion for the greater part of the speed regime. Only at very low speeds is the deck wetness criterion governing. However, in a heavy condition of loading (large draft and smaller freeboard), the slamming criterion is governing only at high speed, whereas the wetness criterion is governing in most of the speed range.

*While both significant wave height ζ and modal period T_0 are the two parameters currently used to characterize the sea state, ζ is the prime parameter and T_0 , while important, is a distinctly secondary parameter. T_0 is a secondary parameter because for any possible value of T_0 , there is always a positive allowable value of ζ that will permit vehicle operation at some speed within the vehicle's operating envelope. The opposite is not true. For very large values of ζ , there is no value of T_0 within the bound of possible T_0 values that exist in the ocean ($0 < T_0 < 32$ sec), that will permit vehicle operation. It follows that every allowable value of ζ is a maximum allowable value, whereas the allowable values of T_0 fall within the range of $0 < T_0 < 32$ sec.

In the current state of development, go, no-go (prescribed) values of the criteria (in the nature of highway speed limits) are employed. The basic assumption is that the Commanding Officer will be informed by instruments (like the automobile speedometer) of the actual value of all possibly constraining seakeeping responses and events. When the actual value of any single response exceeds the prescribed criterion value assigned to that response, presumably the Commanding Officer will call for reducing speed and/or changing heading in the case of Box Scores 2 and 3. Or, in the case of Box Score 1, he must acknowledge that the vehicle's assigned functions can be carried out only with significantly decreased effectiveness. In this respect, the prescribed value of a criterion is analogous to the posted speed limit on a highway, whereas the actual value of the criterion is analogous to the speed indicated by the speedometer of an automobile. While the previous section of this report and Appendix D deal only with the actual values of the vehicle responses, this section deals with both the prescribed and the actual values of the seakeeping criteria.

Table 2 lists the 18 seakeeping criteria that either have been used by Olson* to assess the seagoing characteristics of monohulls and a SWATH¹ or were developed by Stark as specifications for hydrofoil design.^{16,17} The same 18 criteria are used for the other vehicle types included in Table 2. Values of the criteria for all vehicle types included in Table 2 were obtained from the sources given at the head of the table. These values are all prescribed values except those accompanied by a check mark. Those with a check mark are discussed later in this section. The reader is further cautioned that a few of the prescribed criteria values given

*Most of Olson's criteria are based on the work of others. A sampling of other reports on seakeeping criteria include those of O'Hanlon and McCauley,¹⁸ Tick,¹⁹ Ochi and Motter,²⁰ Baitis,²¹ St. Denis,²² Hadler and Sarchin,²³ Warhurst and Cerasani,²⁴ Aertssen,²⁵ McMullen Associates,²⁶ Bales,²⁷ and Lloyd and Andrews.²⁸ Most of the references deal with seakeeping criteria for monohulls. Olson's criteria were used in Table 2 because this is the only work that was extended to the calculation of a seagoing box score for a group of monohulls and a SWATH.

in Table 2 have little meaning without an awareness of the locations on the vehicles to which the values are intended to apply. This issue is also addressed in this section.

The criteria of Table 2 are grouped into three vehicle functions and six different categories. Categories E and F are clearly oriented to very specific military vehicle functions. Category D is vehicle oriented and Category C is both ride quality and vehicle oriented. Category B is entirely oriented toward ride quality. Although the first two criteria of Category A have sometimes been incorrectly assumed to be oriented toward motion sickness,* all the Category A criteria are, in fact, oriented toward either fatigue-decreased-proficiency or vehicle subsystem or payload degradation. Clearly Categories A through D (Criteria 1 through 13) apply to the transit function of vehicles. The small sampling of payload related seakeeping criteria (Criteria 14 to 18) utilized by Olson¹ is not intended to be representative of all payload criteria that have been developed.²⁶ Furthermore, there is no assurance that each of the thirteen vehicle and personnel oriented criteria is essential or that all of them taken together are sufficient for the transit function. There is considerable evidence that new criteria not yet evolved are needed. This evidence is presented in this section.

The categories into which the criteria have been subdivided in Table 2 indicate that the nature and the prescribed values of all seakeeping criteria are dependent on three factors:

1. Human Factors (ride quality)
 - a. Comfort
 - b. Motion Sickness
 - c. Personnel Fatigue

*Motion sickness has historically been associated with the rolling of surface ships (the word nausea comes from the Greek word "naus" meaning ship). The research of O'Hanlon and MaCauley¹⁸ has revealed that it is the vertical accelerations associated with roll (and not necessarily the roll angle itself) occurring within the narrow band of frequencies shown in Figure 4 that induce motion sickness. It happens that the natural rolling frequencies of all monohulls are always close to the lower boundary of the band of frequencies as shown in Figure 4 (taken from Table 3). This accounts for the close historical association between roll motion and motion sickness.

TABLE 3 - VALUES OF ROOT MEAN SQUARE VERTICAL ACCELERATION AND FREQUENCY FOR VARIOUS VALUES OF MOTION SICKNESS INCIDENCE AND EXPOSURE

INTERVALS, t_1 ^{18,26}

RMS Vertical Acceleration		Frequency Constraints in Radians/Second Corresponding to:	
m/s ²	g	MSI = 10 Percent, $t_1 = 4$ hours	MSI = 10 Percent, $t_1 = 2$ hours
0.42	0.043	$\omega = 1.07$	-
0.49	0.050	$0.77 < \omega < 1.50$	$\omega = 1.07$
0.50	0.051	$0.79 < \omega < 1.54$	$0.97 < \omega < 1.23$
0.75	0.076	$0.53 < \omega < 2.07$	$0.58 < \omega < 1.97$
1.00	0.102	$0.44 < \omega < 2.54$	$0.50 < \omega < 2.42$
1.50	0.153	$0.39 < \omega < 3.05$	$0.42 < \omega < 2.83$
2.00	0.204	$0.35 < \omega < 3.36$	$0.36 < \omega < 3.20$
2.50	0.255	$0.31 < \omega < 3.64$	$0.33 < \omega < 3.46$
3.00	0.306	$0.27 < \omega < 3.86$	$0.31 < \omega < 3.71$
		MSI = 20 Percent, $t_1 = 2$ hours	MSI = 35 Percent, $t_1 = 2$ hours
0.75	0.076	$\omega = 1.07$	-
1.00	0.102	$0.68 < \omega < 1.76$	-
1.15	0.117	$0.61 < \omega < 1.98$	$\omega = 1.07$
1.50	0.153	$0.50 < \omega < 2.32$	$0.65 < \omega < 1.70$
2.00	0.204	$0.43 < \omega < 2.73$	$0.55 < \omega < 2.18$
2.50	0.255	$0.38 < \omega < 3.03$	$0.47 < \omega < 2.46$
3.00	0.306	$0.35 < \omega < 3.21$	$0.44 < \omega < 2.61$
3.50	0.357	$0.33 < \omega < 3.37$	$0.41 < \omega < 2.76$
4.00	0.408	$0.32 < \omega < 3.52$	$0.39 < \omega < 2.92$
5.00	0.510	-	$0.35 < \omega < 3.19$
6.00	0.612	-	$0.32 < \omega < 3.42$

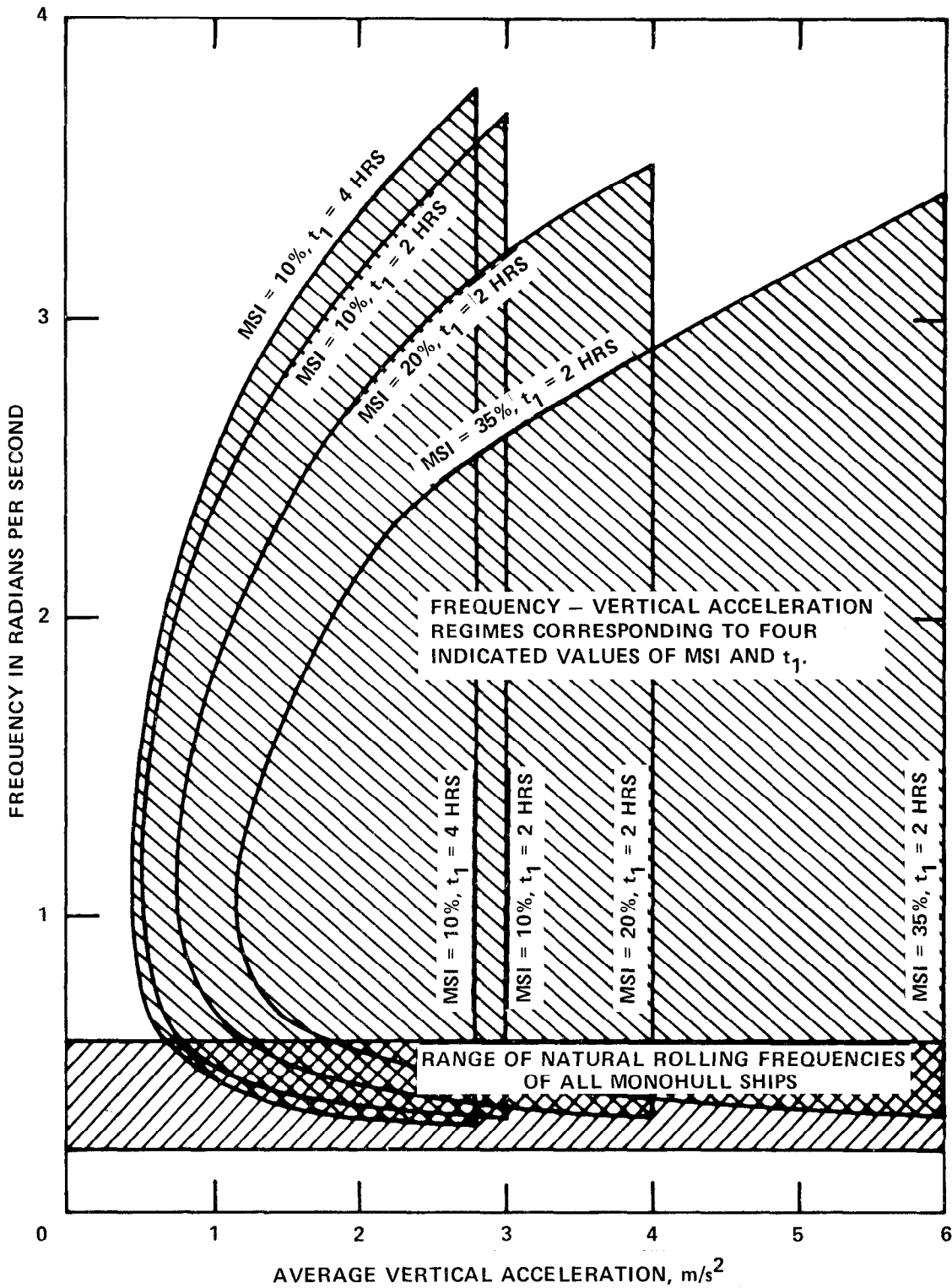


Figure 4 - Frequency-Vertical Acceleration Regimes Corresponding to Four Specified Values of Motion Sickness Index (MSI) and Motion Exposure Time (t_1)^{18,26}

TABLE 3 - VALUES OF ROOT MEAN SQUARE VERTICAL ACCELERATION AND FREQUENCY FOR VARIOUS VALUES OF MOTION SICKNESS INCIDENCE AND EXPOSURE

INTERVALS, $t_1^{18,26}$

RMS Vertical Acceleration		Frequency Constraints in Radians/Second Corresponding to:	
m/s^2	g	MSI = 10 Percent, $t_1 = 4$ hours	MSI = 10 Percent, $t_1 = 2$ hours
0.42	0.043	$\omega = 1.07$	-
0.49	0.050	$0.77 < \omega < 1.50$	$\omega = 1.07$
0.50	0.051	$0.79 < \omega < 1.54$	$0.97 < \omega < 1.23$
0.75	0.076	$0.53 < \omega < 2.07$	$0.58 < \omega < 1.97$
1.00	0.102	$0.44 < \omega < 2.54$	$0.50 < \omega < 2.42$
1.50	0.153	$0.39 < \omega < 3.05$	$0.42 < \omega < 2.83$
2.00	0.204	$0.35 < \omega < 3.36$	$0.36 < \omega < 3.20$
2.50	0.255	$0.31 < \omega < 3.64$	$0.33 < \omega < 3.46$
3.00	0.306	$0.27 < \omega < 3.86$	$0.31 < \omega < 3.71$
		MSI = 20 Percent, $t_1 = 2$ hours	MSI = 35 Percent, $t_1 = 2$ hours
0.75	0.076	$\omega = 1.07$	-
1.00	0.102	$0.68 < \omega < 1.76$	-
1.15	0.117	$0.61 < \omega < 1.98$	$\omega = 1.07$
1.50	0.153	$0.50 < \omega < 2.32$	$0.65 < \omega < 1.70$
2.00	0.204	$0.43 < \omega < 2.73$	$0.55 < \omega < 2.18$
2.50	0.255	$0.38 < \omega < 3.03$	$0.47 < \omega < 2.46$
3.00	0.306	$0.35 < \omega < 3.21$	$0.44 < \omega < 2.61$
3.50	0.357	$0.33 < \omega < 3.37$	$0.41 < \omega < 2.76$
4.00	0.408	$0.32 < \omega < 3.52$	$0.39 < \omega < 2.92$
5.00	0.510	-	$0.35 < \omega < 3.19$
6.00	0.612	-	$0.32 < \omega < 3.42$

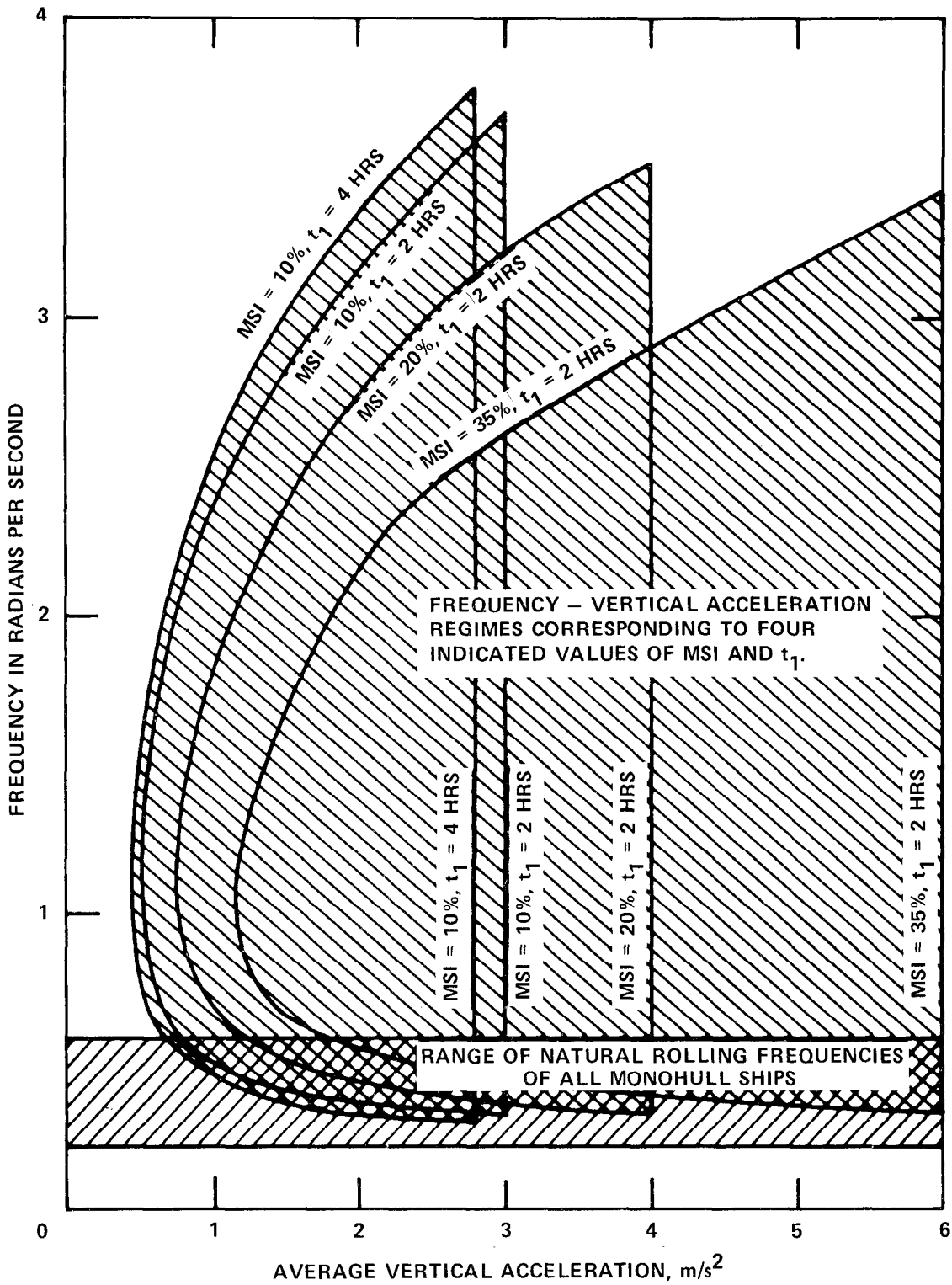


Figure 4 - Frequency-Vertical Acceleration Regimes Corresponding to Four Specified Values of Motion Sickness Index (MSI) and Motion Exposure Time (t_1)^{18,26}

d. Task Proficiency

e. Safety

2. Operational limits of the vehicle payload (for naval ships, this means the weapons and the other combat systems)

3. Operational limits of the vehicle, the vehicle structure, and the subsystems needed by the vehicle, its payload, and its personnel.

The prescribed values of seakeeping criteria developed from factors (1) and (2) should be completely independent of sea, wind, and weather conditions; vehicle type, size, and configuration; location on the vehicle; vehicle operating mode (hullborne or foilborne); or the presence or absence of active motion controls. These values are dependent on vehicle function and may be dependent on mission duration. Prescribed values of seakeeping criteria developed from factor (3) should also be completely independent of sea, wind, and weather conditions, but they are dependent on vehicle function and are likely to be dependent on vehicle features. In contrast to the prescribed values, actual values of the criteria are always dependent on all the environmental and vehicle features, but they are independent of vehicle function.

CRITERIA

Criteria 1 through 7 of Table 2 are ordinary vehicle motions discussed in Appendix D. The Motion Sickness Incidence (MSI), Criterion 8, introduced by O'Hanlon and McCauley¹⁸, is defined as the percent of individuals who would vomit if subjected to motions of prescribed characteristics for a given time interval t_1 . Experiments were reported¹⁸ that yield values of MSI for unacclimated males subjected for various time intervals to a single frequency of vertical sinusoidal motion of varying amplitude a and frequency ω . Values of MSI for various time intervals were plotted as a function of ω and of average vertical acceleration. Thus, the MSI (Criterion 8) imposes a constraint on the vertical acceleration just as (Criterion 6) does, but MSI imposes a frequency constraint as well. The values of these acceleration and frequency constraints are given in Figure 4^{18,26} for the three values of MSI and of t_1 entered in Table 2, and for MSI = 35 percent, $t_1 = 2$ hours as discussed in the second footnote to Table 7.

The slamming/wave contact Criteria 9 through 11 are separately categorized in Table 2 for two reasons. As indicated in Table 2, they apply to vehicle motions that occur in the nonlinear motion domain,* whereas Criteria 6 through 8 apply only to vehicle motions that occur in the linear domain. Secondly, the slamming/wave contact criteria are likely to be ride quality criteria for small vehicles and are likely to be vehicle seakeeping criteria for large vehicles. That is, slamming on large vehicles can cause vehicle and subsystem structural damage before it causes passenger discomfort or injury, whereas on small vehicles it increases personnel fatigue and reduces task proficiency to an unacceptable level before it causes structural damage. The reason for this is discussed later in this section.

The term slamming/wave contact has different connotations depending on the vehicle type to which it is applied. For all vehicle types, slamming is a seakeeping event that involves the sea surface wave elevation as well as one or more vehicle responses. Tick¹⁹ and others postulated that slamming for monohulls occurs when two events occur simultaneously. These two events are:

1. Reentry of the ship's bow into the surface of the ocean after it has risen above the surface of the water, and
2. Relative vertical velocity between the ship's bottom and the water surface in excess of a certain specified value.

In the case of SWATH vehicles, a slam is defined as wave contact with the underdeck of the cross structure of the SWATH. A wave contact is assumed to occur when the average of the 1/10-highest values of the relative vertical displacement between the underdeck of the SWATH and the rough sea surface beneath it exceeds the smooth water clearance to the underdeck. The relative vertical velocity event, which is one of the two conditions of slamming for monohulls, has not been included as a condition for wave contact for SWATH.

In the case of planing craft, a slam is defined as it is for monohulls. In the case of hydrofoils, wave contact is called cresting. The

*Actually Criteria 9 to 11 apply to the boundary between the linear and the nonlinear domain, so that their values are predicted using linear theory.

term slamming is reserved for more severe accelerations. As the foils of a hydrofoil ship come close to the surface of water, they tend to lose lift and, in some cases, this loss of lift is abrupt and lift can momentarily go to zero. This condition is referred to as foil broaching. For severe broaches, fairly large downward accelerations can occur. Subsequent to a foil broach, the hull may slam into the oncoming wave crest. The upward accelerations associated with hull slamming (called slamming decelerations in Table 2) may be, and typically are, larger than the downward accelerations associated with broaching. The actual values of these positive acceleration peaks can become the constraining limit on hydrofoil operations in very heavy seas.

SES's and ACV's also experience slamming. In heavy seas, the pitch angle of these vehicles may become so large that there is leakage of cushion air from under the bow seal. If this occurs, the large downward acceleration of the bow will likely cause slamming.

The prescribed values of Criterion 9 given in Table 2 for monohulls, planing craft, hydrofoils, and surface effect ships are identified by two descriptors. Those for monohulls and planing craft are identified as single amplitude RMS decelerations; those for hydrofoil and surface effect vehicles are identified as peak decelerations. RMS values are used to characterize random or sinusoidal responses, but they are not used to characterize discrete events like slamming for which peak values are more appropriate. In the case of the monohull, slamming introduces large impact pressures acting on a limited area of the ship's bottom which may cause ship structural damage, or it may introduce large whipping stresses in the ship's hull. However, slamming generates smaller relative upward acceleration peaks on large monohulls than on smaller vehicles because of the usually larger size of monohulls and because their hull shape usually severely limits the hull area impacted by a slam.

Actual RMS values for Criterion 9 for monohulls, leading to the prescribed value given in Table 2, were calculated from spectral analysis of

vertical acceleration readings taken during the trials of a large container ship and reported by Aertssen.²⁵ During these trials the sea state was such that the Commanding Officer decided to slow the ship down for fear of slamming damage to the hull. The actual RMS vertical acceleration value occurring in this sea state was taken as the prescribed value of Criterion 9. Clearly the vertical acceleration time history from which this actual RMS value was calculated was composed of a mixture of acceleration values, some of which were induced by slamming but most of which were induced by ordinary oscillatory ship motions.

With planing craft, slamming introduces very large upward accelerations at very frequent intervals even in moderately rough seas. A small sample of a planing craft vertical acceleration time history in head seas is shown in Figure 5. The more frequent, larger upward accelerations, as compared to those of a monohull, are attributable to three planing craft features:

1. Their relatively low deadrise hull shape, which results in a relatively large slamming impact area compared to a monohull.
2. Their small size, which makes them much more responsive to impact loads.
3. Their high speed, which increases the frequency of wave encounter and of slamming in head seas.

Figure 5 shows an interval of only 1.7 seconds between two slams of a planing craft, or a frequency of 35 slams/minute. This should be compared to the prescribed slam frequency (Criterion 11) value of 0.2 to 0.5 slams per minute for monohulls, given in Table 2. Because the upward slamming accelerations on a planing craft are so frequent and so large, their Criterion 9 value is dictated by human fatigue and proficiency considerations rather than by fear of hull damage as it is on large monohulls.

The long term time history of planing craft motions, of which Figure 5 is a very brief sample, can be converted into spectral form, from which an actual RMS value can be calculated by routine means just as it was for the containership of Reference 25. Again as with the containership, this actual value is composed neither of purely discrete slam accelerations nor

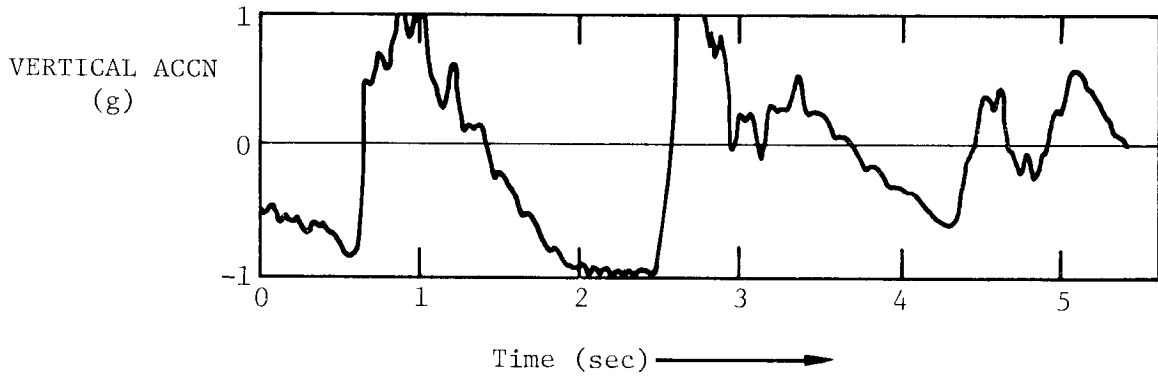


Figure 5a - Planing Craft

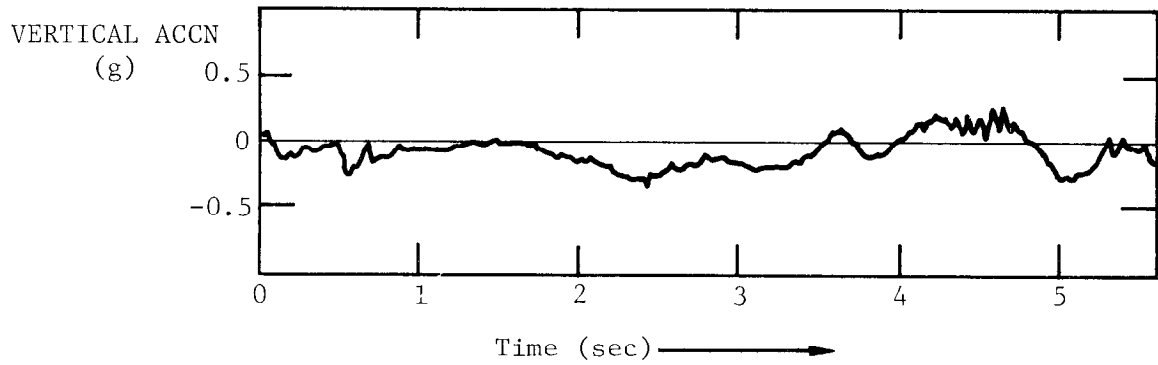


Figure 5b - Hydrofoil

ITEM	SYMBOL	UNITS	PLANING CRAFT	HYDROFOIL (foilborne)
Vehicle Displacement	Δ	Tonnes	73	136
Vehicle Speed	v	Knots	38	38
Significant Wave Height	ζ	Meters	5	10
Non-Dimensional Significant Wave Height	$\zeta/(\Delta/\rho)^{1/3}$	—	1.206	1.961

Figure 5 - Typical Time Histories of the Vertical Acceleration of a Planing Craft and a Hydrofoil in Head Seas

of purely random motion accelerations; rather it is a mixture of both. However, on the basis of Figure 5, it is perhaps correct to say that slamming accelerations make the major contribution to the actual value of Criterion 9 for planing craft.

As on the planing craft, slamming accelerations on hydrofoil* and surface effect ships are very distinct events. Like monohulls, but unlike planing craft, slamming accelerations on hydrofoil and surface effect ships occur quite infrequently. Because slam accelerations are a very distinct, infrequent event on hydrofoils and surface effect ships, it is proper to express the prescribed limiting value on slamming acceleration in terms of a peak, rather than an RMS value, on these two vehicle types.

Criteria 1 through 10 of Table 2 apply to vehicle motions and the equations needed to calculate their actual (not prescribed) values from frequency domain data are described in Appendix D. The equation needed to calculate the actual values of Criteria 11, 12, and 13 is discussed in the next paragraphs.

The two simultaneous events that define slamming for monohulls (bow reimmersion and exceedance of a threshold vertical velocity) are a function of wave elevation ζ , wave vertical velocity $\dot{\zeta}$, ship vertical displacement z , and ship vertical velocity \dot{z} , all measured at a location near the bow of the ship.** The frequency of the simultaneous occurrence of these two events can be counted directly, using data from the time domain data base. Alternatively, since the two events are not independent of one another,*** the frequency of their occurring simultaneously can also be calculated from information in the frequency domain. The equation²⁰ for the actual frequency of slamming of monohulls, which uses information from the frequency domain, is:

$$N_s = \left[\frac{\text{RMS}_{\dot{\zeta}\dot{z}}}{2\pi \text{RMS}_{\zeta z}} \right] \left[e^{-[T^2/\text{RMS}_{\zeta z}^2 + v^*/\text{RMS}_{\dot{\zeta}\dot{z}}^2]} \right] \quad (2)$$

*The hydrofoil depicted in Figure 5 experienced no slams in the indicated time history.

**This location for slamming for monohulls is assumed to be aft of the bow by 15 percent of the ship length.

***See the third part of Appendix D.

where N_s = number of slams per unit time

$RMS_{\zeta_z}^*$ = RMS value of relative vertical velocity between a point on the ship's keel, 15 percent of the ship's length aft of the bow, and a point on the ocean surface immediately below or above the first point

RMS_{ζ_z} = RMS value of the relative vertical displacement between the same two points

e = exponential e

T = ship draft at location where $RMS_{\zeta_z}^*$ and RMS_{ζ_z} are measured

v^* = threshold relative vertical velocity for slamming*

The first bracketed factor in Equation (2) is the frequency of encounter of the ship with the waves. The second bracketed factor is the probability of occurrence of slamming. This is the slamming criterion used by Bales.²⁷ Bales²⁷ prescribed Criterion 11 value is 4 slams in 100 ship-wave encounters. Aertssen's prescribed value is 3 slams in 100 ship-wave encounters,²⁵ which corresponds to about 1 slam every 2 to 5 minutes.

(Statistics other than the frequency of slamming may be more meaningful. Examples of other statistics are the most probable time interval between successive slams and the probability that the time interval between two successive slams will be smaller than a given interval, \dot{t}^* . Psaraftis²⁹ uses the latter statistic to obtain an approximation to the probability that the ship will experience a sequence of N slams separated from one another by an interval shorter than \dot{t}^* . These statistics appear more meaningful than slamming frequency since they are more directly related to the decision of the ship operator to reduce speed or change heading when the ship experiences slamming.)

Equation (2) also applies directly to calculating the wave contact frequency (Criterion 11) for SWATH ships, if the RMS values of Equation (2) are converted to the average of the one-tenth-highest values** and if the symbols of Equation (2) are given the following definitions:

*Ochi's²⁰ value of this velocity is 12 ft/sec (3.66 m/s) for a 520 ft (158 m) ship. Froude scaling is used for ships of different length.

**For normally distributed events, the average of the one-tenth-highest value is 2.55 times as large as the RMS value.

N_s = number of wave contacts per unit time

$RMS_{\dot{\zeta}_z}$ = RMS value of the relative vertical velocity between a point on the underdeck of the SWATH cross-structure, 15 percent of the SWATH length aft of its leading edge, and a point on the ocean surface immediately below the point on the SWATH

RMS_{ζ_z} = RMS value of the relative vertical displacement between the same two points

T = Calm water clearance between the same two points (= 18 ft (5.49 m) for the SWATH of Reference 1)

$\frac{*}{v}$ = 0

Equation (2) is also useful for calculating the actual values of the frequencies of propeller emergence and of deck wetness, Criteria 12 and 13 of Table 2. Actual values of these criteria, like those of Criterion 11, can be calculated either from the time domain or from the frequency domain data bases. In the case of the propeller emergence (Criterion 12) used for SWATH vehicles, a propeller emergence is assumed to occur when the maximum significant vertical displacement between the surface of the waves and the propeller results in the upper 25 percent of the radius of a vertical propeller blade emerging from the water. The number of propeller emergences per unit time can then be calculated from Equation (2), if the RMS values of Equation (2) are converted to significant values* and if the symbols used in Equation (2) are assumed to have the following definitions:

N_s = number of propeller emergences per unit time

$RMS_{\dot{\zeta}_z}$ = RMS value of relative vertical velocity between the propeller hub and a point on the ocean surface immediately above the hub

RMS_{ζ_z} = RMS value of relative vertical displacement between the same two points

T = Draft to the 25 percent propeller blade radius point in the upper vertical position in calm water (= 12.8 ft (3.9 m) for the SWATH of Reference 1)

$\frac{*}{v}$ = 0

*For normally distributed events, the significant value (average of the one-third-highest value) is twice as large as the RMS value.

In the case of the frequency of deck wetness, Criterion 13, the changes in symbol definition needed from those used for slamming are:

N_s = number of deck wetnesses per unit time

T = ship freeboard at a location 15 percent of the ship length aft of the bow

$\frac{v^*}{v} = 0$

Olson applied Criterion 13 to monohulls but not to SWATH's, because wave contact will always occur long before deck wetness for SWATH's.

Deck wetness is simultaneously a vehicle seakeeping criterion as well as a payload dictated criterion.* Water on the deck may, in extreme cases, cause ship structural damage as well as increased risk of material damage to missile launchers, gun mounts, magazines, and fire control systems. It is important to note that the actual values of slamming, propeller emergence, deck wetness, and sonar dome submergence criteria are all quite sensitive to the condition of loading and trim of the ship. Small, operationally feasible changes in trim may alter significantly the actual values of these criteria (not the prescribed values entered in Table 2).

The vertical displacement, vertical velocity, and roll angle (Criteria 14 through 16) are payload dictated criteria postulated by Baitis²¹ because they are important for V/STOL** and helicopter take-off and landing. Since these operations are carried out with the wind over the deck coming from within ± 20 deg of directly ahead, these criteria should be applied primarily to head and bow quartering seas. The PSEPR***/ping (Criterion 17) is also a payload-dictated criterion developed by Olson¹ for the sonar search mission. Criterion 17 states that a certain number of excess ping returns are required for each ping sent out before sonar detection becomes possible. In order to receive a ping return, the sonar dome must remain submerged during the time interval t between ping emission and ping return. This time interval of 30 seconds assigned to Criterion 18 in Table 2 was selected

*Some might also view it as a ride quality criterion.

**Vertical and Short Take-Off and Landing (aircraft).

***Positive Signal Excess Ping Return.

by Olson¹ on the basis of an assumed maximum sonar range of 10 miles. Olson applied Criteria 17 and 18 to monohulls but not to SWATHs because on SWATH the sonar dome is so deep that it never emerges.

Criteria related to the four vehicle functions treated by Olson¹ for monohulls and SWATHs are included in Table 2. These four functions and their applicable seakeeping criteria are summarized in Table 4. Olson included no weapons systems criteria because no reliable criteria for these

TABLE 4 - FOUR VEHICLE FUNCTIONS TREATED IN REFERENCE 1 AND THEIR SEAKEEPING CRITERIA

No.	Function	Applicable Criteria
1	Transit Alone	1, 2, 8, 11, 12, and 13
2	Transit and Helo Operations	1, 2, 8, 11, 12, 13, 14, 15, and 16
3	Transit and Sonar Search	1, 2, 8, 11, 12, 13, 17, and 18
4	Transit, Helo Operations, and Sonar Search	1, 2, 8, 11, 12, 13, 14, 15, 16, 17, and 18

functions have been developed.²⁶ One of the important issues involved in weapon accuracy is that the flexural responses of the vehicle structure are important as well as the rigid body responses of the vehicle as a whole. Because of the complexity of the relation between gun and/or missile accuracy and ship motions, this topic has remained relatively unexplored until some recent work by Rockwell International³⁰ under NAVSEA and NAVSEC sponsorship. A joint NAVSEA-DTNSRDC-Rockwell project to explore this important issue further is planned.

Just as the criteria of Table 2 do not address any weapons system performance requirements, so too, at least one known severe limit on monohull performance in the transit function is not addressed. In moderate to severe stern seas, monohulls experience a coupled yaw and heel motion. This motion can affect a number of shipboard functions and in its worst manifestation can result in the ship turning broadside to the waves and

possibly capsizing. This is an acknowledged, severely limiting seakeeping event, but no calculating techniques or criteria have been developed to deal with it. One of the difficulties is that in very severe astern seas there is always a degradation in the ability to control heading. As a result of Olson's¹ inability to address this phenomenon*, his work shows practically unrestricted operation of monohulls performing the transit function in heavy astern seas (see Figure B.6). This, in the opinion of experienced ship operators, is not realistic.

LOCATIONS AT WHICH THE PRESCRIBED VALUES OF THE CRITERIA APPLY

Location on the vehicle has no bearing whatever on either the actual or the prescribed values of six of the criteria of Table 2. These are Criteria 1 through 5 and 16. This is so because these criteria values apply to angular motions which are independent of location. Location has a bearing on the actual values of all the other criteria. Location may also have a bearing on the prescribed values of a few of the criteria. The following three principles should govern whether the prescribed value of a criterion changes with location:

1. All prescribed values of ride quality criteria, whether based on motion sickness, fatigue-decreased-proficiency, safety, or comfort should be applicable to any location occupied by personnel and should not, a priori, be constrained to a specific location on a vehicle.

2. All prescribed values of payload related seakeeping criteria should be applicable to any location on the vehicle where it is desirable to locate the payload and should not, a priori, be constrained to specific locations on a vehicle.

3. The prescribed values of certain seakeeping criteria related to specific vehicle types are constrained to certain locations on the vehicle.

The locations of the prescribed values of Criteria 6 through 15 and 17 and 18, as specified in the sources of the values of Table 2, are given in Table 5.

*He could not address this issue because the whole community of individuals concerned with the performance of vehicles in rough seas has not dealt with this issue.

TABLE 5 - LOCATIONS ON VEHICLE AT WHICH PRESCRIBED CRITERIA
VALUES OF TABLE 2 APPLY

Vehicle Type	Table 2 Prescribed Criterion Value*	Location at which Prescribed Criterion Value Applies (Taken from sources of Table 2 values)
Criterion 6 Ride Quality Vertical Acceleration		
Hydrofoil	0.11 g	Any location that personnel occupy**
SES	0.10 g	Any location that personnel occupy**
ACV	0.11 g***	Longitudinal location of the vehicle center of gravity
Criterion 7 Ride Quality Lateral Acceleration		
Hydrofoil	0.06 g	Any location that personnel occupy**
SES	0.10 g	Any location that personnel occupy**
Criterion 8 Motion Sickness Incidence (MSI)		
Monohull and SWATH	20 percent-2 hr	Any location that personnel occupy**
Hydrofoil	10 percent-4 hr	Any location that personnel occupy**
SES	10 percent-2 hr	Any location that personnel occupy**
Criterion 9 Nonlinear Vertical Acceleration		
Monohull	0.20 g	15 percent of ship length aft of bow
Planing Craft	0.30 g for 4 hr	Any location that personnel occupy**
Hydrofoil	0.50 g (peak value)	Any location that personnel occupy**
SES	0.60 g (peak value)	Any location that personnel occupy**
Criterion 10 Nonlinear Lateral and Longitudinal Acceleration		
Hydrofoil	0.25 g (peak value)	Any location that personnel occupy**
Criterion 11 Slamming/Wave Contact Frequency		
Monohull	1 per 2 to 5 min	Slamming assumed to occur 15 percent of ship length aft of bow
SWATH	1 per 2 to 5 min	Wave contact assumed to occur 15 percent of ship length aft of bow
Hydrofoil	1 per min	Any location that personnel occupy**
SES	1 per min	Any location that personnel occupy**
Criterion 12 Propeller Emergence		
SWATH	6.4 ft	Longitudinal location of the propeller
Criterion 13 Deck Wetness Frequency		
Monohull	1 per 2 min	Deck wetness measured at 15 percent of ship length aft of bow
Criterion 14 Flight Deck Vertical Displacement		
Monohull and SWATH	2.1 ft	Bull's eye on helicopter deck
Criterion 15 Flight Deck Vertical Velocity		
Monohull and SWATH	3.5 ft/sec	Bull's eye on helicopter deck
Criterion 17 PSEPR'S/PING		
Monohull and SWATH	3 out of 5	Longitudinal location of the sonar dome
Criterion 18 Sonar Dome Submergence		
Monohull	30 sec	Longitudinal location of the sonar dome
<p>*Unless otherwise noted, values given for Criteria 6,7,9,10,12,14, and 15 are single amplitude RMS values.</p> <p>**No constraint on location is given in the sources listed in Table 2.</p> <p>***This value, as noted in Table 2, is an actual, not a prescribed, criterion value. It was measured on the trials of an ACV at the location given in this table.</p>		

According to the criteria categories given in Table 2, Criteria 6 through 8 are clearly ride quality criteria and the locations of their prescribed values should abide by the first principle. Table 5 shows that, with the exception of the ACV value (which is an actual, not a prescribed, criterion value), none of the sources of Table 2 specified locations for Criteria 6 to 8, indicating that the locations of the given prescribed values are in accord with the first principle. Criteria 12 and 13 are clearly vehicle related seakeeping criteria and the locations of their prescribed values in Table 5 abide by the third principle. Similarly Criteria 14, 15, 17, and 18 are payload related seakeeping criteria and the locations of their prescribed values in Table 5 abide by the second principle.

It was noted earlier that Criteria 9 through 11 are ride quality criteria for small vehicles and vehicle seakeeping criteria for large vehicles. Because all built and tested hydrofoil and SES vehicles are in the small vehicle category, their prescribed values of Criteria 9 and 10 are based on considerations of personnel fatigue and task proficiency and not on structural failure. On the other hand, the prescribed values of these criteria for the much larger monohulls and SWATH's are based, in part, on the loads that their structures will accept. It follows, therefore, that the locations associated with the prescribed values of Criteria 9 to 11 follow the first principle for planing, SES, and hydrofoil vehicles, and the third principle for monohulls and SWATH's.

The prescribed values of Criteria 9 to 11 for hydrofoil craft were based on measurements of actual values at the location of the pilot house on the USS TUCUMCARI and the location of the forward foil on the USS HIGH POINT.¹⁷ However, with these measurements as technical substantiation,¹⁷ Stark arrived at the prescribed criteria values given in Table 2¹⁶ and in no way confined the locations at which the values apply.

PRESCRIBED VALUES OF THE CRITERIA

In this section, the prescribed value assigned to each criterion of Table 2 for each vehicle will be discussed. Three issues will be addressed for each vehicle type:

1. The different purposes that led to the specification of the values given in Table 2 for each vehicle type.
2. The substantiation of the values given in Table 2.
3. Basic differences in the seagoing properties of the vehicle types included in Table 2 that cannot be reflected by criteria values.

For Monohulls and SWATH's

Olson's purpose in specifying prescribed values for the seakeeping criteria for monohulls and SWATH's was to determine the upper tolerable limit of significant wave height as a function of vehicle speed. He did this for four combatant monohulls, the DD-963, CG-26, FF-1052, and FFG-7,¹³ and a single 3350-ton SWATH frigate³¹ for the four vehicle functions listed in Table 4. The seakeeping criteria of Table 2 that apply to each of the four functions are given in that table.

Table 6 designates where discussion of the prescribed values of each of the criteria listed in Table 4 for monohulls and SWATH's may be found and also summarizes Olson's substantiation for each prescribed value.

There is speculation that the prescribed value of Criterion 1 for monohulls in Tables 2 and 6 is large because monohulls, by their nature, have larger roll angles than those of the other vehicle types and that these larger values have been adopted as a prescribed criterion value for this reason. This may or may not be so. Fortunately, the prescribed value for roll angle in Criterion 16 for monohulls and SWATH's is in accord with the smaller prescribed values of Criterion 1 for hydrofoils, SES's, and ACV's, although for very different reasons (see Table 6). Therefore, Olson's results¹ are still useful even if a small prescribed value is imposed on roll angle.

Results in Figure A.1 of Appendix A show that Criterion 1, even with its liberal prescribed value, is governing for most of the monohulls of Reference 1 performing the transit-alone or transit plus sonar search functions at ship-wave heading values of $50 \text{ deg} < \mu < 82 \text{ deg}$.^{*} When the

^{*}At $\mu = 75$ degrees, Criterion 1 is governing for 77 of the 80 monohull cases treated in Figure A.1.

TABLE 6 - PRESCRIBED CRITERION VALUE SUBSTANTIATION FOR MONOHULL AND SWATH SEAKEEPING CRITERIA

Criterion			Page No. in Olson's Report ¹	Prescribed Criterion Value Substantiation ¹	Criterion Category
No.	Symbol	Value			
1	ϕ	9.6 deg	10	"...an average roll of 12-deg single amplitude was selected as a motion criterion reflecting consideration of personnel effectiveness." 12 deg/1.25 = 9.6-deg RMS roll.	Task Proficiency
2	θ	2.4 deg	12	"A corresponding pitch criterion was chosen to be 3-deg average single amplitude pitch. While we found no specific pitch criterion based on consideration of human effectiveness, a 3-deg pitch is frequently cited as an operational limit on ship sub-systems such as replenishment-at-sea equipment." 3 deg/1.25 = 2.4-deg RMS pitch.	Operational Limits of Vehicle Sub-systems
8	MSI	20% after 2 hr exposure	D-3	"The developers of MSI found that...individuals who did not vomit within $t_1 = 2$ hours, rarely did during subsequent prolonged exposure." The 20 percent value is not substantiated.*	Motion Sickness
9	\ddot{z}	0.2 g	B-19	Aertssen ²⁵ states that a commercial ship captain will slow down or alter course, if the significant vertical acceleration exceeds 0.4g at the bow; 0.4g/2 = 0.2 RMSg. (Bales ²⁷ suggests a slightly higher value of 0.275 RMSg.)	Vehicle Structural Damage
11	N_s	1 per 2 to 5 min	8,9,16	Aertssen ²⁵ states that a commercial ship captain will slow down or alter course, if a severe slam occurs more frequently than 3 times in 100 cycles. This is equivalent to 1 slam every 2 to 5 minutes. (Bales ²⁷ suggests 4 times in 100 cycles.)	Vehicle Structural Damage
11	N_s	1 per 2 to 5 min	16	The 3350-ton SWATH ¹ was designed with an 18-ft clearance between the smooth water surface and the underdeck. Lamb ³¹ suggests that the 1/10-highest displacement of the relative motion between the SWATH and the waves also be limited to 18 ft; 18/2.55 = 7.1-ft RMS clearance. This is roughly the equivalent of one significant wave contact every 2 to 5 minutes.	Vehicle Structural Damage
12	Propeller Emergence		17	The 3350-ton SWATH ¹ was designed so that a relative vertical displacement of 12.8 ft between the smooth water surface and the propeller would expose 25 percent of the propeller radius in the vertical position. The maximum significant relative vertical displacement between the propeller and the waves was also taken as 12.8 ft; 12.8 ft/2 = 6.4-ft RMS displacement.	Operational Limit on Vehicle
13	N_s	1 per 2 min	9	"...it is suggested that ships rarely choose to take green water over the bow more than once every 2 to 5 minutes especially if gun mounts, missile launchers, or major deck equipment are located forward." One wetness every two minutes was selected by Olson ¹ . (Bales ²⁷ suggests 4 deck wetnesses in 100 cycles.)	Vehicle Structural Damage; Possible Material Damage to Weapons Systems
14	ϕ	3.2 deg	15	The values for these three criteria were stated by Baitis. ²¹ The first is specified as 12.8-deg double amplitude significant roll; 12.8 deg/4 = 3.2-deg RMS roll. The second is specified as 8.34-ft double amplitude significant displacement; 8.34/4 = 2.1-ft RMS. The third is specified as 7-ft/sec significant vertical velocity of the flight deck; 7/2 = 3.5-ft/sec RMS velocity.	Helicopter Operation Limits
15	z	2.1 ft	15		
16	\dot{z}	3.5 ft/sec	15		
17	PSEPR/Ping	3-out-of-5	B-32	PSEPR/Ping of 3-out-of-5 is a commonly accepted sonar performance criterion according to Olson.	Sonar Search Operation Limits
18	t	30 sec	B-32	The value $t = 30$ seconds is based on a sonar search range of 10 miles.	Sonar Search Operation Limits

*See second footnote of Table 7.

transit plus helicopter function (see Figure A.3) is performed, Criterion 16 replaces Criterion 1 as the governing criterion at those headings and extends its dominance to $40 \text{ deg} < \mu < 98 \text{ deg}$.

On the basis of earlier observations concerning roll angle, the large prescribed value of Criterion 1 for monohulls and SWATH's in Table 2 should have no influence on motion sickness. This is so provided the prescribed values of the vertical acceleration (Criterion 6) and MSI (Criterion 8) are not violated.

Although the prescribed values of the seakeeping criteria applied to monohulls and SWATH by Olson are virtually identical, the seagoing qualities of the two vehicles are vastly different. The SWATH's motions are far less strongly coupled to the sea surface than are the monohull's motions. The period of most SWATH motions is longer and the SWATH's motion in head seas of fixed severity will generally decrease with increasing speed, whereas a monohull's motions increase with increasing speed.* In stern seas, the SWATH without active motion controls may have more severe motions than the monohull (see Figures B.6 and B.7) but, as far as it is known, SWATH's do not experience the yaw-heel difficulties in severe astern seas described for monohulls.

For Planing Craft

The slamming acceleration (Criterion 9) is considered the sole governing criterion for planing craft at their higher speeds (above about 30 knots for a 100-tonne vehicle). The prescribed value of Criterion 9 given in Table 2 is used to assess the seakeeping performance of planing craft designed in the U.S. Navy today. Since a value of 0.3 RMSg corresponds to an average 1/10-highest value of lg ,** it is evident from Table 2 that the

*Below the speeds of the supercritical zone of operation. The speeds of this zone are above the maximum speeds of the monohulls treated by Olson.¹

**The factors used in Table 6 to convert RMS values to average, significant, or average of 1/10-highest values are based on the assumption that the responses of Table 6 conform to a Raleigh (normal) distribution.

Fridsma³² found that planing craft vertical accelerations are not distributed in accordance with the Raleigh distribution. Fridsma developed an exponential distribution which yields a factor of 3.3 between the average of 1/10-highest values and the RMS value compared to a factor of 2.55 for the Raleigh distribution.

values of Criterion 9 for monohulls, hydrofoils, and surface effect ships are considerably below that for planing craft. Clearly the personnel who ride planing craft are expected to experience more fatigue than personnel on other vehicle types. In recognition of this fact, a mission duration of only 4 hours is associated with the value of Criterion 9 for planing craft in Table 2. Since no mission duration is mentioned in connection with the other vehicle types in Table 2, their prescribed values of Criterion 9 are not conditioned by it.

The fact that the slamming upward acceleration value is used as the sole means for assessing the seagoing characteristics of high speed planing craft is of great interest. Evidently, because slamming accelerations occur so frequently with planing craft and are so severe, other seakeeping events do not constrain its operations. For example, motion sickness does not appear to be an issue in high speed planing craft ride qualities at all, probably because the low frequency motions in the linear range that induce seasickness are scarcely perceived by planing craft personnel subjected to very frequent, high level slamming accelerations.

For Hydrofoils

Of the advanced vehicle types included in Table 2, only hydrofoil ships have had the benefit of a concerted criteria development effort. Stark specifies criteria and prescribed criteria values for hydrofoil ship control and dynamics for the transit-alone function in one volume¹⁶ and offers technical substantiation of the values in a second volume.¹⁷ Along with specifying prescribed values for each of the seakeeping criteria of hydrofoil ships for the transit function, Stark¹⁶ also specifies (independently) that none of these values should be exceeded for 90 percent of the operating days of the year for operation at a worst case heading relative to the sea. The latter specification is the equivalent of stating that the value of Box Score 1 should be at least 90 percent for the transit function. Functions other than transit are alluded to by Stark only because his criteria are properly intended to apply to the design of hydrofoil ships, independent of the particular payload that will be installed

on them. Table 7 summarizes the substantiations given by Stark¹⁷ for the prescribed criteria values for hydrofoil ships given in Columns 4 and 5 of Table 2.

The substantiations given for the values of Criteria 1 through 4 are similar for both the hullborne and foilborne conditions, yet the values for roll angle and pitch angle are quite different. This may be because smaller roll and pitch angles are much more readily achievable in the foilborne condition than in the hullborne condition. Stark emphasizes that he does not view the values he gives for Criteria 1 through 5 as prescribed values; rather he views them as design guidelines. For that reason they are designated as not being prescribed values in Table 2.

It is significant that Stark^{16,17} chose to call Criteria 1 through 5 "Motion Criteria" rather than "Ride Quality Criteria." Stark's substantiations for the values of these criteria given in Table 7 are based largely on unspecified weapon requirements rather than on task proficiency or motion sickness. Stark clearly does not view Criteria 1 through 5 as ride quality criteria for hydrofoils. On the other hand, results reported by Warhurst and Cerasani²⁴ show that roll angle strongly influences task proficiency on surface ships.

The prescribed values of the hydrofoil ride quality Criteria 6, 7, and 8 of Table 2 are more firmly substantiated in Table 7 than the values of Criteria 1 through 5 on the grounds of motion sickness and task proficiency. The values of the vertical and horizontal acceleration (Criteria 6 and 7) are described in Tables 2 and 7 as being frequency weighted. In the earlier discussion of the MSI (Criterion 8), it was noted that the prescribed vertical acceleration values are frequency dependent. In the past, actual RMS values of vertical acceleration were calculated from measurements during vehicle trials and recorded, but the frequency of their occurrence was not recorded. Therefore a dilemma arises today as to what frequency should be used with these RMS values in order to compare them with the frequency dependent, vertical acceleration values imposed by the prescribed value of MSI.

TABLE 7 - PRESCRIBED CRITERION VALUE SUBSTANTIATION FOR
HYDROFOIL SEAKEEPING CRITERIA

Criterion			Page No. of Stark, Volume 2 ¹⁷	Prescribed Criterion Value Substantiation ¹⁷	Criterion Category
No.	Symbol	Value*			
1 2 3 4 5	ϕ θ $\dot{\phi}$ $\dot{\theta}$ $\dot{\psi}$	3 deg 3 deg 2 deg/sec 2 deg/sec 2 deg/sec	68	These values are for the hullborne condition. They are suggested as good practice guidelines and within the capabilities of hydrofoil ships. Specific requirements from actual combat systems should supercede these values when they are available.	Weapon Accuracy
1 2 3 4	ϕ θ $\dot{\phi}$ $\dot{\theta}$	1.25 deg 1.5 deg 2 deg/sec 2 deg/sec	43-46	These values are for the foilborne condition. They are suggested as guidelines for subsequent combat system requirements, for crew proficiency in rough water and to constrain structural loads on equipments located at ship extremities.	Weapon Accuracy, Task Proficiency and Structural Loads on Vehicle Subsystems
6	\ddot{z}	0.11 g	37-43	This is a frequency weighted RMS value for the foilborne condition. Above 1 hertz, the frequency weighted decreased proficiency curve of MIL-STD-1472B (see Figure 6) was taken for a 4-hour exposure limit. Between 0.1 and 0.2 hertz, the vertical accelerations corresponding to MSI = 10 percent after 4-hours exposure were used. (See Figure 6.)	Task Proficiency and Motion Sickness
7	\ddot{y}	0.06 g	43	This is also a frequency weighted RMS value for the foilborne condition. Substantiation is the same as for Criterion 6 except below 1 hertz, the decreased proficiency curve of MIL-STD-1472B (see Figures 3.2-14 of Reference 17) for a 4-hour exposure limit was extended at a constant level.	Task Proficiency
8	MSI	10 percent after 4-hours exposure	41	MSI = 10 percent was selected because it is a reasonable level for the total young male population. There are some chronic motion sickness subjects who get sick at lesser levels of acceleration. If acclimatization were considered (it was not treated by O'Hanlon et al. ¹⁸) the prescribed value of MSI for a hydrofoil operating crew would be greater than 10 percent.** The 4-hour exposure limit coincides with the standard 4-hour watch period.	Motion Sickness
9 10	\ddot{z} \ddot{y}	0.5 g 0.25 g	25-32	These values are given on page 23 of Volume 1. ¹⁶ The value of Criterion 9 is substantiated on page 32 of Volume 2. ¹⁷ It is based on measured peak accelerations during a slam-after-a-broach on the USS TUCUMCARI.	Task Proficiency
11	N_s	1/min		This value is given on page 23 of Volume 1. ¹⁶ No substantiation is given in Volume 2. ¹⁷ Informal discussion with Stark indicates he assumed that the value for destroyers by Kehoe ³³ would apply to hydrofoil ships.	Task Proficiency
<p>*Values of Criteria 1 through 7 are single amplitude RMS values. Values of Criteria 9 and 10 are peak values.</p> <p>**In contrast to this value of 10 percent and the value of 20 percent used for monohulls in Table 6, the Royal Navy employs an unacclimatized MS¹ value of 35 percent. The rationale for this high value was drawn from the results of a Royal Navy seakeeping questionnaire which revealed that even at the high vertical accelerations associated with an unacclimatized MSI value of 35 percent (see Figure 4), motion sickness was not the governing criterion.</p>					

Stark¹⁷ took the approach of frequency weighting the actual vertical acceleration data according to a curve which has the inverse shape of the upper limit for vertical accelerations prescribed by MIL-STD-1472B. These data are plotted as a function of frequency in Figure 6, which shows that the frequency weighting curve is selected so that it has an amplification factor of 1.0 at a frequency of 1.0 hertz. Figure 6 also shows that the upper limit for vertical accelerations has a value of 0.42 m/sec² at low frequencies between 0.1 and 0.2 hertz (0.63 to 1.26 rad/sec). This value can also be read from Figure 4 at a circular frequency of $\omega = 1.0$ to 1.3 rad/sec corresponding to MSI = 10 percent for 4 hours exposure.

The slamming vertical acceleration (Criterion 9) value of 0.5g (peak) prescribed for hydrofoil craft in the foilborne condition far exceeds the ride quality (Criterion 6) RMS value of 0.11g in Table 2. (Allen and Jones³⁴ have suggested a peak value of 1.5g* for Criteria 9 for hydrofoils). Stark has stated informally that the slamming vertical acceleration (Criterion 9) value represents the principal constraint on hydrofoil seagoing performance.

For Surface Effect Ships

The values given in Column 6 of Table 2 for SES are based on simulation studies of 2000-3000-ton vehicles. However, Fee** proposes these values as tentative prescribed criteria values for SES vehicles. The 1.5-degree prescribed value for SES vehicles for Criteria 1 and 2 is not considered limiting. The most constraining criterion among Criteria 1 to 7 for SES vehicles as far as motion sickness and task proficiency are concerned is Criterion 6 and to a lesser extent Criterion 7. The results of simulation studies showed that the prescribed values of roll and pitch could be larger without reducing task proficiency or increasing motion sickness incidence,

*In this regard, Figure 21 of Allen and Jones³⁴ indicates a peak Criterion 9 value of 0.5g for 4000-ton monohulls. This compares to an RMS value of 0.2g in Table 6 suggested by Aertssen.²⁵ With a peak/RMS ratio of 3.5, the agreement in the case of the monohulls in Reference 34 is much better than in the case of the hydrofoils.

**PMS 309-20 communication of 31 March 1978 to DTNSRDC, Code 117, on "Seakeeping Criteria for SES Vehicles."

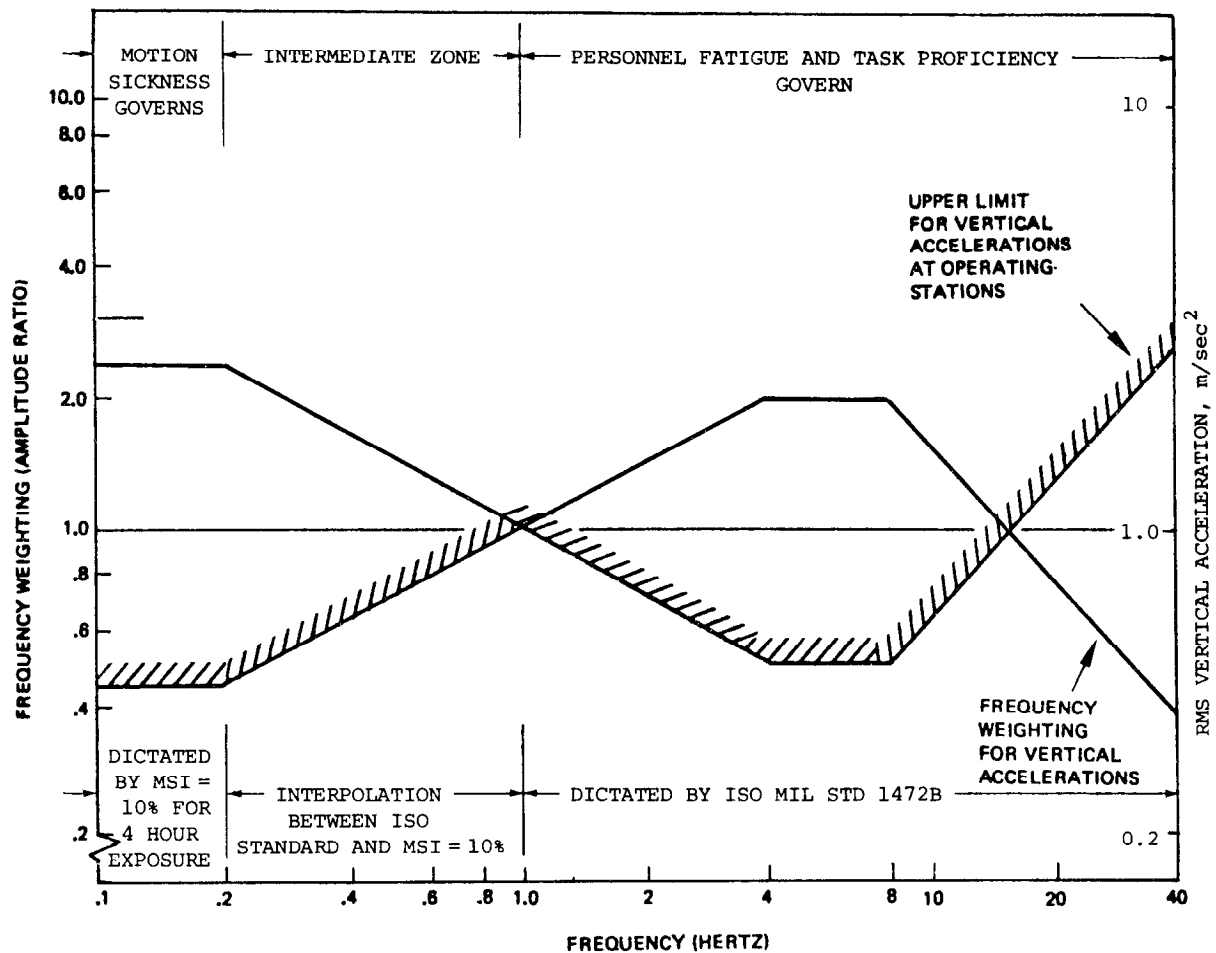


Figure 6 - Frequency Weighting for Vertical Accelerations for Ride Quality Evaluation for Hydrofoil Ships¹⁷

provided that the value of vertical acceleration was not increased. The reason for prescribing the 1.5-degree value for Criteria 1 and 2 is that these values were never exceeded in sea states that were limiting as far as Criterion 6 was concerned.

The accepted view of SES vehicle designers is that a prescribed value of 0.10g for Criterion 6 should provide high confidence of an acceptable ride; 0.15g will provide moderate confidence of such a ride and 0.20g only marginal confidence. The Criterion 6 value of 0.10g for SES vehicles is an attempt to satisfy a motion sickness incidence value of 10 percent for 2 hours duration.* Thus, with regard to Criteria 6 and 8, the hydrofoil and SES vehicles have very similar values. The value of 0.10g for Criterion 7 in Table 2 is applicable to tight turns of the vehicle. In straight runs the value of Criterion 7 is 0.05g.

The prescribed slamming (Criterion 9) peak value of 0.6g for SES in Table 2 agrees remarkably well with the values (0.55g to 0.70g) arrived at independently, given in Figure 21 of Reference 34 for 2000-3000-ton vehicles. As with hydrofoils, the impact of slamming accelerations on personnel fatigue and crew proficiency is a cause of very serious concern with SES vehicles, and active motion alleviation systems are being developed for them.

For Air Cushion Vehicles

The values given in Column 7 of Table 2 for ACV are actual values based on measurements by Wachnik and Pierce** on one of the cross-channel, passenger-carrying SR.N4 class of ACV's in a sea visually estimated as 8.9 ft (2.7 m) significant wave height. The visual estimate was supplemented by wave measuring stations at selected points on the route. The significance of this sea condition is that it represents the level of severity at which the operators of these vehicles suspend them from service because of passenger intolerance.

*See second footnote of Table 7.

**DTNSRDC report in preparation: "SR.N4 Motions" by Z.G. Wachnik and R.D. Pierce.

Since these vehicles are engaged in a strictly commercial, profit motivated service, the decision to suspend service is not taken lightly. Furthermore, the fact that these vehicles have been in service for over a decade means that such decisions are based on firm knowledge of passenger tolerance.* Because of these facts, one of the values given in Column 7 of Table 1 corresponds to the prescribed value of a governing criterion, unless a criterion not yet developed is causing the passenger intolerance.

The value of the acceleration (Criterion 6) in Column 7 of Table 2 is the heave acceleration of the center of gravity of the ACV. Since the values of this criterion for the SES and hydrofoil vehicles in Table 2 are intended to be independent of location, they are directly comparable to the ACV value in Column 7. If Criterion 6 is, in fact, a governing criterion for an ACV, the agreement among three prescribed values of Criterion 6 in Table 2 for the hydrofoil, SES, and ACV is worthy of particular note.

CONCLUSIONS

BOX SCORES

1. Three seagoing box scores developed during the past dozen years offer promise of providing an acceptable way of assessing the operational and technical seagoing worth of competitive vehicle types operating on the ocean surface.

2. The values of all three of these box scores depend on a host of seakeeping criteria whose nature and whose prescribed values have not been adequately investigated.

GENERAL PROPERTIES OF SEAKEEPING CRITERIA AND THEIR VALUES

3. The nature and the prescribed values of all seakeeping criteria are dependent on three factors:

*The vehicles themselves could tolerate even more severe seas.

a. Human Factors (ride quality)

- (1) Comfort
- (2) Motion Sickness
- (3) Personnel Fatigue
- (4) Task Proficiency
- (5) Safety

b. Operational limits of the vehicle payload (for Naval ships, this means the weapons and the other combat systems).

c. Operational limits of the vehicle, the vehicle structure, and the subsystems needed by the vehicle, its payload, and its personnel.

4. The prescribed values of seakeeping criteria developed from 3(a) and 3(b), should be completely independent of sea, wind, and weather conditions; vehicle type, size, and configuration; location on the vehicle; vehicle operating mode (hullborne or foilborne); or the presence or absence of active motion controls. These values are dependent on vehicle functions and may be dependent on mission duration.

5. Prescribed values of the seakeeping criteria developed from factor 3(c) should also be completely independent of sea, wind, and weather conditions but they are dependent on vehicle function and are likely to be dependent on vehicle features.

6. Actual values of the seakeeping criteria are always dependent on both environmental and vehicle features, but they are independent of vehicle function.

SPECIFIC SEAKEEPING CRITERIA AND THEIR PRESCRIBED VALUES

7. Roll angle is not a useful motion sickness criterion. Roll angle is an important criterion for V/STOL and helicopter launch and retrieval from all vehicles and may be a significant criterion for task proficiency on monohulls, but not necessarily on hydrofoils and SES's. Roll and pitch angles may also be important criteria as far as weapon effectiveness is concerned, but this is a relatively unexplored subject.

8. Current knowledge indicates that vertical acceleration (Criterion 6 of Table 2) and MSI (Criterion 8) are the two most important motion sickness criteria.

9. Independent observation and analysis of hydrofoil, SES, and ACV motions has led to a common prescribed ride quality vertical acceleration (Criterion 6) RMS value of about 0.10g.

10. The prescribed values of the slamming vertical acceleration (Criterion 9) for small vehicles are dictated by considerations of personnel fatigue and task proficiency. For large ships they are dictated by concern for hull structural damage.

11. Unlike that for other vehicle types, the vertical acceleration associated with slamming for planing craft is apparently always the governing criterion. With other vehicle types, slamming occurs so much less frequently that other criteria may also be governing. This apparently is not the case with planing craft.

12. A new criterion is needed to address the yaw-heel motion problem of monohulls in astern seas. Because no such criterion has been developed, current assessments of the seagoing performance of monohulls in seas that include moderate to severe stern seas are unrealistically optimistic.

ACKNOWLEDGMENTS

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APPENDIX A
GOVERNING SEAKEEPING CRITERIA FOR MONOHULLS
AND SWATH FROM REFERENCE 1

Olson's results¹ indicate which of the seakeeping criteria of Table 4, in association with their prescribed values of Table 6, are the governing criteria for two vehicle types, monohull and SWATH, both without any active motion controls, and for the four vehicle functions of Table 4. The monohulls considered were the CG-26, DD-963, FF-1052, and the FFG-7;¹³ the SWATH is a 3400-tonne frigate design.³¹ The dimensions of all are shown in Table A.1. The results for these vehicles are displayed in Figures A.1 and A.2 for the transit-alone function, in Figures A.3 and A.4 for the transit plus helicopter operation function, and in Figures A.2 and A.5 for the transit plus sonar search function. Each of these figures shows, as a function of ship-wave heading angle μ , the number of cases in which the indicated criteria are governing out of the total number of cases considered. The total number of cases considered is a function of the number of vehicles, vehicle speeds, and sea state modal periods treated. These values for each figure are given in Table A.2.

Olson¹ treated six of the 13 ride quality and vehicle criteria of Table 2, namely Criteria 1, 2, 8, 11, 12, and 13. Table A.3 shows the number of cases, summed from Figures A.1 and A.2, in which each of these six criteria was governing for the transit function. Clearly, for this function, MSI (Criterion 8) is the most frequent governing criterion for monohulls and deck wetness (Criterion 13) is the least frequent. The roll (Criterion 1) ranks third after Criteria 0* and 8 for the monohull and is never governing for the SWATH. For SWATH, Criteria 2 (pitch), 11 (wave contact), and 12 (propeller emergence) are the most frequent governing criteria for the transit function.

Figures A.3 and A.4 show that, if helicopter operation is added to the transit function, roll (Criterion 1) and pitch (Criterion 2) cease ever to be governing for either monohulls or SWATH's. Instead, as indicated in Table A.4, flight deck vertical displacement (Criterion 14) and the

*See definition of Criterion 0 in Table A.3.

TABLE A.1 - DIMENSION OF THE SHIPS TREATED IN REFERENCE 1

Dimensions	Units	Ship				
		SWATH	DD-963	CG-26	FF-1052	FFG-7
Full Load Displacement	Metric Tonnes	3408	7822	7838	4246	3578
Hull Length	ft (m)	305 (93)	529 (161)	524 (160)	215 (127)	208 (124)
Strut Length	ft (m)	211 (64)	-	-	-	-
Ship Beam	ft (m)	104 (32)	55 (17)	54 (17)	46 (14)	45 (14)
Strut Thickness	ft (m)	6.9 (2.10)	-	-	-	-
Draft	ft (m)	26.3 (8.0)	19.4 (5.9)	18.8 (5.7)	15.5 (4.7)	14.8 (4.5)
Metacenter Height	ft (m)	10.8 (3.29)	4.8 (1.46)	5.6 (1.72)	4.5 (1.36)	4.1 (1.23)
Trim	-	0	0	0	0	0

TABLE A.2 - NUMBERS OF VEHICLES, SPEEDS, AND MODAL PERIODS CONSIDERED IN FIGURES A.1 TO A.5

Figure No.	Function	Vehicle Type	No. of Vehicles	Speed knots	No. of Speeds	Modal Periods sec	No. of Modal Periods	Total No. of Cases
A.1	Transit Alone	Monohull	4	5(5)25	5	7(2)13	4	4x5x4=80
A.2	Transit Alone and Transit Plus Sonar Search	SWATH	1	0(5)35	8	7(2)13	4	1x8x4=32
A.3	Transit and Helo Operations	Monohull	4	5(5)25	5	7(2)13	4	4x5x4=80
A.4	Transit and Helo Operations	SWATH	1	0(5)35	8	7(2)13	4	1x8x4=32
A.5	Transit and Sonar Search	Monohull	3*	5(5)25	5	7(2)13	4	3x5x4=60

*Reference 1 did not treat the CG 26 performing this function.

TABLE A.3 - NUMBER OF CASES AND PERCENT OF CASES WHERE EACH CRITERION IS GOVERNING FOR THE TRANSIT ALONE FUNCTION
(No active motion controls on any vehicle)

Criterion No.	Criterion	Number and Percent of Cases Where Each Criterion is Governing					
		Figure A.1 Monohull		Figure A.2 SWATH		Total Monohulls + SWATH	
		No. Out of 1040* Cases	Percent	No. Out of 416** Cases	Percent	No. Out of 1456 Cases	Percent
0	***	327	31.4	44	10.6	371	25.5
1	Roll Angle	186	17.9	0	0	186	12.8
2	Pitch Angle	56	5.4	97	23.3	153	10.5
8	MSI	415	39.9	13	3.1	428	29.4
11	Slam Frequency	44	4.2	127	30.5	171	11.7
12	Propeller Emergence	†	†	135	32.5	135	9.3
13	Deck Wetness	12	1.2	†	†	12	0.8

*80 cases from Table A.2 x 13 headings = 1040.

**32 cases from Table A.2 x 13 headings = 416.

***Criterion 0 indicates that up to the maximum significant wave height treated in Reference 1, $\zeta = 32$ ft (9.75 m), none of the criteria of Reference 1 were governing.

†Olson applied Criterion 12 only to SWATH and Criterion 13 only to monohulls. All other criteria are applied to both vehicle types.

helicopter operation roll angle limit (Criterion 16) become the most frequent governing criteria for monohulls. Criterion 14 (but not 16) is also the most frequent governing criterion for SWATH while wave contact (Criterion 11) and propeller emergence (Criterion 12) retain the same importance that they held in the transit-alone function. Criterion 15 (flight deck vertical velocity) is also occasionally governing for SWATH performing the transit plus helicopter operation, whereas it is never governing for monohulls. Criterion 2 (pitch) is not governing for SWATH in this function, whereas it ranked third for the transit alone function.

Comparison of Figure A.5 and Figure A.1 indicates that for monohulls the sonar search function alters the governing criteria only at 150 degrees $\leq \mu \leq 210$ degrees. At 165 degrees $\leq \mu \leq 195$ degrees the sonar submergence Criteria 17 and 18 are governing in over 90 percent of the cases, removing Criteria 2, 11, and 13 as governing criteria in that sector. For SWATH, the sonar dome submergence criteria are of no consequence because the lower hulls of the SWATH where the sonar would be located always remain submerged no matter how severe the seas.

Figures A.1 to A.5 provide no information concerning the speeds at which the various criteria are governing. A sampling of this information is included in Appendix B.

CRITERION	Crit. No. (see Table 2)	CRITERION	Crit. No. (see Table 2)
No Governing Criteria	0	MSI	8
Category A Roll Angle	1	Slamming	11
Pitch Angle	2	Deck Wetness	13

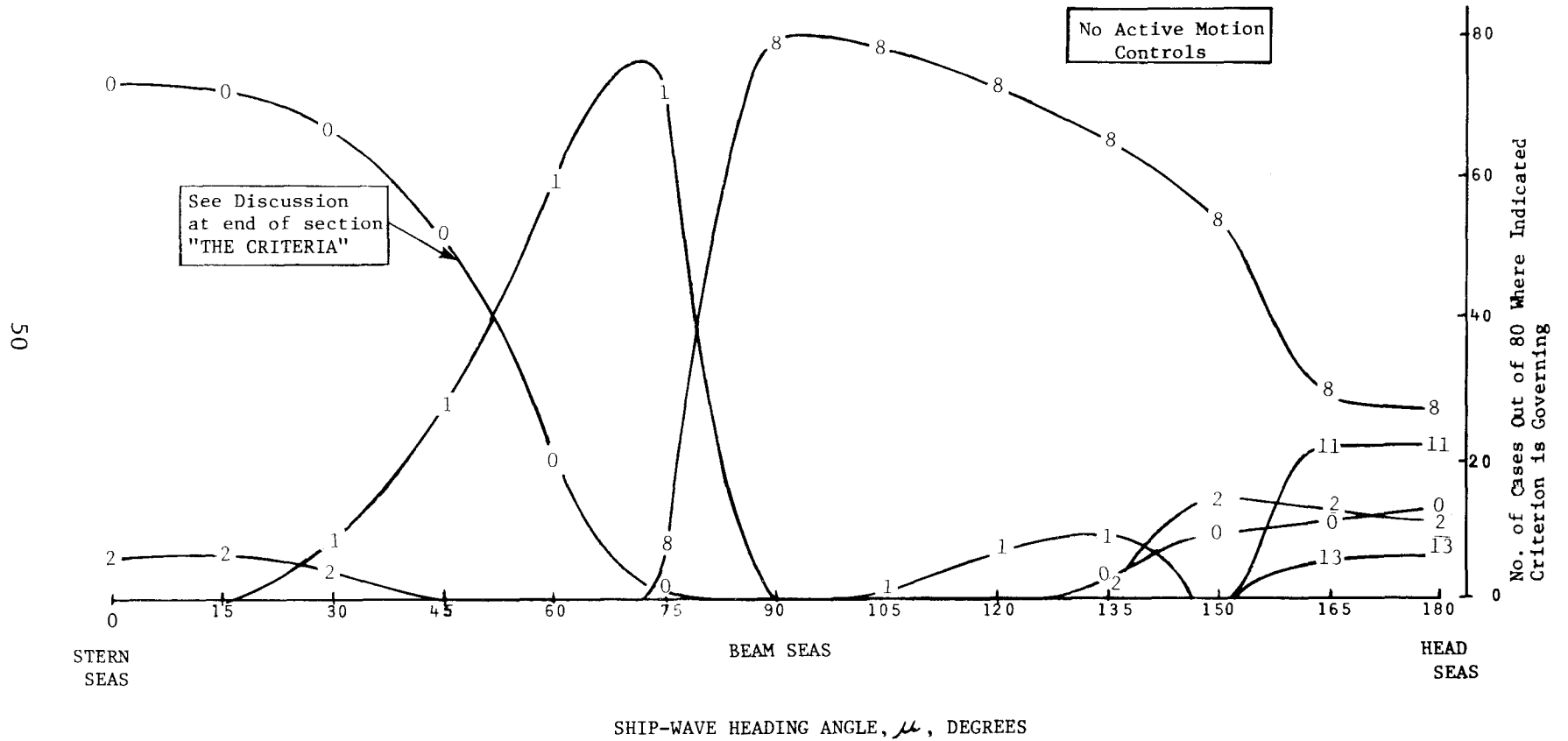


Figure A.1 - Governing Seakeeping Criteria for Monohulls for the Transit-Along Function

CRITERION	Crit. No.
No Governing Criteria	0
Pitch Angle	2
MSI	8
Wave Contact	11
Propeller Emergence	12

No Active Motion Controls

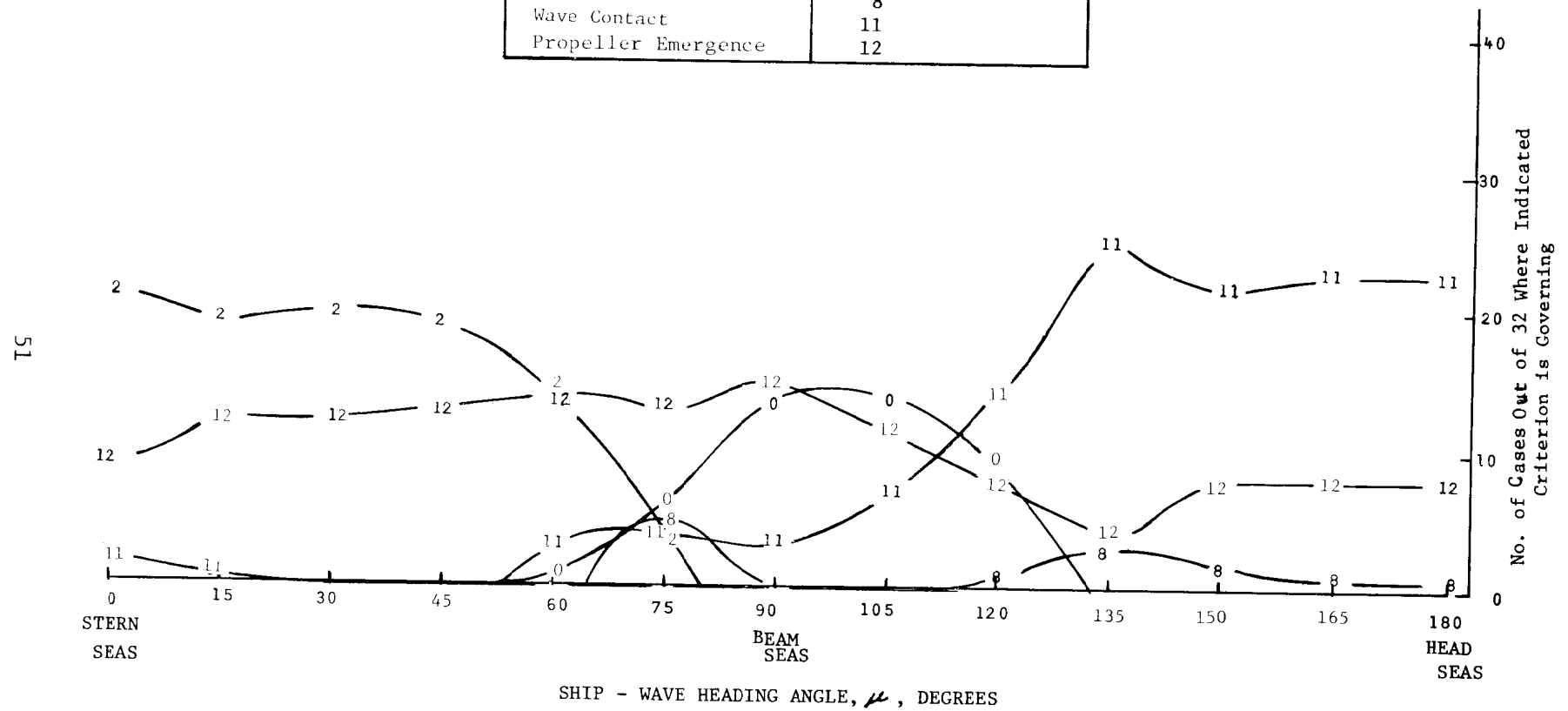


Figure A.2 - Governing Criteria for SWATH for the Transit Alone or the Transit Plus Sonar Search Function

CRITERION	Crit. No. (see Table 2)	CRITERION	Crit. No. (see Table 2)
No Governing Criteria	0	Deck Wetness	13
MSI	8	Flight Deck Vertical Displ.	14
Slamming	11	Flight Deck Roll Angle	16

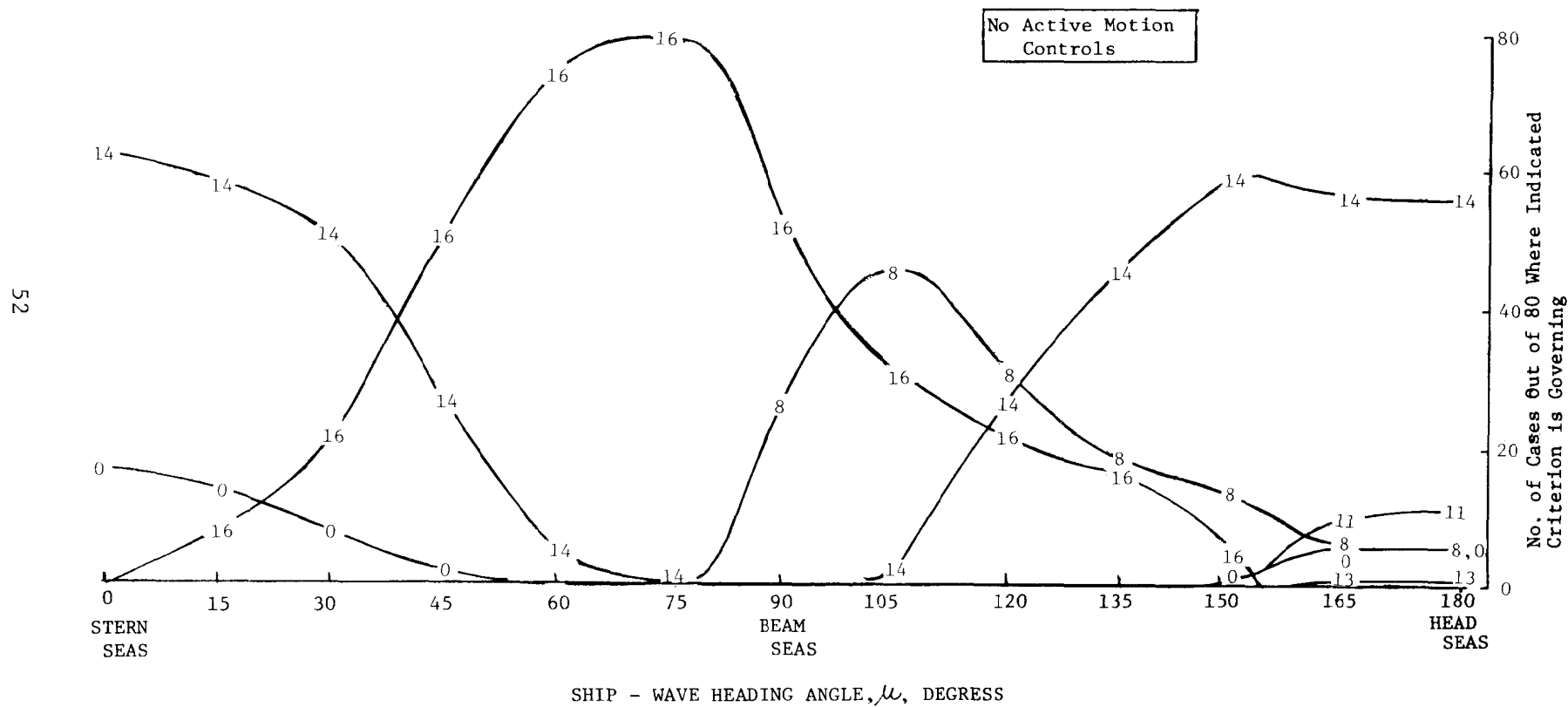


Figure A.3 - Governing Criteria for Monohulls for the Transit Plus Helicopter Operation Function

CRITERION	CRIT. NO (see Table 2)
No Governing Criteria	0
MSI	8
Wave Contact	11
Propeller Emergence	12
Flight Deck Vertical Displ.	14
Flight Deck Vertical Velocity	15
Flight Deck Roll Angle	16

No Active Motion Controls

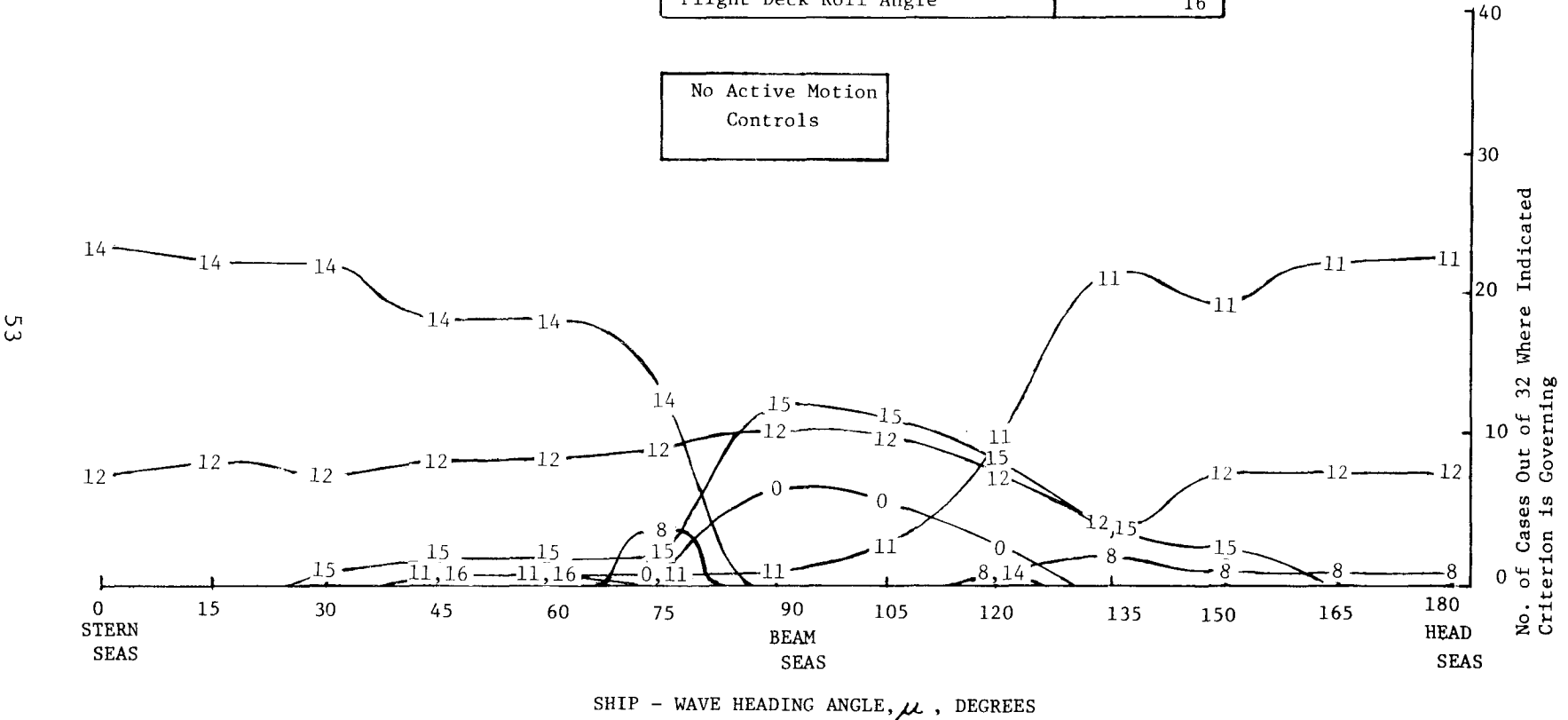


Figure A.4 - Governing Criteria for SWATH for the Transit Plus Helicopter Operation Function

CRITERION	Crit. No. (see Table 2)
No Governing Criteria	0
Roll Angle	1
Pitch Angle	2
MSI	8
Sonar Submergence & PSEPR/PING	18

No Active Motion Controls

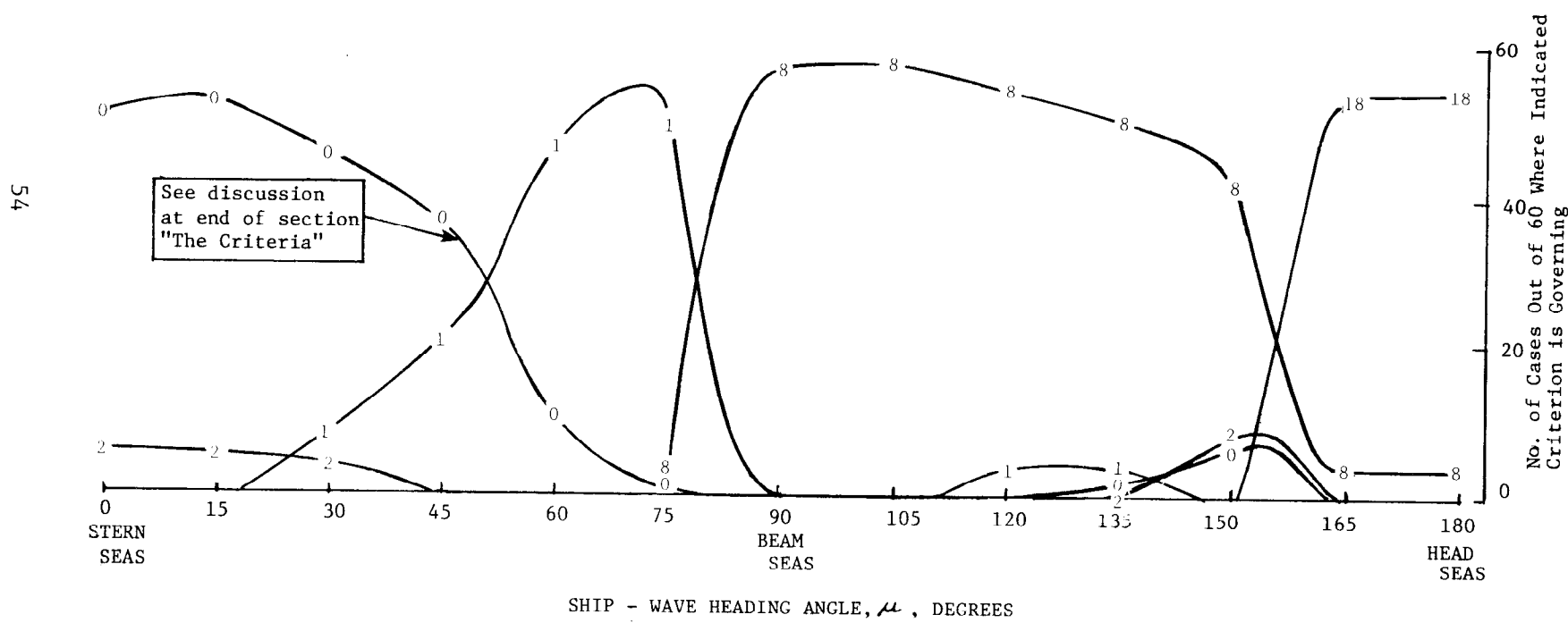


Figure A.5 - Governing Criteria for Monohulls for the Transit Plus Sonar Search Function

TABLE A.4 - NUMBER OF CASES AND PERCENT OF CASES WHERE EACH CRITERION IS GOVERNING
FOR THE TRANSIT PLUS HELICOPTER OPERATION FUNCTION

(No active motion controls on any vehicle)

Criterion No.	Criterion	Number and Percent of Cases Where Each Criterion is Governing					
		Figure A.3 Monohull		Figure A.4 SWATH		Total Monohulls + SWATH	
		No. Out of 1040 Cases	Percent	No. Out of 416 Cases	Percent	No. Out of 1456 Cases	Percent
0	No governing criterion	54	5.2	17	4.1	71	4.9
8	MSI	150	14.4	10	2.4	160	11.0
11	Slam Frequency	21	2.0	105	25.2	126	8.7
12	Propeller Emergence	*	*	111	26.7	111	7.6
13	Deck Wetness	2	0.2	*	*	2	0.1
14	Flight Deck Vertical Displacement	453	43.6	123	29.6	576	39.6
15	Flight Deck Vertical Velocity	0	0	48	11.5	48	3.3
16	Flight Deck Roll Angle	360	34.6	2	0.5	362	24.9

*Olson applied Criterion 12 only to SWATH and 13 only to monohulls. All other criteria are applied to both vehicle types.

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APPENDIX B
LIMITING SIGNIFICANT WAVE HEIGHTS AS A FUNCTION OF
VEHICLE SPEED FROM REFERENCE 1

The governing criteria of Appendix A determine the limiting sea state severities at which a vehicle may carry out the function associated with the selected criteria. Limiting sea state severities indicated by a value of significant wave height ζ , are shown in Figures B.1 to B.7 for the FFG-7, DD-963, and SWATH as a function of vehicle speed and for four values of spectral modal period, $T_0 = 7, 9, 11, \text{ and } 13$ seconds. Also shown in these figures are the governing criterion for each of the speeds of Table A.2. The latter are identified by their criterion numbers which are inserted in Figures B.1 to B.7 at the speed values of Table A.2. Three ship-wave heading angles in association with three different ship functions are shown in Figures B.1 to B.7 as follows:

1. Head Seas, $\mu = 180$ deg
Transit Alone (Figure B.1)
Transit Plus Helicopter Operation (Figure B.2)
Transit Plus Sonar Search (Figure B.3)
2. Beam Seas, $\mu = 90$ deg
Transit Alone or Transit Plus Sonar Search Function (Figure B.4)
Transit Plus Helicopter Operation (Figure B.5)*
3. Stern Seas, $\mu = 0$ deg
Transit Alone or Transit Plus Sonar Search Function (Figure B.6)
Transit Plus Helicopter Operation (Figure B.7)*

Figures B.1 to B.7 demonstrate three important general features that may be valid for many vehicle types, not just for monohulls and SWATH's. These three features are:

1. In over 30 percent of the 80 ζ versus V relationships shown in Figures B.1 to B.7, the governing criterion changes with speed for a single vehicle and a single modal period.

*Transit plus helicopter operation is a highly unlikely function to be carried out in beam or in stern seas.

2. Often, when there is a change in the governing criterion with changes to speed, there is also an abrupt change in the trend of the relationship between ζ and V .

3. For a given vehicle, the most constraining value of ζ as a function of V may depend not only on different governing criteria as speed is increased but also on different values of T_0 .

Each of these features is illustrated by the SWATH data in Figure B.6. This figure shows the ζ versus V relationships for the monohull and SWATH vehicles performing the transit function in stern seas. The first feature is illustrated by the ζ versus V relationships for the SWATH for all four modal periods of Figure B.6:

1. In the $T_0 = 7$ (sec) relation, the governing criterion changes from Criterion 12 (propeller emergence) to Criterion 2 (pitch angle) between 10 and 15 knots. It changes again from Criterion 2 to Criterion 11 (wave contact) between 25 and 30 knots.

2. In the $T_0 = 9, 11, \text{ and } 13$ (sec) relations, the governing criterion changes from Criterion 12 to Criterion 2 between 5 and 10 knots.

The second feature is illustrated by the ζ versus V relations of SWATH in Figure B.6 for three modal periods, $T_0 = 9, 11, \text{ and } 13$ seconds. An abrupt change in trend takes place at 10 knots. Above this speed Criterion 2 severely reduces the tolerable significant wave height as speed is increased. Below this speed, Criterion 12 similarly severely reduces the tolerable significant wave height as speed is decreased.

The third feature is also illustrated by the SWATH data in Figure B.6. As speed is increased from 0 to 35 knots, both the spectral modal period value and the governing criterion that most constrain the sea state severity change. This is shown in Table B.1.

The fact that only three ship-wave heading angles, $\mu = 0, 90, \text{ and } 180$ degrees and only two monohull ships are included in Figures B.1 to B.7 results in two discrepancies between results given in Appendix A and those of this appendix. The two discrepancies are:

1. Criterion 1 (roll angle), which ranks number 3 in importance for the monohulls in the transit alone function in Table A.3, does not appear at all in Figures B.1, B.4, and B.6 of this appendix.

2. Criterion 13 (deck wetness), which appears in Table A.3 also, does not appear in Figures B.1, B.4, and B.6.

The first discrepancy is explained by Figure A.1. Criterion 1 is frequently governing at 15 degrees $\leq \mu < 90$ degrees and at 100 degrees $\leq \mu \leq 145$ degrees in that figure, but it is never governing at $\mu = 0, 90,$ and 180 degrees. The second discrepancy is due to the fact that the 12 cases in which Criterion 13 is governing in Table A.3 apply to the FF-1052, which was included in the results of Appendix A but was not included in the results of this Appendix.

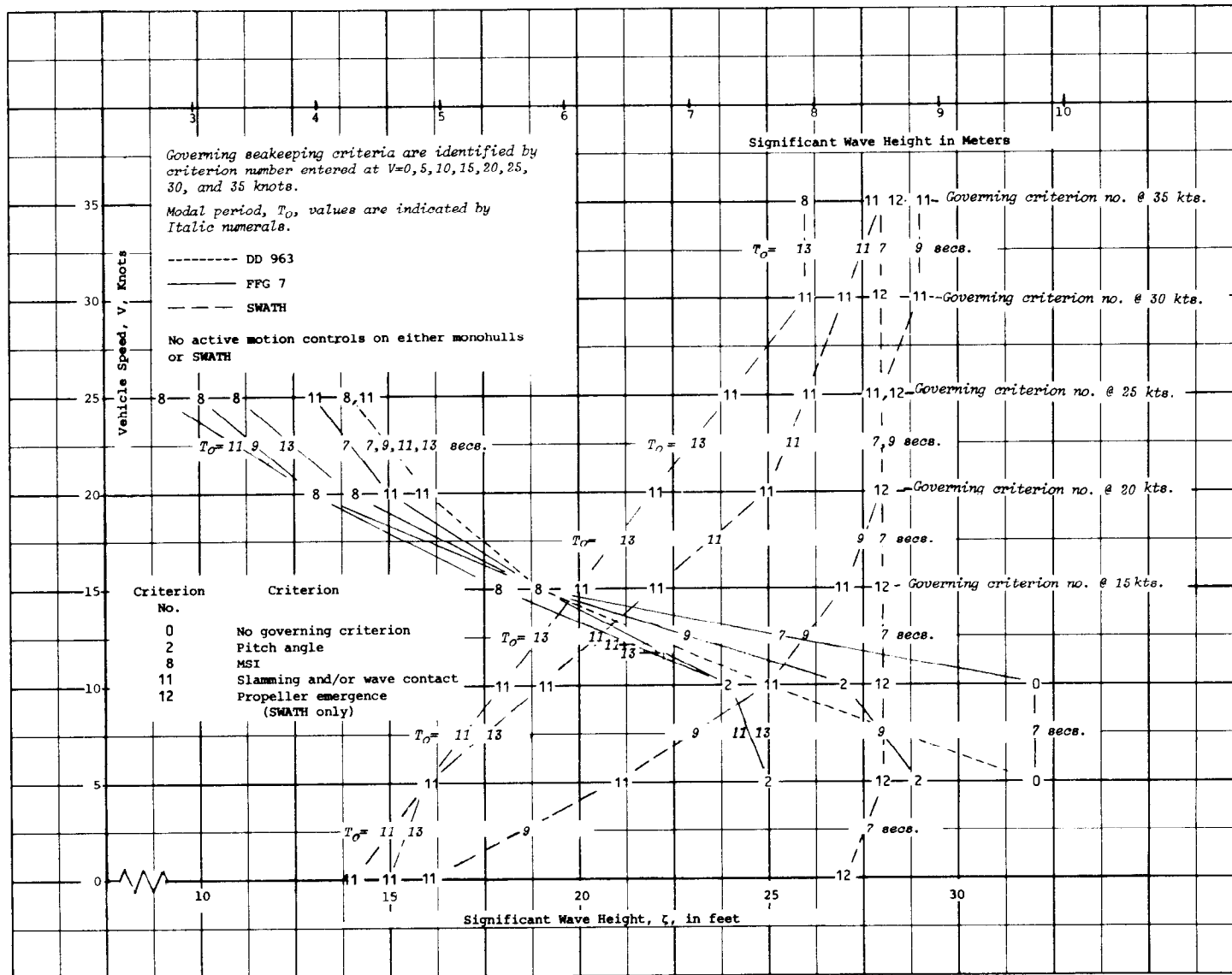


Figure B.1 - Transit Alone, Head Seas

(Limiting significant wave heights and governing seakeeping criteria in head seas for FFG-7, DD-963, and 3350-ton SWATH for the transit alone function)

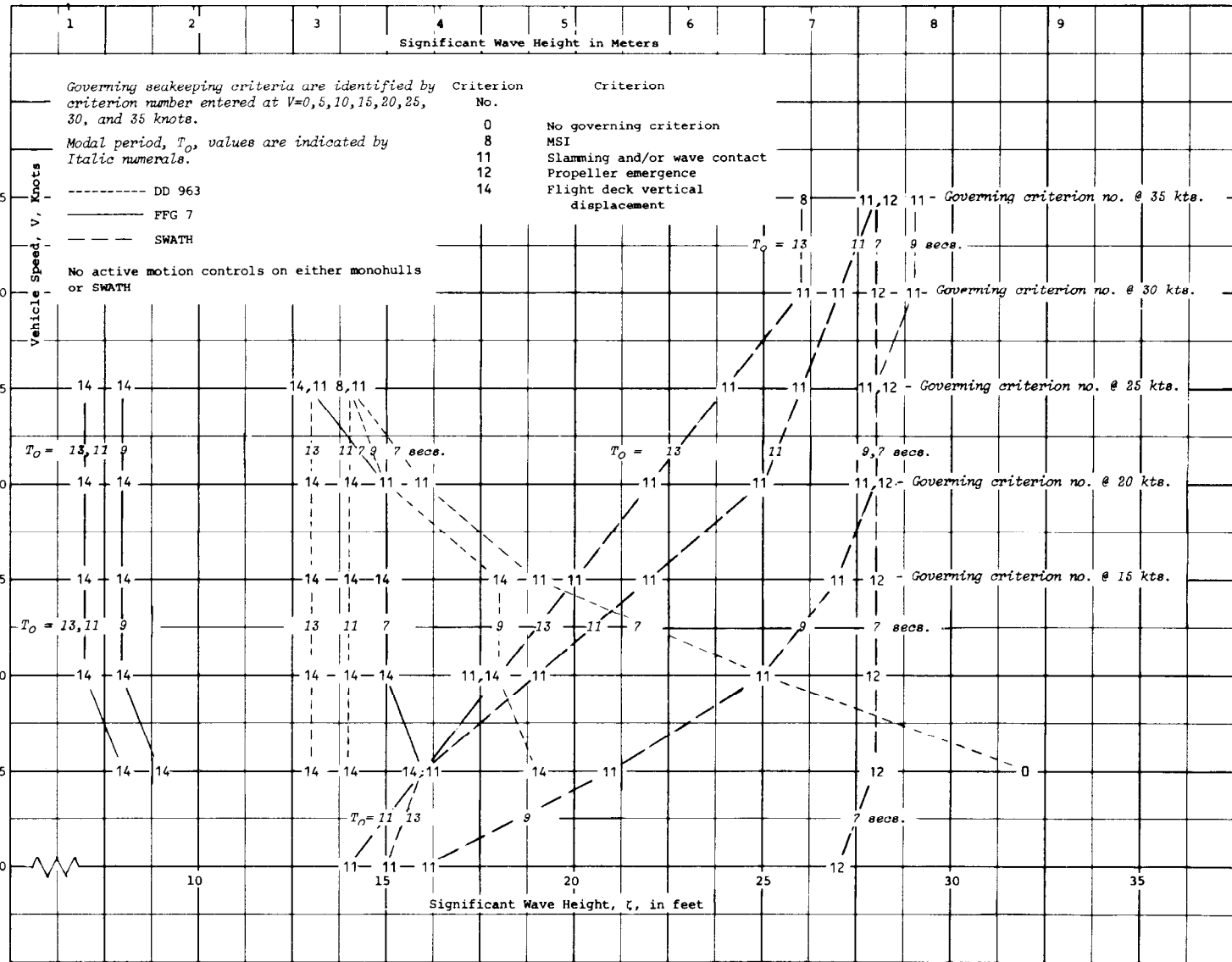


Figure B.2 - Transit Plus Helicopter Operation, Head Seas

(Limiting significant wave heights and governing seakeeping criteria in head seas for FFG-7, DD-963, and 3350-ton SWATH for the transit plus helicopter operation function)

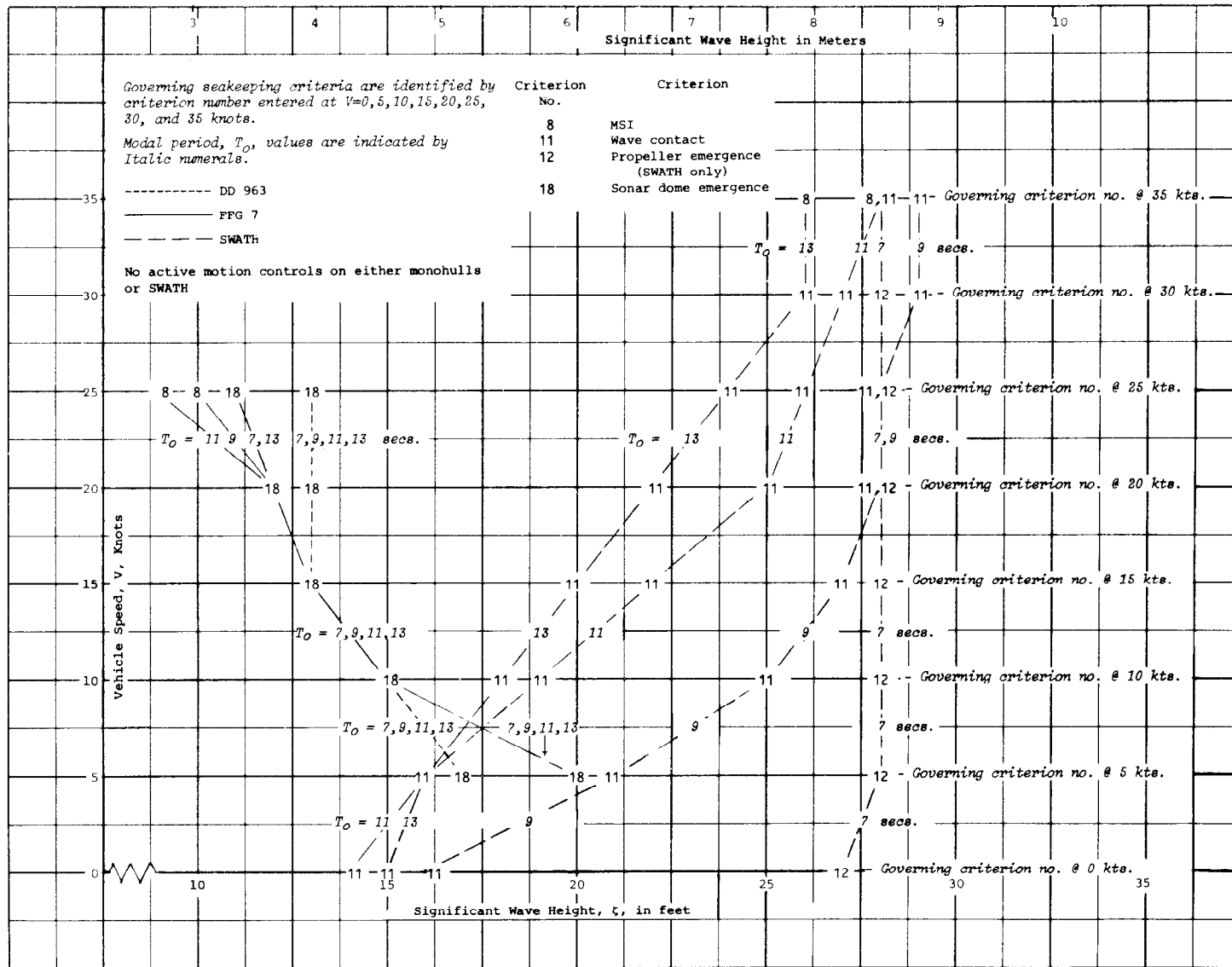


Figure B.3 - Transit Plus Sonar Search, Head Seas

(Limiting significant wave heights and governing seakeeping criteria in head seas for FFG-7, DD-963, and 3350-ton SWATH for the transit plus sonar search function)

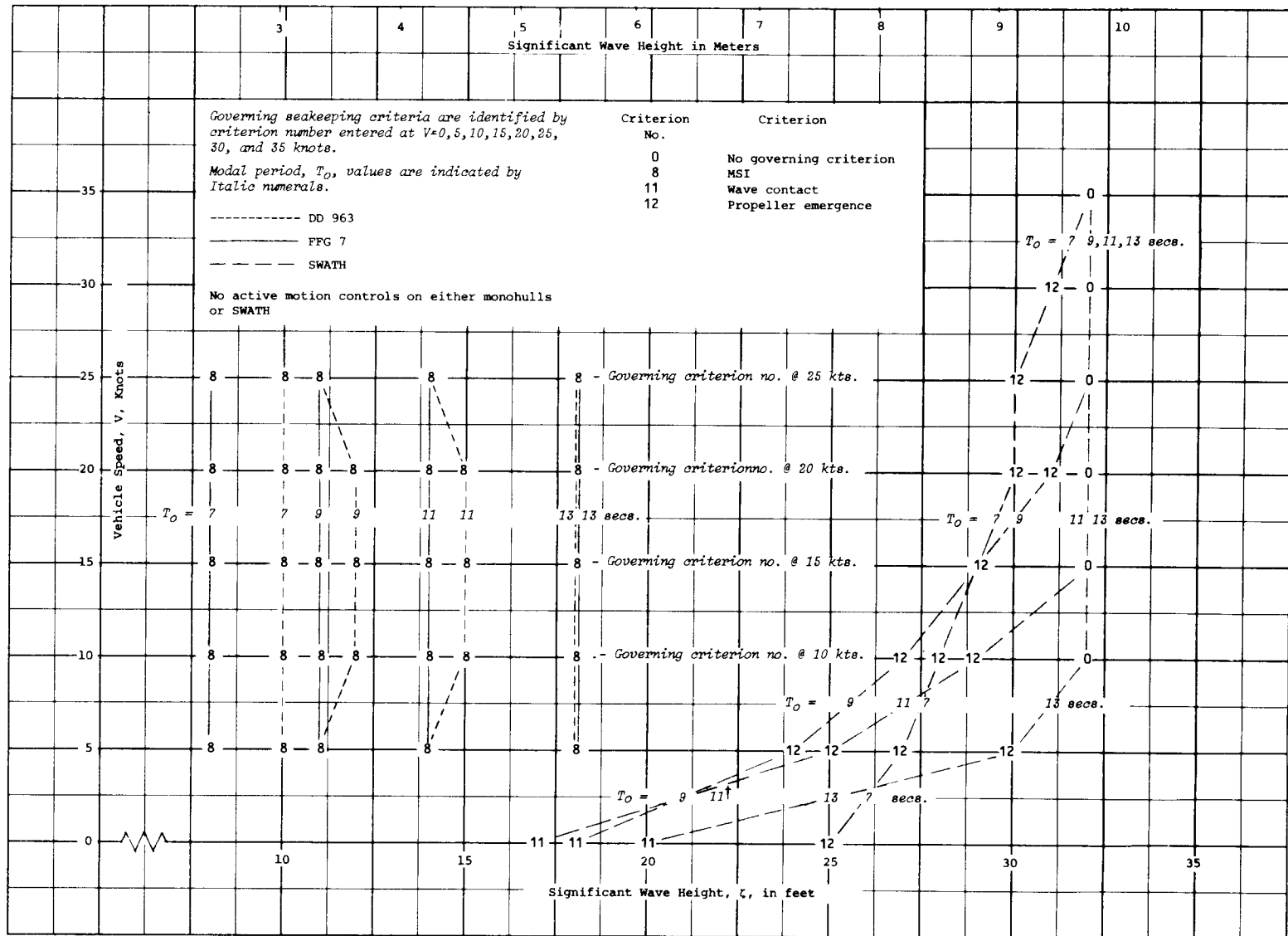


Figure B.4 - Transit Alone or Transit Plus Sonar Search, Beam Seas
 (Limiting significant wave heights and governing seakeeping criteria in beam seas for FFG-7, DD-963, and 3350-ton SWATH for the transit alone or the transit plus sonar search function)

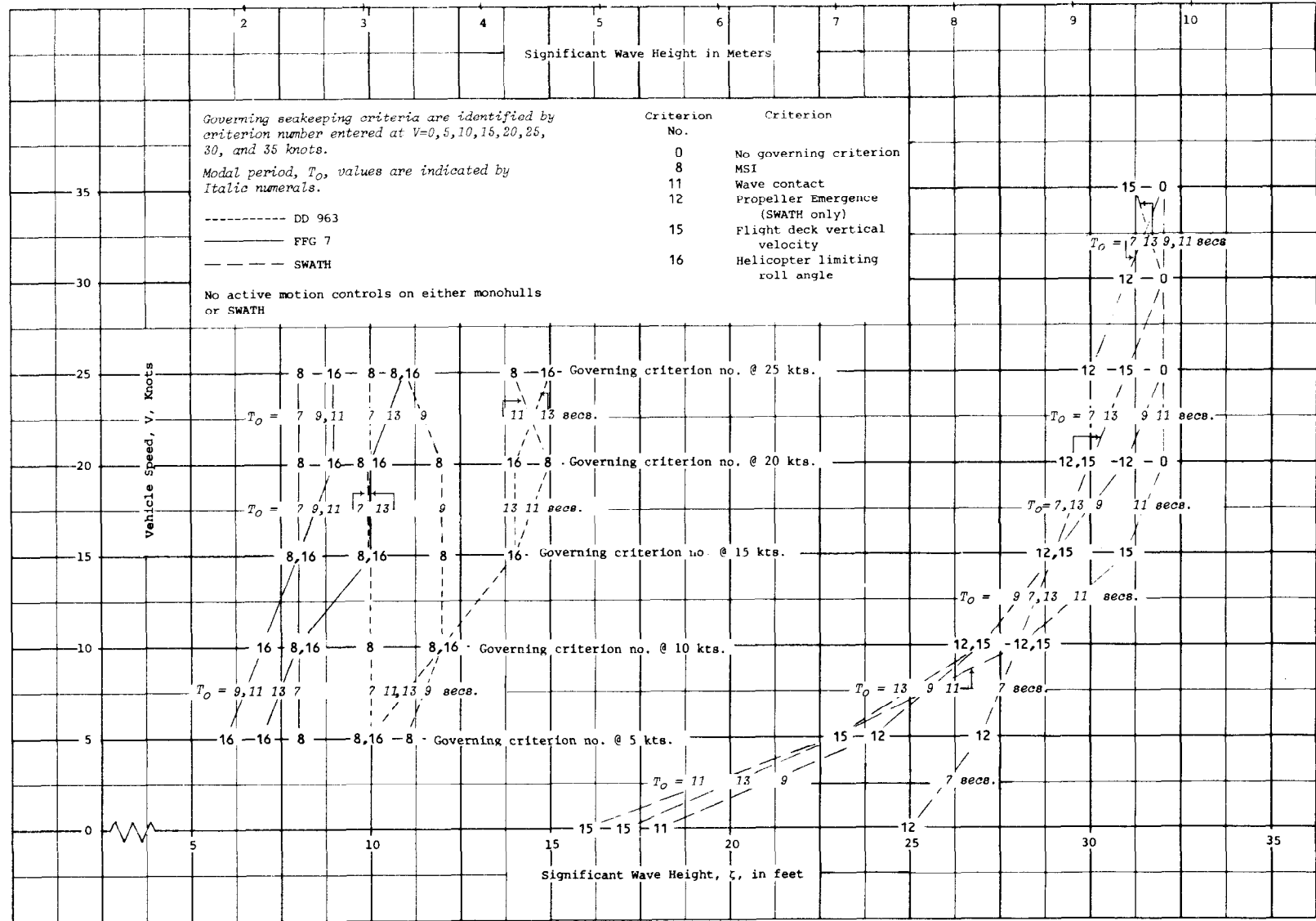


Figure B.5 - Transit Plus Helicopter Operation, Beam Seas
 (Limiting significant wave heights and governing seakeeping criteria in beam seas for FFG-7, DD-963, and 3350-ton SWATH for the transit plus helicopter operation function)

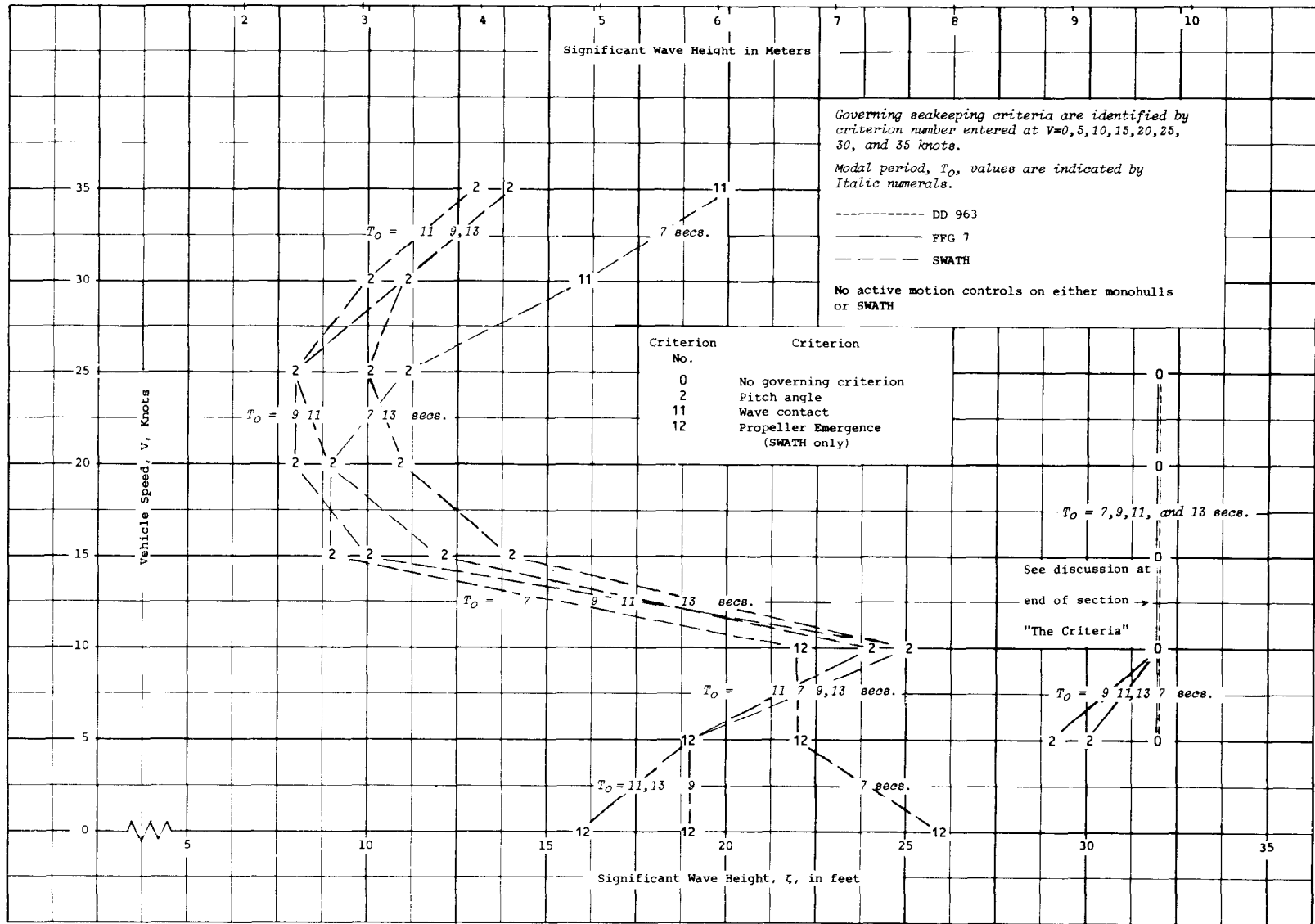


Figure B.6 - Transit Alone or Transit Plus Sonar Search, Stern Seas
 (Limiting significant wave heights and governing seakeeping criteria in stern seas for FFG-7, DD-963, and 3350-ton SWATH for the transit alone or the transit plus sonar search function)

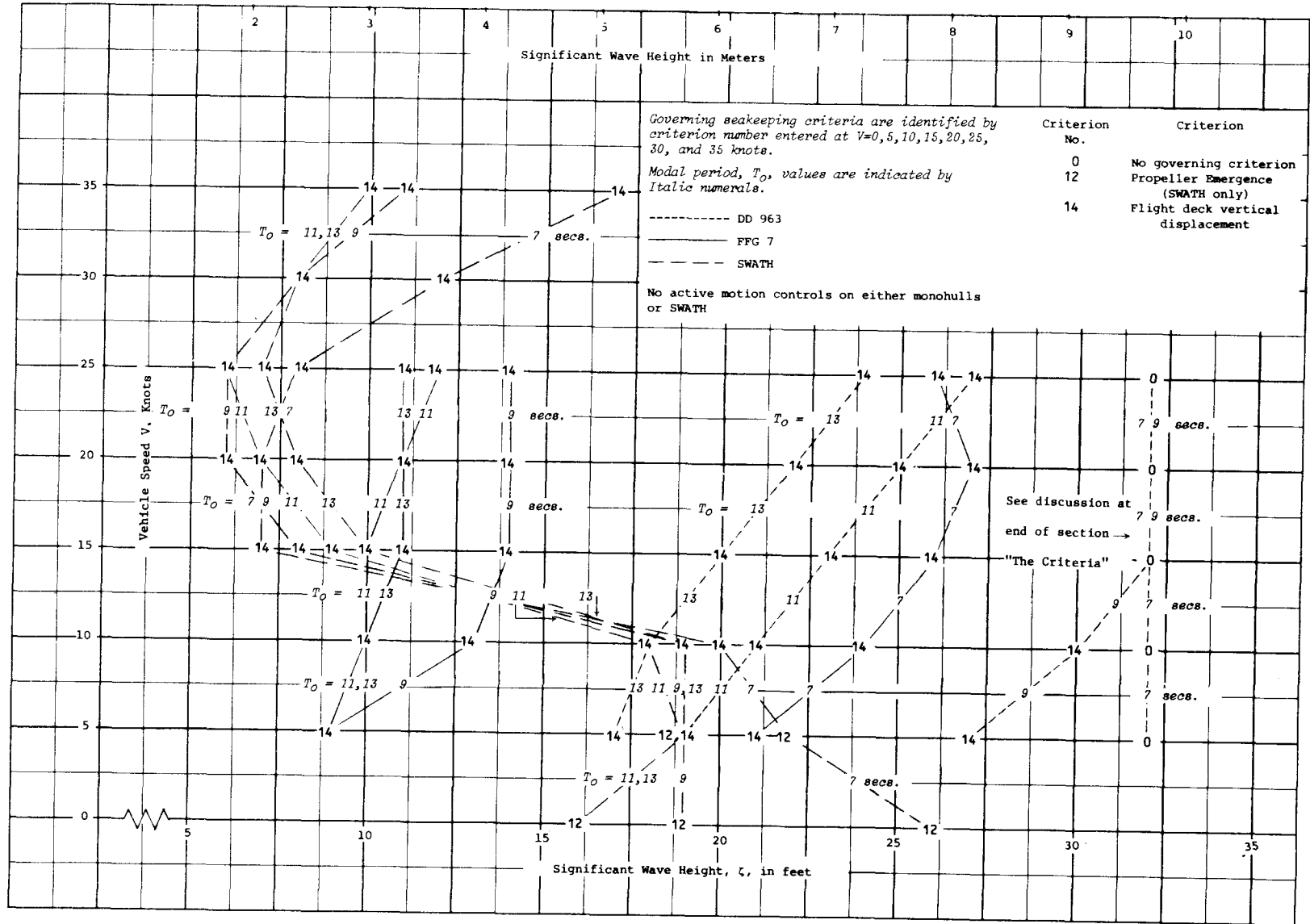


Figure B.7 - Transit Plus Helicopter Operation, Stern Seas
 (Limiting significant wave heights and governing seakeeping criteria in stern seas for FFG-7, DD-963, and 3350-ton SWATH for the transit plus helicopter operation function)

TABLE B.1 - CRITERIA AND SPECTRAL MODAL PERIOD VALUES THAT MOST CONSTRAIN THE VALUES OF ζ AS A FUNCTION OF SPEED FOR SWATH IN FIGURE B.6

Speed	Most Constraining Value of Modal Period	Most Constraining Criterion
	T_o , sec	
$0 \leq v \leq 8$ Knots	11 and 13	12 Propeller Emergence
$8 \leq v \leq 17$ Knots	7	12 and 2
$17 \leq v \leq 25$ Knots	9	2 Pitch Angle
$25 \leq v \leq 35$ Knots	11	2 Pitch Angle

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APPENDIX C
VALUES OF BOX SCORE 1 FROM REFERENCE 1

Values of Box Score 1 were calculated in Reference 1 for the five vehicles described in Table A.1 with no active motion controls and for the four vehicle functions of Table 4. The following assumptions were used in Reference 1 to calculate the Box Score 1 values which are given in Table C.1:

1. Vehicle operations are carried out in a specified North Atlantic Ocean area defined by the eight locations in Figure 4, page 24, of Reference 1.
2. Vehicle operations are carried out in two specified seasons; winter defined as December and January, and summer defined as June and July.
3. Wave height and wave modal period distributions for the preceding ocean area and two seasons are as specified in Table 4, page 25, of Reference 1.
4. The probability of encountering a specific ship-wave heading angle was equally likely for all headings.

Tables C.1 and A.1 show that, for monohulls, increasing the size from the FFG-7's 3578 metric tonnes to the DD-963's 7822 metric tonnes increases the value of Box Score 1 significantly. Table C.2 compares the increases in the Box Score 1 values due to the increase in monohull size to the increases in Box Score 1 values between the SWATH values and the DD-963 values. Although the increases between SWATH and DD-963 are smaller than between DD-963 and FFG-7, the fact that the SWATH is even smaller than the FFG-7 (3408 metric tonnes versus 3578 tonnes) is particularly noteworthy. Also noteworthy is the fact that not all the criteria that constrain the speed of monohulls in practice were considered in Reference 1 (see Conclusion Number 12). It is also remarkable that, in spite of this fact, a 3408-metric tonne SWATH achieves a substantially better Box Score 1 value than a 7822-metric tonne monohull in performing any one of the four functions of Table 4 (at all but one speed).

TABLE C.1 - BOX SCORE 1 VALUES FROM REFERENCE 1

Season:	Winter					Summer				
Ship:	SWATH	DD-963	CG-26	FF-1052	FFG-7	SWATH	DD-963	CG-26	FF-1052	FFG-7
<u>Speed</u>	Transit Alone									
All*	0.91	0.88	0.88	0.81	0.82	0.98	0.97	0.97	0.95	0.95
5	0.92	0.94	0.93	0.89	0.88	0.99	0.99	0.99	0.98	0.98
10	0.96	0.91	0.92	0.86	0.88	1.00	0.98	0.98	0.97	0.97
15	0.93	0.89	0.89	0.82	0.85	0.99	0.98	0.98	0.95	0.96
20	0.90	0.85	0.85	0.77	0.79	0.98	0.97	0.97	0.93	0.93
25	0.86	0.83	0.82	0.73	0.72	0.96	0.96	0.95	0.91	0.90
	Transit Plus Helicopter Operation									
All*	0.87	0.72	-	0.58	0.48	0.96	0.92	0.89	0.84	0.78
	Transit Plus Sonar Search									
All*	0.91	0.87	0.88	0.80	0.81	0.98	0.97	-	0.94	0.95
	Transit Plus Helicopter Operation Plus Sonar Search									
All*	0.87	0.72	0.67	0.58	0.48	0.96	0.92	0.89	0.84	0.78
5	0.92	0.69	0.60	0.51	0.40	0.99	0.92	0.87	0.81	0.73
10	0.95	0.68	0.63	0.55	0.45	1.00	0.91	0.87	0.82	0.76
15	0.88	0.73	0.68	0.61	0.50	0.97	0.93	0.90	0.86	0.80
20	0.83	0.73	0.72	0.62	0.53	0.94	0.92	0.92	0.86	0.81
25	0.79	0.73	0.71	0.60	0.53	0.92	0.92	0.90	0.84	0.81
*All assumes that the speeds at which the ship is operating are equally distributed between 5, 10, 15, 20, and 25 knots.										

TABLE C.2 - INCREASES IN BOX SCORE 1 VALUES BETWEEN SWATH AND DD-963, AND BETWEEN DD-963 AND FFG-7

Increases in Box Score 1 Values				
Speed	Winter		Summer	
	SWATH/DD-963 percent	DD-963/FFG-7 percent	SWATH/DD-963 percent	DD-963/FFG-7 percent
Transit Alone				
All	+ 3.4	+ 7.3	+1.0	+ 2.1
5	- 2.1	+ 6.8	-	+ 1.0
10	+ 5.5	+ 3.4	+2.0	+ 1.0
15	+ 4.5	+ 4.7	+1.0	+ 2.1
20	+ 5.9	+ 7.6	+1.0	+ 4.3
25	+ 3.6	+15.3	-	+ 6.7
Transit Plus Helicopter Operation				
All	+20.8	+50.0	+4.3	+17.9
Transit Plus Sonar Search				
All	+ 4.6	+ 7.4	+1.0	+ 2.1
Transit Plus Helicopter Operation Plus Sonar Search				
All	+20.8	+50.0	+4.3	+17.9
5	+33.3	+72.5	+7.6	+26.0
10	+39.7	+51.1	+9.9	+19.7
15	+20.5	+46.0	+4.3	+16.3
20	+13.7	+37.7	+2.2	+13.6
25	+ 8.2	+37.7	-	+13.6

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APPENDIX D
FOUR PARTS OF VEHICLE RESPONSES

FREQUENCY DOMAIN UNIT RAO DATA (FOR
MONOHULLS ONLY)

The Response Amplitude Operators (RAO) define the actual values of the dynamic responses of the center of gravity of a vehicle in a specified loading condition in the six degrees of freedom of motion. The origin of the vehicle and its axis system is taken at the intersection of the plane of symmetry of the vehicle, its calm water waterplane, and the longitudinal location of the center of gravity of the vehicle. The six degree-of-freedom responses are surge, sway, heave, roll, pitch, and yaw; the first three are translations of the origin in the longitudinal, horizontal, and vertical directions of the earth axes system, and the latter three are rotations about these axes. The RAO's themselves are a function not only of the mass, mass distribution, geometry, and speed of the vehicle (fully appended) but also of the heights ζ , direction μ , and the frequency ω , of the single frequency, sinusoidal wave system assumed to be exciting the vehicle. The computer program used to calculate RAO's for all the monohulls^{13,14,15} was developed by Salvesen and others.³⁵

One of the severe constraints of the current state of the art for predicting the motions of monohulls is that the RAO's are assumed to be linear functions of wave height. This constraint enables the RAO's to be expressed in terms of degrees per unit of wave height for roll, pitch, and yaw, and in terms of units of displacement per unit of wave height for surge, sway, and heave. In this form, they are called unit RAO values. However, this assumption also restricts reliable use of the RAO data bases^{13,14,15} to the linear range. The linear range is considered to exist below those values of the motions which either submerge the deck edge of the main hull of the ship or which cause part of the keel of the ship to emerge from the water.

The RAO data base of Reference 13 consists of $5 \times 13^* = 65$ tables of the unit RAO values just described and 65 tables of phase angle values for

*Five vehicle speeds of 5, 10, 15, 20, and 25 knots expressed as 5 (5) 25 knots and 13 vehicle headings of 0 (15) 180 degrees.

each of its five ships. The phase angle is the angular displacement between the particular response of the origin of the ship (surge, sway, heave, roll, pitch, and yaw) and the exciting sinusoidal wave with the wave crest assumed at the origin. Each table of the RAO data base¹³ contains the values of the unit RAO's and the phase angles for each of the six motions as a function of encounter frequency ω_e (see Equation (D.1) of this Appendix), and wave frequency ω , for 30 values of ω between 0.2 and 2.0 rad/sec ($0.0318 < \text{Hz} < 0.318$). Thus, each table in the RAO part of the data base has $30 \times 6 = 180$ values of unit RAO's and 180 values of phase angle. Since there are 65 tables for each ship, there are $180 \times 65 = 11,700$ values of unit RAO's and 11,700 phase angles for each ship for a grand total of 117,000 data points. This number of data points will be compared to those in the RMS/TOE data base and in the time domain data base in the following two sections of this Appendix.

FREQUENCY DOMAIN RMS/TOE DATA (FOR MONOHULLS ONLY)

The RAO data base and the wave spectral formulation (Equation (1) of the main text) can be combined to produce response spectra. The convention usually adopted to accomplish this is to convert Equation (1) of the main text to encounter frequency, ω_e , rather than wave frequency, ω . This requires two transformations. The first converts ω to ω_e :

$$\omega_e = \omega[1 - (\omega V \cos \mu)/g] \quad (\text{D.1})$$

where V = vehicle velocity

μ = vehicle-wave heading angle

g = gravity acceleration

$\mu = 180$ degrees in directly ahead seas

$\mu = 0$ degree in directly astern seas

The second transformation converts $S_{\zeta}(\omega)$ to $S_{\zeta}(\omega_e)$:

$$S_{\zeta}(\omega_e) = S_{\zeta}(\omega) / [1 - (2\omega V \cos \mu) / g]^* \quad (D.2)$$

The product of the ordinate $S_{\zeta}(\omega_e)$ at a particular encounter frequency times the square of the unit RAO at that frequency equals the ordinate of the response spectrum $S_{\eta}(\omega_e)$. That is:

$$S_{\eta}(\omega_e) = [RAO_{\eta}(\omega_e)]^2 S_{\zeta}(\omega_e) \quad (D.3)$$

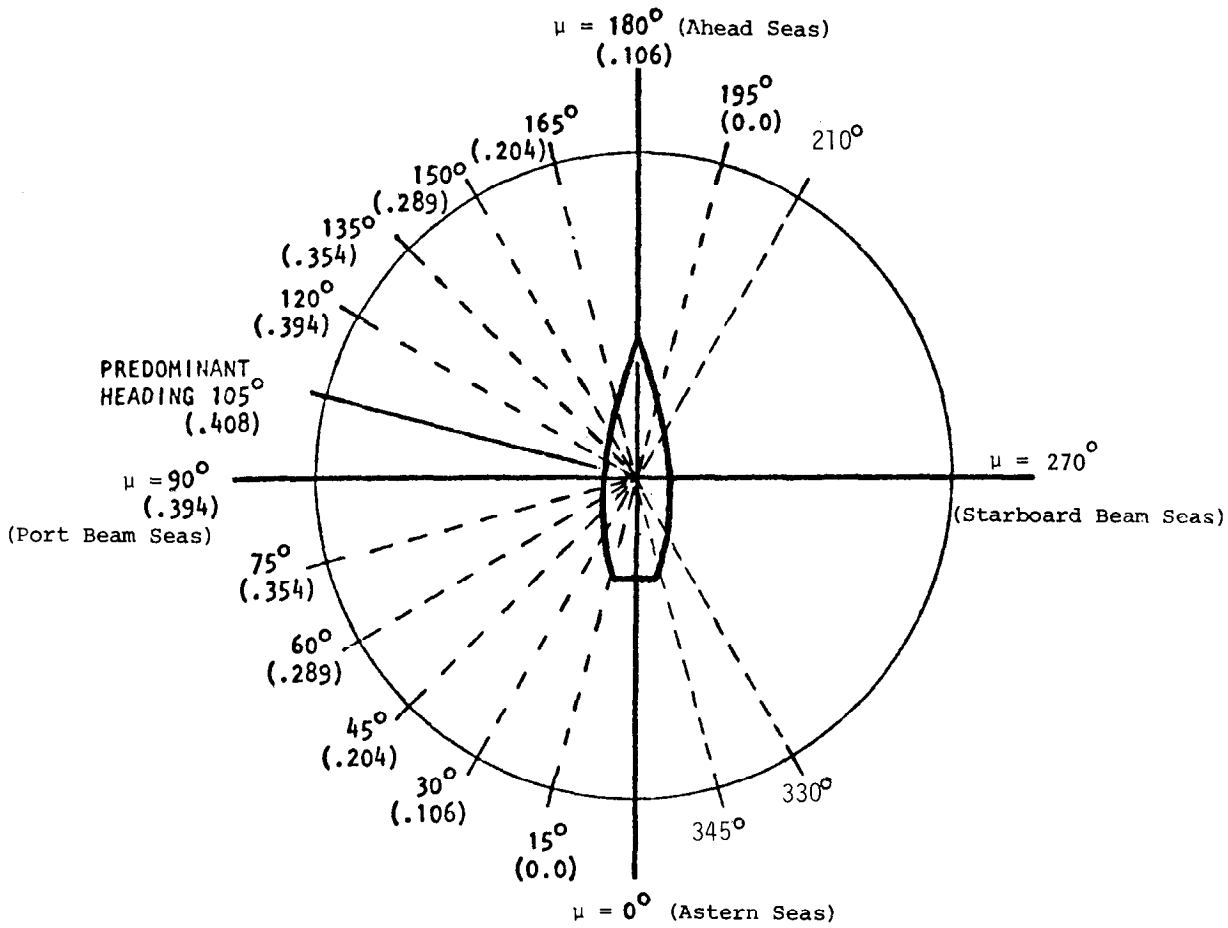
The square root of the area under the response spectrum curve is the root mean square (RMS) value of the response. The peak of the response spectrum occurs at a particular value of encounter frequency ω_e , or period $TOE = \omega_e / 2\pi$. In the Center's RMS/TOE data bases, the values of these two spectral parameters, RMS and TOE, are assumed to represent the entire response spectrum.

Values of RMS and TOE as a function of V , T_o , and μ are given in the RMS/TOE data base¹³ for each response (roll, pitch, etc.) for each ship and for each of two types of seas. Values given are for a significant wave height ζ of 1-ft (0.305 m).** The two types of seas are long crested and short crested. Long-crested (LC) seas assume that all the energy of the ocean waves approaches the ship in a single direction determined by the value of μ . On the other hand, short-crested (SC) seas assume that the energy of the waves is distributed in a \cos^2 fashion to a 180-degree sector centered about the ship's heading relative to the dominant waves. This is shown in Figure D.1 taken from Baitis¹³ for which the ship's dominant heading to the waves is assumed to be 105 deg. The figure shows that the 105-degree wave component would have only a 0.408ζ *** significant wave height, whereas the 120- and 90-degree components

*This transformation insures that the wave energy under the spectrum $S_{\zeta}(\omega_e)$ is identical to the wave energy under the spectrum $S_{\zeta}(\omega)$ (see discussion in text following Equation (1)).

**With the assumption of linearity made earlier in this Appendix, the response RMS values are directly proportional to significant wave height within the constraints mentioned in the previous section of this Appendix.

*** $\zeta = 1$ ft (0.305 m).



NOTE: NUMBERS IN PARENTHESES ARE SHORT-CRESTING WEIGHTS.

Figure D.1 - Short-Cresting Scheme

would have a height of 0.394ζ ,* the 135- and 75-degree components would have a height of 0.354ζ ,* etc., down to a zero wave height at 195 and 15 degrees.

Although the concept of short crested seas corresponds more closely to the reality of most sea conditions, analytical motion predictions using existing Navy programs like that of Salvesen³⁵ for monohulls do not reflect any pitch/roll or yaw/roll coupling. Strictly speaking, therefore, short-crested sea motion predictions are valid only when based on model test generated RAO's which do reflect such coupling. This is not the case with the RAO data base of Reference 13.

The six responses included in the RAO data base¹³ are expanded in the RMS/TOE data base to 11. Two responses of the RAO tables, roll angle ϕ , and pitch angle θ , are retained in the RMS/TOE tables. The other four responses of the RAO data base are combined with roll and pitch and with assumed locations of the axes of rotation of the ship** to form displacements, velocities, and accelerations in the three directions of the earth's axes (longitudinal, lateral, and vertical***), for a total of nine responses:

$$\begin{array}{ccc} x & y & z \\ \dot{x} & \dot{y} & \dot{z} \\ \ddot{x} & \ddot{y} & \ddot{z} \end{array}$$

Values of these nine responses are tabulated for each of three locations on each ship. The first location is the origin of the ship, the second

* $\zeta = 1$ ft (0.305 m).

**The intersection of the calm water waterplane and the transverse, vertical plane through the longitudinal location of the center of flotation of the ship is assumed to be the pitch axis of rotation. The roll axis is assumed to be the intersection of the waterplane and the plane of symmetry of the vehicle. The yaw axis is assumed to be the intersection of the plane of symmetry and the transverse, vertical plane through the longitudinal location of the center of gravity of the ship.

***In Baitis' notation¹³ the words, longitudinal, lateral, and vertical are reserved for motions and for forces acting along the earth axes and at locations other than at the origin of the ship. The words surge, sway, and heave are reserved for the translations along the earth axes of the origin of the ship and roll, pitch, and yaw for rotation of the ship about the earth axes.

location is the aft perpendicular of the ship at the main deck, and the third is the helicopter deck bullseye. Thus, there are $2 + (9 \times 3) = 29$ responses recorded in the RMS/TOE data base.

Each table of the RMS/TOE data base¹³ contains RMS/TOE values for one ship response and for one sea type (LC or SC) for 5 different values of V,* 13 different values of μ ,** and 8 different values of T_o *** for a total of $5 \times 13 \times 8 = 520$ values of RMS and 520 values of TOE. Since there are 29 responses for each ship and two types of seas, LC and SC, there are 58 tables for each of five ships. Thus there are $58 \times 520 \times 2 \times 5 = 301,600$ data points in the RMS/TOE data base¹³ or about 2.6 times as many data points as are in the RAO Data Base.

TIME DOMAIN DATA (FOR MONOHULLS ONLY)

While the frequency domain data base of the previous two sections of this appendix is sufficient to calculate the actual values of most of the applicable seakeeping criteria of Box Scores 1, 2, and 3, it is not sufficient for all applicable criteria. For precise calculation of actual values of three classes of criteria, vehicle motions in the time domain are required. These three classes of criteria are those that:

1. Involve the relative motion of two bodies whose motions are independent of one another (e.g., relative vertical acceleration between a ship and a helicopter approaching it for a landing)
2. Involve highly nonlinear combinations of various vehicle motion components (e.g., shoring forces on objects carried on a deck of a ship that involve motion dependent friction forces), and
3. Depend on the joint (simultaneous) occurrence of any two or more independent vehicle motion components exceeding a certain specified value (e.g., a criterion that stated that the joint occurrence of roll = 5 deg and pitch = 2 deg could not be tolerated).

*V = 5 (5) 25 knots

** μ = 0 (15) 180 deg

*** T_o = 7 (2) 21 sec

The procedure for determining the time history of a response* $r(t)$ from a given response spectrum $S_{\eta}(\omega_e)$ is based on the fundamental premise that any random response is the sum of the responses to each of an infinite number of component sine waves of random phase and amplitude. This premise may be stated as:

$$r(t) = \sum_{k=1}^{k=n} r_k e^{i(\omega_e t + \gamma_k)} \quad (D.4)$$

- where $r(t)$ = response time history
- k = 1,2,3.....(n-1), n (the fundamental premise assumes $n = \infty$; Baitis et al.³⁶ assumes $n = 100$)
- r_k = RMS wave or response amplitude over the frequency interval $\Delta\omega$, with a center frequency ω_k
- $$r_k = \left[\int_{\omega_k - \Delta\omega/2}^{\omega_k + \Delta\omega/2} S_{\eta}(\omega_e) d\omega_e \right]^{1/2}$$
- $\Delta\omega$ = frequency interval
- ω_k = center frequency of each of the k component sine waves
- $S_{\eta}(\omega_e)$ = ordinate of the given wave or response spectrum at each frequency, ω_k
- e = exponential e
- ω_e = encounter frequency
- γ_k = random phase angle between each of the k sine waves
- γ_k = values obtained from a random number generator
- t = time

*The term response is used in a very broad sense here. It includes wave elevation as well as vehicle motion and force responses.

The Time Domain data base of Reference 13 consists of 340 files of 1/2-hour duration, each with values of wave height and responses recorded every 1/2-second or 3600 times. Because of the enormity of the data storage problem, the number of ship speeds was reduced from 5 used in the frequency domain to 4 (5, 10, 20, and 25 knots) in the time domain and the number of wave spectral modal periods was reduced from 8 to 3 (7, 11, and 19 sec). In order to allow the user to generate short-crested ship responses at seven different ship wave-heading angles of 45 deg (15 deg) 135 deg, data for 17 long-crested wave headings -30 deg (15 deg) 210 deg (rather than the 13 in the frequency domain) are included (see Figure D.1).

Each of the 340 files (5 ships \times 4 speeds \times 17 headings = 340) of 1/2-hour duration contains the time histories of the wave elevation and 18 ship responses* in seas having a 10-ft (3.048 m) significant wave height and three values of modal period. Each file therefore contains $19 \times 3 = 57$ time histories. The total number of points stored in the Time Domain data base is, therefore, $57 \times 340 \times 3600 = 69,768,000$ or 167 times as many data points as are in the combined RAO and the RMS/TOE data bases. It should be noted also that the Time Data base applies to only one value of sea severity ($\zeta=10$ ft) whereas the RMS/TOE data base applies to any sea state severity within the linear domain.

Unlike the responses recorded in the RMS/TOE data base¹³, which apply to three different locations on the ship, all 18 responses in the Time Domain data base¹³ apply only to the origin of the ship. The eighteen responses of the origin are:

$$\begin{array}{cccccc} \phi & \theta & \psi & x & y & z \\ \dot{\phi} & \dot{\theta} & \dot{\psi} & \dot{x} & \dot{y} & \dot{z} \\ \ddot{\phi} & \ddot{\theta} & \ddot{\psi} & \ddot{x} & \ddot{y} & \ddot{z} \end{array}$$

However, the Time History Access Computer Program (THACP)¹³ accesses and manipulates the data from the stored Time Domain data base to calculate

*Described in the next paragraph.

1. The nine responses, x , \dot{x} , \ddot{x} , y , \dot{y} , \ddot{y} , z , \dot{z} , and \ddot{z} , for any location in the ship
2. Short-crested time histories (in addition to the long-crested ones in the data base) with dominant wave-ship headings between 45 deg (15 deg) 135 deg
3. The components of the inertial forces due to ship motions exerted on objects supported by the ship in directions parallel to the y_0 axes and the z_0 axes fixed in the ship (not in the earth)
4. The shoring forces required to keep an object resting on the ship's deck from either sliding on the deck or leaving the deck during violent ship motions.

ADDED DRAG AND ALTERED PROPULSIVE EFFICIENCY IN A SEAWAY (FOR ALL VEHICLES)

Because the values of Box Scores 2 and 3 depend on the vehicle speed that can be maintained in a seaway, added drag and altered propulsive efficiency in a seaway are also important responses. However, because Box Score 1 is calculated at a fixed vehicle speed, added drag and altered propulsive efficiency play no role in calculating its value. Only the sea-keeping criteria are needed for its calculation.

Fundamental work on added drag in a seaway for monohulls was done by Maruo.³⁷ His work was constrained to the case of zero forward speed. A recent theoretical extension of that work by Lin and Reed³⁸ accounts for forward speed and is to be used in a new seaway motion and force program for monohulls currently in preparation at the Center. For SWATH's, the theoretical work by Moran and Stephens³⁹ (also based on Maruo's work) is available, but the experimental results by Yeh and Neal⁴⁰ are used for current SWATH predictions. (Because the heave pitch response of a SWATH is highly tuned, their added drag is strongly dependent on wave encounter frequency. This is not taken account of in Reference 39.) Figure D.2 shows typical power increments for foilborne hydrofoils, due to both added drag and altered propulsive efficiency in head seas and power decrements in astern seas as a function of speed. Power predictions, including estimates

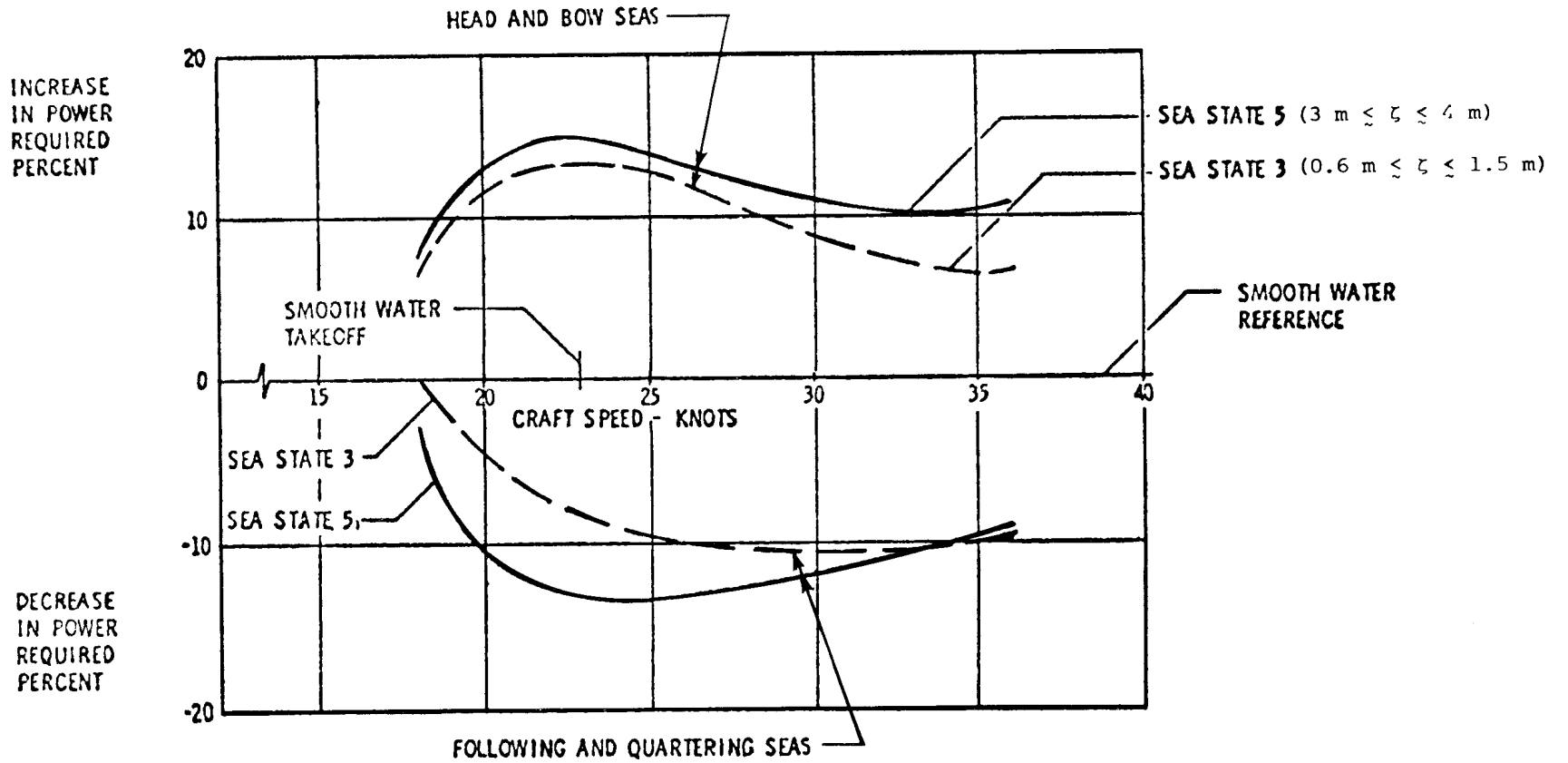


Figure D.2 - Hydrofoil Power Increments and Decrements in a Seaway

added drag in a seaway, are discussed by Wilson and others⁴¹ for SES and by Savitsky and Brown⁴² for planing craft. In the SES reference, account is taken of added skin friction on the inside of the sidewalls due to wave elevation and some account is also taken of Froude-scaled drag on the forward and aft seals. The term "wave pumping" used in SES technology refers to wave action that influences the vertical motions of the vehicle; it is not accounted for in drag predictions for SES's.

The Maruo equation for the dimensional added drag of monohulls in regular waves at zero speed is

$$\Delta R = K(\omega) \rho g (2a)^2 B^2 / L \quad (D.5)$$

The nondimensional coefficient of added drag $K(\omega)$ of Equation (D.5) is defined as

$$\begin{aligned} K(\omega) = & A_{11} [\text{RAO}_z(\omega)]^2 + A_{22} \left(\frac{\lambda}{2\pi}\right)^2 [\text{RAO}_\theta(\omega)]^2 \\ & + A_{12} \left(\frac{\lambda}{2\pi}\right) [\text{RAO}_z(\omega)] [\text{RAO}_\theta(\omega)] \cos(\gamma_{\zeta z} - \gamma_{\zeta \theta}) \\ & + A_{13} [\text{RAO}_z(\omega)] \cos(\gamma_{\zeta z}) \\ & + A_{23} \left(\frac{\lambda}{2\pi}\right) [\text{RAO}_\theta(\omega)] \cos(\gamma_{\zeta \theta}) \\ & + A_{33} \end{aligned}$$

where ΔR = added drag in regular waves

$K(\omega)$ = nondimensional coefficient of added drag

ρ = fluid mass density

g = gravity acceleration

a = regular wave amplitude

B = ship beam

L = ship length

A_{11} = heave nondimensional added drag coefficient

A_{12}	= heave-pitch nondimensional added drag coefficient
A_{13}	= heave-wave nondimensional added drag coefficient
A_{22}	= pitch nondimensional added drag coefficient
A_{23}	= pitch-wave nondimensional added drag coefficient
A_{33}	= wave reflection nondimensional added drag coefficient
$RAO_z(\omega)$	= heave RAO as function of ω
$RAO_\theta(\omega)$	= pitch RAO as function of ω
λ	= wave length
$\gamma_{\zeta z}$	= phase angle between wave excitation and heave
$\gamma_{\zeta \theta}$	= phase angle between wave excitation and pitch
ω	= wave circular frequency

The most significant feature shown by Equation (D.5) is that in regular waves the added resistance is proportional to the square of the wave amplitude. This means that the superposition principle that lay behind all the random responses of the previous two sections of this appendix can be applied to added drag as well. In this case, the RAO will take the form of resistance/(wave amplitude)² = $\Delta R/a^2$. This approach was used by Loukakis and Chryssostomidis¹² and will be used in the new program being prepared at the Center to calculate added drag for monohulls in random seas.

The altered propulsive efficiency in a seaway can be calculated by a program developed by Triantafyllou.⁴³ That program selects a propeller yielding minimum fuel consumption for a selected route. It is thus tailored to the needs of Box Scores 2 and 3. The program was developed to work in conjunction with the seakeeping data available from the seakeeping Standard Series¹², but it can be used for any ship configuration for which a ship motion data base exists.

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