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FOREWORD

This document sets forth the requirements and design criteria for the development of Military Hydrofoil Craft in the areas of ship underway performance and the ship control systems that provide or affect the required underway performance.

This document and its companion document, "Hydrofoil Ship Control and Dynamics Specifications and Criteria - Technical Substantiation" were developed for David Taylor Naval Ship Research and Development Center (DTNSRDC) under Contract N00600-75-C-1107 by Boeing Marine Systems. The subject material herein and the approach to the hydrofoil specification and criteria were developed and guided by a Hydrofoil Design Criteria and Specification Steering Group, under the direction of Mr. R. J. Johnston and Mr. D. J. Clark of DTNSRDC.

The Program Manager for this contract was Mr. C. T. Ray - Manager, Advanced Ship Programs. The Principal Author was Mr. D. R. Stark - Principal Engineer, Ship Controls and Dynamics Staff. Associate authors were Mr. W. E. Farris, Senior Specialist Engineer, and Mr. A. O. Harang, Specialist Engineer.

ABSTRACT

This document sets forth requirements and design criteria for hydrofoil ship control systems and for the controlled ship underway behavior and performance when operating in a seaway.

Key elements of the requirements include ride quality, ship maneuvering and turning, ship operating capabilities in the presence of seas and winds, control system reliability and safety, and control equipment design requirements. Design criteria and guidelines are developed covering dynamic stability, control authority, transient responses, failure modes and effects, hydraulic actuation equipment sizing, electronics development, and design for maintenance.

Analytical tools and methods are also addressed and reporting requirements are defined.

KEY WORDS

Hydrofoil
Requirements
Specifications
Design Criteria
Control and Stability
Ride Quality
Hydraulic Actuation
Ship Steering and Maneuvering
Ship Safety
Control System Hardware

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HYDROFOIL SHIP CONTROL AND DYNAMICS SPECIFICATIONS AND CRITERIA

1. SCOPE

1.1 Content. This specification establishes the general performance, design, development, test, and quality assurance requirements for hydrofoil ship control systems. These requirements include the factors that must be considered in the development of hydrofoil ship control systems and the ship underway behavior or performance features that are strongly influenced or modified by the control systems.

Specific subjects contained in this specification are combined ship underway performance requirements (both foilborne and hullborne); control system design and analysis criteria; reliability and safety criteria; control system hardware requirements; hardware design criteria; and standards for the analytical simulations used in the development of the ship control systems. In a broad sense, those elements commonly ascribed to the terms "seakeeping" and "sea kindliness" are included within these subjects.

In the context of this specification, ship control systems are understood to be those operating systems that cause forces and moments to act on the ship to cause the total ship to maneuver or behave in a desired manner. Excluded are intrinsic systems that may affect control of a ship subsystem but do not by their specific action affect the ship's extrinsic behavior.

This volume is the third in a set of five volumes of "Design Criteria and Specifications for U.S. Navy Hydrofoil Ships" developed under the direction of DTNSRDC for the Naval Sea Systems Command. The title of each volume is given below.

Volume I	General Information Manual
Volume II	Hydrodynamics and Performance Prediction Criteria
Volume III	Hydrofoil Ship Control and Dynamics Specifications and Criteria
Volume IV	Structural Design Criteria
Volume V	Propulsion Systems Design Criteria

A follow-on set of specifications for ship intrinsic subsystems (Volumes VI through XIV) is planned.

In this volume, a major differentiation has been made between requirements and criteria. Requirements identify those major ship or equipment characteristics that are required to enable the ship or subsystem to accomplish given ship missions, or to ensure controllable operation within the range of environments in a manner that is compatible with the human operators. The criteria established herein define those characteristics of the ship and the ship control systems that are considered necessary to satisfy the overall ship requirements. The criteria are not in themselves necessarily a measurable ship *or* equipment response or behavioral characteristic, but their application in the design phase is intended to ensure that the ship and its control system will provide operation compatible with the overall requirements.

1.2 Purpose. The requirements and criteria herein,, in conjunction with the other volumes of "Design Criteria and Specifications for U.S. Navy Hydrofoils", are intended to govern the design, development, and procurement of military hydrofoil ships. As such, they identify the minimum acceptable behavioral characteristics and the minimum design and development activity necessary to ensure that no limitations on ship safety or on the ship's capability to perform its intended missions in its intended wind and sea environment will result from deficiencies in the dynamic performance and control characteristics of the basic vehicle.

1.3 Definitions. For purposes of this volume, the definitions given in the following paragraphs shall hold.

1.3.1 System Definitions

a. Ship Control System - All equipment, displays, and manual input devices necessary for stabilization, attitude control, directional control, and the alleviation of seaway-induced motions of the ship while underway. This includes sensing instruments, computational and signal conditioning equipment, hydraulic actuators, bow thrusters, thrust reversers, electronic power supplies, and power conditioning elements dedicated to the control systems, and those portions of the pilot house console related to input controls and displays of control system parameters and status.

b. Foilborne Control System - All ship control system equipment, displays, and manual input devices necessary to provide foilborne stabilization, attitude and directional control and to alleviate seaway-induced motions. The foilborne control system acts through control surfaces, appendages, or flow modifiers attached to or a part of the foil and strut system.

c. Hullborne Steering and Maneuvering System - All ship control system equipment, displays, and manual input devices necessary for docking, undocking, and maneuvering the ship in the hullborne mode only. The hullborne steering and maneuvering system develops forces and moments through elements independent of the foil/strut system or through control surfaces on the foil/strut system where hullborne operation with struts extended is the intended mode of operation.

1.3.2 **Ship Operation Definitions**

a. Maximum Speed - Maximum speed the ship can attain at the maximum intermittent power setting in calm water under minimum operating condition.

b. Design Speed - Speed at which the ship is capable of operating in calm water at continuous rated power.

c. Cruise Speed - Speed that results in the maximum range factor (minimum fuel consumption per distance traveled) in calm water.

d. Rough Water Design Speed - Average speed which the ship is to be capable of achieving in rough water in at least 90% of the family of sea environments defined in Volume I at any heading relative to the sea on a continuous operating basis.

e. Minimum Foilborne Operating Speed - Minimum speed at which the ship can maintain stable continuous operation in calm water.

f. Hullborne Cruise Speed - Calm water speed which the ship will maintain hullborne using only the hullborne propulsion system(s) at the hullborne cruise power setting.

g. Hullborne Cruise Power - Established power setting of the hullborne propulsion system(s) equivalent to maximum continuous power or a lesser value.

h. Full-Load Displacement - Nominal displacement of the ship at time of delivery with specified allowances for fuel, weapons, crew, and their provisions.

i. Minimum Operating Condition - Displacement of the ship after an extended period at sea. For purposes of this volume the following guidelines shall be used. All ammunition, provisions, and general stores, and all propulsion fuel to be taken at 1/3 of full load. Fresh water and lube oil reserves to be taken at 1/2 of full load. Where salt water ballast is used, normal ballasting procedures shall be presumed.

1.3.3 Environmental Definitions

a. Significant Wave Height - Average height (crest to trough) of the 1/3 highest waves in a sea. Abbreviated H_s.

b. Significant Wave Period - Average period of the 1/3 highest waves. Abbreviated T_s.

c. Fully Developed Sea - For a fully developed sea, the relationship of significant wave height to significant wave period is given by $H_s = T_s^2 (.067)$ when H_s is in meters and T_s is in seconds.

d. Calm Water - Seas with significant wave height less than 0.5 meter.

e. Wind Speed - The average wind velocity measured 10 meters above the mean water level. This velocity can be corrected to other heights using Figure 1.3-1.

1.3.4 Control and Hydrofoil Definitions

a. Flap Control - A method of developing control forces and moments wherein the control forces are developed on a foil or strut by means of appendages to the foil or strut, such as trailing edge flaps. These flaps alter the flow field over the entire foil or strut and thus cause the lift or side forces on the foils or struts to vary, generally in proportion to the flap deflection.

b. Incidence Control - A method of developing control forces or moments wherein the entire foil or strut section is rotated to cause a change in the angle of attack of the foil/strut, which in turn causes forces on the foil/strut to vary generally in proportion to the foil/strut angular deflection.

Data fmm DDS 079-1, "Design
Data Sheet—Stability and Buoyancy
of U. S. Naval Surface Ships",
1 August 1975

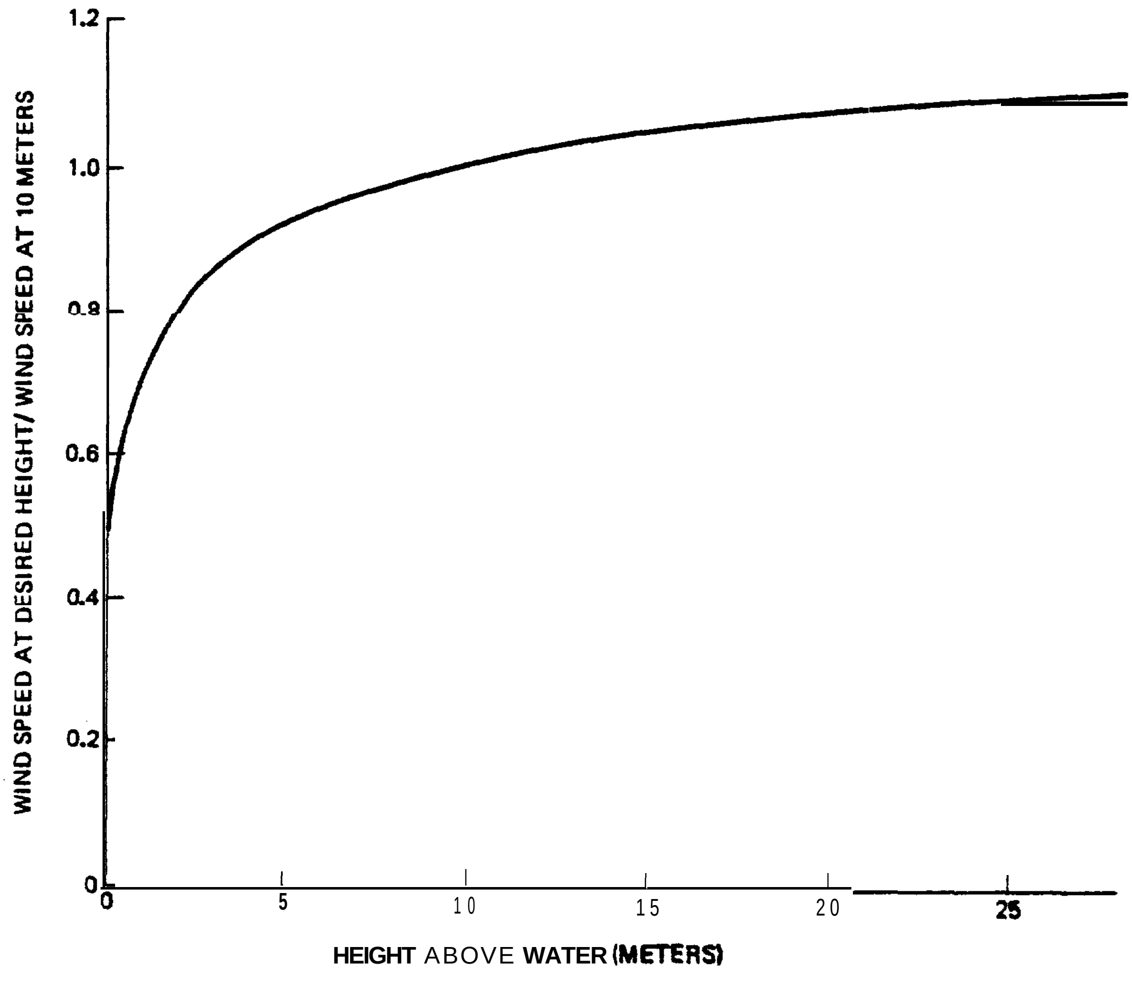

Figure 1.3-1. Wind Speed Correction

c. Line Replaceable Unit (LRU) - That portion of the system (usually a discrete assembly) which by design is the lowest level of breakdown for shipboard fault isolation and replacement.

d. Module - A group of components arranged and packaged together. Generally a line replaceable unit will be comprised of several modules. For example, a printed circuit card with all components mounted and sealed is a typical module.

2. APPLICABLE DOCUMENTS

The following documents, of the issue in effect on the date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein. The requirements of this specification shall govern for control system design where conflicts exist between this specification and other reference specifications.

2.1 Government Documents

2.1.1 Companion Design Criteria and Specification for U.S. Navy Hydrofoil Ships

Volume I	General Information Manual
Volume IA	General Information Manual - Technical Substantiation
Volume II	Hydrodynamic and Performance Prediction Criteria
Volume IIA	Hydrodynamic and Performance Prediction Criteria - Technical Substantiation
Volume IIIA	Hydrofoil Ship Control and Dynamics Specifications and Criteria - Technical Substantiation
Volume IV	Structural Design Criteria
Volume IVA	Structural Design Criteria - Technical Substantiation
Volume V	Propulsion System Design Criteria
Volume VA	Propulsion System Design Criteria - Technical Substantiation

2.1.2 Other Governmental Documents

MIL-STD-1472 - Human Engineering Design Criteria for Military Systems, Equipment, and Facilities

MIL-STD-1378(Navy) - Military Standard Requirements for Employing Standard Hardware Program Modules.

MIL-STD-483 - Configuration Management Practices for Systems, Equipment, Munitions, and Computer Programs

MIL-STD-467 - Electromagnetic Interference Characteristics Requirements for Equipment

MIL-STD-810 - Environmental Test Methods

MIL-STD-167 - Mechanical Vibrations of Shipboard Equipment

3. REQUIREMENTS

3.1 System Description

3.1.1 General. The military hydrofoil ship governed by these specifications is understood to be of the fully submerged subcavitating* foil type employing one or more struts which separate the underwater foil systems from the hull. The hydrofoil ship is capable of operating either foilborne or hullborne.

For purposes of these specifications, the term "foilborne" shall include takeoff, landing, and all operation where the major portion of the lift and/or a major portion of the forces and moments acting on the ship are provided by the foils and struts.

The ship control system shall consist of at least a foilborne control system and a hullborne steering and maneuvering system.

The control systems, for purposes of this specification, shall include:

a. Ship motion and attitude sensors
b. Operational controls and displays
c. Computer systems that process the inputs and generate control commands
d. Actuators that position the control surfaces
e. The hydrodynamic control surfaces that are positioned by the control system
f. All other force producers such as bow thrusters, thrust reversers, etc.
g. Power supplies that provide the basic power for the control signals, forces, and moments.

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* A subcavitating foil system is one where the nominal and intended operating conditions have the foil system fully wetted. This is to differentiate it from the supercavitating regime where the foil system is operated with major portions of the foil deliberately unwetted.

Figure:3.1-1 depicts those elements of the ship that comprise the control systems for purposes of this specification.

Except where specifically stated to the contrary in the subsequent paragraphs, it shall be understood that the terms "hullborne operation" and "foilborne operation" are not to be construed as being exclusionary of any other mode of operation; i.e., it shall be allowable to use foilborne control equipment to augment hullborne steering equipment in the hullborne mode if such is practical.

Unless specifically stated to the contrary, these-requirements shall be satisfied over the normal range of weights and center of gravity locations that occur between full load displacement and minimum operating condition.

3.1.2 Missions. The controlled hydrofoil ship is a platform that can be used for a multitude of missions including patrol and surveillance, antisubmarine, anti-air, surface engagement, fleet defense, etc. The platform (the controlled ship) must be capable of performing in such a manner in all its intended environments and usages that ship motions and accelerations do not pose operating limitations. In this context, the mission of the controlled platform is to assure that the ship is capable of operating in the specified family of sea and wind environments in such a manner that the operator can:

a. Takeoff and land the ship at any heading relative to the sea.
b. Select and maintain any speed within the specified limits.
c. Select and maintain any heading relative to the sea and wind.
d. Maneuver in any direction relative to the sea and wind.
e. Dock and undock without assistance from other vehicles.

3.1.3 Interface Definitions. For purposes of this volume, the following interface definitions shall hold:

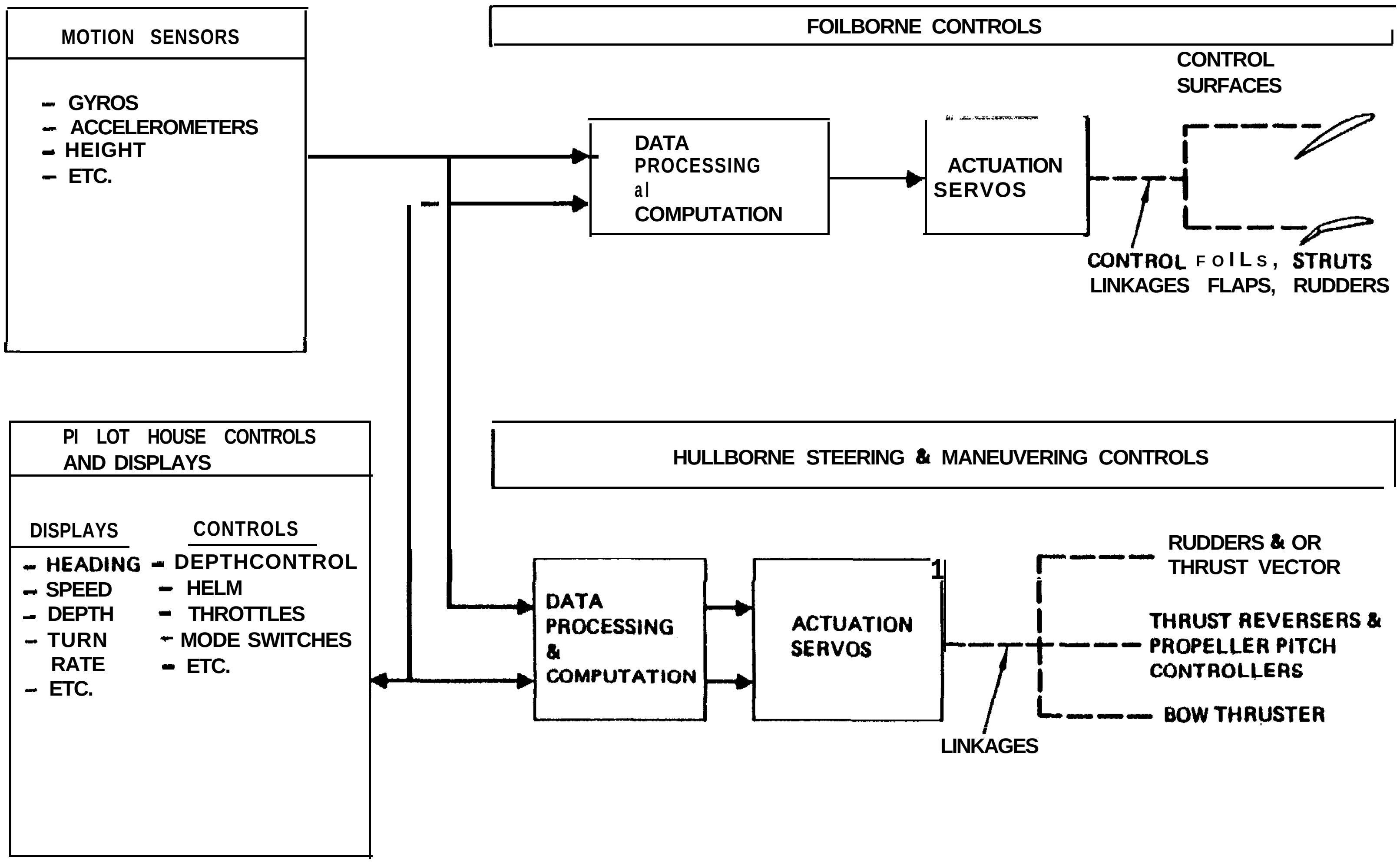


Figure 3. 1- 1. Overview-ship Dynamic Control Systems

a. Ship Axis System - Ship axis system shall be in accordance with Figures 3.1-Z and 3.2-l for all control system and ship performance studies. (It is noted that certain weapon system equipment standards deviate from these definitions). The contractor is responsible for identification of conflicts between other ship system axis notation and those defined herein and for providing proper interfaces between the two wherever these systems are coupled together.

b. Hydraulic System/Control System Interface • For purposes of this specification, the hydraulic actuators and their integral equipment, such as servovalves and transducers, are to be considered a part of the control systems. The hydraulic supplies, prime movers, filters, accumulators, lines, etc., are to be considered part of the hydraulic supply system. This distinction is limited to hydraulic actuators that are used to position control surfaces, rudders, thrust reversers, thrust vectors, etc., which in turn produce control forces and moments on the ship.

c. Electrical/Control System Interface • For purposes of this specification, the electrical equipment that conditions, converts, regulates, transforms, and distributes electrical power to the various control system equipments shall be considered a part of the ship control system. The ship prime movers, generators, and primary power regulation and distribution systems are to be considered a part of the ship's electrical subsystem.

3.1.4 <u>Ship Operating Environment</u>. The potential hydrofoil ship operating environment is in reality an infinite family of sea and wind conditions. For purposes of the ship design criteria and specifications, the sea environment is defined as a family of possible sea conditions and the associated probability of their occurrence.

The specific definition of the sea and wind environments is contained in Volume I, since it is general to all ship systems design. For purposes of

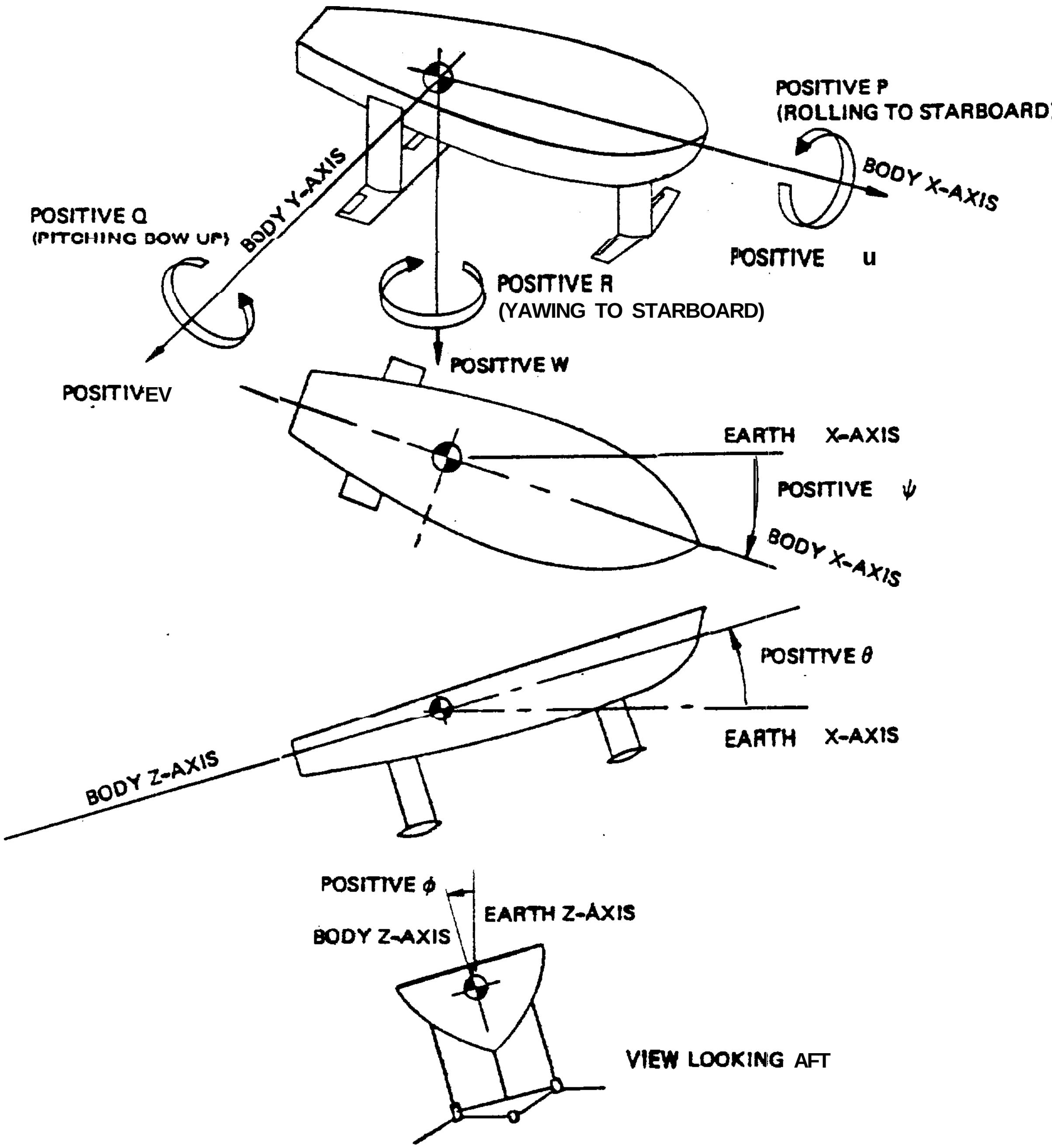


Figure 3.1-2 Ship Axes System & Definitions of Linear & Rotational Vectors

this volume, the format and statistical definitions of the various sea conditions are reprinted for clarity and completeness.

3.1.4.1 Sea Condition Definitions for Design Purposes. The design family of sea conditions is provided in the format of Table 3.1-7, where each individual sea condition is defined by the two parameters, significant wave height (H_s) and significant wave period (T_s). The cognizant program office will determine one or more ocean areas that are the intended areas of operation or that are representative of the intended operational areas and, based on oceanographic data for these selected areas, ,the probability of occurrence data will be supplied for Table 3.1-1. Table 3.1-2 shows a typical specification with the detailed probability of occurrence values for each block filled in. These data are for year-round sea conditions as recorded for the North Sea.

3.1.4.2 Analytical Representation of the Sea. For purposes of design, each block within Table 3.1-l may be represented by one discrete unidirectional (long-crested) sea defined by the following formulation:

$$S(\omega) = 0.11 \left(\frac{2\pi}{T_s}\right)^4 H_s^2 \, \omega^{-5} e^{-.44\left(\frac{2\pi}{T_s \omega}\right)^4}$$

where: $S(\omega)$ = energy density spectrum of the long-crested seaway.

H_s = significant wave height (average height of the 1/3 highest waves).

T_s = significant wave period (average period of the 1/3 highest waves).

ω = wave frequency (radians per second) as observed from a fixed point.

3.1.5 Environmental Operability. Ship motions, performance, and overall effectiveness in accomplishing given missions are affected by the sea and wind environment. As seas and winds become more severe, motions and accelerations tend to increase while perfonance and mission effectiveness

Table 3.1-1. Specification "Family of Operating Sea Conditions"

Significant wave height (meters)	Significant wave period (seconds)								
	*	< 5	6-7	8-9	10-11	12-13	14-21	>21	Totals
< 0.25									
0.5									
1.0									
1.5									
2.0									
2.5									
3.0									
3.5									
4.0									
4.5									
5.0									
5.5									
6.0									
Totals									

*Calm or period undetermined

Table 3.1-2. Typical Specification for Sea Con&ions in the North Sea

Tabulated Numbers show the Percentage of Expected Seas Within Each Height and Period Section

Significant wave height (Meters)	Signifiant wave period (seconds)							
	•	< 5	6-7	8-9	10-11	12-13	14-21	> 21	Totals
< 0.25									
0.5 a25	a45 a33	11.26 4.13	0.24	0.34	0.05	0	0.01	0.07	10.92
						0.01	0.02	0.34	13.94
1.0	0.50	16.75	6.17	1.07	0.26	0.09	0.13	0.16	25.14
1.5	0.38	7.42	6.28	2.15	0.68	0.16	a12	aoi	19.20
20	a29	2.04	5.18	2.46	a64	0.11	0.05	0.04	10.80
25	0.16	0.97	281	2.18	0.80	0.18	0.04	0.01	7.15
3.0	0.05	a52	1.74	1.16	a75	0.18	0.08	0	4.49
3.5	0.14	al7	a92	1.38	a56	a26	0.02	0	3.47
4.0	0.05	0.17	a47	a59	a39	a14	0.05	0	1.87
4.5	0.05	0.08	0.41	0.47	a26	al6	0.10	0	1.53
5.0	0.01	0.03	0.04	0.05	0.08	0.03	0	0	0.23
5.5	0.04	0.01	0.05	0.11	0.09	0	0	0	0.30
6.0	0.03	0.01	0.05	0.11	0.05	0.04	0.02	0	0.31
6.5	0	0	0.07	0.06	0.11	0.04	0.01	0	0.29
7.0	0.01	0.01	0	0.03	0.01	0.03	0	0	0.09
7.5	0	0	0	0.03	0.03	0.01	0.01	0	0.08
8.0	0.01	0.01	0.03	0.04	0	0	0	0	0.09
a5	0	0	0	0	0.01	0	0.01	0	0.03
9.0	0	0	0	0.01	0.01	0	()	0	0.03
9.5	0	0	0	0.03	0.01	0	0	0	0.04
Totals	a50	43.59	27.87	12.33	4.92	1.44	0.71	0.63	100.00

• Calm or period underternined

tend to degrade. The degree of degradation is dependent upon the specific sea and wind conditions, ship size and design parameters, as well as ship operating specifics such as speed, heading relative to the seas and wind, and maneuvering.

The specifications herein are written in the context of environmental operability requirements in that the emphasis is placed on ensuring effectiveness of the ship and its personnel when operating in the large family of sea environments identified in Section 3.1.4.

In the following requirements, the emphasis is on the ship being able to accomplish its intended mission without serious degradation to effectiveness for a vast majority of operating conditions. Thus, the scenario upon which the rough water operational requirements are based is as follows:

a. Design sea conditions (family of year-round sea conditions as defined in sea state specification (Volume 1))

b. Design assumptions (unidirectional sea; ISSC/Bretschneider spectral definition defined by significant wave height (H_s) and significant wave period (T_s))

c. Design wind conditions (family of year-round winds as presented in Volume 1, both steady state and gusts)

d. Ship heading (heading relative to sea, worst case; heading relative to steady state wind, wind aligned with sea; and heading relative to wind gusts, worst case)

e. Operability requirements (under the above defined conditions, the specifications require full compliance with the requirements for 90% of the sea conditions.)

3.1.6 Operational and Organizational Concept. The requirements and criteria contained herein are predicated on the premise that all direct ship operation relating to steering, docking, speed selection, and control system mode selection are to be accomplished by a single crewman, namely the helmsman.

No specific interdependence between the helmsman and the ship's command and control function is required. Likewise, no specific interdependence between the control systems and the ship's navigation systems and weapon systems is intended. It is presumed that necessary interfaces between such functions and systems will be resolved in the detail design phase.

The control system hardware requirements contained herein are based on a maintenance concept that requires repair be accomplished by a remove and replace action, with no onboard repair of equipment other than cables and associated items such as connectors and junction boxes. The requirements are further predicated upon the concept of a depot or other support facilities that provide capabilities to repair and to functional test the shipboard replaceable assemblies in order to ensure that a replacement assembly is operating properly prior to placement in the ship.

3.2 Ship Foilborne Performance Requirements. The requirements outlined in the following sections represent the minimum acceptable behavioral characteristics of the controlled hydrofoil ship, when operating in the design sea and wind environments as defined in Volume 1, Sections 3.6.1 and 3.6.2. In general the requirements are so stated that they should be satisfied at any speed (where speed is applicable) and at worst case headings relative to the sea and the wind for at least 90% of the family of sea and wind environments defined.

It must be recognized that some ship control system requirements can arise from other ship subsystem considerations. For example, requirements for load alleviation to support the structural design may become a very real requirement on the control systems. Such subsystem-related requirements must be developed by the contractor, as necessary to support the overall design, and their omission herein shall not be construed as an intent to relegate their importance to a lower level.

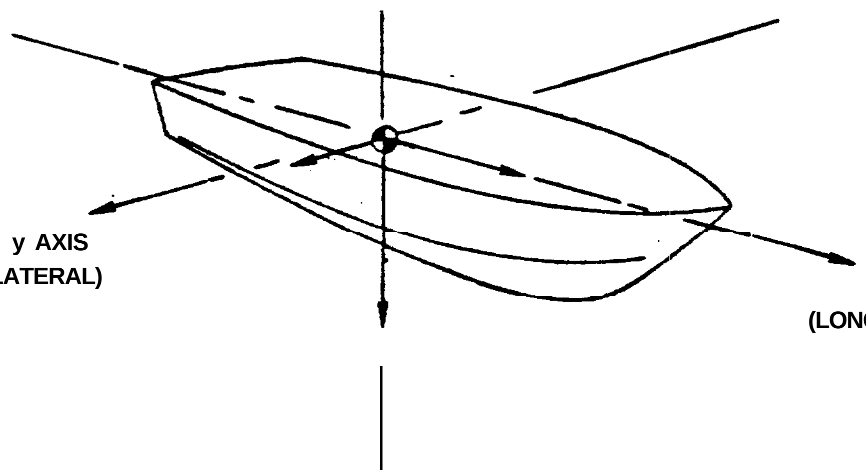
3.2.1 Ride Quality. Ride quality requirements are defined in terms of accelerations in the three principal ship axes: vertical (z axis), longitudinal (x axis), and lateral (y axis). Figure 3.2-1 depicts the ship axis system and defines the sign convention associated with acceleration.

The requirements herein are applicable to the primary ship operating stations and the living areas only. The requirements stated must be satisfied at any heading and at any average operating speed at or below the "design rough water speed." The design sea conditions for which these requirements apply shall be the entire "family of operating sea conditions" as defined per Volume I, Section 3.6.1.

3.2.1.1 Frequency Weighting for RMS Acceleration Measurements. Vertical acceleration measurements shall be frequency weighted according to Figure 3.2-2. Lateral and longitudinal acceleration measurements shall be frequency weighted according to Figure 3.2-3 for all RMS ride quality requirements.

3.2.1.2 Weighted RMS Accelerations. The RMS values of the frequency weighted acceleration function shall be in accordance with the following requirements:

a. Weighted vertical acceleration <.11g RMS 90% of days of year
b. Weighted vertical acceleration <.06g RMS 50% of days of year
c. Weighted lateral acceleration <.06g RMS 90% of days of year
d. Weighted lateral acceleration <.04g RMS 50% of days of year



- Vertical acceleration refers to accelerations directed along the craft z axis. It is the acceleration which would be measured by an accelerometer whose sensitive axis is aligned with thr craft z axk Note that this definition encompasses simple translational accelerations along the z axis and rotational accelerations.
- Lateral acceleration refers to accelerations directed along the craft y axis and similarly thh acceleration is a combination of translational and rotational accelerations as would be measured by an accelerometer whose sensitive axis is aligned with the craft y axis.
- Longitudinal acceleration refers to acceleration directed along the craft x axis and as for the previous definitions, encompasses both lineal and rotational accelerations.

Figure 3.2-1. Acceleration Axes Conventions

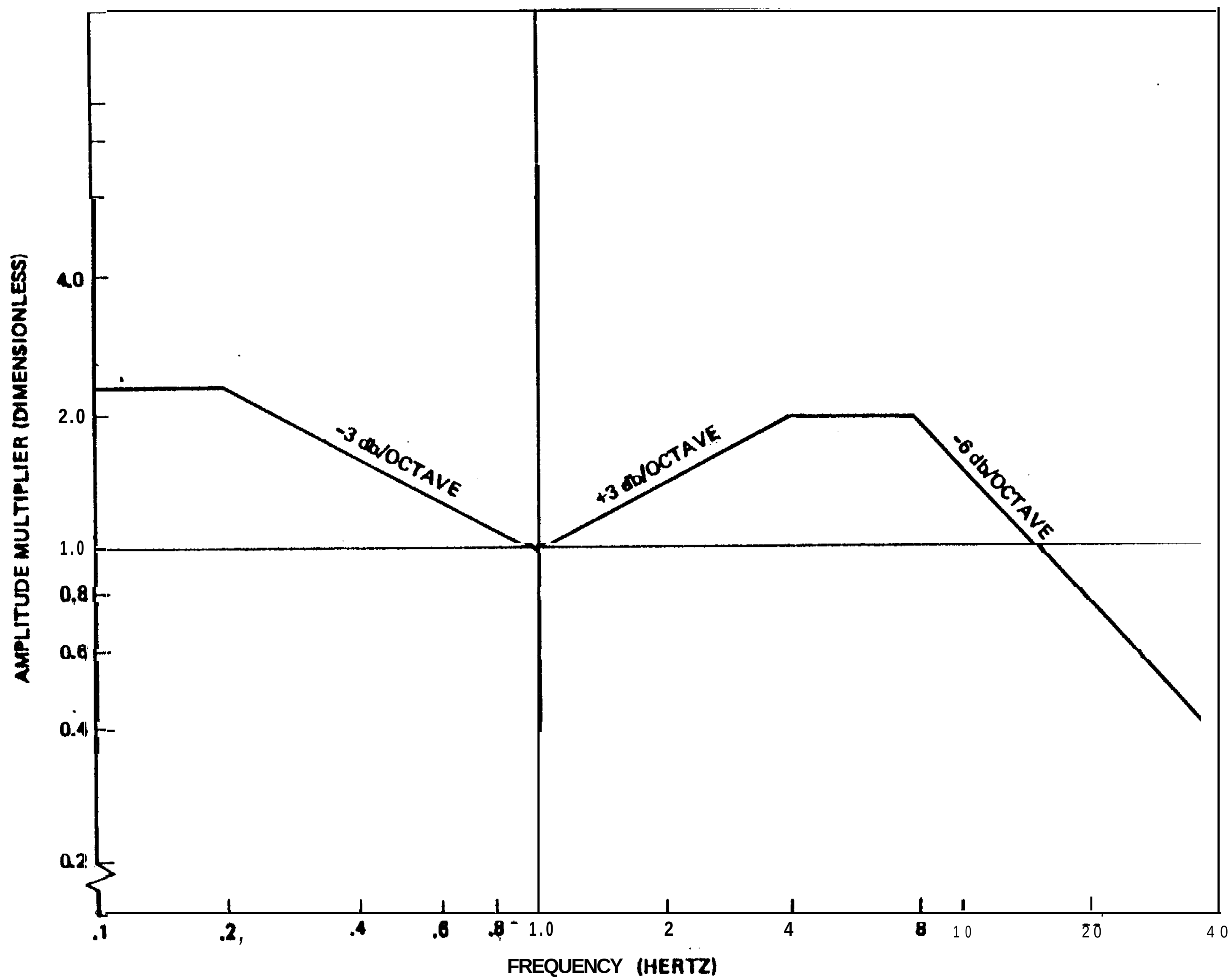


*Figure 3.2-2. **Vertical Acceleration Frequency Weighting for Ride Quality Evaluations***

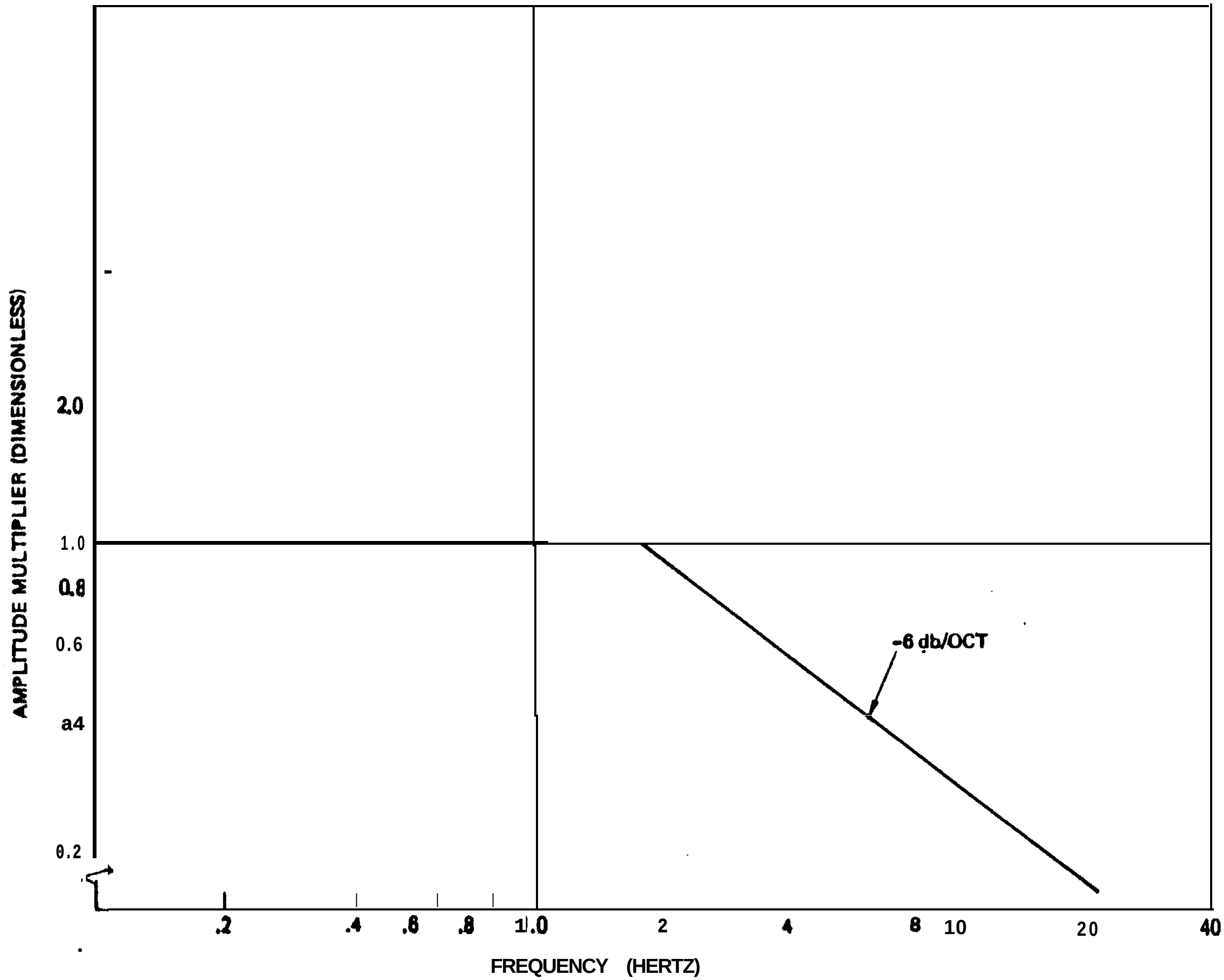


Figure 3 2-3. Lateral Acceleration Frequency Weighting for Ride Quality Evaluations

3.2.1.3 Large Discrete Acceleration Peaks. Large acceleration peaks associated with the occurrences of foil broaching,* hull slamming,† and hull cresting‡ shall be considered in the design. At worst case headings in the family of sea environments as defined in Volume I, Section 3.6.1, the following requirements as related to broaching, slamming, and cresting shall apply for 90% of the days of the year:

a. Vertical acceleration peaks greater than 0.5g < 1/minute
b. Lateral acceleration peaks greater than 0.25g < 1/minute
c. Longitudinal acceleration peaks greater than 0.25g <1/minute

3.2.2 Motions. Ship angular motions for purpose of this specification include pitch angle, roll angle, and pitch, roll, and yaw angular rates. The basic measure of angle and rate motions is the standard deviation of the variable.

The requirements for ship motion are limited to the variations of these five variables which result from seaway disturbances. The steady state or quasi steady state values of these variables are not a part of this requirement.

The ship angular motions and rates shall be such that they do not exceed weapon system requirements while operating at any heading relative to the sea and turning at rates up to the rough water design turn rate in the combined presence of 90% of the expected sea and wind conditions as defined in Volume I.

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* A foil broach is defined as the unwetting of a foil with resultant loss of lift due to the foil coming near to or clear of the air water interface.

† Hull slamming is defined as the impacting of the next wave, following a foil broach.

‡ Cresting is defined as the impacting of a wave crest by the hull in the absence of the downward velocity that characteristically results from a preceding foil broach.

In the-absence of specific requirements from the combat systems, the following requirements should be considered as design guidelines in combined presence of 90% of the expected sea and wind conditions as defined in Volume I, and at any heading:

a. 1σ pitch angle < 1.50 degree
b. 1σ roll angle < 1.25 degree
c. 1σ pitch rate < 2 degrees/second
d. 1σ roll rate < 2 degrees/second

3.2.3 Maneuverability and Turning (Foilborne). Maneuverability and turning are defined in terms of turn rate, tactical diameter, advance, and transfer distances as shown in Figure 3.2-4. The following requirements are to be understood to be limited to turning capabilities as stated, and no companion requirements on speed or pitch attitude are to be implied.

3.2.3.1 Calm Water Turning and Maneuvering. At all foilborne speeds from design speed to minimum foilborne speed, in seas less than 0.5-meter significant wave height, the following requirements shall hold:

a. Advance distance shall be less than 500 meters.
b. Tactical diameter shall be less than 750 meters.
c. The ship shall be capable of accomplishing at least a 180-degree turn at an average turn rate of 6 deg/sec with the speed remaining greater than minimum foilborne.

3.2.3.2 Rough Water Turning and Maneuvering. At foilborne rough water design speed in the presence of seas and winds as defined in Volume I, Section 3.6.1, the following requirements shall hold:

a. Average turn rate shall exceed 4 deg/sec for at least a 180-degree heading change in the combined presence of seas and winds up to the 90% level of wave heights and wind velocity as defined in Volume I, Section 3.6.1.

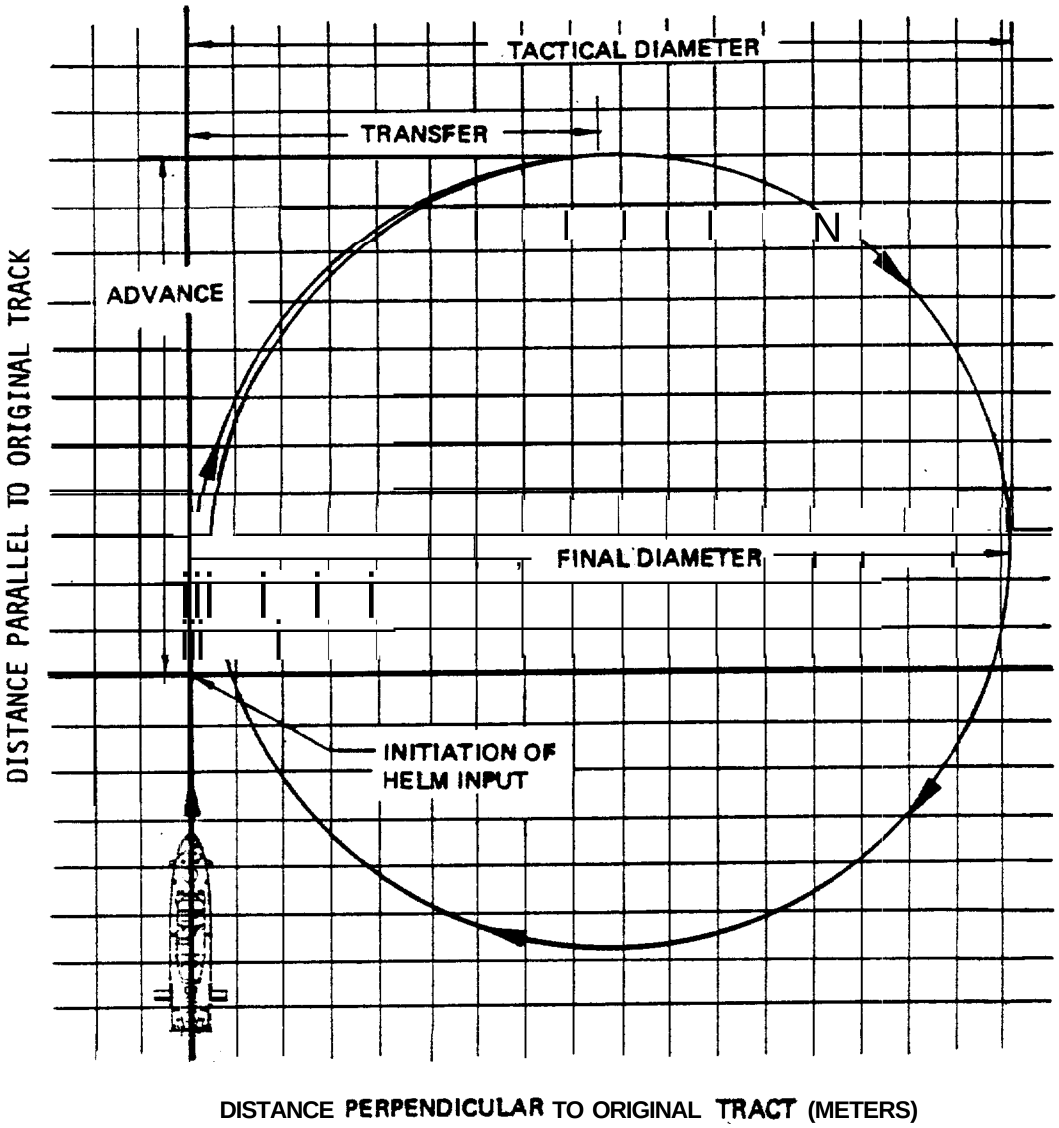

Figure 3.2-4. Maneuvering & Turning Definitions

b. In the presence of wind gusts, up to 50 knots, the ship shall be capable of turning into the gust at a turn rate of at least 1 deg/sec.

c. The ship shall be capable of maintaining any average heading while operating at its design rough water speed in the presence of a W-knot steady state wind.

3.2.3.3 Tactical Maneuvering. The tactical maneuvering requirements for a ship will to a large extent be dictated by the specific missions and the specific offensive and defensive weapons employed. Thus tactical maneuvering requirements should be provided as a part of the "Top Level Requirements" (TLR) for a specific ship or class. Where such tactical requirements are given, they shall supersede the requirements of paragraphs 3.2.3.1 and 3.2.3.2 in those areas where the tactical requirements are more stringent.

If specific tactical turning and maneuvering requirements are not delineated by the contracting office, then the contractor shall conduct an analysis of the ship's tactical maneuvering capabilities, considering both the offensive and defensive tactical missions. Such analyses shall investigate limitations placed upon the weapons deployment by maneuvering, as well as the potential advantage to be attained in combat survivability by evasive maneuvering.

Such investigations shall include but not be limited to the following:

a. Use of battle overrides which would allow degradation of other elements of the ship performance in order to enhance combat effectiveness

b. Use of automatic or programmed maneuvering as evasive tactics

c. Use of partially coordinated or flat turns to enhance weapons effectiveness

3.2.4 Automatic Heading Hold and Maneuvering. Automatic heading hold and maneuvering functions shall be provided for use at the operators option. The system shall have the capability of automatically maintaining the ship on an ordered heading without continuous helm inputs and of causing the ship to perform certain programmed maneuvers upon command as specified below.

3.2.4.1 Heading Hold. At any and all headings relative to the seas and wind as defined in Volume I, and in all seas and winds up to the 90% level of wave height and wind velocity, the ship shall be capable of maintaining a mean heading within ± 2 degrees of the ordered heading, and the standard derivation (1σ value) of heading variation about the mean shall not exceed 3 degrees.

3.2.4.2 Automatic Maneuvering

a. The ship shall be capable of automatically conducting a Williamson turn in the following manner:

   o Williamson turns (see Figure 3.2-5) to the right and to the left shall be selectable.

   o The ship shall return within 100 meters of the point where the maneuver was initiated and at that time be within ± 4 degrees of the reverse course.

b. The ship control system design shall provide for future interfaces with the navigation system and the weapons control systems so that automatic navigation and maneuvering may be accomplished in accordance with input from the navigation system the weapons system.

3.2.5 Foilborne Speed Range. The ship shall be capable of foilborne operation over a sufficiently wide range of foilborne speeds that the operators will have the latitude to freely alter course, maneuver, and to operate in rough water without the need to stabilize at a precise speed before accomplishing any given maneuver. Therefore, the following specific speed range capabilities shall be provided for in the design.

3.2.5.1 Calm Water Speed Ranqe. The ship shall be capable of

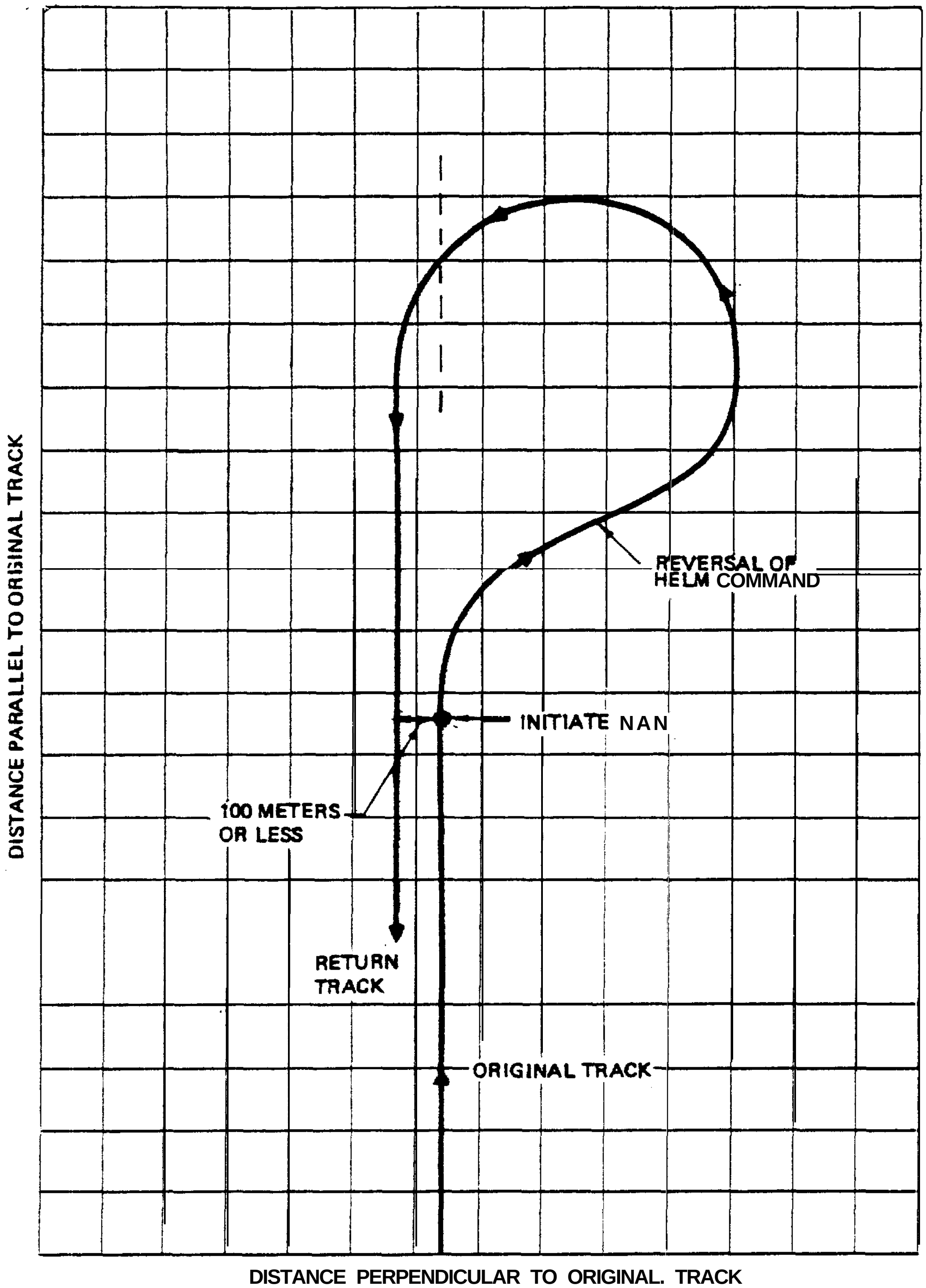

Figure 3.2- 5 Williamson Turn Characteristics

operating in calm water* at any speed between 100% and 70% of the design speed. If tactical requirements specify a lower speed, that lower speed requirement shall hold.

3.2.5.2 Rough Water Speed. The ship shall be capable of maintaining a mean speed of at least 80% of the design speed at any heading in the combined presence of sea and wind conditions up to the 90% level of significant wave heights and wind velocities as defined in Volume I, Sections 3.6.1 and 3.6.2.

3.2.6 Operating Capabilities Beyond Design Conditions

3.2.6.1 Rough Water Capabilities. The ship shall have adequate control capability to operate foilborne in up to 98% of the expected sea conditions as defined in Volume I, if thrust is sufficient to operate in these seas.

3.2.6.2 Maximum Speed Limitation. The maximum operating speed shall not exceed the smooth water design speed by more than 10% unless the following are accomplished:

a. Hydrodynamic and/or full-scale testing and analysis of the foil system to verify adequate control surface effectiveness at speeds greater than 110% of the maximum design speed, and

b. Detailed analysis of ship motions, maneuverability, stability, and safety at speeds greater than 100% of smooth water design speed. These studies shall verify the ship will meet the specified safety requirements.

The ship operation shall be placarded for all speeds not covered by detailed analyses and trials verification. Should excess power be retained and available to the operator for such uses as takeoff and rough water operation, then the throttle quadrants should employ some type of detect or intermittent travel restriction to prvent routine power settings that exceed the placarded speed range.

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* Calm water is defined as seas with significant wave height less than 0.5 meter.

3.2.6.3 Minimum Speed Capability. To ensure safe operation at the low speed end of the operating envelope, a minimum speed envelope shall be developed as a function of turn rate and sea state. The design shall include provisions for incorporating the minimum speed envelope into the ship operations manuals.

Automatic speed control shall be considered to improve the ability to maintain a stable operating speed, and to expand the low speed operating envelope.

3.2.7 Transition From Hullborne to Foilborne. "Transition" refers to the passing from the hullborne operating regime to the foilborne regime. During this transition, when the ship speed is above hullborne cruise and below minimum foilborne operating speed, it shall be possible to conduct turns to either side at turn rates of at least 2 degrees per second in seas of less than 0.5-meter significant wave height and wind velocities less than 5 knots.

3.3 Ship Hullborne Performance Requirements. The requirements outlined in the following paragraphs represent the minimum steerinq, maneuvering, and underway behavioral characteristics of the hullborne ship. It should be recognized that the hydrofoil ship, by nature of its being a "hydrofoil," may have multiple configurations or operating modes when hullborne; for example, foils extended and foils retracted, are both viable hullborne modes. The requirements herein are not intended for a specific ship operating configuration, rather they identify the behavioral and maneuvering requirements in whatever configurations the ship is designed to operate.

3.3.1 Motions. Provisions shall be included in the design for use of the foilborne controls to reduce hullborne motions and enhance maneuverability when underway with the foils extended. In the absence of specific requirements from the combat systems, the following shall be considered as design guidelines.

For hullborne operation with the foils extended, and at hullborne cruise power settings, the angular motions and rates at any heading should be less than the following values for 90% of the expected sea conditions as defined in Volume I, Section 3.6.1.

- 1σ pitch angle < 3 degrees
- 1σ roll angle < 3 degrees
- 1σ pitch rate < 2 degrees/second
- 1σ roll rate < 2 degrees/second
- 1σ yaw rate < 2 degrees/second

3.3.2 <u>Turning and Maneuvering.</u>. With an initial speed equivalent to the hullborne cruise speed and in seas less than 0.5 meter, significant wave height and wind velocities less than 5 knots, the following shall apply:

a. Tactical turning diameter with foils retracted shall be less than four overall ship lengths if foils-retracted operation is a required hullborne operating mode.

b. Tactical turning diameter with foils extended shall be less than six overall ship lengths.

3.3.3 <u>Reversing.</u> In calm seas and wind velocities less than 5 knots, the following shall apply:

a. The ship can be stopped in less than six overall ship lengths when operating straightaway at hullborne cruise speed, or at 12 knots whichever is less.

b. The ship shall be capable of backing at a speed not less than 4 knots at maximum continuous power rating of the propulsion system.

c. When backing at maximum astern speed or 5 knots, whichever is less, the ship shall maintain heading within plus or minus 10 degrees of the ordered heading using normal steering controls.

3.3.4 Docking and Undocking. The ship shall be capable of docking and undocking in a restricted docking area with a 20-knot beam wind opposing the maneuver using normal ship propulsion devices and docking lines. In the absence of specific requirements from the program office, the restricted docking area shall be as long as two overall ship lengths with obstructions at either end equivalent to the ship's maximum beam at the main deck. Figure 3.3-1 depicts the restricted docking area.

3.3.5 Automatic Heading Hold. An automatic heading hold shall be provided that will maintain the mean heading within ±5 degrees of the ordered heading with the struts and foils extended and the ship operating at hullborne cruise power setting at any heading relative to the seas in the combined presence of 90% of the expected sea and wind conditions as defined in Volume I, Section 3.6.1.

If a foils-retracted hullborne operating mode, other than harbor maneuvering and docking, is provided in the design, then an automatic heading hold system shall be incorporated that can maintain the mean heading within ±5 degrees of the ordered heading in calm seas and in the presence of 15-knot winds.

3.3.6 High-Speed Hullborne Operation and Control. Provisions shall be made for activation of portions or all of the foilborne control system for high-speed hullborne operation when operating with the foils extended on either the foilborne or hullborne propulsion system(s).

This high-speed hullborne mode shall utilize the foilborne control system to augment hullborne steering, provide alleviation of hullborne roll motions, and provide trimming of lifting surfaces and hull attitude to minimize overall drag. The range of operation for this mode shall include but not necessarily be limited to speeds from 8 knots to 80% of the speed corresponding to the maximum drag hump during takeoff.

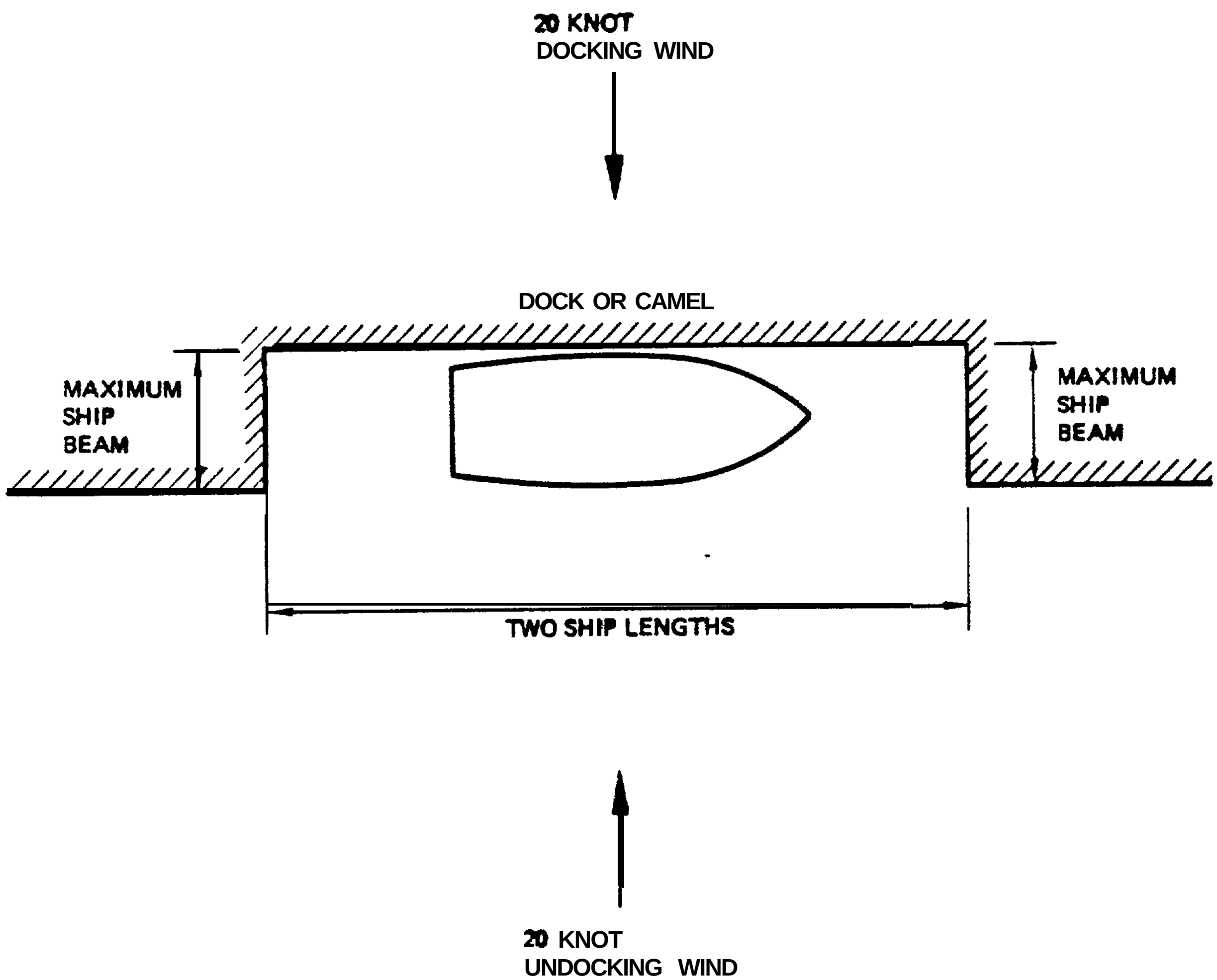

Figure 3.3-1. Restricted Docking Area

3.3.7 . **Emergency Steering.** The ship design shall provide for at least two separate hullborne steering systems operable from the helm station. The foilborne control system may satisfy the requirement for one of these systems. In addition, devices or equipment shall be provided to accomplish emergency steering with all electric and hydraulic supplies inoperative and either the hullborne or foilborne propulsion system operating to provide propulsive power.

The design shall also incorporate devices or equipment which can center or retract any inoperable steering device or thrust reversing device which could prevent steering of the ship with the emergency steering devices.

In satisfying this requirement, separate, hand pumped hydraulic steering capability would be allowed, but it is presumed that both the ship's electrical generating capability and the engine powered hydraulic supplies are all inoperative.

3.4 **Control System Dynamic Analyses and Design Criteria.** In the development and design of a ship or weapon system, there are a multitude of problems and decisions that have to be addressed. In the following sections, design criteria and guidelines are given to ensure adequate capabilities and margins in ship design.

In general, it is understood that the major portion of the control system functional design and significant elements of the ship foil system configuration will be developed using a dynamic simulation of the ship, control system, and seaway. Detail requirements regarding the simulation are covered in Section 3.7.

3.4.1 **Foilborne Trims.** Foilborne trims are the steady state or average value of ship position and attitude relative to the water surface and the mean angle of attack on the lifting surfaces, struts, and control surfaces.

3.4.1.1 **Trim Schedules.** Fitch and height trims will tend to vary with speed and with ship weight and center-of-gravity location. The control system design shall provide pitch and height trims schedules that are optimized for:

a. Maximum ship range in smooth water
b. Maximum takeoff thrust margin
c. Maximum control authority and optimum rough water behavior

Separate trim schedules shall be considered for each of the above if their optimum values differ significantly.

3.4.1.2 **Pitch Trim.** The control system shall provide sufficient control such that the pitch trim is automatically maintained within ±0.5 degree of the programmed or nominal pitch angle, and the! hydrodynamic trim point of a71 the lifting surfaces shall be such that the lifting and control surfaces are operating in the linear regime (no significant cavitation present). The above shall apply between the minimum foilborne operating speed and the design speed, and over the expected weight and center of gravity envelope.

3.4.1.3 **Height Holding.** Variations in height from the commanded value during straightaway operation shall be limited to ±10% of the forward strut length between the minimum foilborne operating speed and the design speed throughout the weight and center of gravity envelopes. When maneuvering in calm water, the ship's height (measured at the forward strut(s))* shall not increase from the straightaway value by more than 10% nor decrease by more than 20% of the forward strut length.

3.4.1.4 **Roll Trim.** The trim positions of the roll control surfaces shall remain within their linear hydrodynamic range (no significant cavitation present) in the presence of a 50-knot wind at any heading to the wind at all

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* If two or more struts are located forward, the ship's height is taken at the centerline.

speeds from minimum foilborne operating speed to design speed.

3.4.1.5 Trim Adjustments. Electrical adjustments shall be provided to bias the ship's pitch, height, roll, and yaw trim from the nominal design trim point or to readjust the trims back to the proper trim points in the event of major hydrodynamic degradation. It shall be possible to accomplish these adjustments while foilborne.

3.4.2 Control Authority

3.4.2.1 Rough Water Operating Envelope. The linear operating envelope of each foil shall be sufficiently broad that cavitation or ventilation of the foil and/or control surfaces occurs infrequently. Figures 3.4-1 and 3.4-2 depict typical linear operating envelopes of a foil system.

For trailing edge flap control, 90% of the 2-sigma variations of angle of attack (α_{90}) due to wave orbital particle velocity shall be within the linear hydrodynamic range in the design sea environment as defined in Volume I.

The change in angle of attack that corresponds to the α_{90} Variation can be calculated as follows:

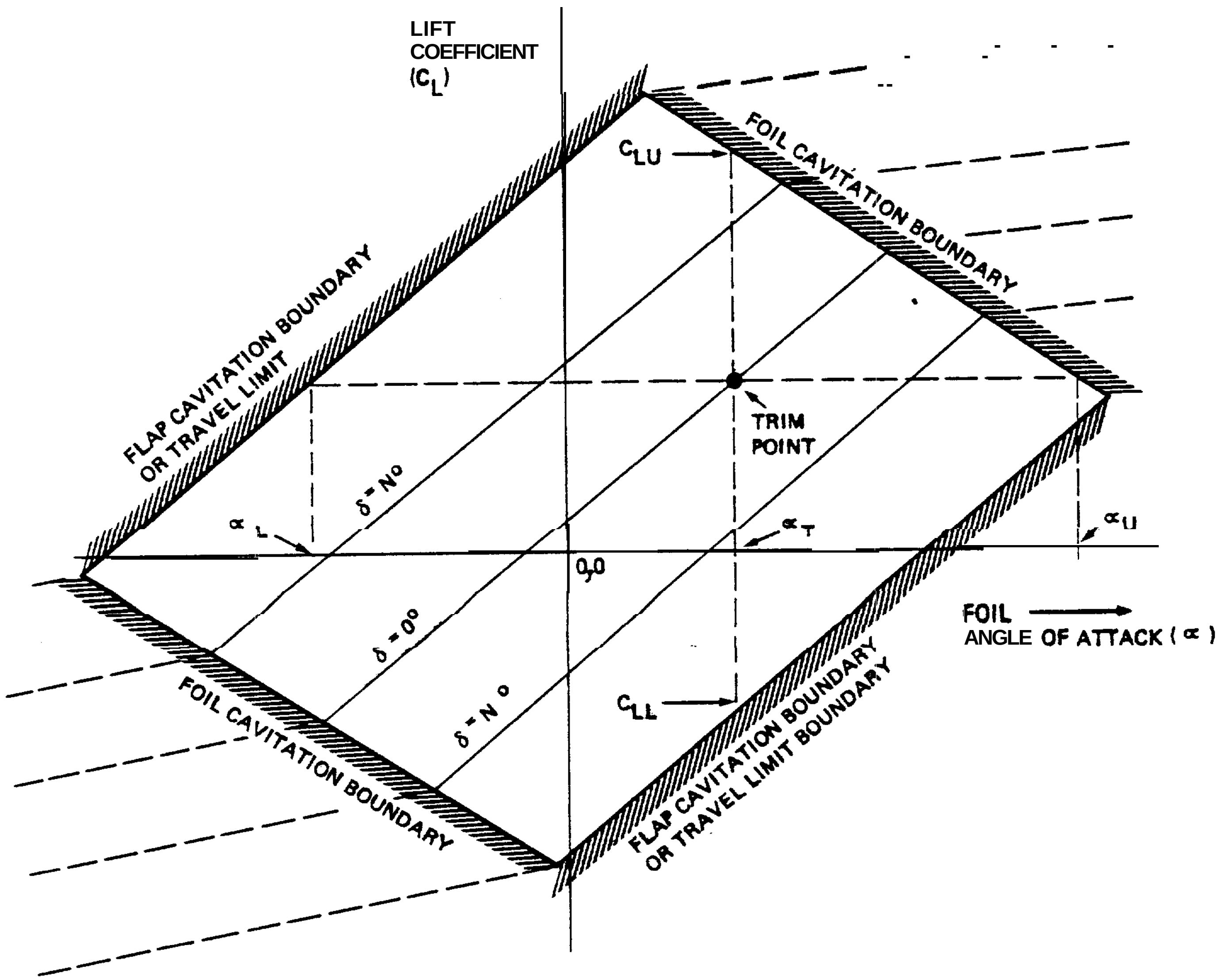
a. Calculate the 2-sigma angle-of-attack variation ($2\sigma_{\alpha}$) for the various expected sea conditions, as defined in Volume I, using the formula

$$2\sigma_{\alpha} = \frac{2\sigma_{v}}{U}$$

Where σ_v = 1-sigma variation in wave orbital velocity in meters/second

U = ship velocity in meters/second

σ_3 = 1-sigma variation in angle of attack in radians



Definitions

- δ – Flap deflection angle
- α_U – α upper limit at trim C_L
- α_L – α lower limit at trim CL
- α_T – Trim angle of attack
- C_{LU} – Upper C_L limit at trim α
- C_{LL} – Lower C_L limit at trim α

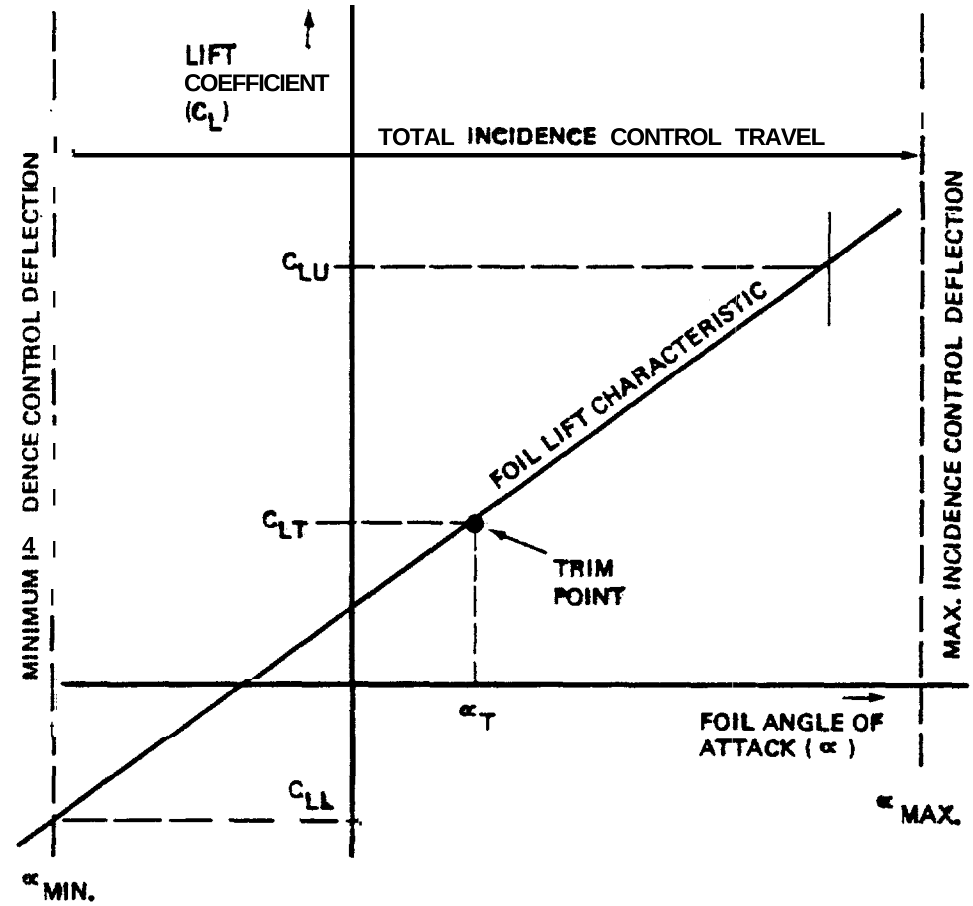
Envelope requirements

$\alpha_U - \alpha_T > \alpha_{90}$*

$|\alpha_L - \alpha_T| > \alpha_{90}$*

● *twfaa:9d definition

Figure 34-1. Typical Linear Hydrodynamic Boundaries for Flap Control



Definitions

α_{Min} = Min. angle of attack (control incidence min. travel limit)

$\alpha_{Max.}$ = Max. angle of attack (control incidence max. travel angle)

Requirements

$\alpha_{Max.} - \alpha_T > 1.1\ \alpha_{90}$*

$|\alpha_{Min.} - \alpha_T| > 1.1\ \alpha_{90}$*

$C_{LU} \geq 1.4\ C_{LT}$

$C_{LL} < 0$

*See text for α_{90} definition

Figure 3.4-2. Typical Control Boundaries for Incidence Control

The l-sigma variation in orbital velocity (σ_V) can be calculated for a given sea condition using the following formula:

$$\sigma_V = 1.703K_d \frac{H_s}{T_s}$$

Where K_d = 0.75, depth effect correction
H_s = significant wave height in meters
T_s = significant wave period in seconds

b. Make a long-term distribution plot of $2\sigma_\alpha$ using the possible. sea conditions for a given area and their probability of occurrence. From this plot, the 2-sigma α can be determined that will not be exceeded 90% of the time (σ_{90}). Figure 3.4-3 is a typical example of a long-term distribution plot of $2\sigma_\alpha$.

The relationship between the operating envelope requirements (α_{90}) and the linear hydrodynamic boundaries is shown in Figure 3.4-l.

For incidence control, the maximum control deflection about the trim point shall be at least 10% greater than the calculated α_{90}. Also, each foil section shall be capable of generating a change in lift within the linear hydrodynamic range 40% greater than and 100% less than the lift at the nominal trim point at design rough water speed.

3.4.2.2 Roll Control Authority. At all foilborne speeds from design speed to minimum foilborne operating speed, the ship shall have adequate roll control moment capability to counter the largest of the following two wave-induced disturbances. The control moment shall be based on the maximum control surface deflection prior to cavitation. Only control surfaces that respond automatically to roll shall be used in determining the control moment.

a. Disturbance I - Assumes a beam sea wave whose height is equal to the forward strut length and length is 7 times the height. The

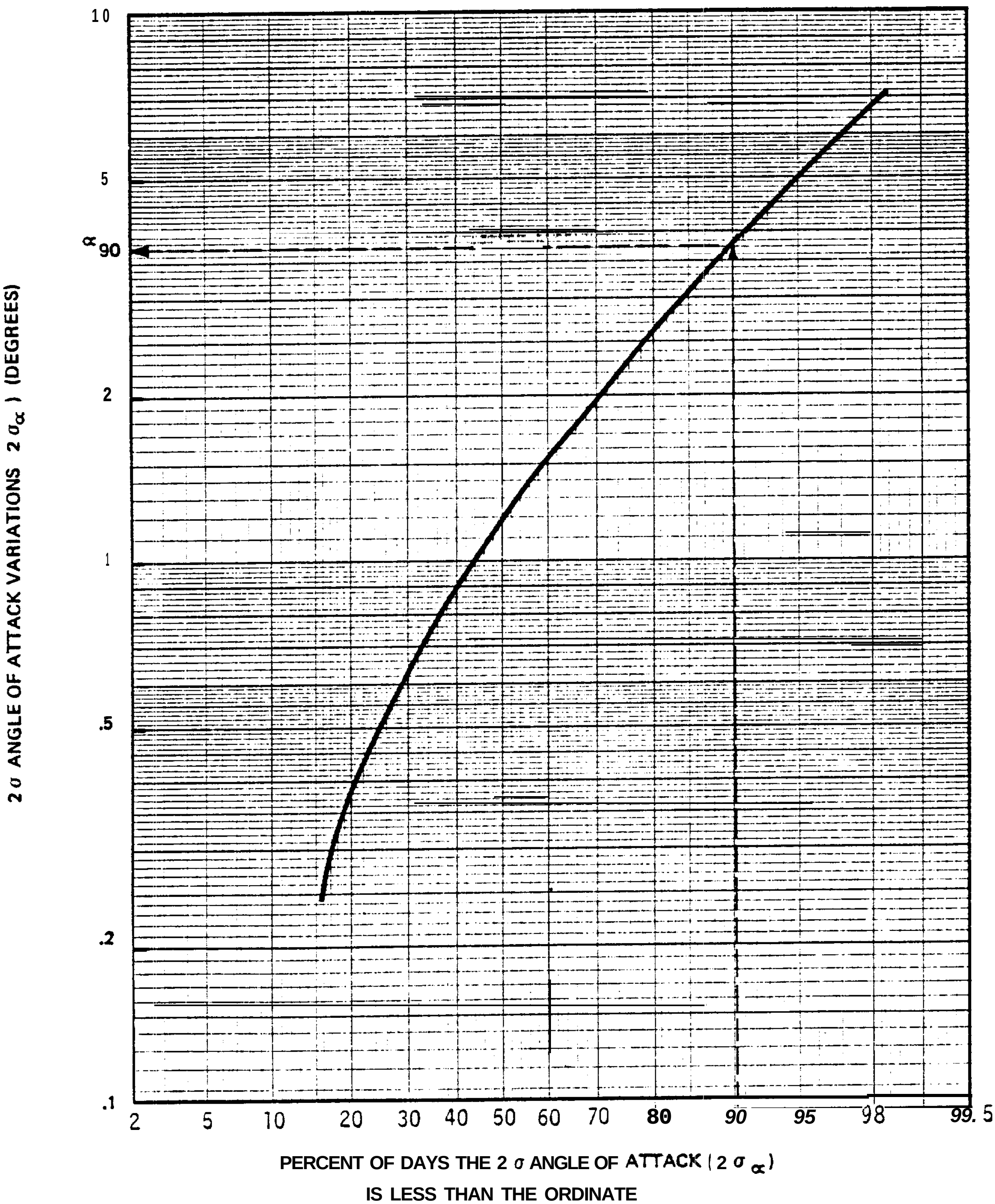


Figure 3.4-3. Typical Long Term Distribution of Foil Angle of Attack Due to Wave Orbital Particle Velocities

outboard strut(s) on one side of the ship is completely immersed in the crest of this wave.

b. Disturbance II - Assumes a wave length equal to the total span of the foil system and a wave height 1/7 the length. The crest of this beam sea wave is at the ship's centerline and thus maximum sideslip is developed on the centerline strut(s).. The angle-of-attack changes on the foils will be of opposite phases on the port and starboard sides and thus cause a rolling moment.

Angle-of-attack change shall be determined by the following formula:

$$\Delta\alpha = \frac{V_W}{u} = \frac{H_W}{2u}\left(\frac{2\pi g}{\lambda}\right)^{1/2} e^{-2\pi d/\lambda}$$

where: $\Delta\alpha$ = change in angle of attack in radians
V_W = orbital particle velocity in meters/second
u = ship velocity in meters/seconds
H_W = wave height in meters (crest to trough)
λ = wave length in meters
g = gravitational constant in meters/second^2
d = foil depth in meters

3.4.3 Strut Length. Strut length required is dependent on sea state requirements, hull shape, and foil unwetting characteristics. An effective strut length, which includes hull shape and foil unwetting characteristics, can be determined from sea state requirements. The actual strut length can then be established from the effective strut length once the hull shape and foil unwetting characteristics are known.

3.4.3.1 Effective Strut Length. The effective strut length of any strut shall be equal to or greater than 1.4 times the significant wave height for the go-percentile sea as described in Volume I, Section 3.1.6. The effective strut length is defined as:

$$L_{EFF} = L_S + L_{HULL} - L_{FOIL}$$

where: L_{EFF} = effective strut length

L_S = actual strut length (hull baseline to top of foil)

L_{HULL} = hull immersion due to cresting which results in 0.5g upward acceleration

L_{FOIL} = minimum foil depth realized before a foil broach occurs (0.5g downward acceleration)

3.4.3.2 Contouring Characteristics. Contouring characteristics, as defined by Figure 3.4-4, shall be designed such that the variation in strut immersion {at any strut) does not exceed the wave height by more than 25% in a regular (sinusoidal) sea for all conditions where the wave encounter frequency is less than 5 radians per second.

3.4.4 Stability Margins. Stability margins are expressed as gain and phase margins and a directional stability boundary. All the requirements in this section apply for all foilborne speeds, ranging from design speed to minimum foilborne operating speed.

3.4.4.1 Gain Margins. Each control loop in the automatic control system shall have at least a 2:1 upper and a 4:1 lower gain margin. Thus any control system gain can be doubled or cut in fourth and the system will remain stable.

3.4.4.2 Phase Marqins. Each control loop in the automatic control system shall have at least a 30-degree phase margin as determined by normal open-loop frequency domain design procedures utilizing Bode, Nyquist, or Nichols diagrams.

3.4.4.3 Directional Stability. The directionally stable boundaries in calm water with the foilborne rudder held fixed shall be as follows:

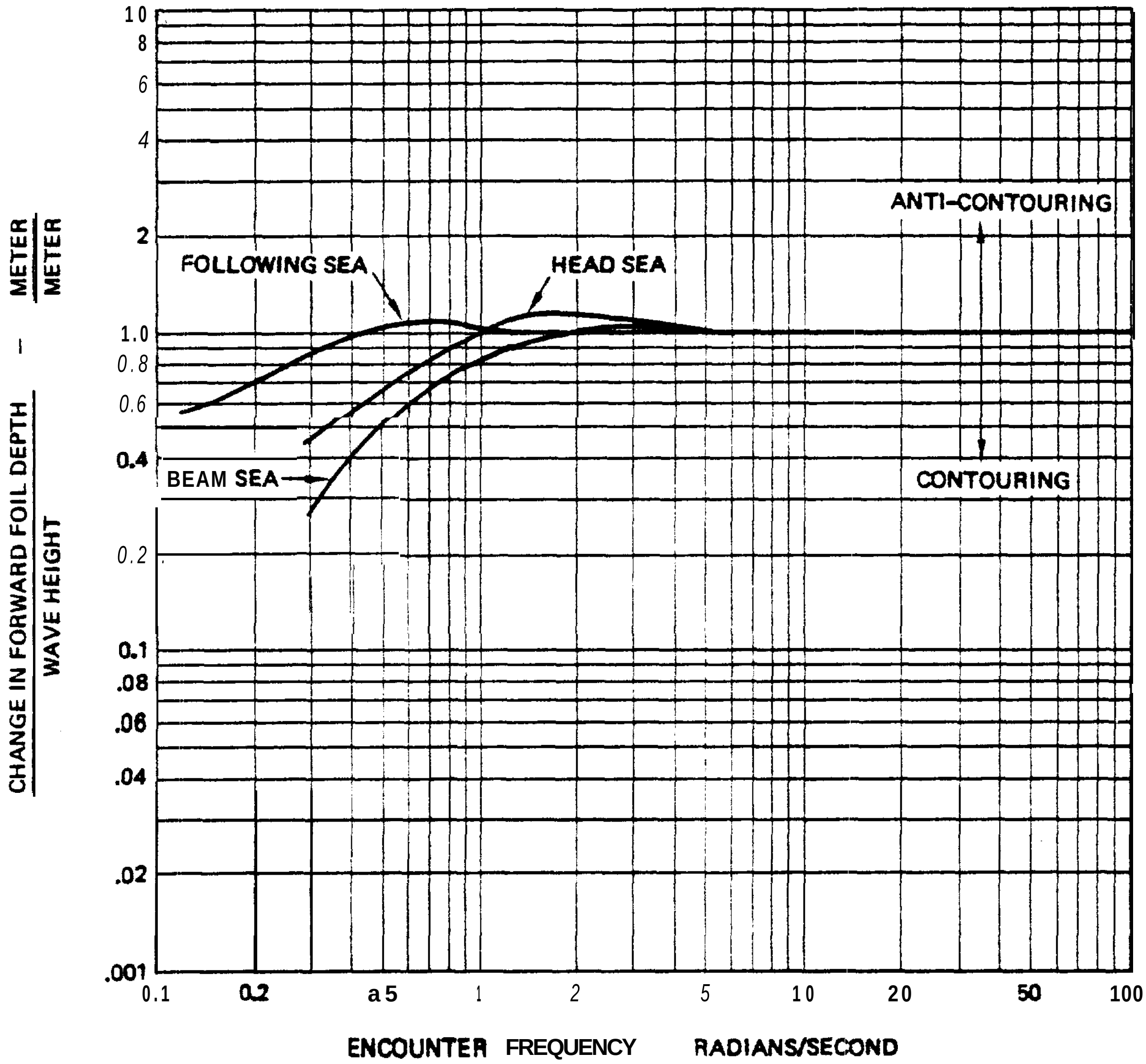


Figure 3.4-4. Contouring Characteristics

a. The lower stability boundary for fully wetted flow on all struts and foils shall be 2 degrees pitch down from the minimum calm water pitch trim. The ship shall be directionally stable at all pitch angles greater than this lower limit and also at zero forward foil depth.

b. The lower stability boundary with all aft struts ventilated and forward strut fully wetted shall be the minimum calm water pitch trim. The ship shall be directionally stable at all pitch angles greater than this limit and also at zero forward foil depth.

Figure 3.4-5 shows the directional stability criteria in the form of a strut submergence plot.

3.4.5 Transient Response

3.4.5.1 Response to Maximum Helm Step. A step reversal in helm position from maximum right (left) to maximum left (right) shall not result in hydrodynamic limiting of the roll control surfaces. Yaw rate and roll angle transient responses shall not exhibit greater than 20% peak overshoot.,

3.4.5.2 Response to Foil Depth Commands. Ship response to a step change in foil depth command that does not result in the hull contacting the water or foil broaching shall be such that depth overshoot is less than 15% of the incremental depth change.

3.4.6 High-Speed Hullborne Operation. The foilborne control system design shall contain provisions for control of the ship in a basically hullborne mode as identified in Section 3.3.6. For this mode of operation, it is desired that the foilborne control system functions be modified within practical limits to enhance the riding qualities, maneuverability, and endurance of the ship. The following paragraphs assume that this mode of operation is exploited to a reasonable degree by specific design criteria.

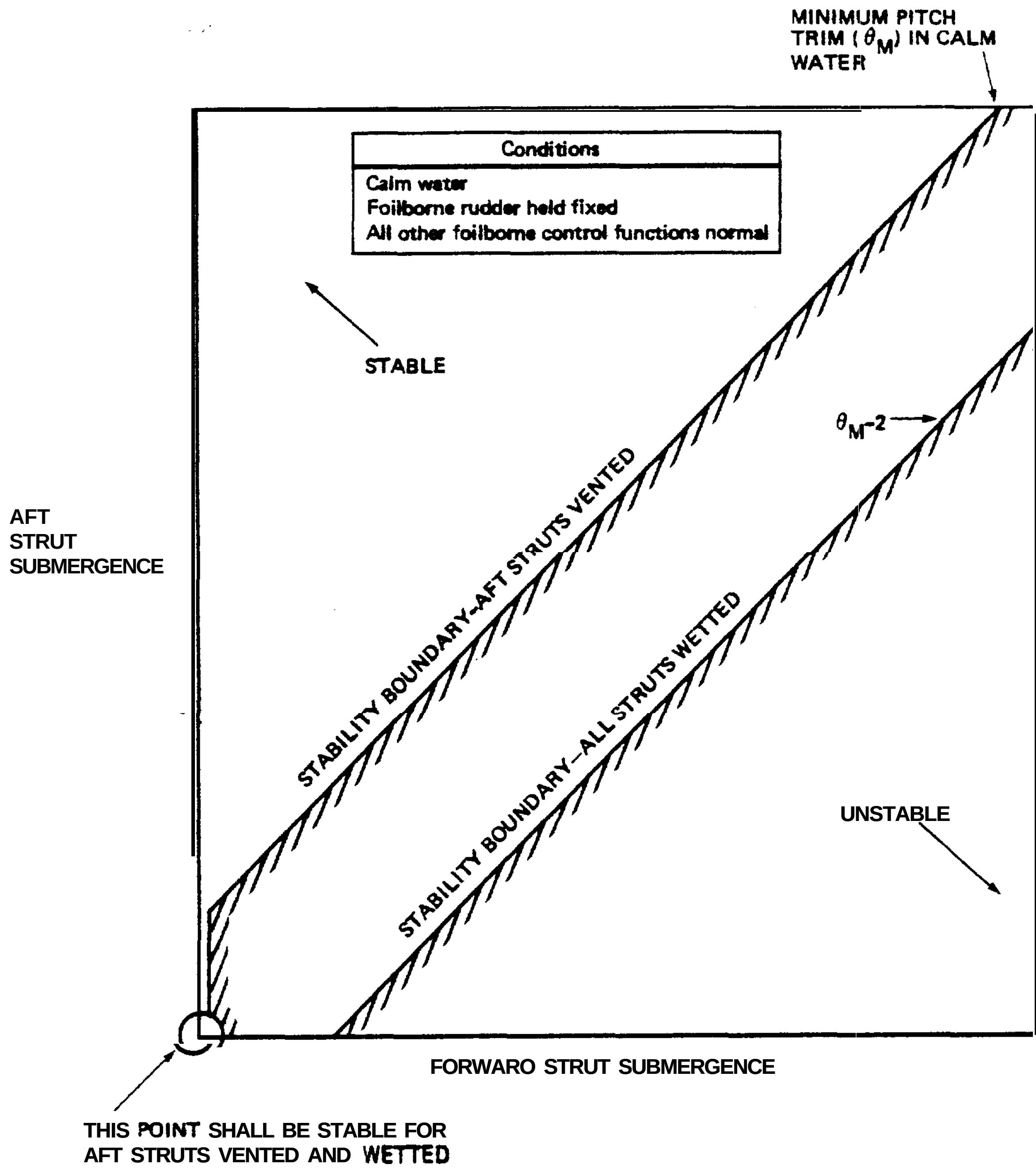


Figure 3.4-5. Directional Stability Boundaries

3.4.6.i' Motion Alleviation. The control system in the high-speed hullborne mode shall be designed to minimize roll motions in a seaway. The control system design shall also augment pitch/heave damping within the practical limits of capability of the foil system.

3.4.6.2 Steering Augmentation. Steering in the high-speed hullborne mode shall be augmented by the foilborne control system. In conjunction with the roll control system, the foilborne steering system shall be designed to provide a basically flat turn for all high-speed turning, and the full capability of the foilborne steering surface shall be made available in the hullborne mode.

3.4.6.3 Trim Augmentation. The foilborne control system shall provide steady-state trims in pitch as well as foil lift so as to reduce the total foil/hull drag to, or near to, the minimum drag configuration for high-speed hullborne operation.

3.4.6.4 Actuator, Linkage, and Control Surface Damage Protection. The foilborne control system design in this mode shall include provisions, where necessary, to prevent the control surfaces from excessive slamming into their travel limits, as this action could unnecessarily shorten the life of actuators, linkage, and bearings. To accomplish this objective, consideration shall be given to the following:

a. Shaped electronic limits on control surface travel
b. Reduced or zero gain in those loops that may be ineffective hullborne (such as might arise in some pitch/heave loops)

3.5 Operational Reliability and Safety Criteria. Failures within the ship control systems both foilborne and hullborne affect both the operational capability and the safety of the ship and its crew. Therefore, it is necessary in the development of the control systems to consider failures and to take appropriate steps in the design to assure the operational reliability and safety levels are adequate for the ship missions. The following paragraphs provide the format for reliability and safety design studies and provide design guidelines to assure adequacy of the overall system for the intended missions.

3.5.1 Operational-Level Definitions

a. Operational Level I (Normal) - All systems are operating within the design tolerances. All performance requirements are met.

b. Operational Level II (Restricted Operation) - The control system(s) is/are in a condition less than normal which involves a degradation or failure of a portion of the overall control system. A moderate degradation in mission effectiveness and some restrictions in the speed and turning envelopes may result; however, the intended mission can still be accomplished. This means that both hullborne and foilborne operation as well as controlled takeoff and landing are possible.

c. Operational Level III (Minimum Operable) - The control systems have degraded to the extent that the system cannot support the mission. The ship will be able to make a safe transition to hullborne or it may be capable of continued foilborne operation, but it might be unsafe for a further level or failure, and its operating envelope is too restrictive to complete the intended mission.

3.5.2 Failure-Related Safety Definitions

3.5.2.1 Fail-Safe Foilborne Ooeration. Following a failure of any control system element, the ship will be capable of remaining foiilborne or may initiate a transition from foilborne to hullborne, but neither the initial transient associated with the failure onset nor the transition to hullborne will be so severe as to cause major damage to the craft, or injury to the operating personnel.

For purposes of safety analysis, the contractor must develop boundaries of ship response such as those depicted in Figure 3.5-l that define

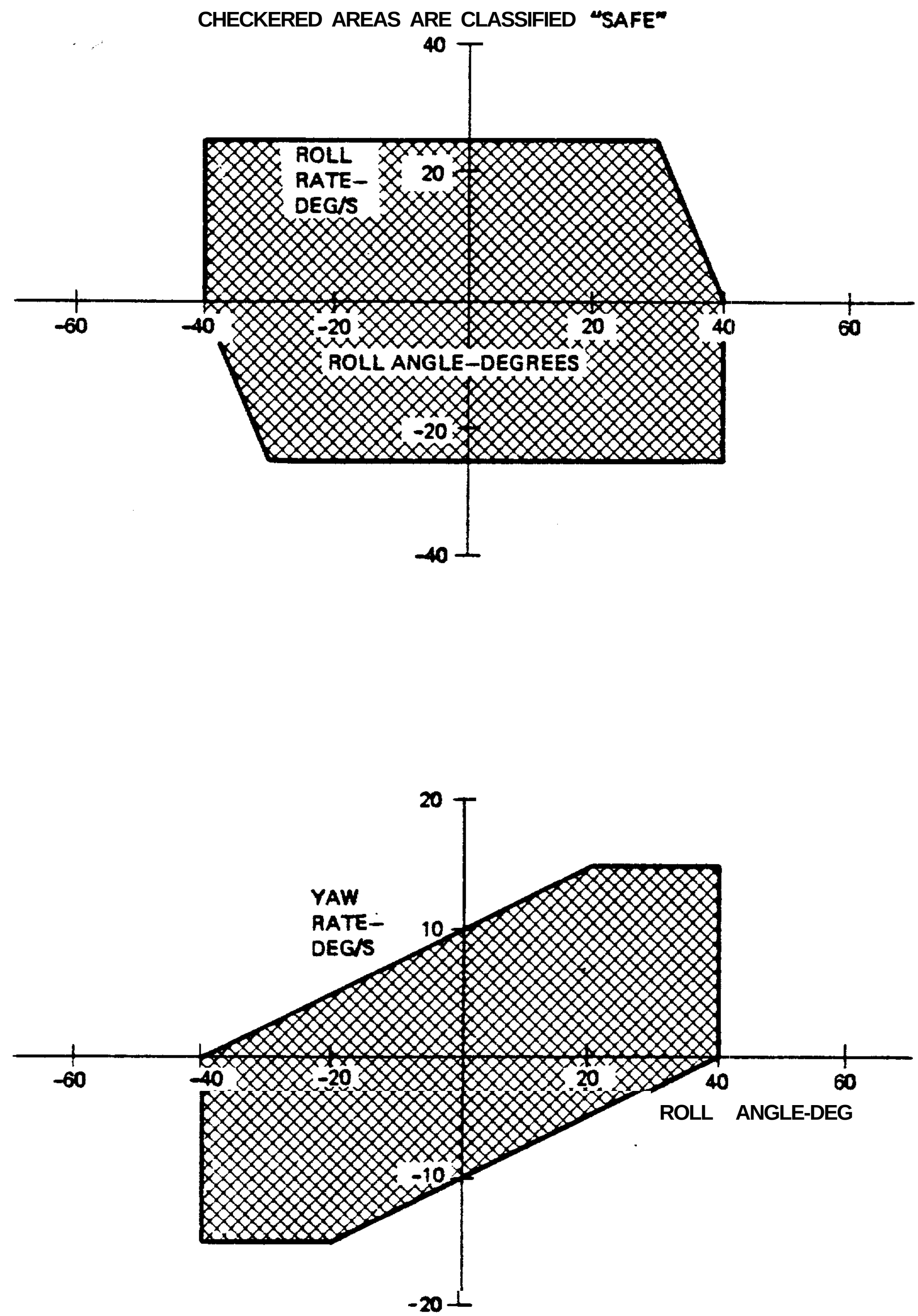


Figure 3.5-1. Typical Safety Boundaries

safe transition to the hullborne mode. For purposes of evaluatinq potential injury to personnel, the following allowable transient accelerations shall be used:

a. Peak vertical acceleration transients $\leq$ 1.0g downward, 1.5g upward

b. Peak lateral and longitudinal acceleration transients $\leq$ 0.6g (any direction)

The above guidelines shall apply only to acceleration transients having a rise time greater than 1/10 second.

3.5.2.2 Fail-Safe Hullborne Operation. Following a failure within the hullborne control system, the ship shall be steerable to both the left or right. The transient acceleration associated with the onset of the failure will not be so severe as to cause injury to the operating personnel. Personnel injury boundaries of Paragraph 3.5.2.1 shall apply here also.

3.5.3 Reliability Criteria. The overall ship mission reliability requirements should derive from the Top-Level Requirements (TLR) for a specific ship or class. The operational reliability for the control systems, both hullborne and foilborne, would then be derived and allocated separately to each system according to the degree of complexity of the overall weapon system and the control system and according to the mission definitions which may also be a part of the TLR.

The following mission reliability or operational reliability requirements shall hold for the ship as delivered:

a. Where overall ship mission accomplishment reliability is specified by the procurement activity:

$$Q_{M(cs)} \leq (1 - R_M)\, A_{M(cs)}$$

where: $Q_{M(cs)}$ = maximum acceptable mission unreliability due to control system material failures.

R_M = specified overall mission accomplishment reliability.

$A_{M(cs)}$ = mission accomplishment allocation factor for the ship control systems.

b. Where the overall mission accomplishment reliability is not specified, the operational reliability shall be such that $Q_{M(cs)} < 2 \times 10^{-4}$ failures/hour for both the foilborne control system and for the hullborne steering system (each considered separately).

For purposes of reliability requirements and analysis, operational levels I and II shall be considered acceptable for satisfying the operational reliability allocation. In addition, those failures which would put the ship in operational level 3 category, but which can be corrected by onboard maintenance within 5% of the nominal mission time, or within 1 hour, whichever is the lesser, may be considered acceptable for satisfying the mission reliability or the operational reliability requirement.

3.5.4 Safety Criteria. The probability of a hazardous ship response to a failure or combination of failures within the ship foilborne control system shall not exceed 1 per million hours of operation.

In meeting this allocation, multiple level failures must be included for those cases where the ship is operational per operational level II after a single failure.

3.5.5 Safety and Reliability Analyses

3.5.5.1 FMECA Requirements. Early in the development stage of a vehicle design, the contractor shall conduct a Failure Modes, Effects and Criticality Analysis (FMECA) for both the foilborne control system and the hullborne steering and maneuvering system.

This study shall identify and catalog the various failure modes of the system, identify the consequences of each failure, catalog the consequences into operational levels II or III, and separately catalog the consequences into either "fail safe" or "fail hazardous". The study must also assign probability numbers (failure rates) to the failures and then combine the probability of failures with the effects or consequences of the failures. The study must identify the predicted mission or operational reliability, and the predicted fail hazardous failure rate of the system.

The contractor shall have the liberty of adjusting either the mission reliability allocation or modifying the control system design to ensure satisfaction of the overall mission reliability requirement.

The contractor shall be obligated to take those steps necessary to ensure that the control system satisfies the specified safety criteria for the as-delivered systems and must therefore assign appropriate margins in the analysis.

3.5.5.2 Analysis Guidelines. The failure studies should include all probable failures within the defined ship control systems. Types of failures considered should include but not be limited to:

a. Hard-over failures (both directions)
b. Dead failures
c. Drift
d. Change in gains
e. Incorrect sign of controller output (digital application)
f. Single faults which could result in multiple equipment failures, such as some power supply faults

The reliability analysis should be formatted per NAVSEC Report No.6112B-130-76, "Tiger Users Manual," dated June 1976.

3.6 Control System Dynamic Specifications and Block Diagram Standards. The dynamic specification of the ship control system is the basic vehicle of communication between the analytical studies and the hardware design. As such, a major emphasis is placed upon identifying and standardizing those elements necessary to completely define the system characteristics and to communicate those required characteristics in well understood, standardized formats.

As a communication vehicle between the analyst and the hardware designer, the specification will be a two-way street in the early phases of design development. As the design approaches finalization, the dynamic specifications stand as the basic requirements that the (control system hardware must satisfy.

The dynamic specifications are defined by the functional block diagram of the control system, supplemented by tabular specifications of the various blocks in the functional diagram as appropriate.

3.6.1 Block Diagram Standards. In order to fully communicate the details of the intended requirements, the dynamic specification shall contain a functional block diagram in the general format of Figure 3.6-l. If more than one ship control configuration is required, each configuration and switching requirements between configurations shall be identifeid. The block diagram shall indicate all signal flow paths, all sensing instruments, all manual controls, all control actuation servos and all control surfaces. Where signals are summed, the diagram will identify the exact point where summing is accomplished. Where switching or multiple modes are incorporated, the diagram shall indicate such and identify the logic source which initiates the change.

3.6.1.1 Sign Convention. The sign conventions used in the specification shall be in accordance with Figure 3.1-2.

3.6.1.2 Dynamic Range and Limits. The block diagram shall indicate and differentiate between dynamic range requirements and dynamic limit requirements. Dynamic range requirements shall be indicated by the symbol;

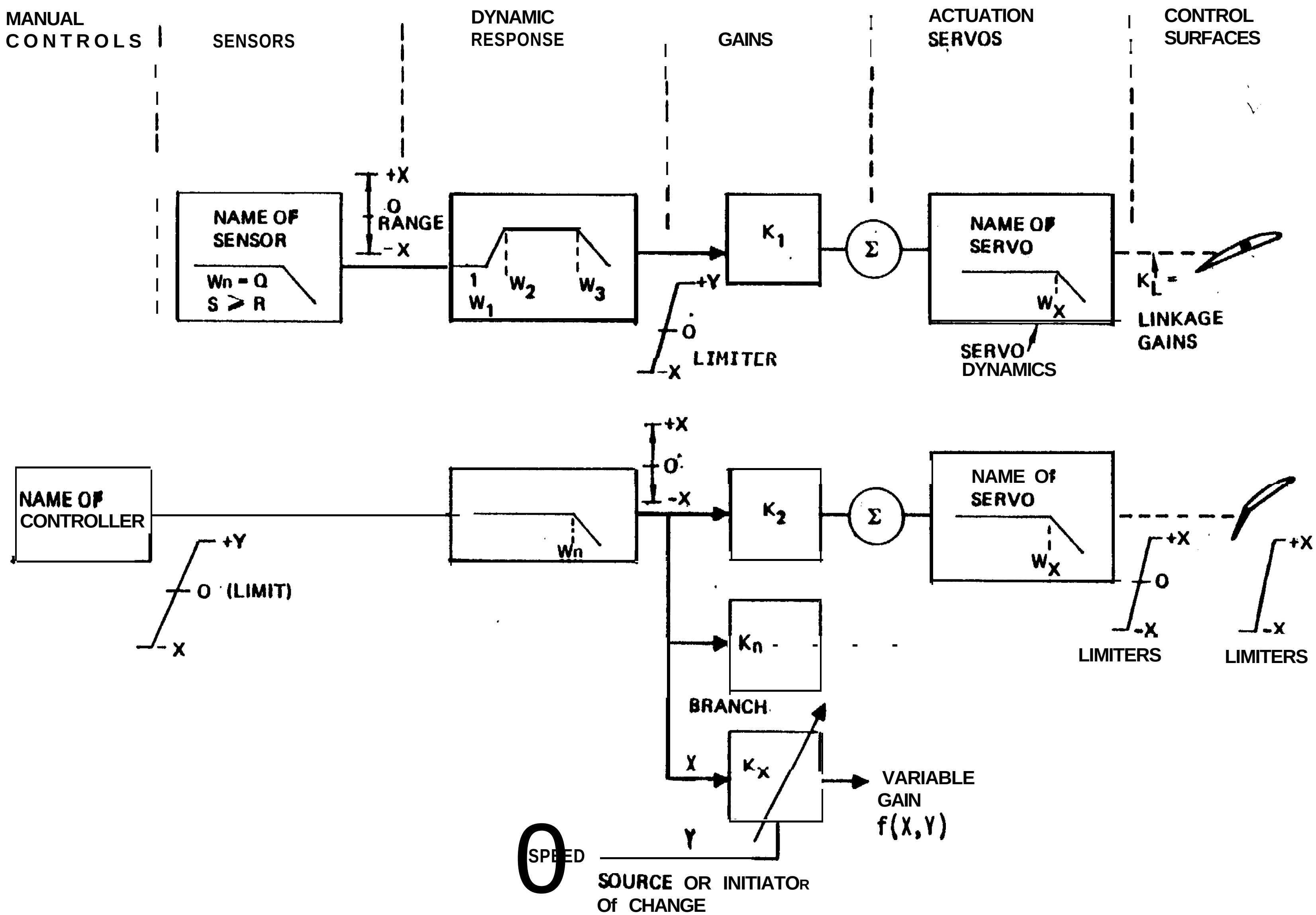
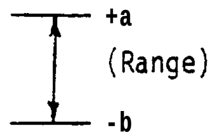
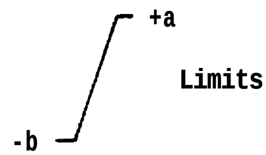


Figure 3.6-1. Functional Block Diagram Standards



and shall be interpreted to mean the range shall be at least that indicated.

Dynamic limits shall be indicated by the symbol:



Dynamic limits shall be interpreted as meaning a specific limit is required, and as such, a tolerance on the limit should be included.

Dynamic range and limit values shall be interpreted to apply to the zero frequency characteristic unless otherwise specified.

3.6.1.3 Other Functions. Where other functions such as nonlinear gains or switching logic are a part of the system, suitable descriptive logic blocks shall be included.

3.6.2 Dynamic Specifications. Tabular specifications shall accompany the block diagram that identify and quantify those elements of the system which are not readily visible from the block diagram or which are too complex to suitably incorporate in the functional block diagram. Tabular specifications shall include as a minimum:

a. Gains
b. Frequency response characteristics
c. Dynamic range and limits
d. Null and offset requirements
e. Resolution or hunting limits
f. Sampling rates (sample data systems)
g. Word size

3.6.2.1 Gains. Gains shall be specified in terms of a control surface deflection per unit change in the input, for example, degrees/degree. Wherever possible the gains shall be specified at zero frequency. Where pure integrals or derivatives are involved; the gain specification must be accompanied by a specific frequency where the given value is applicable.

3.6.2.2 Frequency-Dependent Response Characteristics. Frequency response requirements shall be specified in the S domain in standard Laplace transform notation.

For those elements which are subject to digital implementation, Z plane (Z transform) notation shall accompany the Laplace notation and the bilateral transformations from S to Z domains should be identified.

3.6.2.3 Dynamic Ranges and Limits. Dynamic range requirements and selected limiting must be identified on the functional diagram and defined in detail in tabulations accompanying the specifiation. These tabulations must identify the requirements in terms of a defined variable downstream of the last summation.

Additionally, any function which is implemented by means of feedback and/or feed-forward around an integrator must also specify the dynamic range of the first derivative of that function. A typical example of this is the actuation servos in which the hydraulic actuator is essentially a pure integrator, and to adequately describe the requirements, both control surface travel and rate requirements must be specified.

3.6.2.4 Null Requirements. The total allowable offset from specified control surface nulls shall be specified for each control surface and for each control mode if more than one control mode is involved.

3.6.2.5 Resolution and Huntinq. The acceptable amount of hunting or the required resolution shall be specified for each control surface, for each control mode.

3 . 7 Simulation Standards. In the development of the hydrofoil ship and its control system, a comprehensive simulation of the ship, control system, and seaway shall be employed. The degree of sophistication required for many elements of the simulation may vary depending on either ship type and size and/or upon the type analyses being conducted.

As an initial step in any ship development program, a comprehensive analysis and report on the simulation requirements shall be prepared that identifies the depth and breadth of the simulation needed to support the analysis and design activities.

3.7.1 Simulation Outline. For purposes of these analyses, the simulation is divided into the following categories:

a. Basic ship equations of motion
b. Foil system hydrodynamic forces and moments
c. Hull aerodynamic and hydrodynamic forces and moments
d. Seaway dynamics
e. Control system
f. Propulsion dynamics
g. Structural dynamics

3.7.2 Simulation Details

3.7.2.1 Equations of Motion. In developing the equations of motion, the following factors shall be considered for inclusion:

a. Euler Transformation and Axis Systems - The transformation equations should be suitable for high rate maneuvers and for failure studies where roll angles greater than 30 degrees may be encountered.

b. Mass and Moments of Inertia Variation - Possible variation in mass, CG location, and moments of inertia should be considered, and where these variations are significant between light ship and heavy ship, the variables should be included in the simulation.

3.7.2.2 Foil System Hydrodynamic Forces and Moments. The following factors shall be considered in developing the hydrodynamic simulation:

a. Breakdown of the foils and struts into smaller elements to adequately model local flow and depth effects.
   (1) The foil system shall be sufficiently segmented that localized depth effects due to roll and pitch attitude and localized flow effects from forward foils can be properly accounted for on trailing foils and struts.
   (2) The foil system shall be further segmented such that each independently actuated control surface shall be accounted for separately.
   (3) Hydrodynamic interaction between adjacent, independently actuated control surfaces shall be accounted for.

b. The depth of each independently simulated foil and strut segment shall be included as a function of craft attitude and wave profiles, and the depth effects upon hydrodynamic characteristics appropriately considered.

c. Upwash and downwash effects from forward struts and foils shall be considered in the aft foil system hydrodynamic simulation.

d. Foil and strut cavitation and ventilation as well as unwetting due to foil/strut broaching the free surface shall be considered in the simulation as well as the rewetting characteristics subsequent to such unwetting.

e. Inclusion of frequency-dependent hydrodynamic phenomena for all seaway performance studies shall be considered when the frequency regime of such phenomena is less than 3.0 hertz. For stability analyses, frequencies of considerably higher value will be of concern so the effects of unsteady hydrodynamics will have to be evaluated separately for use with stability analysis.

3.7.2.3 Hull Forces and Moments. Hull and superstructure qerodynamic forces and moments shall be considered in the simulation. Since the hull operates essentially in a homogeneous medium, a single body aerodynamic model is satisfactory.

Hull hydrodynamic forces shall also be considered in the! simulation; and as a minimum, hull forces and moments associated with cresting or bow entry shall be included in the foilborne simulation to assure proper modeling of (1) recovery following foil broaches and (2) acceleration transients which can affect ride quality.

3.7.2.4 Control System. The control system representation for inclusion in the simulation may vary from very gross estimates in early study phases to precise duplication of control system hardware in the final phases of a program. The following topical outline should be used as a guide in the determination of the control system dynamics for inclusion in the simulation.

a. Sensor Dynamics - The frequency response characteristics and dynamic output range of the sensing instruments should be included.

b. Servo Dynamics - Frequency response characteristics of the electrohydraulic servos, as well as the structural dynamic response of the actuation linkages, should be considered in the simulation.

In the solution of the servo dynamic response, it should be recognized that the forward loop gain of a typical hydraulic servo is a highly nonlinear item, being a function of the hydraulic supply pressure and control surface higne moment. Thus, for some studies, a complete nonlinear simulation of the servo may be required; whereas for other studies, a simplified respresentation of the servo such as $\frac{1}{\tau S + 1}$ may be adequate.

Realistic rate and travel limits of the servos should also be considered. Where parallel or in-line duality is used within an actuator system, the individual as well as summed forces of the actuators should be properly accounted for.

c. Electronics - Frequency response characteristics of the electronics are typically the fundamental control system parameter included in the simulation. In addition, the simulation should consider the dynamic range of the variables within the control system.

Where digital implementation is envisioned, the simulation of the control system should be realistically programmed to properly account for sample rate limitations, pure time delays, word size and core size limitations, and input/output interfaces.

Actual flow paths should be included in the simulation for final configuration and failure studies.

3.7.2.5 Seaway Dynamics. The simulation shall include representation of the seaway. Both random sea and simple sinusoidal sea representation should be included, with the ability to simulate operation at any arbitrary heading relative to the seaway. In addition, provisions should be included for turning in a seaway. For that purpose, a simple sinusoidal seaway representation has proven most practical in past studies.

For the random sea model, capabilities for simulation of unidirectional random seas as defined by the ISSC - Bretschneider formulation should be included as a minimum. This formulation is given as follows:

$$S(w) = 0.11 \left(\frac{2\pi}{T_s}\right)^4 \cdot H_s^2 \cdot w^{-5} \cdot e^{-0.44\left(\frac{2\pi}{T_s} w\right)^4}$$

where: $S(w)$ = energy density spectrum of the seaway in meters^2-sec
w = wave frequency (radians per second)
T_s = significant wave period in seconds
H_s = significant wave height in meters

3.7.2.6 Propulsion Dynamics. The simulation should consider the dynamics of the propulsion system. While the output of the propulsor is thrust, the simulation should consider the total response characteristics of the propulsion system so that the simulation studies are realistic of real-lift operation where the basic input to the propulsion system may be throttle position, and thrust is a resultant parameter dependent at least upon throttle position, speed, depth, and engine parameters. Where speed stability is of concern, the time response characteristics of the propulsion system should also be considered.

3.7.2.7 Structural Dynamics. The need for inclusion of structural dynamic and hydroelastic parameters in the simulation should be considered and specific decisions made as to the need for inclusion. The following guidelines for inclusion or omission of the structural dynamics characteristics in the simulations are recommended.

a. Where structural modes exist at frequencies of less than 6 hertz, the structural dynamics associated with those modes should be included in control system stability analyses. For ship motion analyses and any structural loads analyses, all structural modes of frequency less than 3 hertz should be included.

b. Hydroelastic deformations and deflections should be considered where the potential for elastic deformation can significantly modify control effectiveness. Also, elastic deformations of the hull, struts and foils due to thrust and drag should be evaluated and included where these factors are shown to be significant.

3.8 Ship Control System Hardware Requirements. The ship control systems hardware designer must develop equipment that satisfies the required functional characteristics as identified by the Dynamic Specification from Section 3.6 and the safety and reliability requirements identified in Section 3.5. In addition, the control system hardware should be designed to be compatible with the overall ship and with overall Navy approaches to maintenance, component usage, and environmental invulnerability. The, basic requirements to assure the control system hardware is compatible with all the above are detailed in the following paragraphs.

3.8.1 General Requirements. The ship control system hardware design shall implement the functional configuration as specified in 3.6 with components and techniques that meet the requirements of 3.5.

All ship control system signal processing and computation shall be performed by electrical or electronic elements. Consideration shall be given to implementing the electronics in accordance with the requirements of MIL STD-1378 (Navy).

The ship control system shall consist of equipment that is basically dedicated to the task of ship control. Sharing of control equipment with other ship systems is to be discouraged. Where sharing of equipment with other ship systems is necessary, the interfaces with the other systems shall be carefully controlled to ensure that other user functions cannot adversely affect the control system and that the control system cannot be altered or reprogrammed by other systems or other functional entities.

The ship control system design shall include details of the interfaces with the control actuation linkage, the control surfaces or other elements, the ship structure, the steering station, and the ship's electrical and hydraulic power systems.

To the maximum extent practical, the hullborne steering and maneuvering system and the foilborne control system shall be made functionally and physically independent in those elements that are critical to the accomplishment of the control. In those areas where loss of a function is not critical to the intended missions, the equipment may be shared with the two systems (for example, Heading Hold). Where the ship design incorporates nonretractable foils, or retraction for docking only, then it is allowable that foilborne control surfaces and actuators be used for hullborne steering control.

A common helm shall be used for hullborne and foilborne operation, but separate transducers shall be employed where separate hullborne steering devices are provided.

3.8.2 Environmental Requirements. The ship control system shall be designed to meet its specified performance requirements in the environment specified in Volume 1. Qualification to the appropriate environmental requirements, either by test or by prior application, shall be required of all safety-critical and reliability-critical control equipment.

3.8.3 Maintainability Requirements. The ship control system equipment shall be designed for ease of maintenance. Equipment shall.be designed physically for remove-and-replace-type maintenance at the shipboard level.

Modular construction shall be employed within each line replaceable unit, as far as practicable, such that depot level repairs may be accomplished with module removal and replace operations.

A self test capability shall be incorporated into the foilborne control system with the following capabilities at the shipboard level:

a. Verify system readiness prior to underway operation.
b. Detect failures and fault isolate to the line replaceable unit.

3.8.4 Interchangeability. All line replaceable units of like design shall be physically and functionally interchangeable one with the other and between ships of the same design without onboard adjustment. A single noninterchangeable assembly may be provided where adjustments in the ACS are required to trim out ship asymmetries and other ship construction-related tolerances.

3.8.5 Growth Margins. For new designs, the equipment shall provide margin for growth. Physically, the line replaceable units should be designed such that additional modules (at least 20% of the basic design complement) can be added to accomplish future undefined modifications. Electrical power supply units should have at least 40% excess capacity for future growth. For digital equipment, the following margins shall apply:

At the time of first ship acceptance by the procuring activity, the total time used in control computations for worst case conditions shall not exceed 75% of the available computation time allocated for control use. Resident and bulk storage shall be sized such that at least 25% of each type is available for growth at the time of acceptance. Computation algorithms, word size and sample rate shall be selected to ensure that the digital computation process will not introduce unacceptable phase shift, round-off error, nonlinear characteristics, and frequency foldover or aliasing into the system response.

3.8.6 Operating Modes

3.8.6.1 Hullborne Steerinq and Maneuvering System, It shall be possible to energize and operate the hullborne steering and maneuvering system from the helm station independent of the remainder of the ship control system.

It shall be possible to operate portions of the hullborne steering and maneuvering system from the helm station as necessary to place the hullborne steering control surfaces or mechanisms in specific positions to prevent damage during takeoff, landing, or while foilborne.

3.8.6.2 Foilborne Control System. It shall be possible to energize and operate the foilborne control system from the helm station for control of the ship during takeoff, landing, and foilborne operation, as well as during hullborne operation.

It shall be possible to energize and operate portions of the foilborne control system from the helm station as necessary to assist in directional control and to provide alleviation of seaway-induced disturbances while hullborne at speeds up to takeoff speed.

It shall be possible to energize and operate portions of the foilborne control system from the helm station as necessary to place the foilborne control surfaces or mechanisms in specific positions during extension or retraction of the foil/strut systems.

3.8.6.3 Transition from Hullborne to Foilborne and Foilborne to Hullborne. Care shall be taken in the design to ensure ease of transition between hullborne and foilborne modes and to ensure that positive steering control is available at all times during the hullborne to foilborne and foilborne to hullborne equipment transfer.

3.8.6.4 Self-Test Mode. The design shall provide a specific mode for self-test, and where large signals, system alteration, or switching are employed in the conduct of self-test, the design shall employ interlocks to prevent activation of such in any foilborne mode.

3.8.7 Operating Station

3.8.7.1 General. All display and manual control elements necessary for normal operation of ship control systems shall be provided at the helm station and readily accessible to the helmsman. The displays and controls shall meet the general human engineering criteria of MIL-STD-1472.

3.8.7.2 Primary Operating Controls and Displays. These controls and displays shall be under the immediate and continuous command and surveillance of the helmsman and shall occupy a prominent position within his reach and field of view. The primary operating controls and displays shall include the following:

a. Helm - A helm wheel shall be the primary means for introducing (manual) ship directional control commands. A common wheel assembly shall be provided for both foilborne and hullborne directional control. Separate transducers shall be provided for each mode. Maximum wheel travel shall not exceed 180 degrees right or left from the center position. The helm assembly shall include a helm position indicator graduated in increments no greater than 5 degrees.

b. Foil Depth Control - A continuously variable control device shall be provided for the selection of commanded foil depth. The foil depth control shall be located between the helmsman and the officer of the deck (OOD) station. A lever-like control shall be provided for commanding an emergency landing in such a location that the helmsman or the OOD can in one sweep of the hand bring the foil depth command to landing position and the foilborne throttles to zero. This control may be integral with or separate from the continuously variable-depth control device.

c. Foil Depth Indicator - A vertical-scale display of foil depth shall be provided. This display shall have separate indicators or pointers to show commanded foil depth and actual foil depth. It shall be permissible for the direction of the depth indicator movement to be opposite of the direction of the depth control movement. The indicator shall be located immediately adjacent to the foil depth control.

d. Ship Heading - A compass repeater moving card display of the ship's heading shall be provided.

e. Turn Rate - A moving pointer display of foilborne turn rate shall be provided.

f. Hullborne Steering Position - A moving pointer display of the position of the hullborne rudder(s) or hullborne steering control mechanism(s) shall be provided.

g. Heading Hold Command - A continuously variable control device shall be provided for the selection of the commanded heading.

h. Automatic Steering Interfacing - A display shall be provided which is easily viewed from both the helm and 000 stations, dienoting the engagement of any automatic steering option. Engagement of any automatic steering function shall be provided only at the bridge and shall be located such that it is accessible to the helmsman or the 000.

The interface design with all automatic steering functions shall include provisions for disengaging the automatic steering function by turning the helm beyond a predetermined threshold.

i. Foilborne Mode Indicator - If the system employs multiple foilborne modes, a prominent display denoting the current operating mode shall be provided for easy viewing by both the helmsman and the OOD.

j. Foilborne Warning and Ready Displays - A summary warning and foilborne ready display shall be provided with the following features:

(1) A green "ready" indication when all prerequisites for foilborne operation are satisfied and no failures are inciicated on the online monitor system.

(2) An amber "caution" indication to denote failure of a redundant or backup ship control element or to denote transfer from a primary to a backup ship control element or to designate other significant equipment degradation.

(3) A red warning indication and an audible alarm to denote failure of a ship control element requiring immediate termination of foilborne operation.

Documentation shall be included in the ship operations manual delineating operator actions and operational limitations (if any) associated with any amber caution or red warning indication.

3.8.7.3 Secondary Operating Controls and Displays,. These controls and displays are operated or monitored occasionally by the helmsman and shall be located within the limits of his reach and field of view. The secondary operating controls and displays shall include the following:

a. Mode Switch(es) - Switches shall be provided to energize, de-energize, engage, disengage and select the operating modes of the ship control system.

b. Control Surface Positions - A display of the positions of the foilborne control surfaces shall be provided.

c. Ship Attitude Indicators - Displays of the ship pitch and roll attitudes shall be provided.

d. System Status Indicators - For all functions incorporated in a summary status system, such as the foilborne ready and warning displays, separate indicators shall be provided showing the status of each function. Status indicators shall be in accordance with MIL-STD-14728. These status indicators can be located remote from the summary status displays.

3.8.7.4 Digital Readout Displays. Where digital displays and readouts are used, provisions shall be included to limit the flashing effects that accompany updating. Significant digits in the display shall be limited to that level of accuracy required by the underway operations (primarily the helmsman and officer of the deck), and updating should be no more frequent than allowed by MIL-STD-1472.

3.9 Ship Control System Hardware Design Criteria In the development of the control equipment to satisfy the various requirements, many problems and decision points occur and must be addressed. In the following paragraphs, specific design criteria and design guidelines are given to ensure that the finished product will satisfy the overall requirements and provide sufficient margins in the design process.

3.9.1 General

3.9.1.1 Static Errors. For each line replaceable unit or major subassembly of the ship control system, the static error characteristics shall be determined and error limits established. For each control surface or other control element, the net static position error characteristics resulting from the contributions of all upstream subassemblies shall be determined. The Z-sigma value of the net static position error for each control surface or element shall not exceed the value established in 3.6.2.4 over the extremes of the operating environment. This static error criteria also shall be satisfied under the interchangeability requirement of 3.8.4.

The static errors shall be measured as part of the applicable functional or factor test for each line replaceable unit and for the shipboard system tests.

3.9.1.2 Frequency Response Errors. The frequency response (magnitude ratio and phase angle) error limits shall be established for each line replaceable unit or other component in the ship control system. The front-to-back frequency response characteristics of the ship control system hardware from input displacements, rates, and accelerations to control surface positions shall meet the tolerance requirements established in 3.6.2.1 and 3.6.2.2. The interchangeability requirement of 3.8.4 shall be satisfied without exceeding the tolerances of 3.6.2.1 and 3.6.2.2.

3.9.1.3 Resolution and Granularity. The resolution and granularity characteristics of the ship control system hardware shall meet the requirements established in 3.6.2.5. In the absence of a specific requirement, the total resolution and granularity in the command to each servo shall not exceed 0.1% of full-scale travel of the connected control surfaces.

3.9.1.4 Cross-Talk. Electronic cross-talk between signal paths shall not exceed 2% of full scale for the affected path. For purposes of this requirement, each signal path shall be considered from sensor output to servo input commands at each servo.

3.9.1.5 Installation. Enclosures or other methods shall be included as necessary in the ship control system installation to protect the equipment from damage by personnel or other equipment. The installation design and fasteners or electrical connectors of line replaceable units and modules shall be selected as necessary to prevent improper installation or interconnection.

3.9.1.6 Trim Adjustments. Provisions shall be incorporated in the ship control system to permit temporary manual adjustements as specified in Section 3.4.1.5. The adjustments provided shall be sufficiently limited in authority that their improper use will not result in an operating condition lower than operational level II. The adjustment devices shall be located in a secure area remote from the normal operating station.

3.9.1.7 Switching Transients. Transient ship motions in any manned space resulting from operator-initiated switching or mode selection during foilborne operation shall not exceed 0.25g vertical or 0.1g lateral for a duration not to exceed 0.5 second. For automatic switching while foilborne during normal system operation or when transferring to a redundant mode or system, or for failures in interfacing systems, the motions shall not exceed 0.1g vertical or 0.05g lateral for a duration not to exceed 0.5 second.

3.9.1.8 Control Linkage Shock Loads. The ship control system shall be designed to eliminate or to minimize the frequency of occurrence and severity of shock loads or high accelerations in the control surface bearings, linkages, and mechanisms resulting from switching transients and test inputs. In addition, consideration shall be given to electronic rate or position limiting where large inertia loads could cause damage to the actuation system or linkage.

3.9.2 Maintainability. The following paragraphs delineate those features of the design which are necessary to facilitate an efficient maintenance system for both the foilborne control system and the hullborne steering system. Normally, the hullborne steering system will be less complex in function and design. In this case, it may be possible to meet the criteria for readiness verification, fault isolation, and repair time using only test procedures, operational indicators, and portable test equipment. If these criteria can be met, the requirement for built-in test equipment may be waived.

3.9.2.1 Dockside Operability. It shall be possible to operate the ship control systems (hullborne and foilborne) in all modes with the ship moored at dockside without the necessity for operating propulsion equipment. It shall be possible to operate all control surfaces or control elements with struts and foils extended or retracted insofar as is practical.

3.9.2.2 Operational Verification. The built-in self-test system and accompanying procedures shall be capable of verifying foilborne control system operational readiness within one-half hour. Tests shall include checks of sensors, electronics, servos, manual controls, indicators, and power sources and power-conditioning equipment.

3.9.2.3 Fault Isolation and Repair. It shall be possible to fault-isolate to a line replaceable unit and restore the foilborne control system to an operational level I condition by a remove, replace, and retest operation, except for hydraulic actuators, within 2 hours for 90% of all failures. The installation and handling fixtures for ship control system hydraulic actuators shall be designed to allow their removal and replacement without the necessity for drydocking the ship.

Fault isolation within equipment such as cables, junction boxes, and connections that are not designed for removal and replacement may be accomplished by conventional carry-on portable instrumentation, and onboard repair in these areas is allowed.

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3.9.2.4 **Line Replaceable Unit Test.** For each line replaceable unit of the ship control system, there shall be provided test points, test equipment, fixtures, procedures, and programs sufficient to verify satisfactory operation and interchangeability of the unit at the depot level and to fault-isolate to the module level.

3.9.2.5 **Timing Devices.** Equipments with specified maintenance intervals based on operating time shall be equipped with timing devices located so they can easily be viewed without removal of the unit.

3.9.3 **Interface Criteria.** The control system interfaces with many other ship systems. The following paragraphs delineate specific design guidelines to ensure compatibility between the control system and the other ship systems.

3.9.3.1 **Steering Station.** Manual controls and displays of the ship control system shall be located according to the relative priorities established in 3.8.7. The design and integration of the manual controls and displays into the steering station shall follow the criteria and requirements for the given ship and of MIL-STD-1472 in that order. Unless otherwise stated by the contract, a full-scale mockup of the steering station depicting as a minimum the integration of the ship control system manual controls and displays with the overall ship command and control operations shall be constructed and approved by the contracting agency. The mockup shall adhere to the following minimum specifications:

a. Physical Dimensions - The mockup shall include models of equipment, furniture, fixtures and other installed equipment so as to reproduce the general shape and major external dimensions.

b. Functional Details - Equipment functional components, parts, and devices (such as switches, scope faces, connector jacks, meters, and push buttons) shall be shown and labeled as to function. These devices shall be shown by means of the use of actual equipments or by means of affixing to the model photographic enlargements or facsimiles. Details (such as meter divisions, and scope face markings) need not be shown. Equipment with a large number of operational switches (such as action cutout, sound-powered or radio selector switches) shall be labeled with each dial or switch (position) nomenclature and circuit designation.

3.9.3.2 Hull Structure. The structural foundations for all sensing elements of the ship control system shall be located and: designed to minimize dynamic coupling between the ship structure and the ship control system. Unless otherwise noted, each sensor foundation shall be aligned with the appropriate ship axis, referenced to the ship master reference, as follows:

a. Attitude reference (pitch and roll) ± 0.002 radian
b. Other sensors ± 0.01 radian

3.9.3.3 Control Actuation Foundations and Linkage. The foundations, bearings, and linkages for all control actuation equipment shall be designed to minimize dynamic coupling between actuators and control surfaces or mechanisms. Linkage adjustments shall be provided as necessary to permit full actuator travel without the linkage binding *or* contacting any other structure. The capability for normal motions of the ship control surfaces or mechanism with foils and struts retracted as well as extended shall be considered in the ship design.

3.9.3.4 Electrical Power. Electrical power shall be supplied to the ship control system by the ship's electric plant from at least two separate and independent sources, each of which shall be capable of supplying the total ship control system power requirements. Either a parallel connection between sources or automatic transfer between sources may be employed. If a parallel connection is selected, sufficient isolation shall be provided to prevent a short circuit at one source from presenting a short circuit to the other source(s).

Transient ship motions induced through the ship control system as the result of automatic electrical power transfer shall not exceed the limits of 3.9.1.7. The ship control system shall be capable of at least an operational level II-condition for any single failure in the ship's electric plant and distribution system.

One or more sources of electric power shall be provided to enable uninterrupted operation of the ship control system upon loss of all shipboard electrical generating capability. This/these source(s) shall have sufficient capacity to power the ship control system, in the required mode, for a length of time equal to or greater than that for which ship propulsive power and control hydraulic power are available after loss of all shipboard electrical generating capability. This/these source(s) shall also be sized and protected such that no other load on the buses, such as engine starting, can draw the bus below the minimum voltage level established for the control system.

3.9.3.5 Hydraulic Power. The hydraulic supply and distribution system serving the control actuators shall incorporate constant-pressure, variable-flow pumps. Accumulators shall be sized and located as required to meet peak flow demands and minimize hydraulic line dynamic effects. Unless otherwise stated, nominal system supply pressure shall be 20.67 MN/m^2 (3,000 psi). Care shall be exercised in selecting and developing the supply system to assure cleanliness levels compatible with the ship control system electrohydraulic servovalves and actuators. Unless otherwise required, the hydraulic fluid contamination levels at the control actuators shall not exceed NAS 1638 Class 7.

The ship control system shall be capable of an operational level II condition for any single failure of the hydraulic supply system. Redundant hydraulic supplies with parallel operation or transfer capability shall be provided to each actuator to maximize the operational reliability and safety of the ship. Where a sufficient multitude of separately actuated control surfaces are employed, it may be possible to allow an uncorrected failure in one or more actuators-and still provide operational level II capability. In such cases, the requirement for multiple supplies to each actuator is excepted.

Care shall be exercised in the design to minimize the fluid interchange between systems when transferring or operating in parallel.

Consideration shall be given to providing separate, dedicated hydraulic supplies for the ship control system actuators as a means of compliance with the cleanliness, reliability, and safety requirements stated herein.

3.9.3.6 Interface with Other Systems. The design for interfacing systems, with the exception of the primary electrical and hydraulic supplies, shall ensure that failures in other systems do not degrade the overall control system operation. Any transients resulting from failures of the other systems, or from engagement or disengagement of the other systems shall not produce ship motions exceeding the limits of 3.9.1.7.

3.9.4 Electrical Power Conditioning,. All electrical power, for the ship control system sensors, manual controls, displays, indicators, electrical, and electronic signal processing and switching functions shall be provided from dedicated power conditioning equipment connected to redundant buses of the ship's electrical plant per 3.9.3.4.

The power-conditioning equipment shall be capable of supplying the required voltage to each connected load in the presence of input voltage variations and expected variations in the loads. Where current limiting or other overload protection methods are used, the preferred approach is to isolate downstream failures in a connected load by isolating the bus feeding that load while providing normal power to buses supplying all other loads.

3.9.5 Electrical Wiring and Cabling. The design and installation of ship control system wiring and cabling shall include considerations of the expected EM1 environment from sources external to and internal to the ship control system. In general, a single-point ground system shall be provided with separate ground circuits for signal, power, and shields except as required otherwise by specific EM1 considerations. Cables shall be routed to minimize the risk of battle damage or of damage due to normal or abnormal operation of any other shipboard equipment. The use of redundant cables shall be considered to minimize the effects of battle damage and, where practicable, redundant cables should be routed on opposite sides of the ship.

3.9.6 Sensors. Sensors for the ship control system shall be attached to foundations meeting the requirements of 3.9.3.2 at locations in the ship as necessary to produce the desired ship motion data. At each location, means shall be provided to protect the sensor from damage by personnel, equipment, or the local environment.

For ship motions of magnitudes exceeding the dynamic range of any sensor, there shall be no damage to the sensor and no latch-up, oscillation, or phase reversal in its output.

Where vertical or free gyroscopes are used for attitude reference, the gyro spin axis and the gyro mounting base shall be aligned within f0.25 degree.

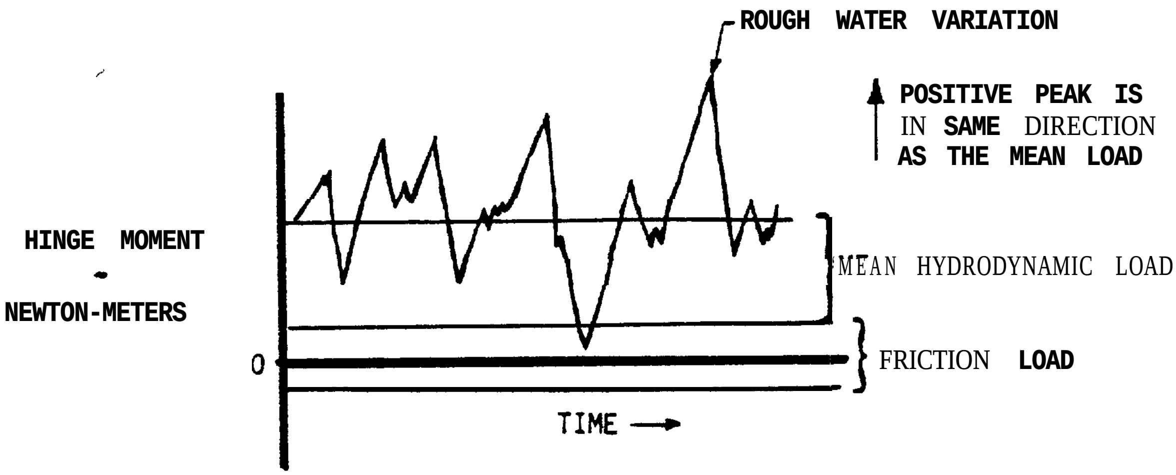
3.9.7 Electronics. The electronic signal processing and computational elements of the ship control system shall be of a fixed configuration determined by interconnecting wiring, wired logic, and nonvolatile memory systems as applicable. Except for the selection of predetermined operating modes per 3.8.6 or internal adaptability, the ship control system configuration shall be unalterable at the shipboard level. Any reprogramming or wiring revisions shall be accomplished at the depot level with appropraite documentation and configuration control. It is permissible to make selected configuration modifications at the shipboard level for lead or experimental ships to accomplish a specific test plan.

The electronic elements of the ship control system shall be capable of processing the maximum signal ranges as specified by 3.6.1. For signals exceedingthese ranges there shall be no latch-up, oscillation, or sign reversal. Signal limiters shall be capable of proper operation per 3.6.1.2 during normal operation and in the presence of failures for which limiting action is required.

3.9.8 Actuation System. The hydrodynamic control surfaces shall be positioned by electrohydraulic servoactuators. Each actuator with its servovalve(s) and transducer(s) shall be designed as an integrated assembly. The sizing of various elements of the control surface actuation system is critical to achieving the required ship performance characteristics in Section 3.2. The determination of the actuation system size will necessitate the use of a simulation that includes vehicle dynamics, control system and hydraulic system characteristics, and the sea environment. Requirements for actuation system sizing, including actuator force capability, control surface travel and rate, and total supply sizing are contained in the following sections. These requirements assume a constant-pressure, variable-flow hydraulic system.

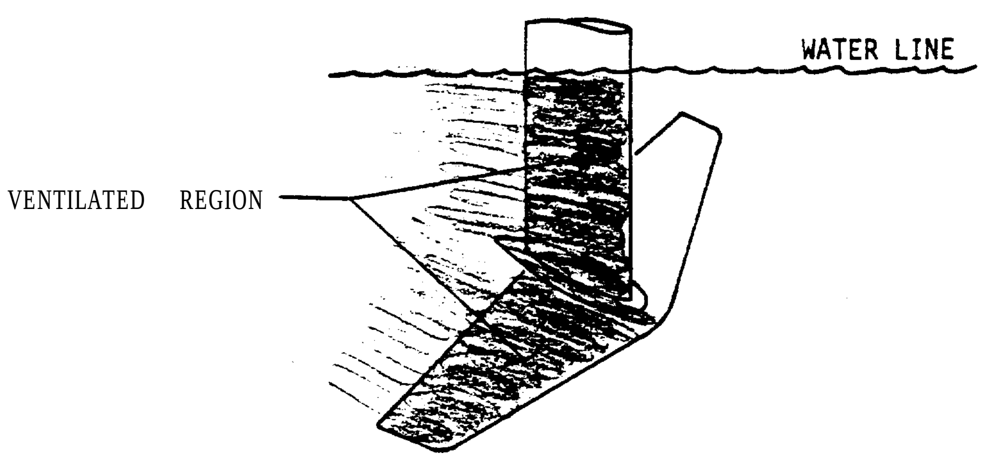
3.9.8.1 Actuator Force Capability. Each control surface actuator shall be sized such that its force capability at 80% of normal supply pressure satisfies each of the following design conditions taken separately.

a. Rough Water Hinge Moment Variations - The actuator force capability shall be such that it is adequate to counter the combination of the friction loads plus the mean hydrodynamic load plus 90% of all the positive peak hydrodynamic loads, as depicted below.



The design shall ensure that the above capability exists for all speeds from minimum foilborne operating speed to 1.1 times the rough water design speed and at all headings relative to the sea, in a fully developed sea having a significant wave height equal to the 90 percentile wave height for the design family of sea conditions. (The 90 percentile wave height is that wave height for which 90% of the seas have significant wave heights less than the given height without regard to period content.)

b. Ventilated Strut Condition - An actuator controlling a swivelled steering strut or a control surface on a strut shall have sufficient force capability to counter the effects of ventilating one side of such strut and the adjacent foil section over the entire range of foil depths from 0.1 foil chord to hull contact.



c. Overpowered Actuator Condition - For those applications where the control surface has a divergent mode such as some incidence-controlled foils, the-actuator must have sufficient force capability to overcome the hinge moment over all foilborne operating conditons (smooth water and rough water) where a divergence of the control surface would either terminate foilborne operation or create an unsafe condition as defined in Section 3.5.2.1. If the control surface is a hullborne rudder, a divergent mode shall not be allowed under any circumstance.

3.9.8.2 Control Surface Travel. The range of control surface deflection shall be large enough to accommodate the requirements of Section 3.2, "Ship Foilborne Performance Characteristics" and Section 3.4.2, "Control Authority". Other modes of operation, such as takeoff and hullborne, shall also be considered in determining maximum deflection requirements. Control surface travel shall be large enough that ride quality, as described in Section 3.2.1, will not be reduced more than 5% if the travel of all surfaces is reduced 10% at any heading on 90% of the expected sea conditions as defined in Volume I, at the design rough water speed. Travel range for hullborne control surfaces such as rudders shall exceed the travel ranges required for steering by at least 10%.

The stroke of each actuator shall be sufficient to position the connected control surface or element through its usable range. Travel limits for each control surface or element shall be established by hydraulically cushioned stops internal to the actuator.

3.9.8.3 Actuator Size. The actuator volume is determined from the maximum force (hinge moment) requirements and control surface travel requirements, as determined per Sections 3.9.8.1 and 3.9.8.2. The actuator volume, presuming a double-ended actuator, shall not be less than that determined from the following formula.

$$VOL = (A)(S) = \frac{(HM)(\delta_T)}{(57.3)(0.8P)}$$

where: VOL = actuator volume ($meter^3$)

A = actuator piston area minus rod area ($meter^2$)

S = actuator maximum stroke (meter)

HM = maximum control surface hinge moment (Newton-meter)

δ_T = total control surface travel (degrees)

P = hydraulic system supply pressure minuw return pressure ($Newton/meter^2$)

Actuator volume is the key parameter in this requirement, and it can be realized with infinite combinations of area and stroke. The preferred approach to control actuation employs relatively long stroke actuators with lesser working areas as opposed to short-stroke, large-area actuators, in order to minimize the effects of construction tolerance and linkage wear on system gains. Unless otherwise required by the dynamic specifications of Section 3.6, linkage gains should be maintained within ±5% of the specified gain.

3.9.8.4 Control Surface Rates. Control surface rates shall be such that ride quality, as described in Section 3.2.1, will not be reduced more than 5% if the rate of all surfaces is reduced 10%. This shall hold at the rough water design speed at any heading in 90% of the expected sea conditions as defined in Volume I.

The combined characteristics of servovalve(valve drive electronics, actuators, and hydraulic supply shall be sufficient to meet the rate requirements of Section 3.2, "Ship Foilborne Performance Characteristics", and other modes of operation such as takeoff.

The average of the absolute value of flow for each actuator shall be determined for the worst case heading at the design rough water speed in a fully developed sea that has a significant wave height equal to the 90% sea conditions as defined in Volume I.

Accumulators shall be provided to accommodate for instantaneous peak flow requirements.

3.9.8.5 Supply System Capacity. The flow capacity of each hydraulic supply system used in support of foilborne control shall be sufficient to satisfy the following requirements:

a. Flow capacity of each system shall be greater than 1.2 times the average flow required by the user actuators when operating at the worst case heading in the 90 percentile seas as defined in paragraph 3.9.8.1. (Worst case heading means that heading relative to the seas that results in the largest total flow requirement of the user actuators on that system.)

b. Where a system is used as a backup to another supply system, its total flow capacity shall be greater than the total average flow requirements of its primary users plus all users for which the system is a backup supply.

c. Accumulators shall be used in the system to provide instantaneous peak flow requirements to the actuators unless the supply capacity exceeds the average flow requirements by greater than 2:1 for both the conditions of 3.9.8.5 a and b.

4. QUALITY ASSURANCE

The overall quality of the ship and its control systems is the aggregate result of many activities including manufacturing, test, design, analysis, and documentation. In the following paragraphs, those activities necessary to ensure the quality and suitability of the final product are delineated.

4.1 General Requirements

4.1.1 Ship Control System Development Plan. A ship control system development plan shall be prepared by the contractor for approval by the procuring agency. This program plan shall include the following as a minimum:

a. A detailed milestone chart showing the necessary development items and the interrelationships between the various work items. Design reviews shall be identified, and all outside and internal data requirements needed to support the major activities shall be identified.

b. A ship control synthesis and analysis plan identifying the general approach and analytical procedures to be used. Analyses planned to generate the requirements for the control system dynamic specification and block diagram of Section 3.6 shall be identified and documentation identified and scheduled.

c. A developmental test plan identifying and scheduling all developmental tests and documentation in support of the control system development.

d. A safety, reliability, and maintainability plan that includes a description of the analytical or other means selected by the contractor for design development and verification in these areas.

4.1.2 Configuration Control. Configuration control is of major importance in the overall product quality. The contractor shall develop and maintain sufficient configuration control documentation and disciplines to assume configuration control. The contractor shall maintain an up-to-date configuration control document that identifies, in total, those documents, drawings, specifications, programs, and test procedures that control the total configuration of the ship control systems.

4.2 Analysis and Documentation. In the development and in the verification of the ship control system designs, many in-depth analyses are required. In the following paragraphs, major analysis and documentation requirements are detailed

4.2.1 Ship Control System Analyses. The design of the ship control systems requires many significant syntheses and analytical studies to ensure that the controlled ship will satisfactorily perform in accordance with the requirements of Section 3. The results of these analyses relating to control system design and ship performance, both hullborne and foilborne, shall be documented. The documentation shall include, as a minimum, the following:

a. Ship Physical Characteristics
   - Weight, inertia, and center-of-gravity values
   - Strut, foil, and sensor locations
   - Principal dimensions

b. Control System Configuration
   - Control paths
   - Gain and filter characteristics
   - Sign conventions and scaling
   - Sensor dynamics
   - Actuator characteristics

c. Requirements
   - Ship foilborne performance requirements
   - Ship hullborne performance requirements
   - Stability requirements
   - tong-term sea conditions

d. Foilborne Analysis

Calm water

Trim characteristics

Maneuvering capabilities

Speed/range

Response to winds

Transition from hullborne to foilborne

Transient response

Rough water analysis

Long-term ride quality characteristics

Long-term motion characteristics

Control authority

Contouring characteristics

Long-term heading hold capabilities

Actuation system analysis

Stability analysis

Directional stability analysis

Gain and phase margin analysis

e. Hullborne Analysis

Maneuvering

Reversing and stopping

Docking and undocking

Heading hold

High-speed hullborne modes

4.2.2 Mathematic Model Report. The mathematic models of the ship, seaway, and control systems used in the syntheses and analyses shall be documented. Documentation shall also include sufficient description of the analytical programs to allow the procuring agency to understand the basic analytical methods. Detail programs containing solution methods need not be provided.

4.2.3 Safety, Reliability, and Maintainability. A report involving safety, reliability, and maintainability shall be submitted and maintained current up to deli very. This report shall contain failure modes, effects, and criticality analyses (FMECA) that identify the various control system failures and their probability of occurrence and that catalog the various failures into the various safety levels and operational levels identified in Section 3.5. The report shall document the results of the various failure studies conducted, including the assumptions made, the approach to the failure and reliability analyses, and the sources of data used. The results shall be discussed and correlated with the requirements of the specification, Section 3.5.

4.2.4 Trade Studies. Major trade studies involved in the selection and specification of the hardware elements shall be documented and their results correlated with the hardware requirements and criteria of Sections 3.8 and 3.9.

4.2.5 Software Documentation. The plans, procedures, and programs necessary to manufacture, program, test, and verify the equipment shall be documented. All digital computer programs related to construction or test of the equipment shall be documented, along with any supporting programs such as compilers and assemblers, as necessary to allow the contracting agency to use any or all such software to modify or verify future systems. All computer languages used must be identified and documented. The computer proqram configuration management practice of MIL-STD-483 shall be used as a guide in the preparation of this documentation.

4.2.6 Dynamic Specification. The dynamic specification and block diagrams required per Section 3.6 shall be formally documented and maintained current.

4.2.7 Design Reviews. The minutes, action items, and all follow-up actions from formal design reviews shall be documented.

4.3 Test Requirements

4.3.1 Qualification Tests. All safety and reliability critical control equipment shall be qualified to the applicable environmental conditions for the specific application. Qualification may be established by any of the following means:

a. Test - Environmental test methods and procedures shall be selected from MIL-STD-810 or MIL-STD-461. Where these are not adequate for the planned usage, the contractor shall be responsible for developing additional methods and procedures. Tests at the line-replaceable-unit level are the preferred approach. Proof of previous qualification by test to conditions at least as severe may preclude necessity to retest.

b. Similarity - Where similarity is used, proof of similarity to units that are qualified to the applicable environmental conditions is the responsibility of the contractor.

c. History of Prior Use - Determination that the unit has satisfactorily performed in one or more relevant applications where the environment, duty cycle, and operating loads are similar or more severe may be used to qualify the unit.

4.3.2 Line-Replacable-Unit Tests. As part of the fabrication process, and prior to delivery for shipboard installation or use as spares, each line replaceable unit or major assembly shall be subjected to a functional test. These tests shall be designed to verify correct assembly of the unit, to verify operability of the components in the unit, and to verify that the input and output characteristics and their relationships are within the design tolerances.

4.3.3 System Integration Tests. Prior to installation of the ship control system in the lead ship or prototype ship, a system integration test shall be conducted in the laboratory. All line replaceable units of the foilborne control system, including controls, displays, sensors, power conditioning, signal processing, and computation and electrohydraulic servos shall be interconnected for this test. Electrical and hydraulic power may be supplied from laboratory systems that simulate the shipboard systems, including the interfaces with the equipment under test. Hydraulic actuator loads may be omitted.

As a minimum, the following testing shall be conducted as part of the system integration test:

a. Functional, dynamic, and static tests to verify that steady-state responses meet specification requirements

b. Electrical power supply variation tests to verify satisfactory system operation over the range of variations expected from the ship's electric plant

c. Tests to verify the predicted results of single and multiple failures as these results are used in safety and operational reliability analyses.

d. Tests to verify system performance and compatibility among components and line replaceable units and with interfacing systems.

4.3.4 Post-Installation Tests, After installation of the ship control system and prior to initial underway operation, the following minimum testing shall be performed:

a. Functional, dynamic, and static tests to verify that all equipment items are properly installed and that steady-state responses meet specification requirements. These tests shall include integrated ship control system and test instrumentation as installed on the ship

b. Servo gain margin tests, if required, to verify stability margin requirements of control loops that are significantly influenced by control surface mass effects

c. Electromagnetic interference (EMI) tests to demonstrate compliance with ship requirements

d. An integrity test to ensure soundness of componnets and connections, adequate clearances, and proper operation.

4.3.5 Self-Test Verification. The built-in test system shall be tested and verified as to its capability to adequately test and fault-isolate in accordance with the requirements of Section 3.

4.4 Verification of Compliance with Specification

4.4.1 Methods for Demonstration of Compliance. Ship control system compliance with each of the applicable requirements of this specification shall be verified using one or more of the following methods. Except where a specific method is required, selection of the method of proof shall be made by the contractor subject to concurrence of the procuring activity.

a. Analysis - Compliance with requirements in cases where testing or inspection would be hazardous or otherwise impractical may be verified through analyses. These analyses may include linear or nonlinear simulations, as defined by the development plan of 4.1.1.

b. Inspection - Compliance with requirements associated with component specifications, the physical arrangement of parts or the physical relationship or parts shall be verifeid by inspection of documentation or inspection of the physical installation. Documentation may include documents showing the qualification status of components that have been qualified to the requirements specifications, or drawings showing clearances or other physical relationships. The development plan of 4.4.1 shall define those items to be verified through inspection.

c. Test - To the maximum extent feasible, compliance with the quantitative requirements of the specification shall be demonstrated by tests. Tests may include laboratory, factory, post-installation, and underway trials as defined in the development plan of 4.1.1. Table 4.1-1 identifies the preferred method of verification for the various requirements of Section 3. The contractor is responsible for the development of the detailed test methodology and procedures.

4.4.2 Rough Water Testing, Verification Method. Many of the rough water performance and behavioral requirements of Section 3 are developed along the statistical theme that the ship shall be capable of meeting the stated requirements in at least 90% or some other specific percent of the defined family of sea environments. The realities of life however, preclude the operating of the ship in a large number of sea conditions to verify compliance with the requirements.

In this section, specific methodology is defined whereby the compliance with the rough water requirements can be realistically demonstrated by a small number of underway trials combined with predictions of the ship behavioral characteristics.

4.4.2.1 Development of Verification Limits for Trials. For those items of section 3 that require compliance with a given requirement in the design family of sea conditions, the contractor shall develop predicted response characteristics, as a function of sea conditions. The predicted responses shall be for worst case headings relative to the sea and in a format similar to Figure 4.3-l.

The contractor shall then develop a long-term distribution of the subject variables for the worst case heading in the design family of sea conditions, similar to that shown in Figure 4.3-2. This prediction is accomplished by combining the response characteristic of Figure 4.3-l with the family of sea conditions defined in Volume I, Section 3.1.6, and as discussed in Section 3.1.4 of this volume. From the predicted long-term distribution of Figure

TABLE 4.1-1

VERIFICATION OF REQUIREMENTS

Section		Method of Verification
3.1	System Description	Not applicable (N.A.)
3.2	Ship Foilborne Performance Requirements	
3.2.1	Ride Quality	Rough water trials
3.2.2	Motions	Rough water trials (where applicable)
3.2.3.1	Calm Water Turning and Maneuvering	Calm water trials
3.2.3.2	Rough Water Turning and Maneuvering	Rough water trials
3.2.3.3	Tactical Maneuvering	Analysis (when applicable)
3.2.4.1	Heading Hold	Rough water trials
3.2.4.2	Automatic Maneuvering	Calm water trials
3.2.5.1	Calm Water Speed Range	Calm water trials
3.2.5.2	Rough Water Speed	Rough water trials
3.2.6.1	Rough Water Capabilities Beyond Design	Analysis
3.2.6.2	Maximum Speed Limitation	Analysis
3.2.6.3	Maximum Speed Capability	Analysis and calm water trials
3.2.7	Transition from Hullborne to Foilborne	Calm water trials
3.3	Ship Hullborne Performance Requirements	
3.3.1	Motions	Rough water trials (when applicable)
3.3.2	Maneuvering	Calm water trials
3.3.3	Reversing	Calm water trials
3.3.4	Docking and Undocking	Calm water trials
3.3.5	Automatic Heading Hold	Rough water trials plus calm water trials (when applicable)
3.3.6	High-Speed Hullborne Operation	Analysis
3.4	Control Dynamic Analysis and Design Criteria	

TABLE 4.1-1 (continued)

Section		Method of Verification
3.4.1.1	Trim Schedules	Analysis
3.4.1.2	Pitch Trim	Calm water trials
3.4.1.3	Height Holding	Calm water trials
3.4.1.4	Roll Trim	Analysis
3.4.1.5	Trim Adjustments	Calm water trials
3.4.2.1	Rough Water Operating Envelope	Analysis
3.4.2.2	Roll Control Authority	Analysis
3.4.3.1	Effective Strut Length	Analysis
3.4.3.2	Contouring Characteristics	Analysis
3.4.4.1	Gain Margins	Analysis
3.4.4.2	Phase Margins	Analysis
3.4.4.3	Directional Stability	Analysis
3.4.5.1	Response to Maximum Helm Step	Calm water trials
3.4.5.2	Response to Foil Depth Commands	Calm water trials
3.4.6.1	Motion Alleviation	Drawing inspection
3.4.6.2	Steering Augmentation	Drawing inspection
3.4.6.3	Trim Augmentation	Drawing inspection
3.4.6.4	Actuator, Linkage, and Control-Surface Damage Protection	Drawing inspection
3.5	Operational Reliability and Safety Criteria	
3.5.1	Operational Level Definitions	N.A.
3.5.2	Failure-Related Safety Definitions	Analysis to support contractor-developed boundaries
3.5.3	Reliability Criteria	Analysis
3.5.4	Safety Criteria	Analysis
3.5.5.1	FMECA Requirements	Analysis
3.5.5.2	Analysis Guidelines	N.A.
3.6	Control System Dynamic Specification and Block Diagram Standards	Inspection
3.7	Simulation Standards	Analysis
3.8	Ship Control System Hardware Requirements	

TABLE 4.1-1 (continued)

Section		Method of Verification
3.8.1	General Requirements	Drawing inspection
3.8.2	Environmental Requirements	Qualification tests
3.8.3	Maintainability Requirements	Analysis and inspection
3.8.4	Interchangeability	Inspection and integration test
3.8.5	Growth Margins	Inspection
3.8.6	Operating Modes	Demonstration
3.8.7	Operating Station	Demonstration/inspection
3.9	Ship Control System Hardware	
3.9.1.1	Static Errors	Analysis and test
3.9.1.2	Frequency Response Tests	Test
3.9.1.3	Resolution and Granularity	Analysis and test
3.9.1.4	Cross-Talk	Test
3.9.1.5	Installation	Inspection
3.9.1.6	Trim Adjustments	Inspection and test
3.9.1.7	Switching Transients	Test
3.9.1.8	Control Linkage Shock Loads	Analysis and inspection
3.9.2.1	Dockside Operability	Demonstration
3.9.2.2	Operational Verification	Demonstration
3.9.2.3	Fault Isolation and Repair	Demonstration
3.9.2.4	Line-Replaceable-Unit Test	Inspection
3.9.2.5	Timing Device	Inspection
3.9.3.1	Steering Station	Inspection
3.9.3.2	Hull Structure	Inspection
3.9.3.3	Control Actuation Foundations and Linkage	Inspection
3.9.3.4	Electric Power	Inspection/test
3.9.3.5	Hydraulic Power	Analysis/inspection
3.9.3.6	Interface With Other Systems	Analysis/test
3.9.4	Electrical Power Conditioning	Analysis/inspection
3.9.5	Electrical Wiring and Cabling	Inspection/test
3.9.6	Sensors	Inspection/test
3.9.7	Electronics	Inspection/test
3.9.8	Actuation	Analysis

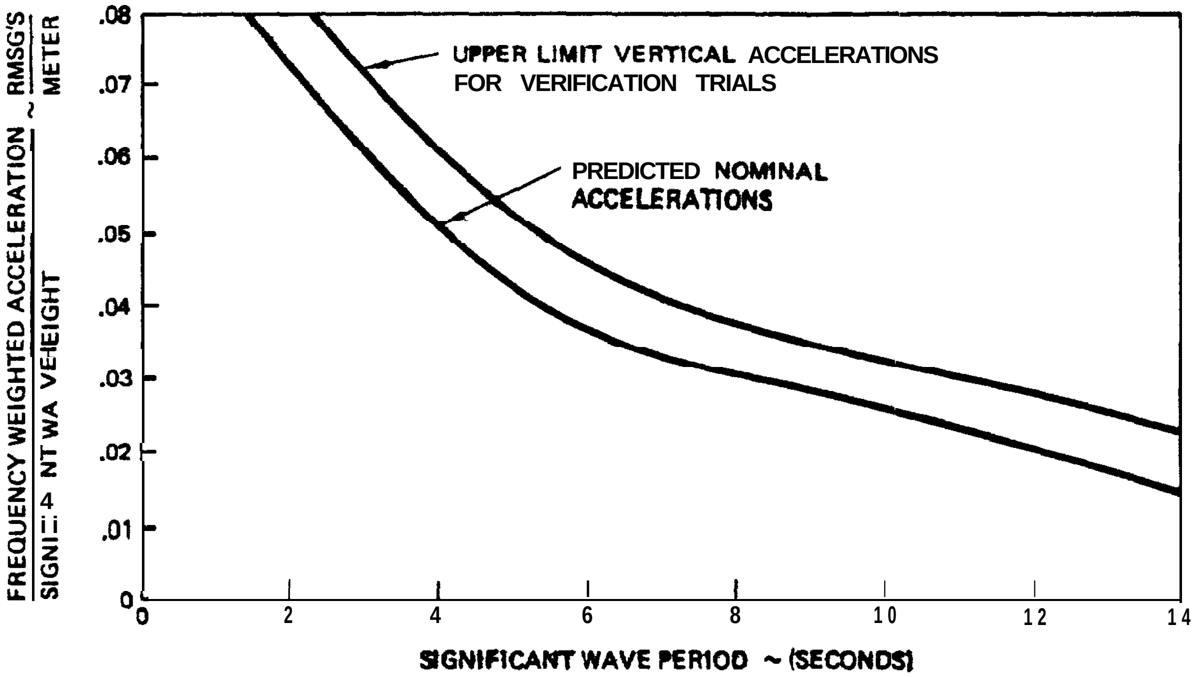


Figure 4.3-1. Typical Ship Response Characteristics in Sea Way

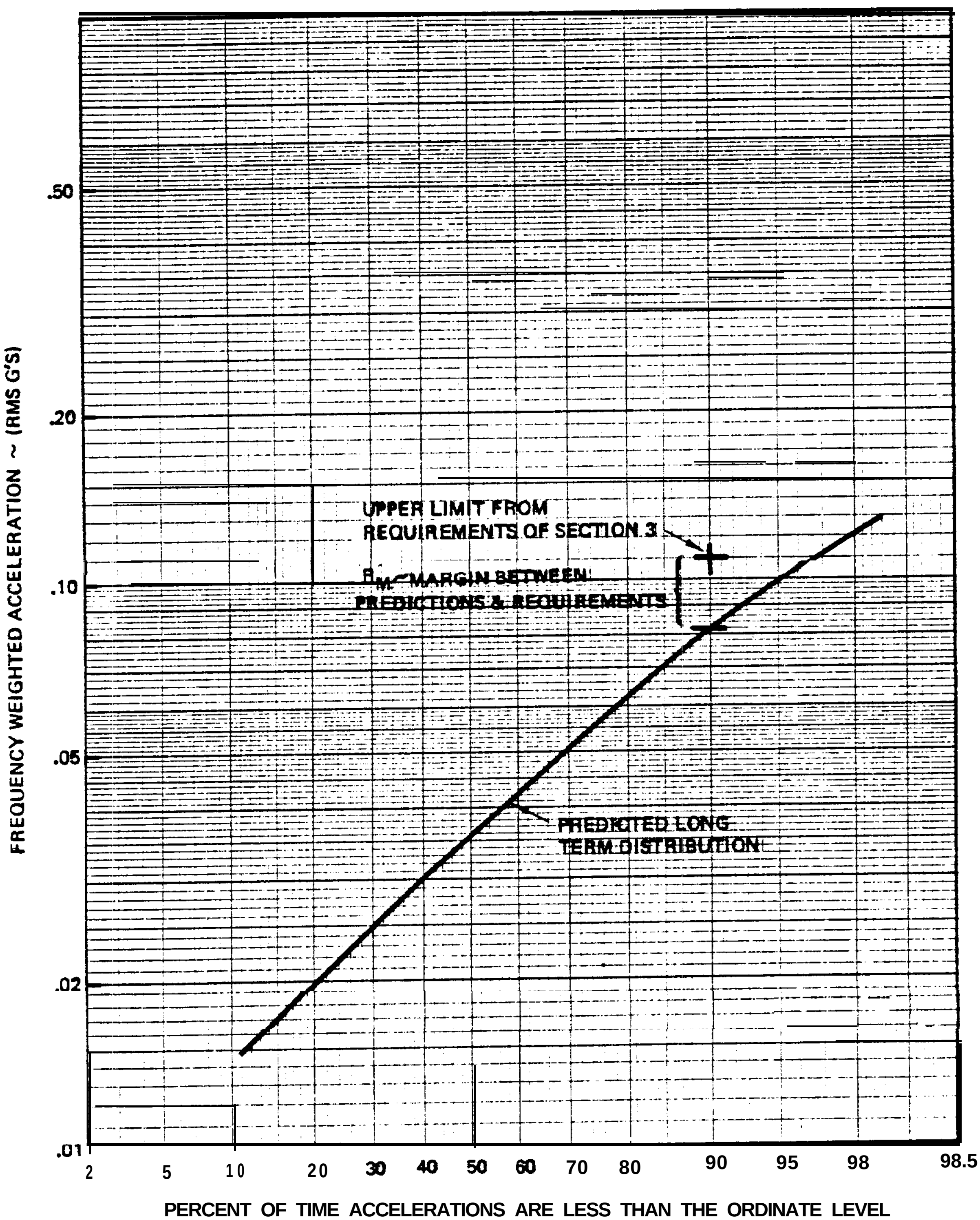


Figure 4.3-2. *Long Term Distribution of Acceleration for Operation at the Worst Case Heading in the Design Family of Sea Environments*

4.3-2, the ratio of the upper limit requirement to the predicted response for the 90% condition is established. This ratio is designated R_m for requirement margin. A second curve shall be drawn in the format of Figure 4.3-l that is scaled upward form the nominal prediction by the ratio R_m. This new curve becomes the upper limit for that measurement for all rough water trials verifications. (It is noted that this upper limit curve when combined with the design family of sea conditions, produces a long-term distribution similar to that shown in Figure 4.3-2 which passes directly through the upper limit requirement at exactly the go-percentile point.)

4.4.2.2 Rough Water Trials Conduct. Compliance with the rough water requirements of Section 3 shall be demonstrated by the conduct of a series of rough water trials in at least three different sea conditions. The trials shall be conducted in sea conditions falling within the boundaries of areas 1 or 2 of Figure 4.3-3, with at least one trial being conducted in seas within the boundaries of area 1.

Each trial shall consist of a series of underway operations at each of eight principal headings relative *to* the sea taken 45 degrees apart, with one heading being directly into the sea (head sea heading). For each trial, the sea state shall be determined in accordance with 4.4.2.3. The measured response at every heading shall be less than the upper limit for verification for the measured sea condition.

4.4.2.3 Sea State Measurements. The sea state may be measured either by a stationary measurement device such as a buoy, or by an onboard wave measurement device. When the measurement is made from a buoy, the buoy must be sufficiently close to the trials area that it accurately represents the seas in which the trials are conducted.

When an onboard wave measurement device is used, the data must be frequency translated to a fixed point reference as follows:

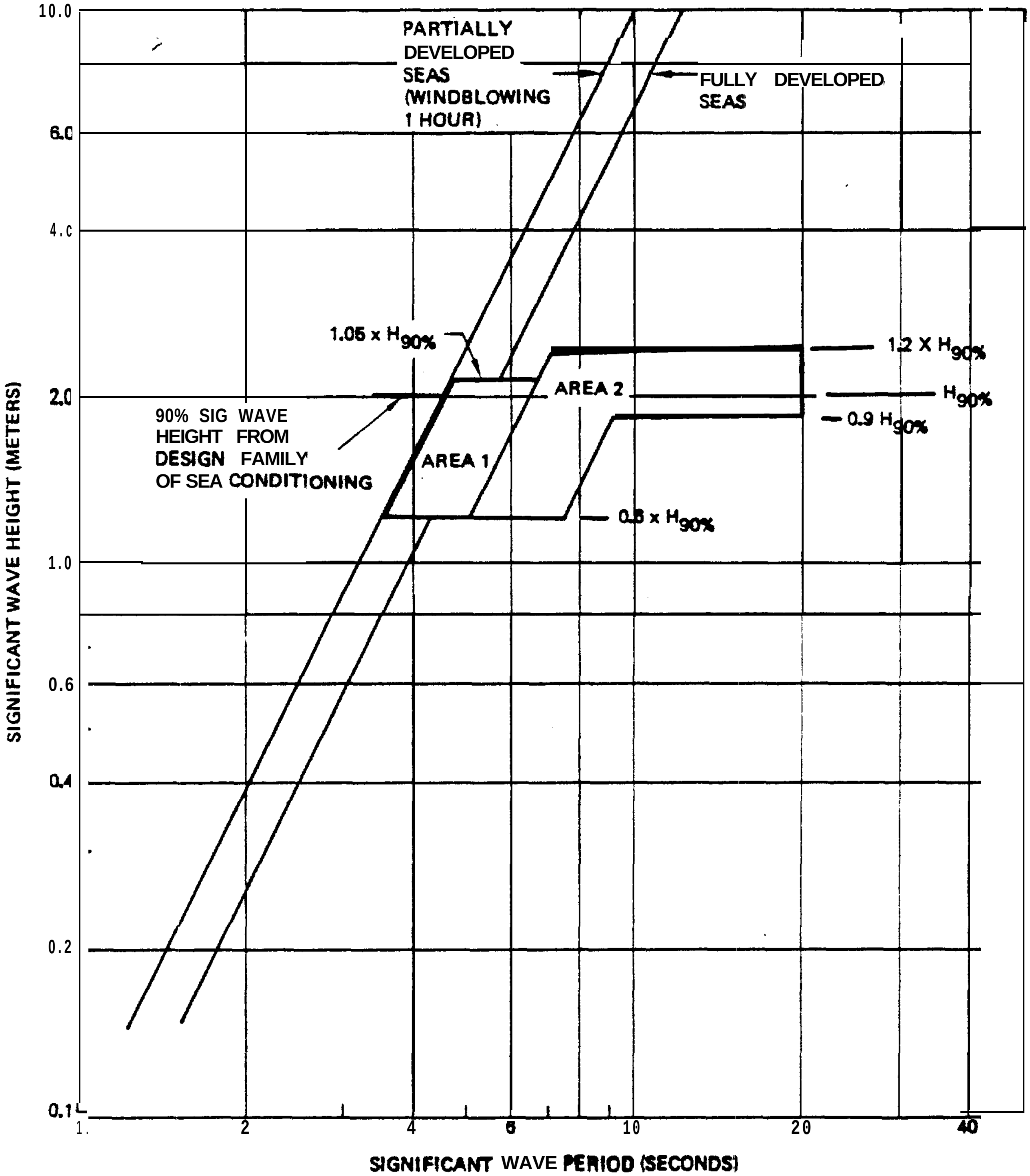


Figure 4.34 Boundary of Sea Conditions for Rough Water Verification Trials

a. Sea, condition is to be measured with the ship operating at a head sea heading, at an average speed between 40 and 45 knots.

b. The average wave encounter frequency shall be determined by counting the number of positive going zero crossings of the wave amplitude trace.

c. The significant wave period is given in Figure 4.3-4 for any average encounter frequency.

Alternatively the significant wave period (T_s) may be computed for any speed of operation in a head sea from the formula:

$$f_e = \frac{1.086}{T_s} + \left(\frac{1.086}{T_s}\right)^2 \left(\frac{2\pi}{g}\right)\left(\frac{V}{1.689}\right)$$

where: f_e = average encounter frequency (hertz)

g = gravitational constant (32 ft/sec^2)

V = ship average speed (knots)

When a stationary wave measurement source such as a wave buoy is used, the significant wave period is to be taken as:

$$T_s = 0.92\ \bar{T}$$

where: $\bar{T}$ = is the average wave period as measured by the average period between positive going zero crossings of the wave measurement trace.

Significant wave height is calculated by normal methods with no translation required.

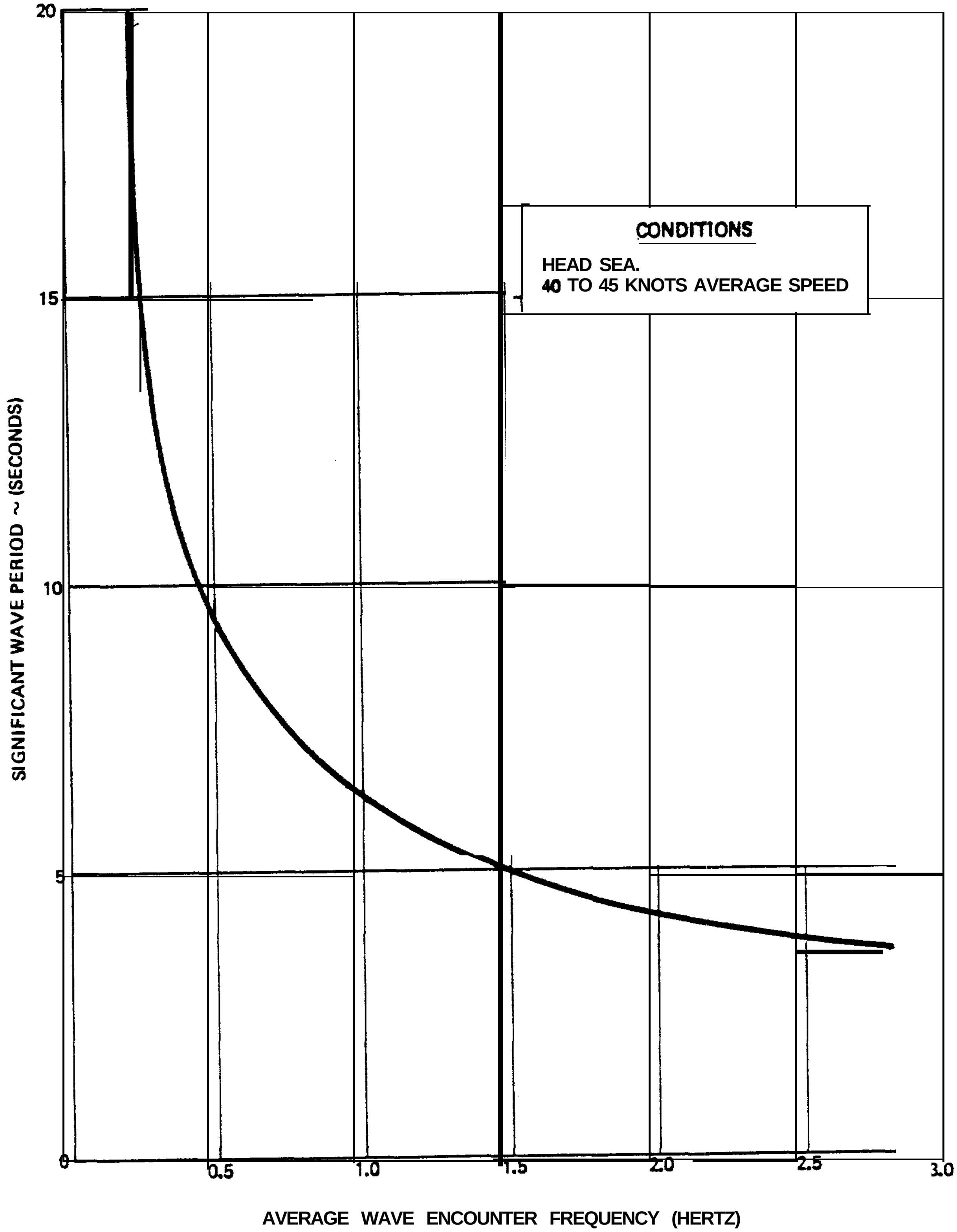


Figure 434. Relationship Between Stationary hint Significant Waw Period and Average Waw Encounter Frequency

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THE BOEING COMPANY

ACTIVE SHEET RECORD

SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR
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THE BOEING COMPANY

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVAL