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HYDROFOIL STRUCTURAL DESIGN CRITERIA

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VOLUME IV

HYDROFOIL STRUCTURAL CRITERIA

FOREWARD

Navy-al criteria for conventional ships are applicable to hydrofoil ships but the unique conditions to, which the latter are exposed while foilborne require special considerations. The following criteria contain specific requirements to ensure that structural capability is provided for high speed foilborne operations in a seaway.

The structural criteria herein consist of specific loads (or specific conditions which result in Loads) and corresponding requirements for specific structural responses to the loads. In general limit loads are to be matched with yield stresses, ultimate loads with ultimate stresses.

ABSTRACT

This criteria contains structural requirements for Navy hydrofoil ship hulls and foi 1 systems. Structural loads, or operating conditions which result in loads, are specified along with required structural responses. Both maximum design loads and fatigue loads are addressed.

KEY WORDS

Hydrofoi 1 Ship
Foi 1 Systems
sea state
fatigue loads
Wave impacts
Hydroelastici ty

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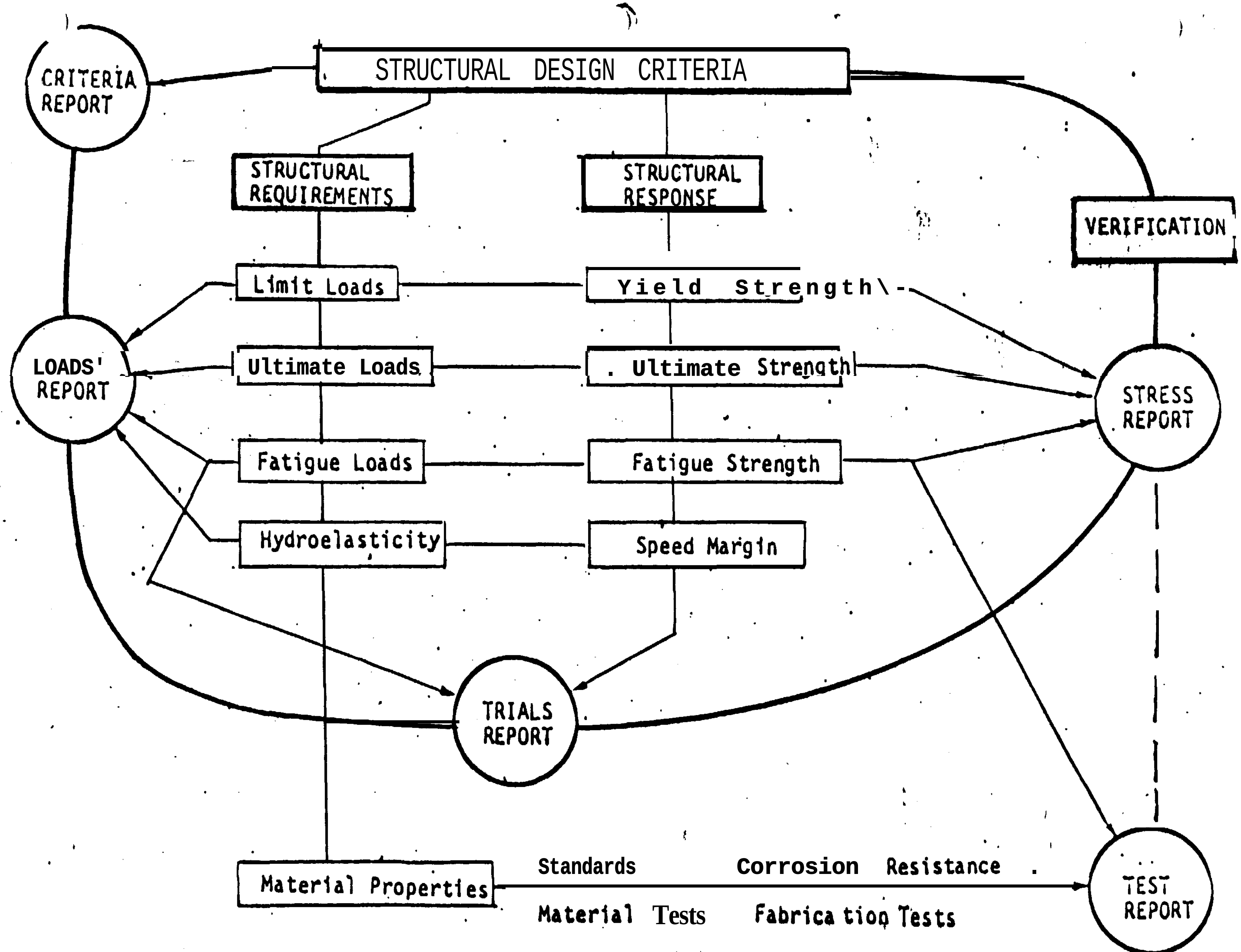


FIGURE 1.0 CRITERIA REQUIREMENTS/RESPONSE/VERIFICATION

1.0 SCOPE

1.1 CONTENT

These criteria contain the requirements for structural loads and structural responses that shall be used for design and verification tests of U.S. Navy hydrofoil ships. Hullborne and foilborne operating conditions described herein shall establish structural design loads for all hull and foil system components. The proposed structure shall be shown by analyses or, if required, by tests, to have stresses not exceeding allowable stresses, to have required fatigue life, and to have stiffness sufficient to prevent hydroelastic problems. The hullborne and foilborne operating conditions shall be used to determine shock and vibration environments applicable to the design of all components and equipment.

This volume is one of the set of design criteria and specification volumes for US. 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.

13 PURPOSE

The criteria and requirements set forth 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. This voume identifies the minimum acceptable structural characteristics and the minimum design and development activity necessary to ensure that strength and rigidity are achieved commensurate with requirements for high speed operations in the intended sea conditions.

1.3 DEFINITIONS

1.3.1 Sea Environment

1.3.1.1 Significant Wave Height and Significant Wave Period

Signficant Wave Height - Average height (crest to trough) of the one-third highest waves in a sea. Abbreviated H_s.

Significant Wave Period - Average period of. the one-third highest waves. Abbreviated T_s.

1.3.1.2 Distributed Wave Heights and Periods - The relative frequency of Occurrence of wave heights and wave periods used herein to determine structural loads shall have statistical distributions based on an accepted sea spectrum.

Appendix 10.1 is an example of accepted spectra.

20 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.

21 GOVERNMENT DOCUMENTS

2.1.2 Specifications

Federal Specification
Military Specifications

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 Performance Prediction Criteria
Volume IIA	Hydrodynamic and Performance Prediction Criteria - Technical Substantiation
Volume III	Hydrofoil Ship Control and Dynamics Specifications and Criteria
Volume IIIA	Hydrofoil Ship Control and Dynamics Specifications and Criteria - Technical Substantiation
Volume IVA	Structural Design Criteria - Technical Substantiation
Volume v	Propulsion System Design Criteria
Volume VA	Propulsion System Design Criteria - Technical Substantiation

Detail Specification for Design and Construction of Hydrofoil Ship ( )

General Specifications for Ships of the United States Navy.

2.1.2 Standards

Federal Standards

Military Standards

MIL-STD-167 Vibration of Equipment and Machinery

2.13 Other Publications

Manuals

DDS 100-4 Strength of Structural Members

Regulations

Handbooks

MIL-HDBK5 Strength of Metal Aircraft Elements .

23 NON-GOVERNMENT DOCUMENTS

Specifications

Standards

Other Publications

3.0 REQUIREMENTS

3.1 GENERAL

The requirements of these criteria shall apply to U.S. Navy hydrofoil ships having fully submerged foils with the foilborne hull supported at two longitudinal locations and with an automatic control system for stabilization. These criteria shall be the basis for structural design except as ammended by the Detail Specification, or as ammended in an approved Structural Design Criteria Report. Design requirements given in the General Specifications for conventional surface vessels of the U.S. Navy are also applicable. Each hullborne structural requirement therein shall be included in the design unless the requirement is specifically deleted or is in conflict with these criteria. The construction of the ship shall be in conformance with the requirements of the Detail Specification.

3.1.1 Configurations

The ship shall be considered complete and capable of hullborne or foilborne operations for the weights of 3.1.2 and load conditions of 3.2 and 3.3.

3.1.2 Design Weights

3.1.2.1 Maximum Foilborne Weight (W_M) - For this condition the vessel shall be considered complete in every respect (including a growth margin if specified) and loaded with crew, cargo, and full foilborne allowances of fuel, potable water, provisions and stores, ammunition and other consumables as specified to perform its design mission.

3.1.2.2 Average Foilborne Weight (W_{AV}) - This condition of loading is the same as W_M except all consumable loads shall be reduced to 60 percent of full foilborne allowances.

3.1.2.3 Minimum, Foilborne Weight (W_{MIN}) - This condition of loading is the same as W_M except cargo shall be considered discharged and all consumable loads reduced to 10 percent of useable foilborne allowances.

3.1.2.4 Hoisting–(Blank)

3.1.3 Mass Properties

3.134 Center of cavity – An' envelope, as shown in Figure 3.1.1, shall be prepared indicating locations 'of -the center of gravity for all configurations including those with the most forward and most aft center of gravity locations and those defined in 3.1 .2.

3.1.3.2 Moments of Intertia – Pitch, roll and yaw moments of inertia shall be calculated for the design weights of 3.1.2 and reported in the Structural Loads Report.

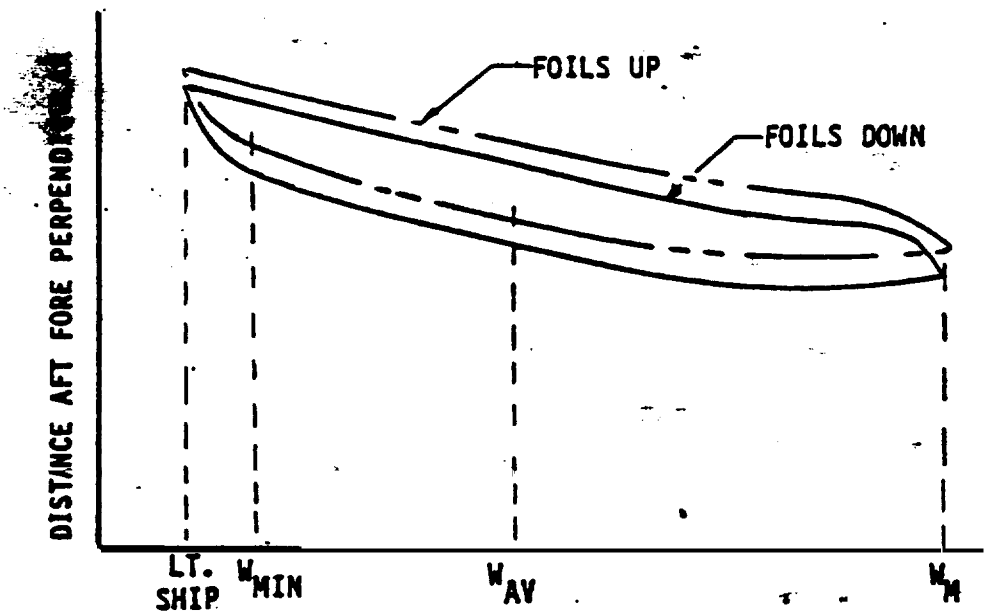
3.1.4 waves

The sea environment shall be defined to match wave heights and wave periods given in the Detail Specifications. A Significant Wave Height and A Significant Wave Period shall be identified and a statistical distribution of waves, as defined in l.3.1.2, shall be used to develop hull and foil system loads.

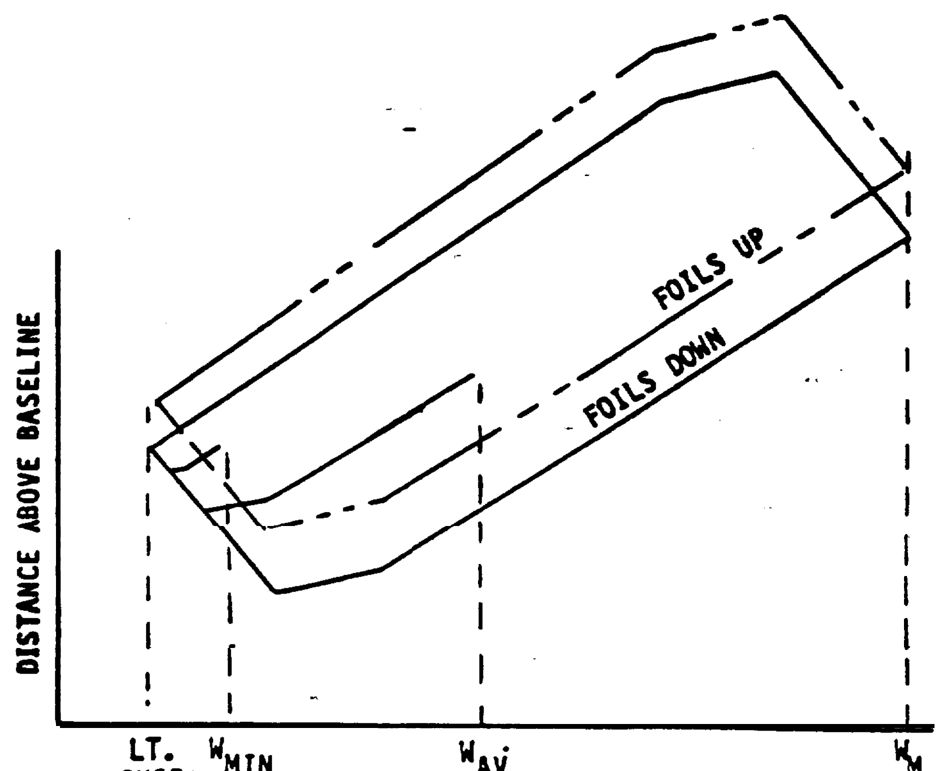
3.15 Design Speeds

3.1.5.1 Maximum Foilborne Speed (V_M) – The maximum foilborne speed shall be the steady state calm water speed attainable at full military power rating of the propulsion system and at W_{MIN}.

3.1.5.2 Rough Water Foilborne Cruise Speed (V_C) – The rough water cruise speed shall be the average speed attainable in head and bow seas at maximum continuous power rating of the propulsion system.



(a) LONGITUDINAL CENTER OF GRAVITY



(b) YERTICAL CENTER OF GRAVITY

FIGURE 3.1-1: CENTER OF GRAVITY ENVELOPE

3.1.5.3 Maximum **Foilborne Rough Water Speed (V_{RW})** – The maximum intermittent rough water speed for loads calculations shall be 5 knots greater than V_C.

3.1.5.4 Hullborne Speed, Foils Extended (V_{FIB}) Hullborne speed with foils extended shall be the average speed attainable at the maximum continuous power rating of the foilborne propulsion system in calm water or, if stated in the Detail Specifications, shall be the required Speed of Advance.

3.1.6 Applied Loads

The basis of the strength design of the ship shall be Yield, Ultimate, and Service Loads. The ship shall be in equilibrium under the action of applied loads with inertia loads accounting for imbalances. Applied loads shall be calculated for the loading conditions of 3.2 and 3.3 for the operational conditions of 3.1. The applicability of 3.1 is shown in Table 3.1.6.

3.1.6.1 Limit Loads – The loads derived from the requirements of this document shall be Limit Loads unless otherwise specified. Whenever the provisions of this specification as applied to a particular hydrofoil ship fail to identify potentially critical loading conditions, or result in inappropriate Limit Load-magnitudes for specified conditions, new or revised Limit Load criteria shall be proposed by the contractor in the initial submittal of the Structural Design Criteria Report of 4.1.

3.1.6.1 Yield Loads – Yield Loads are Limit Loads multiplied by the Yield Factor of Safety. Unless otherwise specified herein, the Yield Factor of Safety shall be 1.00.

3.1.6.3 Ultimate Loads – Ultimate Loads are Limit Loads multiplied by the Ultimate Factor of Safety, or are loads specifically designated herein as Ultimate. The Ultimate Factor of Safety shall be 1.50.

3.1.6.4 Service Loads – Loads to be employed in fatigue strength and crack growth analyses are Service Loads which shall be derived from operational environments specified in the Detail Specification and from time-related load requirements of 3.2.6 for the foil system and 3.3.1.5 for the hull.

TABLE 3.1-6
LOAD CONSIDERATIONS

Load Condition	Configuration 3.1.1	Weight 3.1.2			H_s	Waves 3.1.4		Speed 3.1.5			
		WM	WAV	WMIN		H1/10	Spectra	VM	VC	VRW	VHB
Hydroelasticity 3.1.8	Foilborne			✓				✓			
Foil-Strut Force 3.2.2, 3.2.3	Foilborne								✓		
Maneuver Loads 3.2.4	Foilborne		✓				✓	✓	✓	✓	✓
Debris Impact 3.2.5	Foilborne								✓		
Service Loads 3.2.6	Foilborne & Hullborne		✓				✓		✓		✓
Hydrostatic Pressure 3.2.7	Foilborne										
Propulsion Loads 3.2.8	Foilborne										
Retraction-Extension 3.2.9	Hullborne										
Foilborne Cruise 3.3.1.2	Foilborne	✓					✓				
Rough Water Takeoff 3.3.1.3.2	Foilborne	✓		✓					✓		✓
Emergency Landing 3.3.1.3.3	Foilborne		✓						✓		
Rough Water Broach 3.3.1.3.4	Foilborne	✓		✓		✓			✓		
Rough Water Maneuver 3.3.1.3.5	Foilborne					✓			✓		
Hull Service Loads 3.3.1.5	Foilborne & Hullborne		✓				✓		✓		

3.1.7 Strength Requirements

Adequate strength of proposed structures shall be demonstrated by analyses or tests which shall be fully reported in the Structural Substantiation Report, 4.1. Proposed deviations from the following Strength Requirements shall be fully substantiated and approved by the Navy before being incorporated in the design.

3.1.7.1 **Yield Strength** – The application of Yield Loads shall not cause elastic or permanent deformations which interfere with the intended function of a structural component or require its replacement or repair as a result of their application. Hull plating subjected to yield pressure loads shall not have a calculated permanent set greater than .005 times the distance between stiffeners.

3.1.7.2 **Ultimate strength** – The application of Ultimate Loads shall not cause structural failure.

3.1.73 **Fatigue Life** – Fatigue life of structure subjected to Service Loads of 3.1.6.4 shall be no less than the 'specified Service Life. Fatigue life shall be determined by calculations or tests, or, if required by the Detail Specifications for certain structures, by tests only. Fatigue life of structures immersed in salt water or exposed to salt spray shall be calculated using "in sea water" material fatigue data. Cyclic stresses shall include notch factors from pitting or crevices due to sea water corrosion. Fatigue life calculations shall include Fatigue Rating Factors based on consequences of failure and inspectability as given in Tables 3.1.7(a) and (b).

3.1.7.4 **Flaw Growth ad Residual Strength** – Calculations shall be made showing that initial undetected flaws shall not grow so large as to reduce component static strength below that required to sustain all limit loads employed in structural design. Calculations of flaw growth and residual strength for foils and struts and other components made with ferrous materials shall use initial flaw sizes given in Table 3.1.7(c). Minimum size of undetected surface flaws to be expected in non-ferrous materials subject to this requirements shall be reported and substantiated in the Structural Design Criteria Report and shall not be used in the design until approved by the Navy.

The number of service load cycles used for flaw growth analyses shall be multiplied by the Crack Growth Reliability Factor of Table 3.1.7(d). In designing for through-crack failure, the maximum stress shall be calculated from the the critical plain-strain fracture toughness value (K_{1C}). For 15-5PH stainless steel, K_{1C} is 130 ksi $\sqrt{\text{inch}}$.

3.1.8 Hydroelastic and Stiffness Requirements

A hydroelastic analysis report shall be submitted in accordanc with 4.1 showing compliance with the requirements of this section.

3.1.8.1 Control Reversal - Foils and struts shall be free of control reversal to speeds at least 1.6 times (V_{MAX}) at all strut immersions with the vessel at minimum operating weight.

3.1.8.2 Divergence - Foils, struts and other components subject to high velocity water flow shall be free of hydroelastic divergence to speeds at least 1.6 times (V_{MAX}) at all strut immersions with the vessel at minimum operating weight.

3.1.8.3 Flutter - Each foil-strut configuration shall be free of flutter to speeds at least 1.6 times (V_{max}) for all strut immersions with the vessel at minimum operating weight. Analytical or experimental data, or both, shall demonstrate compliance with this requirement.

3.1.8.4 Buffeting and Panel Flutter - Plating panels subject to highly turbulent flow, such as from the wake of propellers or in waterjets, shall be checked for excessive stress cycling which would result in early fatigue failures. Assurance of freedom from this type of failure shall be verified during underwdy trials.

TABLE 3.1.7(a): Fatigue Reliability Factor

Failure Rating	Inspectability Rating[1]	
	I	II
A	2.0	1.5
B	1.5	1.0

[1] For use with material allowable S-N curves representing the 95% probability and 95% confidence level.

TABLE 3.1.7(b): Definition of Failure and Inspectabilty Ratings

Failure Rating	Definition	Inspectability Rating	Definition
A	Could cause loss of ship, serious injury to personnel, unavailability for more than seven days or cause a mission in progress to be aborted.	I	Requires disassembly of strut/foil system or removal of large equipment items on or in the hull; locally uninspectable area; or inspectable only while dry docked with no more than minor disassembly.
B	All failures not classified as A.	II	All component areas not rated I, or for Flaw Growth detectable by scheduled inspections.

TABLE 3.1.7(c): Initial Flaws in Ferrous Materials
(Undetected Surface Flaws)

Base Metal	1.2 x 4.32	
	Longitudinal	Transverse
Standard Weld	1.52 x 12.70	1.52 x 12.00[2] 1.52 x 5.08[3]
Blind Weld	2.54 x 127.0	2.54 x 12.70[2] 2.54 x 5.08[3]

[1] All dimensions in millimeters
[2] Gas tungston Arc and Gas Manual Arc
[3] Plasma Arc and Electron Beam

TABLE 3.1.7(d): Crack Growth Reliability Factors

Failure Rating'	Inspectability Rating'	
	I'	II'
A	1.5	1.0
B	1.0	0.5

'The definitions of Table 3.1.7(b) shall apply

3.1.8.5 Static Deflection - Components which rotate or slide shall be free of binding or excessive friction due to deflection of the supporting structure with limit Loads applied. Control flaps, actuation linkages, push rods, etc., shall have self-aligning bearings if necessary to ensure free motion.

3.1.9 Shock and Vibration

Equipment and foundations shall be designed for shock loads caused by hull-wave impacts and for vibrations due to rotating machinery; Shock load factors as shown herein are considered separately from 3.1.10. Equipment weighing 1350 N (300 lbs) or less shall be subject to shock loads shown on Figures 3.1.2 and 3.1.3 which give acceleration levels versus the fundamental natural frequency of the equipment. If natural frequencies are unavailable, the following guideline may be used:

Weight, Newtons	Shock Spectra Frequency (Hz)
Less than 20.0	200
20.0 to 110.0	100
110.1 to 335.0	50
335.1 to 00.0	35
670.1 to 1350.0	20

Load factors on Figures 3.1.2 and 3.1.3 are also applicable to installations of equipment weighing over 1350 N, however for such equipment the factors used shall not exceed inertia load factors calculated in accordance with 3.3.1.4.

Lightweight equipment installations shall be designed for vibration load factors as well as shock. Figures 3.1.4 and 3.1.5 are typical sinusoidal and random vibration environments. These or other data, if more applicable, shall be used for evaluation and designing such installations.

Vibration requirements of MIL-STD-1678 are also invoked to the extent they may exceed the above requirements.

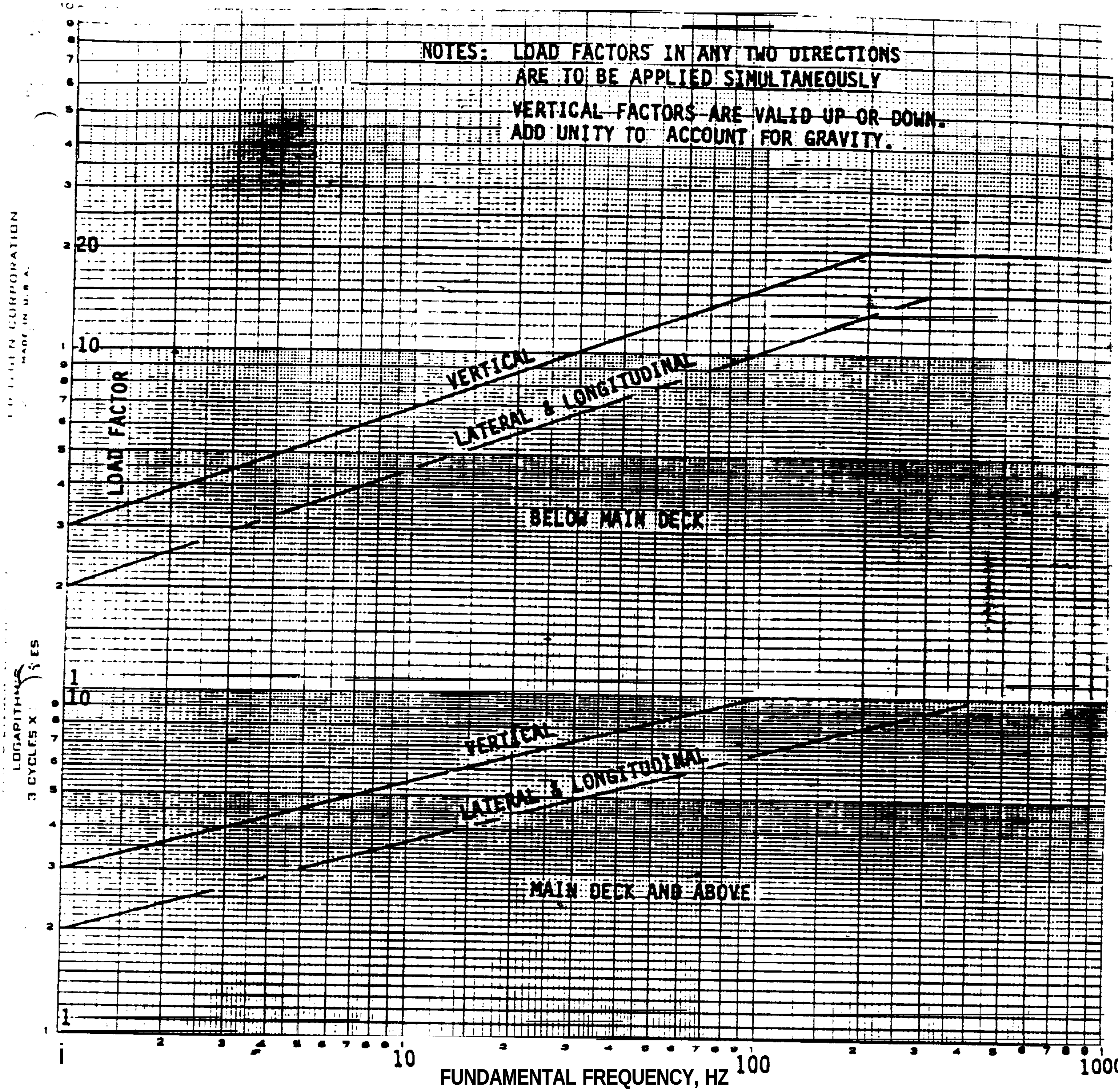


FIGURE 3.1.2: SHOCKLOAD ENVELOPE FOR EQUIPMENT INSTALLATIONS IN FORWARD 1/3 LENGTH

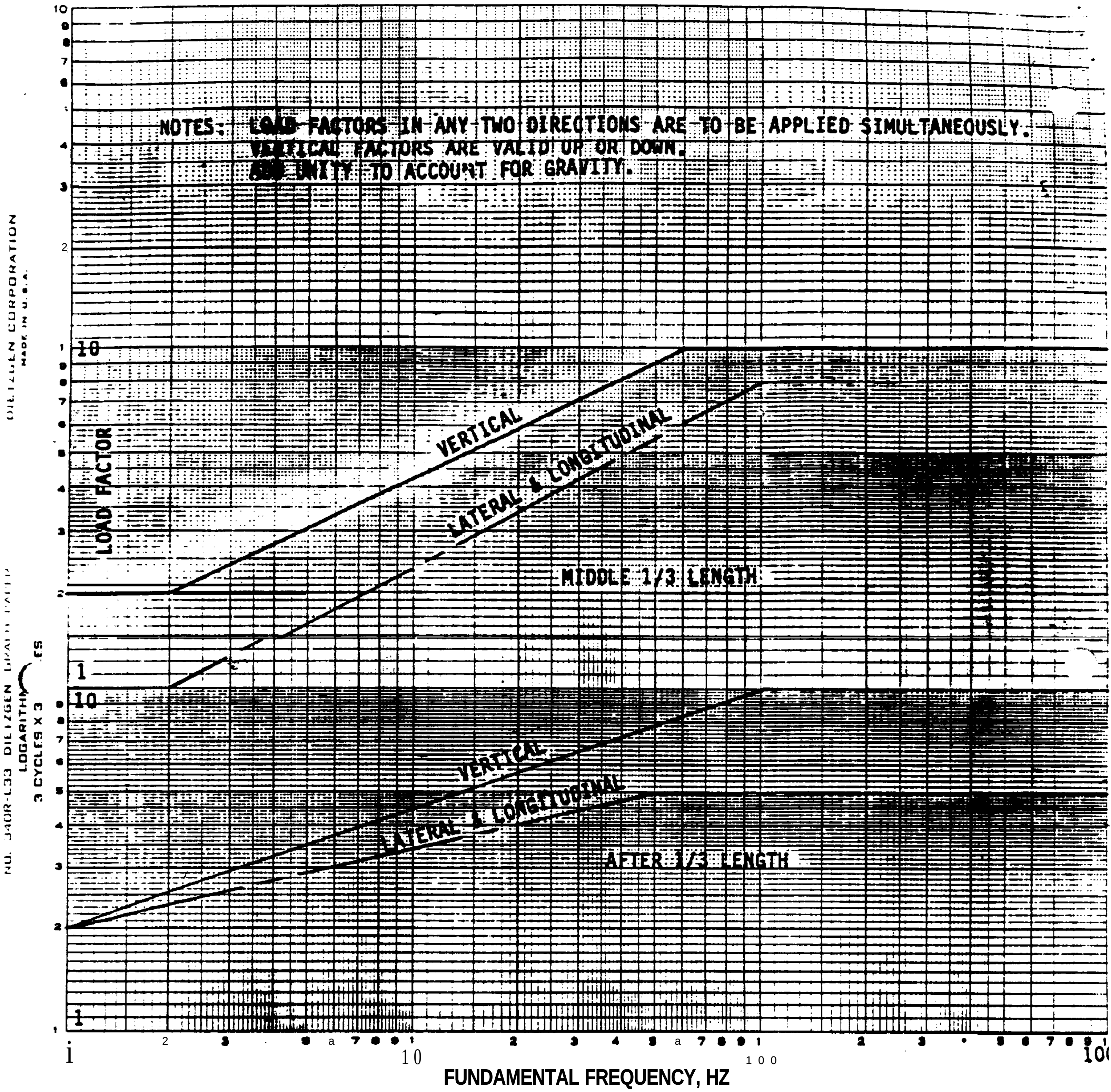


FIGURE 3.1.3: SHOCK LOAD ENVELOPE FOR EQUIPMENT INSTALLATIONS IN AFTER 2/3 LENGTH

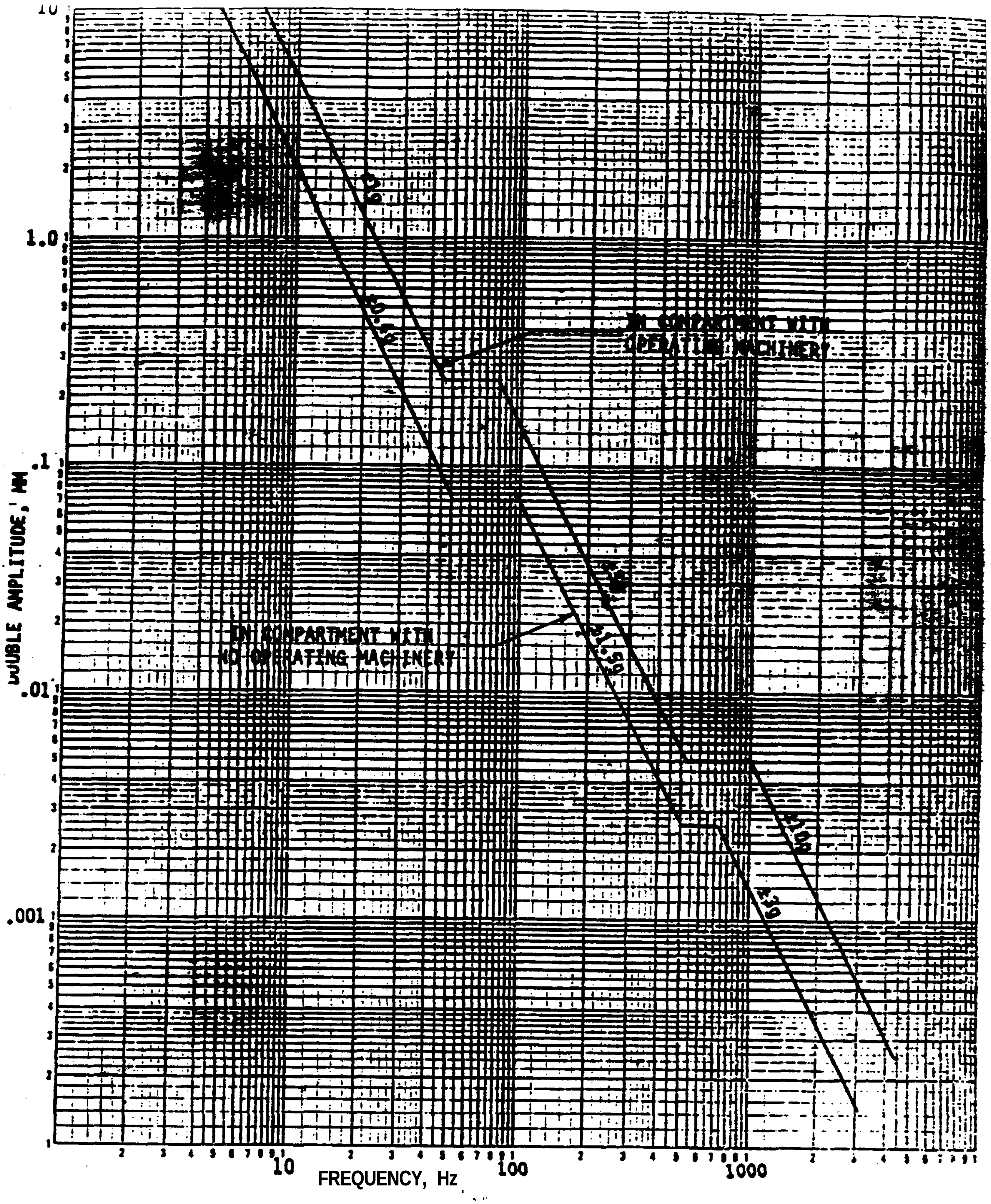


FIGURE 3.1.4: SINUSOIDAL VIBRATION ENVRIONMENT

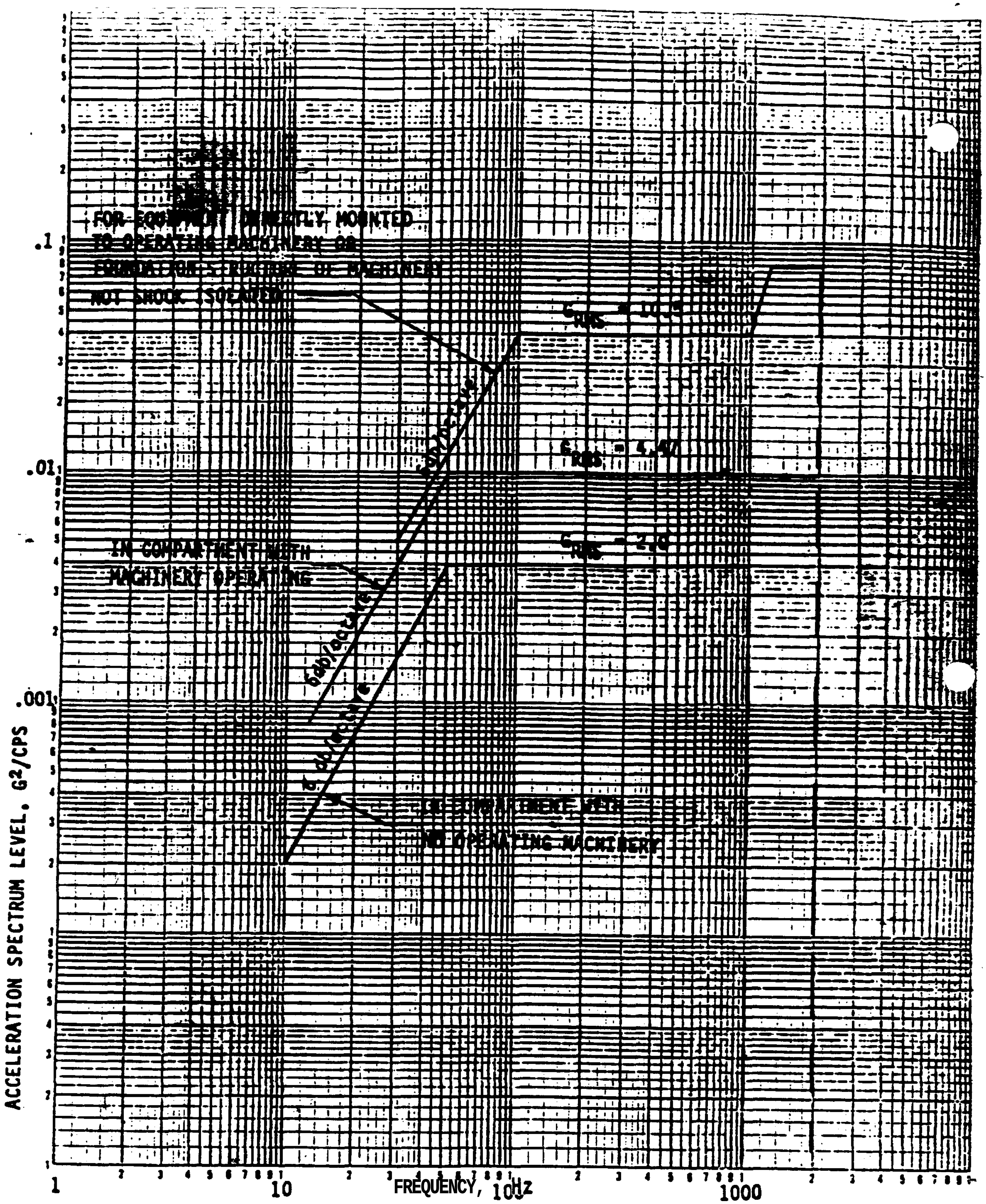


FIGURE 3.1.5: RANDOM **VIBRATION** ENVIRONMENT

3.1.10 Weapons Loads

3.1.10.1 Gun Firing – Gun blast pressures shall be as specified for the particular gun or in the absence of such data, shall be calculated from the following expression:

$$P = DMF \frac{200\,(1 + \cos\delta)^2}{(x/d)^{3/2}}, \text{ psi}$$

$$P = DMF \frac{1379\,(1 + \cos\delta)^2}{(x/d)^{3/2}}, \text{ kPa}$$

where:

PO	limit static equivalent pressure
x =	radius vector from gun muzzle
d =	gun-bore; same units as x
δ =	angle between radius vector and gun barrel
DMF =	dynamic magnification factor
	1.4 for design of plating panels or panel attachments
	1.0 for design of framing in support of panels subject to gun blast pressure loads

3.1.10.2 Missile Launching – Missile blast pressures and temperatures shall be as specified by the manufacturer(s) of the weapon and launching system. In the absence of such data, the environmental characteristics associated with missile firing shall be in accordance with Section 100a of the General Specifications. Pressures and temperatures and their time histories shall be considered for normal firing. and also for the longer time period associated with accidental missile ignition.

3.1.10.3 Explosive Air **Blast** – Requirements for structure exposed to air blast, in addition to 3.1.10.1, are given in the Detail Specifications.

3.1.10.4 Hullborne Underwater Explosion - Requirements for hull structure subject to underwater explosion ate given in the Detail Specifications.

3.1.10.5 Foilborne Underwater Explosion - Foils, struts, strut to hull attachments, submerged pods containing foilborne control or propulsion components and submerged structure subject to underwater explosion shall be designated as shock Grade A as defined in the General Specification.

3.1.11 Simulations

Simulations shall be designed and used to predict hull and foil system service loads in the design sea conditions. Simulations shall include hull and foil system geometry, mass characteristics, foil system hydrodynamics, control system characteristics, and other physical characteristics of the ship and the sea. Loads defined by the simulations shall become part of the loads used for design of the ship and shall be used for predicting structural behavior during trials. Justification and validation of the simulations shall be reported in the Structural Simulation Report, 4.1.

At least one simulation shall include responses in six degrees of freedom (surge, side-sway, heave, roll, pitch, and yaw) and shall be capable of predicting variations in forces and moments for each hydrodynamic surface. This simulation shall recognize and be responsive to combined effects of ship heading and speed in sea states. This simulation shall use the same parameters and constants, insofar as practical, as Control Simulations required in Volume III.

3.2 FOIL SYSTEM

3.2.1 General

The foil system shall to support the craft and its contents in the foilborne operating mode and shall withstand loads resulting from operations in smooth water and in a seaway. In addition, the foil system shall withstand loads associated with integral elements of propulsion and control systems and loads induced by hydroelastic deflections and dynamic responses.

32.2 Foil Maximum Force

3.2.2.1 Lift ad Moment - Maximum upward and downward forces normal to the foil chord plane are the maximum probable hydrodynamic loads on each T-foil semispan or on each span between supporting struts. The loading shall be ● cleast as great as given by,

$$\frac{L}{S} = k\left(4180 + 128h + .466\, V_c^{\,2}\left(\frac{AR}{AR+3}\right)\right), \text{ psf,}$$

or, $$\frac{L}{S} = k\left(200 + 20.1h + .466\, V_c^{\,2}\left(\frac{AR}{AR+3}\right)\right), \text{ kPa.}$$

Where, h = Strut length from foil-chord plane to hull baseline, feet or meters

k = .5 for forward foil system
.6 for after foil system

V_c = Rough Water Cruise Speed, knots

AR = Aspect Ratio, $Span^2/Area$

Spanwise limit bending moments shall be calculated with the above pressure distributed according to foil taper ratio as follows:

Taper Ratio (Tip Chord/Root Chord)	Spanwise Center of Pressure, % of Semispan
0.0	41
0.2	42
0.4	43
0.6 - 1.0	44

3.2.2.2 Foil Maximum Drag – Foil maximum drag in the foil chord plane shall be 20% of the total force being considered and shall be so distributed as to have the same spanwise center of pressure.

3.2.3 Strut Maximum Force

3.2.3.1 Side Force and Moment – Strut maximum side force normal to the strut chord plane shall be as follows for rough water cruise speed, V_C, of 40 knots;

Aspect Ratio	Maximum Side Load (kPa)	(psf)
1	32.6	680
2	52.7	1100
3	65.3	1360
4	74.8	1560

Aspect Ratio = $Span^2$/ Area

Span = Strut length from bottom of strut including pod, to hull baseline

Area = Projected area of strut from bottom of strut, including pod, to hull baseline.

For other than 40 knots, values shall be changed in the ratio, $(V_k/40)^2$. Values for intermediate aspect ratios can be interpolated.

Strut maximum side forces shall be distributed such that the spanwise center of pressure fa the strut immersed to the hull baseline shall be 60% of the depth below the baseline.

3.2.3.2 Strut Maximum Drag – Strut maximum drag shall be 20% of the total face being considered and shall be so distributed as to have the same spanwise center of pressure.

3.2.3.3 Foil Chord-Plane Loads – With the strut subjected to the maximum side force and drag loads, above, the foils shall be considered loaded as follows:

T-foil semispans shall be loaded as follows with the net bending moment at the foil-strut intersection such as to increase strut bending moment:

Aspect Ratio	Vented Semispan Load		Wetted Semispan Load	
	(kPa)	(psf)	(kPa)	(psf)
3	19.6	410	78.8	1645
4	22.5	470	90.0	1880
5	24.7	515	98.6	2060
6	263	550	104.9	2190
7	27.5	575	110.1	2300

Drag shall be 20% of the force on each semispan. The center of pressure shall be located spanwise in accordance with taper ratio as shown in 3.2.2.1.

A foil supported by two or more struts shall have for each strut, considered separately, all span segments on one side wetted and all span segments on the other side vented. In addition, the span segments which are part of the ship's roll control system shall have their faces directed such as to simulate the most severe combination of loading. Foil drag shall be as for T-foil semispans, above, except that the center of pressure for each span segment between struts shall be at the spanwise location of its center of area.

3.2.4 Maneuver Loads – In addition to the requirements of 3.2.2 and 3.2.3 other loading conditions shall be investigated that might lead to more severe limit load combinations. conditions to be investigated shall include the following, at least, and others which may be unique to a proposed configuration. All speeds of 3.1 .5 shall be considered. The results of these investigations shall be included in the Structural Loads Report (4.2).

3.2.4.1 Flat Turn – The ship shall be in a steady flat turn such as to develop maximum forward strut side force. The side force shall be produced by rudder deflection. Roll control surface deflections shall be as required to maintain a bank angle of 0 degrees. Rudder deflections may be reduced if required to avoid exceeding maximum available roil control authority.

33.43 Hardover Helm – The ship shall be in a steady turn corresponding to full helm displacement. With normally operating control system the helm shall be instantly reversed to maximum opposite deflection. Propulsion forces shall correspond to the initial steady turn. Foil system loads resulting from the abrupt helm displacement shall be determined by a dynamic analysis of ship response using simulations as described in 3.1.11.

3.2.4.3 Maneuver in Waves – The ship shall be in equilibrium with a lateral load of 0.2g applied at the center of gravity which is balanced by steady side forces on the struts. Foil depth shall be one-half of the available strut length. The foil system shall be subjected to incremental forces as follows:

a. The side loads shall be increased by sudden immersion of the foil system to the baseline.

b. Incremental lift to produce an upward acceleration of 0.25g shall be applied to the foils with a dynamic magnification factor of 2.0.

c. Steady state one-factor loads and the incremental lift of (b) shall be redistributed to a 60-40 percent distribution about foil centerlines in the most adverse manner.

3.2.5 **Debris Impact** - Each foil/strut shall withstand without failure of the foil/strut or its foundation, an ultimate, aft acting, 30 millisecond, half-sin load pulse with amplitude equal to its steady lift and applied at the tip. The actuation mechanism of a steerable strut shall be protected from structural failure for the event of the strut being subjected to this loading.

3.2.6 **Service Load Spectrum** - The occurrence frequencies of foil system loads shall be ascertained for use in fatigue life calculations and shall be reported per 4.1. Consideration shall be given to hullborne and foilborne operations induding takeoffs, landings and maneuvers in a seaway with equal time at each heading. Ship speeds shall be VC, foilborne, and, V_{HB}, hullborne. Service Loads shall be applied with factors specified in3.1.7.

Full scale service load measurements from previous data shall be used whenever possible. The development of component service loads by sea state, heading, and operating mode shall be dearly shown; summary curves and tables of service loads alone are unacceptable. Maximum values of service loads shall be compared to the corresponding limit loads. Consideration shall be given to foil system buffet loads due to cavitation cavity shedding as well as all loads associated with control surface deflections. Consideration shall also abe given to the influence of hydro-elastic deflections on foil and flag load distribution.

3.2.7 **Hydrostatic Pressure** - Built-up elements of foil system structure, when not flooded or pressurized, shall withstand the hydrostatic pressures associated with their operating depths without leakage, or deflections that affect their hydrodynamic properties. These requirements shall be met in combination with any of the foregoing load conditions.

3.2.8 **Propulsion Loads** - The foil system shall withstand loads associated with normal operation of the propulsion system for any power setting up to maximum engine rpm and in combination with any of the foregoing load conditions. Foil systems containing propulsion shafting shall be capable of sustaining an ultimate load caused by transmission seizure at the design cruise speed in calm water. Struts containing ducting for waterjet propulsion systems shall be capable of sustaining an ultimate load caused by sudden blockage of the ducting on the discharge side of the propulser.

32.9 Retraction and Extension - The foil system shall be capable of withstanding loads associated with extension or retraction at maximum rate while the ship is underway hullborne in a seaway such that the foil system experiences incremental vertical accelerations of ±0.5g and relative water velocities of up to 10 knots normal to foil system surfaces. Up-lock mechanisms shall be capable of securing and restraining the foil systems in position against loads associated with the foil system weights and inertia forces due to craft. motion while hullborne in the design sea state and shall not fail if the Retraction-Extension system is inadvertently activated.

X2.10 Foil and Strut Structure

Structural frequencies of less than 6 hz shall be avoided to reduce interference with automatic control system frequencies.

3.2.11 Pods and Fairings

X211.1 Hydrodynamic Loads - Pods and fairings shall withstand hydrodynamic pressures implied in the development of the foil system design loads. Due consideration shall be given to the internal loading of hollow pods and fairings, whether sealed, ventilated, flooded, or pressurized.

f2.111 Deflection Loads - Pods and fairings shall withstand loads arising from deflections of the foil system structure to which they are attached. These loads shall be sustained simultaneously with the pressure loads of 3.2.11.1 associated with the foil system loading condition under consideration.

3.2.11.3 Hydrostatic Loads - Pods and fairing shall withstand hydrostatic pressure loads associated with their operating depths. These loads shall be sustained simultaneously with the other loads of this section.

3.2.12 Control System

The requirements of this section shall be applied to all elements of ship control including flaps, incidence surfaces, linkages, bearings, and attachments.

3.2.12.1 Hydrodynamic Loads—Elements of the control system shall be designed to withstand hydrodynamic loads associated with craft speeds and attitudes implied or specified in the foil system design limit and service loads of 3.2. Consideration shall also be given to the limit load associated with the control surface or device fully deflected with full cavitation on the low pressure side.

3.2.12.2 Actuation L--Hydraulic actuation loads shall be calculated using the system maximum pressure, which shall be 10% greater than relief valve cracking pressure, increased by dynamic factor of 2.0, or alternatively by a rational analysis of control system response to a step voltage input at the actuator. Actuator applied loads shall be reacted by hydrodynamic and added mast loadings at the control surface.

3.2.12.3 Deflection Loads—Control system elements shall withstand loads arising f tom deflections of the foil system structure to which they are attached. These loads shall be sustained simultaneously with the loads associated with the foil system loading condition under consideration.

3.3 HULL

The hull shall be capable of operating in all combinations of design sea state and speeds as provided by the Detail Specifications, without exceeding the structural limitations-of 3.1.7. To ensure that this capability is achieved, loads used for structural design shall meet or exceed loads associated with the following load conditions.

3.3.1 Load Conditions

3.3.1.1 Hullborne Loads – The hydrofoil vessel shall be capable of withstanding all loads included in the General Specifications for Building Ships of the U.S. Navy applicable to a conventional vessel of similar size and hullborne capabilities.

X3.1.2 Foilborne Cruise Loads – Since a hydrofoil ship hull is supported at two discrete points along its hull when foilborne, unlike the buoyant support of hullborne ships, it is necessary to assure that such point loads can be adequately sustained. For the conditions of this section, it shall be assumed that the vessel is at maximum foilborne weight, W_M.

3.3.1.2.1 Straightaway – The hull girder shall withstand, in foilborne straight-ahead operation, steady-state loads increased by the lift required to produce an incremental vertical acceleration of l-g.

3.3.1.2.2 Maneuvering – The hull girder shall withstand steady state loads imposed by the foil system, increased by the lift required to produce an incremental vertical acceleration of 0.5 g. Simultaneously, additional loads shall be applied to the foil system to produce a lateral acceleration of 0.5 g.

3.3.1.3 Foilborne Wave Impact Loads

3.3.1.3.1 General – Foilborne rough water operations will result in hull-wave impacts which are the most severe sea state loads a hydrofoil vessel is expected to encounter. The hull shall be designed to minimize impact loads for normal f oilborne operations. However, the hull shall be structurally capable of with standing ail foilborne wave impacts which may occur with the ship in adverse attitudes and with adverse motions. The following conditions of impact shall be investigated and the resulting pressures, forces and accelerations shall be the basis of hull structural design except as may be necessary to meet requirements of other sections of these criteria. Appendix 10.3 describes typical considerations for hull-wave impact analysis.

The ship shall be considered to make the following maneuvers which result in hull-wave impact limit toads while at maximum and minimum foilborne weights (W_M and W_{min}) with normally operating automatic control system. hnpact forces shall be calculated using the ($H_{1/10}$) wave height-in the foilborne maximum design sea. Wave lengths shall be the most severe for the impact condition being considered but need not be less than 15 times wave height.

3.3.1.3.2 Rough water Takeoff - While operating in the maximun sea state for foilborne operation as required by the Detail Specification, the ship shall be considered to make a rapid head-sea takeoff. The takeoff may be manual or programmed. Wave impacts which may occur during the maneuver shall be investigated considering ship speed and pitch-up attitude.

3.3.1.3.3 Emergency Landing - While operating at the speed of (V_C) in a head sea in the maximun sea state for foilborne operation as required by the Detail Specification, the ship shall be considered to become rapidly hullborne by an emergency landing maneuver. This maneuver shall be investigated for wave impacts which occur at all possible locations along the length of the hull considering the speed and attitude of the ship.

3.3.1.3.4 Rough Water Broach - While at the speed of (V_{RW}) in a head sea, in the maximum sea state for foilborne operations as required by the Detail Specification, the forward foil system shall be considered to have emerged through the surface on the back of a wave completely losing lift. Subsequent ship motions shall result in the fore part of the vessel impacting the next oncoming wave. The impact shall be investigated considering motions and attitudes of the vessel at the instant of impact. If the forward foil system consists of separate port and starboard foils, then only one shall be considered to lose lift and the resulting roil attitude and roil motions shall be included in the impact evaluation.

3.3.1.3.5 Rough Water Maneuver - While foilborne in the maximum sea state for foilborne operations as required by the Detail Specification, the ship shall be considered to make a maneuver which results in a head sea impact with an oncoming wave. The conditions of impact shall be at least as severe as the following:

ship speed:	Maximum rough water foilborne speed, VRW.
Sink Speed:	5 Foot/second (1.5 M/second) at the CG
Roll Attitude:	Consistent with a coordinated turn at the maximum design turn rate, or 12 degrees, whichever is greater
Pitch Attitude:	Up to ± 5 degrees from design foilborne attitude for ship displacement up to 100 tons, varying linearly from ± 5 degrees to ± 3 degrees for displacements between 100 and 200 tons, and ± 3 degrees for displacements over 200 tons.
Wave:	$H_{1/10}$ wave height and wave length such that the maximum slope is the same as the buttock line slope at thepoint-of contact but no greater than 12 degrees.

3.3.1.4 Wave Impact Acceleration - Acceleration envelopes shall be es&shed 'for vertical, lateral and surge accelerations which result from 'wave impacts. Consideration shall be given to the probable structural overshoot caused by impulsive loading; in lieu of more specific information, a-dynamic magnification factor of 1.5 shall be applied to calculated wave'impact accelerations.

3.3.1.5 Service Loads - Load spectrums shall be generated in sufficient detail to allow fatigue life evaluations for the locations noted in 3.3.3.4. In lieu of more specific data it may be assumed that load peak values are Ray leigh distributed such that,

$$P(n > x) = e^{-x^2/2 \sigma^2}$$

where: $P(n > x)$ is the probability that a load peak, n, exceeds x, and σ is the standard deviation of loading.

Loads shall be described in tables or curves indicating load. magnitudes versus occurrence rates and shall be reported in the initial submittal of the Structural Design Criteria Report.

3.3.2 Hull Structural Capability

The hull as a girder and hull components that" form framing, shell and interior support structure shall be capable of sustaining pressures, forces and accelerations for each load condition of this specification without exceeding the yield, ultimate, and fatigue strength requirements of 3.1.7.

3.3.3 Hull Girder

333.1 **Hullborne -** The hull as a girder shall be capable of sustaining bending moments and-sheers associated with hullborne speeds of 3.1.5.4, foils up and foils down, in the sea states required by the Detail Specification.

Although hullborne bending moments are expected to be less than for foilborne, assurance of this fact must be established for each design.

3333 **Foilborne Cruise -** The hull girder shall be capable of sustaining the foilbome loads of 3.3.1.2 and simultaneously, the reaction' and pressure loads from weapons firing as stated in 311.10.

3.3.3.3 Foilborne Wave Impacts - Bending moments and sheers due to foilborne hull-wave impacts are expected to be far more severe and varied than those from hullborne or other foilbome operations. Forces from wave impacts may occur anywhere along the length of the hull causing hogging or sagging bending moments. For hull-rolled wave impacts the forces will have both vertical and lateral components so that vertical and lateral bending moments will occur simultaneously. Local stresses due to impact pressures will also be additive to bending stresses.

Maximum values of positive and negative bending moments and sheers for the loading conditions of 3.3.1.3 shall be developed for sufficient locations along the length of the hull to ensure the adequacy of the hull girder. Consideration shall be given to the following concurrent loads:

positive or negative vertical bending moment,
lateral bending moment,
positive or negative vertical sheer,
lateral sheer, and
impact pressure.

Wave impact forces and inertial responses shall be applied to the hull girder with a dynamic magnification factor of 1.5.

The vessel shall be in static equilibrium considering impact forces, foil system forces, and inertia forces.

3.3.3.4 Fatigue – Bending moment spectra shall be generated from the load spectra of 3.3.1.5 for sufficient locations to allow evaluation of the fatigue life of the hull girder. The locations selected shall include strut foundations, stepped decks, ends of fore and aft tunnels and other potential discontinuities in the hull girder.

33.4 Shell Bottom Plating

Hull bottom plating and stiffeners below the chine or turn of the bilge shall be capable of withstanding wave impact pressures that occur at the speed of V_{RW} with the hull rolled and pitched within the following limits:

Pitchup to ± 5 degrees from design foilbome attitude for ship displacement up to 100 tons, varying linearly from ± 5 degrees to ± 3 degrees for displacements between 100 and 200 tons, and ± 3 degrees for displacements over 200 tons.

Roll: Local deadrise angle or 12°, whichever is less.

The wave impacted shall have a slope parallel to the shell plating being considered, that is,

wave slope = local buttock line slope + pitch,
but not greater than 12 degrees.

The wave height shall be the $H_{1/10}$ for the design sea.

Limit load pressures shall be equal to or greater than those calculated by the following expressions:

for $\beta' < 7^{\circ}$,

$$p = A \frac{\pi}{2} \dot{\zeta}^2 \left((0.0129 - 0.1348 \beta') 8' + x5020 \right)$$

and for $\beta' \geq 7^{\circ}$,

$$p = A \dot{\zeta}^2 \left(\frac{90}{\beta'} - 1\right)^2 (\tan \beta')$$

where,

P	= limit pressure, psf or kPa
A	= 10.05 for metric units,
A	= .0138 for English units
β'	= $\beta - \phi$, degrees
β	= local hull deadrise, degrees
ϕ	= ship roll angle, degrees
$\dot{\zeta}$	= relative normal velocity, fps or mps
	= $V_{RW} \sin \tau + V_s \cos \tau + V_o \cos(\omega - \tau)$
V_{RW}	= ship speed, fps or mps
V_s	= sink speed, 5 fps or 1.52 mps
V_o	= $\sqrt{g \frac{\pi}{2} \frac{H^2}{L}}$ = wave orbital velocity, fps or mps
τ	= $t - \theta$
τ	= local trim angle
θ	= ship pitch angle
L	= wave length such that $\gamma = \tau$ unless $\tau > 12^{\circ}$
γ	= wave slope = $\sin^{-1}(\frac{\pi H}{L}) \leq 12^{\circ}$

H = $H_{1/10}$ wave height, design sea state

ω = phase angle of V_o

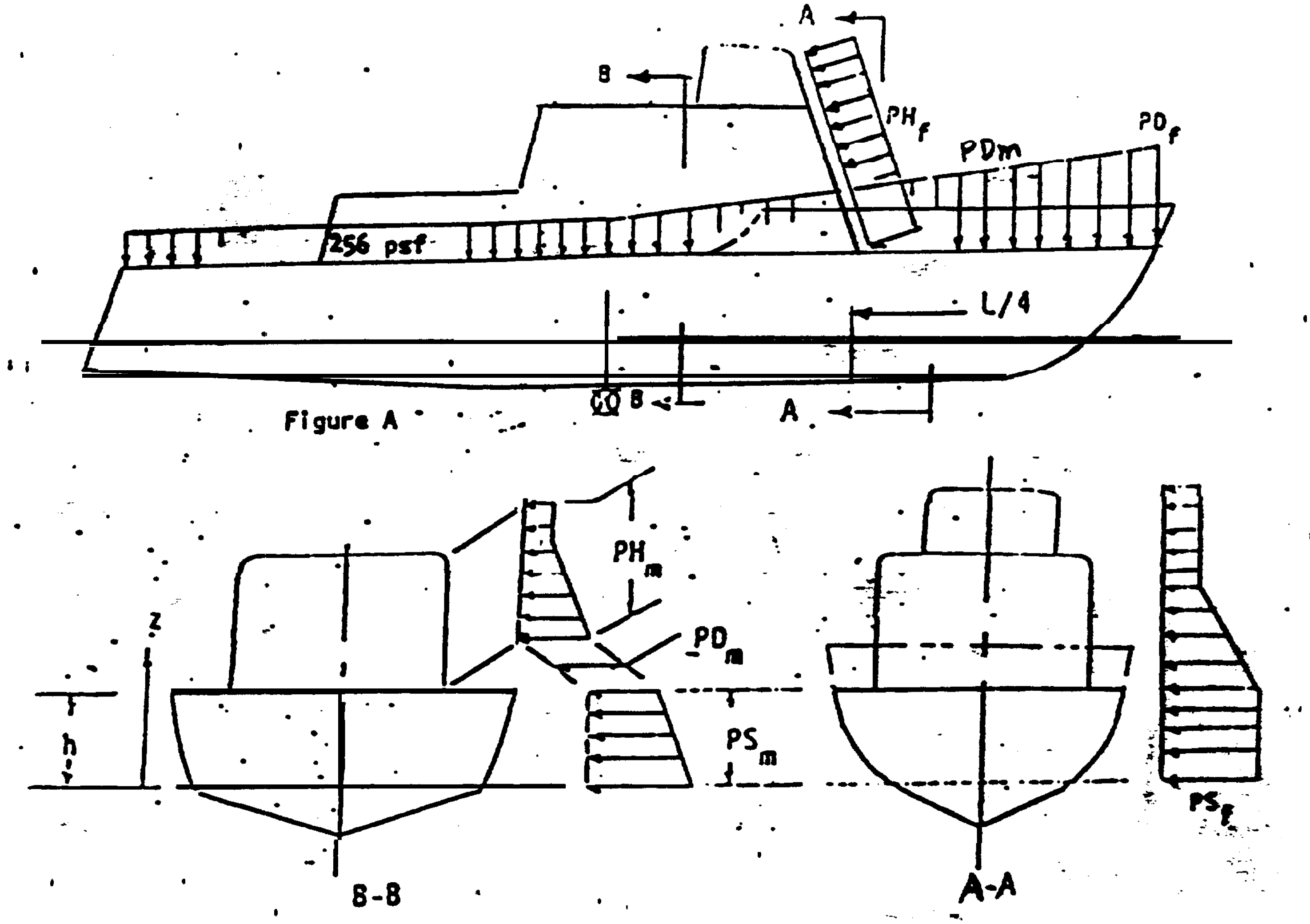
Pressures derived for this condition shall not be combined with other loading conditions.

Shell plating response to these' pressures shall take advantage of the membrane capability of the plate between longitudinals and frames; however, permanent deformation normal to the plate under Yield Load shall not exceed .005 millimeter per millimeter (0.005 inch per inch) of stiffener spacing.

3.3.5 shell Topsides, Weatherdeck and Superstructure

3.3.5.1 Wave **Pressure Loads** – The shell plating above the design waterline, the weatherdecks and the superstructure shall be capable of withstanding pressure loads from boarding seas when the ship is hullborne. The forward sideshell plating shall also be capable of withstand* pressure loads which may occur from foilborne wave impacts in oblique seas or when the ship is rolled as in a coordinated turn in a head sea. These capabilities shall be considered assured for structure designed to meet the requirements of this section.

The wave pressure loading applicable to the sideshell, weatherdecks and superstructure shall be equal to or greater than those indicated on Figure 3.3.1.a or .b for the design sea state.



$PD_f = 64\ H_s$ psf

PD_m From Figure A

$PH_m = PD_m + 64\,(h-z),\ z \geq h;\ PH_m \geq 256$ psf

$PH_f = PD_m$

$PS_m = PD_m + (h-r),\ z < h$

$PS_f = 1.5\ PD_m$, to L/4

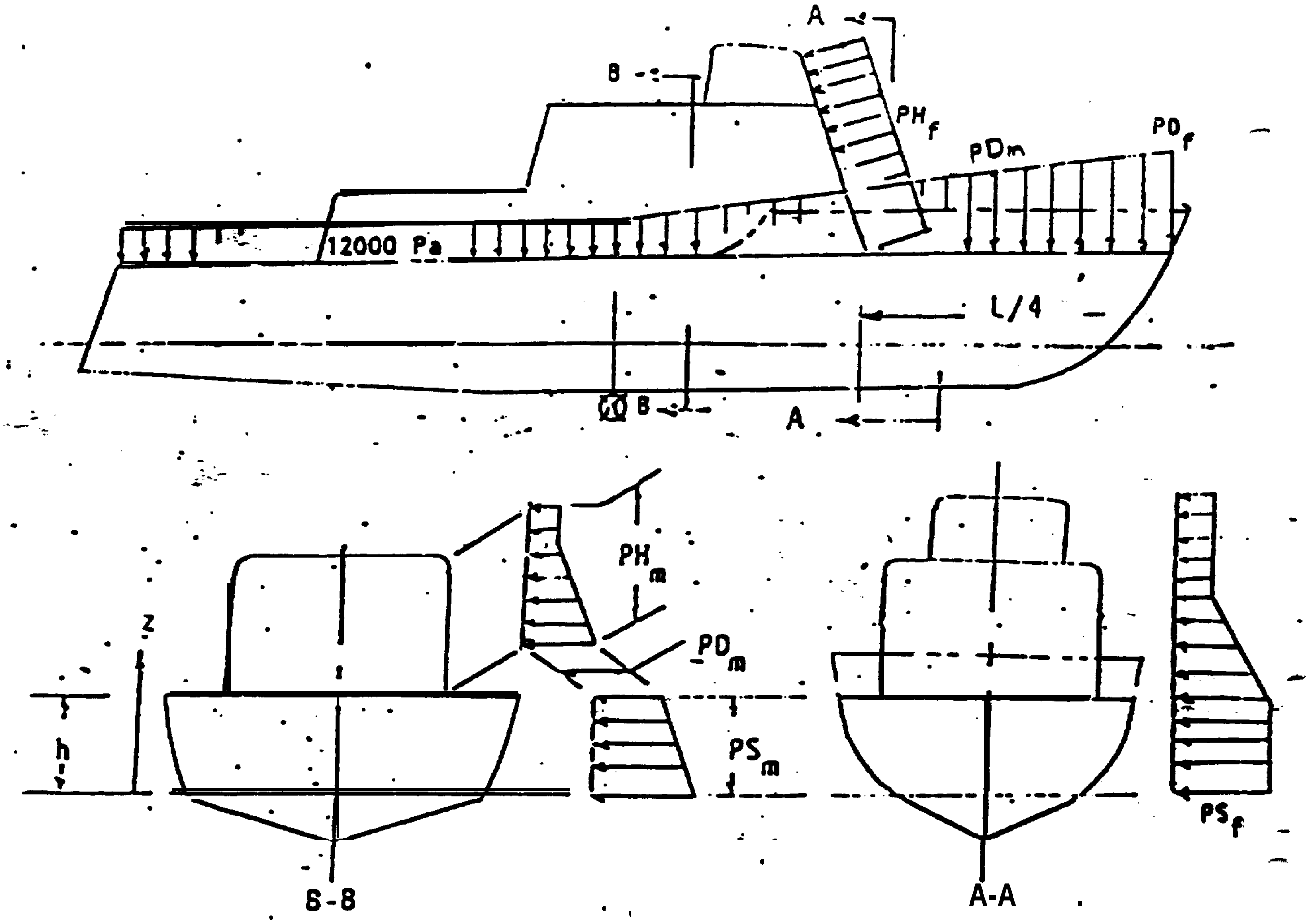
H_s = Significant Wave Height, ft

8 ft $\leq H_s \leq$ 12 ft

FIGURE 3.3.1a . Limit Pressure Loads for Sideshell,

Weatherdeck and Deckhouses

(English)



$PD_f = 3060\ H_s$

PD_m From Figure A

$PH_m = PD_m + 3060\ (h-t)\quad z \geq h;\ PH_m \geq 12000$ Pa

$PH_f = PD_m$

$PS_m = PD_m + 3060\ (h-t),\ z < h$

$PS_f = 1.5\ PD_m$, to L/4

H_s = Significant Wave Height, meters

$2.62\ m \leq H_s \leq 3.94\ m$

FIGURE 3.3.1b Limit Pressure Loads for Sideshell, Weatherdeck and Deckhouses (Metric)

3.3.5.2 Weapon Firing Loads - Decks and superstructures in way of weapon installations shall be capable of withstanding blast pressure loads from weapon firing. These pressure loads shall be sustained. in combination with loads from foilborne loading conditions of 3.3.1.2.

3.3.6 Frames and Bulkheads

Hull frames and bulkheads shall react pressure loads on the bottom, sideshell and decks caused by boarding seas and hull-wave impacts. Separate loading combinations for these conditions are defined below. Recognition shall be given to the loading on transverse bulkheads due to reacting deck loads and longitudinal framing loads. Watertight bulkheads shall be capable of withstanding pressure loads in accordance with General Specifications for Ships of the United States Navy.

3.3.6.1 **Hullborne** - Framing supporting sideshell, weatherdecks and superstructure shall withstand pressure loads described in 3.3.5 with the loads applied simultaneously to one side of the hull, weatherdeck and superstructure. Where the weatherdeck is continuous across the beam, the weatherdeck shall be loaded from one side to the other.

3.3.6.2 Foilborne - Hull framing supporting shell areas subject to the wave impact conditions of 3.3.1.3 shall be capable of withstanding the associated pressure loads from those conditions. For framing design, the pressure loads shall be applied with a dynamic factor of 1.25.

3.3.7 Keel

3.3.7.1 Docking - The keel shall be capable of supporting the vessel when resting on keel blocks.

3.3.7.2 Foilborne - The keel supporting frames, bulkheads and shell plating shall be capable of withstanding pressures and hull girder loads from the wave impact conditions of 3.3.1.3. The keel shall be capable of withstanding the hull girder loads of 3.3.1.2.

3.3.8 Hull Recesses

Various hull recesses, such as for bow thrusters, inlets for waterjet propulsion units, and strut foundations shall have a pressure capability at least equal to the surrounding structure. The boundaries of hull recesses that can be completely filled with water with no egress, and exposed to direct hydrodynamic flow, shall be capable of withstanding stagnation pressure,

$$P = 2834\ V_c^2\ (psf) = .136\ V_c^2\ (kPa)$$

where: P = Limit Pressure

V_c = Rough water foilborne cruise speed, knots

Boundaries of recesses open to the air, or with other means of water egress, and exposed to direct hydrodynamic flow, shall be capable of withstanding the design pressure of hull sideshell amidships as specified in 3.3.5.

3.3.9 Foundations

3.3.9.1 Foil System Foundations - The hull attachments for struts shall be capable of reacting limit and service loads on the foil system for the load conditions of 3.2. Since it is likely that the material of the foundations will be different than the material of the struts, with different modulus of elasticity, care shall be taken to ensure that both strength and deflections of the foundations are compatible with strut retraction/extension and with f oilborne operation.

X3.9.2 Machinery and Equipment Foundations - Foundations for machinery and equipment shall be capable of withstanding shock and vibration requirements of 3.1.9 and inertia loads of 3.3.1.4 in addition to normal operating loads of such machinery and equipment.

3.3.9.3 Weapon Foundations - Weapon foundations shall be capable of supporting the weapon weight for the inertia forces of 3.3.1.4. These loads shall not be combined with firing loads.

weapon foundations shall be capable of sustaining weapon firing loads in combinations with weapon weight and inertia forces associated with foilborne operation specified in 3.3.1.2.

3.3.10 Tanks

Tank boundaries shall be designed to withstand the following limit load conditions:

a. Pressure caused by overfilling the tank and discharging through the overflow at the maximum allowable pumping rate of the system.

b. Dynamic pressures associated with the inertia forces of 3.3.1.4. For these conditions the tank shall be full, with no liquid in the fill piping above the tank top.

3.3.11 Interior Decks

3.3.11.1 **Watertight Decks** - Watertight decks shall be capable of withstanding a head of water to the height of the uppermost watertight deck above. These decks shall also be capable of withstanding the loading imposed by equipment installed on the deck with inertia loads of 3.3.1.4. In either case, the minimum load shall be as shown in Figure 3.3.2.

3.3.11.2 **Non-Watertight Decks** - Interior non-watertight decks shall be capable of withstanding the same loads as for watertight decks except for hydrostatic loading which shall be omitted.

3.3.12 **Non-Structural Bulkheads** - Non-structural bulkheads shall be capable of sustaining either of the following loads, applied separately:

a. 250 lbs (1110 N) applied on any square foot ($0.09 m^2$) of the bulkhead.

b. 15 psf (0.72 kPa) pressure uniformly distributed over the bulkhead.

3.3.13 Masts

Masts shall be capable of withstanding the inertia loads of 3.3.1.4 in addition to wind loads on the mast and the equipment mounted thereon.. The wind loads shall be taken as 30 psf (1.44 kPa) on projected areas.

3.3.14 Watertight Compartment Tests

The enveloping structure of each watertight compartment shall be capable of withstanding watertightness test pressures without excessive: deflection or permanent set. Unless otherwise specified the test pressure should be the hydrostatic head from the mid-height of the compartment to the uppermost watertight deck.

3.3.15 Mooring and Towing

Mooring fittings, bitts, chocks, and cleats, shall be light weight and capable of withstanding a load equivalent to twice the breaking strength of the specified mooring lines.

An arrangement for towing shall be provided which shall be capable of sustaining loads from towing with foils down, at 10 knots in calm water.

TYPICAL LIVE LOADS		
TYPE OF COMPARTMENT	LIVE LOADING (LBS/SQ. FT.)	DESIGNATION USED IN FIGURE 4-3
Living and control spaces, offices and passages, main deck and above	75	
Living spaces below main deck	100	
Offices and control spaces below main deck	130	
Shop Spaces	200	
Storerooms/Magazines	300'	

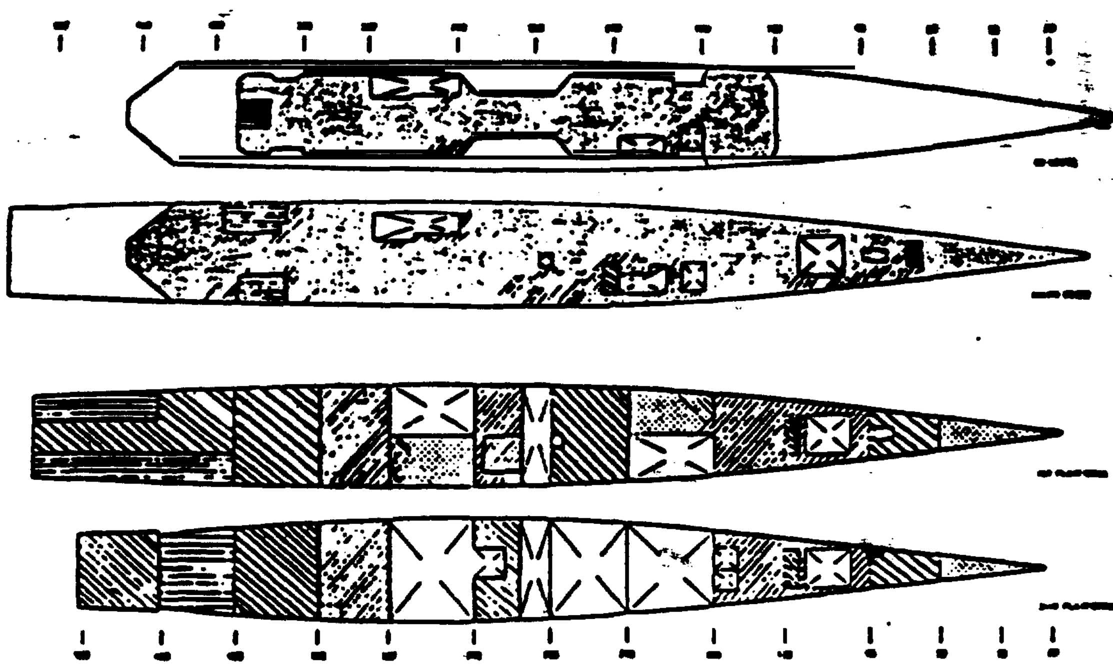


FIGURE 3.3.2: Interior Deck Loads --

4.0 QUALITY ASSURANCE

4.1 REPORTS

The following reports shall be submitted by the contractor for Navy approval:

4.1.1 Structural Design Criteria Report

The factors which affect design of structural components of the proposed hydrofoil ship shall be set forth in this report in detail. The report shall include structural requirements from the criteria herein, from General Specifications for Ships of the U.S. Navy, from Detail Specifications for the Ship, from special mission requirements and other considerations. The information presented shall include, but not be limited to:

Ship- Dimensions	Control Method
Displacement	Sea State Requirements
Arrangement	Annual usage
Speed	Expected Life

4.1.2 Structural Load Simulation Report

This report shall describe each simulation used to generate structural loads. In this context a simulation is a complex digital or analog mathematical modeling of the ship in the sea which is capable of calculating ship motions and force. The equations of the mathematical models shall be given and the form of the output shall be described, whether force-time histories, frequency responses, statistical data or other. Data and or analyses substantiating the validity of the simulations are considered of primary importance and shall be included. The following simulations are required. Additional simulations may be used at the contractors option.

4.1.2.1 A six degree-of-freedom simulation capable of calculating foil system loads in calm water for all possible automatic control system inputs.

4.1.2.2 A six degree-of-freedom simulation capable of calculating foil system loads in a seaway.

4.1... A six degree-of-freedom simulation capable of calculating hull-wave impact forces.

AL.3 **Structural Loads Report**

This report shall contain the loading conditions and design lads to be used for the proposed hydrofoil ship.. Design loads shall be in the form of appropriate tables, diagrams, summary curves, or equations. Calculation assumptions and rationale shalt be clearly shown. Where loads are based on test data, the test philosophy, scaling, accuracy, conditions, applicability, and data shall be fully described.

4.1.4 **Structural Substantiation** Report

This report shall contain predictions of structural component responses to the design loads of the proposed hydrofoil ship. Such responses, determined by &al)!?&--or tests, in accordance with 4.3, shall be described in detail showing, finally, in each instance, the margin of compliance with the requirements of the Structural Design Criteria.

All information necessary to substantiate each conclusion shall be shown, including:

- analysis assumptions
- support reactions
- material properties
- column stability limitations
- data from special tests
- reference to pertinent commonly available data.

Compliance with the Structural Design Criteria shall be considered assured if analysis by accepted techniques shows that the structure under consideration is not stressed beyond yield or ultimate stress for conservative combinations of Yield or

Ultimate Loads respectively. Similarly, compliance is assured if analysis by accepted technique shows that the structure has capability Of accepting the Yield Load without permanent set. Allowable yield and ultimate stresses for the material shall be the "A" probability stresses given in MIL HDBK 5 unless otherwise stated in the detail specifications. The calculated stress shall account for combined stresses due to bending, torsion and axial tension (or compression) using appropriate interaction formulas such as given in DDS 100-4.

4.1.5 Hydroelastic Analysis Report

This report shall contain information concerning divergence, control reversal and flutter speeds of foil systems and other hydrodynamic surfaces of the proposed hydrofoil ship. All data used in the analyses shall be clearly shown including distributed and nodal stiffnesses and masses. Analysis methods shall be described in detail. Calculated in-air and in-water vibration modes and frequencies shall be listed.

4.2 (Blank)

4.3.3 Structural Tests

Test articles shall duplicate the design for the ship; they shall be constructed of the same materials and use the same fabrication methods. The tests shall use Yield, Ultimate, or Service Loads, as applicable, and, to be acceptable, must show compliance with 3.1.7. Sufficient numbers of the same article shall be tested to demonstrate high probability of achieving test results on the ship. Structural tests shall be reported in the Structural Substantiation Report (4.1).

10.0 APPENDIX

10.1 WAVE SPECTRA

The statistical distribution of wave heights and periods which occur in a particular ocean area can be described by the long term occurrence frequencies of significant wave heights and significant periods. Table 10.1.1 is an example of the annual distribution of waves in the North Sea. Each block within the table can be represented by one discrete unidirectional wave height spectrum defined by the following formula:

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

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

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

H_S = significant wave height, average of one-third highest waves

T_S = significant period, average period of one-third highest waves

Figure 10.1.1 shows spectral distributions of wave heights for a significant wave height of 3 meters and for average significant periods.

Wave heights in the random sea are Rayleigh distributed and have commonly used wave height ratios given in Table 10.1.2.

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

Significant wave height (Meters)	Significant wave period **(seconds)**								
	*	5	6-7	8-9	10-11	12-13	14-21	21	Totals
0.25	6.33	4.13	0.24	0.09	0.05	0	0.01	0.07	10.92
0.5	0.45	11.26	1.31	0.34	0.09	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	8.28	2.15	0.68	0.16	0.12	0.01	19.20
2.0	0.29	2.04	5.18	2.46	0.64	0.11	0.0s	0.04	10.80
2.5	0.16	0.97	2.81	2.18	0.80	0.18	0.04	0.01	7.15
3.0	0.05	0.52	1.74	1.16	0.75	0.18	0.08	0	4.49
3.5	0.14	0.17	0.92	1.36	0.59	0.26	0.02	0	3.47
4.0	0.05	0.17	0.47	0.59	0.39	0.14	0.05	0	1.87
4.5	0.05	0.08	0.41	0.47	0.26	0.16	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
a.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
8.5	0	0	0	0	0.01	0	0.01	0	0.03
9.0	0	0	0	0.01	0.01	0	0	0	0.03
9.5	0	0	0	0.03	0.01	0	0	0	0.04
Totals	8.50	43.59	27.87	12.33	4.92	1.44	0.71	0.63	100.00

***Calm or** period undetermined

Table **10.1.1** Typical Specification for Sea Conditions in the North Sea

Table 10. I .2

Wave Height Relationship	
Average of one-tenth highest waves	$H_{1/10} = 1.27\ H_s$
Average of one-third highest waver	H_s
Average wave	$H_{AVG} = .62\ H_s$
Root-M ean-Square	$H_{RMS} = .25\ H_s$

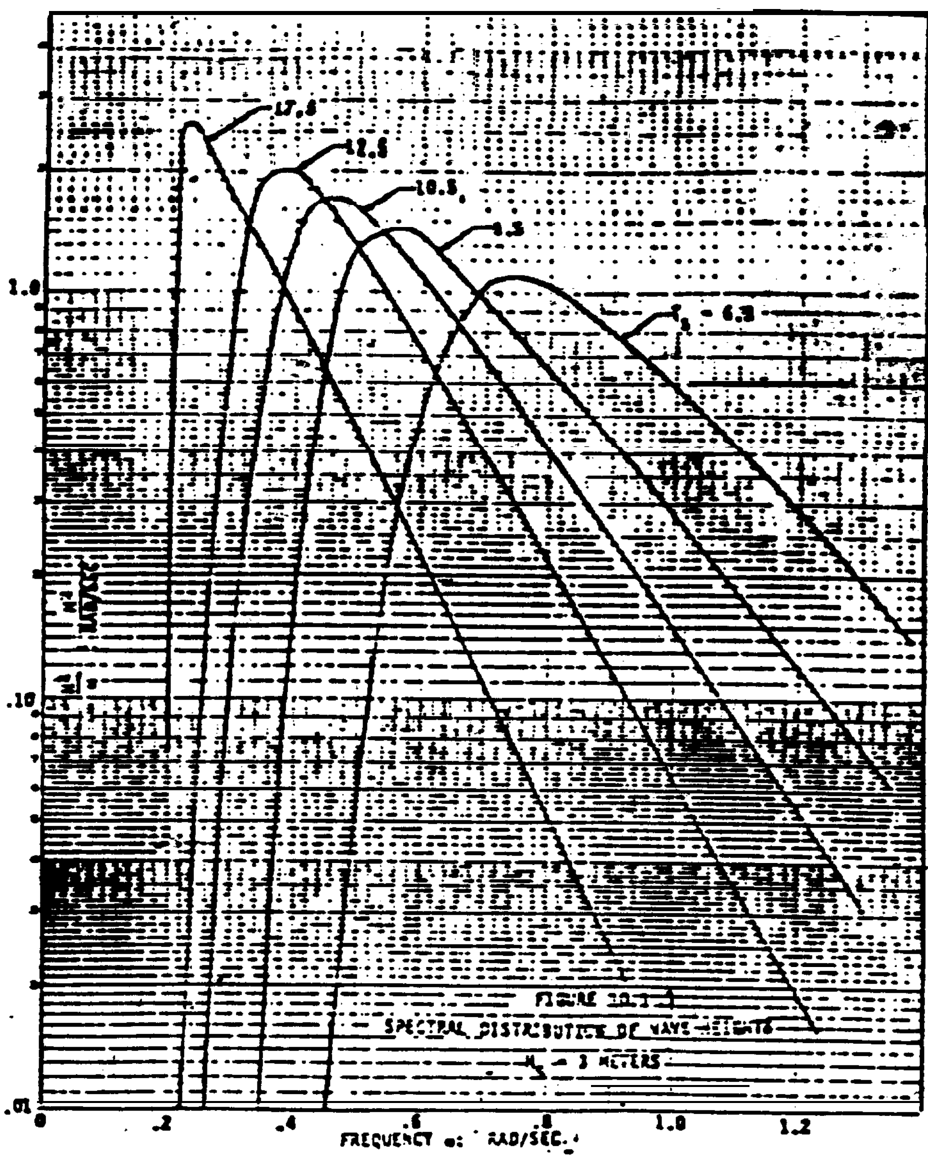


Figure 10.1 Spectral Distribution of Wave Heights

10.2 (Blank)

10.3 CALCULATION OF WAVE IMPACT LOADS

Reference 10.3.1 presents a method for calculating the instantaneous impact force of a hydrofoil hull immersed in a wave. This method takes into account the hull shape by replacing the immersed hull with a series of equivalent, prismatic, wedges normal to the keel with deadrises and local trims dependent upon the actual hull. The equivalent wedges have impact velocities dependent upon craft motions and wave water particle velocity. A term for longitudinal keel shape is also included which accounts for increase or decrease in pressure associated with flow along a curved keel. The computation as presented in the Reference results in an impact force distribution which when integrated along the wetted length gives the instantaneous impact force on the hull. A force time history of an impact occurrence can be generated by successive application of the instantaneous force calculation, accounting at each calculation for the changes of attitude and motion of the hull and of its position in the wave.

The equation for calculating the impact force on a symmetrical wedge as given in Reference 10.3.1 uses the Wagner-Sydow expression for virtual mass (see Reference 10.3.2 for instance) as follows:

$$m = \rho \frac{\Pi}{2} \left(\frac{90}{\beta} - 1\right)^2 \zeta^2$$

Where ρ is the mass density, β is the effective deadrise and ζ is the immersion of the wedge to the wave rise line. Comparisons of predicted and measured pressures using the Wagner-Sydow virtual mass show good agreement for deadrises above about 7 degrees. For lower deadrises the added mass must be modified to agree more closely with test data. The following empirical expression for added mass gives good agreement with average pressures for wedges with less than 7 degrees deadrise:

$$m = \rho \frac{\Pi}{2} \left(.0129\beta - .1348\ \beta^2 + 17.502\right) \zeta^2$$

Where $\beta > 7^{o}$.

The constants for this equation were deduced from pressure data such as presented in Reference 10.3.3.

In order to calculate a wave impact force-time history values of ship motion variables are selected within the limits of the criteria in a combination that would cause the most severe impact force for the location of impact. For instance, if the hull of a ZOO-ton hydrofoil has 10-degree deadrise at a location along the hull where an impact is assumed to occur, then the hull roll angle should be 10° so that the effective deadrise for calculations is zero at the point and is minimized elsewhere. Also, at the lo-degree roll angle, if the keel trim is 3 degrees then the wave length would be selected such as to give a maximum wave slope of 6 degrees (the keel trim of 3 degrees plus the ship pitch angle of 3 degrees).

A hand calculation of a hull-wave impact force time-history is impractical because of the necessity to use very small time increments (about 1/15 of the impact period) and the number of variables involved. The calculation has been computerized taking into account three-dimensional ship form, rolled impacts in trochoidal waves, ship motions in six degrees of freedom, buoyancy forces and foil system forces with appropriate responses of the latter to an active automatic control system.

Typical inputs (with limits specified by the criteria) are:

1) A computer representation of the hull form

2) Ship weight and mass inertias

3) Ship attitude and motion at the instant of impact

4) Wave size

5) Point of hull-wave contact

6) Hydrodynamic characteristics of the foils and struts

7) Automatic control system characteristics

[illegible] wave impacts are a prime source of hull structural loads the output of the [illegible] program includes loads data applicable to various structural components for each iteration. Typical output consists of the following:

1) Axial forces at the cg

2) Moments about the cg

3) Translational and rotational accelerations

4) Translational and rotational velocities

5) Distribution of impact and buoyancy forces along the wetted length

6) Average pressures along the wetted length

7) Wetted beams and immersed depths along the wetted length

8) Roll and pitch angles of the ship relative to an earth axis system.

Further, for rolled impacts the values along the wetted length are given port and starboard.

The application of wave impact loads data to particular elements of the hull structure is covered in the criteria. Since acceleration data are necessary for establishing inertia factors for deck loads, foundation loads, hull girder loads, tank loads, and loads for other classes of structure,. an envelope of accelerations is derived from the impact calculations. The information for this envelope comes from impacts that' have initiated at several points along the hull. Figure 10.3.1 shows fully factored accelerations based on the impact calculations made for the PEGASUS (PHM-1). The acceleration at each point along the hull is the sun of the lg acceleration component (the ship was initially rolled 15 degrees) and incremental translational and rotational accelerations. **The incremental** accelerations have been multiplied by a dynamic factor Of 1.5, as rquired by the criterion, and the summed values are to be multiplied by a safety factor of 1.5. In equation form, the acceleration in g's is:

$$\ddot{Z} = \left[\text{Cos}\,\phi\ \text{Cos}\,\theta + (\ddot{Z}_{cg} - Qx + Py)\frac{1.5}{32.2}\right]1.5$$

$$\ddot{Y} = \left[\text{Sin}\,\phi\ \text{Sin}\,\theta + (\ddot{Y}_{cg} + Rx - Pz)\frac{1.5}{32.2}\right]1.5; \quad (\psi = 0)$$

$$\ddot{X} = \left[-\text{Sin}\,\theta + (\ddot{X}_{cg} - Ry + Qz)\frac{1.5}{32.2}\right]1.5$$

The symbols for these equations are identified in Figure 10.3.2.

LIST OF REFERENCES

10.3.1 Jensen, Wm. R., “Hydrofoil Boat Hull-Wave Impacts,” ASME 60-WA-326, 1961

10.3.1 Pierson, J. D., "On the Virtual Mass of Water Associated with an Immersing Wedge,” JAS, June 1951.

10.3.3 Lewison, G., and Maclane, W. M., "The Effect of Entrapped Air Upon the Slamming of Ship’s Bottoms,” University of California, Berkeley, Col. of Eng., NA-66-5, March 1966.

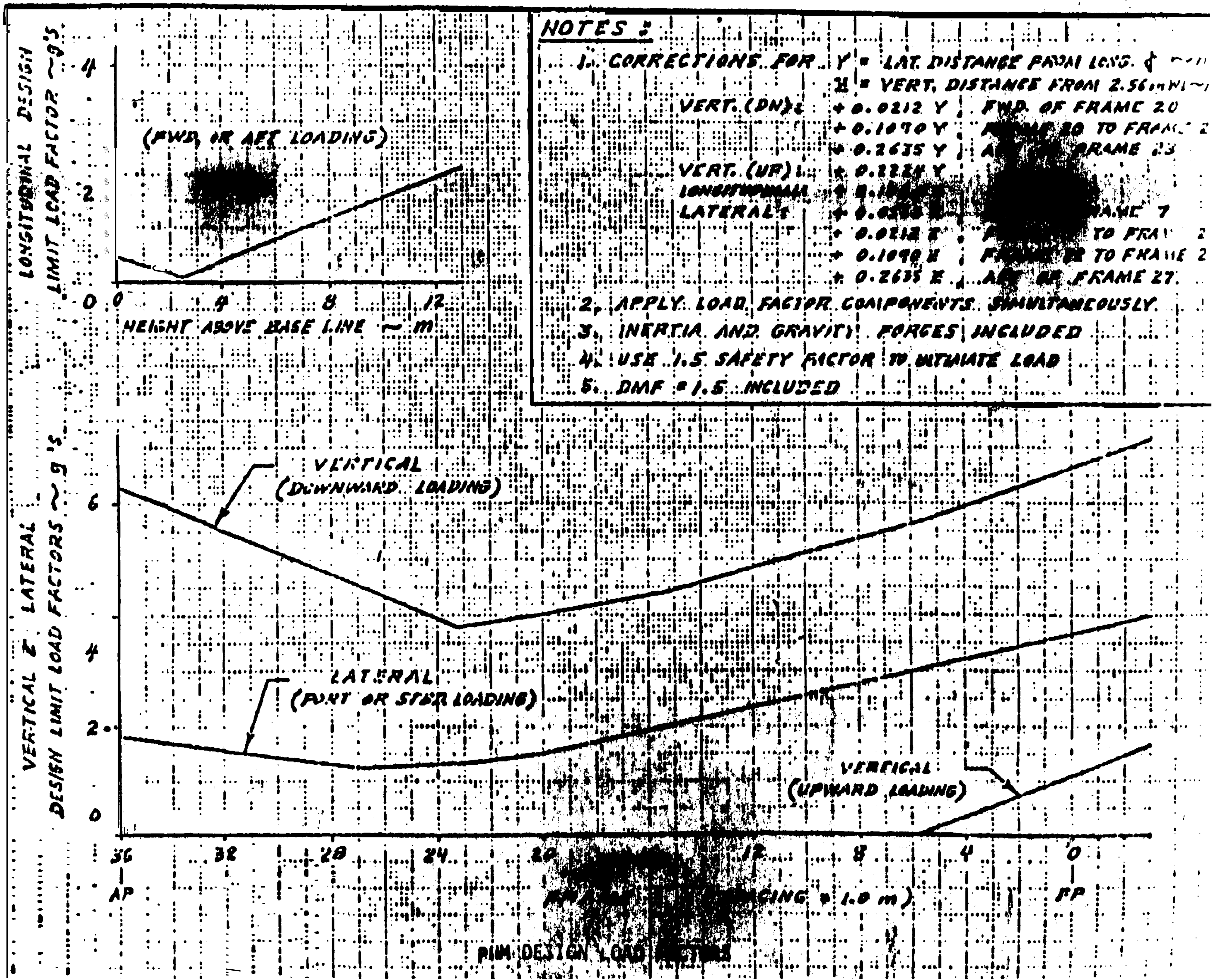
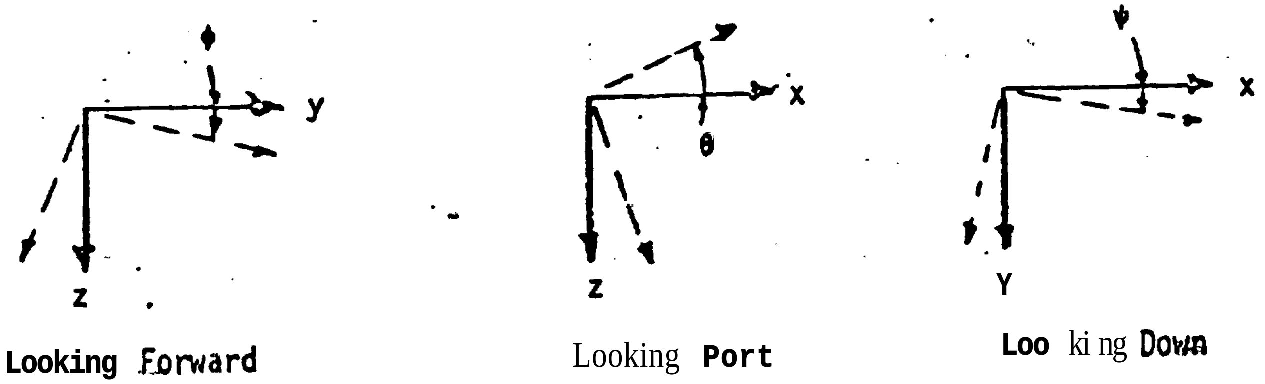
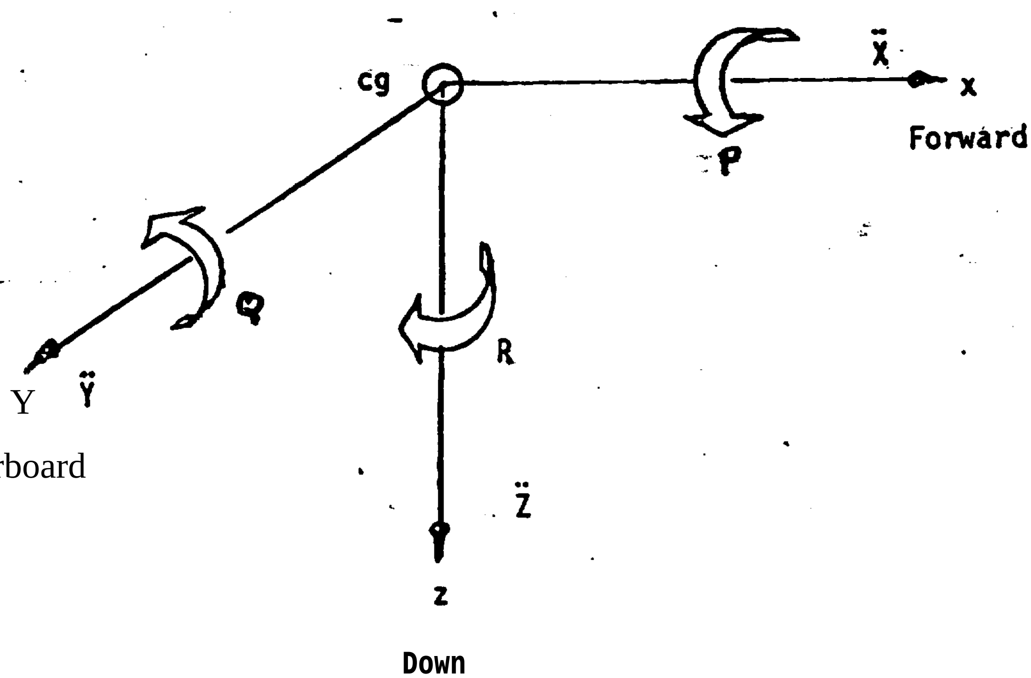


Figure.10.3.1 PHM Hull Load Factors

Note from IHS: Although this file is supposed to contain Vols IVA and V, they are missing from the scan. We will attempt to locate and restore them in a future edition of the AMV CD-ROM.



Earth Axis System



Ship Axis System

Figure 10.3.2 Coordinate Systems for Ship Motions