Naval Surface Warfare Center
Carderock Division
West Bethesda, MD 20817-5700

NSWCCD-80-TR-2017/002 **February 2017**

Naval Architecture and Engineering Department

Technical Report

Standardized Laboratory Test Requirements for Hardening Equipment to Withstand Wave Impact Shock in Small High-Speed Craft

by

Michael R. Riley, The Columbia Group
Heidi P. Murphy, NSWCCD
Scott M. Petersen, NSWCCD
Dr. Timothy W. Coats, NSWCCD

DEPARTMENT OF THE NAVY
UNITED STATES OF AMERICA

NSWCCD-80-TR-2017/002 Standardized Laboratory Test Requirements for Hardening Equipment to Withstand Wave Impact Shock in Small High-Speed Craft

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
6-2-2017

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
March 2016 to Sep 2016

4. TITLE AND SUBTITLE
Standardized Laboratory Test Requirements for Hardening Equipment to Withstand Wave Impact Shock in Small High-Speed Craft

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Michael R. Riley, Heidi P. Murphy, Scott M. Petersen, Dr. Timothy Coats

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NAVSEA Carderock
Surface Warfare Center Division
Combatant Craft Division
2600 Tarawa Court, #303
Virginia Beach, Virginia 23459-3239

8. PERFORMING ORGANIZATION REPORT NUMBER
NSWCCD-80-TR-2017/002

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Commander, U.S. Special Operations Command
Program Executive Office Maritime, PMSS
7701 Tampa Point Boulevard
MacDill Air Force Base, FL 33621-5323

10. SPONSOR/MONITOR'S ACRONYM(S)
USSOCOM SOFAT&L,PEO-M, PMSS

11. SPONSOR/MONITOR'S REPORT

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT This report documents standardized laboratory test requirements to minimize the risk of equipment malfunction or failure due to shock forces caused by wave impacts in high-speed craft. The engineering rationale, assumptions, and methodology for transitioning craft acceleration data to laboratory shock test requirements are summarized and example requirements for procurement documents are presented.

15. SUBJECT TERMS
Shock Wave slam shock test equipment operability risk reduction

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON:** Scott Petersen
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified	See 12.	46	757-462-4166

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

THIS PAGE INTENTIONALLY LEFT BLANK

CONTENTS

FIGURES

TABLES

SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A_{MAX}	peak or maximum acceleration
ASRS	acceleration shock response spectrum
c	damping coefficient
DSRS	relative displacement shock response spectrum
f	natural frequency
ft	feet
g	acceleration due to gravity (32.2 ft/sec^2)
Hz	Hertz (cycles per second)
k	stiffness coefficient
m	meter
msec	millisecond
π	approximately 3.14159
VSRS	pseudo-velocity shock response spectrum
sec	second
SDOF	single degree-of-freedom
SRS	shock response spectrum
t	time
ϖ	circular frequency
x, y, z	coordinate axes
X	craft surge coordinate axis, positive forward
Y	craft sway coordinate axis, positive to port
Z	craft heave coordinate axis, positive up
Z_{MAX}	maximum vertical relative displacement

ADMINISTRATIVE INFORMATION

This work was performed by the Combatant Craft Division (Code 83) of the Naval Architecture and Engineering Department at the Naval Surface Warfare Center, Carderock Division (NSWCCD). Analysis of acceleration data for Naval Special Operations craft was sponsored by the U.S. Special Operations Command, Special Operations Forces Acquisition, Technology, and Logistics (SOF AT&L), Program Executive Office Maritime, Program Manager Surface Systems (PMSS), and managed by Naval Special Warfare Group 4, Code N81, Virginia Beach, Virginia. Analysis of acceleration data for Navy and U.S. Coast Guard craft was sponsored by Naval Surface Warfare Center, Carderock Division, Naval Innovative Science and Engineering (NISE) Section 219 research and development program under the direction of Dr. Jack Price.

ACKNOWLEDGEMENTS

Mr. Scott Petersen, Code 832 Branch Head, Systems Design and Integration Branch, Combatant Craft Division (CCD), Naval Surface Warfare Center Carderock Division initiated research in 2010 for standardizing test procedures for evaluating the ruggedness of sensitive electronics to withstand severe wave slams in high-speed planing craft. Those efforts served as the foundation for the developments achieved during this project. NSWG4, Code N81 directed the project for special operations craft and provided management oversight. Mr. Willard Sokol, CCD Naval Architecture Branch Head, Mr. Brandon Bagwell, CCD, Systems Integration Branch, and Mr. Malcolm Whitford, CDI Marine, Inc. provided valuable suggestions for the first draft of the report. Mr. Donald Jacobson, CCD, Naval Architecture Branch added clarity to the scope of the report. Mr. T. Lee Hinson, Space and Naval Warfare Systems Center Atlantic and Dr. Luke Martin, Naval Surface Warfare Center Dahlgren provided laboratory shock test machine acceleration data and operational experiences with laboratory testing methods and procedures. The authors also thank Dr. Jack L. Price, Director of Research, Naval Surface Warfare Center, Carderock Division, for overall management of wave slam phenomenology investigations. Their collective knowledge and experience and their willingness to share are sincerely appreciated.

SUMMARY

This report documents standardized laboratory test requirements to minimize the risk of equipment malfunction or failure due to shock forces caused by wave impacts in high-speed craft. The engineering rationale, assumptions, and methodology for transitioning craft acceleration data to laboratory shock test requirements are summarized and example requirements for procurement documents are presented.

INTRODUCTION

Background

It has been known for a long time that there is risk of failure or malfunction of sensitive electronics equipment due to severe wave impacts in high-speed craft [1]. Shock isolation mounts may be able to provide protection if properly designed, but until recently there was little known about the physical characteristics of individual wave impacts and how to quantify the environment. A renewed interest in a deterministic data analysis approach, applied in this report, has resulted in a better understanding of craft motion mechanics and is now being used as a consistent approach for quantifying wave impact load for evaluating equipment ruggedness, shock isolation seat effectiveness, and hull strength [2, 3].

The method used for many years to mitigate the risk of electronic equipment failures in high speed craft has been to specify laboratory shock machine tests, but there has been no standardized approach to establishing test severities and no standard requirements for which to set as design criteria when developing new equipment. This resulted in numerous shock pulse severities that varied across different organizations and among different craft [4]. Recent analyses of acceleration data recorded during rough water trials of more than 21 craft has yielded benchmark information that provides the foundation for the standardized test requirements presented in this report.

Scope

The database of test results used to develop this report and the included assumptions, analysis, and conclusions consisted of manned, high speed planing mono-hulled craft operating in rough seas at displacements and in conditions simulating the performance of missions with a military or civil defense focus. The craft database included ten mono-hulls with lengths ranging between roughly 35 and 85 feet, weighing between 14,000 and 160,000 pounds, traveling at planing speeds that varied from approximately 20 knots to 40 knots, in significant wave heights from 2.3 feet to 6.5 feet. The volumetric Froude numbers ranged from approximately 1.9 and 4.3. Recommendations included in this report are immediately applicable to craft with similar missions and the method used to arrive at these recommendations is more generally applicable with careful modification of some underlying assumptions.

The primary focus of this report is on hard mounted, electrical and electronic communication, navigation, control, computer, and sensor systems. It does not address propulsion machinery or shock isolation seats. Propulsion machinery and power generation components are more massive and inherently rugged in order to withstand internal operating loads, so they are better able to withstand wave impact forces. They typically do not require laboratory shock testing for wave impact effects.

Purpose

The purpose of this report is to document standardized laboratory test requirements to mitigate the risk of equipment malfunction or failure of hard mounted electrical and electronics equipment in high-speed craft due to wave impacts. The goal is to simplify procurement specifications with a single set of shock requirements that apply to all craft at any location in all operational environments, and to explain how the shock test requirements were derived from seakeeping data. Optional test requirements are also presented for craft specific and location specific applications.

Risk Mitigation Approach

Minimizing the risk of equipment failure can be achieved by either protecting an item or by hardening the item. The hardening approach specifies a laboratory test that simulates the operational shock environment or simulates the effects of the environment. If an item survives the test it can reasonably be expected to survive the operational environment. If it fails during the lab test, design modifications are made until the item is able to survive the test (i.e., the equipment is hardened vice protected). The hardening approach is the most practical approach for procuring electronics equipment for naval craft. Laboratory shock tests are specified in procurement documents so ruggedness can be demonstrated in the lab before installation in a craft. Equipment protection can also be pursued, but it will be shown later in this report that the test requirements presented in this report should not be used for equipment installed on shock isolation mounts. Shock mount design for high speed craft is challenging because the long duration of wave impact shock pulses require large excursion envelopes.

Equipment Damage Mechanisms

There are numerous damage mechanisms (i.e., damage modes) that can lead to equipment malfunction or failure, including failure of attachment bolts, screws, enclosures, or internal structures due to overstressed material, broken lead wires, cracked solder joints, delaminated printed circuit boards, and electrical shorts. Failures can also occur due to broken or disconnected plugs, sockets, circuit cards, or circuit card subcomponents. In high speed craft these damage modes can be excited by a single severe wave slam, which can lead to any of the modes of failure, or damage modes can be excited by hundreds of lower severity wave impacts that can lead to solder joint failures or dislodged friction fittings (e.g., circuit cards or plugs) over time. Laboratory test methods must therefore be required that simulate the effects of both failure modes: a single severe impact and repeated low severity impacts.

Laboratory Shock Tests

Previous interim guidance for laboratory drop tests took the approach of simulating typical long-duration wave slam shock pulses for equipment positioned near a craft’s longitudinal center of gravity (LCG). The shock pulses had a half-sine shape and shock pulse durations that varied from 140 milliseconds (msec) to 340 msec depending upon craft weight. The shock severity varied with drop heights that depended upon the craft maximum speed and wave height requirements [4]. The long duration half-sine pulses could be achieved during laboratory drop tests at facilities with large sand impact mediums, but many existing environmental test facilities with shock test machines could only produce short duration half sine pulses. The approach taken in this report to extend the range of test facility use was therefore to simulate in a lab test the effects of a long duration wave slam pulse using a test machine that produces a higher amplitude pulse with shorter duration. The shorter duration shock pulse can be created by shock test machines available at many government and commercial testing laboratories. The technique for establishing equivalent shock severity for short and long duration pulses is explained in Appendix A.

Figure 1 shows an example of a laboratory test machine capable of generating short duration shock pulses. In this photograph a small test item is installed on a test fixture on top of the test machine. On this machine the load capacity varies from 650 lbs to 1100 lbs (for 20 g – 23 msec and 15 g – 23 msec half-sine pulses, respectively).

Figure 1. Example Laboratory Shock and Vibration Machine[1]

Maximum Wave Slam Shock Severity and Test Machine Margin

The peak accelerations recorded during rough water trials of all the craft were surveyed to identify the most severe wave slams. The time histories were then scaled to a maximum severity level and compared with the severity of three shock machine pulses (i.e., 23-msec pulse duration) used in previous procurement documents. Data scaling methods, engineering assumptions, test margins, and criteria for comparing shock severities are presented in the appendices. Appendix A explains the shock response spectrum (SRS) approach for simulating the effects of shock in a laboratory test. Appendix B summarizes key lessons learned in craft motion mechanics from previous studies of individual wave impacts in high-speed craft.

---

[1] Ling Dynamic Systems Vibration System, Model V894/440T S/N 89101; photograph provided courtesy of Space and Naval Warfare Systems Center Atlantic

Appendix C summarizes engineering assumptions and explains how the accelerations recorded for the most severe wave impacts were scaled to a higher maximum severity level. Appendix D presents example computational results that compare shock machine test severities with wave impact shock severity levels. It also explains shock test margin assumptions. Appendix E addresses the use of shock isolation mounts.

The recommended shock test machine severities include two margins for uncertainties. A factor of 1.2 was selected to account for measuring and processing acceleration data, and a margin of 1.5 was selected for differences and uncertainties between actual at-sea wave impacts and laboratory shock machine impacts.[2] The rationale for these numbers is presented in Appendix C and Appendix D.

RECOMMENDED SHOCK TEST REQUIREMENTS

The shock test requirements presented herein are consistent with Procedure I - Functional Shock cited in Military Standard, MIL-STD-810G, Change 1, Method 516.7, Shock [5] when implemented using laboratory shock test machines. Procedure I tests equipment in its functional modes to assess physical integrity, continuity, and functionality when exposed to the effects of operational shock loads. Alternative testing methods such as ANSI Standard S2.62-2009 may also be used [6].

Standardized Requirements

The following standardized requirements are applicable for all craft. Equipment may be installed at any location on any craft in any orientation for all planned craft speeds and operating sea states after successful completion of these tests. It is recommended that two types of shock tests be required to minimize the risk of equipment malfunction or failure in high-speed craft. The first test is a single severe shock test in each axis direction repeated 3 times.[3] The second test is one with 800[4] lower severity shock pulses spaced at 1-second intervals repeated in each axis direction. Example language for hard mounted equipment requirements is presented in the following paragraphs.

Single Severe Shock Test

> *The test item shall maintain its physical integrity, continuity, and functionality during and following a laboratory shock machine test that subjects it to a single half-sine acceleration pulse of 20g – 23 msec in each direction of its three axes (or as specified) in accordance with MIL-STD-810G w/change 1, section 516.7, Procedure 1, Functional Shock. Each test shall be repeated 3 times. Operational testing and visual inspection shall be conducted after each test to verify physical integrity, continuity, and functionality.*

---

[2] The use of shock machine test margins is recommended by MIL_STD-810G.

[3] Three repeated shock tests per axis direction are recommended by MIL-STD-810G.

[4] The 800 number was selected to simulate a 15 to 20 minute seakeeping trial. Experience suggests that new equipment that can withstand its first exposure to low severity trials will not fail in this mode during subsequent runs.

Repeated Low Severity Shock Test

> *The test item shall maintain its physical integrity, continuity, and functionality during and following exposure to 5.0 g - 23 msec half-sine pulses, 800 pulses at 1.0 second intervals in each of its three axis directions (or as specified) in accordance with MIL-STD-810G w/change 1, section 516.7, Procedure 1. Operational testing and visual inspection shall be conducted after the test to verify physical integrity, continuity, and functionality.*

Known Orientation and Location Case

Except for equipment mounted on a mast, arch, or cabin top, equipment that is installed only in a vertical (Z) up orientation may be subjected to a half-sine pulse of 10g – 23 msec in its X (surge) and Y (sway) axes, and 20 g – 23 msec in its vertical (Z) axis each test repeated 3 times.

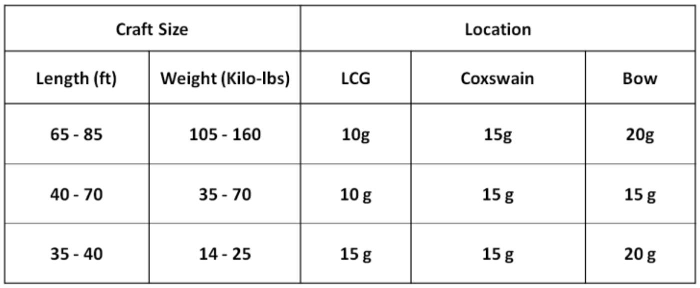
High speed craft equipment orientation during testing should represent realistic conditions in which the equipment may experience wave impact shock. Dominant wave impact shock loads occur only in craft axes +Z (vertical up), -X (aft), and +/- Y (port/starboard). Equipment installed in any orientation should be tested in positive and negative test orientations for all three equipment axes per MIL-STD-810G, Shock, Procedure I. The +X and –Z craft orientations should be omitted during Procedure I testing for equipment installed only in a vertical up orientation.

Craft rigid-body pitching in rough seas results in severe response motions on the mast (or arch, or cabin-top) in the x direction that can be equal in amplitude to the bow vertical acceleration depending upon moment arm relationships. Therefore equipment installed in the vertical up orientation on a mast, arch, or cabin top structure should be tested in surge (X), sway (Y), and heave (Z) directions using the 20 g - 23msec pulse.

Limited Application Case

Table 1 lists test severity options for acquisition flexibility for unique procurements (e.g., high value or fragile components) where general cross platform use at any location is not anticipated. Instead of the general 20 g single-severe test for the vertical (Z) axis, a 10 g or 15 g peak acceleration may be used for the 23 msec half-sine shock pulse as a function of craft size (i.e., length and weight). See Appendix E for details.

Table 1. Limited Application Requirements by Craft Size



Craft Size		Location		
Length (ft)	Weight (Kilo-lbs)	LCG	Coxswain	Bow
65 - 85	105 - 160	10g	15g	20g
40 - 70	35 - 70	10 g	15 g	15 g
35 - 40	14 - 25	15 g	15 g	20 g

.

Isolated Equipment

The peak acceleration amplitudes for the 23-msec half-sine shock pulses listed in Table 1 are applicable only for hard mounted equipment. Equipment items installed in craft on vibration mounts or with internal vibration mounts shall be machine shock tested with vibration mounts installed. The peak acceleration amplitudes for the 23-msec half-sine shock pulses listed in Table 1 are not applicable for testing equipment installed in craft on shock isolation mounts. Appendix E explains why these test requirements are not applicable and provides guidance for shock isolated hardware.

Summary

Table 2 summarizes the single severe shock tests (i.e., 3 times in each axis direction) for general and limited applicability cases. The additional test with 5 g – 23 msec half-sine pulses delivered 800 times at 1-second intervals is applicable for both general and limited applicability cases.

Table 2. Standard and Limited Application Single Severe Test Requirements

Test Requirement	Scope	Equipment Test Axis	Half-sine Shock Pulse
Standard	**All craft, all orientations, all sea states, all locations including masts and arches**	**X**	**20 g - 23 msec**
		Y	**20 g - 23 msec**
		Z	**20 g - 23 msec**
Limited Applications	**Equipment installed only vertical up (except masts/arches)**	**X**	**10 g - 23 msec**
		Y	**10 g - 23 msec**
		Z	**20 g - 23 msec**
	Other rationale, high value, craft specific, location specific	**See Table 1**	

RECOMMENDED EQUIPMENT VIBRATION REQUIREMENT

Procurement documents typically specify requirements for dynamic environments under the general heading of shock and vibration. The following vibration requirement applicable to all craft is provided here to support total requirement development [4].

> *The test item shall maintain its physical integrity, continuity, and functionality when exposed to vibration testing in accordance with MIL-STD-810G, change 1, Method 514.7, using the vertical power spectral density (PSD) curve of Figure 514.7C-4, one hour in each required axes.*

EXAMPLE TEST REQUIREMENTS

The following text is an example of combined shock and vibration technical requirements for equipment operational service in high-speed craft.

1. Functional Shock. “System name” shall maintain its physical integrity, continuity, and functionality in accordance with MIL-STD-810G CHG-1 Method 516.7, Procedure I, paragraph 4.6.2 as follows

a. Severe Intermittent Wave Slams Indicative of Transits in Rough Seas. “System name” shall remain fully operable following exposure to shock of 20 g, 23 millisecond, half-sine pulses, minimum of 3 pulses in each direction of its (3) axes.

b. Repetitive Wave Slams Indicative of Transits in Rough Seas. “System name” shall remain fully operable following exposure to shock of 5 g, 23 millisecond, half-sine pulses, minimum of 800 pulses at 1-second intervals, in each direction of its (3) axes.\

2. Vibration. “System name” shall maintain full operational service in the presence of random vibration defined by the vertical power spectral density (PSD) curve of MIL-STD-810G CHG-1 Method 514, Procedure 1, Figure 514.7C-4, one hour in each of its (3) axes.

REFERENCES

1. Du Cane, P., *The Planing Performance, Pressures, and Stresses in a High-Speed Launch*, Presented in London at a Meeting of the Institution of Naval Architects, 7 June 1956.
2. Riley, M.R., Coats, T., Haupt, K.D., Jacobson, D.R., *The Characterization of Individual Wave Slam Acceleration Responses for High Speed Craft*, Proceedings of the 29th American Towing Tank Conference, Annapolis, Maryland, August 2010.
3. Riley, Michael R., Murphy, Heidi P., Coats, Dr. Timothy W., *An Integrated Approach for Developing Rough Water Methodologies for Small High-Speed Craft Structure, Equipment, Shock Isolation Seats, and Human Performance At-Sea*, 10th Symposium on High Performance Marine Vehicles, HIPER 2016, Cortona, Italy, 17 – 19 October 2016.
4. Riley, Michael R., Haupt, Kelly D., Murphy, Heidi, “Test Specification Guide for Electrical and Electronic Equipment to Withstand Wave impacts in Planing Craft”, Naval Surface Warfare Center Carderock Division Report NSWCCD-23-TM-2012/03 Revision A, January 2012.
5. Department of Defense Test Method Standard, *Environmental Engineering Considerations and Laboratory Tests*, Military Standard, MIL-STD-810G with Change 1, 15 April 2014.
6. ANSI/ASA S2.62-2009, *Shock Test Requirements for Equipment in a Rugged Shock Environment*, American National Standards Institute, Acoustical Society of America, Melville, N.Y., 9 June 2009.

APPENDIX A. SHOCK RESPONSE SPECTRUM

A wave slam half-sine shock pulse (e.g., peak amplitude less than 10 g and duration 100 msec to 150 msec) can have the same damage potential as a higher peak acceleration (e.g., 15 g to 20 g) half-sine pulse with a shorter duration (e.g., 23 msec). The shock response spectrum is the mathematical tool used to determine equivalent (or higher) damage potential for different pulses. (Note: A short duration of 23 msec is used in this report because several previous equipment test specifications for craft used this duration, and testing facilities can easily achieve the pulse for the peak acceleration amplitudes of interest.)

A shock response spectrum (SRS) is a computational tool used extensively to compare the severity of different shock motions [references A1 to A7]. It is also referred to as a maximum response spectrum that can be used to analyze any dynamic event, even vibration signals [Reference A7]. It is especially useful for comparing field shock test data to laboratory shock test data that have different pulse shapes, peak amplitude, jerk, and pulse duration. It is therefore used in this report to demonstrate that short duration laboratory shock machine pulses are more severe (with a margin) than long duration shock pulses recorded during craft seakeeping trials.

The SRS uses a model of the single-degree-of-freedom (SDOF) system shown in Figure A1 to compute the effects of an input motion X (t) on the SDOF system. The system has a base attached to a mass (m) by a spring with stiffness k and a damper with damping coefficient c. For a prescribed time varying shock input motion X (t) at the base of the system the resulting response of the mass (m) is Y (t). The relative displacement Z (t) between the base and the mass is X (t) minus Y (t). The equation of motion of the system given by equation (A1) is obtained by summing the inertial force of the mass and the forces within the spring and damper.

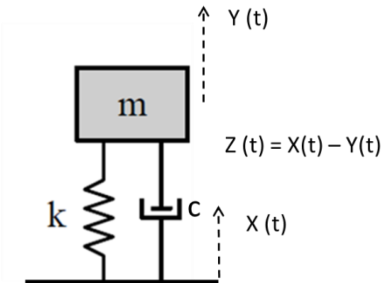


Figure A1. Single-degree-of-freedom Mathematical Model

$$m\,\ddot{y}(t) = -k\,z(t) - c\,\dot{z}(t) \tag{A1}$$

Where *t* is time and:

$$\omega = \sqrt{\frac{k}{m}} \tag{A2}$$

The undamped natural frequency (f) in Hertz (Hz) of the SDOF system is given by equation (A3).

$$\mathrm{f} = \frac{\omega}{2\pi} = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k}{m}}\ \text{Hz} \tag{A3}$$

The solution of equation (A1) provides the predicted response motion of the mass (m) caused by the base input motion either in terms of the absolute motion of the mass Y(t) or the relative displacement Z(t) between the base and the mass.

An SRS is the maximum response of a set of single-degree-of-freedom (SDOF), spring-mass-damper oscillators to an input motion. The input motion is applied to the base of all oscillators, and the calculated maximum response of each oscillator versus the natural frequency make up the spectrum [A7]. The relative displacement SRS is often used as a parameter to compare shock severity when two input shock motions are being compared. It is an intuitive engineering measure of severity because the relative displacement is proportional to the strain in the spring. The shock pulse that causes the larger strain, and therefore the largest damage potential, is judged to be the more severe of the two base input motions. Figure A2 shows three vertical acceleration time histories recorded at different locations on a craft. The plot on the right is the computed maximum relative displacement SRS (DSRS) for each time history. Visual inspection of the time histories on the left indicate that the red bow shock pulse is the most severe. The DSRS curves on the right quantify the difference in severity. The key feature of the SRS approach is that it quantifies shock severity based on its effect on SDOF oscillators.

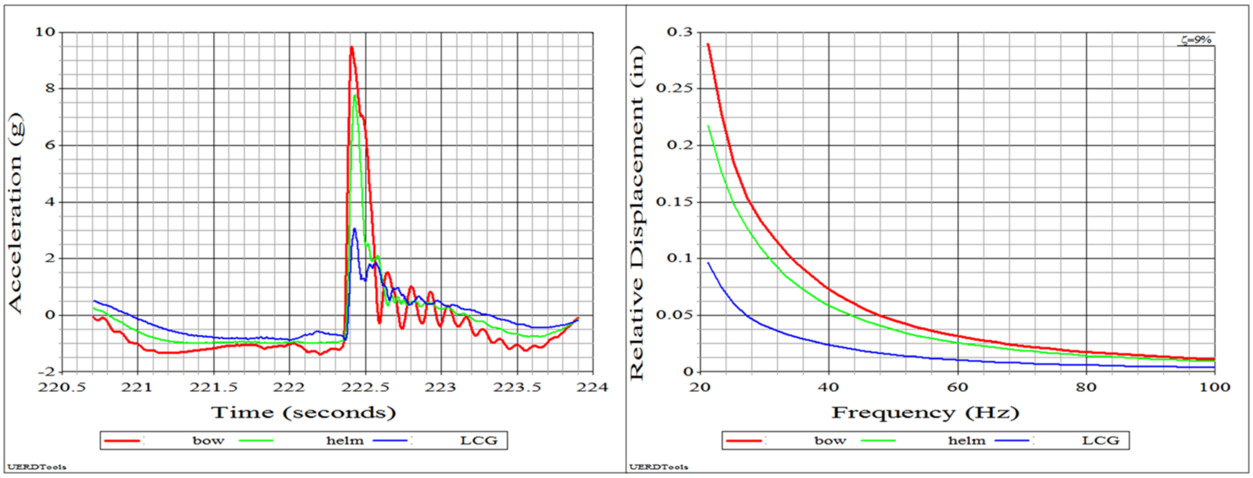


Figure A2. Three Wave Slam Shocks and Relative Displacement SRS[5]

The following example illustrates use of DSRS to demonstrate that a shock pulse from a laboratory shock machine has equal or greater shock severity compared to a wave slam pulse.

---

[5] All data plots and SRS shown in the report were created using UERDTools [A8].

Figure A3 shows two shock pulses. The red curve is a plot of vertical acceleration recorded during a severe wave impact at the bow of a craft. The shock portion of the time history has a peak of 8.5 g and pulse duration of 125 msec. The blue curve is the vertical shock pulse recorded during a laboratory shock machine test of an equipment item. The shock machine was not capable of creating shock pulses with durations from 100 msec to 125 msec, but it could produce vertical pulses with 23 msec duration. The peak acceleration of the blue shock machine pulse is 10 g (i.e., 10 g – 23 msec half-sine pulse). The shock machine oscillations before and after the shock pulse are the run-up and after portion required to generate the 10 g half-sine pulse and return the table to its original position.

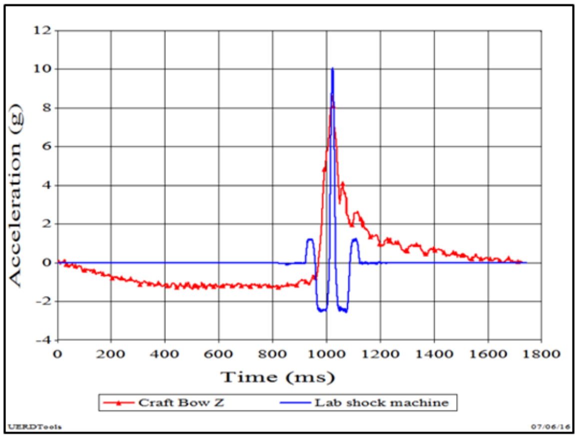


Figure A3. Wave Slam and Shock Machine Pulses

Figure A4 shows the DSRS computed using the two time history accelerations in Figure A3 as shock inputs. The physical interpretation of the frequency scale in Figure A4 is related to the natural frequencies of the fundamental modes of response of an equipment item (i.e., natural modes of vibration or eigenvalues). For SDOF natural frequencies (i.e., equipment fundamental modes of response) greater than 10 Hz the DSRS for the shock machine pulse has larger maximum relative displacements (i.e., larger strain in the springs) compared to the shock pulse of the actual wave impact. This indicates the machine test is more severe for equipment response modes with natural frequencies greater than 10 Hz. The machine test is therefore useful for mitigating the risk of failure at sea as long as the natural response modes of the equipment is greater than 10 Hz. Equipment natural frequencies are typically from 45-50 Hz to several hundred Hz.

The SRS can also be plotted using other SDOF response parameters as shown in Figure A5. In this figure the spectra compare the severity of a 3g – 100-ms half-sine pulse to the severity of a 2 g – 150-ms half-sine pulse. The upper left plot shows the two input pulses in the time domain; the other three plots show maximum responses in the SRS frequency domain (i.e., as a function of oscillator natural frequency). The upper right plot shows how the absolute peak acceleration response of the mass varies with system natural frequency. They are called the absolute acceleration shock response spectra (ASRS).

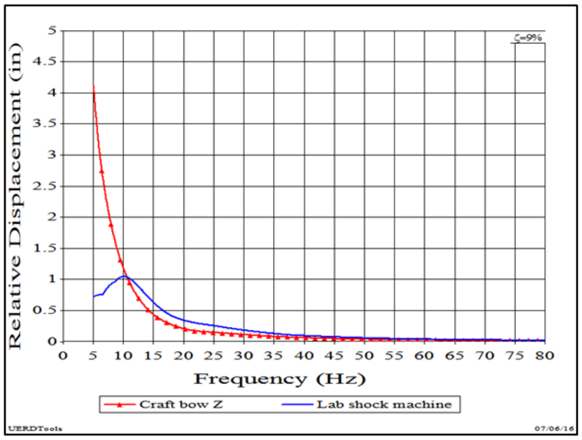


Figure A4. DSRS for Wave Slam and Shock Machine Pulses

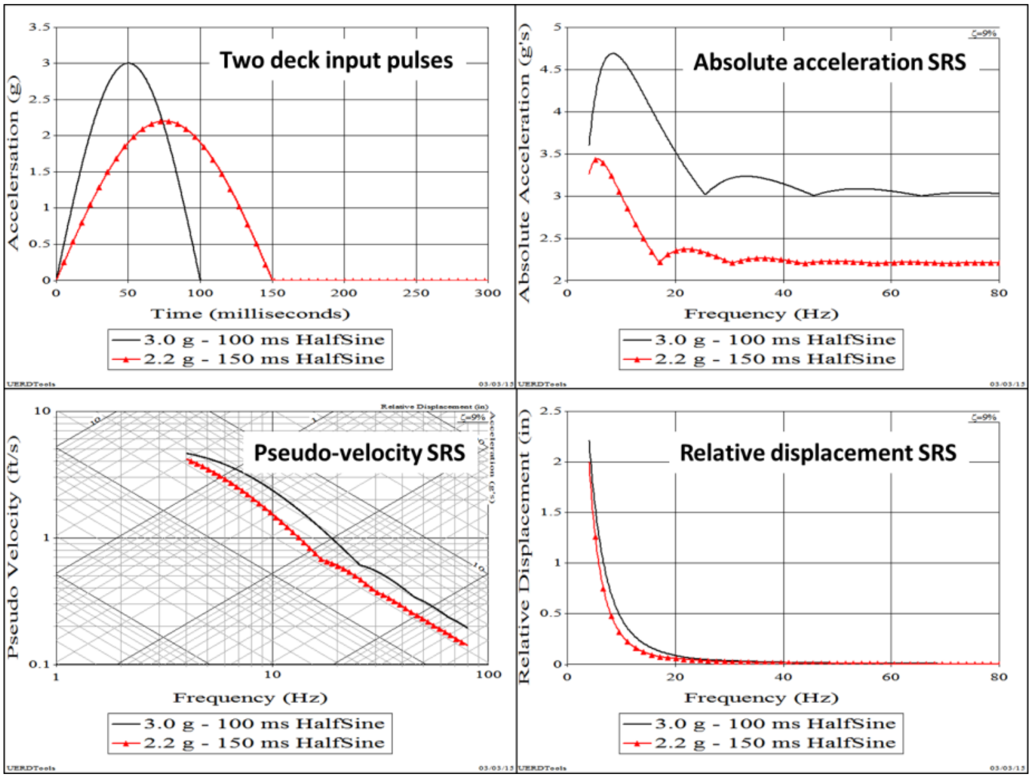


Figure A5. Different Types of Shock Response Spectra

The lower right plot in Figure A5 is the relative displacement SRS for each input pulse, and the lower left plot is the pseudo- velocity SRS (VSRS) for each pulse. Logarithmic scales are used on all four axes of the VSRS. The horizontal lines are the pseudo-velocity scale. Vertical lines are the system natural frequency scale. Lines sloping downward to the left show the predicted maximum relative displacement scales. Lines sloping downward to the right show the predicted maximum response accelerations. The log-log VSRS is a useful format because it provides a measure of the shock severity in units of maximum displacement, velocity, and acceleration. The acceleration scale is referred to as the pseudo-acceleration (A_{MAX}) for damped systems and the velocity scale is referred to as the pseudo-velocity when the maximum values are calculated using equations (A5) and (A6), which applies for lightly damped or zero damped systems [A1]. Z_{MAX} is the maximum relative displacement.

$$\mathrm{A}_{\mathrm{MAX}} = \left(2\pi f\right)^2 Z_{MAX} \tag{A5}$$

$$\mathrm{V}_{\mathrm{MAX}} = \left(2\omega f\right) \mathrm{Z}_{MAX} \tag{A6}$$

Appendix A References

A1. Harris, Cecil M., editor-in-chief, *Shock and Vibration Handbook, Fourth Edition*, McGraw-Hill Companies, Inc., New York, New York, 1995.

A2. ANSI/ASA S2.62-2009, *Shock Test Requirements for Equipment in a Rugged Shock Environment*, American National Standards Institute and Acoustical Society of America, Melville, N.Y., 2009.

A3. Department of Defense Test Method Standard, *Environmental Engineering Considerations and Laboratory Tests*, Military Standard, MIL-S-810G, change 1, Method 516.7, Shock, 15 April 2014.

A4. STANAG 4559, *Testing of Surface Ship Equipment on Shock Testing Machines*, NATO Standardized Agreement, 13 May 2008.

A5. Alexander, J. Edward, *The Shock Response Spectrum – A Primer,* Society of Experimental Mechanics Inc., Proceedings of the IMAC XXVII, Orlando, Florida, USA, 9 – 12 February 2009.

A6. Gaberson, Howard A., *Shock Severity Estimation*, Sound and Vibration Magazine, Volume 46 Number 1, January 2012.

A7. ISO-18431-4: 2007, *Mechanical vibration and shock – Signal processing – Part 4: Shock response spectrum analysis*, International Organization for Standardization, Geneva, Switzerland, 2007.

A8. Mantz, Paul A., Costanzo, Fredrick A., *An Overview of UERDTools Capabilities: A Multi-Purpose Data Analysis Package*, Proceedings of the IMAC-XXVII Conference and Exposition on Structural Dynamics, Society of Experimental Mechanics, Inc., 9-12 February 2009, Orlando, Florida, 2009.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. CRAFT MOTION MECHANICS

This appendix summarizes recent lessons learned in the study of craft motion mechanics. They provide the foundation for creating standardized laboratory test requirements for minimizing the risk of equipment malfunction or failure due to wave slam shock pulses.

Deterministic Approach

In 2005 a research project was initiated to understand why acceleration values documented in historical test reports from different agencies could not be used in craft comparative analyses [B1]. Methods to extract peak accelerations were implemented subjectively by different analysts, which invariably led to processed peak accelerations that were not comparable. One of the products of this study was the standardized process for computing $A_{1/N}$ values referred to as *StandardG*[6], [B2]. The study evolved further into a pursuit to understand craft motion mechanics and the cause-and-effect physical relationships between impact loading and craft responses. Figure B1 shows an unfiltered acceleration time history of three wave impacts. The responses to each impact damp out before the next wave impact, therefore each impact can be analyzed one at a time.

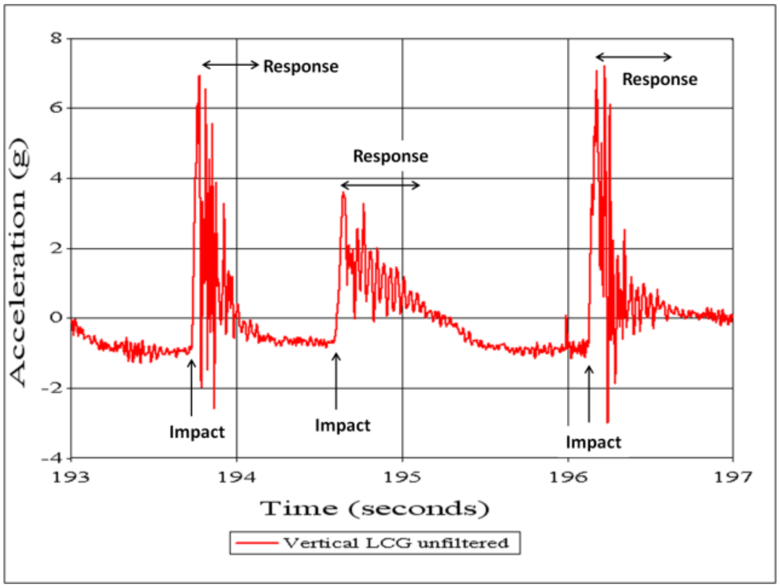


Figure B1. Wave Slam Input and Response Phenomena

---

[6] Available free by contacting the Branch Head of the United States Naval Academy Hydrodynamics Laboratory. Contact information is available at www.usna.edu/Hydrodynamics/Contact.php.

Response Mode Decomposition

Accelerometers record relative structural motions and absolute motions (i.e., rigid body motions) of a craft simultaneously. In marine craft the relative motions include millimeter deck vibrations caused by propulsion systems, power generation machinery, and forced structural vibrations after a wave impact. The absolute motions include heave, surge, and sway. The heave acceleration is the measure relevant to the study of shock (i.e., wave slam) load transmission within a craft structure [B3]. The analysis of wave slam shock effects therefore requires that raw acceleration data be low-pass filtered to attenuate the vibration content in the record, leaving the majority content in the filtered record attributed to rigid body content. Figure B2 illustrates the response mode decomposition process of separating rigid body and vibration accelerations. The plot on the left shows a time history of the raw vertical acceleration (gray line) and the rigid body heave acceleration (black line) obtained by low-pass filtering. The rigid body heave acceleration is typically that motion about which the local vibrations oscillate. The plot on the right shows the vibration content obtained by high-pass filtering the recorded acceleration. The rigid body acceleration at any cross-section can be used as a measure of the severity of a wave impact load in units of g.

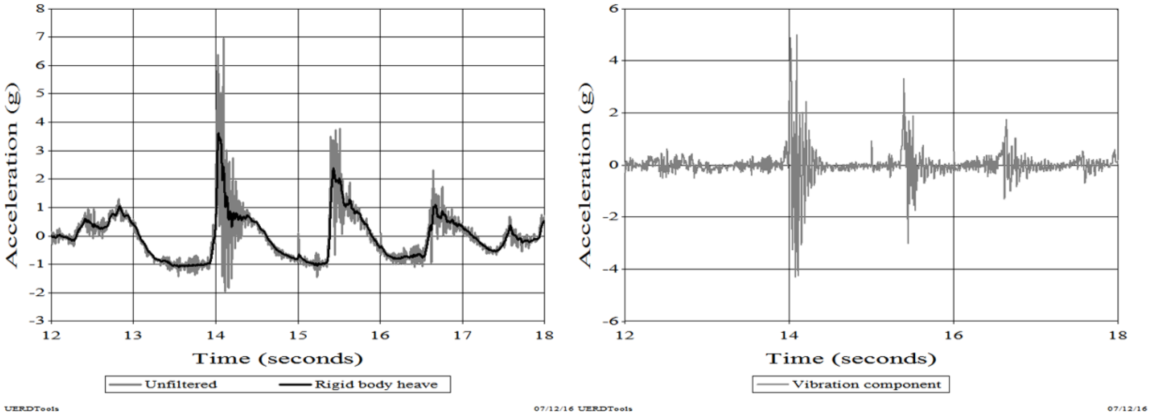


Figure B2. Rigid Body and Vibration Accelerations

Individual Wave Slam Lessons Learned

The Combatant Craft Division of Naval Surface Warfare Center Carderock Division has conducted full-scale seakeeping trials of many craft since its establishment in 1967. Consistent testing protocols provide a useful data base for analyzing response trends. The lessons learned summarized herein were based on analysis results for craft that weighed approximately 14,000 pounds (6.35 metric tons) to 116,000 pounds (52.6 metric tons) with lengths that varied from 33 feet (10 meters) to 82 feet (25 meters). Deadrise values varied from 18 to 22 degrees [B4].

Sequence of Events

A vertical acceleration time history for one wave impact sequence and the velocity and absolute displacement (i.e., heave) curves obtained by integration are shown top to bottom in Figure B3. The curves illustrate the wave impact period and non-impact periods. At time A, the -0.9 g vertical acceleration indicates a condition very close to free fall. The relatively constant -

0.9 g from time A to time B and the linear decrease in velocity suggests that the craft is rotating downward with the stern in the water. The drop in height from time A to B is most likely a combination of heave and pitch. At time B, the craft impacts the incident wave, the velocity is at a minimum, the negative slope changes rapidly to a positive slope, and the force of the wave impact produces a sharp rise in acceleration. From time B to time C, the craft continues to move down in the water, the velocity approaches zero, and the acceleration decreases rapidly. At time C the downward displacement of the craft reaches a maximum, the instantaneous velocity is zero, and the impact event is complete. From time C to D forces due to buoyancy, hydrodynamic lift, and components of thrust and drag combine to produce a net positive acceleration. From time D to E, gravity overcomes the combined forces of buoyancy, hydrodynamic lift, and components of thrust and drag as another wave encounter sequence begins.

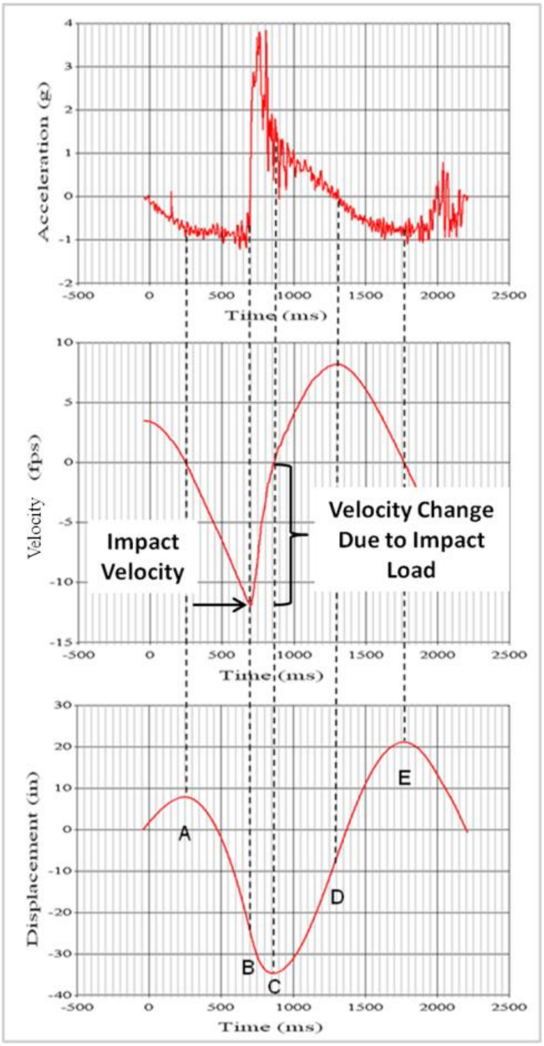


Figure B3. Wave Impact Sequence of Events

The period of time in Figure B3 from point B to point C is the wave impact period, i.e., the shock pulse. It is this period of time from B to C that is important for understanding and evaluating shock effects caused by wave impacts. Five parameters are important for characterizing the acceleration shock pulse, including pulse shape, rate of acceleration application (i.e., jerk), peak amplitude, pulse duration, and load direction [B5].

Wave Slam Type

The time history responses of individual wave slams tend to follow three characteristic patterns before and after the wave impact phase. The patterns are used to characterize types of wave impacts referred to as Alpha, Bravo, and Charlie wave slams [B6]. The Type Alpha slam is one where the craft is airborne prior to impact. The stern of the craft impacts the water first and this induces significant bow down pitching just prior to a severe wave impact. The Type Bravo slam is one where the craft may be airborne or the stern may be in the water, and impact occurs with little or no significant bow down pitching prior to impact. Prior to impact there is typically a temporary loss of forward momentum for Type Alpha and Bravo slams. The acceleration data shown in Figure B4 illustrates the Type Bravo slam and the shock pulse caused to the wave impact. The red curve is the low-pass filtered vertical (i.e., heave) acceleration and the green curve is the low-pass filtered fore-aft (i.e., surge) acceleration. Prior to the time of impact at time B the vertical accelerometer indicates a free fall event while the green fore-aft curve shows a decrease in forward thrust. The duration of the shock pulse from time B to C is indicated by the arrows. Time C is referred to as the transition point in the acceleration record because the dominant forces transition from shock due to impact to combined buoyancy and hydrodynamic lift forces after point C.

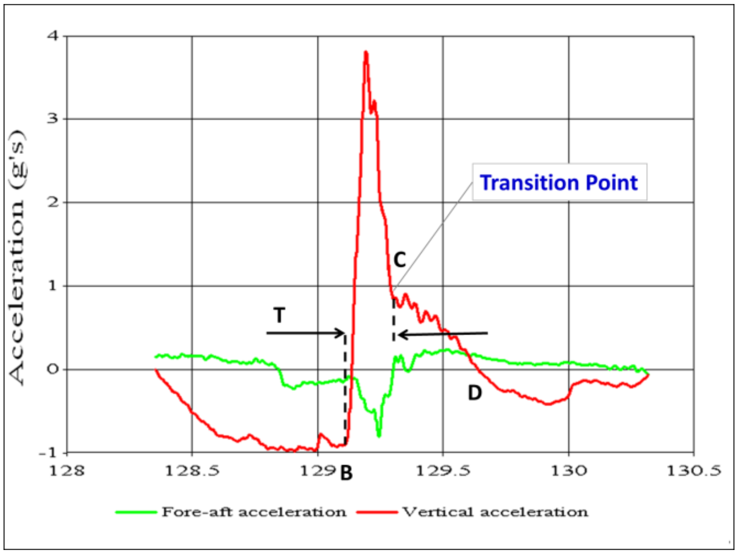


Figure B4. Example Type Bravo Wave Slam

The Type Charlie slam is one where the craft is in the water, there is no lose of forward momentum. There is little or no bow-down pitching prior to impact and the impact causes rapid bow up pitching. The significance here is that even in what is described as a random seaway in fully developed seas, the response motions observed in craft follow repeatable patterns.

Shock Pulse Shape and Direction

At any measurement point on a craft the direction of the shock pulse during a wave slam can be aligned with coordinate axes X (surge acceleration, positive forward), Y (sway acceleration, positive to port), and Z (heave acceleration, positive up). The shape of the rigid body vertical acceleration when impact forces dominate can be simplified for analytical study as a half-sine pulse [B7]. Figure B5 illustrates the half-sine representation of the rigid body vertical acceleration pulse for a wave impact where the largest amplitude is A_{max} and the pulse duration is T. While the sequence of wave encounters in terms of wave height and time between impacts is random, the vertical response of the craft to a single wave impact appears to be repeatable in shape with amplitudes that vary primarily with speed, craft weight, wave period, and wave height [B4].

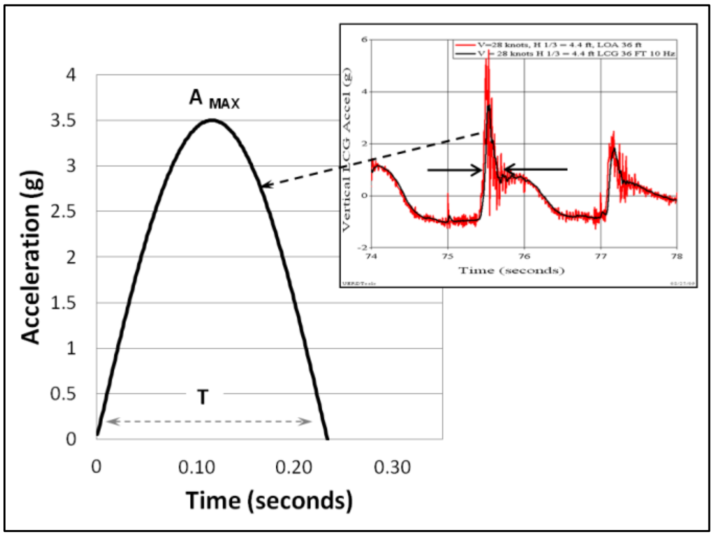


Figure B5. Half-sine Pulse Shape

Shock Pulse Duration

Figure B6 is a plot of wave impact duration versus peak acceleration recorded at the LCG in 13 different craft during head-sea trials in rough water [B8]. All wave impacts with peaks greater than 3 g where analyzed. Lower amplitude pulses were surveyed for trends. The squares in the plot correspond to six craft that weighed from 22,000 pounds to 38,000 pounds. The circles correspond to six craft that weighed from 14,000 pounds to 18,000 pounds. The triangles were recorded on a craft that displaced 105,000 pounds. The peak acceleration is the rigid body peak acceleration estimated using a 10 Hz low-pass filter. The data indicates that the shortest impact durations regardless of impact severity are on the order of 100 msec, and the longest durations decrease from about 450 msec to 150 msec as peak acceleration increases to about 7 g. The variation in the impact duration for a given peak acceleration is caused by several variables, including craft weight, speed, wave height, impact angle, deadrise, and where the craft impacted the wave (e.g., on the leading flank, crest, or following flank).

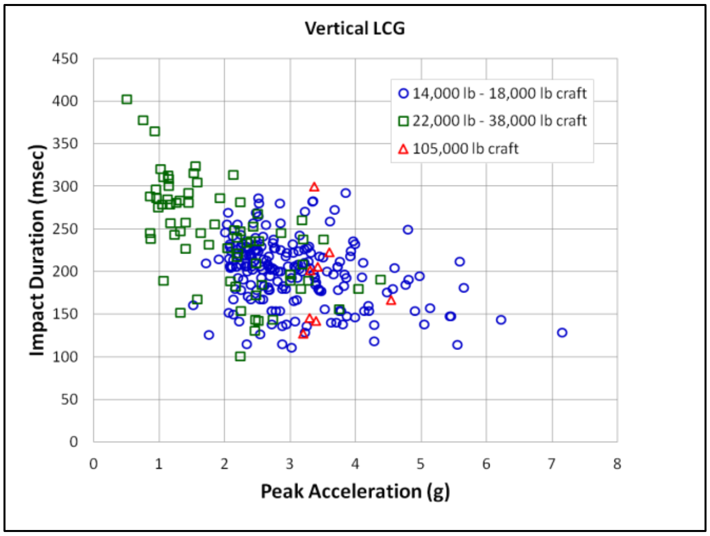


Figure B6. Wave Impact Pulse Duration

Appendix C References

B1. Jacobson, A., Coats, T., Haupt, K., Pogorzelski, D., Jacobson, D., *Working Towards Vertical Acceleration Data Standard*s, Maritime Systems and Technology (MAST) Contone Congressi, Porto Antico, Genoa, Italy, 14 – 16 November 2007.

B2. Riley, M. R., Haupt, K. D., Jacobson, D. R., *A Generalized Approach and Interim Criteria for Computing* $A_{1/n}$ *Accelerations Using Full-Scale High Speed Craft Data*, Naval Surface Warfare Center Carderock Division Report NSWCCD-23-TM-2010/13, April 2010

B3. Riley, M.R., Coats, T. W., Murphy, H. P., *Acceleration Response Mode Decomposition for Quantifying Wave Impact Load in High-Speed Planing Craft*, Naval Surface Warfare Center Carderock Division Report NSWCCD-80-TR-2014/07, April 2014.

B4. Riley, M. R., Coats, T. W., Murphy, H. P., *Acceleration Trends of High-Speed Planing Craft Operating in a Seaway*, Society of Naval Architects and Marine Engineers, The Fourth Chesapeake Powerboat Symposium, Annapolis, Maryland, 23-24 June 2014.

B5. Eiband, M., *Human Tolerance to Rapidly Applied Accelerations: A Summary of the Literature*, Lewis Research Center, National Aeronautics and Space Administration, Memorandum 5-19-59E, Cleveland, Ohio, June 1959.

B6. Riley, M., Coats, T., Haupt, K., Jacobson, D., *The Characterization of Individual Wave Slam Acceleration Responses for High-Speed Craft*, Proceedings of the American Towing Tank Conference, Annapolis, Maryland, August 2010.

B7. Riley, M. R., Coats, T.W., *Development of a Method for Computing Wave Impact Equivalent Static Accelerations for Use in Planing Craft Hull Design*, The Society of Naval Architects and Marine Engineers, The Third Chesapeake Powerboat Symposium, Annapolis, Maryland, USA, June 2012.

B8. Riley, M., Haupt, K., Murphy, H., *An Investigation of Wave Impact Duration in High-Speed Planing Craft*, Naval Surface Warfare Center Carderock Division Report NSWCCD-80-TR-2014/26, April 2014.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C. SCALING DATA TO MAXIMUM DESIGN LEVEL

Most Severe Wave Impacts Recorded

The trials report for each craft in the database tabulated rigid body peak accelerations recorded during transits in head seas, port or starboard bow seas, beam seas, port or starboard quartering seas, and following seas[7]. The tables were surveyed to identify which runs produced the largest peak accelerations at bow, coxswain or helm (if recorded) and longitudinal center of gravity (LCG) locations. The original archived digital data for each run with the largest peak accelerations were processed to create new time history files of the unfiltered data. A Fourier spectrum of each unfiltered acceleration signal was developed and the frequency content was analyzed. After analyzing all the signals for each craft a low-pass filter was selected to estimate the rigid body acceleration time history [C1]. Figure C1 shows the 20 Hz low-pass filtered data for a craft that resulted in the largest amplitude wave slams at the bow and LCG gage locations. The largest bow slam occurred at 177 seconds in the record (i.e., slam # 177), and the largest LCG slam occurred at 28 seconds (i.e., slam # 28). There was no gage at the coxswain location so the rigid body vertical acceleration at that location was estimated assuming linear interpolation between the LCG and the bow. The estimated maximum acceleration for the coxswain location is shown in Figure C1.

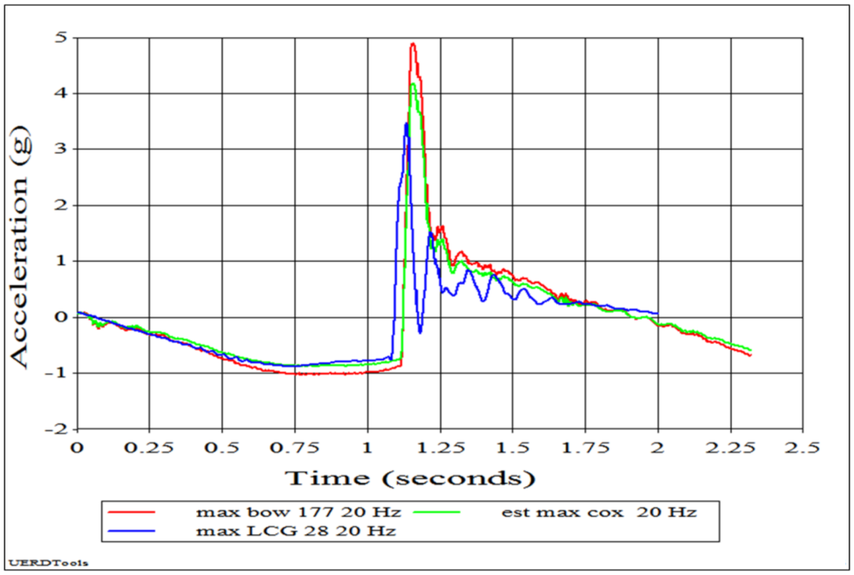


Figure C1. Example Largest Peak Accelerations at Bow, Coxswain, and LCG

---

[7] Reference trials reports, craft descriptions, recorded acceleration data, and computational results are presented in a limited distribution report.

Acceleration Scaling to Maximum Severity

It was assumed that the largest peak accelerations recorded on each craft during rough water trials were not the largest peaks that could have occurred. Numerous factors could lead to larger peaks including higher craft speed, higher sea states, or transiting with a less skilled coxswain. It was therefore necessary to develop an extrapolation scheme for scaling the recorded peak accelerations up to a higher maximum level for equipment hardening tests.

The rationale for scaling to a higher severity level involves the concept of maximum safe speed achieved during seakeeping trials. Seakeeping trials are typically performed not only in different headings but also at different speeds (e.g., patrol, cruise, and maximum safe speed). The largest peak accelerations always occur at the higher speeds for a given sea condition. The maximum safe speed is usually, but not always, the maximum speed determined by the coxswain at which the craft can be operated safely without operating the throttle (i.e., no throttling, which is typically used to improve the ride quality). Recent analyses of seakeeping data for more than 20 different craft in varying sea states found that the maximum safe speeds achieved by different experienced coxswains corresponded to $A_{1/10}$ values[8] from 2.7 g to 3.2 g [C2]. This range is consistent with an earlier paper that reported an $A_{1/10}$ value of 3 g as being described by naval crews as extremely uncomfortable. The maximum safe speed is one judged by coxswains to be extremely uncomfortable with no desire to want to achieve a higher speed because of concerns for personnel safety and craft stability for the existing sea conditions. It was therefore assumed that the ride severity with a value of $A_{1/10}$ equal to 4.0 g plus a 20-percent margin is an appropriate baseline level for establishing maximum severity levels for equipment testing. In other words, a ride with $A_{1/10}$ equal to 4.8 g is a reasonable baseline severity for establishing maximum severity levels for equipment testing.

The 20-percent margin was chosen to account for unknowns related to possible gage location effects and data processing. In the database all the accelerometers were installed on the deck in spaces close to equipment. If equipment is mounted above the deck in flexible cabinets the flexure of the cabinet could amplify the deck input acceleration (estimated 15%). This is a phenomenon related solely to long duration pulses with pulse durations greater than the natural period of vibration of a cabinet structure. Another unknown involves estimating the rigid body peak acceleration from raw acceleration using a low-pass filter to post process the data. It was therefore assumed that choice of a higher low-pass filter value could increase the peak acceleration by 5%.

All time history data was scaled using a coxswain scale factor given by equation C1, where $A_{1/10}$ is the average of the highest ten percent of peak accelerations computed using the *StandardG* algorithm[9] for each acceleration time history used in this study.

$$\text{Coxswain scale factor} = 1.2\left[\frac{4.0}{A_{1/10}}\right] \qquad \text{(C1)}$$

---

[8] $A_{1/10}$ is the average of the highest ten percent of peak accelerations recorded during a seakeeping trial run.

[9] See Appendix B.

Figure C2 presents an example of scaled data using equation C1.The time history plots on the left are the most severe impacts recorded on a craft at the LCG and the bow. The time history plots on the right are the scaled curves using a 1.8 scale factor from equation C1.

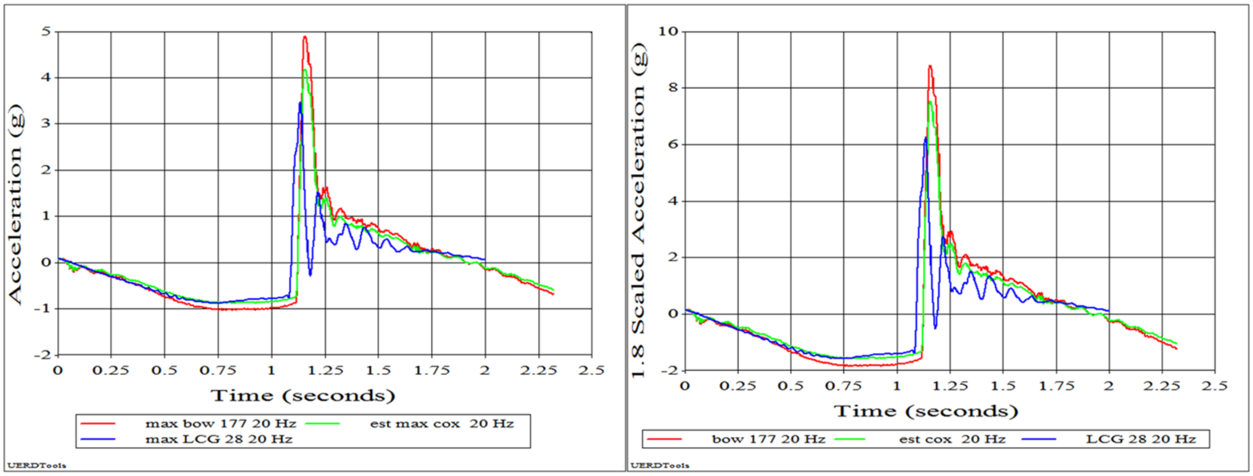


Figure C2. Recorded and Scaled Wave Impact Accelerations

There are several factors that could lead to higher peak accelerations than predicted using equation C1, including standing versus seated coxswains, use of shock isolation seats, coupled heave, pitch and roll effects, or multi-axis shock pulses. To account for these uncertainties a laboratory test machine margin was also used. The test machine margin is discussed in Appendix D.

Figure C3 shows the DSRS (on left) and VSRS (on right) for the scaled data shown on the right in Figure C2. Since the frequency range of interest for hard mounted equipment is greater than roughly 30 Hz the VSRS plotting format will be used in plots for ease of visual comparisons. DSRS or ASRS plots can also be used when comparing the severity of two different spectra because they are related to the Z_{MAX} values in the DSRS as shown by equations (C2) and (C3).

$$A_{MAX} = (2\pi f)^2 Z_{MAX} \tag{C2}$$

$$V_{MAX} = (2\omega f) Z_{MAX} \tag{C3}$$

Z_{MAX} is the maximum relative displacement plotted in the DSRS. V_{MAX} is the maximum pseudo-velocity plotted in the VSRS [C4]. A_{MAX} is the maximum acceleration plotted in the ASRS.

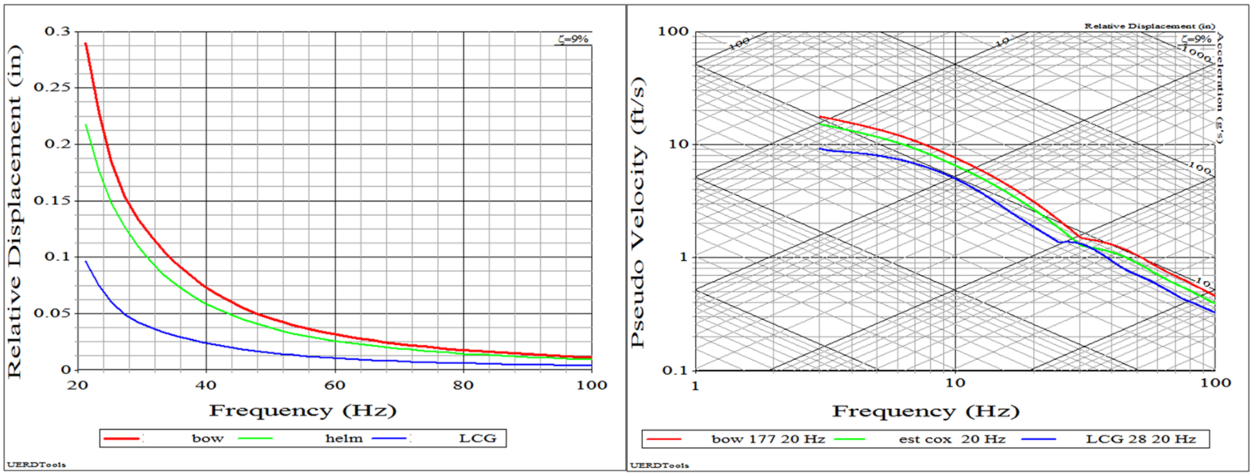


Figure C3. DSRS and VSRS of Scaled Wave Impact Pulses

Appendix C References

C1. Riley, Michael R., Coats, Timothy W., Murphy, Heidi P, "Acceleration Response Mode Decomposition for Quantifying Wave Impact Load in High-Speed Planing Craft", Society of Naval Architects and Marine Engineers, The Fourth Chesapeake Powerboat Symposium, 23-24 June 2014, Annapolis, Maryland, USA

C2. Riley, Michael R., Ganey, Dr. H. Neil., Haupt, Kelly, *Ride Severity Profile for Evaluating Craft Motions*, Naval Surface Warfare Center Carderock Division Report NSWCCD-80-TR-2015/002, January 2015.

C3. Savitsky, Daniel, Koelbel, Joseph, *Seakeeping of Hard Chine Planing Hulls*, SNAME, Technical and Research Bulletin No. R-42, June 1993.

C4. Harris, Cecil M., editor-in-chief, *Shock and Vibration Handbook, Fourth Edition*, McGraw-Hill Companies, Inc., New York, New York, 1995.

APPENDIX D. LABORATORY SHOCK TEST SEVERITY

Figure D1 shows three half-sine shock machine pulses with peak amplitudes of 10g, 15g, and 20g (i.e., the left plot). The duration of each pulse is 23 msec. The oscillation before and after each pulse is called the run-up and after motion required to create the pulse and to return the table to its pre-test position. These peak accelerations and the 23 msec pulse duration were selected because they were used in previous equipment specifications and easily achieved on shock test machines. Although the information is anecdotal, equipment subjected to the 20 g – 23 msec shock machine pulse have no known failures in very rough seas at high speeds. The pseudo-velocity SRS for each pulse is shown on the right in Figure D1.

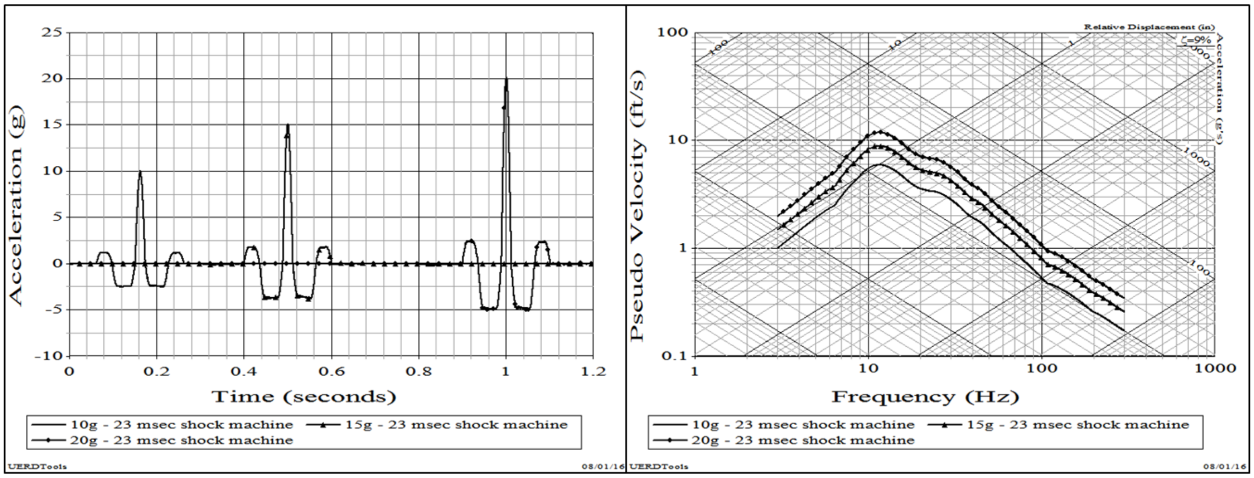


Figure D1. Three Shock Machine Half-Sine Pulses and VSRS

The VSRS of the scaled acceleration time histories for bow, coxswain, and LCG locations were compared to the VSRS of the three shock machine pulses. Figure D2 shows an example comparison of craft wave slam data and shock machine data. Each of the three shock machine VSRS curves is observed to be equal to or greater than the scaled craft VSRS curves. This indicates that the machine 23-msec pulses have equal or greater potential for causing shock damage compared to the scaled wave slam pulses. Therefore, they are all acceptable candidate laboratory test severities for consideration.

The standard practice for establishing shock machine test severities is to ensure that the maximum machine shock test severity is greater than the maximum field shock severity by a margin that accounts for uncertainties [D1]. For example, a margin of 1.4 is recommended for establishing shock machine test requirements for equipment to be installed in space vehicles [D2]. But the uncertainties associated with in-flight shocks are different than uncertainties for shocks caused by wave impacts. It was therefore necessary to evaluate the uncertainties associated with differences between actual at-sea wave slams and shocks induced by a machine in a laboratory test.

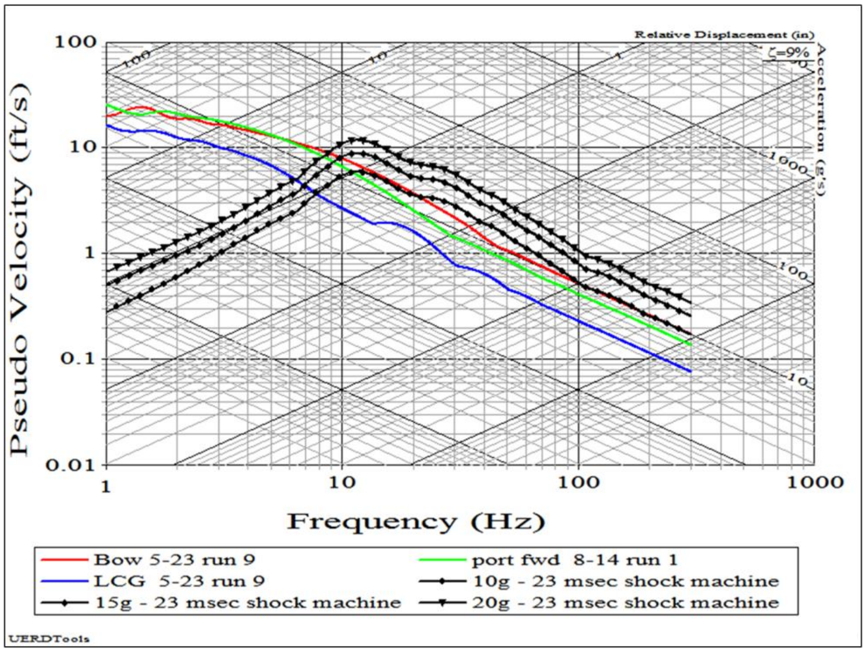


Figure D2. VSRS for Scaled Wave Impact Data and Shock Machine Pulses

A test machine margin of 1.5 was selected as a reasonable and achievable margin to account for uncertainty related to the following at-sea factors. The laboratory test applies shock pulses in one coordinate axis at a time, while the at-sea environment may include wave slam shock pulses applied to multiple axes simultaneously. The angle of impact varies depending upon where the craft impacts a wave on the leading flank, the crest, the following flank, or the trough (5% uncertainty assumed). The laboratory test applies shock loads to each axis of the equipment separately (i.e., uncoupled inputs), while the at-sea environment can include the rigid body translation plus the application of bending moments due to pitch and roll, i.e., coupled inputs (10% uncertainty assumed). The laboratory test exposes equipment to one severe shock pulse repeated three times. In the at-sea environment the equipment will be subjected to more than three severe impacts (10% margin assumed). The installation details in the lab test may vary slightly from the actual installation in the craft (5 % margin assumed). The severity of the most severe at-sea wave slam could have been higher if the coxswain had been either standing or seated in a shock isolation seat (20% margin assumed). The combined 1.5 margin means the laboratory test is fifty percent more severe than the scaled maximum wave slam severity. As a comparison criterion the test machine ASRS must be 1.5 times greater than the scaled wave slam ASRS.

Figure D3 shows the test machine margin curves for the 10 g, 15 g, and 20 g half-sine pulses obtained by dividing the lab test DSRS by the scaled wave slam DSRS. The lowest margins always occur at the dip close to 100 Hz or at 300 Hz. Dividing the lab test ASRS by the scaled wave slam ASRS yields the same curves. Curves like the ones shown in Figure D3 were developed for all craft.

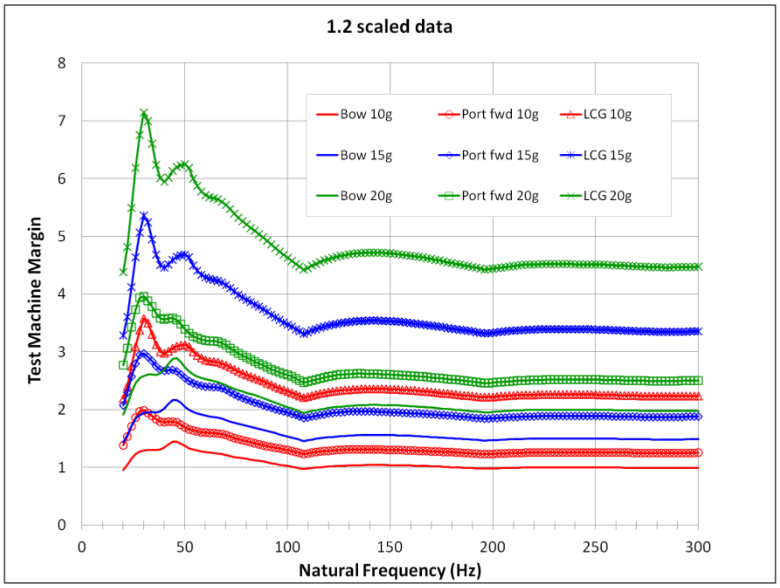


Figure D3. Test Machine Margins for Scaled Wave Impact Shock Pulses

Appendix D References

D1. Department of Defense Test Method Standard, *Environmental Engineering Considerations and Laboratory Tests*, Military Standard, MIL-S-810G, change 1, Method 516.7, Shock, 15 April 2014.

D2. Payload Test Requirements, National Aeronautics and Space Administration Technical Standard NASA-STD-7002A, September 10, 2004.

D2. Riley, M.R., Coats, T. W., Murphy, H. P., *Acceleration Response Mode Decomposition for Quantifying Wave Impact Load in High-Speed Planing Craft*, Naval Surface Warfare Center Carderock Division Report NSWCCD-80-TR-2014/07, April 2014.

THIS PAGE INTENTIONALLY LEFT BLANK.

APPENDIX E. EQUIPMENT SHOCK ISOLATION MOUNTS

The purpose of this appendix is to document the rationale for not using 23-msec shock machine pulses during tests of shock-mounted equipment, and to explain why the majority of electronics equipment installed in small craft should be shock hardened rather than shock isolated.

Figure E1 shows a shock isolated electronics enclosure tested during rough water seakeeping trials of a craft. The yellow circles show the positions of the two accelerometers installed above and below the shock mounts. The isolated enclosure was installed at the bow of the craft. Figure E2 shows the two rubber shock mounts that isolated the enclosure.

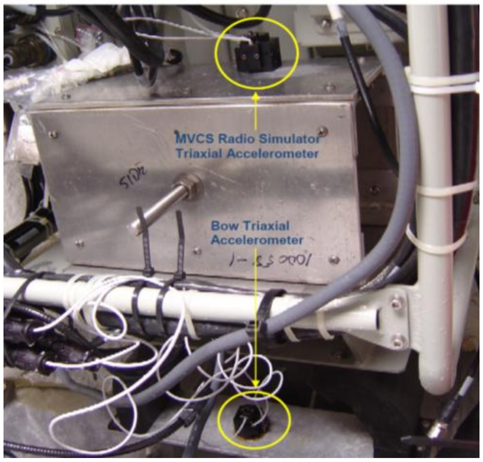


Figure E1. Shock Isolated Electronics Enclosure

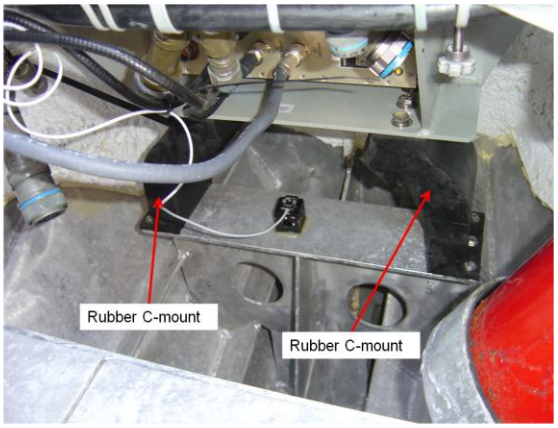


Figure E2. Rubber Shock Mounts Supporting Electronics Enclosure

During the trials the record accelerations above and below the mounts showed that the shock mounts amplified the wave impact accelerations. This is shown in the top data plot in Figure E3. The blue curve is the vertical acceleration recorded below the shock mounts. The red curve is the acceleration recorded above the mounts. The pulse durations are approximately the same, but the peak accelerations above the mount are greater than below the mount. The explaination for this amplification can be illustrated mathematically using the single degree of freedom (SDOF) model shown in the figure. The black curve in the lower right plot is the same acceleration below the mounts shown in the upper plot between 348 and 349 seconds. It was used as the shock input pulse for the SDOF model. The red curve is the predicted motion above the mounts for a shock isolation system with a natural frequency of 12 Hz and 20-percent damping. The prediction shows shock mount amplification similar to that observed in the data.

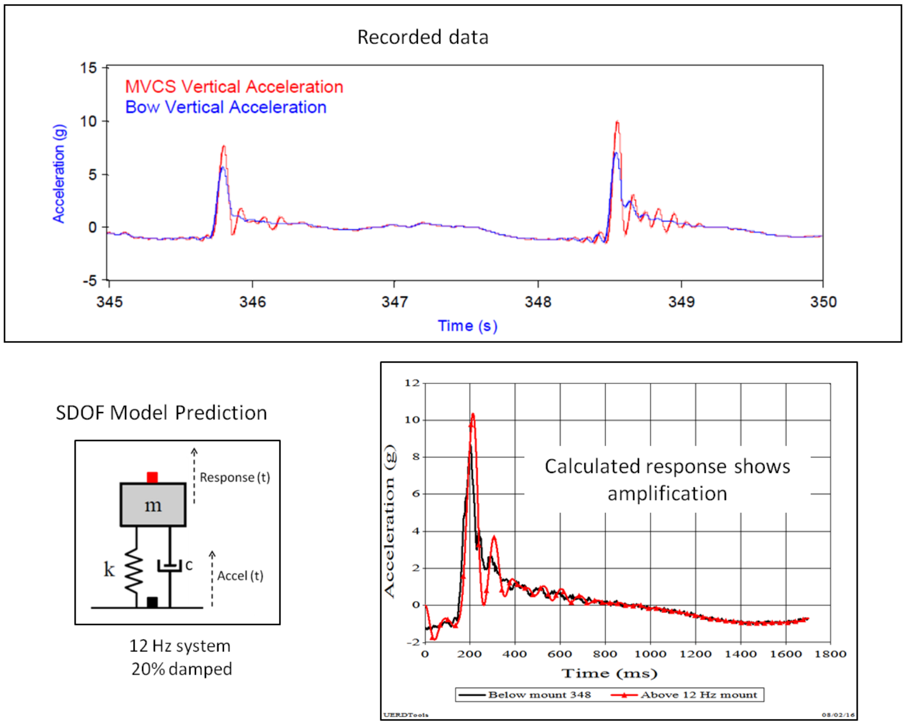


Figure E3. Recorded and Predicted Shock Mount Amplification

The reason for the amplification is related to the ratio (R) of the duration of the shock pulse (T)[10] to the natural period of oscillation of the mount (τ) given by equation E1.

$$R = \frac{T}{\tau} = T\left(f_{SYS}\right) \tag{E1}$$

and

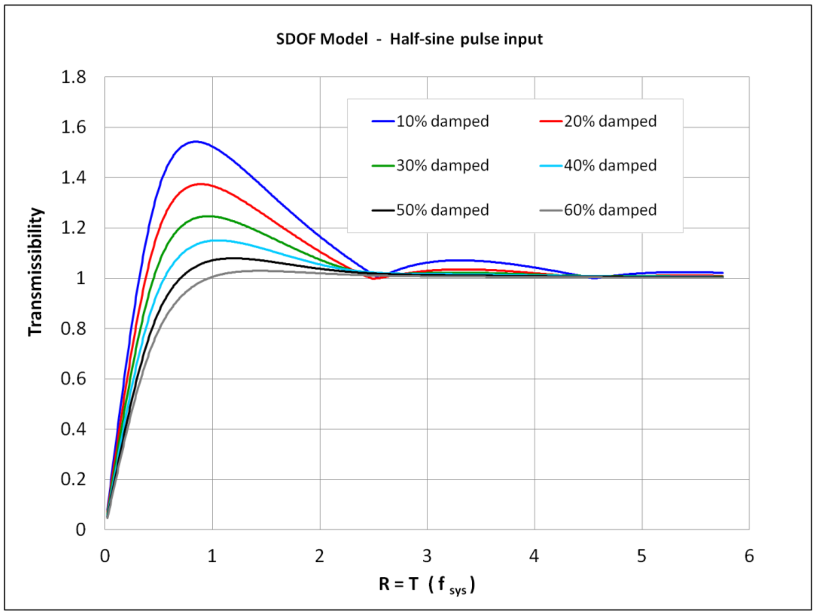
---

[10] Some references use the half-sine period (2T) rather than the half-sine pulse duration (T)

$$f_{SYS} = \frac{\omega}{2\pi} = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k}{m}} \text{ Hz} \tag{E2}$$

In order for mitigation to occur the ratio R must be less than a limit value that varies with the damping coefficient. The R limit value causes the response peak acceleration above the mounts to be equal to the peak acceleration of the input below the mounts.

Figure E4 presents a plot of the transmissibility curve for half-sine shock pulse inputs. It plots the mitigation ratio (i.e., response peak acceleraqtion / input peak acceleraqtion) as a function of R. For 10-percent damping the blue curve shows that a half-sine shock input pulse creates a peak response acceleration 1.54 times the input peak acceleration when R is 0.84 (i.e., 54 percent amplification of the input shock pulse has occurred). The blue curve crosses a mitigation ratio of 1.0 when the R value is 0.314. Thus mitigation is achieved for a mount with 10-percent damping only when R is less than 0.314 (i.e., the limit value for 10% damping). As damping increases from 20 percent to 60 percent the curves show that the R limit value moves to the right: 0.382 for 20%, 0.455 for 30%, 0.557 for 40%, 0.704 for 50%, and 0.971 for 60%. These curves apply for any below mount peak acceleration amplitude because the SDOF system is a linear SDOF model. For example, if the below mount input is 7 g – 100 msec, the above mount peak acceleration will also be 7 g when R = 0.314.



Figue E4. Shock Transmissibility Curve for Half-sine Pulses

The curves in Figure E4 are useful because they can be used to compare how shock input pulse duration effects mount mitigation.. They were used to create Table E1. The numbers on the left show the mount frequencies (f_{SYS}) in Hertz (Hz) and damping values needed to achieve Mitigation ratios (i.e., response acceleration/input acceleration) from 0.3 to 1.0 for an input pulse duration of 0.025 seconds (sec) (i.e., a short duration shock machine pulse). The numbers on the right show the mount frequencies (f_{SYS}) in Hertz (Hz) and damping values needed to achieve mitigation ratios from 0.3 to 1.0 for an input pulse duration of 0.10 sec (i.e., a typical severe wave slam duration). The frequencies on the right for a 0.10 sec shock input are 4 times less than the frequencies on the left for the 0.025 sec shock input because the wave slam pulse duration is 4 times greater than the shock machine pulse duration.On the left the mounts with frequencies from 10 Hz to 26 Hz can mitigate the 0.025 sec input pulse, but on the right, mitigation requires much lower frequencies from about 0.9 Hz to 6.6 Hz depending upon damping. In other words, a shock mouint could perform well by mitigating the input pulse during a shock machine test (i.e., 0.025 sec pulse), but during actual wave impacts (i.e., above 2 g peak acceleration) the same mount system would amplify the shock inputs. Short duration shock machine pulses should therefore not be used for test and evaluation of shock isolated systems.

Table E1. Shock Mount Frequency to Achieve Mitigation Ratio

For shock pulse duration T = 0.025 sec							For shock pulse duration T = 0.10 sec						
Mitigation Ratio	Frequencies (Hz) needed to achieve mitigation						Mitigation Ratio	Frequencies (Hz) needed to achieve mitigation					
	10% damped	20% damped	30% damped	40% damped	50% damped	60% damped		10% damped	20% damped	30% damped	40% damped	50% damped	60% damped
0.3	3.48	4.00	4.60	5.04	5.64	6.04	0.3	0.87	1	1.15	1.26	1.41	1.51
0.4	4.68	5.32	6.04	6.80	7.52	8.32	0.4	1.17	1.33	1.51	1.7	1.88	2.08
0.5	5.88	6.80	7.72	8.64	9.72	10.68	0.5	1.47	1.7	1.93	2.16	2.43	2.67
0.6	7.16	8.28	9.36	10.64	11.96	14.64	0.6	1.79	2.07	2.34	2.66	2.99	3.66
0.7	8.44	9.72	11.20	12.68	14.52	16.36	0.7	2.11	2.43	2.8	3.17	3.63	4.09
0.8	9.80	11.40	13.24	15.08	17.48	20.40	0.8	2.45	2.85	3.31	3.77	4.37	5.1
0.9	11.20	13.24	15.48	18.04	21.52	26.32	0.9	2.8	3.31	3.87	4.51	5.38	6.58
1	12.68	15.28	18.20	23.08	28.16	38.84	1	3.17	3.82	4.55	5.77	7.04	9.71

Tabulated values on the right in Table E1 for the 0.10 sec shock pulse duration indicate shock input reductions from 10 percent to 70 percent (i.e., mitigation ratios from 0.9 to 0.3) can be achieved with mount system frequencies from roughly 1 Hz to 7 Hz depending upon mount damping characteristics.

The challenge for designing practical high-speed craft isolation systems is providing sufficient excursion space to avoid mount bottoming and equipment impacts with contiguous structure or people. As a general guide, wire rope (i.e., cable) mounts typically result in pulse-period mismatch and should not be used for wave slam protection when natural frequencies are in the 5 Hz to 20 Hz range. Leaf spring mounts in the range of 4 Hz to 7 Hz are available commercially. Pneumatic solutions can provide isolation systems with frequencies less than 3 Hz, but these tend to require very large relative displacement excursion envelopes. These frequency ranges can be compared with values tabulated on the right in Table E1 as a first step in evaluating the practicality and effectivness of isolation mounts for wave slam protection.

The only way to avoid dynamic amplification (i.e., pulse-period mismatch) for typical wave impact shock pulses in small high-speed craft is to design a shock mount system that has a natural frequency less than approximately 5 Hz (and high damping properties). Low frequency means large excursion allowances (i.e., large relative displacements) and high damping may require large mechanisms for absorbing energy, both of which lead to very difficult isolation solutions for most electronics equipment in small craft. Equipment shock isolation can be pursued for very sensitive electronics or expensive hardware, but effective solutions will likely only be achieved by experienced shock isolation designers who pursue unique isolation strategies (e.g., seismic-mass dampers, pneumatic or hydraulic isolation systems) in multiple degrees of freedom. The risk of equipment malfunction or failure due to wave impacts should therefore be mitigated for the majority of equipment installations in small high-speed planing craft by equipment hardening. Individual components or racks of hard mounted equipment should be subjected to standardized laboratory shock machine tests as described herein to demonstrate wave impact ruggedness.

Alternative test methods can be used to test shock mounted equipment. For example, laboratory drop testing can be used to achieve long duration pulses to simulate long duration wave impacts. This approach usually requires special test apparatus were an impact medium such as sand is used to create a long duration shock pulse with a half-sine shape [E1]. Figure E5 shows a drop test platform with a wedge foundation that produces a nominal 100 msec half-sine pulse by impacting sand [E2]. It was used to evaluate the mitigation performance of shock isolation seats. Table E2 lists standardized laboratory drop tests developed to demonstrate the effectiveness of shock isolation seats for military and non-military high-speed craft [E3].

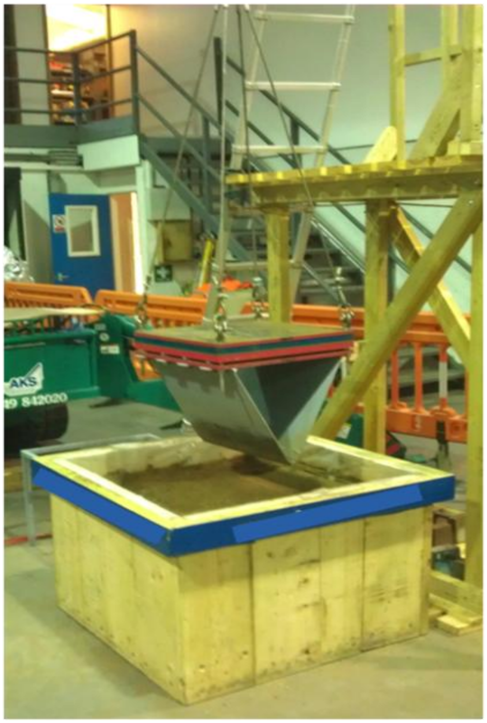


Figure E5. Drop Test Apparatus for Long Duration Shock Pulse[11]

---

[11] United Kingdom Crown copyright photograph with permission

Table E2. Half-sine Pulse Shapes for Shock Isolation Seat Tests

Test Severity						Craft Class				
Threshold Level	Peak Acceleration		Nominal Impact Duration	Nominal Drop Height		Class 4			Class 3	Class 2
	m/sec/sec	g	sec	m	ft	Military 4-3	Military 4-2	Military 4-1	Search and Rescue	High Speed Commercial or Leisure
6	100	10.19	0.10	2.07	6.78	▨	No	No	No	No
5	80	8.15	0.10	1.32	4.34	▨	▨	No	No	No
4	60	6.12	0.10	0.74	2.44	▨	▨	▨	▨	No
3	50	5.09	0.10	0.51	1.69	▨	▨	▨	▨	▨
2	40	4.08	0.10	0.33	1.08	▨	▨	▨	▨	▨
1	30	3.05	0.10	0.18	0.61	▨	▨	▨	▨	▨

The shaded boxes in Table E2 indicate the series of drop tests to be performed for seats installed in each class of craft. These drop test pulses are also applicable for testing equipment installed in craft either on shock isolation mounts or hard mounted. The different classes correspond to different craft missions, sizes, and operating environments.

Comparison of DSRS for shock isolation seat drop test data (i.e., 100 msec pulses) with the DSRS for the 23 msec pulses of the shock test machine at 10g, 15 g, and 20 g yields the following results for military classes 4-1, 4-2, and 4-3. When the 6 g – 100 msec drop test pulse is used to test shock mounted equipment, this severity corresponds to a 10 g – 23 msec machine test pulse with a test machine margin (TMM) > 1.5 for hard mounted equipment. The 8 g – 100 msec drop test pulse corresponds to a 15 g – 23 msec machine test pulse with TMM > 1.5. The 10 g – 100 msec drop test pulse corresponds to a 20 g – 23 msec machine test pulse with TMM > 1.5.

Appendix E References

E1. Military Test Procedure 5-2-506, *Shock Test Procedures*, U.S. Army Test and Evaluation Command, White Sands Missile Range, New Mexico, December 1966.

E2. T E Coe, T.E., Dyne, S., Smith, J.N., Gunston, T., Taylor, P., Rees, T., Charboneau, D., Coats, T., Riley, M., Gannon, L., Sheppard, P., Hamill, M., *Development of an International Standard for Comparing Shock Mitigating Boat Seat Performance*, Royal Institute of Naval Architects, Innovation in Small Craft Technology, London, UK, 13-14 April 2016.

E3. Riley, Michael R., Ganey, Dr. H. Neil., Haupt, Kelly, Coats, Dr. Timothy W., “Laboratory Test Requirements for Marine Shock Isolation Seats”, Naval Surface Warfare Center Carderock Division Report NSWCCD-80-TR-2015/010, May 2015.

DISTRIBUTION

	Hard Copies	*Digital Copies*
Commander U. S. Special Operations Command 7701 Tampa Point Boulevard MacDill Air Force Base, FL 33621-5323, Attn: CDR Brian O'Lavin, B. Kennedy SOF AT&L		2
Commander Naval Special Warfare Group 4 2220 Schofield Road Virginia Beach, VA 23459 Attn: Code N8, Code N81		2
Commander Naval Special Warfare Dev Group 1639 Regulus Avenue Virginia Beach, VA 23461-2299 Attn: Code N54-4		1
Naval Sea Systems Command PEO Ships, PMS 325G 1333 Isaac Hull Avenue SE Building 197 Washington Navy Yard, DC 20376 Attn: Jon Thomas, C. Rozicer		2
Naval Sea Systems Command TWH Small Boats and Craft 2600 Tarawa Court, Suite 303 Virginia Beach, VA 23459 Attn: Mr. Dean Schleicher		1
United States Coast Guard Surface Forces Logistic Center 2401 Hawkins Point Road Baltimore, MD 21226 Attn: Lew Thomas SFLC-ESD-NAME-NAV ARCH		1
Defense Technical Information Center 8725 John J. Kingman Road Fort Belvoir, VA 22060-6218		

NSWC, CARDEROCK DIVISION INTERNAL DISTRIBUTION

Code	Name	*Hard Copies*	*Digital Copies*
661	Rhonda Ingler		1
801	Joseph Gorski		1
809	D. Intolubbe	1	1
830	Technical Data Repository		1
831	Willard Sokol, III		1
832	Scott Petersen		1
832	Larry Michelon		1
833	Kent Beachy		1
835	David Pogorzelski		1
835	Heidi Murphy		1
830X	Dr. Timothy Coats		1
1033	TIC SCRIBE		1

NAVSEA
WARFARE CENTERS
Carderock