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AN INVESTIGATION OF WAVE IMPACT DURATION IN HIGH-SPEED PLANING CRAFT IN ROUGH WATER

by

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Administrative Information

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Summary

This report summarizes the investigation of wave impact duration. Example data plots are presented that show that impact durations vary from 100 milliseconds to 450 milliseconds for craft that weigh from 14,000 pounds to 105,000 pounds and have deep-V hulls with deadrise from 18 degrees to 22 degrees. Simple theoretical calculations are presented to show why impact duration is critical to understanding the effects of impact loads on physical systems.

Introduction

Background

The effects of wave slam have been a primary concern for high-speed planing craft because of the obvious pressure loads on the hull structure as well as the possible deleterious effects of impact motions on equipment and people. The parameter most often recorded during full-scale and model scale investigations to study wave impacts is the acceleration response of the craft over a given period of time. Figure 1 shows an example of the vertical acceleration response at the coxswain station in an 82-foot planing hull traveling at an average speed of approximately 35 knots in rough seas. For all data shown in this report the sampling frequency was 512 samples per second.

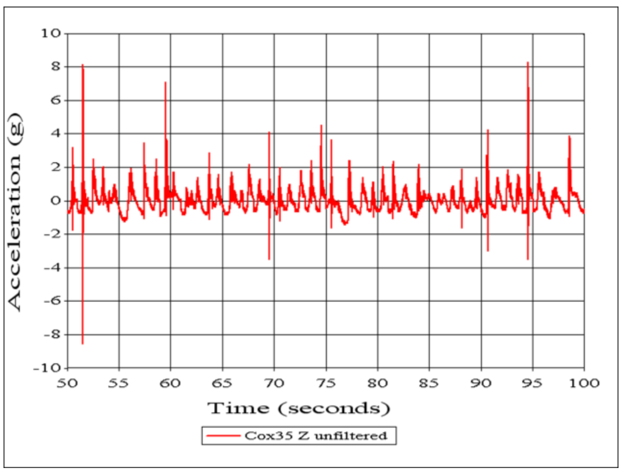

Figure 1. Example of Unfiltered Vertical Acceleration Record

In Figure 1 each wave encounter is seen as an acceleration spike followed by more smooth positive and negative acceleration curves until the next wave impact occurs. The parameter of primary interest for investigating the effects of the acceleration spike has been the peak vertical acceleration, and in several references published from1973 to 2001 the impulsive nature of individual wave slam events has been characterized by citing the duration time of individual wave impacts. Durations from 2 ms to 200 ms were reported with typical values cited as 30-ms to 75-ms [1 to 5]. While short duration pulses from 2 to 50 ms may be physically possible for small flat-bottom vessels, this report will show that a more definitive range of impact durations exist for deep-V planing hulls (nominally less than 100 feet in length) with deadrise on the order of 18 degrees to 22 degrees.

Purpose

The purpose of this report is to summarize recent wave impact data that clarifies the typical range of impact duration values for high-speed planing craft (i.e., with deep-V hulls), and to explain why the magnitude of the impact duration is important for evaluating the effects of impacts on physical systems.

Scope

The illustrated examples in this report are based on studies of acceleration data recorded during seakeeping trials of manned and unmanned high-speed planing craft in moderate and rough seas [6]. The craft in the database weighed approximately 14,000 pounds to 105,000 pounds and had lengths that varied from approximately 33 feet to 82 feet. The deadrise of the craft varied from 18 degrees to 22 degrees. The craft were operating at various planing speeds in seas with significant wave heights that ranged from approximately 1.9 feet to 6.5 feet.

Terminology

Modal Decomposition

The mathematical separation of a recorded transient response into its different relevant modes of response is referred to as modal decomposition. The modes of response typically recorded in small craft acceleration data are the rigid body modes and the vibration modes.

Rigid Body Motions

Rigid body motions of a craft are its absolute translations (heave, surge, and sway) and rotations (pitch, roll, and yaw) in a seaway. It is also referred to as solid body motion or global motion in some fields of study. In the context of this report, the rigid body vertical acceleration of a craft is its heave acceleration at a cross section.

Shock

The term shock is used to imply an impulsive load in a manned or unmanned physical system (i.e., as opposed to electrical shock or chemical shock) that is characterized by suddenness and severity of effects on physical systems [7].

Velocity Change

Velocity change refers to the sudden change in rigid body vertical velocity (V_v) at a cross section caused by a wave impact. It may be used synonymously with impact velocity. For example, in a free fall impact, the maximum velocity at the time of impact becomes zero velocity in a very short period of time. The sudden change in velocity of the falling object due to the impact is therefore equal to the absolute value of the impact velocity just prior to impact.

Vertical Direction

Deck mounted accelerometers installed in full-scale trials are typically oriented so that the vertical direction of the gage is oriented normal to the deck. As shown in Figure 2, the vertical direction of the accelerometer may therefore be oriented at some angle (theta) relative to the horizon during impacts. In this report vertical means normal to a flat deck.

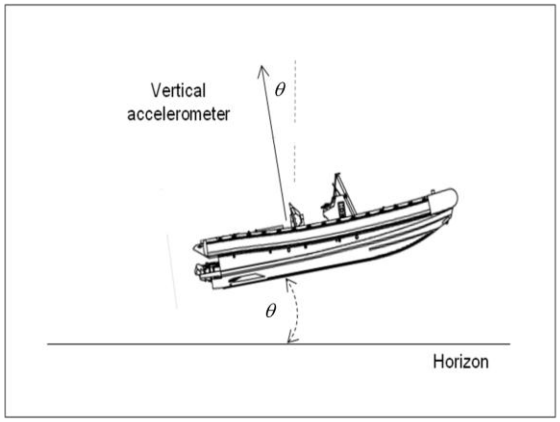

Figure 2. Orientation of Vertical Accelerometer

Vibration Motion

Vibrations in planing craft are local flexural motions of structural elements (e.g., stiffeners, deck plates, etc.) caused by operating machinery and wave impacts. Small amplitude sustained vibrations that vary with location are caused by operating machinery and hull-water interactions. Potentially larger amplitude transient vibrations that vary with location are caused by wave impacts.

Wave Slam

A wave slam is a violent impact between a craft and an incident wave. A wave impact is typically considered a more general term that may infer both low severity and high severity wave encounters. Impact severity depends upon the amplitude and the duration of the sudden change in rigid body acceleration. A wave slam subjects a craft, installed equipment items, and passengers and crew to rapid changes in rigid body acceleration and rapid changes in velocity during the wave impact period (i.e., time of impact duration).

Wave Impact Duration

Sequence of Events

Figure 3 shows the typical sequence of events for wave impacts in head seas with peak acceleration amplitudes greater than 2 g [6]. The upper plot is the recorded vertical acceleration time history (unfiltered) that illustrates how the acceleration response varies prior to, during, and after a single wave impact. The wave impact period is observed as the rapid rise to a peak value followed by decay to an ambient value.

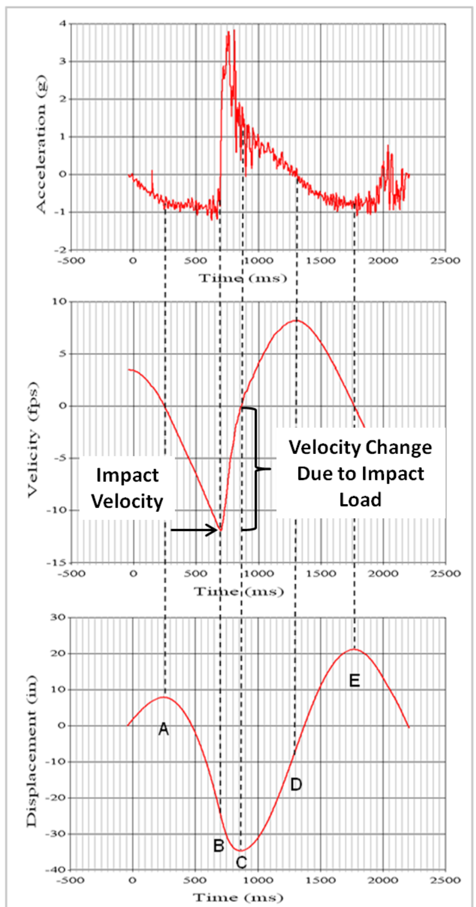

Figure 3. Wave Impact Duration from Point B to Point C

The middle plot in Figure 3 is the velocity time history obtained by integrating the acceleration record [8], and the lower plot is the absolute displacement motion (i.e., vertical heave) at the gage location. The important part of this sequence of events is the impact period from time B to time C. At time B the hull impacts the water. At time C the craft has reached its deepest plunge into the water and the impact is complete. From time B to time C the vertical velocity at the gage location changes from the largest downward velocity (i.e., the velocity just prior to impact) to zero velocity. This is the period of time when the vertical forces caused by the hull-water impact occur. The upper plot shows that the summation of impact forces in the vertical direction (i.e., the impact pressure load) causes a vertical change in the acceleration time history at the gage location that appears similar to a half-sine pulse for dominant wave impacts. The rigid body component of this portion of the acceleration signal, the duration of the impact (i.e., the duration time of the acceleration pulse), and the positive change in velocity from the negative peak (i.e., velocity minimum) back up to zero velocity are the key parameters that characterize the severity of the impulsive load of the wave impact.

For the purposes of this report the duration time of the wave impact (T) is the approximate period of time from the time of first impact (i.e., time B, easily seen in the acceleration and velocity plots) to the time when the instantaneous velocity is zero at time C. The estimated time from point B to point C in Figure 3 is 160 ms. Determining the time at which the instantaneous velocity is zero is more challenging because of signal processing steps (e.g., high-pass filtering) required before integrating the acceleration record. Appendix A summarizes lessons learned from integrating acceleration records.

Another approach to estimating the duration time is to use the rigid body acceleration plot to identify the transition point in time (i.e., point C) between the impact period and the subsequent period dominated by hydrodynamic lift and buoyancy forces. This is illustrated in Figure 4. In the figure the red curve is the vertical rigid body acceleration created by applying a 10 Hz low-pass filter to the original unfiltered record.

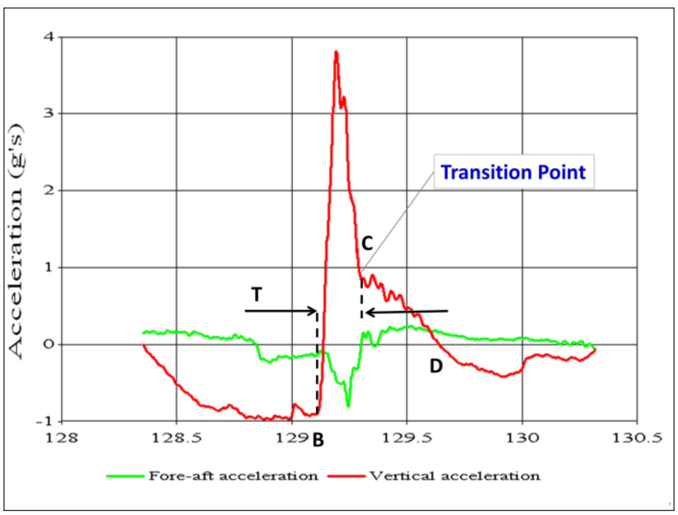

Figure 4. Impact Duration Time Based on Transition Point

The green curve is the 10 Hz filtered fore-aft acceleration at the gage location. Moving backward in time from point D (zero crossing point in red curve), the somewhat rounded shape of the vertical acceleration profile with amplitude less than 1 g is characteristic of the hydrodynamic lift and buoyancy phase of response. The end of the impact period (i.e., the rapid drop in acceleration) intersects the hydrodynamic lift and buoyancy phase at point C. The fore-aft acceleration curve is also helpful for locating the end of the impact period at time C. In the rigid body acceleration plot (i.e., the red curve) the duration of the impact (τ) is estimated between time B and time C to be 180 ms.

Data Base Summary

Figure 5 is a plot of wave impact duration versus peak acceleration (i.e., rigid body) for individual wave impacts recorded at the longitudinal center of gravity (LCG) in 13 different craft during head-sea trials in rough water. The green squares in the figure correspond to six craft that weighed from 22,000 pounds to 38,000 pounds, and the blue circles correspond to six craft that weighed from 14,000 pounds to 18,000 pounds. The red triangles were recorded on a craft that displaced about 105,000 pounds. The data set for the 22,000 pound to 38,000 pound craft has more data points because more time was spent analyzing some of the lower amplitude impacts in the 0.5 g to 2.0 g range. These trials were conducted between 1996 and 2013, but all the raw data was processed between 2012 and 2014 using the same standardized data processing and data analysis methods [6, 8]. The peak acceleration is the rigid body peak acceleration estimated using a 10 Hz low-pass filter on the original unfiltered data.

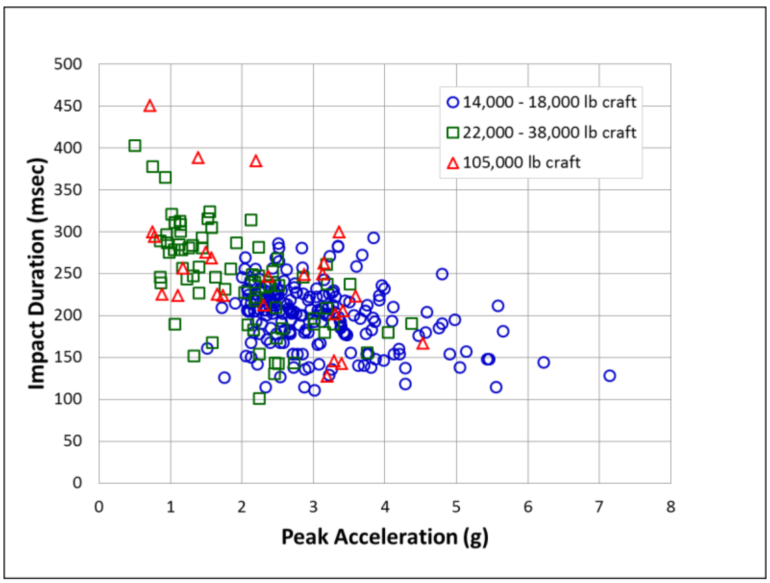

Figure 5. Full-Scale Data Impact Duration versus Peak Acceleration

The data indicates that the shortest impact durations regardless of impact severity for these craft are on the order of 100 ms, and the longest durations decrease from about 450 ms to 150 ms 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).

Evolution of the Data Acquisition System

Background

Man’s desire to describe the physical world is nothing new. For centuries, the scientific method has been employed to support theories about physical phenomena. The scientific method is a five-step process that includes 1) formulating a question, 2) presenting hypotheses, 3) predicting outcomes, 4) testing, and 5) analysis. Typically, for boat design, the first three steps fall under the domain of the naval architect during the design process, whereas testing and analysis generally are conducted by others. The focus of this report is on testing and analysis.

For the purposes of this report, data acquisition system, data recording system, and data collection system are all considered synonymous. In general, a data acquisition system consists of a sensor (or sensors), signal conditioning, signal processing/conversion, data storage, and display. Such a system can be as simple as an engineer using a stopwatch (sensor) to measure the time it takes a boat to traverse a measured course, calculating its average speed (signal processing), and then writing down the result using a grease pencil on a clipboard (data storage and display).

Today’s digital data acquisition systems are obviously much more complex than that, incorporating highly sensitive micro-machined accelerometers, pressure transducers, and temperature sensors, among myriad others; analog-to-digital conversion schemes that include anti-alias filters, multiplexers, sample-and-hold circuits, sophisticated microprocessors, and terabytes of data memory; data processing algorithms that allow for the nearly instantaneous calculation of time and frequency domain statistics; and high-resolution displays that can be customized for nearly any process.

A discussion of measurement objectives, early data acquisition systems, and current state-of-the-art data acquisition systems follows.

Measurement Objectives

The goal of the full-scale testing is to acquire performance data that can be used by the naval architect to validate and improve craft design. Typically, craft motions, collected in the form of vertical accelerations during trials in rough water, have been used to characterize structural loading and slamming effects on equipment and personnel. Ultimately, the designer would prefer pressure data rather than accelerations, but problems inherent with pressure measurements on marine craft make these measurements impractical.

Fortunately, the effects of dynamic accelerations on the craft hull are well understood and can be effectively applied in craft design. It is apparent that the acceleration factors used in craft design for nearly a century have been adequate, since there have been no widespread reporting of structural failures due to excessive loads within design operating envelopes.

Early Data Acquisition Systems

For nearly half a century, the Combatant Craft Division (CCD) has been characterizing high-speed craft performance in a seakeeping environment. Initially, craft motions data acquisition took the form of 120 Vac reel-to-reel magnetic tape recorders and servo-type accelerometers. Data analysis was performed using hardware FFT analyzers, which eventually gave way to the earliest digital computers. Sea state information was written to paper strip chart recorders. Sea state analysis was a manual effort which was performed on the lab floor with the chart paper spread out to its entire length while peaks and troughs were marked by hand with a pen.

The reel-to-reel tape recorder was eventually replaced with battery powered seven-channel cassette analog magnetic tape recorders with a frequency bandwidth of dc to 1.25 kHz per channel. VHS magnetic tape recorders that provided up to 14 analog channels with a total bandwidth of up to 50 kHz were the next generation of data recording devices. By this time, servo accelerometers had been replaced by piezoresistive types that were smaller and less expensive, but provided the requisite sensitivity and frequency bandwidth. Data analysis was being performed on a first generation PDP-8 micro-computer with 128k of solid-state memory.

The first entry into the digital domain was with a 16-channel digital cassette data recorder that suffered from extreme sensitivity to humidity. These devices were easy enough to use, but were temperamental, and more than once a full day's worth of data was lost due to some sort of malfunction. Figure 6 provides an illustration of the magnetic tape recorders used. Clockwise from left the picture shows a 16-channel digital cassette, a 14-channel VHS, a 4-channel data cassette, and a 7-channel data cassette.

Figure 6. Examples of Magnetic Tape Data Recorders

By the early 1990's computer-based digital data acquisition was introduced to the marketplace. The early digital data acquisition systems were assembled on printed circuit boards that were connected to a personal computer's ISA or PCI slot. The data acquisition process was governed by software written in BASIC, C, and Fortran among other common computer languages. These systems were not well suited to a field environment, particularly one where high levels of mechanical shock and sea water were present. Around the same time, CCD bought its first self-contained digital data logger. The Instrumented Sensor Technology (IST) EDR-2 included a tri-axial accelerometer, signal conditioning, a 10 bit digital-to-analog converter (DAC), microprocessor, and 1 mega-byte (MB) of memory all contained in a rugged, environmentally sealed, portable unit. Custom software written exclusively for the EDR-2 allowed the user to define recording control parameters and analyze the data. By the mid 1990’s, IST’s next generation of environmental data logger, the EDR-3 was being used to collect craft motions data. IST’s EDR-6DOF MotionMaster® (Figure 7), which was released in the early 2000’s, incorporated 4 MB of memory and an angular rate sensor, allowing measurements in six degree of freedom.

Figure 7. IST EDR-6DOF MotionMaster® Self-contained Data Acquisition System

Improvements in the hardware and software of the EDR-3 allowed for more flexibility in data collection. However, its memory limited total data acquisition time, requiring creativity on the part of the test engineer. To maximize recording time, instead of allowing the EDR to run continuously, it was programmed to collect accelerations data based on pre-defined trigger thresholds. For most of the earlier test efforts, the EDR was programmed to acquire 1-second data events when a trigger threshold of 0.5 g for 50 ms or longer was exceeded. While many of these events were contiguous over the course of a test, occurring one immediately after another, occasionally, there were delays between these events.

Software for conducting statistical analyses on the accelerations data, previously developed for the PDP-8 and subsequent Honeyewell HTMS micro-computers, had not been adapted for the personal computer (PC); nonetheless, analysis was conducted on the one-second data events using IST’s Dynamax software in a philosophy similar to that used on these early computers, and what is currently employed in *StandardG*. All of the one-second data events were sorted from largest to smallest and the averages of the top 1/3rd, 1/10th, and 1/100th peak accelerations were computed.

Problems have arisen when trying to compare the results of data sets collected at different times without the full understanding of the data acquisition or analysis processes. For example, some of the data initially collected with IST hardware was analyzed using Dynamax software over its full data bandwidth of dc to 200 Hz. Recognizing that post-process filtering had an effect on the data statistics, early data sets were not filtered. Low-pass filtering accelerations data at a rate meaningful to characterize craft motions affect not only data peaks, but also pulse durations.

It turns out that data analyzed over the full acquisition bandwidth of 200 Hz, provided an interpretation of not only whole-body motions, but also of the flexural or vibration components of the signal. Because this raw, unfiltered data signal contained higher frequency content, it could easily be misinterpreted during the analysis process.

While it may be intuitive that low-pass filtering will reduce acceleration peaks, it may not be obvious that it also affects interpretation of pulse durations. Although current methods calculate pulse duration based on an understanding of hydrodynamics, Dynamax software calculated the same parameter as the time between the points on the acceleration waveform that is 10 percent of the peak value, immediately before and after the peak value. An example of such a misrepresentation is illustrated in Figure 8, where an unfiltered event is compared with the same event low-pass filtered during post-processing. Here, a peak acceleration of 4.71 g and corresponding duration of 75 ms is identified for the unfiltered data, while a peak acceleration of 2.51 g with duration of 235 ms is identified for data low-pass filtered at 10 Hz.

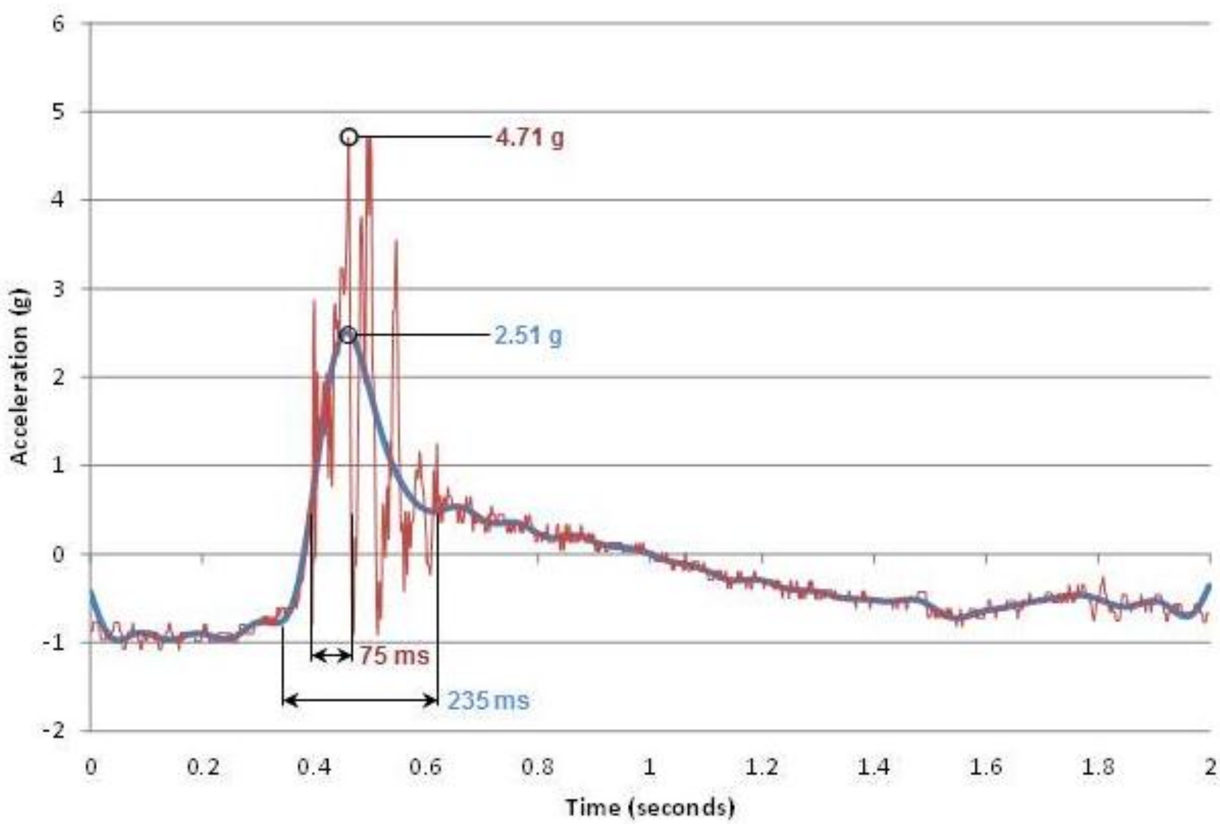

Figure 8. Misrepresentation of Impact Duration

Advances in Technology

As digital signal processing technology advances, so does the ability to collect more data at faster rates over longer periods of time. Whereas the IST recorder afforded 10 bits of digital resolution, the next generation data acquisition system performed the analog-to-digital conversion with a resolution of 16 bits. This means that a signal representing 50 g full-scale can be resolved to more than 65,000 parts (or approximately 0.0008 g) with a 16 bit analog-to-digital (A/D) converter as compared with just a little more than 1,000 parts (roughly 0.05 g) for a 10 bit A/D converter. The system currently used by CCD for its measurements employs 24 bit A/D converters (resolution of 16,777,216 parts).

Newer data acquisition systems take advantage of high capacity, inexpensive, solid-state memory. Typical systems today store data on 4 GB flash drives which allow higher sampling rates and longer data acquisition periods. Compared with 4 MB of memory on IST's EDR-6DOF, current data memory permits thousands of times more data to be collected, which translates into days, rather than minutes, of recording time.

At the same time, data acquisition hardware is becoming smaller, lighter, less expensive, and more capable of withstanding the rigors of the rough-water environment. CCD's CObIA system shown in Figure 9, based on National Instruments Compact RIO, has proven itself suitable for seakeeping measurements in even the most extreme conditions.

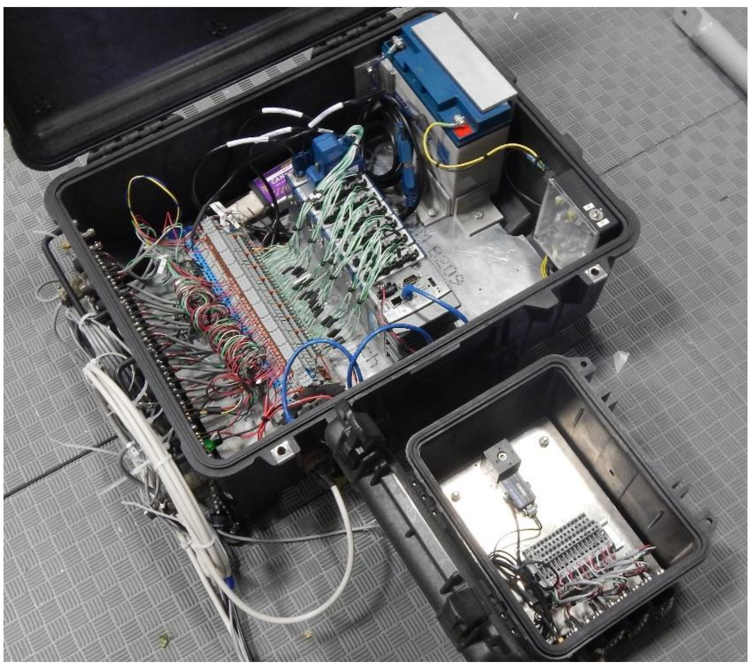

Figure 9. CCD's CObIA cRIO Data Acquisition System

Personal computers have also improved, allowing engineers to take advantage of general purpose software to develop specialized programs for analyzing seakeeping data. DADiSP™, is an example of an interactive graphics software program that allows for the importing, display, and analysis of scientific and technical data. CCD's *StandardG* has been developed to run in DADiSP™, LabVIEW, and MATLAB® programming environments. Further, free software like UERDTools [9] is frequently used to analyze seakeeping data and gain further insight into the physics of wave slam.

MK V Special Operations Craft Data

Historical Review

Figure 10 shows a figure originally published in an earlier document that reported wave impact durations for a naval craft were typically from 30 ms to 75 ms [4]. These numbers were obtained from data recorded in 1996[1] and 1997[2] on the Mark V Special Operations Craft (SOC). The shape of the wave form is consistent with a physical description of the high-severity wave impact followed by a hydrodynamic lift and buoyancy phase before the acceleration returns to zero. But the reported typical impact duration from 30 ms to 75 ms is significantly less than expected values from 100 ms to 450 ms as shown in Figure 5. The reason for the very low 30 to 75 ms misunderstanding is related to the type of data recorder used and to the automated processing and use of unfiltered data to extract impact durations. This will be explained in the next section.

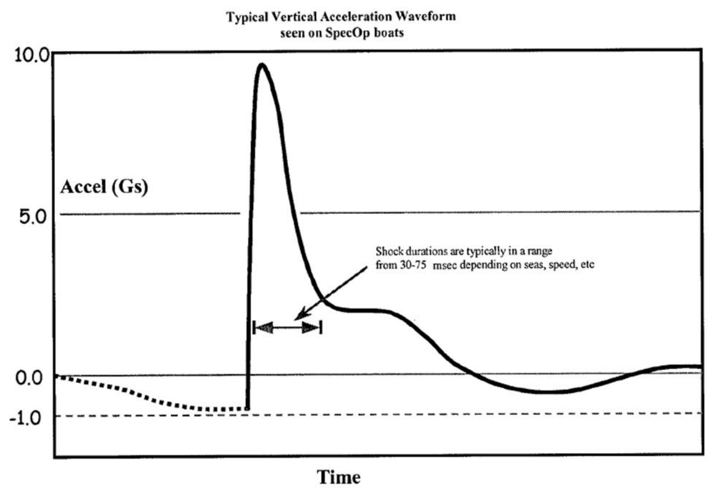

Figure 10. Acceleration Waveform Published in Historical Reference

MK V SOC Data Revisited

MK V Data circa 1996-2000

In 1996 and 1997 accelerometers were installed in two MK V Special Operations Craft to monitor motions while the craft were underway at high speeds in rough seas. The measurement

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[1] CRDKNSWC-TM-20-96-42, October 1996.
[2] CRDKNSWC-TM-20-97-39, October 1997.

and data recording system included use of a 200 Hz anti-alias filter and a sampling rate of 512 samples per second. In 2000 the recorded acceleration data was shared with other government, industry, and academic participants interested in developing improved shock isolation systems. Figure 11 shows a sample of the acceleration plotting capability at that time[3], and Table 1 shows one of the 18 tables of data that were shared [4]. Peak accelerations in the table were from unfiltered data and the shock pulse duration was extracted by the recording system using an automated algorithm.

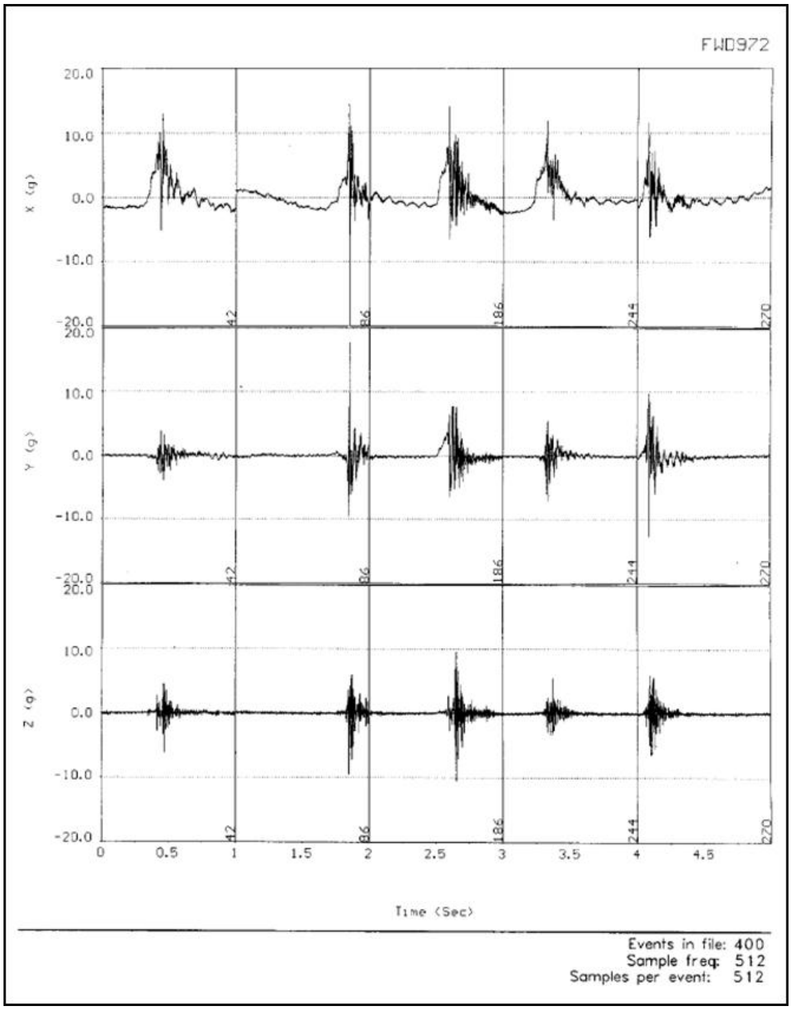

Figure 11. Example Vertical (X), Transverse (Y), and Longitudinal (Z) Acceleration Plots

[3] CRDKNSWC-TM-20-97-39, October 1997

Table 1. Example Summary Data Table

MkV SOC Craft Motion (Coxswain station in 2.5-3 ft seas @ 35 knots)						
	Peak Accelerations			Shock Pulse Duration		
	Longitudinal (g's)	Lateral (g's)	Vertical (g's)	Longitudinal (sec)	Lateral (sec)	Vertical (sec)
Max	10.4	2.84	7.13	0.037	0.201	0.346
Min	0.22	0.17	0.36	0.004	0.002	0.002
Avg	1.43	0.86	2.99	0.012	0.018	0.033
1/3	2.31	1.32	4.82	0.016	0.034	0.087
1/10	3.40	1.87	5.83	0.021	0.055	0.180

The original peak acceleration and shock pulse duration values were primarily reported based on averages as well as the maximum and minimum values. For example, in Table 1 the maximum pulse duration from the vertical acceleration data on the deck below the coxswain's seat was 346 ms, the minimum value was 2 ms, the average of the largest 1/3rd of all values was 87 ms, and the average of the largest 1/10th of all values was 180 ms. The automated algorithm that extracted the shock pulse duration was based on the time between the points on the acceleration waveform that are 10-percent of the peak value immediately before and after the peak value. This method is a common approach to determining pulse duration in data processing algorithms that avoids zero crossing uncertainties in unfiltered data [10]. The 180 ms average (1/10th highest) and the 346 ms maximum value are within the range of values observed in Figure 5, but the 2-ms minimum value and the 33-ms average value are misrepresentations as shown in Figure 8.

The original shock pulse duration values for the unfiltered acceleration data in all of the original eighteen tables of data are listed in Table 2. The data corresponds to different locations on each craft and different headings, including head sea runs, bow-quartering, beam, and following sea runs. The values with an asterisk were recorded at the bow. Most of the average values are greater than 100 ms, but even an average of 100 ms out of four hundred pulses means that many of the individual pulse durations were less than 100 ms. It was originally not clear why the earlier interpretations of the data concluded that the typical wave slam duration was 30 to 75 ms. The next section addresses this disparity and summarizes a re-assessment of the 1996 and 1997 MK V SOC data, especially the shock pulse durations.

Table 2. Tabulated Average Vertical Shock Pulse Durations (circa 1996 – 1997)

Shock Pulse Duration (msec)			
Average	1/10th Highest	Average	1/10th Highest
14 *	50*	102	263
14 *	41*	181	327
15 *	55*	112	281
139	289	189	319
33	180	137	300
87	239	104	227
113	261	113	241
35	117	48	145
100	261	90	224

MK V Data Analysis Circa 2014

The following re-analysis of the 1996 data uses modern digital data analysis hardware and software not available in 1996 to 2000, and it applies new methods and criteria for interpreting motions within the unfiltered acceleration data [6, 11]. The analysis approach included the concepts of response mode decomposition to separate the rigid body acceleration mode and the vibration modes of response from the unfiltered data.

Fourier spectral analysis and visual inspection of individual wave impact responses in the original time history data indicated that the dominant vibration modes in the deck structure surrounding the gage were greater than 20 Hz, so a 10 Hz low-pass filter was employed to estimate the rigid body acceleration response. The rigid body acceleration response during the impact can be used to quantify the severity of the wave impact load in terms of acceleration amplitude and pulse duration [6].

Figure 12 shows the original vertical acceleration response for four hundred 1-second intervals recorded on the deck at the base of the coxswain’s seat. The red curve is the unfiltered acceleration and the black curve is the 10 Hz low-pass filtered acceleration (i.e., the rigid body heave acceleration).

The use of modern digital processing hardware and software enables an almost effortless expansion of the time scale to better evaluate individual wave impacts. Figure 13 shows a 10-second segment taken from the record. The data clearly shows the vibration modes of response after each impact that damp out prior to the next impact.

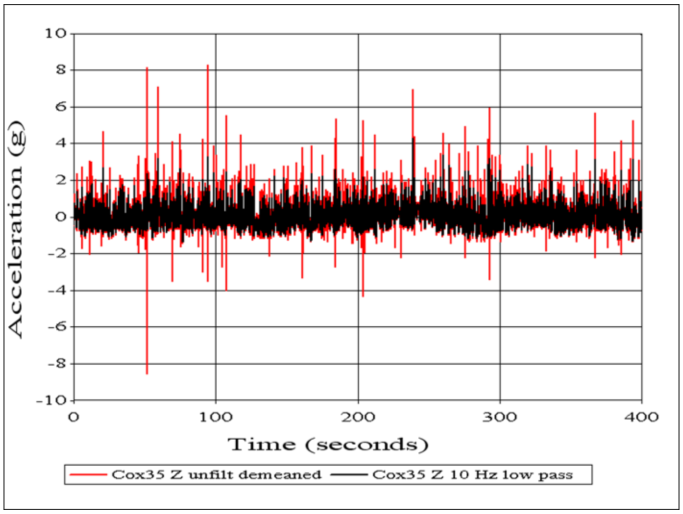

Figure 12. Vertical Deck Acceleration at Base of Coxswain Seat (circa 2014)

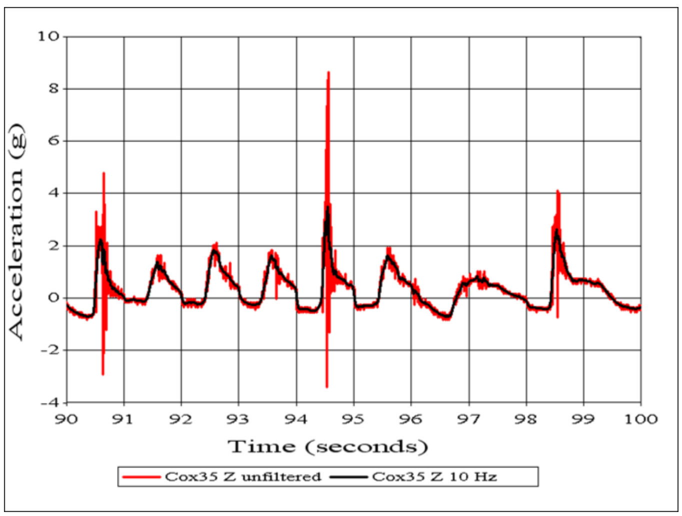

Figure 13. Expanded Time Scale to See Individual Wave Impacts

Further expansion of the time scale shown in Figure 14 illustrates one of the wave impacts with an overall waveform shape similar to the historical rendering of a typical waveform shape (i.e., shown in Figure 10). The impact causes a rapid rise to a peak rigid body acceleration of approximately 2.6 g, then it drops to a value that corresponds to a hydrodynamic lift and buoyancy phase of response (approximately 0.7 g), before dropping back to zero.

It is now understood that the amplitude and duration of the input wave slam pulse is more easily seen using the low-pass filtered acceleration shown as the black curve in Figure 14. The unfiltered red curve shows the apparent source of the very small values reported previously (i.e., listed in Table 1 and 2) that are based on using the unfiltered acceleration and the automated algorithm to capture impact durations. The high frequency vibration of the local structure in the vicinity of the gages caused zero crossings that were misrepresented by the algorithm as the wave impact pulse duration.

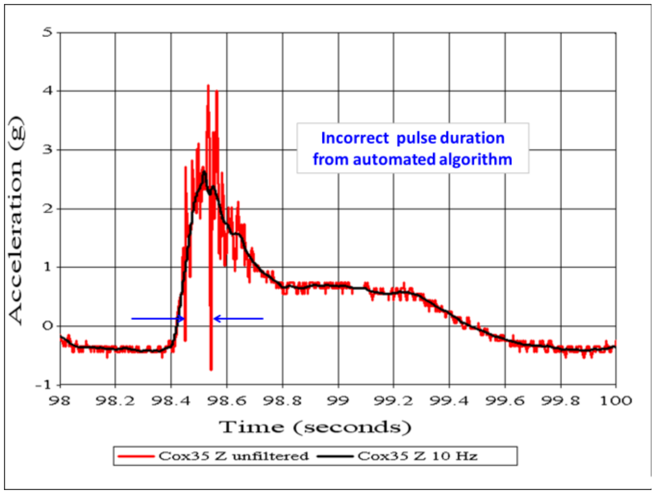

Figure 14. Incorrect Pulse Duration from Automated Algorithm on Unfiltered Data

When the physics-based sequence of impact events is evaluated with the help of the velocity record, the estimated shock pulse duration is 247 ms as shown in Figure 15.

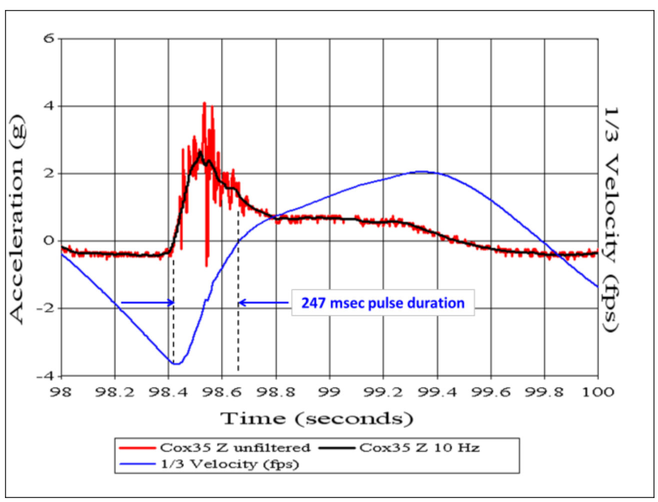

Figure 15. Actual Pulse Duration Based on Rigid Body Sequence of Events

The pulse duration in Figure 15 ends when the velocity crosses zero. This corresponds to the transition point C shown in Figure 4 between the impact phase and hydrodynamic lift phase of response. Another physical observation that helps determine the transition point in the unfiltered acceleration data is the cessation of forced transient vibrations caused by the impact.

In Figure 15 the larger amplitude deck vibrations caused by the impact damp out within one-half cycle after the craft velocity crosses zero (i.e., the deepest plunge into the water). This rapid damping after zero crossing is observed in many impact events with relatively large transient vibration content. It is harder to discern for lower severity impacts when gages are located on relatively stiff locations with small amplitude forced transient vibrations that are the same order of magnitude as motor-driven vibrations.

Re-analysis of the 1996 Mk V data shows that typical wave impacts vary from approximately 128 ms to 451 ms. Twenty-five of these durations are shown in Figure 5 as the red triangles. The largest impact durations occur for the lower amplitude peak accelerations with a trend that closely follows the trend for the lighter weight craft. The next section summarizes why the pulse duration is important when evaluating the effects of wave impacts

Effects of Impact Pulse Duration

Computational Method

A simple computational approach for investigating the effects of parametric variations in a dynamic environment is to use the single degree of freedom (SDOF) mathematical model shown in Figure 16 [7]. Although not as rigorous as a multiple degree-of-freedom finite element model calculation, its simplicity and ease of use renders it an excellent first step toward understanding the importance of pulse duration.

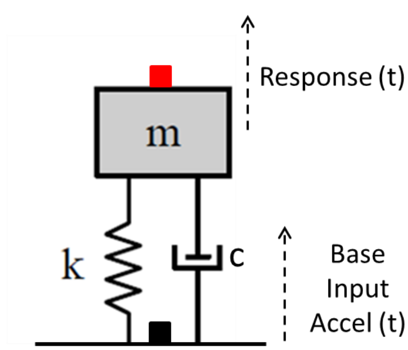

Figure 16. Single-Degree-of-Freedom Model

In the mathematical model the base represents any location in a craft where the rigid body acceleration is known. The acceleration of the base is the rigid body acceleration that drives other dominant system responses. The mass (m) represents the combined weight of the supported structural system of interest (e.g., structure, equipment, or shock mitigation seat). The spring stiffness (k) and critical damping coefficient (c) are properties of the system support elements, like supporting structure, equipment foundations or mounts, or seat spring-damper systems. The system responses can be calculated for different acceleration input pulses. The model is useful for predicting two response parameters that are relative measures of impact response severity. The first parameter is the peak acceleration of the mass (m). The second parameter is the maximum relative displacement across the spring (k). The relative displacement (i.e., between the base and the mass) is proportional to the strain in the spring. The response with the larger relative displacement (i.e., the larger strain in the spring) will correspond to greater potential for damage when comparing different base input motions.

Conceptually the use of the SDOF model to evaluate impact severity transitions the analysis to an assessment of response severity that infers the relative severity of different input pulses (regardless of peak acceleration and duration). The input that causes the most severe response is considered the most severe input (i.e., possibly for a given response frequency).

Heavily Damped Example

In Figure 17 the red curves are the computed responses of a SDOF system with a system natural frequency of 18 Hz (i.e., 55.5-ms period) and a critical damping coefficient of 20 percent. These responses are examples of a notional shock isolation system. The curves were developed using a finite difference solution to the governing partial differential equations of motion of the SDOF. The four different plots correspond to base input pulses (i.e., the black curves) with the same 7 g peak acceleration and varying durations of 10 ms, 50 ms, 100 ms, and 300 ms.

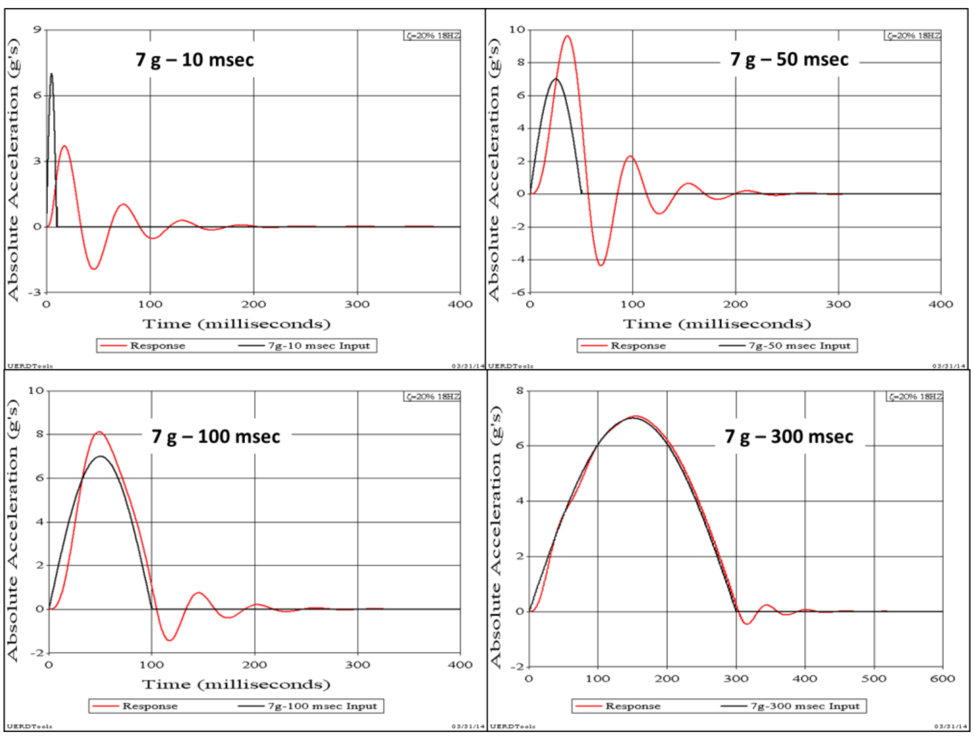

Figure 17. 18 Hz SDOF System Predicted Time History Responses

It is clear that the general shapes of the response curves are all very different. In the upper left plot the peak acceleration response of the mass (m) is about half the 7g input pulse. For the

50-ms pulse the peak response acceleration is about 9.5 g. For the 100-ms pulse the peak response is about 8 g, and for the 300-ms pulse the peak is almost identical to the 7 g input pulse. This shows that for constant input peak acceleration the peak response acceleration of the mass depends greatly upon the duration of the input pulse.

Table 3 lists the predicted response peak accelerations for the 18 Hz SDOF system for the four pulse durations shown in Figure 17 as well as six additional pulse durations. As the ratio of the pulse duration to the response period increases, the ratio of the peak acceleration response to the 7 g input acceleration increases from about 0.5 up to 1.37 and then back down to 1.0. The range of responses where this ratio is greater than unity is referred to as dynamic amplification (i.e., amplification of the base peak acceleration). This occurs when the ratio of the pulse duration to the response period is from about 0.38 to 3.7.

Table 3. 18 Hz SDOF System Responses (20% Critical Damping)

Pulse Duration	Response Period	Input Peak Acceleration	Response Peak Acceleration	Pulse Duration / Response Period	Peak Acceleration Response / Input
Tau - msec	T - msec	g	g		
10	55.556	7.0	3.69	0.180	0.527
20	55.556	7.0	6.74	0.360	0.963
21	55.556	7.0	6.97	0.378	0.996
30	55.556	7.0	8.63	0.540	1.233
40	55.556	7.0	9.43	0.720	1.347
50	55.556	7.0	9.61	0.900	1.373
100	55.556	7.0	8.12	1.800	1.160
200	55.556	7.0	7.22	3.600	1.031
250	55.556	7.0	7.03	4.500	1.004
300	55.556	7.0	7.06	5.400	1.009

Fortunately it is not necessary to generate hundreds of plots like those shown in Figure 17 to generate a plot of the peak acceleration response for systems with different natural frequencies. Computational algorithms have been developed to generate a plot of the peak response as a function of the system natural frequency. Four examples, called shock response spectra (SRS), are shown in Figure 18 [7]. Each curve shows at a glance how the peak acceleration response varies with system natural frequency. The half-sine input pulses for each of the four different curves are listed in the legend. The peak acceleration for each input was 7 g but the pulse durations varied from 10 ms to 40 ms. The 4 stars in Figure 18 are the predicted peak accelerations listed in Table 3 for these pulse durations.

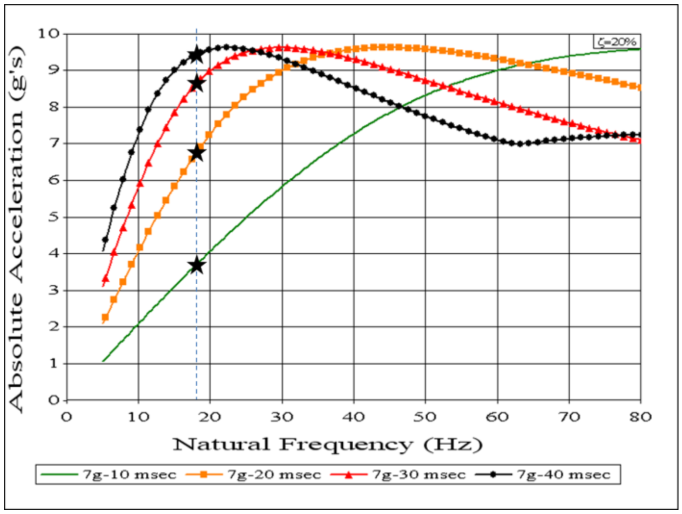

Figure 18. Peak Acceleration Response versus System Natural Frequency

Figure 19 shows the computed peak acceleration SRS for the 7g half-sine pulses (i.e., 20 percent critical damping) with longer durations of 50 ms, 100 ms, 200 ms, and 250 ms. It shows that for system natural frequencies between about 50 Hz to 80 Hz the four different pulses result in very similar peak acceleration responses (e.g., 7.0 g to 7.2 g, small dynamic amplification).

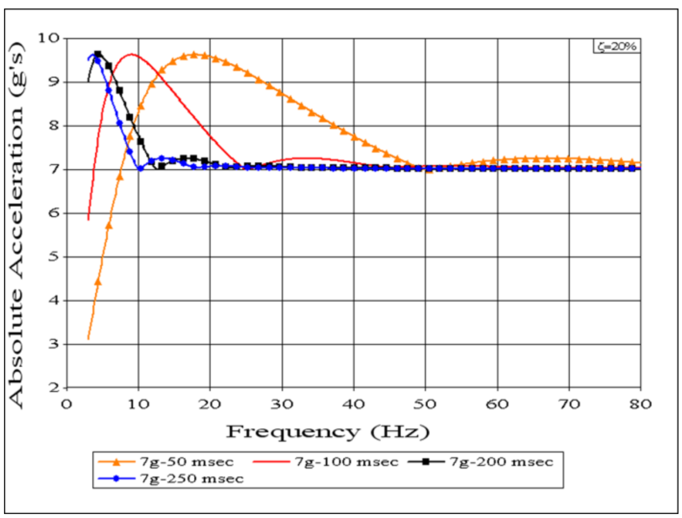

Figure 19. Acceleration SRS for Longer Duration Pulses

Figure 18 however shows that for this same range of natural frequencies (i.e., 50 Hz to 80 Hz) the 10 ms to 40 ms pulses result in peak acceleration responses that vary from about 7 g to 9.7 g. In the same plot the 8 Hz SDOF system results in peak acceleration responses less than the input 7 g value for pulse durations from 10 ms to 40 ms (i.e., the input peak acceleration is mitigated). But in Figure 19 the 8 Hz SDOF system responds to the longer duration pulses (i.e., 50 ms to 250 ms) with peak accelerations approximately equal to or greater than the 7g input (i.e., dynamic amplification). These are very different results for the different pulse duration ranges. It illustrates how shock isolation can be achieved (i.e., peak response less than peak input), but depending upon pulse duration, it is achieved only below a certain system natural frequency.

Lightly Damped Example

In Figure 20 the red curves are the computed responses of a SDOF system with a system natural frequency of 36 Hz (i.e., 27.7 ms period) and a critical damping coefficient of 5 percent. The 36 Hz natural frequency with 5 percent critical damping is representative of a notional deck plate, so the predicted responses are characteristic of deck transient vibrations induced by the rigid body half-sine pulses. The four different plots correspond to base input pulses (i.e., the black curves) with the same 7 g peak acceleration with varying durations of 10 ms, 50 ms, 100 ms, and 250 ms. Table 4 lists the predicted peak responses for this 36 Hz SDOF system and the ratio of the response and the input for pulse durations from 50 ms to 300 ms. It shows that dynamic amplification can occur as the ratio of the pulse duration to the system response period increases from 0.36 to 3.6. This is similar to the 0.38 to 3.7 range for the 20-percent critical damping example (See Table 3).

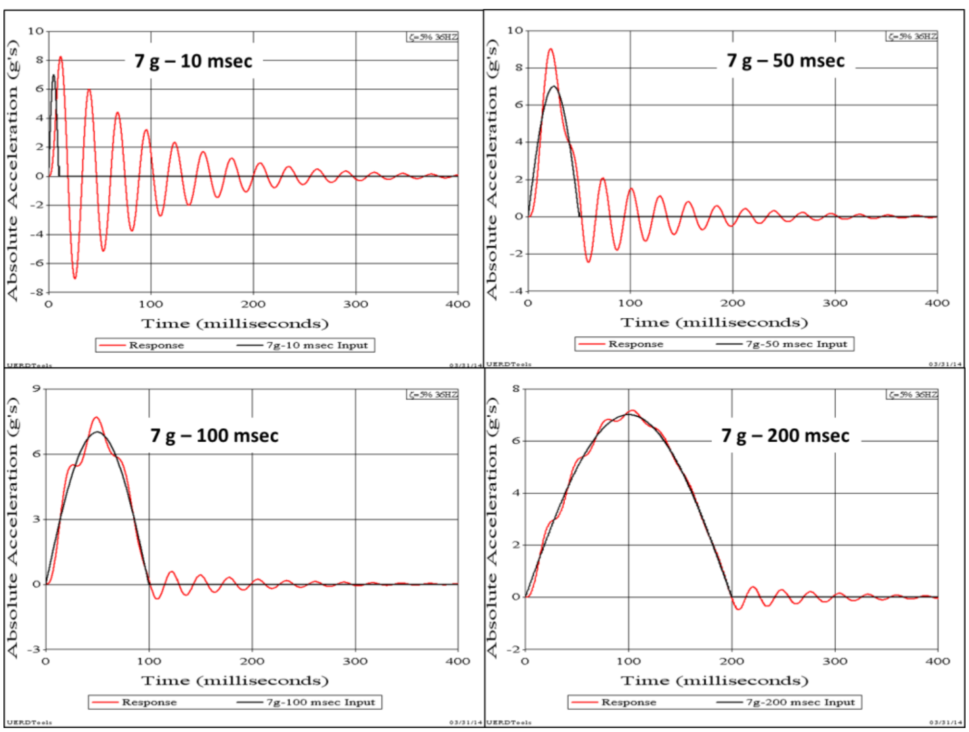

Figure 20. 36 Hz SDOF System Predicted Time History Responses

Table 4. 36 Hz SDOF System Responses (5% Critical Damping)

Pulse Duration	Response Period	Input Peak Acceleration	Response Peak Acceleration	Pulse Duration / Response Period	Peak Acceleration Response / Input
Tau - msec	T - msec	g	g		
10	27.778	7.0	8.23	0.360	1.176
20	27.778	7.0	11.42	0.720	1.631
21	27.778	7.0	11.48	0.756	1.640
30	27.778	7.0	11.16	1.080	1.594
40	27.778	7.0	10.12	1.440	1.446
50	27.778	7.0	9.03	1.800	1.290
100	27.778	7.0	7.70	3.600	1.100
200	27.778	7.0	7.17	7.200	1.024
250	27.778	7.0	7.08	9.000	1.011
300	27.778	7.0	7.04	10.800	1.006

Figure 21 shows the computed acceleration SRS for 5-percent critically damped systems. The shapes of each spectrum are very similar to those in Figures 18 and 19, but the peak acceleration responses are larger for each value of system natural frequency. These results show that pulse duration is also an important parameter for stiffer systems like deck structure. The peak acceleration response depends upon pulse duration for a given system.

Peak Acceleration versus Pulse Duration

The shock response spectra shown in the previous sections showed peak response acceleration versus system natural frequency for different pulse durations. When the peak responses are re-plotted versus pulse duration the result is shown in Figure 22. Each of the 10 curves is the peak acceleration response for different system natural frequencies from 8 Hz to 40 Hz. The 8 Hz value is representative of a flexible shock isolation mount, and the 40 Hz value is representative of a stiffer deck plate bending frequency. The input half-sine pulse has a peak acceleration of 7 g and the duration of the pulse is on the curve abscissa from 10 ms to 350 ms. The critical damping coefficient of 9 percent used for these curves is characteristic of damped transient structural vibrations excited by an impact load. For higher values of critical damping the curves would have had lower acceleration amplitudes and would shift to the left. The change in velocity for four pulse duration values (i.e., 50, 100, 150, and 200 ms) is also shown to illustrate that the curves could also have been plotted as peak acceleration versus impact velocity. The curves indicate that for a 7 g half-sine pulse the peak response acceleration will be less than 7g when the duration of the pulse is from 10 ms to approximately 40 ms depending upon system natural frequency. For pulse durations greater than 100 ms the peak acceleration responses are equal to or greater than the 7 g half-sine input pulse. In each of the curves the peak response accelerations greater than 7 g correspond to the predicted ranges of dynamic amplification.

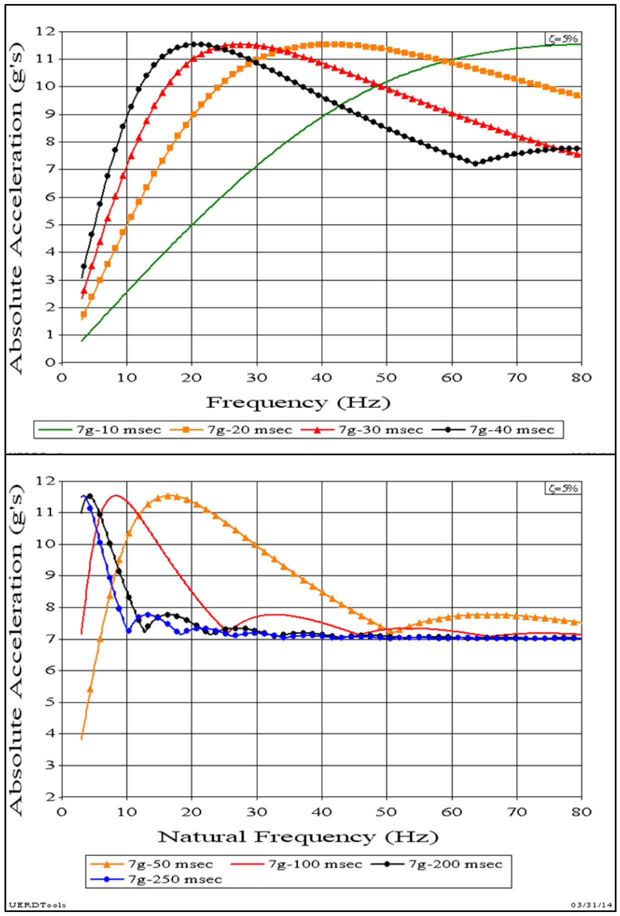

Figure 21. Acceleration SRS for 5-Percent Critical Damping

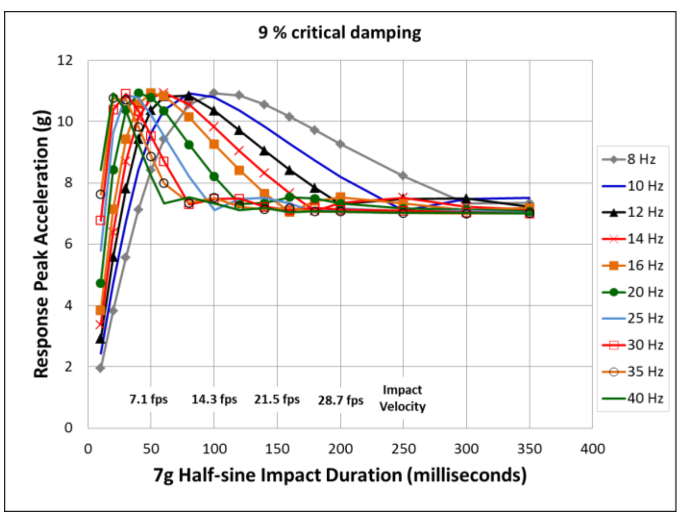

Figure 22. Response Peak Acceleration vs. Pulse Duration

Relative Displacement vs. Pulse Duration

Shock response spectra can also be constructed to show how the maximum relative displacement across the spring of the SDOF model varies with system natural frequency. The relative displacement is proportional to strain in the spring so it is a good measure for comparing response severity. The larger the predicted strain the larger the potential for damage to occur. Figure 23 shows four relative displacement SRS for four 7 g half-sine pulses with durations from 10 ms to 40 ms. Each curve in the plot shows the maximum relative displacement caused by the input pulse as a function of system natural frequency. The figure shows that maximum relative displacements decrease with increasing system natural frequency, and for frequencies less than 40 Hz the larger durations lead to larger relative displacements (i.e., larger response severity). When these results are combined with relative displacement SRS for pulse durations from 50 ms to 350 ms the results are plotted as shown in Figure 24.

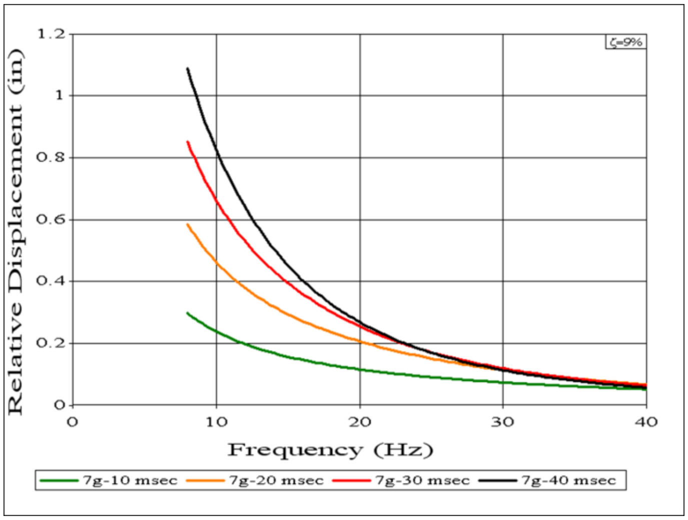

Figure 23. Relative Displacement Shock Response Spectra

Each curve in Figure 24 corresponds to system natural frequencies from 8 Hz to 40 Hz as shown by the legend. Natural frequencies from 8 Hz to 16 Hz are characteristic of relatively soft systems like shock isolation mounts. Frequencies from 20 Hz to 40 Hz are characteristic of transient bending vibrations in deck plating and stiffeners. These curves show that when material strain (i.e., maximum relative displacement) is used as a measure of response severity the duration of the pulse is very important, especially for system natural frequencies less than approximately 20 Hz. The curves also show that for system frequencies greater than about 25 Hz the response severity is relatively insensitive to changes in pulse duration.

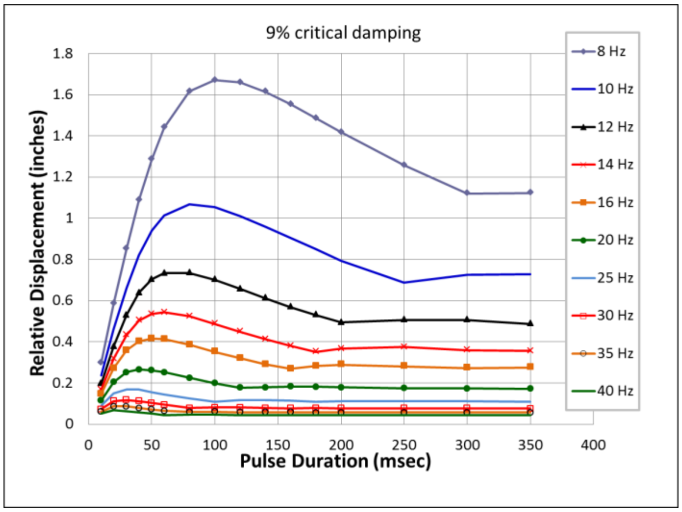

Figure 24. Response Maximum Relative Displacement vs. Pulse Duration

Implications for Laboratory Testing

Analyses of vertical acceleration data for high-speed planing craft that weigh from 14,000 pounds to 105,000 pounds indicate that the duration of wave slam impacts are on the order of 100 ms to 450 ms (see Figure 5). The typical wave slam pulse duration is not from 2 ms to 50 ms as previously reported. This has important implications for laboratory testing intended to demonstrate system ruggedness or shock mitigation characteristics prior to installation on a craft.

Laboratory testing methods that employ pulse machines or free-fall drop impacts have been developed to simulate various impact environments [7, 12 – 14]. The shock response spectra calculations presented above demonstrate that the duration of the impact pulse is important when attempting to simulate system responses to in-service impact loads. This is true for lower frequency systems nominally less than about 20 Hz and for higher frequency systems nominally greater than 40 Hz.

Lower Frequency Systems

Examples of systems with lower natural frequencies (i.e., less than 20 Hz) would be shock isolated equipment or shock mitigation seats.

In Figure 24 the maximum relative displacement values for one of the lower system frequencies, like the 8 Hz SDOF system (i.e., the upper curve), decrease significantly as wave impact duration increases from 100 ms to 350 ms. This would suggest that a conservative laboratory test intended to simulate maximum in-service relative displacements (i.e., strain) should employ a test methodology with impact duration of 100 ms rather than 350 ms. The curve for the 8 Hz system also indicates that the 50-ms pulse duration in a laboratory would result in a maximum relative displacement roughly 80 percent of the relative displacement for the 100-ms wave impact. In other words the 50 ms pulse in the laboratory would not simulate the severity of the in-service relative displacements.

The other indicator of response severity (i.e., the peak acceleration response) shown in Figure 22 also shows issues for the shorter duration pulses from 10 ms to 50 ms depending upon system natural frequency. These shorter duration pulses may result in peak acceleration responses less than peak acceleration responses for the 7 g – 100 ms wave impact. In this type of scenario where short impacts of a laboratory test may or may not be appropriate (i.e., depending upon the test item) it is best to test with the minimum in-serve pulse duration of 100 ms.

Higher Frequency Systems

Installations of electronics equipment or propulsion machinery would be an example of systems installed on craft with higher natural frequencies (i.e., higher than 8 Hz to 20 Hz shock isolation mounts or 20 Hz to 40 Hz flexible deck structures).

The shorter duration pulses (i.e., 10 ms to 40 ms) may be appropriate for laboratory testing if it is assumed that electronics equipment is characterized by system natural frequencies greater than roughly 40 Hz. This would be based on the rationale that typical equipment items are housed within cabinets whose support structure, internal construction, and component design is relatively stiff compared to typical shock isolation mounts.

This is illustrated by peak acceleration and relative displacement spectra shown in Figures 18, 19, and 24. For example, for a system natural frequency of 40 Hz or more, the 10 ms and 20 ms pulses result in larger peak acceleration responses than the 50 ms and 100 ms pulses (i.e., even for very different critical damping assumptions). This suggests that for certain classes of equipment items whose system natural frequencies can be shown to be in higher frequency ranges, the shorter impact pulse durations like 10 ms to 40 ms may be appropriate for conservative laboratory testing (i.e., they create more severe responses than in-service wave impacts). It is recommended that typical equipment natural frequencies be investigated to investigate alternative test pulses less than the typical wave impact duration (i.e., 100 ms).

Summary Conclusions and Recommendations

The impact duration of a wave slam can be observed in the vertical (i.e., heave) velocity time history as the interval from the time of largest negative velocity prior to impact to the subsequent time of zero crossing after the impact. It can also be observed in vertical and fore-aft acceleration time histories as the interval between the water impact and the time after the peak acceleration at which transition occurs (i.e., point C in Figure 4) from the impact phase to lower amplitude accelerations caused by hydrodynamic lift and buoyancy. Observing all three records (velocity, vertical rigid body acceleration, and fore-aft rigid body acceleration) clearly identifies impact duration.

Acceleration data for craft within the scope of this report indicates that the shortest impact durations regardless of impact severity are on the order of 100 ms, and the longest durations decrease from about 450 ms to 150 ms 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).

Impact durations from 2 ms to 75 ms reported in historical documents for similar sized craft were often misrepresented due to the use of automated zero-crossing algorithms on unfiltered data. Re-analysis of archived data for one craft indicates impact durations were from 128 ms to 451 ms rather than previously reported values of 2 ms to 75 ms for typical impacts.

The dynamic response of any physical system can be very sensitive to impact duration depending upon the natural frequency and damping properties of the system. For the craft cited in this report short impact durations (e.g., 2 ms to 50 ms) should not be used in laboratory tests to simulate wave impact responses of low frequency systems (e.g., shock mitigation seats or shock mounted equipment with natural frequencies nominally less than 20 Hz to 25 Hz).

Single-degree-of-freedom calculations indicate shorter impact pulse durations like 10 ms to 40 ms may be appropriate laboratory impact pulses for certain classes of rigid equipment whose system natural frequencies can be shown to be in higher frequency ranges (e.g., 40 Hz or more). It is recommended that natural frequencies of craft equipment be investigated to study the alternative use of shorter duration laboratory test pulses that are less than the typical wave impact duration (i.e., 100 ms to 450 ms).

Symbols, Abbreviations, and Acronyms

θ .... impact angle of deck relative to horizon
c .... critical damping coefficient
f .... system natural frequency
FFT .... fast Fourier transform
ft .... feet
g .... acceleration due to gravity (32.2 ft/sec^2)
Hz .... Hertz (cycles per second)
k .... structural stiffness
LCG .... longitudinal center of gravity
m .... mass
msec or ms .... millisecond
sec .... second
SDOF .... single degree-of-freedom
SRS .... shock response spectrum
T or tau .... wave impact shock pulse duration
V_{ac} .... Volts alternating current

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Appendix A. Wave Impact Velocity

In the vertical direction the severity of a wave impact for high-speed planing craft should be characterized by multiple parameters, including the shape of the impact acceleration pulse, the peak acceleration, the impact duration, and the change in velocity during the pulse. The change in velocity is useful because it is equal to the magnitude of the craft's impact velocity just prior to wave impact. The vertical impact velocity is directly proportional to an equivalent free-fall drop height that can be used in laboratory drop tests to investigate wave impact effects.

Velocity values can be measured directly using inertial measurement units or by integration of recorded acceleration data. When impact velocity values are obtained by integrating acceleration data, the following steps are recommended to minimize drift and to compensate for the unknown constant of integration. Demean the acceleration record, subject it to a 0.025 Hz high-pass filter, and then integrate it to obtain velocity. Evaluate other closely-spaced high-pass filter values to ensure consistent results. The physics-based criteria for selection of the high-pass filter amplitude should be that the filter does not reduce wave impact velocity significantly.

If average impact velocities are of interest, such as the average of the highest 1/100th, 1/10th, or 1/3rd, the following computational process is recommended. Multiply the velocity time history by negative one to invert the record. Input the inverted record into the *StandardG* algorithm to extract the peak velocity values. This approach is appropriate because *StandardG* is not just an acceleration algorithm. It is a general purpose code for peak amplitude extraction tailored to wave impact sequences in high-speed planing craft. It is recommended that the RMS velocity be used as the vertical threshold, and 0.5 seconds be used as the horizontal threshold in the *StandardG* velocity computation.

The shock response spectra presented in this report for various wave impact acceleration pulses (i.e., half-sine pulses with durations of 100 ms or more) demonstrate that the peak acceleration parameter is a good relative measure of impact severity for systems that can be modeled as a single-degree-of-freedom. The impact velocity parameter is useful for determining equivalent drop heights for laboratory drop tests, but it is not a good relative measure of wave impact severity by itself for high-speed planing craft. Figures 22 and 24 show that as impact velocity increases the maximum response (both peak acceleration and maximum relative displacement) can decrease or remain the same depending upon the natural frequency of the system. The reason for this is related to the long duration of typical wave impacts (e.g., 100 ms or more) relative to typical system response periods (less than 50 ms).

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