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Technical Report

QUANTIFYING MITIGATION CHARACTERISTICS OF SHOCK ISOLATION SEATS IN A WAVE IMPACT ENVIRONMENT

by

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NSWCCD-80-TR-2015/001 Quantifying Mitigation Characteristics of Shock Isolation Seats in a Wave Impact Environment

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Administrative Information

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Summary

This report presents recommended metrics for evaluating the mitigation characteristics of marine shock isolation seats. A mitigation ratio based on shock response spectra is introduced. Acceleration data recorded during seakeeping trials of a high-speed craft are used to compare mitigation ratios of shock response spectra with ratios based only on peak accelerations. The recommended computational approach applies to evaluating seat isolation effectiveness using either high-speed craft seakeeping data or laboratory test data.

Introduction

Background

Quantifying the severity of a shock motion is performed by design engineers in numerous disciplines to ruggedize systems and for test engineers to specify laboratory test methods intended to simulate in-service shock motions or the effects of shock. The characteristics of specific shock motions for commercial automotive, airline, aerospace, rail, packaging, building design (for earthquakes), and military applications vary significantly, but the fundamental physics of impulse-momentum relationships fit mathematical models that apply universally. As a result multi-disciplinary handbooks provide guidance on how to apply common engineering methods for developing shock test specifications (including impact drop tests) and evaluating shock test data [References 1, 2][1]. These methods are directly applicable to laboratory testing of shock isolation seats.

The recommended method for evaluating the mitigation characteristics of a shock isolation seat in a laboratory test is to use a vertical free-fall drop test method[2]. The vertical free-fall converts the potential energy of the test mass from a given drop height to mass kinetic energy characterized by an impact velocity just prior to impact. Upon impact a pulse shaping mechanism will control the shape, amplitude, and duration of the impact deceleration. The impact deceleration in the drop test will be tailored to simulate the input load (i.e., the vertical acceleration pulse) at the base of a shock mitigation seat caused by a wave impact in high-speed planing craft.

The drop test method is widely used in many engineering applications to simulate dynamic shock loads characterized by rapid and severe input motions to evaluate system ruggedness and functionality [References 3 - 7]. Several standard methods use a plot referred to as a shock response spectrum (SRS) to quantify the severity of a transient dynamic motion [References 1-3, 8-10]. A definition of the SRS and examples will be presented later in this report as well as a discussion of its relevance to shock isolation seat testing and seat performance measurement.

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[1] Numbers in brackets are references listed at the end of this report.
[2] This information is contained in a limited distribution U.S. Navy report.

The typical isolation components of passive shock isolation seats are a parallel combination of a spring and a shock-absorber (commonly referred to as a damper). The purpose of the spring-damper assembly is to mitigate (i.e., attenuate or reduce) the severity of the shock pulse delivered to the base of the seat. The objective is to achieve a response motion above the spring-damper that is less severe than the input shock motion. A comparison of the shock motion at the base of a seat and the shock motion above the spring-damper combination determines whether the spring-damper mitigated the shock input, provided little-or-no mitigation, or amplified the shock input motion.

Objective

The objectives of this report are to (1) summarize an established approach that should be used in the planned ISO standard to select and define performance measures for evaluating the mitigation characteristics of marine shock isolation seats, and (2) to explain the engineering rationale for using a seat performance measure that includes the effects of three important shock severity parameters (peak acceleration, shock pulse duration, and the rate at which the acceleration is applied).

Terminology

Mechanical Shock. Mechanical shock is a non-periodic excitation (e.g., a motion of the foundation or an applied force) of a mechanical system that is characterized by suddenness and severity [Reference 1]. Non-periodic excitation means non-oscillatory (i.e., not a vibration), but it may be a repeated shock excitation like intermittent wave impacts.

Shock Response Spectrum. A shock response spectrum (SRS) is a plot of the maximum response experienced by a single-degree-of-freedom system, as a function of its own natural frequency, in response to an applied dynamic motion. The maximum response may be expressed in terms of acceleration, velocity, or displacement [Reference 9]. ISO Standard 18431-4:2007 states the shock response spectrum should be called the maximum response spectrum, because the computational approach is applicable to any dynamic input motion, including vibration motions [Reference 10].

ANSI Standard S2.62-2009

American National Standard S2.62-2009 defines graduated thresholds of shock severity for laboratory drop testing [Reference 3]. The severity of the tests are defined by drop height and shock pulse severity (half-sine shape and duration), and alternatively by the pseudo-velocity shock response spectra (PVSRS). The severity of the drop test impact must be recorded by an instrumentation system to ensure that the appropriate severity is achieved. For a 100-msec half-sine pulse the severities correspond to peak accelerations from approximately 1.6 g to 16 g. The test procedure includes the option to mount the test item at an angle on the test platform if the service environment includes multi-axis shock inputs. Two acceptance criteria are specified related to achieving the required shock severity and ensuring post-test item operability and functionality. This standard serves as the foundation for discussions in this report and it is directly applicable to the planned ISO standard, so it should be referenced as a normative document.

Seat Performance Measure

Shock Response Spectrum

The simple representation of a passive shock isolation seat shown in Figure 1 will be used to illustrate how the shock response spectrum (SRS) is used as a standard performance measure for shock testing. It is assumed that the seat occupant is securely fastened in the seat with restraints. This is not a critical assumption, however, since the maximum compression in the spring-damper assembly (i.e., the maximum load transmission) occurs during the first half-cycle of response in a drop test.

The performance of the seat during a wave impact is based on the ability of the spring-damper assembly to protect the occupant from the rapid change in vertical acceleration, velocity, and displacement at the seat's location in a craft. A seat that protects the occupant is one that mitigates (or reduces) the effects of the rapid change in acceleration that occurs at the base of the seat. In the sketch on the left in Figure 1 the rapid change in acceleration is measured by a vertically oriented accelerometer at the base of the seat (black square). In the time domain this is the shock input motion. The shock response motion of the seat is typically measured by an accelerometer (red square) positioned on the seat pan or on the seat cushion (referred to in the figure as the pad). A direct comparison of the shock severity of the deck input motion and the severity of the seat shock response determines the level of mitigation achieved by the seat's spring-damper assembly.

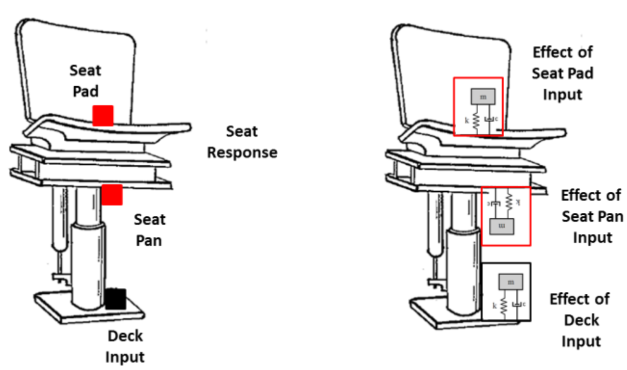

Figure 1. Shock Spectrum Approach to Evaluating Seat Performance

The shock severity of the base input motion and the severity of the seat response motion are determined by estimating the effect each motion has on a single-degree-of-freedom (SDOF) mathematical model. The effects of a shock input on the SDOF model are quantified by use of a shock response spectrum (SRS). In the sketch on the right in Figure 1 the SRS is represented by the sketch of the SDOF model. The SRS provides a measure of how severe the shock effects would be on the simple mathematical model as a result of the shock input. The mathematical model of the SDOF system in this application is simply a mathematical ruler for relative comparisons of shock intensity. Shock mitigation occurs when the effect of the seat pan motion (or seat cushion motion) on the SDOF model is less severe than the effect of the deck input motion on the SDOF model.

Appendix A discusses difficulties associated with shock motion comparison in the time domain and summarizes why the shock response spectrum is used to evaluate and compare shock severity in the response domain. It also discusses three important shock parameters that influence the effects of shock, including peak acceleration, shock pulse duration, and the rate at which the acceleration is applied (i.e., jerk). Examples of shock response spectra are presented to illustrate how they are used to estimate which shock motion is more severe when different shock motions are compared. SRS analysis methods are documented in ISO Standard 18431-4:2007 [Reference 10].

Mitigation Ratio

A direct measure of the ability of a spring-damper assembly to mitigate shock inputs is the ratio of the shock response spectrum of the seat response acceleration divided by the shock response spectrum of the deck input acceleration.

$$\text{Mitigation Ratio} = MR_{SRS} = \frac{\text{SRS for Seat}}{\text{SRS for Deck}} \qquad \text{Equation (1)}$$

It can be shown that the ratio of the acceleration SRS yields the same value as the ratio of relative displacement SRS, which is also equal to the ratio of the pseudo-velocity shock response spectra used primarily in ANSI Standard S2.62-2009 [References 3, 9, 10]. When MR_{SRS} is less than 1.0, shock mitigation has occurred. For example, if the ratio is 0.6 the mitigation can be described as a 40-percent reduction in shock severity. When MR_{SRS} is greater than 1.0, dynamic amplification has occurred and the seat motion is more severe than the deck input motion. When MR_{SRS} = 1.0, the seat motion has the same shock severity as the deck input motion.

The benefit of using the MR_{SRS} parameter is that the shock response spectrum calculation takes into account the effects of varying amplitude of shock pulses as well as the effects of varying pulse duration and jerk. All three parameters (i.e., amplitude, duration, and jerk) are important for evaluating the effects of shock severity on different types of systems. It will be shown that the variation of MR_{SRS} with SDOF natural frequency is very important when evaluating the shock mitigation performance of different seats; for example, comparing stiffer spring-damper assemblies to more flexible spring-damper assemblies. Appendix B shows how the MR_{SRS} parameter was used to evaluate the performance of a shock isolation seat using acceleration data recorded during at-sea trials in a high-speed planing craft operating in rough seas.

Conclusions and Recommendations

The shock response spectrum (SRS) is an established shock severity parameter used in many applications to compare different shock severity levels. The SRS accounts for the effects of different shock pulse shapes, shock amplitudes, pulse durations, and jerk. The mitigation ratio (MR_{SRS}) given by equation (1) is therefore a well suited performance measure for evaluating shock isolation seat performance during laboratory drop testing. It is recommended that the mitigation ratio based on shock response spectra be the primary performance measure for laboratory testing of marine shock isolation seats.

The following standards should be included as normative documents in a seat testing standard:

ANSI Standard S2.62-2009, “Shock Test Requirements for Equipment in a Rugged Shock Environment”

ISO Standard 18431-4: 2007, “Mechanical vibration and shock – Signal processing – Part 4: Shock response spectrum analysis”.

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Appendix A. Different Approaches for Comparing Shock Severity

Performance Measure Approach

The National Space and Aeronautics Administration (NASA) studied human tolerance to abrupt accelerations using numerous testing methods devised to simulate different impulsive loads (e.g., catapult acceleration and ejection seat accelerations) that could push the limits of human tolerance [References A1 - A3]. They focused on the rigid body accelerations related to aircraft dynamics or ejection seat thrust. Their conclusions were that human tolerance to rapidly applied acceleration depends primarily upon (1) the direction in which the accelerating force is applied, (2) the magnitude of the accelerating force, (3) how long the accelerating force is applied, and (4) how rapidly the accelerating force is applied.

For shock mitigation seats the initial direction of applied force of primary interest is the vertical direction. The magnitude of the shock load input into a seat is characterized by the peak vertical acceleration recorded at the base of the seat (A_{max}). The pulse duration (T) defines how long the load is applied and the average jerk (average rate of change in acceleration) for the half-sine pulse ($2*A_{max} / T$) is a measure of how rapidly the load is applied. The following discussions will focus on how these parameters are used for comparing shock pulse severity.

Shock Severity in the Time Domain

The plot on the left in Figure A1 shows two hypothetical shock pulses (half-sine) with equal duration (100 msec) but different amplitudes (7 g and 10 g). The plot on the right is the integral of each plot showing the change in velocity associated with each shock pulse. The change in velocity is proportional to the impulse of each of the applied loads. The most straight forward and most common comparison approach is to compute a ratio of the peak acceleration values as shown in equation (A1).

$$\text{Mitigation Ratio Peak Acceleration}\left(MR_{PEAKS}\right)=\frac{A_{PEAK\,1}}{A_{PEAK2}} \qquad \text{Equation (A1)}$$

In this example the peak acceleration ratio is 10/7 = 1.43, thus the 10 g pulse is roughly 43 percent more severe than the 7 g pulse. The average jerk from zero to the peak acceleration for each pulse is also shown in the figure to help illustrate the example. The ratio of the average jerk values and the ratio of the velocity values is also 1.43. This is a very straight forward comparison approach often used as an initial indicator of severity because it is easy to calculate ratios once the peak acceleration values have been identified. It is simple and it appeals to one’s intuition because of the physical inference to a larger shock impulse having been applied to create the larger peak acceleration value. The larger the shock force the larger the severity of the shock pulse.

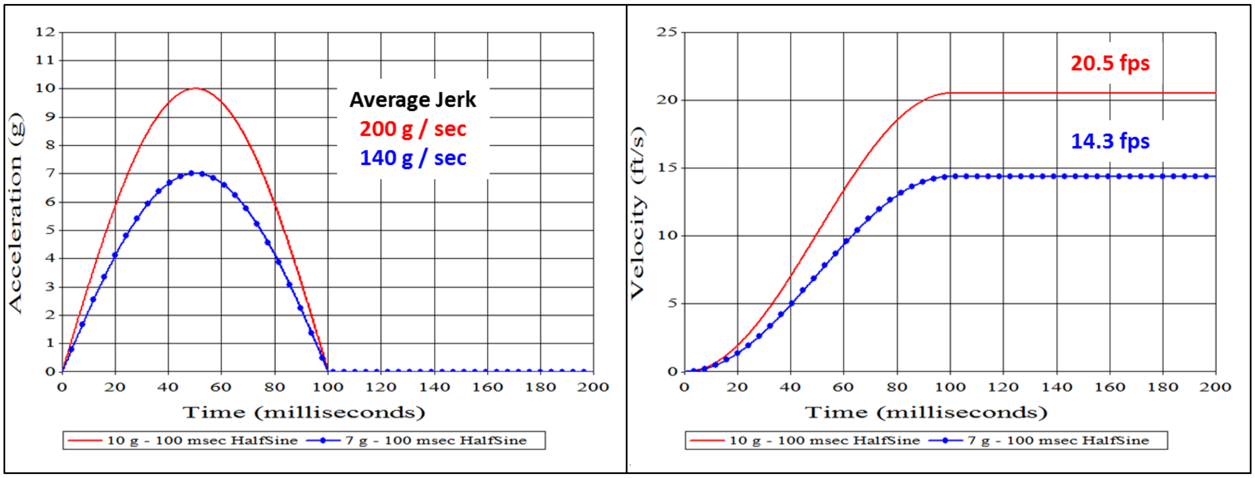

Figure A1. Equal Duration - Different Amplitude Shock Pulses

The peak ratio approach has difficulty however with comparisons of different pulse durations as shown by two examples in Figure A2. For these examples one's intuition may or may not be physically accurate. In Figure A2 the upper left plot shows two shock pulses with peak accelerations of 8 g, but one has 100-msec duration and the other 175 msec. The velocity curves on the right show that the longer duration 175-msec pulse corresponds to a higher change in velocity, so it is tempting to conclude that the pulse with the higher shock velocity change is more severe. What is more important: peak acceleration, average jerk, or velocity change? Intuitively some would say that peak acceleration is more important so the two 8 g pulses have equal severity, but others may argue that the larger change in velocity (i.e., the larger total impulse) is more severe.

The same intuitive dilemma occurs for the lower left plot in Figure A2. The peak acceleration for the 225-msec pulse is half the peak acceleration of the 100-msec pulse, the average jerk is 77.8 percent less, but the velocity change is 12 percent higher. Again, what is more important: peak acceleration, jerk, or change in velocity?

The previous discussions demonstrate that it is not intuitively obvious how shock severity should be compared in the time domain when all three parameters may be different (i.e., peak acceleration, jerk, and pulse duration). The classical engineering approach used to obviate this problem is to transition the comparison of shock severity from the time domain (i.e., the shock pulse curves) into the response domain using a simple single-degree-of-freedom mathematical model. This approach uses the shock response spectrum to compare different pulse severities in the response domain.

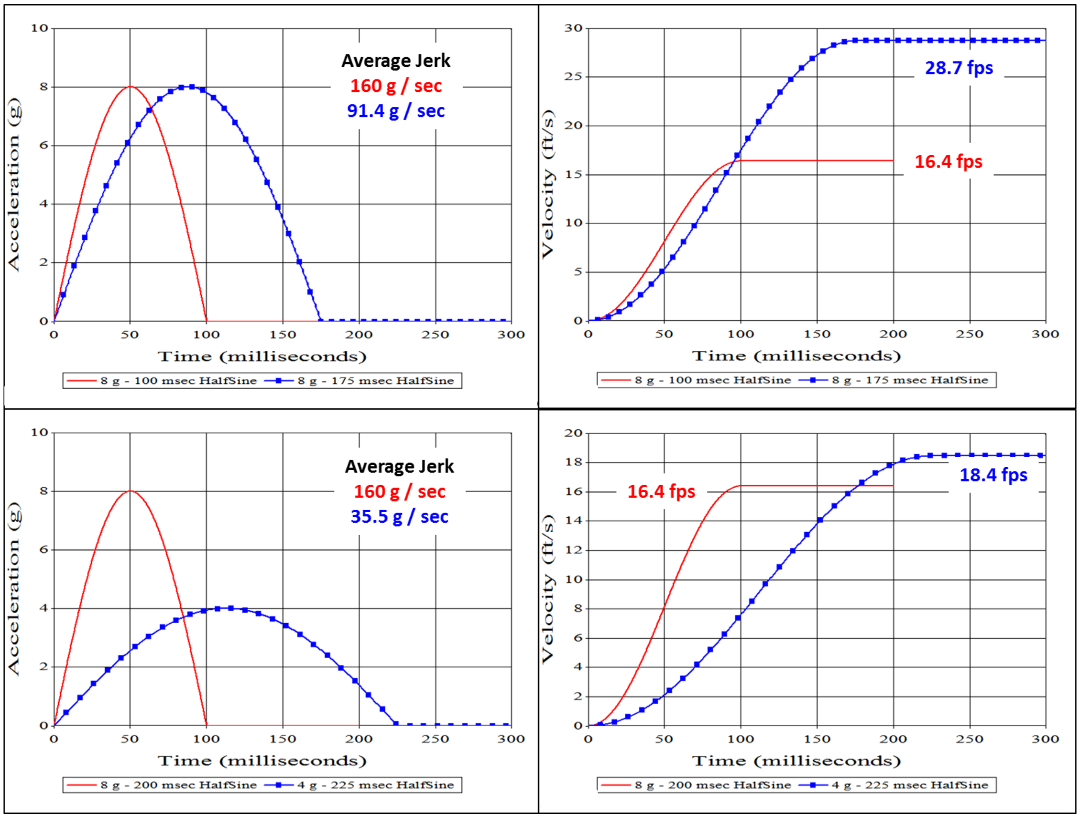

Figure A2. Acceleration Shock Pulses, Average Jerk, and Velocity Change

Shock Response Spectrum

A shock response spectrum (SRS) is a computational tool used extensively in shock analyses to compare the severity of different shock motions. Example applications include (1) comparing field shock test data to laboratory test machine data to ensure laboratory tests simulate the severity of actual field conditions, or (2) comparing field shock test data to draft shock design levels to ensure shock design criteria conservatively envelope actual field conditions, or (3) evaluating how systematic changes in test parameters affect shock response severity. The SRS is therefore very useful for comparing the severity of different shock motions.

Before introducing the shock response spectrum, the following paragraphs present an example calculation to illustrate how a mathematical model of a single-degree-of-freedom (SDOF) system is used to evaluate and compare the severity of two different shock motions that have the same peak acceleration, but different durations, different changes in velocity, and different average values of jerk.

Figure A3 shows a model of a SDOF system. The system has a base attached to a mass (m) by a spring (with stiffness k) and a damper (with critical 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 is obtained by summing the inertial force of the mass and the forces within the spring and damper.

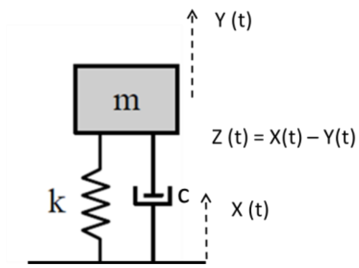

Figure A3. Single-degree-of-freedom Mathematical Model

$$-\ddot{y}(t) + 2\xi\omega\dot{z}(t) + \omega^2 z(t) = 0 \qquad \text{Equation (A2)}$$

Where *t* is time and:

$$\xi = \frac{c}{2m\omega} \qquad \text{Equation (A3)}$$

$$\omega = \sqrt{\frac{k}{m}} \qquad \text{Equation (A4)}$$

The natural frequency (f) in Hertz (Hz) of the SDOF system is given by equation (A5).

$$f = \frac{\omega}{2\pi} = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k}{m}}\ \text{Hz} \qquad \text{Equation (A5)}$$

The solution of equation (A2) 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 motion Z(t) between the base and the mass. Mathematical solutions to equation (A2) for different pulse shapes are presented in reference 4.

The maximum predicted acceleration response of the SDOF mass (m) is a useful measure for comparing shock severity because it is proportional to the maximum inertial force (i.e., shock force) acting on the mass as a result of the shock input. Likewise, the maximum predicted relative displacement across the SDOF spring is a useful measure because it is proportional to the maximum strain in the spring. Both maximum values (i.e., peak acceleration response and maximum relative displacement) are a measure of the severity of the shock input (in terms of shock force acting on the mass and strain in the spring). When two different shock pulses are being compared, the one that results in the larger maximum acceleration and larger relative displacement in the SDOF model is the more severe shock pulse. This is illustrated further in the following paragraphs.

The left plot in Figure A4 shows the two hypothetical shock pulses from Figure A3 with the same 8 g peak accelerations arbitrarily denoted shock input A and B. Shock pulse B has the longer duration (175 msec versus 100 msec). For the purpose of the mathematical comparison a SDOF mathematical model (with 9% critical damping) with a natural frequency of 13.5 Hz is arbitrarily selected to evaluate severity in the response domain.

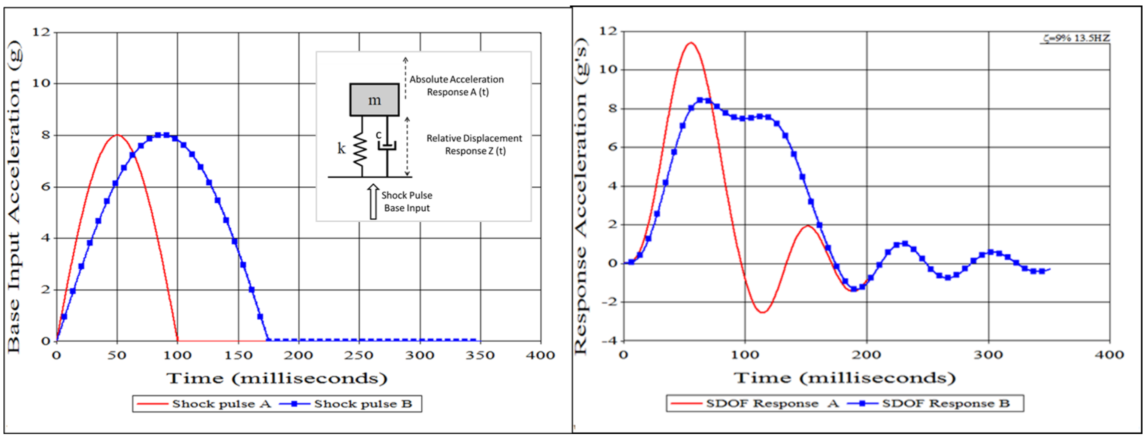

Figure A4. 13.5 Hz SDOF System Input and Response Accelerations

The plot on the right in Figure A4 shows the predicted absolute acceleration responses of the mass (m) caused by shock pulse A and shock pulse B. The peak acceleration response for pulse A is predicted to be 11.39 g and the peak response for pulse B is 8.46 g. These values along with the predicted maximum relative displacements for the SDOF system are listed in Table A1. The predicted maximum relative displacement for pulse A is 0.015 millimeters and for pulse B it is 0.011 millimeters. These results in the response domain indicate that pulse A is predicted to result in a larger peak acceleration response and a larger maximum relative displacement, thus pulse A is more severe than shock pulse B for a 13.5-Hz SDOF system.

Table A1. 13.5 Hz SDOF System Maximum Responses

Shock Pulse Input	13.5 Hz System Response			
	Response A_{MAX}		Response Z_{MAX}	
	m/sec^2	g	mm	inch
A	111.736	11.390	0.015	0.606
B	82.993	8.460	0.011	0.449

In this example the 13.5-Hz SDOF system was chosen arbitrarily to illustrate the comparison. When many other calculations are made for other values of SDOF system natural frequency, the plot of the maximum response (either peak acceleration response or maximum relative displacement) for a given shock input versus system natural frequency is referred to as a shock response spectrum. It is a plot of SDOF system maximum response versus SDOF model natural frequency. The following examples illustrate the shock response spectrum concept.

The acceleration plots in Figure A5 show predicted response motions (i.e., acceleration versus time) for a 30-Hz SDOF system (red circles) and a 5-Hz SDOF system (blue triangles). The shock input motion for each prediction was assumed to be a half-sine acceleration pulse with a peak of 10 g and 50-millisecond duration (black curve). The maximum response acceleration predicted for the 30-Hz system is 13.6 g. The maximum response predicted for the 5-Hz system is 8.2 g. Thus it is observed that the maximum response (i.e., peak acceleration in this example) of the SDOF system is a function of the natural frequency (f) of the SDOF model.

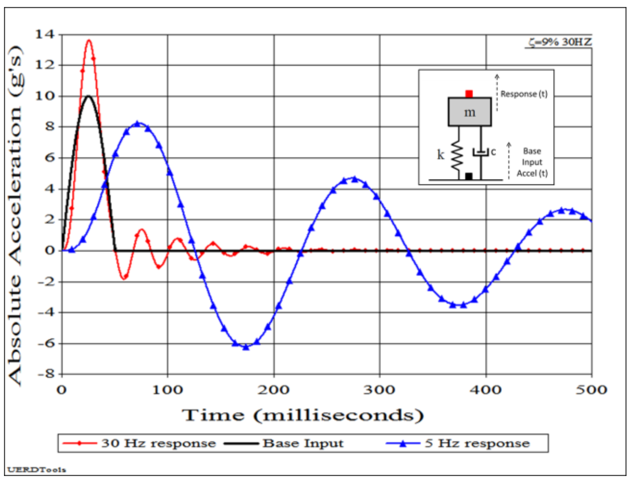

Figure A5. Single-degree-of-freedom System with Sample Base Input and Responses

Figure A6 presents a plot of the maximum acceleration response of the SDOF model for model natural frequencies from 4 Hz to 80 Hz for the 10 g – 50 msec base input pulse. It is called an acceleration shock response spectrum (ASRS). The symbols in the figure identify the two predicted peak response values shown in Figure A5 (i.e., 13.6 g for 30 Hz and 8.2 g for 5 Hz).

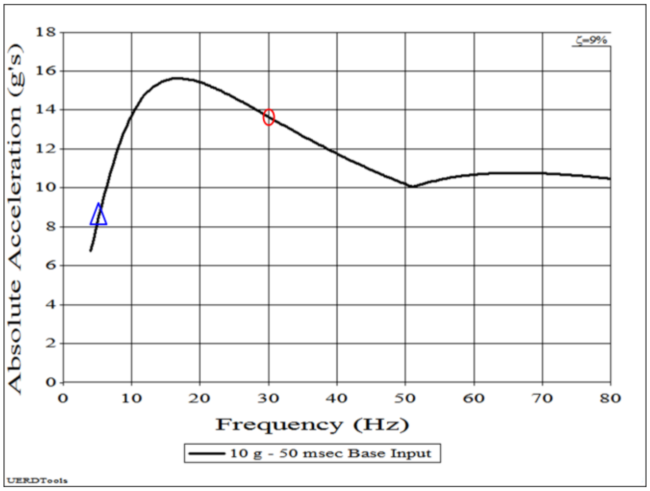

Figure A6. Acceleration SRS for 10 g-50 msec Base Input

The maximum response of the SDOF system can also be plotted as a function of the maximum relative displacement (Z_{MAX}) across the SDOF model's spring. Figure A7 shows a plot of the maximum relative displacement caused by the 10 g -50 msec base input acceleration (half sine) as a function of model natural frequency. It is called a relative displacement SRS (DSRS).

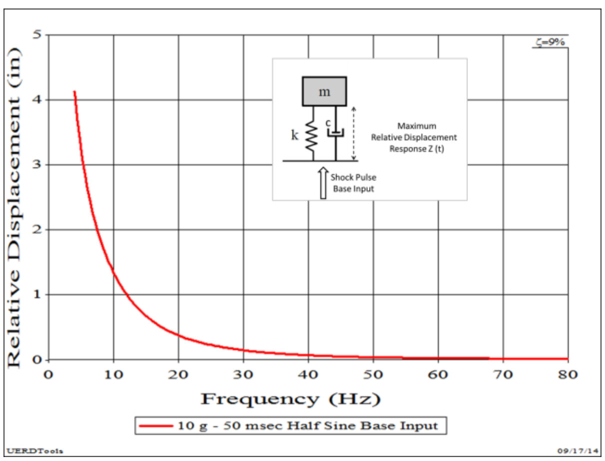

Figure A7. Maximum Relative Displacement SRS

The maximum acceleration and the maximum relative displacement values from Figures A6 and A7 can be combined into a convenient four-coordinate plot referred to as a pseudo-velocity shock response spectrum (PVSRS) as shown in Figure A8. Logarithmic scales are used on all four axes. 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 and lines sloping downward to the right show the predicted maximum response acceleration scales.

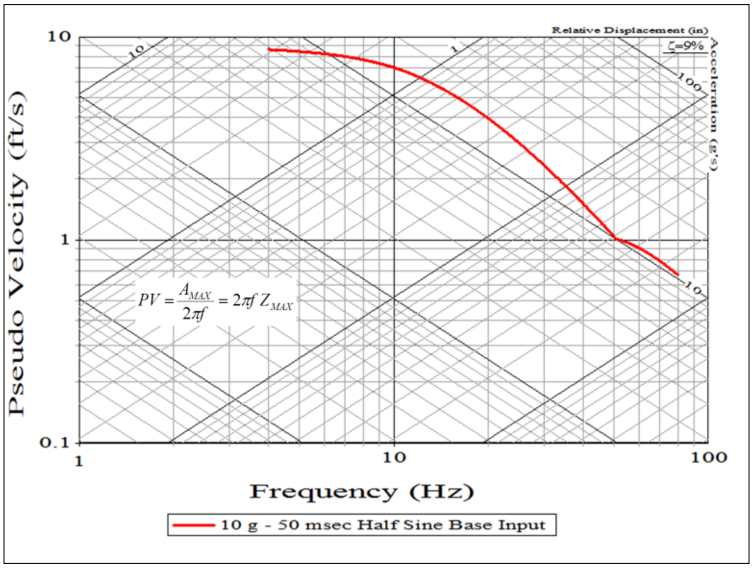

Figure A8. Pseudo-Velocity SRS

The log-log PVSRS provides a measure of the shock severity in units of displacement, velocity, and acceleration. The acceleration scale is sometimes referred to as the pseudo-acceleration for damped systems if the acceleration values are calculated using equation (A5), which applies for lightly damped or zero damped systems.

$$\mathrm{A}_{\mathrm{MAX}} = (2\pi f)^2 Z_{MAX} \qquad \text{Equation (A5)}$$

Shock Mitigation Ratio

Equation (A6) defines the shock mitigation ratio as the ratio of shock response spectra computed for shock pulses measured at the deck and on the seat. If the ratio is greater than 1.0, the shock pulse measured on the seat is more severe than the shock pulse measured on the deck (i.e., amplification has occurred). If the ratio is less than 1.0, the shock pulse measured on the seat is less severe than the shock pulse measured on the deck (i.e., mitigation has occurred).

$$\text{Mitigation Ratio} = \mathrm{MR}_{\mathrm{SRS}} = \frac{\text{SRS for Seat}}{\text{SRS for Deck}} \qquad \text{Equation (A6)}$$

As an example, Figure A9 shows relative displacement SRS (DSRS) for two hypothetical shock pulses: 7 g – 100 msec and 5 g – 210 msec half-sine pulses. The question is how much more severe is one shock pulse compared to the other pulse? To answer this question Figure A10 was constructed by dividing the 5 g – 210 msec DSRS by the 7 g – 100 msec DSRS (i.e., equation (A6)). It shows that throughout the frequency range of interest the 5 g – 210 msec shock pulse is less severe than the 7 g – 100 msec pulse (i.e., the ratio is less than 1.0). For natural frequencies greater than approximately 40 Hz the mitigation ratio is 0.70 (i.e., the 5 g pulse is 30 percent less severe than the 7 g pulse). Between 8 Hz and 17 Hz the mitigation ratio is from 0.5 to 0.6 (i.e., 40 percent to 50 percent less severe).

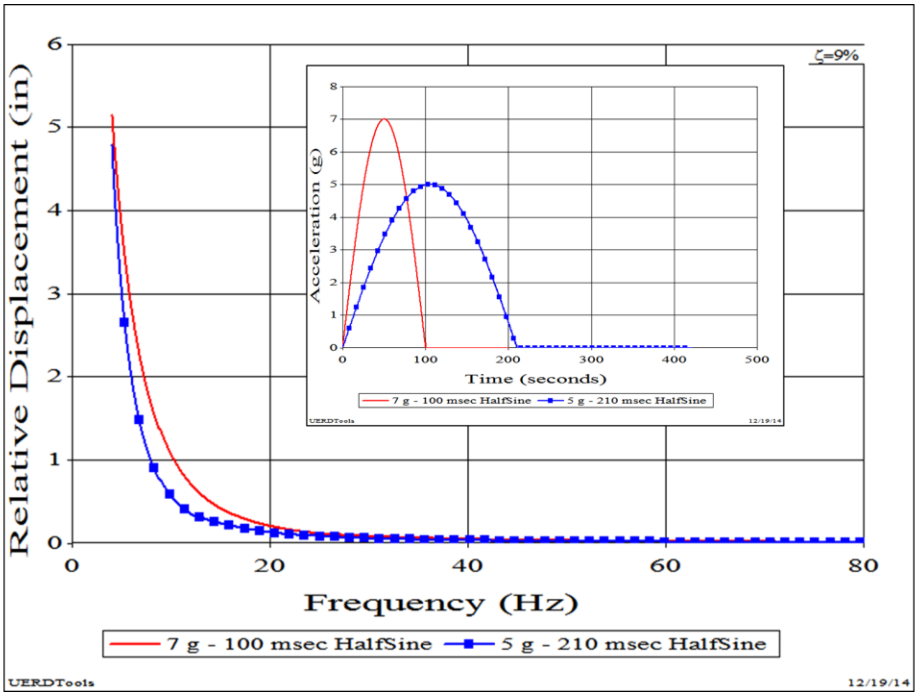

Figure A9. Comparison of Hypothetical DSRS

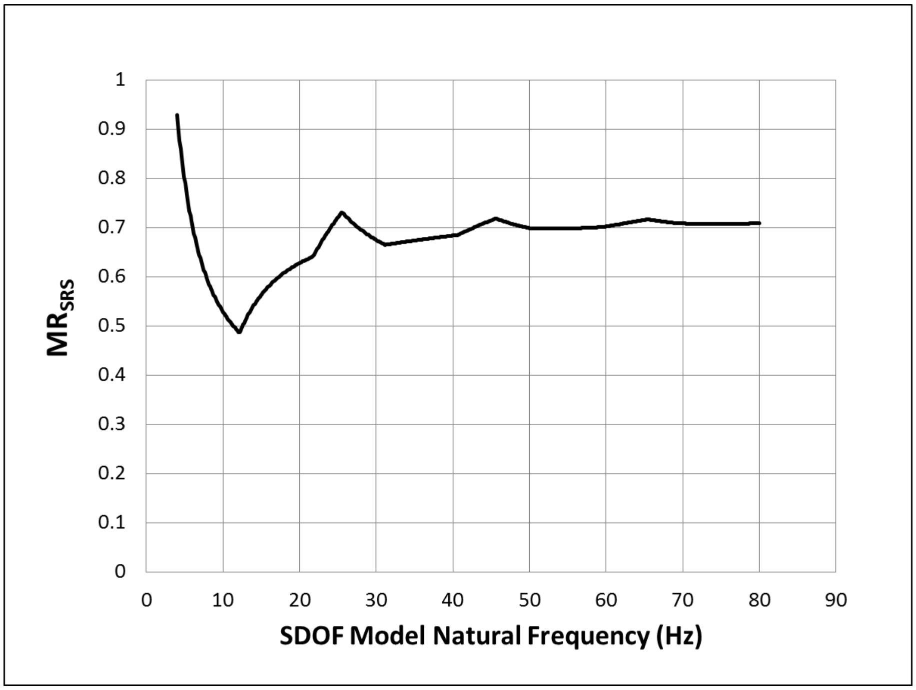

Figure A10. Mitigation Ratio for 5 g DSRS and 7 g DSRS

The mitigation ratio based on relative displacement shock response spectrum (DSRS) is a convenient relative measure of shock input severity because (1) it takes into account the effects of acceleration magnitude, pulse duration, and the rate of acceleration application (i.e., jerk), and (2) because of its relationship to compressive strain or stress in the SDOF mathematical model. The concept of stress as a measure of shock severity is not new. The early NASA studies concluded that magnitude (i.e., peak acceleration) alone does not define shock severity, nor does acceleration cause damage in a system. Stress (or strain), a result of acceleration, causes damage [A2]. The comparison of displacement shock response spectra is therefore a convenient measure for comparing the relative damage potential between two shock pulses.

It can be shown that the ratio of acceleration shock response spectra and the ratio of pseudo-velocity shock response spectra for two different shock pulses yield the same mitigation ratio plot as the ratio of the relative displacement shock response spectra, so it does not matter which spectra are used to compute the SRS mitigation ratio.

Frequencies of Interest

Selection of the frequency value of interest or the frequency range of interest for the mitigation ratio MR_{SRS} is based on the assumption that there is no intent to accurately model the item being subjected to the shock. The mathematical model of the SDOF system in this application is simply a mathematical ruler for relative comparisons of shock intensity. But the ruler can be calibrated depending upon the frequency (or frequencies) of interest. If very stiff items are being subjected to shock, then the frequencies of interest may be 80 Hz or more. If the item being subjected to shock is more flexible a lower frequency like 12 Hz may be more relevant for the mathematical ruler. The intent is not to accurately model the item being subjected to the shock, but rather to select a relevant frequency that renders the mathematical ruler (i.e., the mitigation ratio) more meaningful for the application. As an example, the occupant of a shock mitigation seat is not a stiff 80-Hz system like an aluminum truss structure. Previous comfort studies for seat occupants subjected to whole body vibration exposure suggest the range of interest is 4 Hz to 8 Hz [References A4, A5]. Therefore, for ease of calculation, the mitigation ratio (i.e., the mathematical ruler) used in Appendix B is chosen to be 8 Hz. The intent is not to model a seat occupant, but rather to render the mathematical ruler more relevant to evaluating shock isolation seat performance.

Appendix A References

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Appendix B. Example Analysis Using the SRS Mitigation Ratio

Individual Wave Impacts in Trials Data

The use of the shock response spectrum (SRS) mitigation ratio (MR_{SRS}) as a seat performance measure will be demonstrated using acceleration data recorded during trials of a high-speed planing craft in rough water. The intent is to show how MR_{SRS} is computed and how it is used to evaluate the shock mitigation characteristics of the seat.

The seat was loaded with 175 pounds (79.3 kg) of sand bags securely fastened vertically and horizontally to the seat. Accelerometers oriented vertically were installed on the deck at the base of the seat, on the seat pan, and on the seat cushion under the ballast weight. Two trials were conducted at an average speed of approximately 20.1 knots in head seas in significant wave heights of 3.7 ft (1.1 m) and 4.6 ft (1.4 m). The average wave periods were 6.6 seconds and 5.2 seconds, respectively.

Response mode decomposition was used with each data set to separate rigid body heave accelerations from local structural vibrations [B1]. The frequency analysis of the signal content indicated a 20-Hz low-pass filter was appropriate for both the deck and seat accelerations to evaluate shock pulse transfer through the seat assembly. Figure B1 shows an example of the filtered acceleration data recorded at the deck (black curve) and on the seat pan (red curve) during the run with a 4.6 ft (1.4 m) significant wave height. For each location during the two runs from 387 to 434 wave impacts (on average 408 impacts per run) were recorded. The largest deck peak accelerations recorded during each run were 3.5 g and 6.0 g.

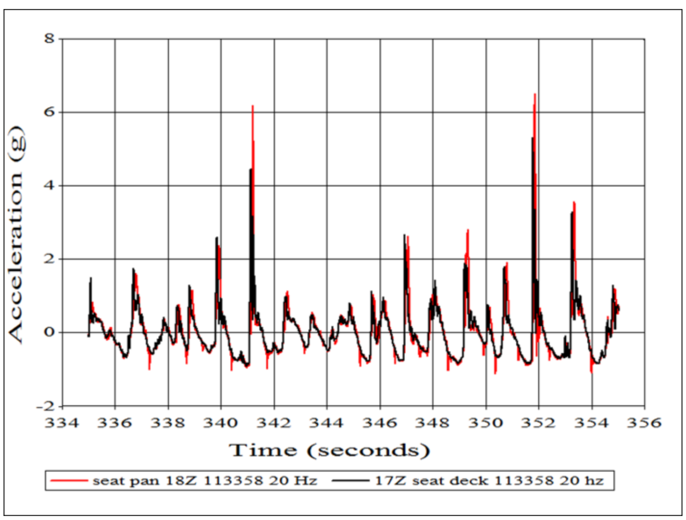

Figure B1. Example Acceleration Data

Figure B2 shows the acceleration time histories recorded on the deck below the seat (black curve) and on the seat pan (red curve) for one wave impact that occurred 221seconds after the start of the data acquisition system. Wave impacts are numbered according to the time at which they occurred, so this is wave slam 221. The seat pan response acceleration (red curve) has the lower peak acceleration and the duration of the pulse is longer compared to the deck pulse (black curve).

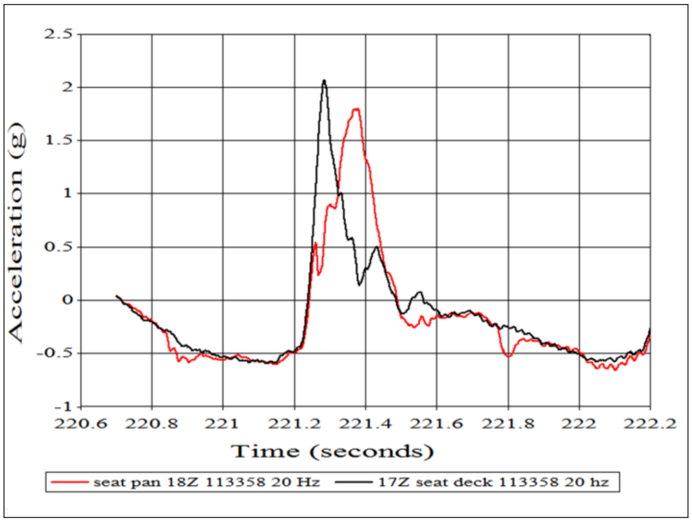

Figure B2. Deck and Seat Pan Accelerations at 221 Seconds

The relative displacement shock response spectra (DSRS) for the two acceleration pulses in Figure B2 are shown on the left side of Figure B3 plotted from 4 Hz to 80 Hz for comparison purposes. The plot on the right is the MR_{SRS} for slam 221 computed by dividing the pan DSRS (red curve) by the deck DSRS (black curve). The MR_{SRS} plot on the right shows that for natural frequencies between 4 Hz and 80 Hz the seat mitigates the deck input with ratios ranging from approximately 0.62 to 0.97. The plot lists the average MR_{SRS} as 0.85 across the full frequency range. Although averaging is a common approach that provides *one number* when several parameters are involved, it can lead to a loss of insight into the physical phenomena that cause differences across the frequency spectrum (4 Hz to 80 Hz), so caution is advised when considering broad averaging. For example, from 40 Hz to 80 Hz the MR plot indicates the stiffer SDOF models experience on the order of 10 percent to 15 percent shock mitigation, while more flexible SDOF models from 4 Hz to approximately 16 Hz experience on the order of 25 percent to 35 percent mitigation. The reason for the different responses between stiff systems and more flexible systems is related to jerk and the duration of the input shock pulse compared to the natural response period (i.e., 1/f) of the SDOF model. At one specific frequency like 8 Hz the mitigation ratio indicated on the right in Figure B3 is 0.66.

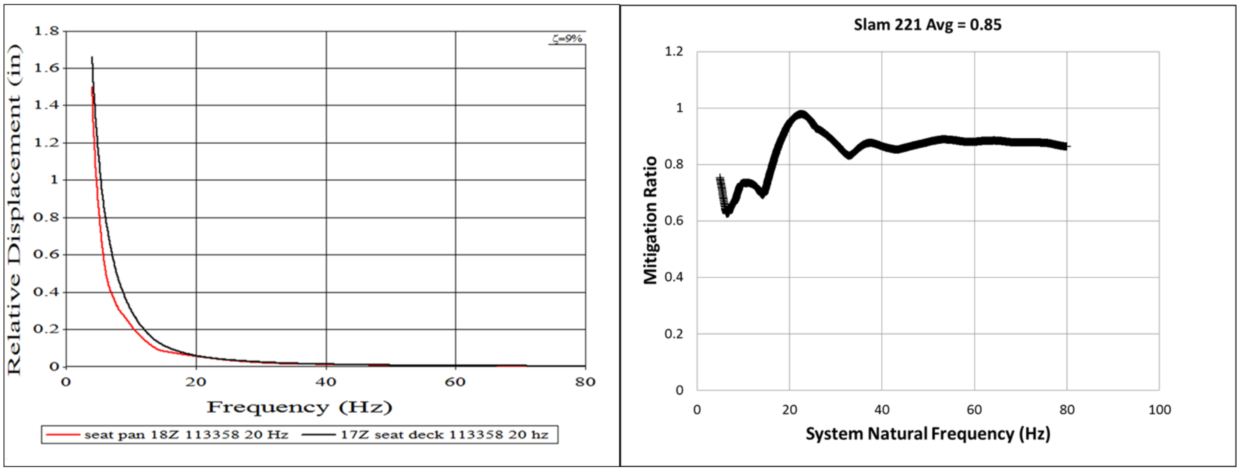

Figure B3. DSRS and Mitigation Ratio$_{SRS}$ for Wave Slam 221

Another example of comparing the severity of deck and pan acceleration pulses is shown in Figure B4. The plot on the left shows the pan acceleration has about the same peak amplitude as the deck acceleration but the duration is longer and the jerk is lower. The computed DSRS curves are shown on the right. For an SDOF model with a natural frequency of 8 Hz the mitigation ratio is 0.76. In other words, an 8 Hz SDOF system would experience a 24 percent reduction in compression for the seat-pan acceleration pulse compared to the deck acceleration pulse. The average MR from 5 Hz to 8 Hz is 0.78.

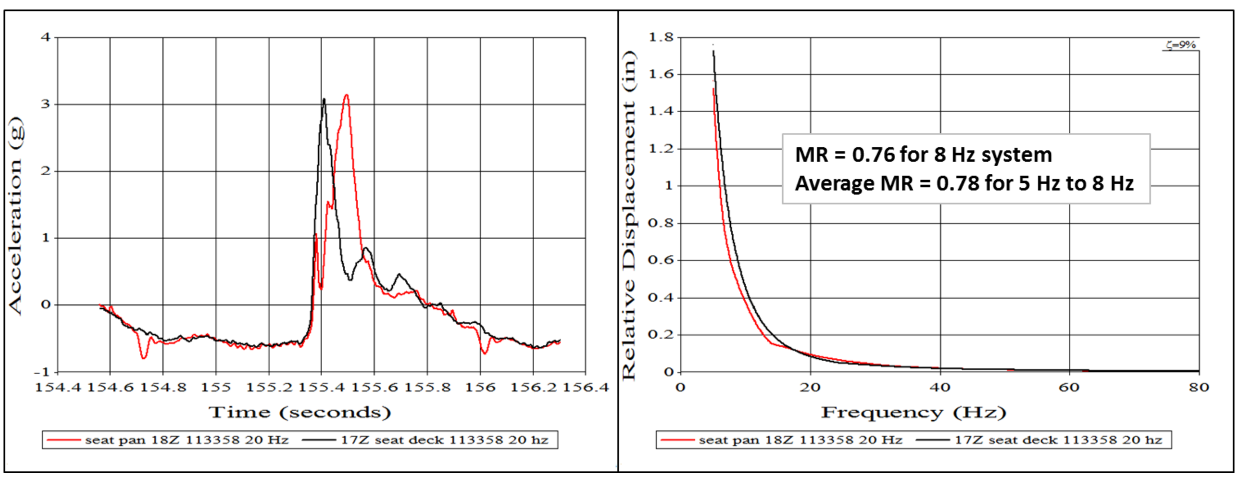

Figure B4. DSRS and Mitigation Ratio$_{SRS}$ for Slam 155

If a mitigation ratio based on only peak accelerations were used (i.e., MR_{PEAKS}), the comparison of the two acceleration pulses shown in Figure B4 would result in MR_{PEAK} = 1.0. In other words, a performance measure based on peak acceleration alone would indicate no mitigation occurred. When the difference in pulse duration and jerk are accounted for by the SRS calculation, the result is MR_{SRS} = 0.76 (i.e., 24 percent mitigation) for a performance measure based on a SDOF system with an 8 Hz natural frequency.

The DSRS plots and MR curves were also used to evaluate 136 additional wave impacts observed in the two at-sea runs. This included all wave impacts with deck peak accelerations greater than or equal to 2 g and a sampling of the hundreds of impacts between 0.5 g and 2 g. For comparison purposes MR_{SRS} values for a SDOF natural frequency of 8 Hz are used rather than an average MR value over the range of frequencies from 4 Hz to 80 Hz. Averaging the full range from 4 Hz to 80 Hz is too broad to discern the effects of pulse duration and jerk. All computed MR_{SRS} values for an 8-Hz SDOF system for both runs are shown in Figure B5.

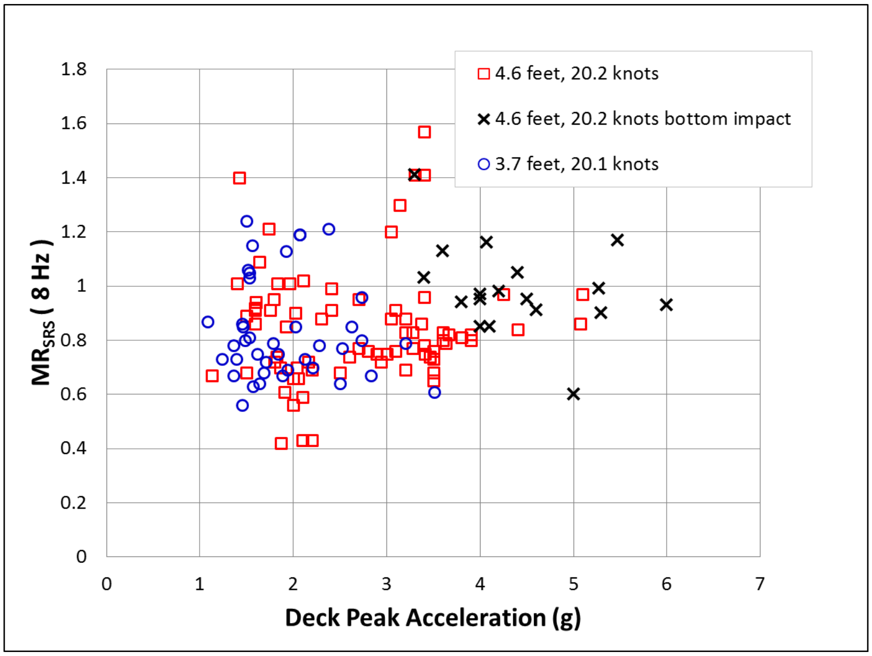

Figure B5. MR_{SRS} for 8-Hz System versus Deck Peak Acceleration

In Figure B5 the wave slams that resulted in seat bottom impacts during the run in 4.6-foot seas are indicated by the black X. During this run no seat bottom impacts occurred when deck peak accelerations were less than 3.3 g. During the run in 3.7-foot seas (blue circles) the maximum deck peak acceleration was 3.5 g and no seat bottom impacts were observed.

The plot also shows that there is no trend in MR_{SRS} (for an 8-Hz system) with deck peak acceleration. For example, a majority of the MR_{SRS} values vary from 0.6 to 1.2 for deck peak accelerations from 1 g to 5 g. In an attempt to explain this broad scatter the effect of wave impact angle was investigated by considering the ratio of the deck vertical peak acceleration (Z) to the deck peak fore-aft acceleration (X). The ratio of these values is a rough estimate of the tangent of the impact angle.

Figure B6 shows there is a trend in MR_{SRS} values with the (Z/X) ratio. The symbols in the legend identify different ranges of vertical deck peak accelerations. The ratio of the Z and X acceleration vectors is used as an indicator of the change in impact angle for different types of wave impacts (i.e., skimming on a wave crest or impacts on the leading flank of a wave). When Z is large and X is small (largest Z/X value is 25) there is very little fore-aft deceleration (i.e., resulting in no lurching forward during an impact). The tangent for these vectors indicates the total acceleration vector is on the order of 87.7 degrees from the deck surface (or 2.3 degrees from normal to the deck, as in skimming a wave crest or impacting the following flank of a wave). Thus the spring-damper system is being acted on by a force vector more aligned with its vertical axis.

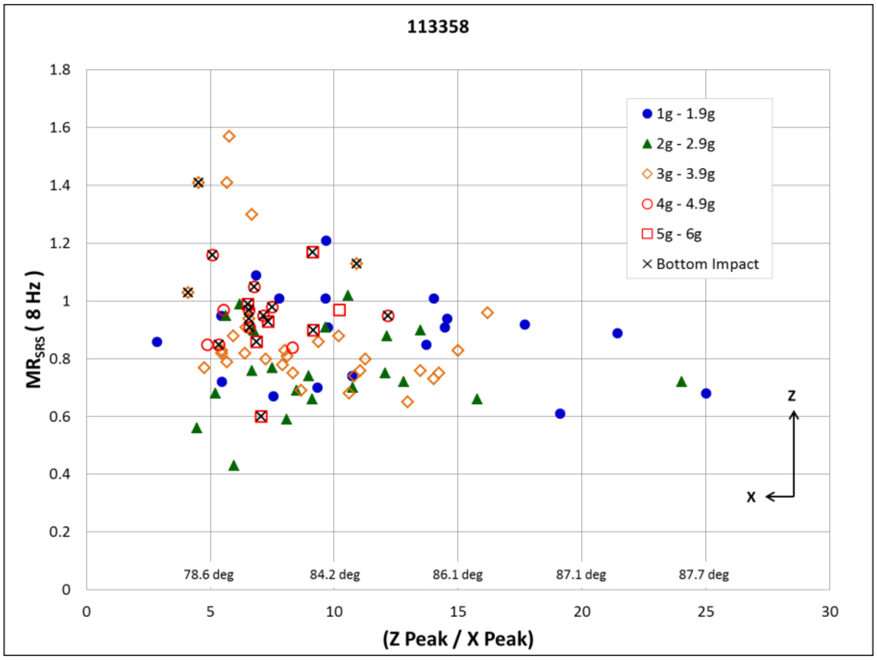

Figure B6. MR_{SRS} versus Angle of Impact for Run 113358 (4.6 feet)

When the fore-aft X acceleration is larger and the vertical Z acceleration is smaller (smallest Z/X value is about 3) the acceleration vector is about 78.6 degrees from the deck surface, or 11.4 degrees off the vertical axis. This larger angle off the vertical may correspond to an impact on the leading flank of a wave. In Figure B6 the values of MR greater than 1.0 correspond to impacts with Z/X ratios less than 15. The implication is that the angle of incidence off the vertical affects the performance of the spring-damper assembly, perhaps caused by friction or binding in the seat spring-damper assembly.

MR_{PEAK} versus MR_{SRS}

Mitigation ratios based only on peak acceleration values were also computed (i.e., MR_{PEAK}). Figure B7 compares MR_{PEAK} ratios with the corresponding MR_{SRS} ratios (for an 8-Hz system) for 138 wave impacts. This includes all deck peak accelerations greater than or equal to 3 g and several from the 0.5 g to 3 g range. The four quadrants in the plot labelled A, B, C, and D are separated by the dashed red lines into regions that correspond to shock mitigation ($MR_{SRS} < 1.0$ and $MR_{PEAK} < 1.0$) and no shock mitigation ($MR_{SRS} > 1.0$ and $MR_{PEAK} > 1.0$). Each data point corresponds to one wave impact plotted at coordinates where the MR_{PEAK} value computed for the impact is the abscissa and the computed MR_{SRS} value is the ordinate. The different symbols shown in the legend identify the amplitude range of the deck peak acceleration. The legend shows the range of deck input peak accelerations for each impact. All bottom impacts are shown by the black circles.

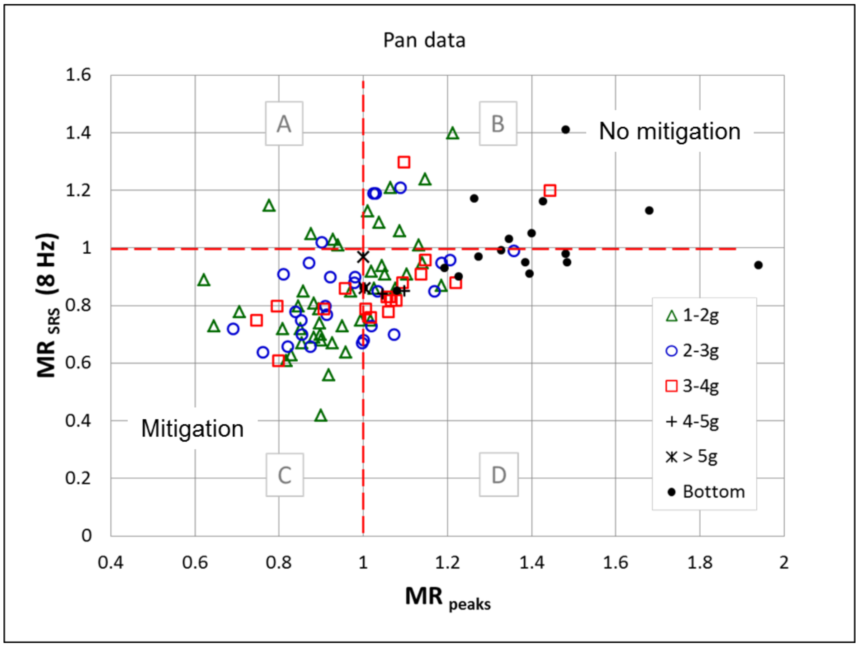

Figure B7. Comparison of Performance Measures for Both Runs

The dashed red lines in Figure B7 define four quadrants labelled A, B, C, and D for mitigation ratios less than and greater than 1.0. Quadrant C corresponds to impacts where both MR_{SRS} and MR_{PEAKS} indicate mitigation has occurred with values less than 1.0. Quadrant B corresponds to impacts where both MR_{SRS} and MR_{PEAKS} indicate amplification of the deck acceleration has occurred with values greater than 1.0. The relatively large percentage of points in quadrant D is where the MR_{PEAK} value indicates amplification, but the MR_{SRS} value for the same impact indicates mitigation. Slight mitigation is even indicated for several of the bottom impacts.

Quadrants A and B show the wave impacts where the MR_{SRS} ratio indicates the pan acceleration pulse was more severe than the deck input acceleration pulse. Many of these data points correspond to non-bottom impacts. This clearly disproves the myth that seat amplification only occurs during bottom impacts. Non-bottom wave impact in quadrants A and B are data points where dynamic amplification occurred.

The data points in quadrant D illustrate the shortcoming of using a performance measure based solely on peak acceleration. The MR_{PEAK} parameter is a ratio of peaks that does not take into account the effects of jerk or the duration of the pulse. This may not be a problem if the deck input and seat response accelerations have durations that do not vary significantly. It may also not be a problem if the systems being exposed to the shock pulse are relatively stiff systems (e.g., greater than 40 to 60 Hz).

Figure B8 shows a cumulative distribution plot of the same results to show the percentage of values less than or equal to an MR value. MR_{SRS} values indicate that 80 percent of the impacts were mitigated by the shock isolation seat. MR_{PEAK} values indicate only 40 percent of the impacts were mitigated. This disparity is an indication of the shortcoming of using a seat performance measure based solely on peak acceleration. The MR_{PEAK} parameter is a ratio of peaks that does not take into account the effects of jerk or the duration of the pulse. This may not be a problem if the deck input and seat response accelerations have durations that do not vary significantly, but this will likely not be the case for shock isolation seats that function by distributing the input pulse over a longer period of time. Close inspection of the data in Figure B8 for deck input accelerations from 1g to 3 g shows the MR_{SRS} and MR_{PEAK} values tend to be distributed evenly along the trend lines (i.e., the S-shaped curves). But for the more punishing non-bottom impacts greater than 3 g there is an interesting trend shown in Figure B9.

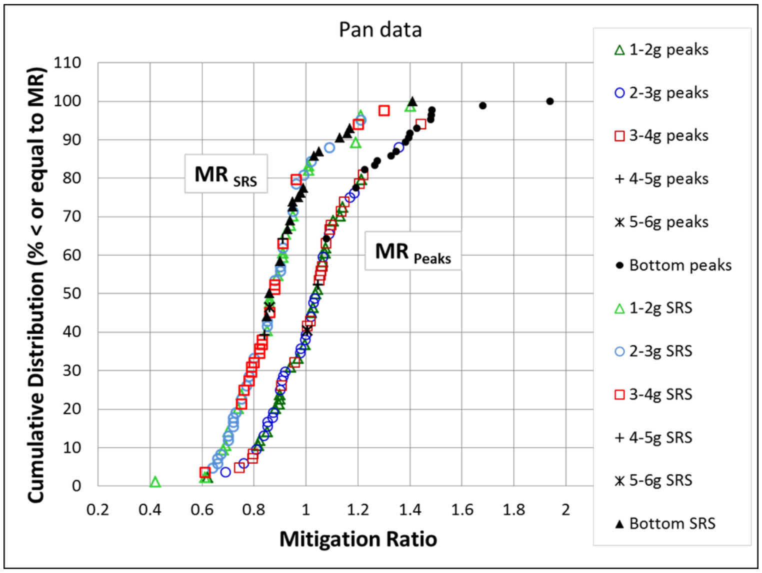

Figure B8. Comparison of Performance Measures for One Run

Figure B9 shows the MR_{SRS} and MR_{PEAK} values computed for the more severe deck inputs with peak accelerations from 3 g to 6 g. The MR_{PEAK} criterion indicates 75 percent of the impacts are amplified (i.e., $MR_{PEAK} > 1.0$) and 25 percent are mitigated. But when pulse duration and jerk are included by the MR_{SRS} criterion, only 10 percent are amplified and 90 percent are mitigated. These numbers tend to corroborate the physical events that likely occur. The more severe impacts cause larger relative displacements that occur over longer periods of time compared to less severe impacts with smaller relative displacement. The only mechanism for mitigation is related to pulse duration and jerk when peak accelerations on the pan are greater than deck input accelerations. This clearly demonstrates that pulse duration and jerk are important parameters and that peak acceleration alone should not be the seat mitigation criterion.

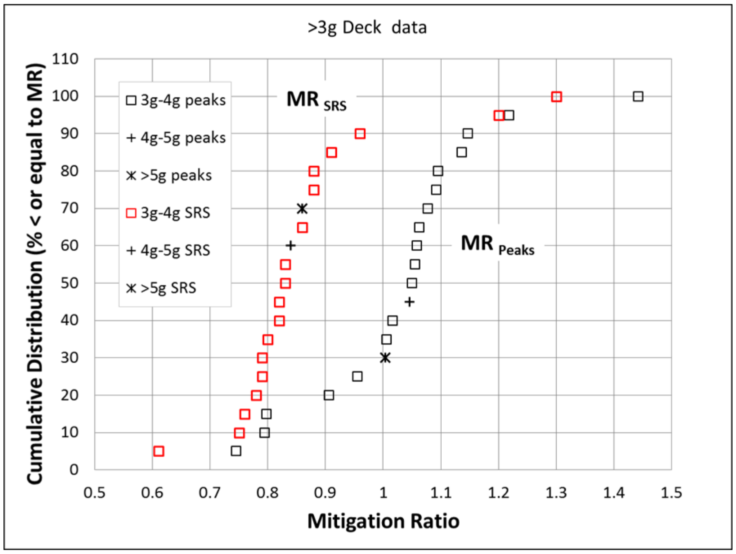

Figure B9. Trends for Most Severe Impacts

Seat Cushion (Pad) versus Seat Pan Responses

It is very important to understand differences between seat cushion and seat pan acceleration responses. Studies performed to investigate seat performance during simulated airplane crashes reported that soft seat cushions can be more hazardous than firm cushions during impact conditions [B2]. Similar observations were also made based on seat cushion data recorded during earlier high-speed craft trials (Riley 2013b). The MR_{SRS} values computed using pad acceleration data were therefore also compared with the pan MR_{SRS} values. These results are shown in Figure 14. The legend shows the levels of deck input peak acceleration. The bottom impacts are the black circles. The dashed-blue line has slope 1:1 indicating equal pad and pan values. Above the dashed line the ratios indicate the pad is more severe than the pan. Below the dashed line the pad is less severe than the pan.

The weak linear trend between the pad and pan data is less interesting than the general trends above and below MR_{SRS} values of about 0.9. More of the data points are below the 1:1 line when $MR_{SRS} < 0.9$, indicating more of the pad data is less severe than the pan data, but the pad is more severe when $MR_{SRS} > 0.9$. This is observed more clearly in the cumulative distribution plot of the MR_{SRS} values shown in Figure B11. The legend identifies the deck input acceleration levels and the bottom impacts for the pad and pan data.

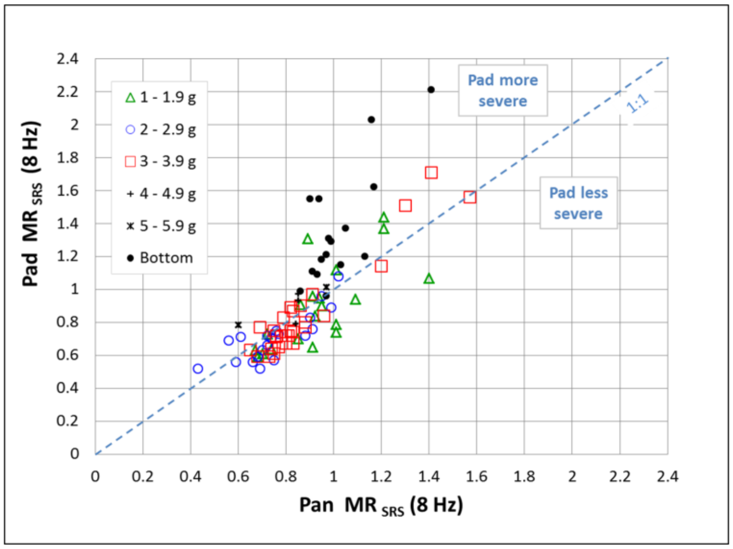

Figure B10. Seat Pad versus Seat Pan Mitigation

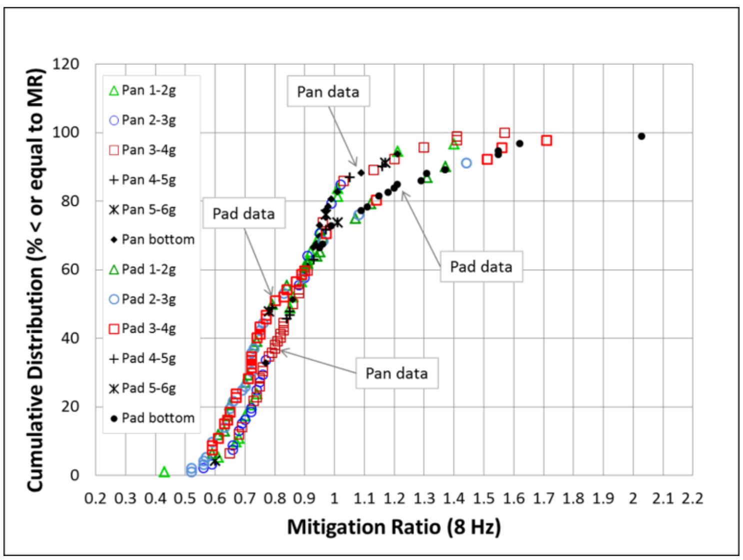

Figure B11. Seat Pad versus Seat Pan Mitigation

The interesting result in Figure B11 is that the two trend lines cross at approximately MR_{SRS} = 0.9. Below 0.9 the pad data trend indicates there are 10% to 20% more impacts mitigated at a specific MR_{SRS} value; or for a given percentage the pad trend indicates a lower MR_{SRS} ratio by about 0.1 (i.e., roughly 10% additional mitigation on pad). In other words when mitigation is indicated (i.e., MR_{SRS} = 0.9 or less) the data shows more impacts are mitigated on the cushion at a specific level compared to the pan. The cushion is mitigating more than the pan or mitigating a little more often.

Conversely, when amplification is indicated (i.e., above values of MR_{SRS} = 1.0), the pad data trend indicates there are about 10% less impacts mitigated at a specific MR_{SRS} value; or for a given percentage the pad trend indicates a higher MR_{SRS} ratio by about 0.1 to .3 (i.e., roughly

10% to 30% more amplification by the cushion). In other words, the cushion is more of a hazard more of the time under more severe impact conditions.

The data in Figure B11 clearly shows that seat cushions do not provide additional protection against severe wave slams. For the more severe slams the cushion may do more harm than good. The selection of seat cushion materials is therefore a compromise between soft-compliant materials that provide comfort and harder seat materials that prevent or limit impact load amplification [B2].

Implications for Laboratory Testing

The shock isolation seat data presented in this report is for a specific seat design. There are trends in the data that suggest the scatter in MR_{SRS} values on the pan from 0.4 to 1.4 may be related to the angle of impact between the craft and wave, perhaps causing binding in the spring-damper assembly as impact angle increases. This type of seat mitigation scatter is not expected during controlled laboratory tests where the axis of the base input acceleration (i.e., base input load) is co-linear with seat spring-damper motion.

The data indicates that the shock isolation seat installed in the craft began experiencing bottom impacts at a deck input of 3.2 g. From 3.2 g to 5.1 g most but not all wave impacts resulted in seat bottoming; from 5.2 g to 6.0 g all impacts resulted in seat bottoming. The seat responds differently in different impact severity regimes. Therefore, when seats are evaluated during successively more severe laboratory tests (e.g., as deck input g-levels increase), the results of all tests should not be averaged. This is also supported by results shown in Figure 13 where 90-percent of the impacts equal to or greater than 3 g were mitigated. If these MR_{SRS} values had been averaged with lower severity impacts, the significance of the seat more effectively mitigating the 3g to 4 g impacts would not have been observed.

There are many different types of passive shock isolation seats with unique designs that result in some seats that are more flexible while other seats may be stiffer, and damping characteristics will vary. These differences will affect the duration of the acceleration pulse response and the rate of acceleration increase (jerk) on the seat (either pan or cushion locations). The MR_{PEAK} ratio will not account for these important differences. Therefore the MR_{SRS} ratio is considered a more appropriate criterion for evaluating seat mitigation.

Seat cushions are an integral part of a seat’s design. It is recommended that seat mitigation be computed using the seat cushion acceleration data and the seat base data. Accelerometers should also be positioned on the seat pan. Analysis and comparison of the seat pan data with seat cushion data provides insight into how the cushion performs during impacts.

The new paradigm of studying wave impacts one-at-a-time has opened the door for laboratory testing of shock isolation seats [B4]. Acceleration data recorded during each test can be used to quantify mitigation characteristics before installation in a craft. The efficacy of the MR_{SRS} ratio method to quantify mitigation by taking into account differences in acceleration peak amplitude, rate of acceleration application (jerk), and pulse duration has been demonstrated in this paper using seat acceleration data recorded on a craft during high-speed trials. This method is also appropriate and should be used to evaluate acceleration data recorded during laboratory tests of shock isolation seats.

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