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A COMPARISON OF SHOCK ISOLATED SEAT AND RIGID SEAT ACCELERATION RESPONSES TO WAVE IMPACTS IN A HIGH-SPEED CRAFT

by

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SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A_{MAX}		peak or maximum acceleration
ASRS		acceleration shock response spectrum
ATD	.....	anthropomorphic test device
c	.....	damping coefficient
CCD	.....	Combatant Craft Division
DRI	.....	dynamic response index
DSRS	.....	relative displacement shock response spectrum
f or f_{SYS}	.....	natural frequency
FFT	.....	Fast Fourier Transform
fix	.....	fixed seat
ft	.....	feet
g	.....	acceleration due to gravity (32.2 ft/sec ²)
HSC	.....	high speed craft
Hz	.....	Hertz (cycles per second)
iso	.....	isolated seat
k	.....	stiffness coefficient
kg	.....	kilogram
kt	.....	knot
lb	.....	pound
LCG	.....	longitudinal center of gravity
m	.....	meter
MR	.....	mitigation ratio
msec	.....	millisecond
N	.....	number of wave impacts
π	.....	approximately 3.14159
R	.....	ratio of pulse duration divided by natural period
RIB	.....	rigid-hull inflatable boat

sec	second
SDOF	single degree-of-freedom
SRS	shock response spectrum
T	wave impact shock pulse duration
τ_{SYS}	natural period of SDOF oscillator
V_{MAX}	maximum velocity
VSRS.....	pseudo-velocity shock response spectrum
ϖ	circular frequency
X and Y	input and response motions of a SDOF oscillator
Z_{MAX}	vertical maximum relative displacement
ζ	zeta, percent of critical damping
#.....	number
%	percent

ADMINISTRATIVE INFORMATION

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SUMMARY

This report introduces three relative measures of shock mitigation performance useful for quantifying different shock response phenomena observed on side-by-side rigid and shock isolated seats during wave impacts in a high-speed craft. Numerous data plots for the different measures are used to explain why the severity on a shock isolation seat can be less severe than on a similar rigid seat even when seat bottom impacts and dynamic amplification occurs on the shock isolated seat.

INTRODUCTION

Background

In 2014 the Combatant Craft Division of Naval Sea Systems Command, Naval Surface Warfare Center Carderock conducted an extensive series of seakeeping trials of an instrumented 11-meter (m) cabin rigid-hull inflatable boat (RIB) [1]. They were part of a larger study of craft motion mechanics and wave slam phenomenon in small high-speed craft. It is a study of the effects of individual wave impacts to gain a better understanding of physical cause and effects relationships that could lead to improvements in design applications that address multiple factors associated with seaworthiness, including hull design loads, component ruggedness, and personnel comfort and safety. During the seakeeping trials two side-by-side seats were instrumented with accelerometers to measure deck inputs and seat pan and seat cushion responses to investigate parameters for quantifying seat mitigation performance¹. Both seats were identical passive shock isolation seats, except on one seat the spring-damper assembly was removed and replaced with a rigid link. The modified seat was therefore in a relatively rigid or fixed condition².

The acceleration data for the isolated seat has already been used to investigate the relative merits of different seat performance metrics for laboratory drop tests [2 – 4]. Seat acceleration data recorded during earlier seakeeping trials demonstrated that seat pads exhibited the same amplification phenomenon for single impacts previously documented for pilot ejection seats and airplane seat cushions during simulated crashes [5 – 7]. It has been widely reported that high-speed craft (HSC) shock isolation seats can amplify deck shock inputs [8-18], but the effects of the observed amplification have not been systematically investigated relative to a fixed-rigid seat.

Purpose

The purpose of this report is to introduce three relative measures of shock mitigation performance useful for investigating the effects of vertical shock inputs caused by wave impacts on side-by-side rigid and shock isolated seats in a high-speed craft.

¹ The seat cushion location is referred to as the seat pad location throughout the report.

² The fixed seat was not perfectly rigid due to connecting pin joints and seat cushion motions.

Mechanical Shock Attenuation

Passive shock isolation seats are installed in high-speed craft to reduce the severity of the shock force experienced by a seat occupant during severe wave impacts. When the severity of the shock force transmitted through the seat assembly is less than the severity of the impact force at the base of the seat it is referred to as mechanical shock attenuation. The word mechanical refers to the excitation of the mechanical spring-damper assembly in the seat.

Two system conditions must exist to achieve effective mechanical shock attenuation (i.e., shock mitigation). First, there must be sufficient excursion space across the spring-damper assembly to prevent a bottom impact. This is primarily a function of the severity of the wave impact force. The larger the impact force the larger the excursion space required. Second, the ratio of the shock pulse duration divided by the natural period of response of the passive spring-damper assembly (i.e., the inverse of the system natural frequency) must be less than a limit value that depends upon the system stiffness and damping properties. If the ratio of the shock pulse duration divided by the system natural period is larger than the limit value the spring-damper assembly will amplify the deck inputs. Appendix A shows examples of time history accelerations for seat bottom impact and dynamic amplification and explains the limit value curves.

This report compares the mechanical shock attenuation performance of the shock isolated seat with the performance of the fixed rigid seat.

Shock Mitigation Metric

When using acceleration data recorded during single shock events, the shock response spectrum (SRS) is used for quantifying and comparing shock severity at different locations. It is the preferred metric because it takes into account all the key shock parameters in a wave impact pulse, including, pulse shape, jerk, peak amplitude, and pulse duration [19-22]. It is an intuitive metric because it is a measure of the relative displacement produced in a hypothetical set of single-degree-of-freedom (SDOF) oscillators (i.e., lumped mass models). The relative displacement is proportional to strain which is an indicator of the damage potential of a shock pulse. The larger the predicted strain in the SDOF model the more severe the shock pulse. In this investigation the SRS is used to compare the severity of the recorded acceleration response on the seat to the severity of the recorded acceleration input at the deck. The ratio of these severities computed using equation (1) provides the mitigation ratio (MR) which is the measure of the seat's mechanical attenuation performance. The $\ddot{Y}(t)$ term is the vertical response acceleration time history recorded on the seat. The $\ddot{X}(t)$ is the vertical deck input acceleration time history. An MR value less than 1.0 indicates mitigation has occurred (i.e., mechanical shock attenuation). A value greater than 1.0 indicates shock amplification.

$$MR = \frac{\text{SRS of } \ddot{Y}(t)}{\text{SRS of } \ddot{X}(t)} \quad (1)$$

Additional discussions on the rationale for using the SRS mitigation performance metric and its relationship to the Dynamic Response Index (DRI) are presented in Appendix B³.

ANALYSES OF 2014 ACCELERATION DATA

Seakeeping Trials

The craft employed during the 2014 seakeeping trials was the 11-m cabin RIB shown in Figure 1. The craft is approximately 36 feet (ft) (11 m) long with a scale-weight of 15,845 pounds (lb), 7,187 kilograms (kg). The longitudinal center of gravity (LCG) was approximately 10.5 ft (3.2 m) forward of the transom-keel intersection [1]. The data analyzed and presented in this report was recorded during two head-sea runs in different sea conditions (referred to herein as Run I and Run II) in open ocean areas that were north and north-east of the Cape Henry lighthouse⁴. Table 1 lists the significant wave height, the average wave period, and the craft's average speed during each run.



Figure 1. Figure Composite Hull 11m Cabin RIB

Table 1. Sea Conditions and Craft Average Speeds

Parameter	Run I	Run II
Significant Wave Height (feet)	4.6	2.1
Average Wave Period (sec)	5.2	5.6
Craft Average Speed (knots)	20.1	35.2

³ MR_{SRS} calculations in this report use a natural frequency of 8 Hz and 22% damping.

⁴ Located in southeast Virginia at the mouth of the Chesapeake Bay.

Seat Installations

Two identical shock isolation seats were installed side-by-side in the craft cabin just aft of the coxswain position [1]. The back of each seat was approximately 1.5 ft (0.45 m) forward of the craft's longitudinal center of gravity (LCG). The spring-damper assembly for the seat installed on the starboard side was removed and the seat was fixed rigid using a securely fastened rigid link. It is referred to herein as the fixed seat. The port side seat, with the original passive spring-damper assembly is referred to herein as the shock isolated seat.

Each seat was outfitted with identical 175 lb (79.4 kg) ballast bags⁵ as seat payload to simulate seat occupant weight. They were secured to the seat using ratchet straps in a manner that did not compress the seat cushion beyond the static payload compression.

Data Acquisition and Processing

The acceleration data presented in this report was recorded by vertically oriented accelerometers⁶ secured to the deck adjacent to each seat, on the seat pan (i.e., the seat frame above the spring-damper assembly), and fixed to the seat pad below the center of each simulated occupant weight (referred to herein as the pad sensor location). Figure 2 shows the deck, pan, and pad accelerometer locations for the fixed seat.

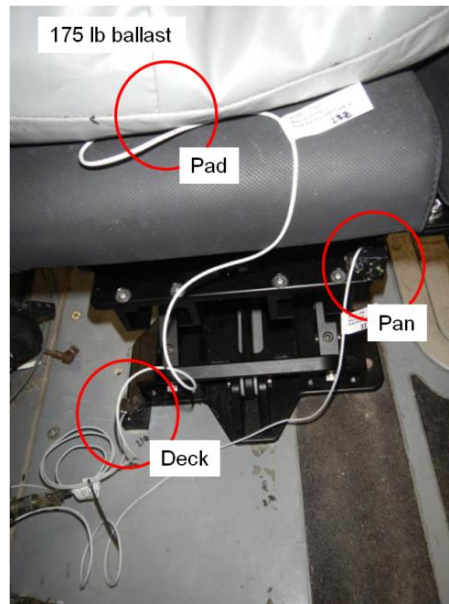


Figure 2. Deck, Pan, and Pad Accelerometer Locations for the Starboard Fixed Seat

Each run provided acceleration signals that were recorded over a 10-minute period. Reference 1 describes measurement system details and gage accuracy. The recorded unfiltered acceleration data was input into a Fast Fourier Transform (FFT) algorithm to investigate the rigid body content and vibration signal content in each record. Example FFT plots are shown in

⁵ Each large ballast bag contained five small 25-lb (11.3 kg) tightly packed sand-filled ballast bags.

⁶ The vertical direction of the gage is oriented normal to the deck, thus a craft reference frame vice earth.

Appendix C. A 20 Hz low-pass filter was selected to estimate the rigid body content in each acceleration record. The rigid body acceleration (i.e., heave acceleration) is a measure of the shock force acting in the vertical direction during each impact.

Peak Acceleration Comparisons

The rigid body peak acceleration is not the only parameter that should be used when comparing shock severity⁷, but peak acceleration comparison plots like the one shown in Figure 3 are useful for quick-look analyses to assess general trending. For this plot the StandardG algorithm was used to extract peak accelerations from the deck accelerations recorded during the 10-minute runs at the base of the rigid and isolated seats. The algorithm was run within the DADiSP[®] software environment. A 20 Hz low-pass filter was used to estimate the rigid body peak accelerations⁸. The development of StandardG is described in reference 23⁹.

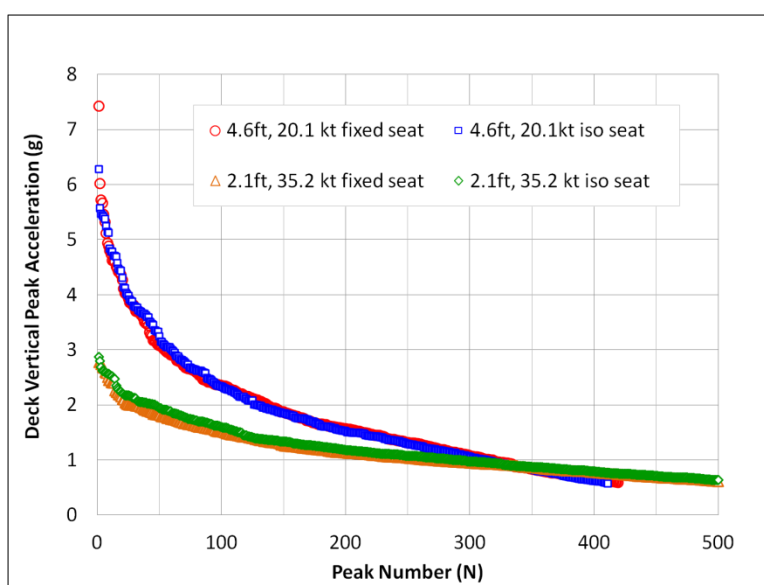


Figure 3. Plot of Peak Deck Accelerations and Calculated Averages

In Figure 3 the peak accelerations at the deck for each wave impact with amplitudes greater than the root-mean-square (rms) acceleration are plotted largest to smallest for each run. The largest peak acceleration for each run (A_{MAX}) and the other acceleration statistics are shown in the table insert. The number of wave impact peaks (N) for each gauge location is also tabulated. The plot shows that the largest deck peak accelerations recorded during Run I (4.6 ft significant,

⁷ Shock severity is also a function of shock pulse shape, rate of acceleration application (i.e., jerk), and pulse duration.

⁸ The low-pass filter in DADiSP is a Kaiser window, finite impulse response, with 24 Hz stop band, 5% pass band ripple, and 1% stop band attenuation. StandardG tabulates the peak accelerations greater than the RMS value of an entire acceleration record.

⁹ The StandardG algorithm can be obtained free of charge by contacting the Branch Head of the United States Naval Academy Hydrodynamics Laboratory. Contact information is available at www.usna.edu/Hydrodynamics/Contact.php.

20.1 kt) are 2 to 3 times larger than the largest peaks recorded during Run II (2.1 ft significant, 35.2 kt). Many of the data plots in later sections therefore focus on the more severe Run I results.

Figure 4 shows deck and seat pad peak acceleration comparisons for each wave impact from StandardG output for the fixed and isolated seats. The red circles are fixed seat data points. The blue squares are the data points for the shock isolated seat when the seat did not experience a seat bottom impact. The black-X indicates when the isolated seat experienced a seat bottom impact (i.e., it bottomed out)¹⁰. The dashed blue and red lines have slopes of 1:1 and 2:1, respectively. The format of this ride severity plot is convenient because any data point above the blue dotted line (1:1) means the pad peak acceleration is greater than the deck peak acceleration (i.e., an indication of amplification of the deck input peak acceleration).

The red circles in the figure show that the pad peak accelerations recorded on the fixed seat pad are greater than the deck input peak accelerations (above 1:1 slope line) for all but three wave impacts¹¹. In other words on the fixed seat the pad peaks are almost always greater than the deck peaks by a factor as high as a factor of 2 (i.e., the dashed red line has a slope of 2 to 1). This is the first indication that the fixed seat pad amplifies the deck inputs.

For the shock isolated seat pad (blue squares and black-X in Figure 4) the data shows very different trends relative to the deck inputs. Some of the pad peaks are less than the deck peaks indicating mitigation (i.e., below 1:1 line), some are about the same as the deck peaks (on or close to the 1:1 line), and some of the pad peaks are greater than the deck peaks (above the 1:1 line).

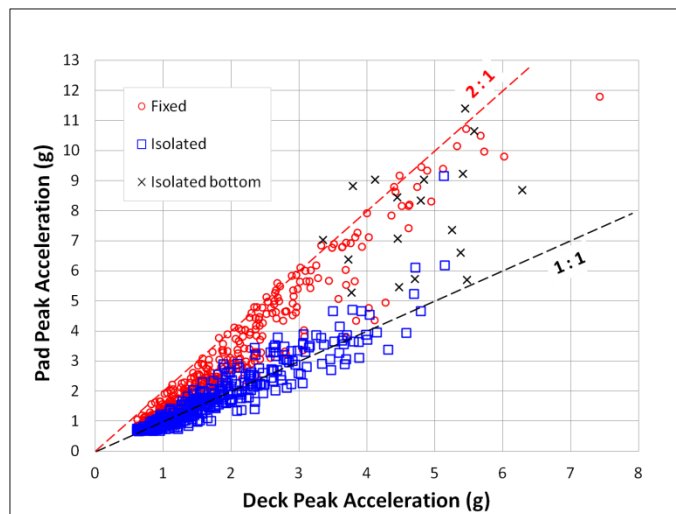


Figure 4. Pad vs. Deck Peak Rigid Body Accelerations (Run I, 4.6 ft, 20.1 kt)

When the isolated pad peaks in Figure 4 are compared relative to the fixed pad peaks during the same wave impacts there is an interesting result that is initially not intuitive. It suggests that for many impacts the fixed seat pad has higher peak accelerations than the isolated

¹⁰ This occurs when the relative displacement excursion limit of the seat is reached.

¹¹ The amplification phenomenon caused by seat cushions is explained in the next section of this report.

seat pad, even when the shock isolated seat pad was higher than the deck peak acceleration. This is the first indication that the isolated seat pad can have a peak greater than the deck input peak, but still be less than the pad peak on the adjacent fixed seat.

These observations are based solely on peak acceleration comparisons. The next section presents shock severity comparisons that also take into account differences in shock pulse shapes, pulse durations, and jerk. Additional plots comparing peak accelerations for Run I and Run II are presented in Appendix A.

Acceleration Time History Plots

The full 10-minute acceleration time histories (unfiltered and 20 Hz low-pass filtered) are shown in Appendix C for Run I and Run II. During both runs more than 400 wave impacts were recorded. Before presenting seat mitigation results it is important to understand the cause and effect relationships associated with seat shock input and shock response motions. Knowledge of these effects provides a foundation for understanding the results of the mitigation calculations. The following paragraphs explain the physical differences between a typical fixed seat response and the isolated seat response during the same wave impact.

Figure 5 shows an example of accelerations recorded during Run I on the fixed seat for a wave impact that occurred at approximately 112 seconds (i.e. slam # 112). It includes unfiltered and 20 Hz low-pass filtered data for the deck, pan, and pad locations. The large 9 g to 11.9 g spikes in the red unfiltered pan data are caused by chatter (i.e., high frequency vibration on the order of 100 Hz) in the seat pan assembly.

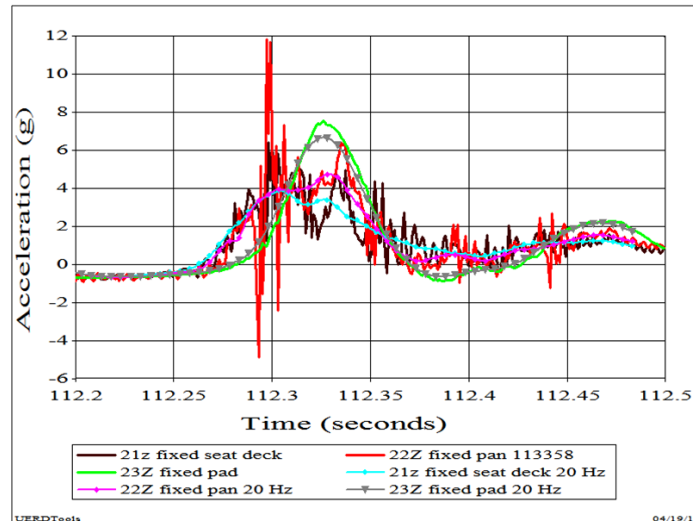


Figure 5. Shock Input and Fixed Rigid Seat Responses at 112 Seconds¹²

¹² UERDTools, a general purpose software package, was used to process and create all time history plots [19].

During the initial shock loading period the magenta 20 Hz seat pan response in Figure 5 follows the same rate of force (acceleration) application (i.e., jerk) as the blue 20 Hz deck input acceleration (indicating the relatively rigid link between the deck and the pan). But on the fixed seat pad (green curve) the acceleration increase is delayed due to the compression of the seat pad. This delay of the seat pad response results in an amplification phenomenon previously reported for jet fighter ejection seats and high speed craft seats [5-7]. Seat pad amplification on the fixed seat is observed during almost all of the wave impacts in the acceleration record. The amplification is discussed further in Appendix A.

Recorded accelerations for the isolated seat during the same Run I slam 112 are shown in Figure 6. The same colors are used for the pad, pan, and deck as the curves for the fixed seat shown in Figure 5. The 20 Hz deck input acceleration (blue) amplitude and duration are almost the same as the fixed seat, and the same chatter caused by high frequency vibrations is observed in the red unfiltered pan data. But the response of the green isolated seat pad is very different than the green fixed seat pad response shown in Figure 5.

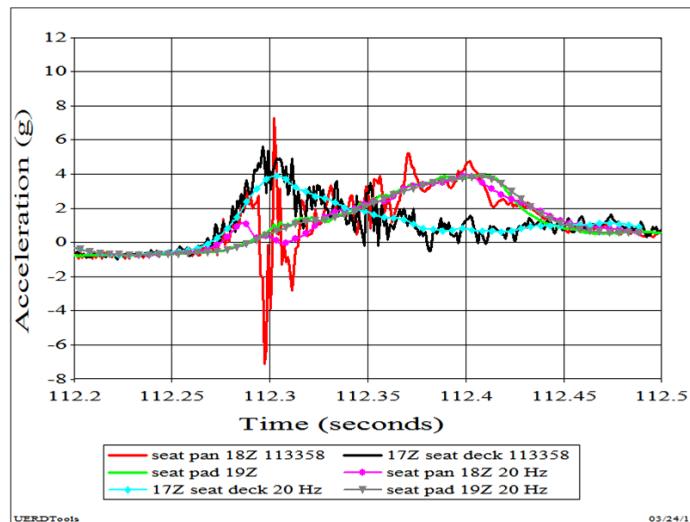


Figure 6. Shock Input and Shock Isolated Seat Responses at 112 Seconds

In Figure 6 the magenta isolated pan acceleration and the green isolated pad acceleration are the same throughout most of the response period. This shows that the compression of the spring-damper assembly extends the time period over which the shock input force is applied. This results in isolated pad (i.e., cushion) and isolated pan accelerations that have a lower slope (jerk) and lower peak acceleration than the fixed seat.

Figure 7 compares the rigid body (20 Hz low-pass filtered) acceleration responses from Figures 5 and 6 for the fixed seat and the isolated seat. The rigid body accelerations are directly proportional to the forces acting during the load transfer process through the seat assemblies. The following descriptions explain the different responses for the fixed and isolated seat pads.

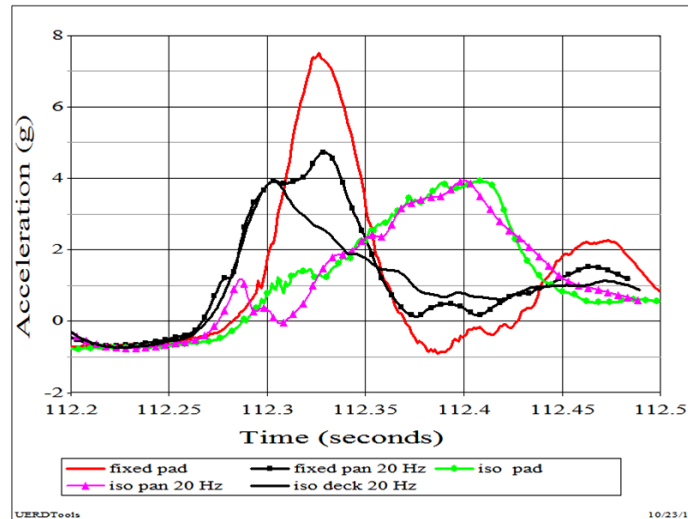


Figure 7. Comparison of Fixed and Shock Isolated Seat Responses

In Figure 7 only the deck input acceleration for the isolated seat (black curve) is shown for simplicity¹³. On the fixed seat the pan response (black with circle) is nearly identical to the deck input (solid black) during the pre-impact negative acceleration phase. During this phase the deck and the seat payload mass reach the same negative (downward) velocity prior to impact. The momentum of the simulated seat occupant (i.e., the payload mass) in the fixed seat is about the same prior to impact as the momentum of the payload mass in the isolated seat. When the impact occurs, the deck, seat pans, and seat pads immediately begin to accelerate (i.e., caused by the positive upward force of the impact). On the fixed seat the pan acceleration (black circles) increases at the same high rate (i.e., jerk) as the deck acceleration (black) due to the rigid link. On the isolated seat the pan (magenta triangles) begins to increase with a slight delay at about the same high rate (jerk) as the deck (black), until about +1g is achieved. At this point in time the upward force is sufficient to compress the spring and the pan acceleration decreases toward zero.

On the fixed seat the compression of the pad delays the time at which the majority of the shock force is transferred to the fixed seat payload. The pulse duration on the fixed pad is therefore shorter than the pulse duration on the deck. The force transfer over a shorter period of time requires a higher shock force (i.e., peak acceleration) on the fixed pad (7.5 g red) compared to the fixed seat deck force (3.9 g black). This results in peak shock force (i.e., acceleration) amplification of the deck input caused by compression of the fixed seat pad.

On the isolated seat when the force through the spring-damper assembly reaches about +1 g the isolated pan acceleration (magenta triangles) drops back to zero due to the compression of the spring. As spring-damper compression continues the much lower acceleration rate (jerk) on the isolated pan (magenta triangles) and the isolated pad (green circles) are about the same until the peak acceleration on the pan is reached. The lower acceleration rate (i.e., jerk) is caused by compression of the spring-damper assembly which results in a longer period of time (i.e.,

¹³ Both fixed and isolated seat deck inputs are nearly identical with peak acceleration inputs of 3.9 g (20 Hz) and 118 msec shock pulse duration.

duration) for shock force transfer¹⁴. Although slight pad compression and extension is observed by the relative oscillation between the isolated pan acceleration (magenta triangles) and the isolated pad acceleration (green circles), the fact that the two curves are about the same when the 3.9 g peak is achieved indicates the isolated pad did not compress enough to lead to significant amplification as observed on the rigid seat pad. The lower jerk on the isolated seat and the longer pulse duration on the isolated seat pad are indications of mechanical shock attenuation for seat occupants. This will be demonstrated in the next section. Additional time history plots of individual wave impacts are shown in Appendix D.

Shock Response Spectrum Mitigation Ratios

The shock mitigation metric that accounts for all the important shock parameters, including peak acceleration, pulse duration, jerk, and pulse shape, is the SRS mitigation ratio obtained using equation (1). For slam 112 shown in Figures 5 and 6 the calculated mitigation ratio is 1.58 for the fixed seat and 0.86 for the isolated seat. In other words the pad on the fixed seat amplified the deck shock input 58 percent, while the isolated spring-damper-pad assembly mitigated the deck shock input 14 percent (i.e., $1 - 0.86$).

As another example, Figure 8 shows the calculated MR_{SRS} values for the wave impact at 300 seconds when a seat bottom impact occurred. The isolated seat MR_{SRS} value is 1.20 (i.e., 20 % amplification). The fixed seat MR_{SRS} value is 1.63. Even though the isolated seat bottom impact occurred, it amplified the deck input less than the fixed seat assembly.

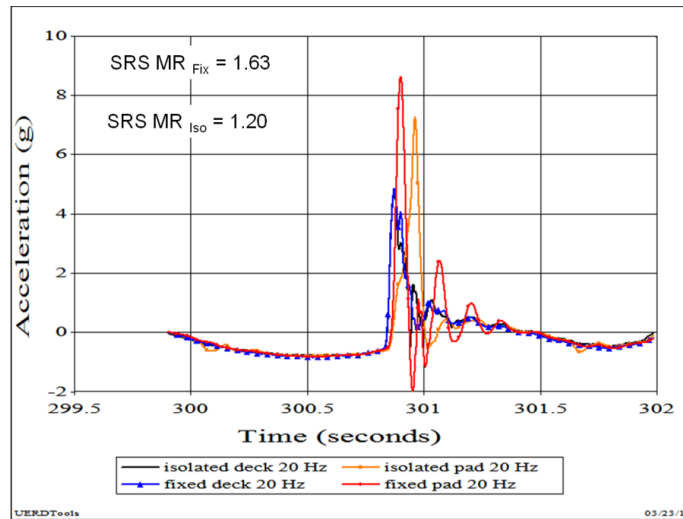


Figure 8. Mitigation Ratio for Isolated Seat Bottom Impact

More than 400 individual wave impacts were recorded during each of the two runs. Run I was the more severe run with deck peak accelerations up to about 7 g. For this run the mitigation performance analysis included calculations for all wave impacts with deck input peak accelerations equal to or greater than 3 g (51 wave impacts) and a sampling of deck inputs

¹⁴ The time and shape of the isolated pan and isolated pad responses depends upon the force-deflection characteristics of the spring-damper and seat cushion material.

between 1 g and 3 g (41 impacts). Run II was much less severe. The largest peak acceleration was only 2.6 g (+/- 0.2 g). The Run II analysis therefore included only the 45 most severe wave impacts.

The time history accelerations for deck, pan, and pad locations for all 137 wave impacts were used to compute shock response spectra and mitigation ratios for the fixed and isolated seat locations¹⁵. Appendix B explains the computational process. All computed mitigation ratios are tabulated in Appendix E. Computed MR_{SRS} values for Run I are compared in Figure 9 as a function of the isolated seat deck peak acceleration.

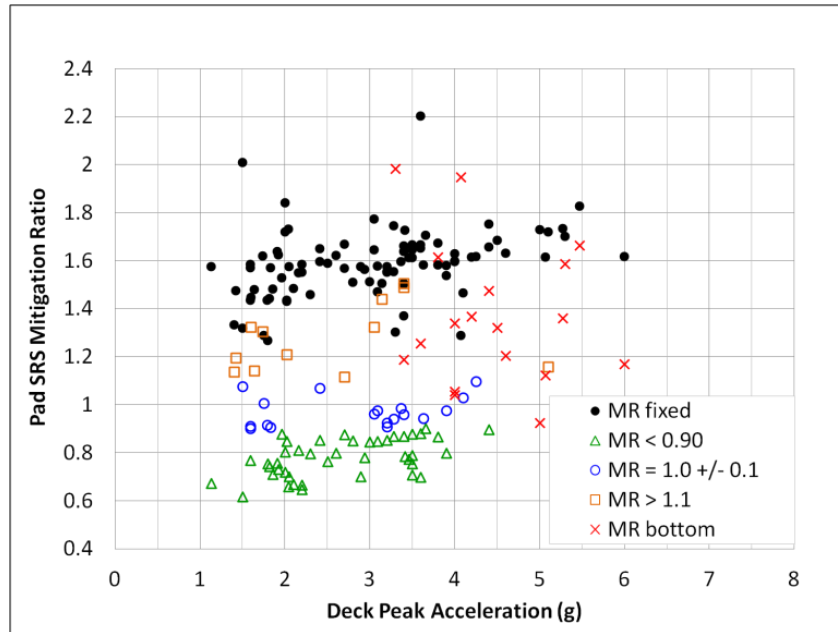


Figure 9. Run I Isolated Seat Pad MR vs. Fixed Seat Pad MR

For the isolated seat the MR_{SRS} values vary from 0.61 to 1.98¹⁶. The black circles are for the fixed seat pad. The isolated seat pad MR_{SRS} values are grouped in four categories: values less than 0.9 (46 green triangles), values equal to 1.0 +/- 0.10 (19 blue circles), values great than 1.10 for non-bottom impacts (13 orange squares), and bottom impacts (20 red X). The non-bottom impacts with $MR < 0.9$ show an increasing trend from 0.6 to 0.9 as the deck input acceleration varies from roughly 1.5 g to 4.4 g, but the scatter is roughly the same order of magnitude as the increase, so the trend is very slight. No seat bottom impacts occurred for deck input peak accelerations less than approximately 3.3 g. Both plots show that the pad (i.e., cushion) on the fixed seat amplified all the deck shock inputs.

¹⁵ The computational process uses a consistent 4-zero crossing time history that spans a wave encounter sequence as shown in Figure 8.

¹⁶ In an earlier investigation it was found that the craft's angle of wave impact may have been contributing to the range of MR values greater than 1.0 for non-bottom impacts [24]. The implication is that the angle of incidence off the vertical may affect the performance of the spring-damper assembly, perhaps caused by friction or binding in the seat spring-damper assembly. The different durations of the wave slams also contribute to MR value variation.

Figure 10 shows the MR_{SRS} values for Run I and Run II. There were no bottom impacts observed during Run II. The red X symbols indicate bottom impacts on the isolated seat and the blue circles are the MR values for no bottom impacts on the isolated seat. Run II values are the green squares. During Run II there were 6 of 45 impacts that resulted in seat dynamic amplification (i.e., $MR > 1.0$ with no bottom impact). During the more severe Run I there were 35 of 92 impacts that resulted in isolated seat pad dynamic amplification (i.e., $MR > 1.0$) and 57 impacts with $MR < 1.0$. The dotted blue line in the figure has a slope of 1.0, so values above that line are for impacts where the isolated seat was more severe than the fixed seat. All but three of the data points fall below the dotted line, indicating that the fixed seat pad was more severe than the isolated seat pad for 132 of the 135 impacts analyzed.

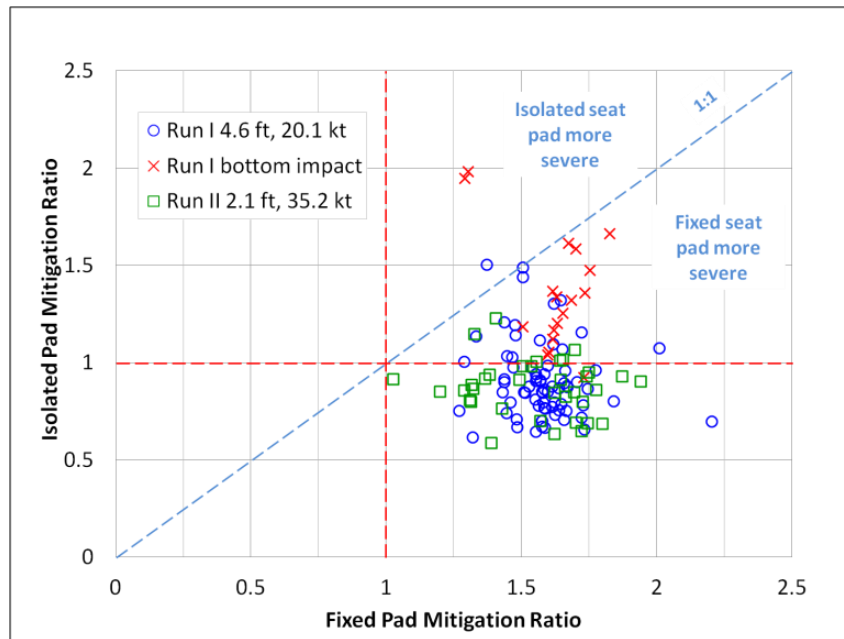


Figure 10. Run I and Run II Isolated Seat Pad MR vs. Fixed Seat Pad MR

The cumulative distribution plots for the fixed and isolated seat MR values are shown in Figure 11. On the isolated seat pad 62% of the MR_{SRS} values are less than 1.0 during Run I (blue circles). During Run II (green squares) 87% were less than 1.0. For both runs the fixed seat pad MR_{SRS} values are greater than 1.0.

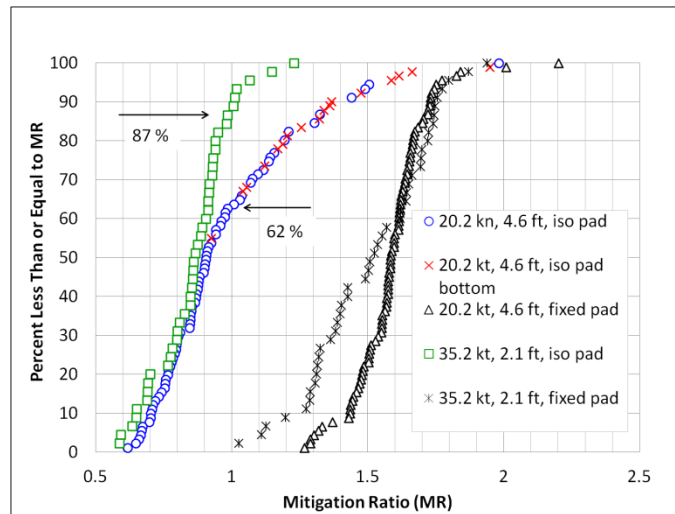


Figure 11. MR Cumulative Distribution Plots for Fixed and Isolated Seat Pads

Isolated Seat Performance Relative to Fixed Seat

The MR_{SRS} values plotted in Figures 9, 10, and 11 are a measure of the shock pulse severity on the seat pad relative to the deck shock input severity. Another comparison parameter is the shock pulse severity on the isolated seat pad relative to the severity on the fixed seat pad. This is obtained by dividing the isolation seat pad MR value by the fixed seat MR value for each wave impact. The resulting ratios for Run I (20.2 kt, 4.6 ft) and Run II (35.2 kt, 2.1 ft) MR values are shown in Figure 12 plotted as a function of the isolated pad MR value for each wave impact.

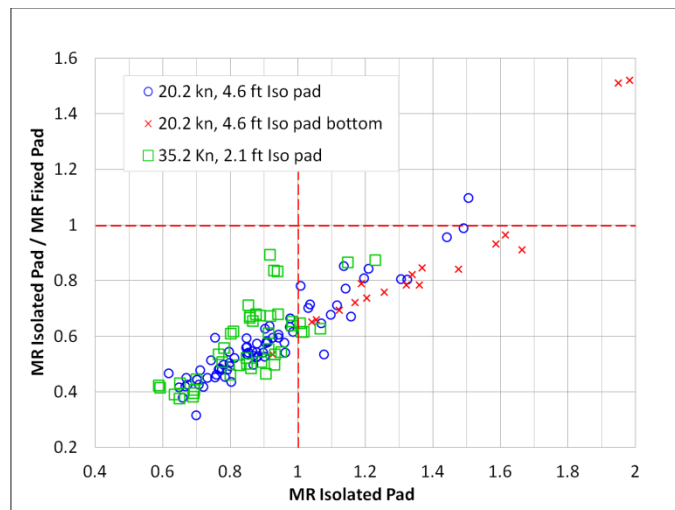


Figure 12. Isolated Pad MR Values Relative to Fixed Pad MR Values

The red vertical dotted line in Figure 12 shows the $MR = 1.0$ line for the isolated pad MR values (i.e., abscissa axis). On the ordinate axis the red horizontal dotted line is the $MR = 1.0$ line for the ratio of the isolated pad MR divided by the fixed pad MR value. When this ratio is less than 1.0 the isolated pad is less severe than the fixed pad. The data clearly shows that the isolated pad shock severity is less than the fixed pad for all but three impacts even when isolated seat bottoming occurs or when the isolated seat causes dynamic amplification of the deck shock input.

The plot shows that when the isolated pad mitigates the shock input by 10 to 40 percent (i.e., MR isolated pad values from 0.9 to 0.6), the shock severity on the isolated pad is roughly 40 percent to 60 percent less severe than the fixed pad severity. When the isolated pad does not mitigate the deck input (i.e., $MR = 1.0$), the isolated pad severity is on the order of 20 percent to 40 percent less severe than the fixed pad severity. When the isolated pad amplifies the deck input from 10 to 65 percent it is still roughly 10 percent to 30 percent less severe than the fixed pad shock severity.

The general trend of the data in Figure 12 shows that as the isolated pad MR value increases past $MR = 1.0$, it approaches an isolated-to-fixed seat ratio of about 1.0, in other words, the amplification of the isolated pad approaches the amplification caused by the fixed pad.

Figure 13 shows Run I cumulative distribution curves for isolated pad MR values (blue circles and red X), the fixed pad MR values (black triangles), and the ratio of isolated to fixed MR values (green triangles and red plus sign). The green triangles show that for 96% of the impacts the isolated pad is less severe than sitting on the fixed pad. It was hypothesized previously, that when seat bottom impacts occur, the shock load would be worse on the isolated seat than sitting on a rigid seat. The data however shows that the opposite is true for this specific seat design; the isolated pad is less severe than the fixed pad, even when most of the bottom impacts occur on the isolated seat.

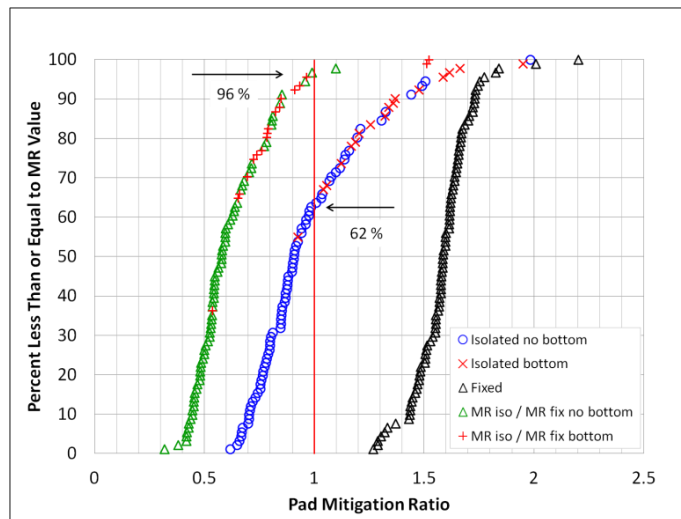


Figure 13. Run I Performance of Isolated Seat Relative to the Fixed Seat

Shock Pulse Durations

Figure 14 compares the pad shock pulse duration with the deck input pulse duration for the fixed seat and the shock isolated seat. The blue dotted line has a slope of 1:1, so any data point above that line is when the pulse duration on the pad is greater than the duration of the deck shock input. All of the pad pulse durations for the isolated seat for no bottom impacts (blue circles) are above the dotted line (i.e., pad duration > deck duration). This is a positive indicator that shock mitigation may be occurring. Figure 6 showed example acceleration time histories when the pad pulse duration is greater than the deck input pulse duration. The combined action of the spring-damper-pad assembly for this seat design is what increases the pad pulse duration.

Data points in Figure 14 below the dotted line are when the pad pulse duration is less than the deck pulse duration. This condition exists for the majority of the data points for the fixed seat pad (green triangles). The shorter pulse duration on the seat pad typically leads to dynamic amplification of the deck shock input. The acceleration time histories in Figure 5 illustrate seat pad amplification.

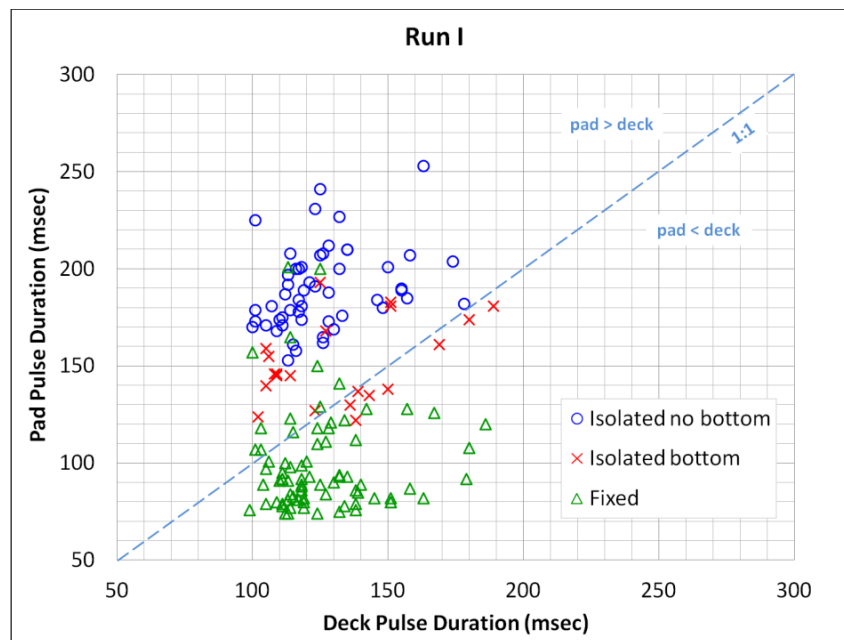


Figure 14. Shock Pulse Durations on Fixed and Isolated Seat Pads

Figure 15 shows how the pad MR values vary with the ratio of the pad pulse duration divided by the deck pulse duration. When the pad pulse duration is larger than the deck pulse duration (X axis greater than 1.0) the data clearly shows there is a greater likelihood that mitigation will occur (isolated seat blue circles). Likewise if the pad pulse duration is less than the deck pulse duration (X axis less than 1.0) the data clearly shows there is a greater likelihood that shock pulse amplification will occur (fixed pad green triangles).

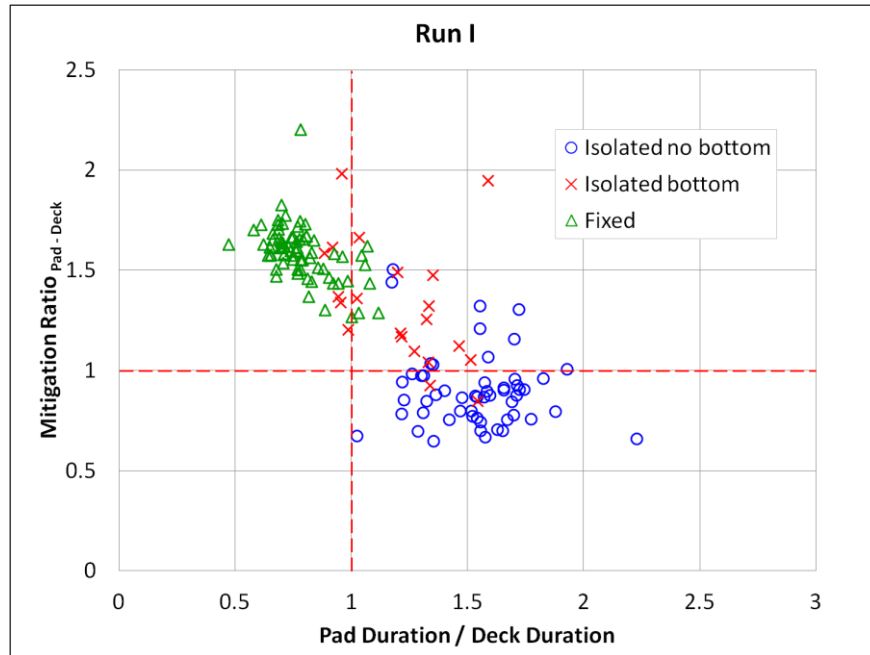


Figure 15. Pad Mitigation Ratio vs. Pulse Duration Ratio

The pulse duration ratio shown in Figure 15 is not the only indicator of shock mitigation. Lower peak acceleration and a lower jerk observed on the pad also affect the magnitude of the seat's mitigation ratio. Shock pulse duration values are tabulated in Appendix E. Additional shock pulse duration plots are presented in Appendix F.

Seat Cushion Dynamic Performance

The dynamic performance of the seat pad (i.e., cushion) relative to the seat pan is shown in Figure 16. The ratio of pad MR values divided by pan MR values ($MR_{PAD-PAN}$) is plotted as a function of the deck input peak acceleration. When the ratio is greater than 1.0 the indication is that the pad amplified the pan shock severity. When the ratio is less than 1.0 the pad mitigated the pan severity. The green data points (Run I triangle and Run II plus sign) indicate that the seat pad amplified the pan severity on the fixed seat for all impacts (i.e., $MR_{PAD-PAN} > 1$). The red X symbols indicate the isolated seat pad amplified the pan severity during all seat bottom impacts.

For non-seat bottom impacts the isolated seat ratios in Figure 16 for Run I (dark blue circles) and the isolated seat ratios for Run II (light blue circles) vary from 0.76 to 1.19. Thirty-nine (33%) of the values are greater than or equal to 1.0. Seventy-nine (i.e. 67%) are less than 1.0, but only twenty (17%) are less than 0.9. It is interesting to note that 98 (77%) of the $MR_{PAD-PAN}$ values for the non-bottom isolated seat impacts fall between 0.9 and 1.1. In other words, the isolated seat pad reduced the pan severity for 67 percent of the impacts, but only by less than 10 percent for most of them. The isolated pad also amplified 33 percent of the impacts, but less than 10 percent for most of them. This suggests that the pad (i.e., the cushion) on the isolated seat had little or no significant effect on the majority of the pan severities for non-bottom impacts. Additional pan and pad data plots are shown in Appendix G.

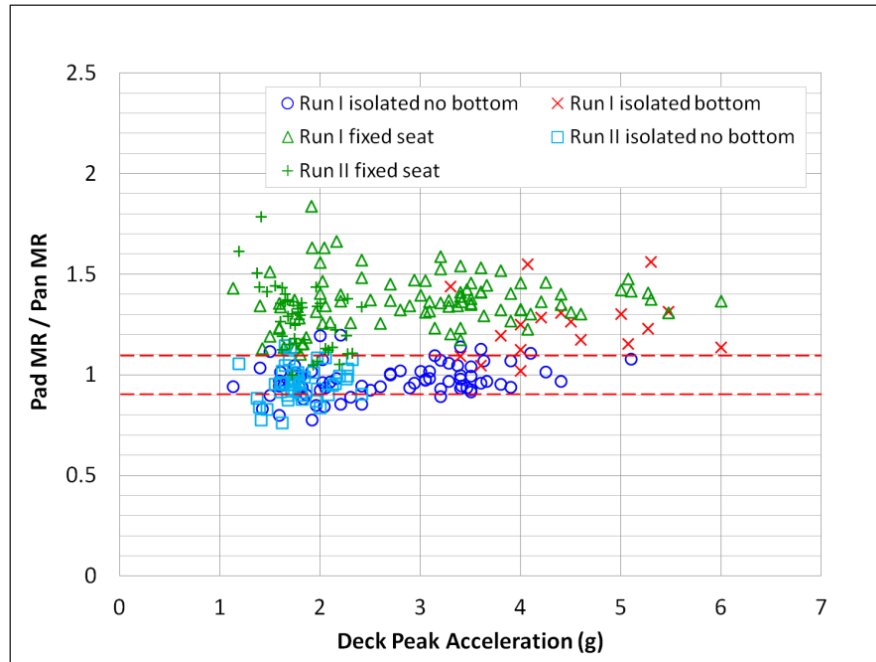


Figure 16. Pad MR Values Relative to Pan MR Values

Seat Occupant Perception

During the 2014 11m cabin RIB trials the side-by-side seats were loaded with ballast weights to simulate the weight of seat occupants. Human perception was not part of the trials. In 2003 however, eight volunteers took part in comparison tests of side-by-side isolated and non-isolated seats [17, 18, 25]. The 2003 test results and the effects of an 80 Hz low-pass filter are summarized in Appendix H. While the craft was operating at high-speeds in rough seas eight volunteers took turns sitting in the different seats and provided their subjective feedback on the comfort of each seat. It is not surprising that the test participants preferred the shock isolated seat as a better ride (i.e., more comfortable) and judged it to be an acceptable ride. They judged the non-isolated (i.e., rigid) seat as unacceptable. What is surprising is that the acceleration data clearly shows that the isolated seat was amplifying many (but not all) of the deck inputs, but not as much amplification as the non-isolated seat. These results are the same as the acceleration data results shown in Figure 13 for the 2014 11m cabin rib trials. The 2014 shock isolated seat amplified some (but not all) of the deck inputs, but not as much amplification as the non-isolated seat. The volunteers in the 2003 trials were able to perceive and judge the comfort of the isolated seat pad relative to the fixed seat pad, but they did not sit on the deck, so they could not perceive when the shock isolated seat was amplifying or mitigating the deck inputs.

OBSERVATIONS

Peak Acceleration Comparisons

Peak acceleration plots like the one shown in Figure 4 (and in Appendix A) are useful for quick-look analyses to assess general trending. Most engineering handbooks and texts that deal with shock use the ratio of input and response peak accelerations to construct a shock transmissibility curve. However, peak acceleration is not the only important parameter to consider when evaluating the effects of long duration shock pulses on seat occupants. The MR_{PEAK} values over-estimated the mitigation ratio for 87% of the wave impacts for the isolated seat and 62% of the impacts for the fixed seat (see Figure A7). The MR_{PEAK} ratio should not be used as the metric for evaluating marine seat mechanical shock mitigation performance.

Seat Cushion Dynamics

The $MR_{ISO-FIXED}$ values in Figure 12 that compare the isolated seat pad relative to the fixed seat pad clearly show that it is better to be sitting on the isolated seat than sitting on the fixed seat during 96% of the impacts analyzed, even when seat bottom impacts and dynamic amplification occurred on the isolated seat. It appears the reason for this is related to the consistent occurrence of seat pad amplification on the fixed seat illustrated by the $MR_{PAD-PAN}$ values shown in Figure 16. On the shock isolated seat however, some pad amplification is observed, especially when seat bottom impacts occurred. For non-bottom impacts the isolated pad mitigated some impacts relative to the pan while amplifying others. The majority (77%) of the non-bottom impacts however had $MR_{PAD-PAN}$ values between 0.9 and 1.1 (i.e., plus or minus 10 percent). The reason the pad does not have a significant effect¹⁷ on the shock isolated seat is shown in Figure 7 by the lower rate of acceleration application (i.e., jerk) on the isolated seat pan. The lower jerk on the isolated pan prevents (or minimizes) seat pad compression that can lead to shock load amplification.

The physical sequence of events shown in Figure 7 are identical to the shapes of pad responses reported during vertical shock tests of anthropomorphic test devices (ATD) in cushioned fixed seats [5, 6]. This suggests that the mass of the ATD may be more relevant than subsequent ATD response motions when evaluating seat mitigation performance for single impacts¹⁸ and that the use of an inert payload (e.g., the ballast bag shown in Figure 2) is sufficient for evaluating shock load transmission through a passive spring-damper assembly.

¹⁷ Here the word significant means greater than roughly plus or minus 10 percent.

¹⁸ The use of an ATD with internal force transducers is a good choice for studying shock load transfer through different seats. But seat mitigation or amplification occurs during the initial compression of spring-damper-cushion configurations, so seat attenuation is probably not affected significantly by subsequent ATD body motions after initial compression. The mass of the ATD provides the significant force that acts during the loading phase (i.e., seat and ATD compression phase), so subsequent ATD arm, leg, and body motions would likely have only a second order effect on seat attenuation. The use of seat payload weights is therefore an acceptable option.

The data presented in Figure 16 and Appendix G clearly shows different levels of mitigation achieved on the isolated seat pan and the isolated seat pad. The pan data is very useful, but the overall dynamic performance of the seat (i.e., its mechanical shock attenuation) must be evaluated using seat pad (i.e., cushion) data and deck data.

Relative Seat Comfort versus Seat Shock Attenuation

The results of the 2003 experiments lead one to question the dichotomy of why a shock isolation seat can amplify deck peak accelerations, but still be judged by seat occupants an acceptable ride relative to a rigid seat. This is not a unique observation. Anecdotal feedback from other recent seakeeping trial participants has been similar. They report that they preferred to be sitting in a shock isolation seat even though subsequent analysis of the acceleration data clearly showed dynamic amplification was occurring. The likely answer to the dichotomy is related to the difference between relative measures of seat comfort and direct measures of shock attenuation.

The analysis results for the 2014 acceleration data lead to the same conclusion as the 2003 experiments when the severity on the isolated seat pad was evaluated relative to the fixed seat pad (i.e., $MR_{ISO\ PAD}$ divided by $MR_{FIXED\ PAD}$). The seat occupants could compare the ride comfort of the isolated seat *relative to* the non-isolated seat (i.e., $COMFORT_{ISO-FIXED}$)¹⁹, but they could not evaluate the comfort of the shock isolated seat pad relative to the deck (i.e., $COMFORT_{PAD-DECK}$) because they did not also sit on the deck with the same pad (i.e., cushion). In other words, seat occupants can evaluate and compare seat comfort between different seats, but they cannot evaluate the mitigation performance (i.e., mechanical shock attenuation) of seats unless they also sit on the deck with the same cushion²⁰.

The preferred method for quantifying the mitigation performance of a shock isolation seat is by comparing recorded acceleration data on the deck with data recorded on the seat cushion.

SRS Mitigation Ratios

The MR_{SRS} ratio is the preferred measure for seat shock attenuation in a wave impact environment because it takes into account in a single computation differences in all the key shock severity parameters, including shock pulse shape, rate of acceleration application (jerk), peak amplitude, and pulse duration. In this investigation the relative displacement SRS was used as the comparison metric for evaluating seat mitigation performance. The relative displacement SRS is used because of its intuitive relationship to shock induced strain and therefore damage potential in a shock pulse.

Three different seat SRS mitigation ratios (i.e., MR values) were used in this investigation. The first was the seat pad MR (i.e., either isolated or fixed) relative to the deck input ($MR_{PAD-DECK}$). It is the preferred measure of mechanical shock attenuation for a shock isolation seat.

The second SRS ratio presented in the report was the isolated pad mitigation ratio divided by the fixed pad mitigation ratio. It is a measure of the severity on the isolated seat pad relative to the shock severity on an adjacent fixed seat pad (i.e., $MR_{ISO-FIXED}$)²¹. It is an important

¹⁹ The word comfort is used here to imply human perceived comfort.

²⁰ This is likely impractical due to different leg positions and body postures.

²¹ The SRS of the isolated pad acceleration was not divided by the SRS of the fixed pad acceleration for this relative comparison because the deck inputs for the fixed and isolated seats are not always equal.

measure for evaluating human comfort and perception that provides results that explain why seat occupants prefer to sit on a passive shock isolation seat (i.e., compared to a fixed seat) even when recorded acceleration data shows that the shock isolation seat was amplifying the deck shock inputs.

The third SRS ratio presented in the report was the seat pad mitigation ratio divided by the seat pan mitigation ratio ($MR_{\text{PAD-PAN}}$). It is a measure of the performance of the seat pad relative to the seat pan for both fixed and the shock isolated seats. It addresses the question, does the pad amplify or mitigate the pan shock severity.

The use of the three different mitigation ratios adds new insight for evaluating the absolute and relative mitigation performance of a passive shock isolation seat, and how seat occupants evaluate relative comfort. The data analysis process used in this investigation can also be applied to laboratory drop test data. The general process is described in Appendix I.

Caveats

The mitigation ratio values presented herein are applicable only to the seats installed in the 11-meter RIB during the 2014 trials. During future trials different seats with different stiffness, different damping, and different seat cushion characteristics will result in different calculated mitigation ratios. In general terms the mitigation performance of the shock isolation seat was primarily a function of wave impact severity (e.g., peak rigid body acceleration) and shock pulse duration. Several key parameters can change these values. For example, peak accelerations will vary primarily with craft displacement, significant wave height, average wave period, craft heading relative to waves, and craft average speed. Shock pulse durations vary primarily with craft displacement, craft speed, craft heading, and where the craft impacts a wave (e.g., leading flank, crest, following flank). Any changes in these variables in future trials would tend to shift the data points presented herein. But, for any specific deck peak input acceleration (e.g., 4 g) and shock pulse duration (e.g., 150 msec), the shock mitigation performance of the seat would be expected to be similar to what was observed during the 2014 trials²². In other words, for future trials the sea condition statistics and craft characteristics may change, but the ability of the seat to mitigate a wave impact is a deterministic phenomenon that remains primarily a function of shock input peak acceleration and shock pulse duration.

CONCLUSIONS AND RECOMMENDATIONS

In this investigation three different shock response spectrum (SRS) mitigation ratios (MR) were used to study the effects of wave impact shock pulses on side-by-side fixed rigid and shock isolated seats.

First, the MR for the fixed seat and the isolated seat were obtained by dividing the seat pad response SRS by the deck input SRS. This is a measure of the seat pad shock response severity

²² This is based on assuming the wave impact pulse shape follows the classic half-sine pulse shape and the impact force vector is parallel to the vertical axis of the seat.

relative to the deck shock input severity, $MR_{PAD-DECK}$. It is a direct measure of the mechanical shock attenuation performance of a shock isolation seat.

Second, the relative MR for the isolated seat was obtained by dividing the SRS MR value for the isolated seat pad by the SRS MR value for the fixed seat pad. This is a measure of the isolated seat pad severity relative to the fixed seat pad severity (i.e., $MR_{ISOPAD-FIXEDPAD}$). It is a measure closely related to human perception of the relative comfort for different seat pads.

Third, the MR of the seat pad relative to the pan was obtained by dividing the SRS MR value for the seat pad data by the SRS MR value for the seat pan data for both fixed and isolated seats. This $MR_{PAD-PAN}$ ratio is a useful measure for evaluating the effects of the seat pad (i.e., the seat cushion) on fixed and shock isolated seats.

The $MR_{PAD-DECK}$ for the isolated seat relative to the deck indicates that the seat analyzed in this investigation mitigated (i.e., $MR < 1$) 62% of the 92 individual wave impacts that were analyzed. The mitigation of the isolated seat pad relative to the fixed seat pad, $MR_{ISO-FIXED}$ indicates that the severity on the isolated pad is less than the severity on the fixed pad for 96% (89 of 92) of the impacts analyzed, even when dynamic amplification and seat bottom impacts occurred for isolated seat. This explains why seat occupants prefer to sit in shock isolation seats rather than fixed seats even when recorded data subsequently shows the isolated seat was amplifying deck shock inputs (i.e., either dynamic amplification or seat bottom impacts).

The $MR_{ISOPAD-FIXEDPAD}$ relative measure of seat performance explains why seat occupants can evaluate and compare seat pad comfort between different seat pads while underway in high-speed craft, but they cannot evaluate the mechanical attenuation performance of a shock isolation seat unless they also sit on the deck with the same pad (i.e., $MR_{PAD-DECK}$). It is therefore recommended that the mitigation performance of shock isolation seats continue to be determined during seakeeping trials and during laboratory drop testing by comparing the SRS of acceleration data recorded at the deck with the SRS of acceleration data recorded on the seat pad.

In this study, shock response spectrum mitigation ratios for the shock isolated seat were computed using both the seat pan acceleration data and the seat cushion (i.e., pad) data. These comparisons show that the seat pad (i.e., cushion) is an important element in the spring-damper-pad assembly. Seat pad amplification of the input shock pulse was observed in this study for the fixed seat and for some of the isolated seat impacts. It is therefore recommended that the overall performance of a shock isolation seat continue to be quantified by comparing seat pad acceleration data with deck acceleration data. The results show that the pad on the isolated seat did not exhibit the same level of amplification observed on the fixed seat unless seat bottom impacts occur. These results are preliminary, but the data suggest that the use of more firm pads to prevent seat pad amplification may not be required for marine shock isolation seats. The results suggest the compression of the spring-damper assembly can significantly reduce or prevent pad amplification observed on the fixed rigid seat. Seat comfort over long periods of underway time is still very important.

The data presented herein also demonstrates that the ratio of peak acceleration recorded on the seat pad and the peak acceleration on the deck should not be used to evaluate the mechanical shock attenuation performance of marine shock isolation seats. Peak acceleration ratios do not take into account important differences in pulse shapes, pulse durations, or jerk. The SRS mitigation ratio is the preferred measure of seat mitigation performance.

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APPENDIX A. AMPLIFICATION OF DECK SHOCK INPUTS

Seat Bottom Impact

Passive shock isolation seats are installed in small high-speed craft to reduce the severity of shock forces caused wave impacts. If the spring-damper assemblies are not designed properly they will cause higher shock severities on the pad than on the deck at the base of the seat. Two different phenomena can lead to this undesirable result. The first one is very intuitive. It is referred to as seat bottom impact. Figure A1 shows an example of seat bottom impact in the unfiltered acceleration data recorded at the base of a shock isolated seat (black curve) and on the seat pan (red curve). The event is characterized by very large negative and positive acceleration spikes (e.g., > 20 g). The acceleration spikes occur when the spring bottoms-out due to metal-to-metal contact across the spring.

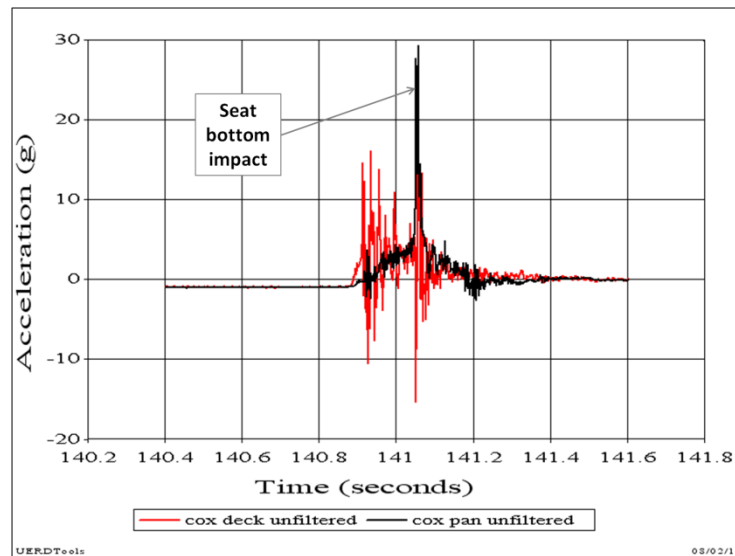


Figure A1. Example of Seat Bottom Impact

The second undesirable phenomenon is referred to as seat dynamic amplification. It is caused by pulse-period mismatch.

Pulse-Period Mismatch

An example of dynamic amplification caused by pulse-period mismatch is shown in Figure A2. The black curve is the 20 Hz low-pass filtered acceleration on the deck at the base of a shock isolated seat. The red curve is the 20 Hz low-pass filtered seat pan acceleration. The seat

pan 3.5 g peak acceleration (red) is greater than the 2.5 g deck peak acceleration with no indication of the occurrence of a seat bottom impact (i.e., peaks > 10 g). This is an example of dynamic amplification of the input shock pulse due to pulse-period mismatch.

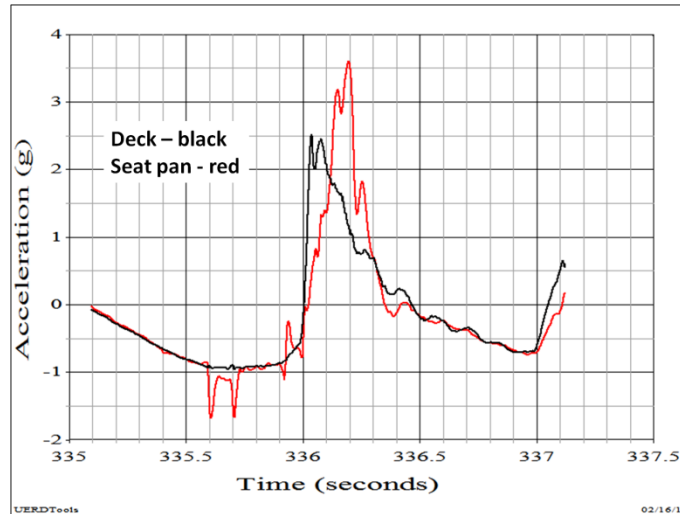


Figure A2. Dynamic Amplification Due to Pulse-Period Mismatch

The goal of shock isolation system design is to ensure that the mechanical properties²³ of the isolation system are properly tuned to avoid shock amplification²⁴. If not properly tuned it leads to pulse-period mismatch. The physical characteristics that result in pulse-period mismatch and dynamic amplification are illustrated by the shock and vibration transmissibility curves shown in Figure A3. The figure shows classical transmissibility curves for linear single-degree-of-freedom (SDOF) isolation mounts where the X-ordinate axis is the ratio of the natural period of the isolator divided by the natural period of the excitation force²⁵. The blue curves are for a sinusoidal vibration excitation. The red curves are for a half-sine shock pulse. In each set of curves the upper curve is for 10 % damping with successive lower curves for 20 %, 30%, and 40% damping. The Y-ordinate axis is the transmissibility axis, but it is labeled here as the mitigation ratio. In this example the mitigation ratio is the peak response acceleration on the seat pan divided by the deck input peak acceleration. The curves show that there are regions where the mitigation ratio (i.e., transmissibility) is greater than one, meaning the excitation is amplified. In vibration environments this is referred to as a resonant condition. For a shock pulse excitation it is referred to as dynamic amplification²⁶. The design parameter in this simple example that controls effective mechanical shock attenuation (i.e., $MR < 1.0$) is the ratio of the isolator's natural period divided by the shock pulse duration. For the red shock transmissibility curves this means the ratio of the shock pulse duration and the isolator natural period must be greater than approximately 2 to 3 depending upon the damping characteristics of the system. If the ratio is less than 2 to 3 the mitigation ratio will be greater than 1 and dynamic amplification will occur.

²³ Example seat mechanical design parameters include stiffness, damping, and excursion space.

²⁴ This is analogous to properly tuning vibration mounts to avoid resonance.

²⁵ The period of shock excitation for this example is the half-sine pulse duration.

²⁶ This is not seat bottom impact.

For shock pulses a ratio less than 2 to 3 is referred to as pulse-period mismatch. In other words the shock isolator has not been properly tuned for the shock pulse duration.

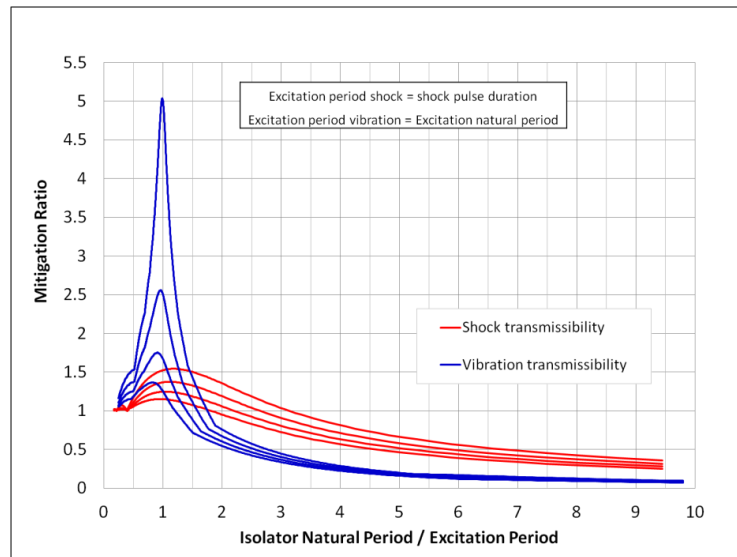


Figure A3. Transmissibility Curves for Shock and Vibration

The next section provides an example time history comparison to illustrate dynamic amplification.

Dynamic Amplification Due to Pulse-Period Mismatch

Figure A4 shows calculated responses of a vertically oriented passive spring-damper SDOF model for two different shock inputs. The SDOF system natural frequency is 2 Hertz (Hz) and the damping ratio is 20 percent.

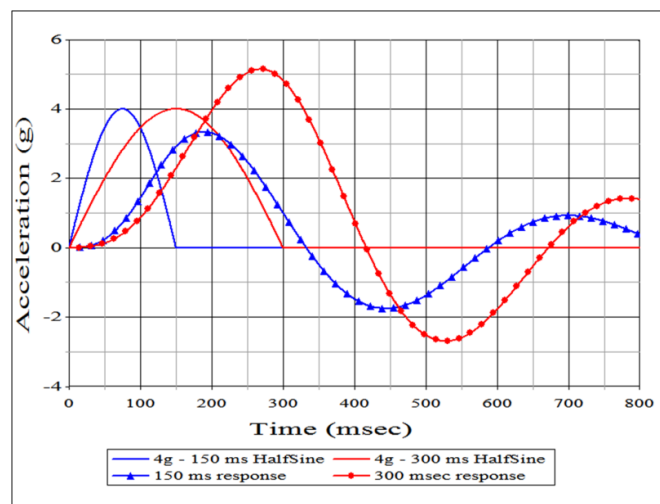


Figure A4. SDOF Model 2 Hz – 20 % Damped Responses

One shock input (blue solid line) is represented by a half-sine pulse with peak amplitude 4 g and pulse duration of 150 milliseconds (msec). The calculated time-history response to this input (shown by the blue line with triangle symbols) reaches a maximum acceleration of 3.33 g. This is an example of shock mitigation. The peak acceleration has been reduced.

The second shock input in Figure A4 is also a half-sine pulse with the same 4 g peak amplitude, but it has a 300-msec pulse duration. The SDOF peak response for this input is 5.14 g. This is an example of dynamic amplification where the response peak acceleration is greater than the input peak acceleration. This is the first indication that if shock isolation seat stiffness and damping properties are chosen incorrectly, the system may amplify the peak acceleration input rather than reduce it.

The ratio of the peak acceleration on the pad divided by the peak acceleration on the deck has often been used as an estimate of the seat pad mitigation ratio (MR_{PEAKS}). Most engineering handbooks and texts that deal with shock use the ratio of input and response peak accelerations to construct a shock transmissibility curve [A1]. This approach is appropriate for shock pulses with durations much less than the natural frequencies (i.e., modes of vibration) of the system subjected to the shock pulse (e.g., shocks caused by blast). But for long duration wave impact shocks the peak acceleration ratio will often overestimate the magnitude of the mitigation ratio (i.e., underestimate mechanical shock attenuation [A2]). This is because the ratio of peaks does not account for differences in jerk and pulse duration between the input and the response accelerations.

Deck Peak Acceleration Comparisons

Figure A5 shows the deck peak accelerations for the fixed seat (blue) and the isolated seat (red) tabulated largest to smallest and plotted as a function of the peak number. This format is used to compute the statistical $A_{1/N}$ values tabulated in the figure. In general it shows that the side-by-side deck peak acceleration amplitudes are very similar except for a few of the largest peaks recorded during Run I. This format however does not show a comparison of peak values that occur during the same wave impact (i.e., peaks are plotted largest to smallest).

In Figure A6 the deck peak accelerations from Figure A5 (i.e., sorted largest to smallest) for the fixed and isolated seats are plotted as X-Y pairs (black triangles). Except for the four largest peaks the plot shows the deck inputs are about the same (i.e., 0.99 slope). The orange triangles compare the deck peaks that occur at the same time for each wave impact. The data shows the deck peak accelerations for a given wave impact are typically not the same, but many are within about 10-percent. Close inspection of the time history data shows eight impacts likely occurred with significant port or starboard roll in addition to the heave acceleration (as indicated by the isolated seat deck peak acceleration not the same as the fixed seat deck peaks). These differences are accounted for in the detailed time-history data analysis procedures. It is interesting to note that the peak accelerations sorted largest to smallest and plotted as X-Y pairs (i.e., the black circles) form a very good average through the variation of orange triangles (i.e., peaks that occur at about the same time).

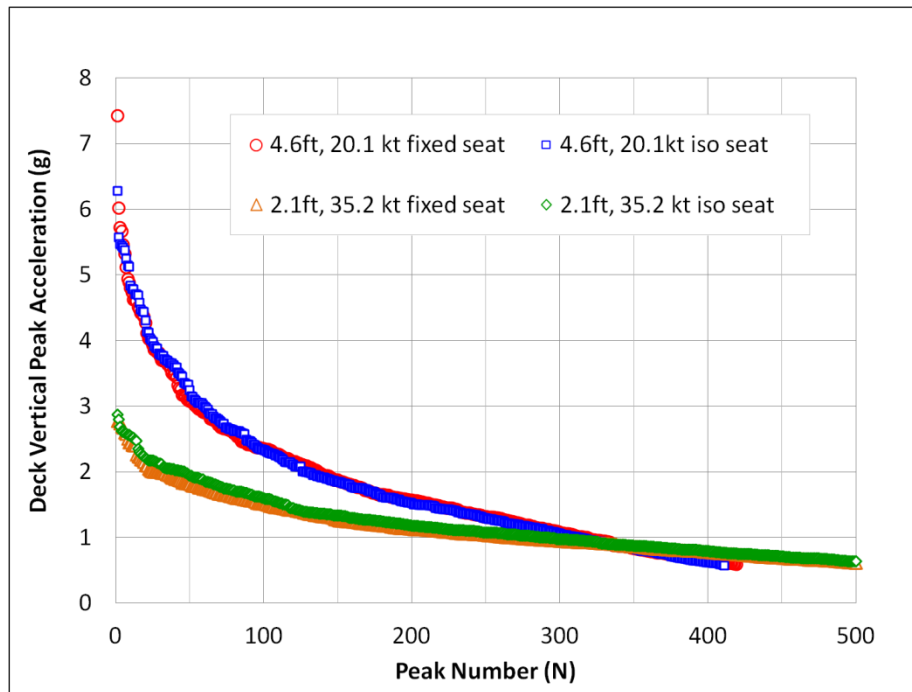


Figure A5. Deck Vertical Peak Accelerations (20 Hz)

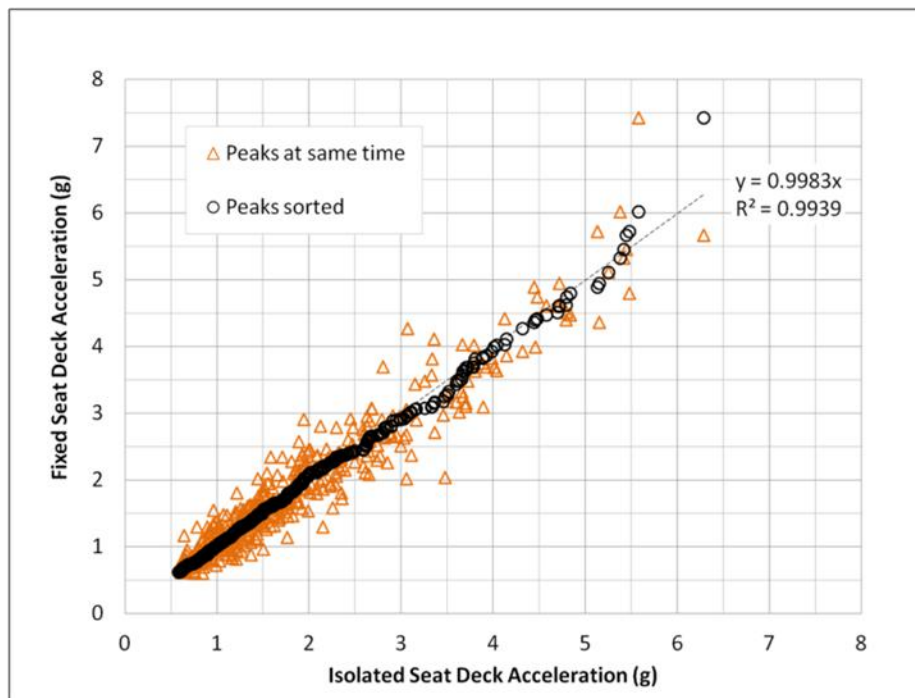


Figure A6. Run I Deck Peak Accelerations at the Same Time (20 Hz)

Fixed Seat Cushion Peak Response vs. Fixed Deck Peak Input

Figure A7 shows that the pad peak accelerations on the fixed seat (red circles) are from 1.0 to 2.0 times larger than the deck peak accelerations during individual impacts. These are peaks that occur at about the same time for each wave impact. There are many impacts where the pad peak is on the order of 10-percent larger than the deck peaks, but there are also many impacts where the pad peak is more than 1.5 times the deck input peak, especially for deck inputs greater than roughly 2.5 g.

The cause of the pad (i.e., cushion) amplification is related to the compliance of the pad. The seat payload weight must experience the same change in velocity as the deck motion, but because the pad compresses (during an impact) further beyond its static position, the payload weight stops in a shorter period of time, thus creating a higher rigid body peak acceleration on the pad. Thus the shock load transferred to the seat payload is amplified by the soft pad.

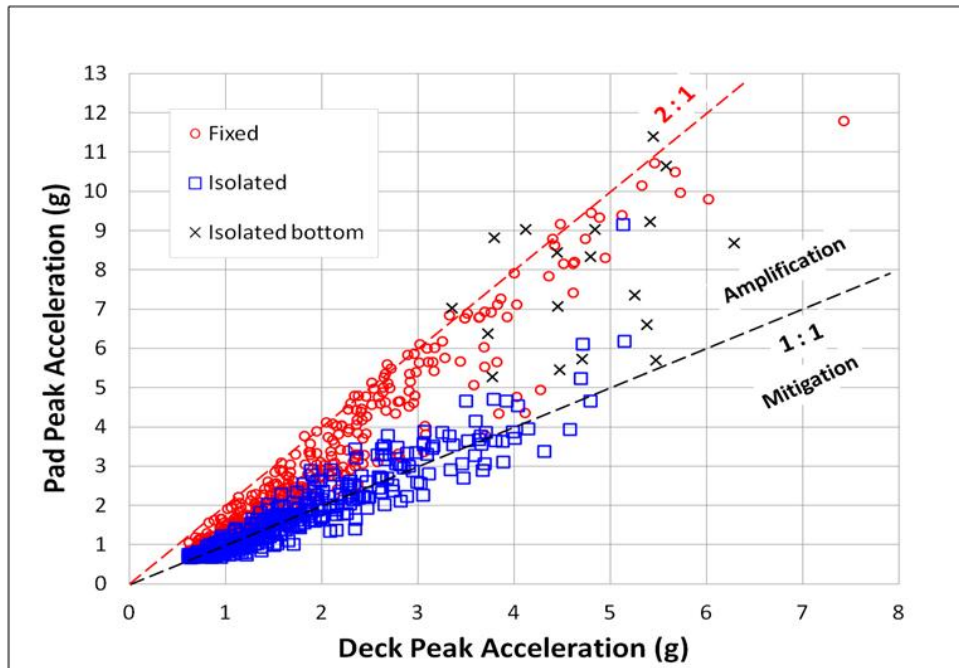


Figure A7. Run I Fixed Seat Pad Peak Acceleration vs. Deck Peak Acceleration (20 Hz)

Isolated Seat Pad vs. Isolated Deck Peak Accelerations (20 Hz)

The blue squares in Figure A7 compare the isolated seat pad peak acceleration with the deck input peak acceleration. The general trend is for the isolated pad peak acceleration to be less than the fixed seat pad acceleration, even when the isolated seat bottoms out during some impacts²⁷. This is investigated further in Figure A8.

The ratio of the pad-to-deck peak accelerations are shown in Figure A8 as a function of the deck input peak acceleration. The ratio is a measure of the reduction in peak acceleration

²⁷ Seat bottom impacts were determined using time history acceleration plots of individual impacts.

between the deck and the pad. A ratio greater than 1.0 indicates the deck peak acceleration was amplified, and a value less than 1.0 indicates it was reduced. All but two of the fixed seat pad-to-deck ratios (black circles and black stars) are greater than 1.0 indicating the seat pad and the seat assembly amplified of the deck peak acceleration for the majority of the impacts. The ratio values for the isolated seat (blue circles and red X) span a range from roughly 0.6 to 1.5. Some seat pad peak accelerations are less than the deck input, and some are greater. The general trend shows that the isolated seat ratios are less than most of the fixed seat ratios.

The peak acceleration ratio of the isolated pad divided by the fixed pad is plotted in Figure A9 as a function of the isolated deck input peak acceleration. This ratio is a measure of the peak pad acceleration relative to the fixed pad peak acceleration. A ratio less than 1.0 indicates the isolated seat pad peak is less than the fixed seat pad peak. The blue circles are for non-bottom impacts and the red X symbol is for the bottom impacts.

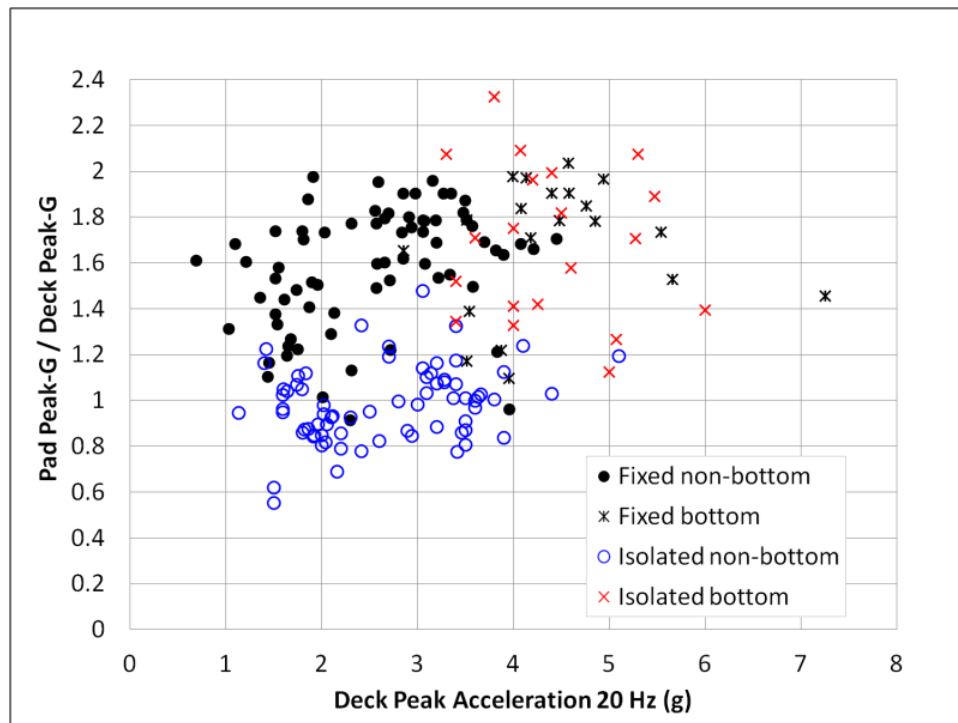


Figure A8. Ratio of Pad to Deck Peak Accelerations (Run I)

The peak acceleration comparisons in Figures A8 and A9 are useful for a quick look assessment of general trends in the data. They illustrate the general trend of larger peak accelerations on the fixed seat than the isolated seat as a result of seat pad amplification on the fixed seat. These results should not however be used for the final assessment of shock load transmission or seat mitigation performance because they do not account for pad and deck acceleration differences in pulse shape, jerk, or pulse duration.

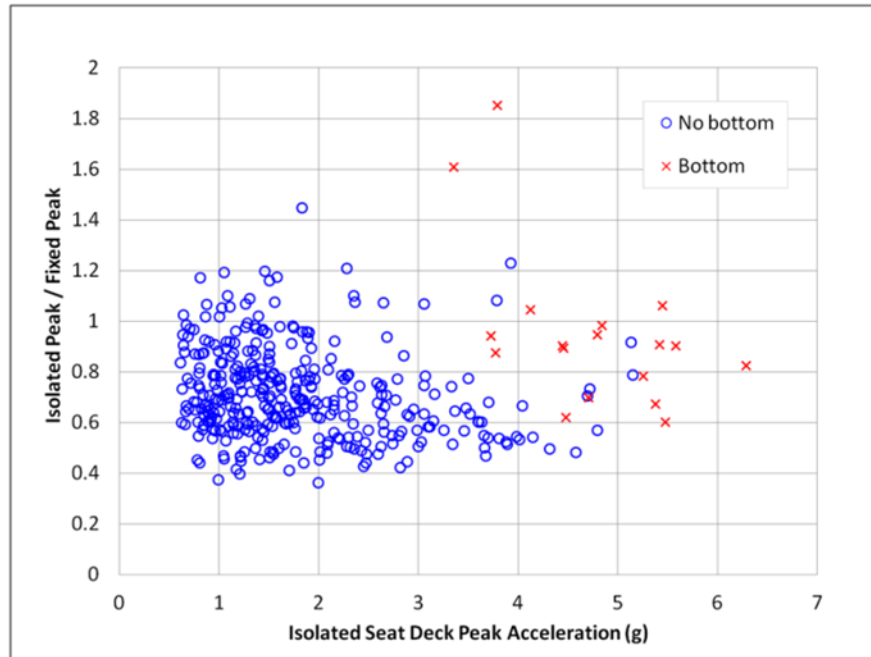


Figure A9. Ratio of Isolated Pad to Fixed Pad Peak Accelerations (20 Hz Run I)

MR_{PEAK} Compared to MR_{SRS}

The acceleration data recorded during the 2014 11m cabin RIB trials was used to construct the plots shown in Figures A10, A11, and A12. The plots indicate that for Run I data the MR_{PEAK} values range from 0.57 to 1.44 for the isolated seat pad and 0.63 to 1.21 for the fixed seat pad. The MR_{PEAK} ratios over-estimate mitigation performance for 87% of the wave impacts on the isolated seat and 62% of the impacts on the fixed seat. These results show why the mitigation performance of a shock isolated seat should not be based solely on peak acceleration values.

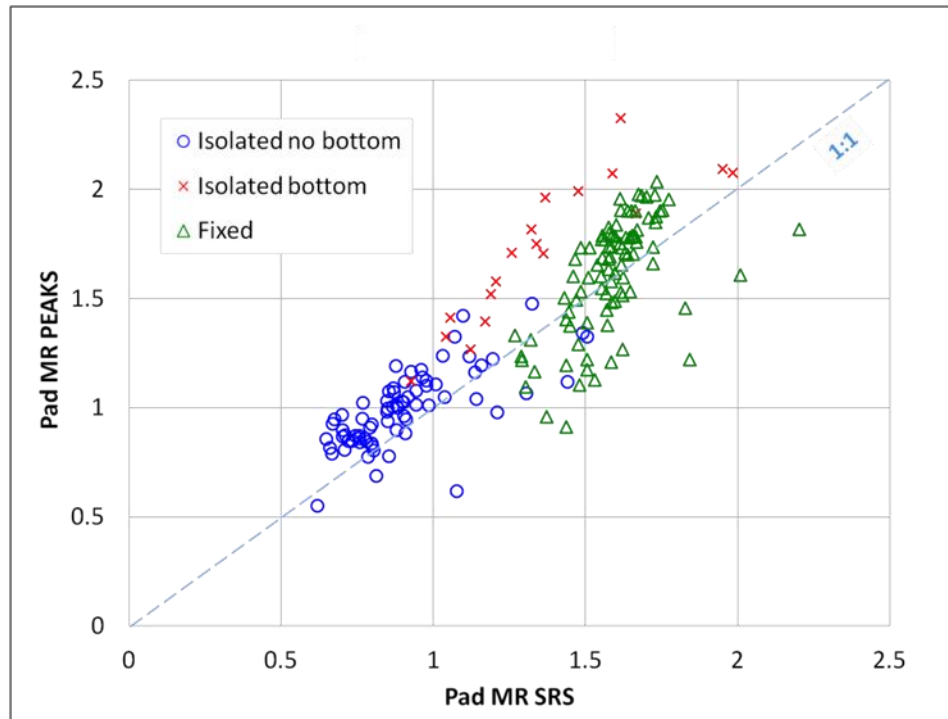


Figure A10. Pad MR PEAKS vs. Pad MR SRS (Run I)

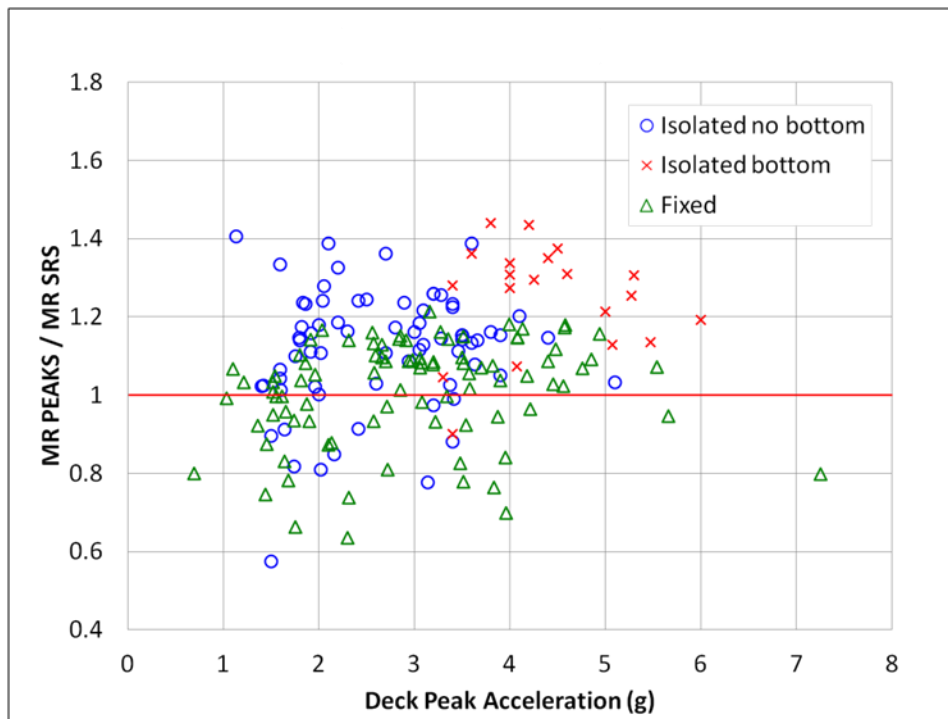


Figure A11. Ratio of MR PEAKS and MR SRS (Run I)

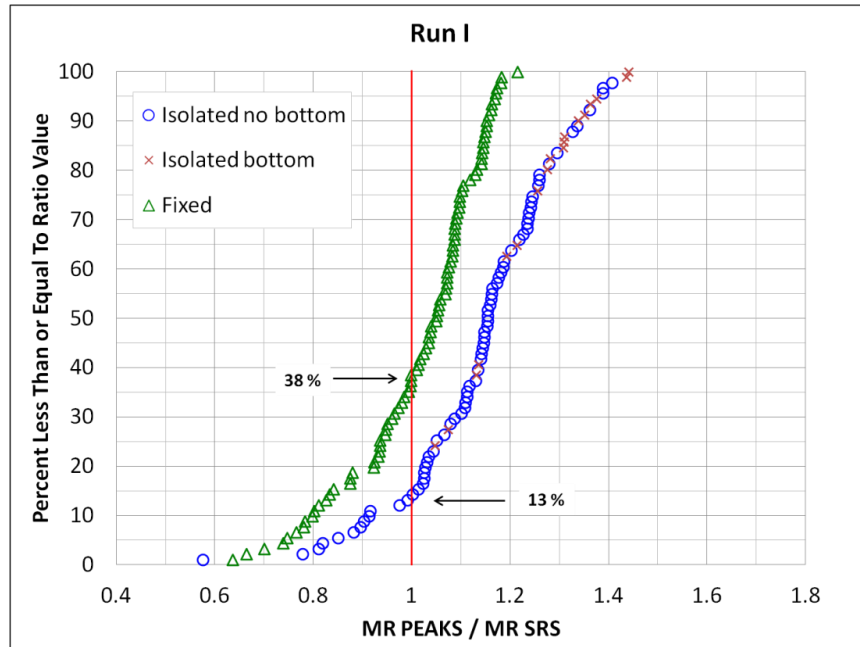


Figure A12. Cumulative Distribution Curves for MR_{PEAKS} / MR_{SRS}

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APPENDIX B. SHOCK RESPONSE SPECTRUM

The shock response spectrum (SRS) is a computational tool used internationally to compare the severity of different shock motions [B1 to B10]. It is also referred to as a maximum response spectrum that can be used to analyze any dynamic event, even vibration signals [B7]. It is especially useful for evaluating and comparing two different shock pulses that have different pulse shapes, peak amplitude, jerk, and pulse duration. It is used in this report as a measure of shock isolation seat mitigation performance by comparing the deck input acceleration SRS with the seat (pad and pan) response acceleration SRS for individual wave impacts.

The SRS uses a model of the single-degree-of-freedom (SDOF) system shown in Figure B1 to compute the effects of an input motion $X(t)$ on the SDOF system. The system has a base attached to a mass (m) by a spring with stiffness k and a damper with damping coefficient c . For a prescribed time varying shock input motion $X(t)$ at the base of the system the resulting response of the mass (m) is $Y(t)$. The relative displacement $Z(t)$ between the base and the mass is $X(t)$ minus $Y(t)$. The equation of motion of the system given by equation (B1) is obtained by summing the inertial force of the mass and the forces within the spring and damper.

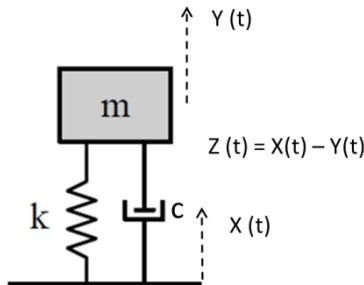


Figure B1. Single-degree-of-freedom Mathematical Model

$$m \ddot{y}(t) = -k z(t) - c \dot{z}(t) \quad (B1)$$

Where t is time and:

$$\omega = \sqrt{\frac{k}{m}} \quad (B2)$$

The undamped natural frequency (f) in Hertz (Hz) of the SDOF system is given by equation (B3).

$$f = \frac{\omega}{2\pi} = \left(\frac{1}{2\pi} \right) \sqrt{\frac{k}{m}} \text{ Hz} \quad (\text{B3})$$

The solution of equation (B1) provides the predicted response motion of the mass (m) caused by the base input motion either in terms of the absolute motion of the mass $Y(t)$ or the relative displacement $Z(t)$ between the base and the mass.

An SRS is the maximum response of a set of single-degree-of-freedom (SDOF), spring-mass-damper oscillators to an input motion. The input motion is applied to the base of all oscillators, and the calculated maximum response of each oscillator versus the natural frequency make up the spectrum [B7].

The relative displacement SRS is often used as a parameter to compare shock severity when two input shock motions are being compared. It is an intuitive engineering measure of severity because the relative displacement is proportional to the strain in the spring in Figure B1. The shock pulse that causes the larger strain, and therefore the largest damage potential, is judged to be the more severe of the two shock pulses. Figure B2 shows three vertical acceleration time histories recorded at different locations on a craft. The plot on the right is the computed maximum relative displacement SRS (DSRS) for each acceleration shock pulse. Visual inspection of the time histories on the left indicate that the red bow shock pulse is the most severe because of its higher amplitude. The DSRS curves on the right quantify the differences in severity. The key feature of the SRS approach is that it quantifies shock severity based on its effect on SDOF oscillators with varying natural frequencies. It characterizes the shock severity in the response domain, so that the effects of shock pulse shape, peak amplitude, jerk, and pulse duration can be taken into account for systems across a broad range of natural frequencies.

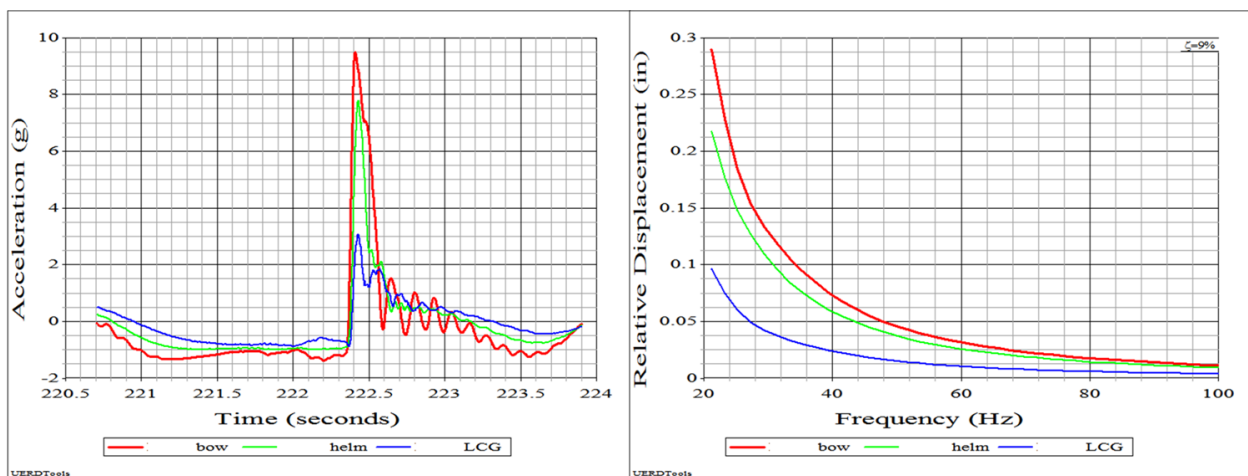


Figure B2. Three Wave Slam Shocks and Relative Displacement SRS²⁸

²⁸ The percent of critical damping (zeta) used in the SRS calculation is shown in the upper right.

The SRS can also be plotted using other SDOF response parameters as shown in Figure B3. In this figure the spectra compare the severity of a 3g – 100-ms half-sine pulse to the severity of a 2 g – 150-ms half-sine pulse. The upper left plot shows the two input pulses in the time domain; the other three plots show maximum responses in the SRS frequency domain (i.e., as a function of oscillator natural frequency). The upper right plot shows how the absolute peak acceleration response of the mass varies with system natural frequency. They are called the absolute acceleration shock response spectra (ASRS).

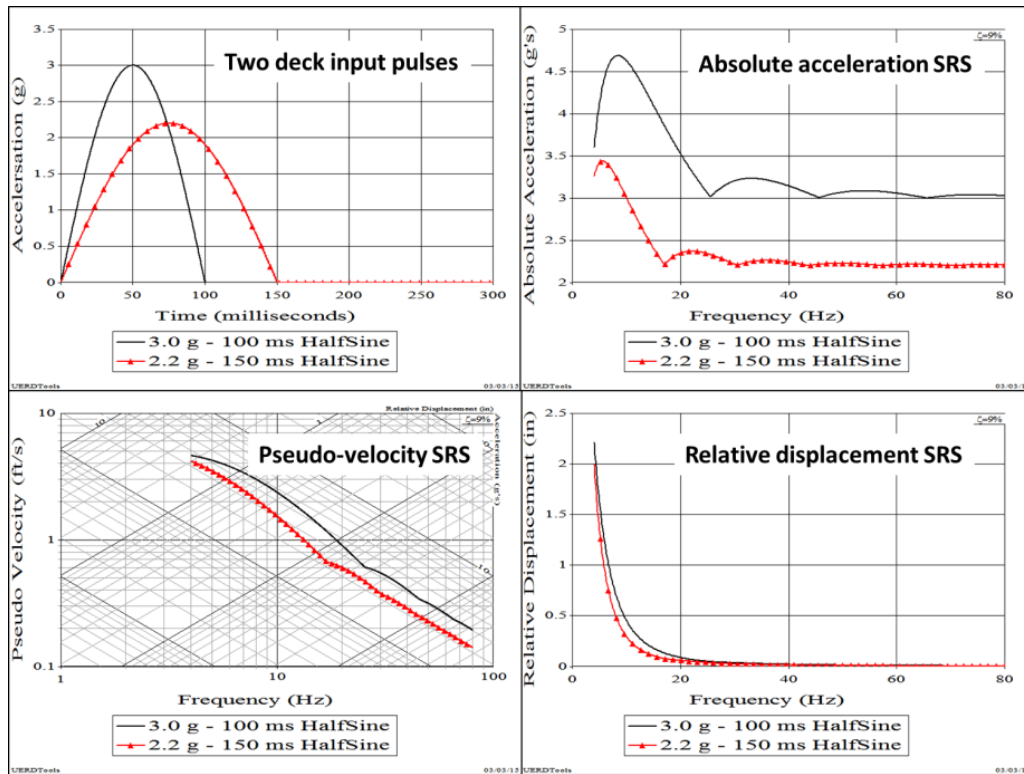


Figure B3. Different Types of Shock Response Spectra

The lower right plot in Figure B3 is the relative displacement SRS for each input pulse, and the lower left plot is the pseudo-velocity SRS (VSRS) for each pulse. Logarithmic scales are used on all four axes of the VSRS. The horizontal lines are the pseudo-velocity scale. Vertical lines are the system natural frequency scale. Lines sloping downward to the left show the predicted maximum relative displacement scales. Lines sloping downward to the right show the predicted maximum response accelerations. The log-log VSRS is a useful format because it provides a measure of the shock severity in units of maximum displacement, velocity, and acceleration. The acceleration scale is referred to as the pseudo-acceleration (A_{MAX}) for damped systems and the velocity scale is referred to as the pseudo-velocity when the maximum values are calculated using equations (B5) and (B6), which applies for lightly damped or zero damped systems [B1]. Z_{MAX} is the maximum relative displacement.

$$A_{MAX} = (2\pi f)^2 Z_{MAX} \quad (B5)$$

$$V_{MAX} = (2 \omega f) Z_{MAX} \quad (B6)$$

Mitigation Ratio Using SRS

The universal approach to quantifying shock transmissibility is by dividing the severity of the shock response pulse above the isolation mounts by the severity of the base input shock pulse [B1]. In this report the term shock mitigation ratio is the same as shock transmissibility. Many texts define the mitigation ratio (or transmissibility) as the ratio of the peak response acceleration above the mounts divided by the peak acceleration of the shock input. This is appropriate as long as the shock input pulse and the shock response pulse above the mounts have similar shape, jerk, and pulse duration.

When pulse shapes, jerk values, and pulse durations are not similar, the preferred method of quantifying shock mitigation is to use the shock response spectra ratio given by equation B7. This is because the SRS ratio inherently accounts for differences in the key shock parameters, including shape, duration, and jerk, as well as differences in peak acceleration.

$$\text{Mitigation Ratio} = \frac{\text{SRS}_{\text{Response}}}{\text{SRS}_{\text{Input}}} \quad (B7)$$

If the ratio is greater than 1.0, the shock pulse for the response is more severe than the shock pulse for the base input. This called dynamic amplification. If the ratio is less than 1.0, the shock pulse for the response is less severe than the shock pulse for the base input. As an example, Figure B4 shows relative displacement SRS (DSRS) for two hypothetical half-sine pulses, 7 g – 100 msec base input acceleration and 5 g – 210 msec above-mount response acceleration. The question is how much less severe or more severe is the above-mount response pulse compared to the base input pulse?

Figure B5 was constructed to answer this question by dividing the DSRS for the 5 g – 210 msec pulse by the DSRS for the 7 g – 100 msec pulse. A damping ratio of 22 percent was assumed for the calculations. It shows that over a broad frequency range 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 from approximately 45 Hz to 500 Hz the mitigation ratio is approximately 0.71 (i.e., the 5-g pulse is 29 percent less severe than the 7-g pulse). Between 4 Hz and 30 Hz the mitigation ratio varies from 0.55 to 0.7 (i.e., 30 percent to 45 percent less severe).

The mitigation ratio based on relative displacement shock response spectra (DSRS) is a convenient relative measure of shock severity and mitigation performance 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 [B11]. 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. Stress (or strain, i.e., relative displacement), a result of acceleration, causes damage [B12].

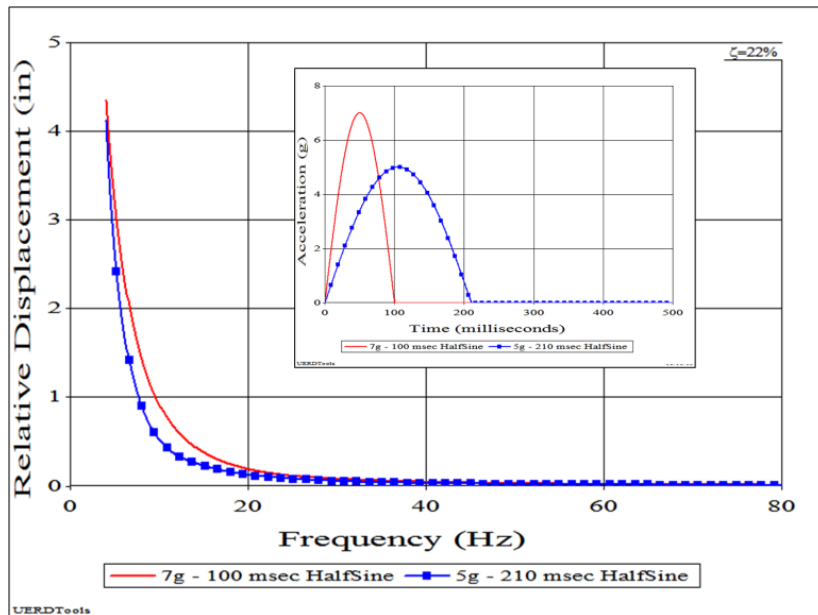


Figure B4. Comparison of Hypothetical DSRS

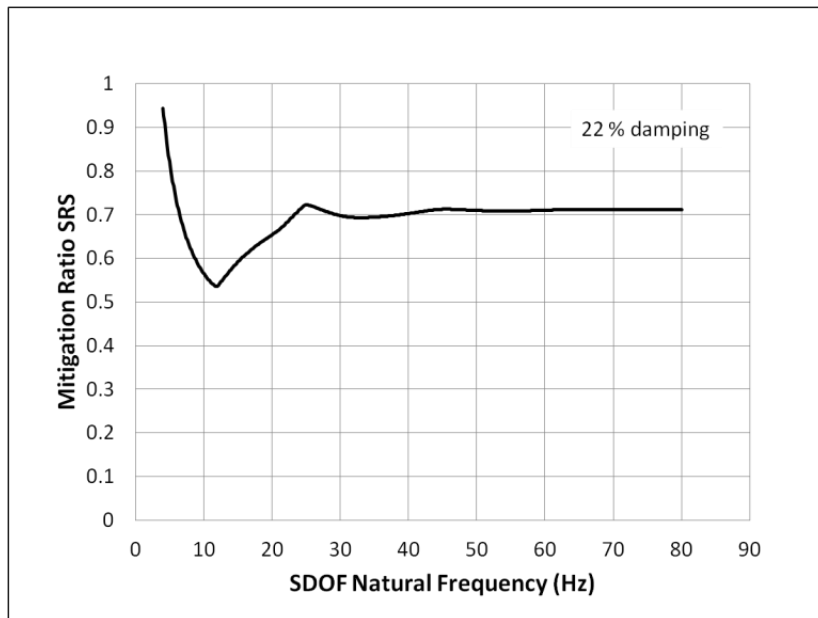


Figure B5. Mitigation Ratio for 5 g and 7 g Half-sine Pulses

SRS Frequency of Interest

Numerous studies of the effects of a vertical shock load on a seated human have used an analogous, lumped mass model of the human body consisting of a mass, a spring, and a damper.

The lumped mass model (i.e., single-degree-of-freedom model) was first studied in 1957 [B13] and applied in 1969 [B14] to describe the impact of jet aircraft ejection seats to the human body. It was reported to be a simple model that was well validated for the risk of spinal injury based on ejection seat data and able to account for shock pulse duration dependency [B15]. The model, called the Dynamic Response Index (DRI) computes the maximum relative displacement of the lumped mass model assuming a natural frequency of 8.4 Hz and 22.4% damping ratio. The maximum relative displacement is determined by solving equation (B1). Since it is a single degree of freedom model as shown in Figure B1, it is identical to an SRS calculation for specific frequency and damping values (i.e., 8.4 Hz and 22.4% damping). These values represent the natural frequency and damping ratio of interest applicable for SRS mitigation ratio calculations.

When the SRS mitigation ratio is calculated using equation (B7) with values of 8.4 Hz and 22.4% damping it is equal to the ratio of the DRI value for the pad response acceleration divided by the DRI value of the deck input acceleration. Within this report all SRS mitigation ratios were computed using 8 Hz and 22% damping.

Table B1 lists numerous other applications where the DRI (i.e., SRS at 8.4 Hz and 22% damping) has been specified or used as a criterion for quantifying spinal load for seated occupants caused by vertical acceleration forces during single shocks.

The DRI has been used in numerous studies of the effects of different types of single shock pulses on seated humans. It is specified by the International Maritime Organization as the criterion for evaluating spinal force and seat occupant safety during ship lifeboat drop tests [B16]. It is specified by the North Atlantic Treaty Organization (NATO) as the criterion for evaluating the risk of spinal injury to seat occupants in armored vehicles [B17, B18]. It has been used as a shock isolation seat design criterion for individual severe wave impacts in a high speed craft [B19], and it has been used to quantify the severity of different individual wave impacts recorded during high speed craft tests [B20]. The DRI is the only metric currently available that is applicable to single impact shock effects on seated humans able to quantify and compare the severity of different shock pulses that have different shapes, peak amplitudes, jerk values, and pulse durations. As a relative measure of impact severity (i.e., especially when used in a mathematical ratio) it provides a consistent mathematical tool for determining the relative severity of different shock pulses.

Table B1. Use of DRI Thoraco-Lumbar Spinal Load Criterion for Single Shocks

Document Type	Seat Occupant Application	Document Title	Organization	Reference
Test Standards and Criteria	Ship lifeboat freefall water impact	Testing and Evaluation of Life Saving Appliances, Lifeboat Drop Tests	International Maritime Organization (IMO)	IMO-MSC.81(70), 2003
	Land vehicle mine effects	Procedure for Evaluating the Protection Level of Armored Vehicles	North Atlantic Treaty Organization (NATO)	NATO-AEP-55, Volme 2 (Edition 2), 2011
	Land vehicle mine effects	Test Methodology for Protection of Vehicular Occupants Against Anti-Vehicular Landmine Effects	North Atlantic Treaty Organization (NATO) Human Factors and Medicine Panel	NATO-RTO-TR-HFM-090, 2007
Engineering Handbook / Guide	Fixed and rotary wing aircraft crash protection	Crew Systems Crash Protection Handbook	US Dept of Defense	JSSG-2010-7
	General vertical shock load applications	Effects of Shock and Vibration on Humans, Chapter 41	McGraw-Hill publication	Harris' Shock and Vibration Handbook, 2010
Technical documents	Seated anthropomorphic test device shock load response comparison	Comparative Analysis of THOR-NT-ATD and Hybrid-III ATD in Laboratory Vertical Shock Testing	US Army	ARL-TR-6648, 2013
	Aircraft ejection seat cushion study	Seat Interfaces for Aircrew Performance and Safety	US Air Force	AFRL-RH-WP-TR-2010-0083, 2010
	HSC shock isolated seat design study	Analysis, Optimization, and Development of a Specialized Passive Shock Isolation System for High Speed Planing Boats	Tayloe Devices, Inc, and Tayco Developments, Inc.	A. Klembezyk, M. Mosher, 2003

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APPENDIX C. DATA FILTERING AND RESPONSE MODE DECOMPOSITION

Mass Effect

Understanding how relative motions between large and small masses affect each other is very important. This involves the topic of mass participation in dynamic environments. The participating mass associated with a structural motion determines the transfer of shock force during motions caused by impact. This is explained further in the next paragraph by considering the mass of a vibrating deck in a craft, a 200-lb mass positioned on the deck, and the mass of a craft at a specific cross-section.

Consider a single vertical accelerometer installed on the deck at the center of a deck plate. The recorded acceleration time history will include motions with acceleration components attributed to both local deck-plate vibrations and rigid body heave. If a 200-pound mass had been installed next to the accelerometer location the deck vibrations would not drive the mass to vibrate at the same frequency as the deck. This is because the 200-lb mass is large relative to the mass of the contiguous deck plating that is vibrating. The presence of the mass would change the deck vibration characteristics, but it would not change the wave impact shock amplitude or pulse duration of the rigid body heave acceleration on the deck next to the mass. This is because the 200-pound mass and the mass of the contiguous deck plate is relatively small compared to the mass of the craft at the cross-section where the accelerometer is positioned. The 200-lb mass is not large enough to change the heave motion of the craft. Vibrations in craft do not transmit wave impact shock force to equipment or people. Rigid body heave motions (e.g., the rapid change in heave acceleration) transmit shock load in high-speed craft.

Frequency Analysis

The unfiltered acceleration data recorded on the fixed seat during the 10-minute head sea Run 1 is shown in Figure C1. The larger peak acceleration spikes for the deck (black curve) and pan (red curve) locations are on the order of minus 20 g to plus 30 g. Most of the unfiltered peaks for the pad location vary from about minus 1 g to plus 5g to 10 g. These different amplitude ranges above and below the pad illustrate the effectiveness of the seat pad in mechanically filtering out the vibrations recorded on the deck and the seat pan.

Figure C2 shows the Fast Fourier Transforms (FFT) of the fixed seat unfiltered accelerations (i.e., from Figure C1). FFT curves are used to evaluate the frequency content in an acceleration record. The large spikes on the left side of each curve are caused by rigid body heave motion, in this case motions with frequency content much less than 20 Hz. Frequency content above 20 Hz is caused by the structural vibrations that occur in the vicinity of each gage. The ability of the cushion to isolate the pad accelerometer from the deck and pan vibrations is observed by the lower amplitude green FFT curve relative to the higher red (pan) and black (deck) curves as frequencies increase up to 500 Hz.

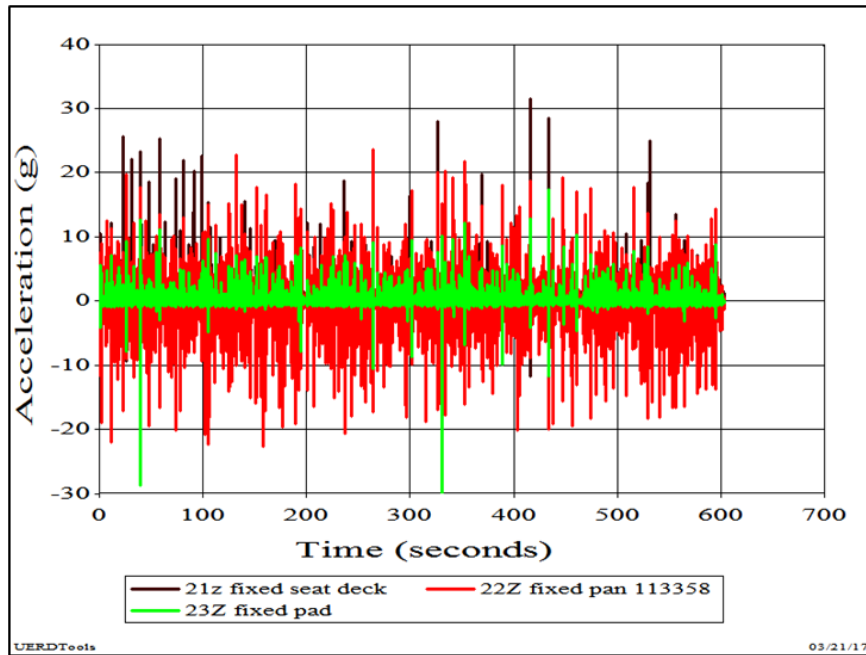


Figure C1. Fixed Seat Unfiltered Acceleration Data

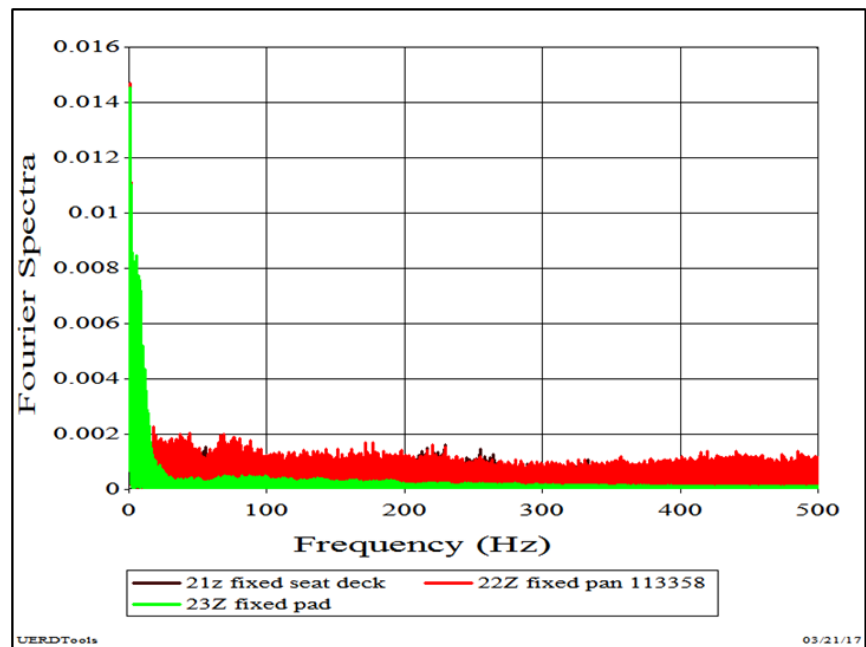


Figure C2. Fast Fourier Transform of Fixed Seat Unfiltered Acceleration Data

The same effects for the isolated seat deck, pan, and pad gages are shown in Figure C3. The high frequency vibration content on the isolated pad is much lower than the vibration content at the deck or on the isolated pan. The seat cushions on both the rigid seat and the isolated seat are very good vibration isolators.

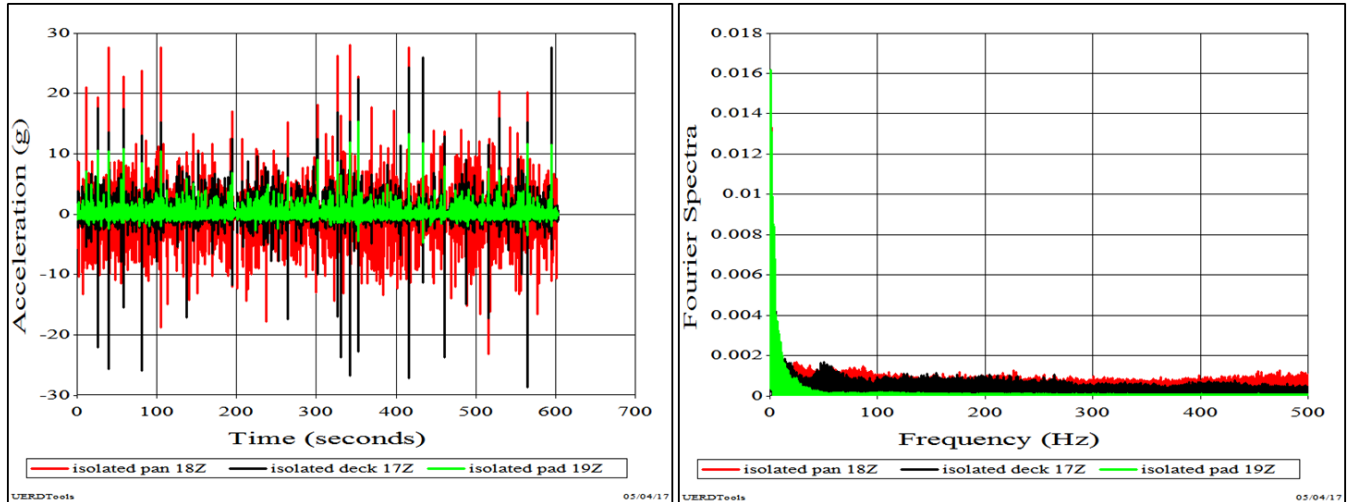


Figure C3. Shock Isolated Seat Unfiltered Acceleration Data and FFT

Response Mode Decomposition

The process of separating rigid body content and vibration content in an unfiltered acceleration signal is referred to as response mode decomposition [C1]. It is important because the transfer of wave impact shock load (i.e., force) is directly proportional to the difference in rigid body acceleration at different locations. The use of low-pass filtering is a method for estimating the rigid body acceleration content in a signal. Based on the relative amplitudes in the FFTs shown in Figure C2 and Figure C3, a 20 Hz low-pass filter was selected to separate the vibration content from the acceleration time histories. This is referred to as the vibration cut-off frequency. The 20 Hz low-pass filtered acceleration time histories are shown in Figure C4.

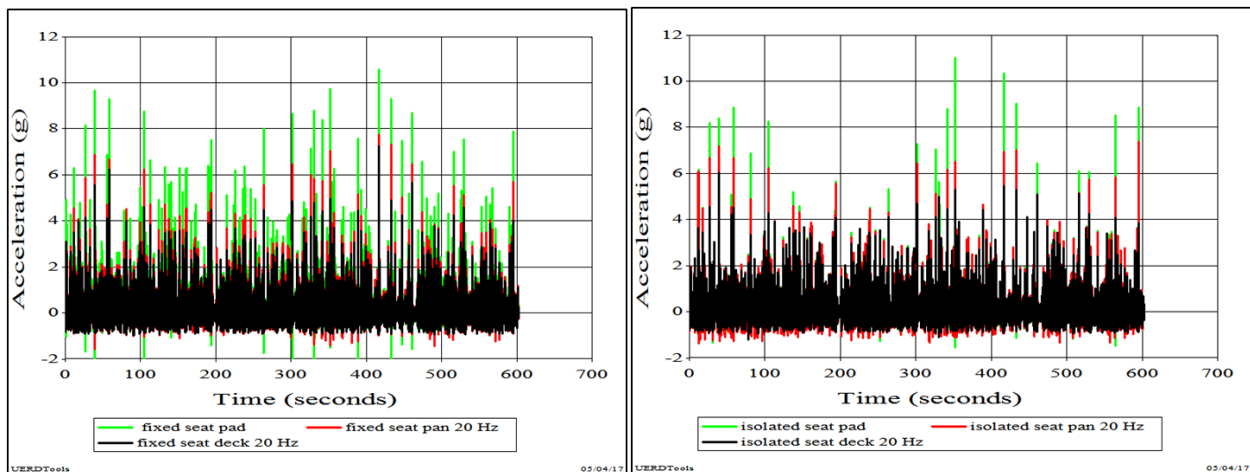


Figure C4. 20 Hz Low-pass Filtered Acceleration Data for Fixed and Isolated Seats

The filtered deck (black), pan (red), and pad (green) data for the fixed seat is shown in Figure C4. The isolated seat data is on the right. It is important to notice that the amplitudes of

the spikes (i.e., the peak accelerations) for the low-pass filtered data for the rigid and the isolated seats fall within -2 g to + 12 g, rather than -20 g to + 30 g for the unfiltered data. This illustrates the fact that the vibration content in a signal can be the same order of magnitude or greater than the rigid body content.

Figure C5 illustrates the response mode decomposition process for the wave impact that occurred at 131 seconds in the time history (i.e., impact #131). The top plot shows the unfiltered acceleration (orange curve) and the superimposed rigid body acceleration (black). The middle black curve is the rigid body acceleration and the lower plot is the vibration portion (orange) of the unfiltered acceleration signal. When the lower orange vibration plot is superimposed on the middle black rigid body curve it produces the original unfiltered orange acceleration curve in the top plot.

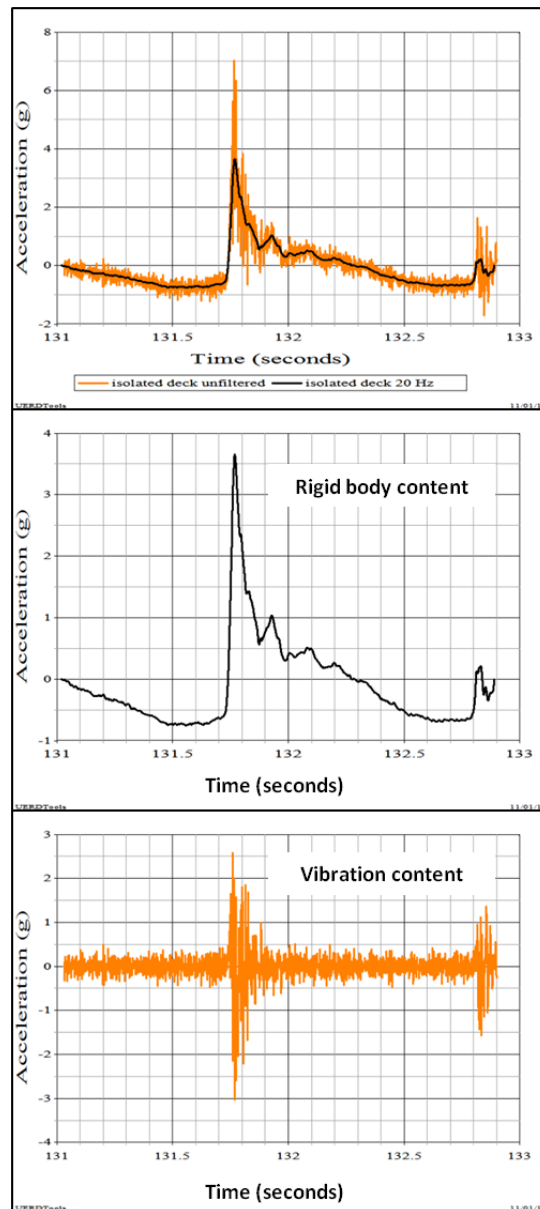


Figure C5. Components of Rigid Body and Vibration Accelerations in Wave Impact #131

Figure C6 shows another example of the seat pad mitigating vibrations observed on the seat pan and on the deck at the base of the seat. The three curves are unfiltered acceleration signals at the deck (green), the seat pan (blue), and the seat pad (pad, red). Before the wave impact (i.e., when downward acceleration is about -0.8 g) the high-frequency vibrations are on the order of 320 Hz at the deck (green) and 260 Hz on the seat pan (blue). The seat pad response (red) during the same period is almost vibration free. It is an example of the seat pad mitigating the vibration signal observed in the seat pan. During and immediately after the wave impact the same trend is observed. The seat pad response has almost no vibration content while the deck and pan accelerations have significant transient vibration content.

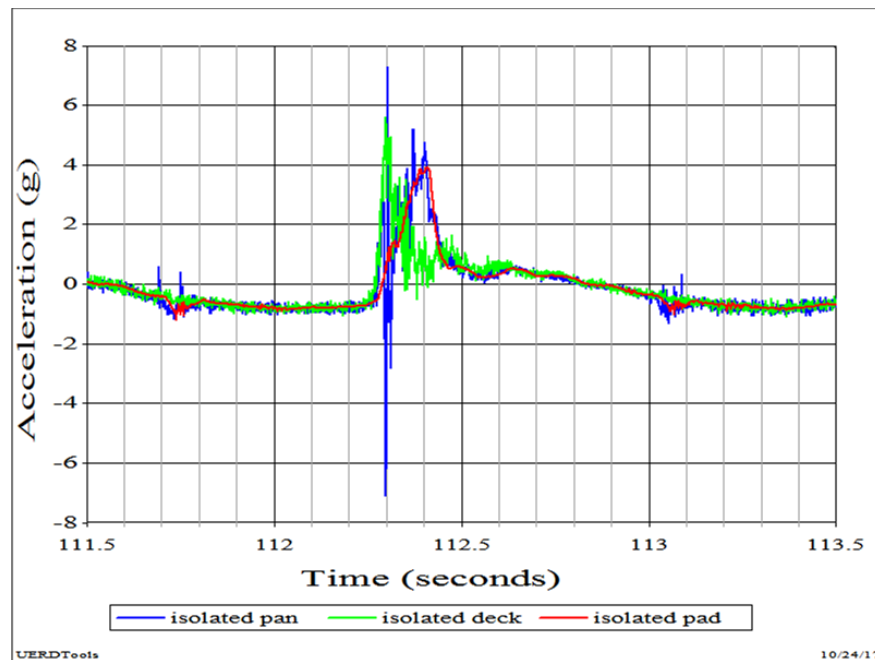


Figure C6. Vibration Mitigation by Seat Pad

Unfiltered vs. Filtered Acceleration Data

The use of unfiltered acceleration data can significantly misrepresent the shock mitigation performance of a seat when only peak accelerations are compared. Before shock attenuation can be evaluated the data must be decomposed into the rigid body component and the vibration components within the unfiltered acceleration signal. This process is called response mode decomposition [C1]. The process applies low-pass filtering to estimate the rigid body content, and high-pass filtering to estimate the vibration content²⁹.

Response mode decomposition is illustrated in Figure C7. The curve on the left is the unfiltered deck and seat pad data for one wave impact recorded during one of the runs in the

²⁹ In small high-speed craft the vibration content in an acceleration signal is typically caused by flexural oscillations in the structure at the gauge location (on the order of +/- 0.05 inches and less for a 4 g sine wave with 25 Hz frequency), but it may also include hull girder bending motions (i.e., especially at bow locations in craft with composite hulls).

2014 trials. The black curve is the unfiltered vertical deck acceleration recorded at the base of the shock isolated seat. Its content includes both rigid body heave acceleration and local deck vibrations (hence the fuzzy appearance of the record). The red curve on the left is the unfiltered vertical acceleration recorded on the seat pad (i.e., below the seat payload weight). The smooth appearance of the red curve on the left demonstrates how the seat spring-damper-pad assembly removes the vibration content observed in the deck acceleration.

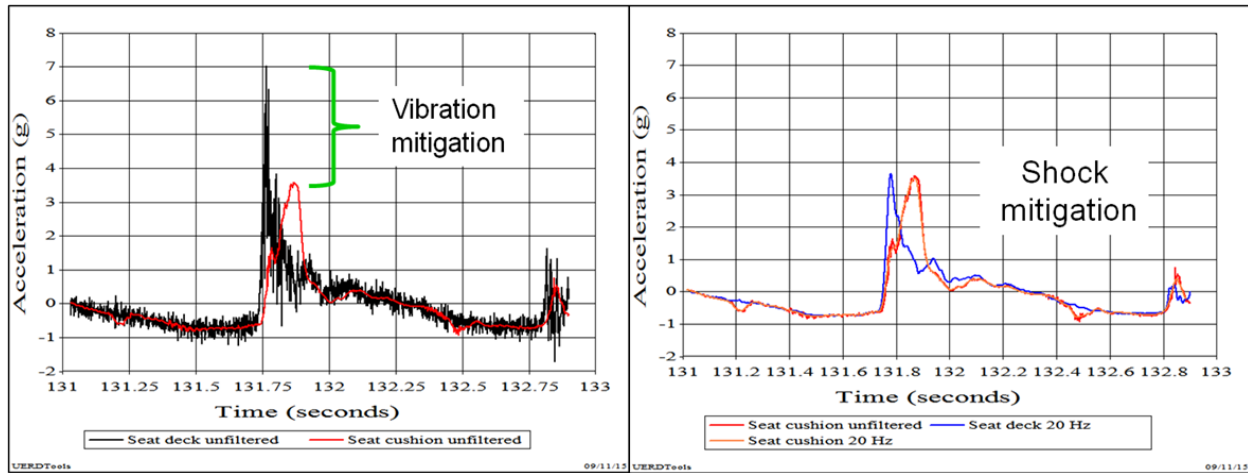


Figure. C7. Examples of Vibration Mitigation and Shock Mitigation

The unfiltered data shown on the left side in Figure C7 was subjected to a 20 Hz low-pass Bessel filter to estimate the rigid body content in the two signals. The low-pass filtered acceleration signals are shown on the right side in Figure C7. The blue curve is the estimated rigid body heave acceleration at the deck location and the orange curve is the low-pass filtered seat pad acceleration. The orange filtered curve on the right is almost identical to the red unfiltered curve on the right, illustrating that the red unfiltered seat pad data on the left has little or no vibration content. The red curve on the left is therefore primarily attributed to rigid body heave motion. In the left plot the large reduction in the high frequency deck peak acceleration (black curve, about 7 g) compared to the pad peak (red curve about 3.6 g), and the removal of the “fuzzy” character of the black deck data (compared to the smooth red pad data) is an example of vibration mitigation.

The effectiveness of the spring-damper-pad assembly in reducing the severity of the deck heave acceleration is determined by comparing the two rigid-body accelerations shown on the right in Figure C7. Effective shock mitigation occurs when the rigid-body peak acceleration (i.e., the blue curve on the right in Figure C7) is reduced in amplitude, the rate of acceleration application (i.e., jerk) is reduced, and the duration of the shock pulse is increased.

Effect of Different Low-Pass Filter Types

During different stages of the analyses different software with different 20 Hz low-pass filters were used. The StandardG peak accelerations [C2] were obtained running DADiSP® with a Kaiser window filter, 5% allowable pass band ripple, 24 Hz stop band limit with 40 dB attenuation. The time history analyses and shock response spectrum calculation were performed

using UERDTools with a 2-pole Bessel filter, 6 dB attenuation per pole, and a 24 Hz stop band [C3]. Figure C8 compares the deck peak acceleration amplitudes for the Kaiser and Bessel 20 Hz low-pass filters. The least squares best-fit line passing through zero has a slope of about 1.055 for all the data, and the scatter is about ± 0.3 g for peaks from 1 g to 3 g, and ± 0.5 g for peaks from 3 g to 7 g.

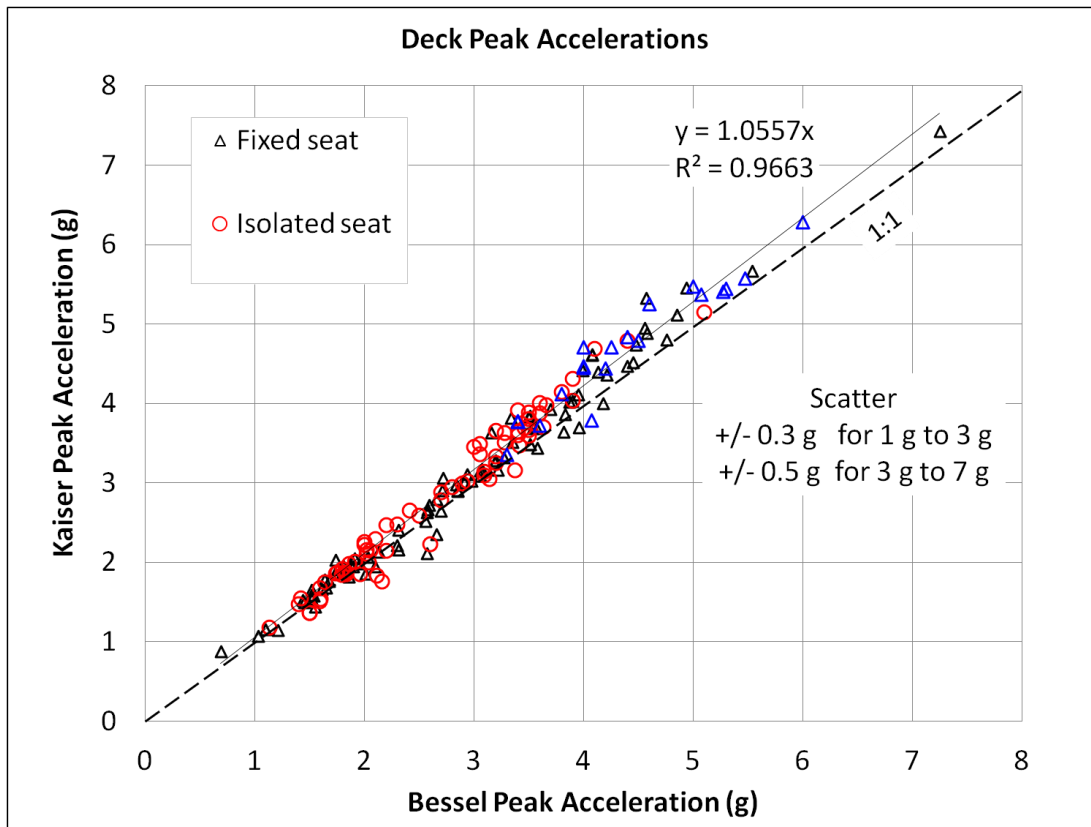


Figure C8. Comparison of Bessel and Kaiser Low-Pass Filters

Appendix C Reference

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- C2. Riley, M., Haupt, K., Jacobson, D., *A Generalized Approach and Interim Criteria for Computing $A_{1/N}$ Accelerations Using Full-Scale High-Speed Craft Trials Data*, Naval Surface Warfare Center Carderock Division Report NSWCCD-TM-23-2010/13, April 2010.
- C3. Mantz, Paul A., Costanzo, Fredrick A., *An Overview of UERDTools Capabilities: A Multi-Purpose Data Analysis Package*, Proceedings of the IMAC-XXVII Conference and Exposition on Structural Dynamics, Society of Experimental Mechanics, Inc., 9-12 February 2009, Orlando, Florida, 2009.

- C4. ISO 2631-1: 1997, *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration, Part 1: General Requirements*, International Standards Organization, 1997.
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- C6. ISO 2631-5:2004, *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration, Part 5: Method for Evaluation of Vibrations Containing Multiple Shocks*, International Standards Organization, 2004.
- C7. *Testing and Evaluation of Life-Saving Appliances*, Maritime Safety Committee Resolution MSC.81(70), Life-Saving Appliances, 2003 Edition, International Maritime Organization, 2003.

APPENDIX D. ACCELERATION DATA COMPARISONS

Time History Comparisons

Figure D1 illustrates the repeatability of response accelerations when the deck motion inputs are the same. The wave impact on the left occurred at approximately 131 seconds. The wave impact on the right occurred at 152 seconds.

Seat pad acceleration responses for the fixed and isolated seats are shown in Figures D2, D3, and D4 to illustrate typical time history responses.

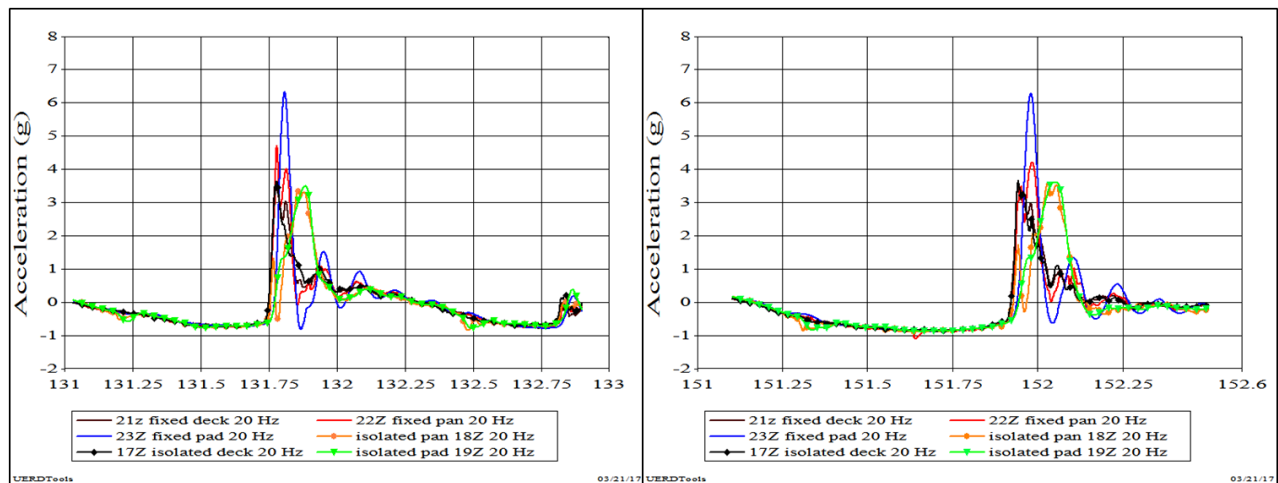


Figure D1. Two Different Wave Impacts with the Same Seat Response Accelerations

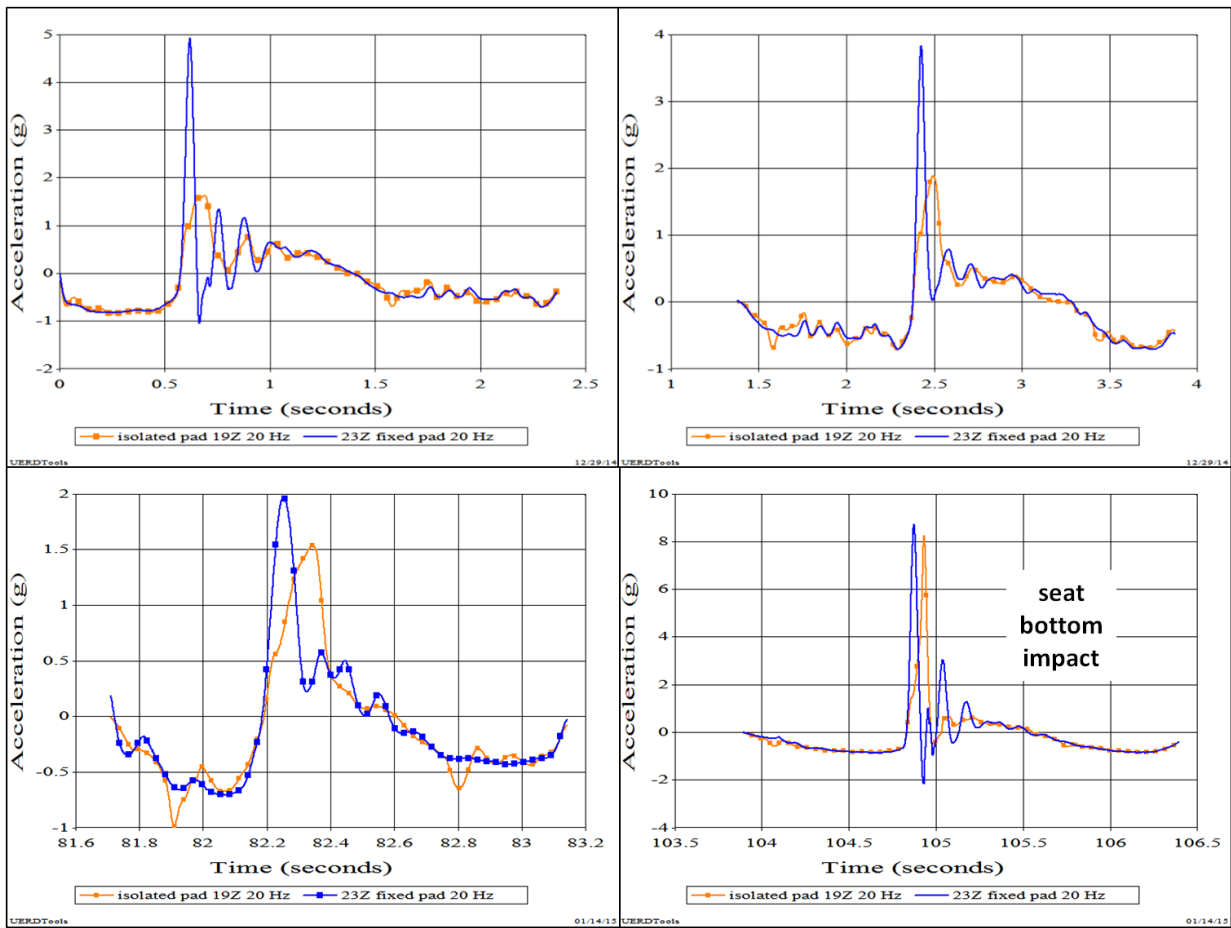


Figure D2. Examples of Fixed Pad Peak-G greater than Isolated Pad Peak-G

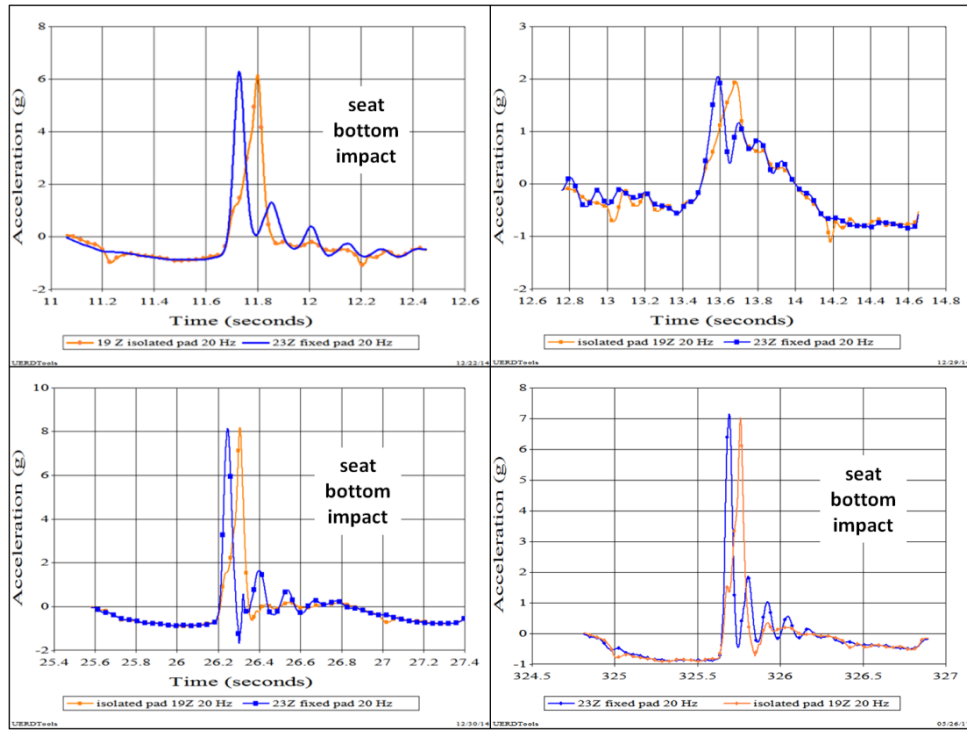


Figure D3. Examples of Fixed Pad Peak-G equal to Isolated Pad Peak-G

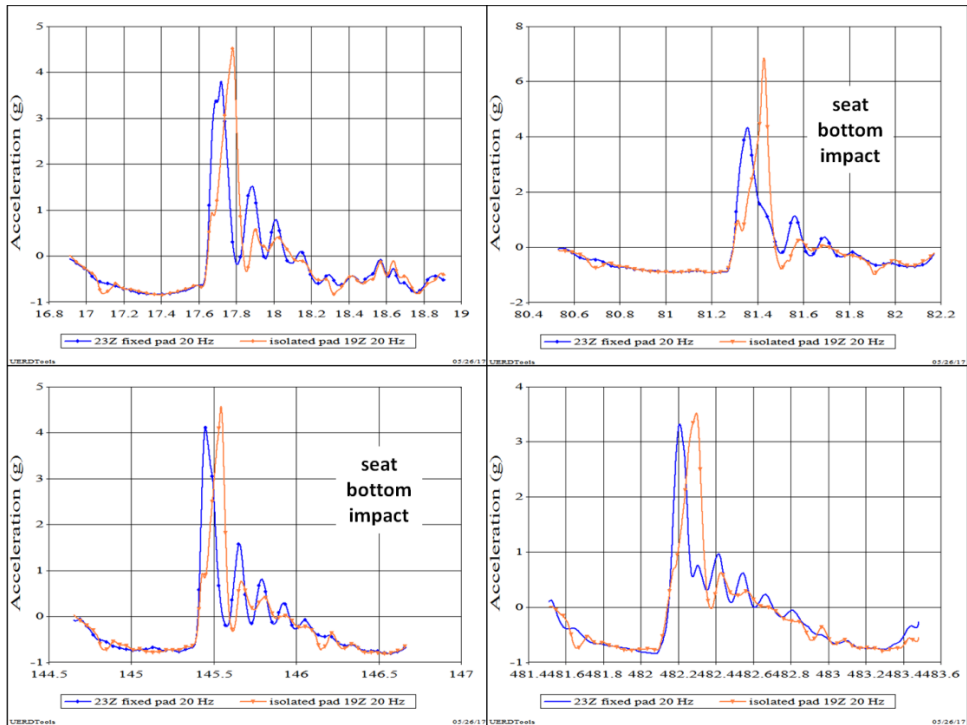


Figure D4. Examples of Fixed Pad Peak-G less than Isolated Pad Peak-G

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APPENDIX E. TABULATED DATA

The following tables list peak accelerations, computed MR_{SRS} values, and shock pulse durations for wave impacts analyzed during this investigation. Numbers highlighted in red indicate wave impacts that caused seat bottom impacts on the shock isolated seat. Bottom impacts were identified by studying the unfiltered time history accelerations for each impact. The wave impact number shown in the left most column in each table is the approximate time in seconds at which each impact occurred during the 600 second trial.

Table E1 lists rigid body (20 Hz low-pass filtered) peak accelerations for Run 1 extracted from the time history data by the StandardG algorithm. Table E2 lists the pad and pan computed SRS mitigation ratios for the fixed and isolated seats for Run I. Table E3 lists the pulse durations for the more severe wave impacts during Run I. Many of the wave impacts with peak rigid body accelerations less than 2 g were not included in the pulse duration portion of the investigation, so Table E3 lists fewer values than Tables E1 and E2. Table E4 lists pulse duration and mitigation ratio values sampled from Run II data.

Table E1. Run I Peak Accelerations from StandardG (20 Hz)

Wave Impact #	Isolated Deck 20 Hz Peak (g)	Isolated Pad 20 Hz Peak (g)	Fixed Deck 20 Hz Peak (g)	Fixed Pad 20 Hz Peak (g)
1	1.92	1.63	3.08	4.92
2	2.41	1.88	2.57	3.83
6	1.59	1.63	1.55	2.45
7	2.3	2.13	2.66	4.26
11	3.6	6.16	3.51	6.28
12	2.6	2.14	1.9	2.88
13	1.75	1.94	1.65	2.04
17	3.4	4.51	3.96	3.80
19	2.5	2.38	2.66	4.77
26	4.5	8.18	4.13	8.14
27	2.1	1.95	2.03	3.52
29	1.8	1.55	1.54	2.05
31	2.2	1.74	1.74	2.58
32	3	2.95	2.84	4.92
39	6	8.37	5.54	9.61
41	1.86	1.63	1.52	2.33
46	1.74	1.86	1.68	2.13
47	1.91	1.61	1.81	3.08
55	4.1	5.08	4.08	6.86
61	1.82	1.59	1.61	2.32
68	1.79	1.88	1.87	2.63
73	1.64	1.71	1.44	1.59
81	3.3	6.85	3.95	4.33
82	1.59	1.53	1.64	1.96
85	2.2	1.89	2.31	4.09
96	1.83	2.05	2.13	2.94
98	2.7	3.34	2.71	4.13
100	3.5	3.05	3.06	5.46
105	4.2	8.25	4.58	8.73
112	3.8	3.82	3.83	4.64
124	2.7	3.22	2.7	4.90
125	2	1.61	1.75	2.14
128	2.94	2.49	2.57	4.55
131	3.6	3.49	3.48	6.33
136	3.4	5.17	3.54	4.92
140	3.5	2.83	3.19	5.70
145	3.4	4.57	3.51	4.12
151	3.6	3.6	3.57	6.28
155	3.09	3.19	2.91	5.24
159	3.4	3.65	3.27	6.22
161	3.2	3.73	3.51	6.28
186	1.59	1.51	1.36	1.97
189	3.2	3.44	3.9	6.38
192	3.9	4.39	3.82	6.32
194	4	5.65	4.08	7.50

Table E1. Run I Peak Accelerations from StandardG (20 Hz) Continued

Wave Impact #	Isolated Deck 20 Hz Peak (g)	Isolated Pad 20 Hz Peak (g)	Fixed Deck 20 Hz Peak (g)	Fixed Pad 20 Hz Peak (g)
200	1.42	1.74	2.1	2.71
206	2.02	1.98	2.3	2.10
207	1.4	1.63	1.45	1.69
221	2.05	1.84	1.8	3.13
223	2.89	2.51	2.56	4.68
225	3.5	3.54	3.16	6.19
237	3.4	4	3.35	6.37
238	3.05	4.51	3.07	5.47
240	1.6	1.68	1.52	2.09
246	3.28	3.54	3.2	5.40
249	1.5	0.93	0.69	1.11
252	3.5	3.19	3.22	4.94
255	2	1.7	1.52	2.64
263	4	5.31	4.48	8.00
268	2.8	2.79	2.58	4.12
300	4.6	7.26	4.85	8.64
306	1.96	1.76	2.31	2.61
325	4	7.01	4.18	7.15
330	5	5.62	4.76	8.80
333	3.2	2.83	3.34	5.17
335	1.5	0.83	1.03	1.35
341	4.4	8.77	4.4	8.38
351	5.3	11	4.94	9.72
353	3.28	3.58	2.98	5.67
356	3.9	3.27	3.7	6.26
388	4.4	4.53	4.45	7.58
392	3.09	3.41	3.58	5.35
396	2.02	1.9	1.96	2.95
403	2.04	1.67	1.86	3.49
415	5.47	10.34	7.25	10.57
432	5.27	9	4.57	9.30
434	1.13	1.07	1.1	1.85
456	3.46	2.98	2.94	5.16
460	5.07	6.43	5.66	8.66
473	3.66	3.76	3.5	6.55
482	3.14	3.52	2.72	3.32
483	2.11	1.97	2.01	2.04
486	3.41	2.65	1.91	3.77
515	5.1	6.1	4.21	6.99
525	3.63	3.69	3.06	5.31
528	4.25	6.04	4.56	7.55
552	3.37	3.41	2.85	4.61
556	2.16	1.49	1.21	1.94
558	3.05	3.48	2.59	5.06
563	4.07	8.52	3.87	4.72
566	2.41	3.2	2.85	5.42
594	3.8	8.84	3.99	7.89

Table E2. Run I SRS Mitigation Ratios

Wave Impact #`	Isolated Deck Peak G (20 Hz)	MR fixed pan	MR fixed pad	MR isolated pan	MR isolated pad
1	1.92	0.99	1.62	0.94	0.73
2	2.41	1.02	1.60	1.00	0.85
6	1.59	1.29	1.58	0.96	0.77
7	2.3	1.16	1.46	0.89	0.80
11B	3.6	1.17	1.65	1.20	1.26
12	2.6	1.29	1.62	0.85	0.80
13	1.75	1.13	1.29	1.00	1.01
17	3.4	1.17	1.37	1.51	1.50
19	2.5	1.16	1.59	0.83	0.76
26B	4.5	1.28	1.68	1.04	1.32
27	2.1	1.18	1.48	0.69	0.67
29	1.8	1.15	1.27	0.76	0.75
31	2.2	1.16	1.59	0.56	0.67
32	3	1.08	1.51	0.83	0.85
39B	6	1.18	1.62	1.03	1.17
41	1.86	1.25	1.48	0.79	0.71
46	1.74	1.18	1.62	1.25	1.30
47	1.91	0.89	1.64	0.75	0.76
55	4.1	1.12	1.47	0.93	1.03
61	1.82	1.25	1.44	0.79	0.74
68	1.79	1.12	1.44	0.98	0.92
73	1.64	1.30	1.48	1.20	1.14
81B	3.3	1.08	1.30	1.38	1.98
82	1.59	1.16	1.44	0.95	0.90
85	2.2	1.11	1.55	0.76	0.65
96	1.83	1.36	1.57	1.03	0.91
98	2.7	1.08	1.57	1.11	1.12
100	3.5	1.23	1.67	0.82	0.75
105B	4.2	1.18	1.61	1.06	1.37
112	3.8	1.20	1.58	0.91	0.87
124	2.7	1.22	1.67	0.88	0.88
125	2	1.18	1.84	0.67	0.80
128	2.94	1.06	1.56	0.81	0.78
131	3.6	1.44	2.20	0.62	0.70
136B	3.4	1.22	1.50	1.09	1.19
140	3.5	1.22	1.66	0.76	0.71
145	3.4	1.07	1.50	1.31	1.49
151	3.6	1.18	1.67	0.92	0.88
155	3.09	1.16	1.58	0.86	0.85
159	3.4	1.18	1.64	0.89	0.87
161	3.2	1.14	1.55	0.99	0.93
186	1.59	1.16	1.57	0.94	0.91
189	3.2	0.99	1.58	0.96	0.85
192	3.9	1.21	1.54	0.91	0.98
194B	4	1.21	1.60	1.03	1.06

Table E2. Run I SRS Mitigation Ratios (continued)

Wave Impact #	Isolated Deck Peak G (20 Hz)	MR fixed pan	MR fixed pad	MR isolated pan	MR isolated pad
200	1.42	1.30	1.48	1.44	1.20
206	2.02	0.98	1.44	1.12	1.21
207	1.4	0.99	1.33	1.10	1.14
221	2.05	1.17	1.57	0.75	0.70
223	2.89	1.17	1.57	0.75	0.70
225	3.5	1.17	1.61	0.88	0.88
237	3.4	1.08	1.66	1.03	0.96
238	3.05	1.25	1.64	1.35	1.32
240	1.6	1.08	1.45	1.02	1.04
246	3.28	1.16	1.55	0.89	0.94
249	1.5	1.33	2.01	0.96	1.08
252	3.5	1.13	1.65	0.76	0.79
255	2	1.22	1.72	0.78	0.72
263B	4	1.20	1.60	0.92	1.04
268	2.8	1.14	1.51	0.83	0.85
300B	4.6	1.25	1.63	1.03	1.20
306	1.96	1.16	1.53	1.04	0.88
325B	4	1.12	1.63	1.07	1.34
330B	5	1.22	1.73	0.71	0.93
333	3.2	1.02	1.55	0.85	0.91
335	1.5	1.11	1.32	0.69	0.62
341B	4.4	1.25	1.75	1.13	1.48
351B	5.3	1.23	1.70	1.02	1.59
353	3.28	1.27	1.74	0.90	0.87
356	3.9	1.12	1.58	0.85	0.80
388	4.4	1.23	1.66	0.93	0.90
392	3.09	1.12	1.47	0.96	0.98
396	2.02	1.14	1.43	0.88	0.85
403	2.04	1.06	1.73	0.78	0.66
415B	5.47	1.40	1.83	1.27	1.66
432B	5.27	1.23	1.73	1.10	1.36
434	1.13	1.10	1.58	0.72	0.67
456	3.46	1.13	1.61	0.83	0.77
460B	5.07	1.09	1.61	0.97	1.12
473	3.66	1.18	1.71	0.93	0.90
482	3.14	1.22	1.51	1.31	1.44
486	3.41	1.27	1.73	0.83	0.78
515	5.1	1.21	1.72	1.07	1.16
525	3.63	1.22	1.58	0.88	0.94
528	4.25	1.11	1.62	1.08	1.10
552	3.37	1.19	1.60	0.94	0.98
556	2.16	0.93	1.55	0.82	0.81
558	3.05	1.21	1.77	0.99	0.96
563B	4.07	1.05	1.29	1.26	1.95
566	2.41	1.11	1.65	1.13	1.07
594B	3.8	1.10	1.67	1.35	1.61

Table E3. Run I Shock Pulse Durations

Wave impact #	Isolated deck pulse duration (msec)	Isolated pad pulse duration (msec)	Fixed deck pulse duration (msec)	Fixed pad pulse duration (msec)
7	123	231	138	112
11	127	168	127	84
12	132	200	132	94
13	125	241	125	129
17	157	185	157	128
19	111	171	111	92
26	105	140	112	74
27	111	175	121	93
32	107	181	125	107
39	102	124	103	75
46	132	227	132	141
47	101	179	132	93
55	128	173	135	122
61	135	210	134	111
68	128	212	127	120
81	189	181	186	165
82	125	207	114	123
85	113	153	114	89
96	116	200	104	100
100	112	187	112	83
105	143	135	115	88
112	118	174	118	84
124	118	181	114	92
128	113	192	118	97
131	126	162	105	82
136	151	183	151	118
140	105	171	103	80
145	151	181	151	116
151	116	158	115	86
155	133	176	138	98
159	114	179	114	80
161	101	173	119	89
189	155	190	140	90
192	130	169	130	92
194	105	159	111	82
206	163	253	163	150

Table E3. Run I Shock Pulse Durations (continued)

Wave impact #	Isolated deck pulse duration (msec)	Isolated pad pulse duration (msec)	Fixed deck pulse duration (msec)	Fixed pad pulse duration (msec)
221	126	208	124	93
223	135	210	132	86
225	117	200	118	82
237	118	201	119	82
238	123	191	145	101
240	150	201	120	118
246	117	184	128	101
252	126	165	106	81
263	109	145	117	89
268	125	193	125	110
300	139	137	124	77
306	121	193	119	126
325	169	161	167	79
330	109	146	111	76
333	113	197	99	78
341	108	146	111	76
351	138	122	138	80
353	109	168	109	85
356	128	188	139	91
388	110	174	110	87
392	158	207	158	107
403	101	225	101	81
415	136	130	113	79
432	123	127	105	74
434	126	182	113	118
456	117	178	124	95
460	106	155	111	78
473	115	161	134	92
482	174	204	179	121
486	148	180	129	79
515	100	170	100	77
525	155	189	138	128
528	114	145	114	74
552	146	184	142	108
558	114	208	124	89
563	180	174	180	201
566	119	189	118	99
594	150	138	113	91

Table E4. Run II Sampled Data

Wave Impact #	MR fixed pan	MR fixed pad	MR isolated pan	MR isolated pad	Isolated deck peak G	Isolated deck pulse duration (msec)
20	1.12	1.40	0.80	0.78	1.75	152
27	1.14	1.53	0.83	0.78	1.97	143
61	1.11	1.29	0.87	0.88	1.76	132
77	1.10	1.27	0.80	0.86	1.69	231
79	1.20	1.43	0.62	0.59	1.62	141
114	1.18	1.51	0.68	0.65	1.79	142
117	1.22	1.76	1.17	0.89	1.62	167
159	1.07	1.13	0.93	0.94	1.93	175
178	1.05	1.11	0.93	0.93	2.19	243
186	1.10	1.54	0.86	0.98	1.65	213
191	1.14	1.64	1.05	0.91	1.96	140
236	1.12	1.32	0.90	0.89	1.84	202
237	1.21	1.74	1.11	0.93	1.39	222
253	1.25	1.66	0.94	0.83	1.82	158
256	1.16	1.57	0.78	0.70	1.81	119
265	1.33	1.73	0.87	0.80	1.8	173
280	1.23	1.69	0.95	0.85	1.67	135
285	1.19	1.80	0.78	0.69	1.37	123
286	1.22	1.62	0.86	0.85	1.78	177
293	1.05	1.87	1.20	0.93	1.41	140
297	1.23	1.39	0.58	0.59	1.62	165
319	1.23	1.70	1.07	1.07	2.27	173
331	1.07	1.31	0.85	0.81	2.15	155
355	1.03	1.49	0.96	0.91	1.55	148
360	1.25	1.38	0.91	0.94	2.27	146
373	1.32	1.70	0.79	0.69	1.68	158
375	1.27	1.72	0.77	0.65	2	130
381	1.14	1.55	0.96	1.01	1.65	193
402	1.23	1.74	0.84	0.69	1.47	128
408	1.14	1.29	0.79	0.86	2.05	166
412	1.02	1.03	0.96	0.92	1.72	118
427	1.18	1.31	0.74	0.80	2.32	137
476	1.20	1.64	1.05	1.01	1.73	159
485	1.12	1.40	1.10	1.23	1.7	242
486	1.12	1.20	0.79	0.85	1.97	185
495	1.16	1.32	0.91	0.87	2.12	171
513	1.18	1.32	1.27	1.15	2.08	186
532	1.13	1.43	0.80	0.76	1.6	149
534	1.31	1.77	0.94	0.86	1.6	139
536	1.14	1.36	0.94	0.92	2.26	171
540	1.26	1.65	1.01	1.02	1.78	170
552	1.27	1.50	1.06	0.98	1.74	197
556	1.08	1.75	0.90	0.95	1.19	200
561	1.24	1.62	0.69	0.63	1.72	130
572	1.45	1.94	1.00	0.90	2.41	156

APPENDIX F. SHOCK PULSE DURATION PLOTS

Figure F1 shows pulse durations from Run I deck acceleration data for the isolated seat with no bottom impacts (blue circles), the isolated seat when bottom impacts occurred (red X), and the fixed seat (green triangle). The light blue squares are data from deck accelerations recorded during Run II at the base of the isolated seat. During the less severe Run II no seat bottom impacts occurred on the isolated seat.

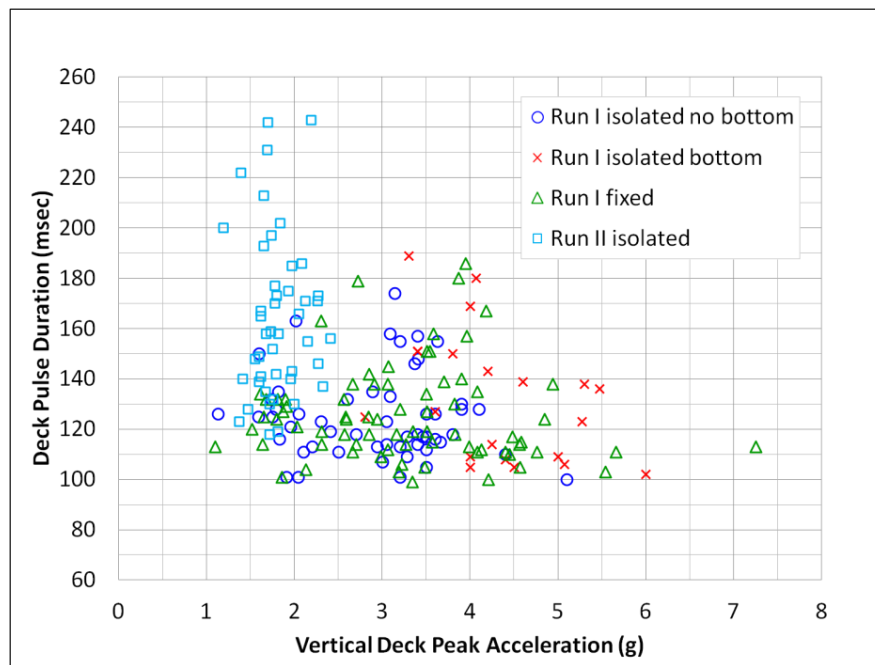


Figure F1. Deck Pulse Duration vs. Deck Peak Acceleration Run I

Figures F2 plots the ratio of the Run I isolated duration divided by the fixed seat duration as a function of deck input peak acceleration. Figure F3 shows the Run I pad mitigation ratio versus the deck pulse duration. Figure F4 shows the Run I pad mitigation ratio versus the ratio of pad duration divided by the deck duration. Figure F5 shows the Run II pad mitigation ratio versus the deck pulse duration.

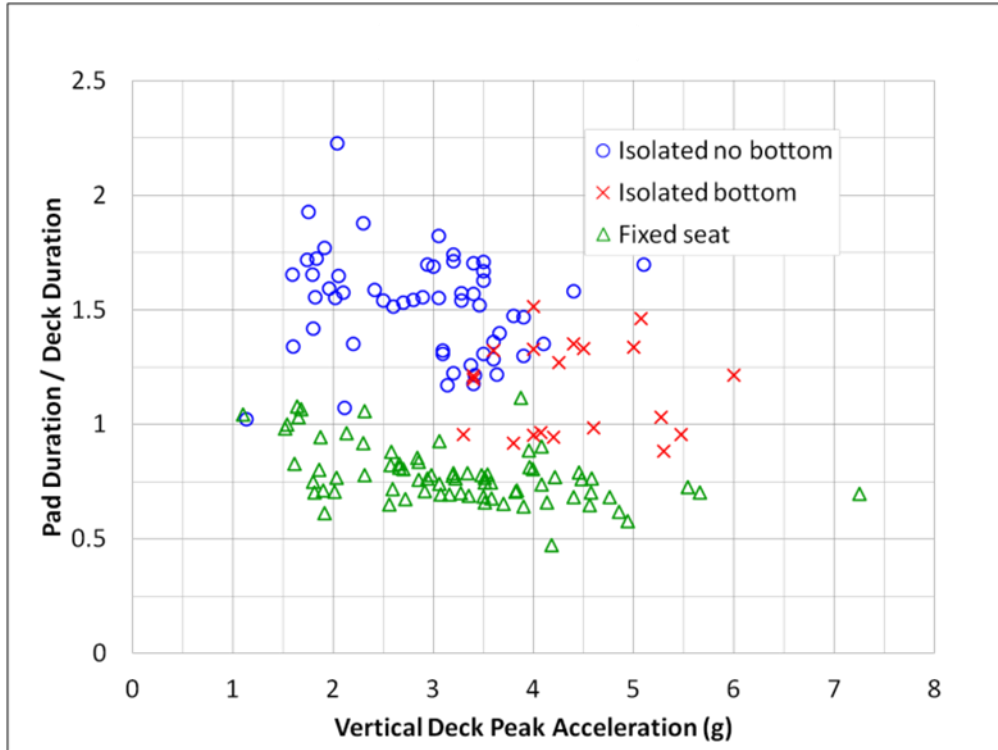


Figure F2. Pad Duration Ratio vs. Isolated Seat Deck Peak-G Run I

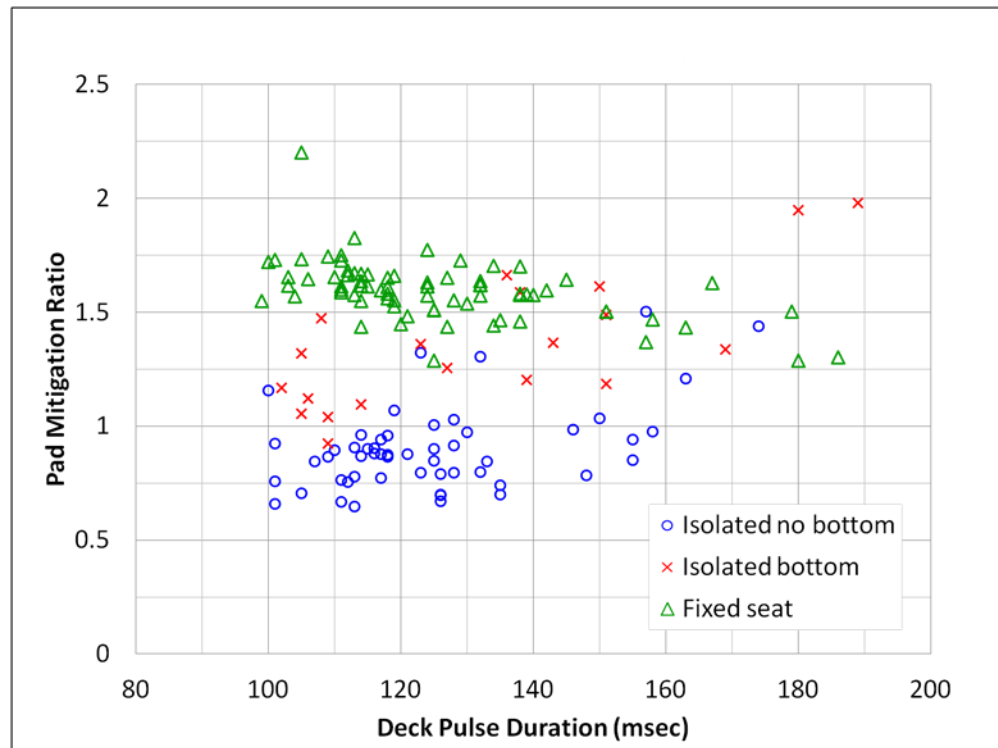


Figure F3. Pad Mitigation Ratio vs. Isolated Seat Deck Pulse Duration Run I

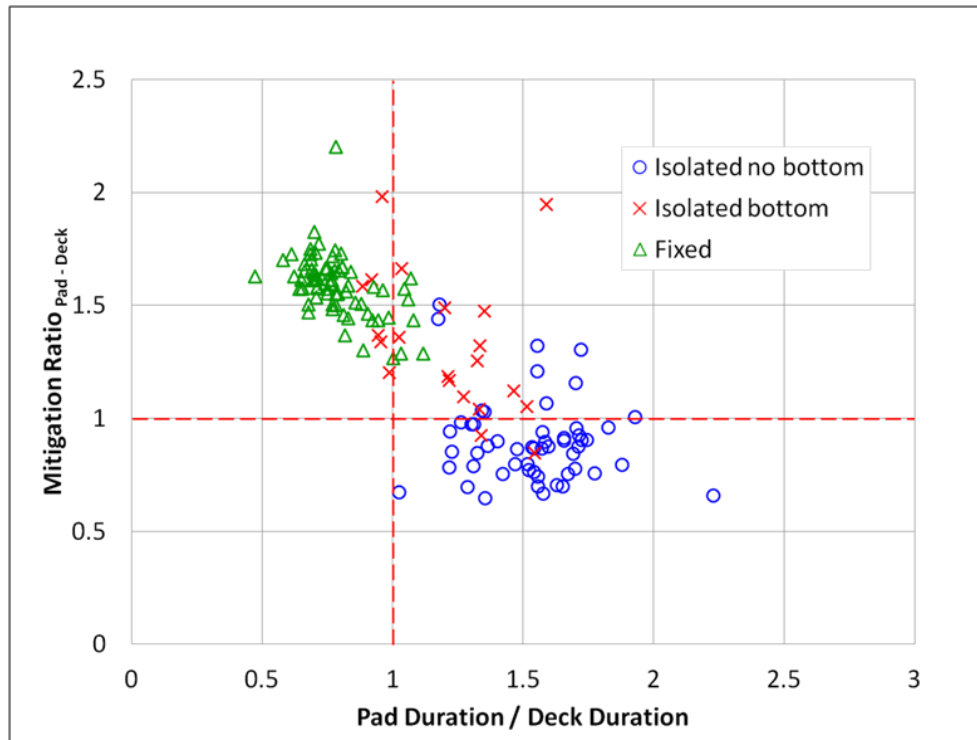


Figure F4. Pad Mitigation Ratio Plots Run I

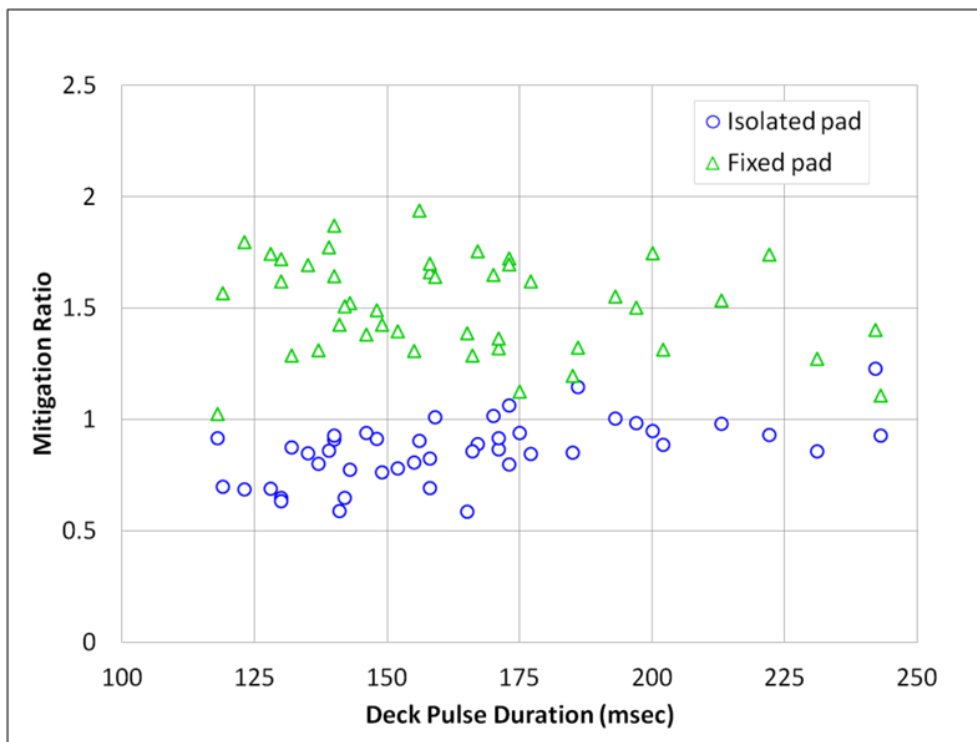


Figure F5. Pad Mitigation Ratio vs. Isolated Seat Deck Pulse Duration Run II

Figure F6 shows the increasing trend of the pad MR values (i.e., blue circles and light blue squares) as deck pulse duration increases for the shock isolated seat. This trend is predicted by theory.

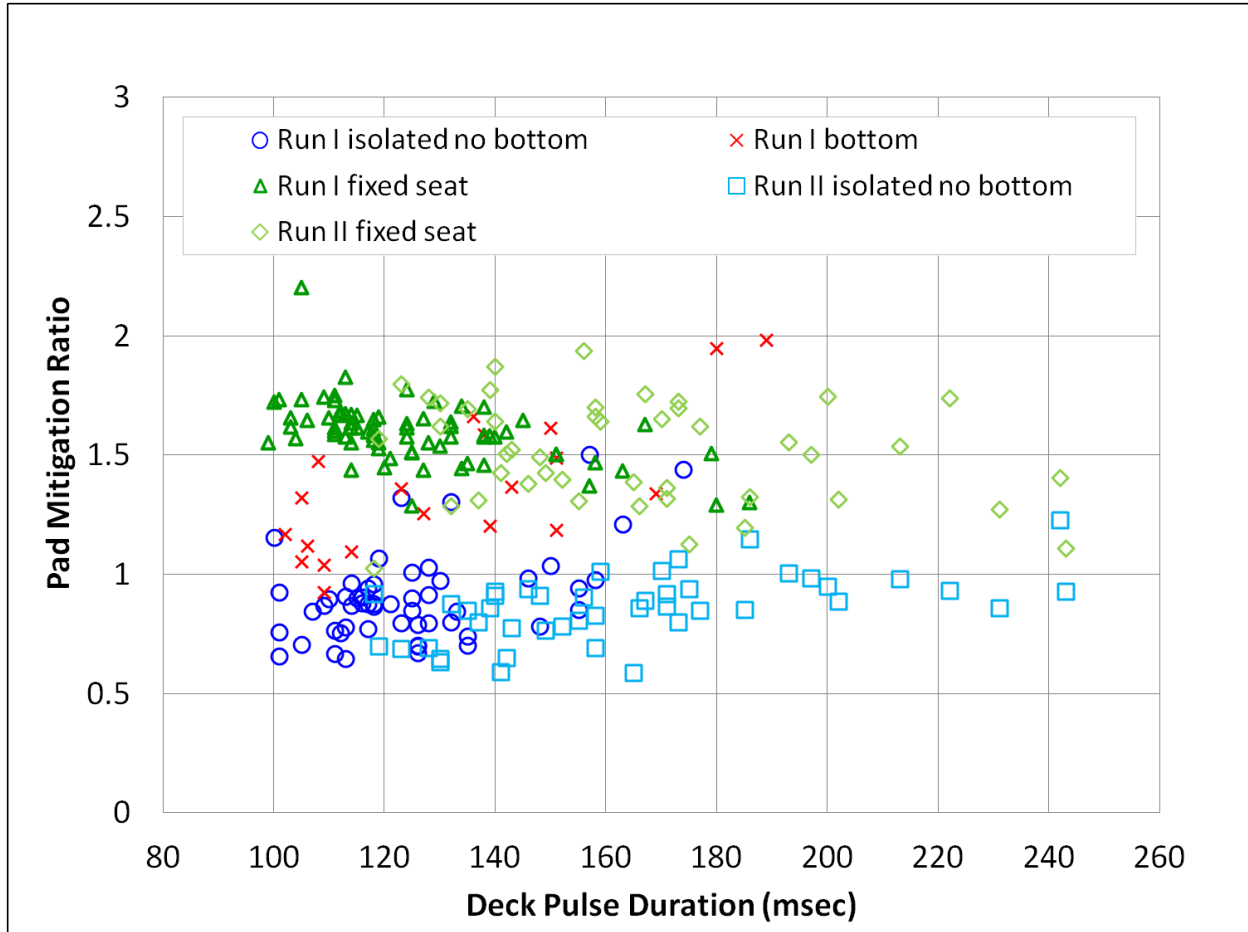


Figure F6. Run I and Run II Pad MR vs. Isolated Seat deck Pulse Duration

Figure F7 shows that the deck shock pulse durations observed during Run I and Run II for the fixed and isolated seats fall within the range of values recorded during seakeeping trials of other craft. The other craft data was recorded on craft weighing up to approximately 170,000 pounds and 85 foot length.

The black triangles are data points recorded at the bow on a craft with a more flexible hull structure that exhibited slight hull girder whipping. On this craft the natural period of the damped bow whipping motion resulted in pulse durations at the bow less than 100 milliseconds.

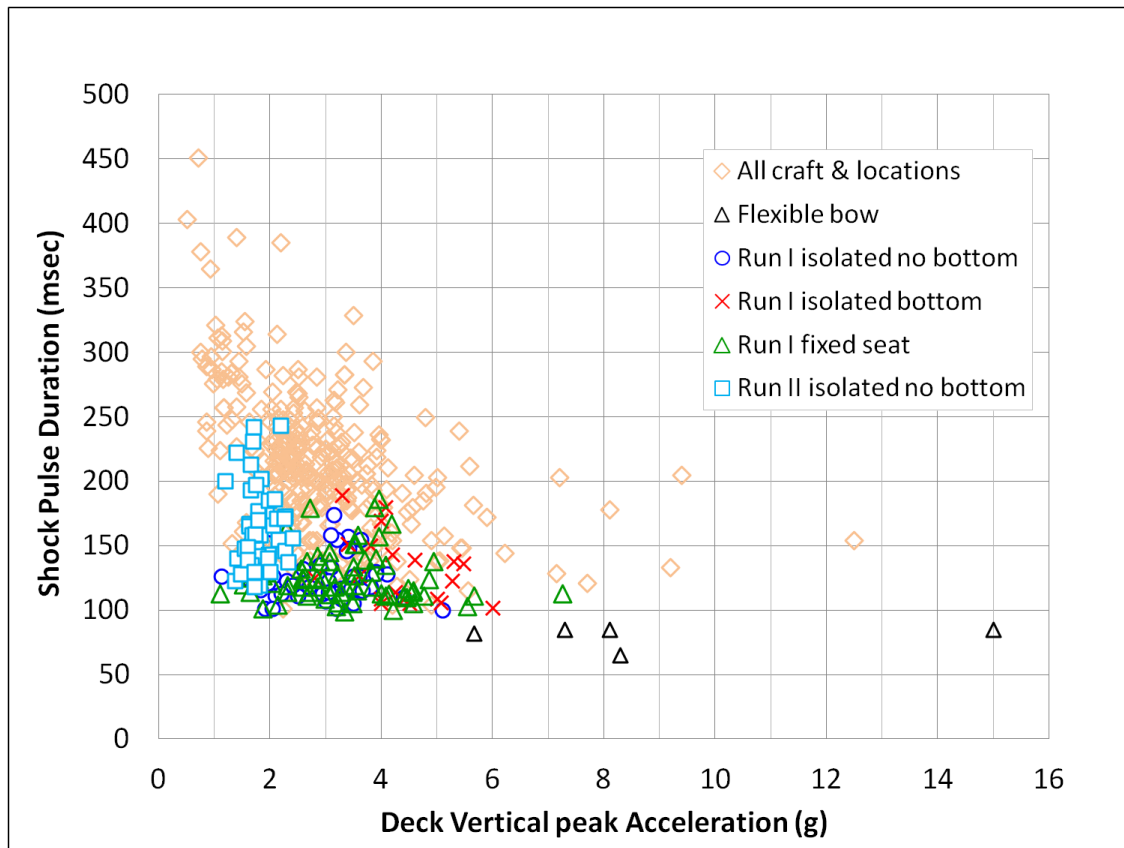


Figure F7. Run I and Run II Data Compared with All Other Craft Data

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APPENDIX G. SEAT PAN MITIGATION RATIOS FOR RUN I

The mitigation ratios for the pan accelerations are also useful. When compared with mitigation ratios for pad data it provides a measure of the effect of the pad combined with the spring-damper assembly. Figure G1 compares the pad and pan MR values for the fixed seat (on the left plot) and the isolated seat (on the right plot) for Run I. The visual differences between the two plots illustrate the different physical phenomenon occurring on the fixed seat compared to the isolated seat.

The fixed seat plot on the left clearly shows that the pad and pan values have distinctly different amplitudes. Most of the pan MR values (orange diamonds) vary from roughly 1.0 to 1.25. This amplification appears to be caused by the relative motion that occurs within the metal seat assembly (i.e., the seat is not actual fixed rigid). The fixed pad MR values (blue circles) are greater than the orange pan MR values. Most of the pad values vary from roughly 1.4 to 1.75, indicating further amplification beyond that on the pan due to compression of the pad during each wave impact.

The majority of the MR values for the isolated seat (blue circles and red X on the right in Figure G1) are less than the fixed pad values (blue circles on the left). The isolated pad values on the right also do not show the same distinct separation between the pad and the pan seen in the left plot. The isolated pad and the isolated pan MR values are close to the same order of magnitude and both vary from roughly 0.5 to 1.5.

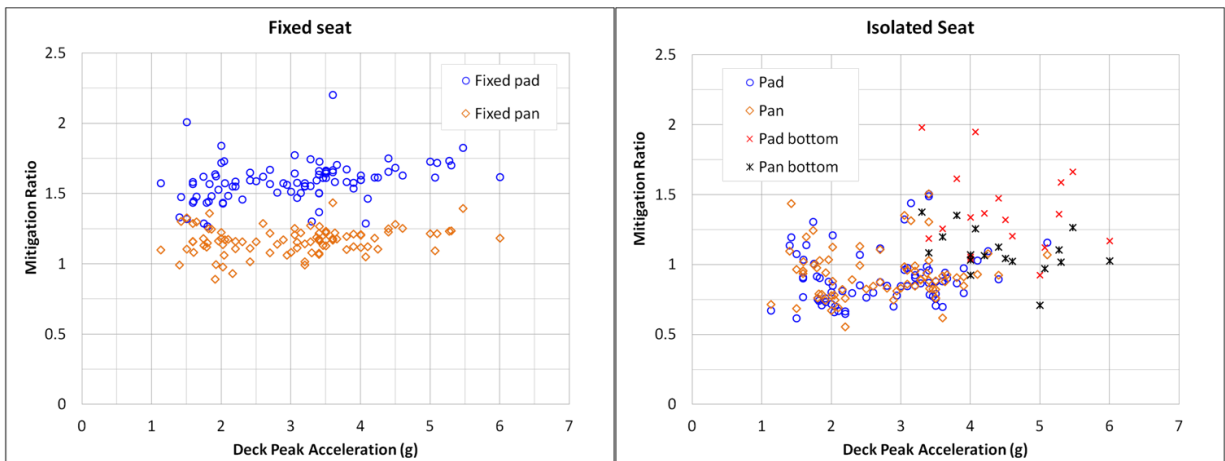


Figure G1. Pad and Pan Mitigation Ratios vs. Deck Peak Acceleration (g)

Figure G2 shows the pad MR values versus the pan MR values for both the fixed seat (black squares) and the isolated seat (blue circles and red X). It clearly shows that the fixed pan

amplifies all but six of the deck shock inputs, and the fixed pad location amplifies all the impacts. For the isolated seat the plot shows some pad MR values are greater than the pan values (i.e., above the 1:1 slope line) indicating pad amplification relative to the pan, while some of the isolated pad values are less than the pan values (indicating pad mitigation relative to the pan).

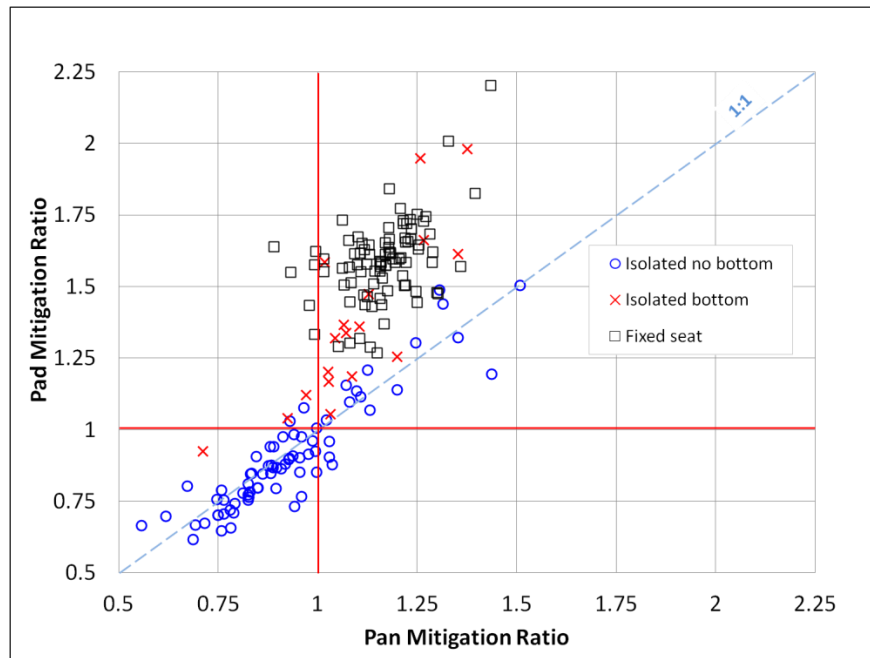


Figure G2. Pad vs. Pan Mitigation Ratios

Figure G3 shows the ratio of the isolated seat MR values divided by the fixed seat MR values. This ratio provides an indication of the isolated seat performance relative to the fixed seat. The pan data for both seats has been added to show the difference in the pan and pad relative performance. The difference between the orange pan ratios and the blue pad ratios clearly shows how the spring-damper-pad assembly improves the isolated pan performance with lower MR values relative to the fixed seat.

The cumulative distribution curves for all the data are shown in Figure G4. It combines the curves for the fixed pan (grey squares) and the isolated pan MR values (light blue diamonds and red plus symbol) with the pad MR values. The black stars for the fixed pad and grey squares for the fixed pan show that the fixed seat pad amplifies all of the fixed pan values (also shown in Figure G3). For the isolated seat, when $MR < 1.0$, the distribution of the blue isolated pad MR values are the same order of magnitude as the light blue isolated pan MR values. The isolated pad (dark blue) and the isolated pan (light blue) MR values indicate approximately 62% of the impacts are mitigated by the spring-damper assembly. The effect of the pad causing successively more dynamic amplification as MR increases above 1.0 is shown by the separation of the pad (dark blue) and pan (light blue) values above 62%. But even though the isolated pad amplifies above the isolated pan values, it amplifies less than the pad on the fixed seat.



Figure G3. Ratio of Isolated and Fixed Pad and Pan MR Values

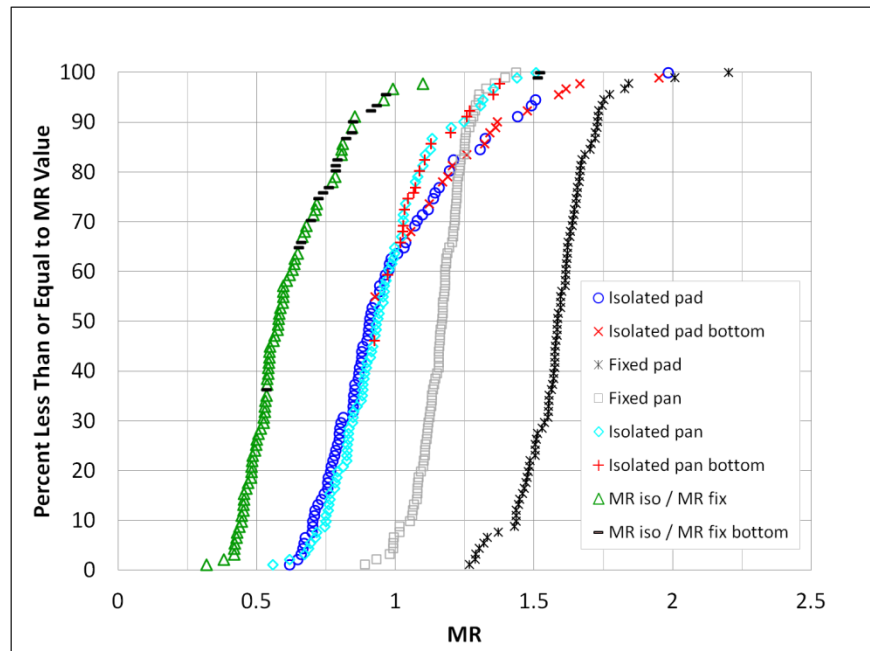


Figure G4. Fixed and Isolated, Pan and Pad Seat Performance

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APPENDIX H. MK V SPECIAL OPERATIONS CRAFT TRIALS

2003 Trials Data

In October 2003 experiments onboard a MK V Special Operations Craft were conducted to evaluate shock and vibration exposure to humans. Accelerations were recorded on side-by-side rigid and shock isolated seats [H1-H4]. Three axis accelerometers were installed on the seat frames (i.e., the pan above the isolator), on the seat pads (i.e., on the cushion between the seat and the occupant), and on the deck below each seat [H2]. The acceleration data was processed using an 80 Hz low-pass filter in accordance with ISO Standard 2631 Part 5, Evaluation of Human Exposure to Whole Body Vibration [H3]. The focus was on comparing different spine injury models for repeated exposure to wave impacts.

Response motions during individual impacts were not the primary focus, but some interesting results were documented. For example, Figure H1 shows a plot from reference H2 illustrating the accelerations recorded on the deck and on the seat pads (i.e., cushions) during a single impact. The relatively low severity deck input acceleration has a peak value on the order of 1.3 g, the isolated pad has a peak of approximately 2.2 g (with slightly lower jerk and perhaps longer pulse duration), and the rigid seat pad peak acceleration was 3.4 g (with similar jerk and shorter duration than the deck). The data for the rigid seat pad clearly illustrates dynamic amplification of the deck peak acceleration caused by the compression of the seat pad during the early phase of the wave impact.

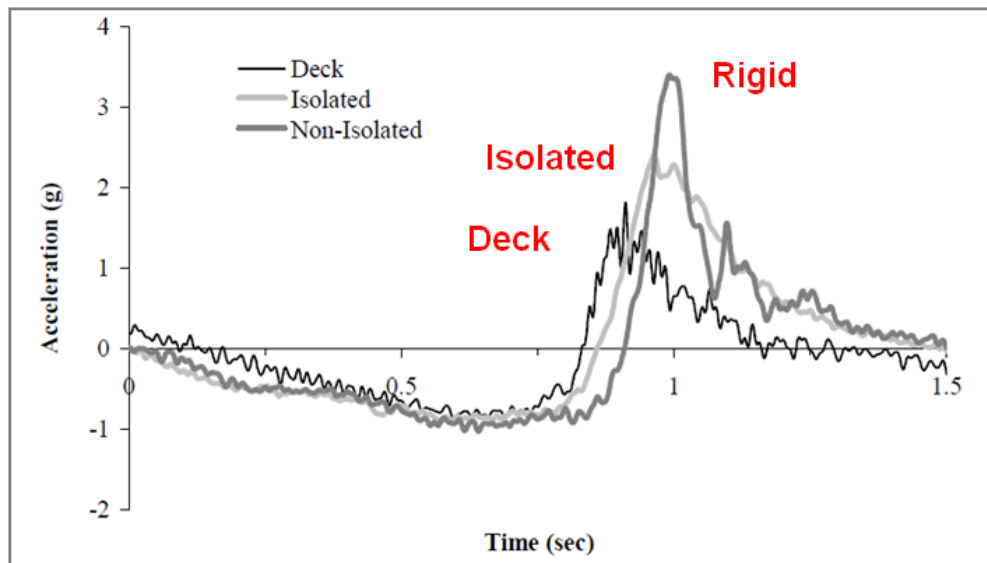


Figure H1. Individual Wave Impact Recorded During 2003 Trials

Figure H2 shows the original statistical distribution plot of all the recorded peak accelerations (80 Hz low pass) in a dual axis format [H2].

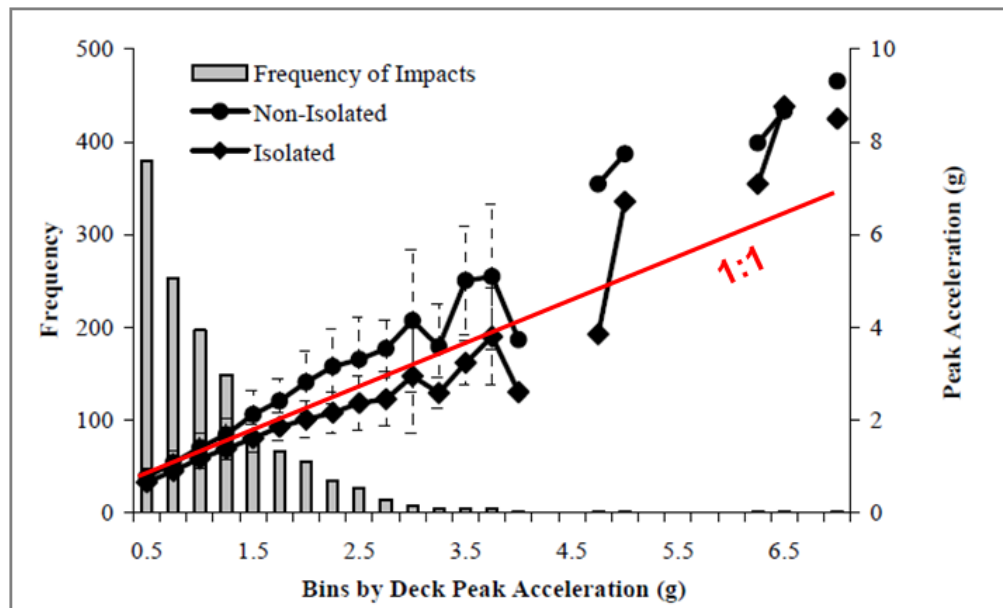


Figure H2. Statistical Presentation of Recorded Peak Accelerations (80 Hz low pass)

The axis on the left in Figure H2 is a histogram of the number of deck peak accelerations observed in 0.25 g bins. The axis on the right plots the average seat pad peak acceleration response for each bin as well as the range of peak accelerations in the bin. The red line with slope of 1 has been added to show when the average peak acceleration on the seat pad is equal to the deck peak acceleration bin. The average acceleration in each bin is plotted with a circle for the rigid seat pad (i.e., non-isolated) and a diamond for the isolated seat pad. The ranges of values (i.e., the vertical bars) are difficult to interpret, but the rigid non-isolated seat pad (i.e., circles) clearly has average amplitudes in each bin greater than the deck peak acceleration. This indicates dynamic amplification by the rigid seat pad was likely occurring during the majority of the impacts. For the isolated seat pad the average peak accelerations are less than the deck values, but the ranges of vertical bars appear to span values greater than the deck peak values (the red line). In other words, the averages in each bin were less than the deck, but some values greater than the deck were observed in many of the bins. This indicates some individual impacts had isolated pad peak accelerations less than the deck input, and some were greater than the deck input. In other words, the isolated seat was amplifying some (but not all) of the deck inputs, but it was still judged by seat occupants to be better (i.e., more comfortable) than the rigid seat pad.

Appendix H References

- H1. Peterson, R., Pierce, E., Price, B., *Shock Mitigation for the Human on High Speed Craft: Development of an Impact Injury Design Rule*, NATO RTO AVT Symposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion, Prague, Czech Republic, 4-7 October 2004.

- H2. Bass, C., Salzar, R., Ziemba, A., Lucas, S., Petersen, R., *The Modeling and Measurement of Humans in High Speed Planing Boats Under Repeated Vertical Impacts*, International Research Council on Bio-dynamics of Impact Conference, Prague, Czech Republic, September 2005.
- H3. ISO 2631-5:2004, *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration, Part 5: Method for Evaluation of Vibrations Containing Multiple Shocks*, International Standards Organization, 2004.
- H4. Klembezyk, A., Mosher, M., *Analysis, Optimization, and Development of a Specialized Passive Shock Isolation System for High Speed Planing Boats*, SAVIAC 2003, 74th Shock and Vibration Symposium, San Diego, CA, October 2003.

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APPENDIX I. DATA ANALYSIS PROCESS FOR EVALUATING THE MECHANICAL ATTENUATION PERFORMANCE OF MARINE SHOCK ISOLATION SEATS

1. Perform an FFT analysis of the acceleration time history to determine the frequency content and what low-pass filter to use to estimate rigid body accelerations. Apply the low-pass filter to the acceleration data.
2. Perform a quick look analysis of the acceleration data for the side-by-side seats. Compare deck, pan, and pad peak accelerations and acceleration ratios. For seakeeping data, use StandardG to obtain peak accelerations from the entire time history. For laboratory drop tests, tabulate peak accelerations.
3. Select the individual shock events of be analyzed, using either at-sea wave impact data or laboratory drop test data.
4. Using the time history plots of individual impacts (4-zero crossings), compute the relative displacement shock response spectrum value (for 8 Hz and 22% damping) for deck, pan, and pad (i.e., cushion) locations.
5. Compute the SRS mitigation ratio (MR) for the pad (and pan) relative to the deck for both fixed and isolated seats.
6. Compute the SRS MR for the isolated seat pad relative to the fixed pad. (Divide the SRS MR for the isolated seat pad by the SRS MR for the fixed seat pad, and plot versus the SRS MR for the pad relative to the deck.)
7. Evaluate pad (i.e., cushion) dynamics by comparing pan and pad SRS MR.

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