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Technical Report

A Comparison of the Mechanical Shock Mitigation Performance of a Shock Isolation Seat Subjected to Laboratory Drop Tests and At-Sea Seakeeping Trials

by

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14. ABSTRACT This report compares shock isolation seat data recorded during laboratory drop testing with data recorded on a similar seat during craft seakeeping trials. The laboratory test data demonstrated the seat's mitigation performance prior to installation in the craft. The seakeeping trial data shows similar wave impact shock mitigation performance. These results provide an interim, partial validation of the laboratory test requirements.

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SYMBOLS, ABBREVIATIONS, AND ACRONYMS

A_{MAX} .... peak or maximum acceleration
ASRS........ acceleration shock response spectrum
c........ damping coefficient
CCD .... Combatant Craft Division
DRI........ dynamic response index
DSRS........ relative displacement shock response spectrum
f or f_{SYS}........ natural frequency
ft .... feet
g........ acceleration due to gravity (32.2 ft/sec^2)
HSC........ high speed craft
Hz .... Hertz (cycles per second)
k........ stiffness coefficient
lb(s) .... pound
LCG........ longitudinal center of gravity
m .... mass
MR .... mitigation ratio
msec .... millisecond
N........ number of wave impacts
π .... approximately 3.14159
SDOF .... single degree-of-freedom
SRS .... shock response spectrum
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
ς .... percent of critical damping
% .... percent

ADMINISTRATIVE INFORMATION

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SUMMARY

This report compares acceleration data recorded during laboratory drop tests of a shock isolation seat with acceleration data recorded on similar seats during at-sea trials. The laboratory tests subjected the seat to vertical half-sine shock pulses that simulate a range of wave impact shock pulses expected for this craft while operating at high speeds in rough seas. The purpose of the laboratory tests is to evaluate the mechanical shock mitigation performance of the seat before installation in a craft. This was the first time a shock isolation seat was required to be laboratory tested before installation in a U.S. Navy craft.

The laboratory drop tests included testing with three inert payload weights. The test data showed that the seat design reduced the severity of the required input shock pulses. The seat did not amplify any of the shock input pulses and seat bottom impacts did not occur.

Seats of the same design tested in the laboratory were subsequently installed in two craft and instrumented with acceleration gauges prior to at-sea testing. Two seats in each craft were instrumented: an aft passenger seat and the coxswain seat. The aft passenger seats were located roughly 3 feet aft of the longitudinal center of gravity (LCG). The coxswain seats were located roughly 3 feet forward of the LCG. The trial results indicate that in the impact severity range of interest from 3 g to 5.3 g that shock mitigation was achieved, dynamic amplification did not occur, and seat bottom impacts did not occur. The at-sea testing did not achieve wave impact severities up to the full 6 g threshold value for pan and cushion locations. The results show that the at-sea shock mitigation performance overlaps the ranges of the laboratory test mitigation. This overlap, and the lack of dynamic amplification and seat bottom impacts during at-sea testing, provide an interim, partial validation that the goals of the laboratory tests were achieved. Continued laboratory testing is recommended.

When invoked by acquisition documents, completion of laboratory testing and successful demonstration of reduced shock inputs to seat occupants is a first step toward integration into a craft design. Many other seat design attributes related to form, fit, function, comfort, fatigue and safety must also be considered to determine which seat design is most appropriate for different high-speed craft applications.

INTRODUCTION

Background

Passive shock isolation seats are installed in high-speed craft to provide comfort and to mitigate the effects of severe wave impacts encountered during high-speed transits in rough seas. Numerous publications between 2003 and 2013 reported that the shock mitigation goal was not always achieved, and that seat designs could amplify the shock pulses recorded on the deck below the seats [1-12]. To address this issue a review of available seat data was initiated in 2010. Newly developed standardized procedures for analyzing the shock severity of individual wave impacts were applied [13-15]. A review of acceleration data from six different seakeeping trials confirmed the findings. Shock isolation seats from five different manufacturers exhibited little or no mitigation, or showed signs of amplifying severe shock inputs. It was therefore desirable to be able to conduct laboratory tests before installation in a craft that could show that: (1) mechanical shock amplification does not occur, and (2) simulated wave impact forces can be mitigated [16]. Conceptually, after demonstrating these objectives in laboratory testing, a seat design could be considered for installation in a craft.

From 2011 to 2016 a working group of naval researchers from Canada, the United Kingdom, and the United States shared laboratory drop test data and at-sea trials data to develop standardized laboratory test requirements for shock isolation seats [17-32]. Results of seat laboratory testing conducted in Canada in 2014 demonstrated that the drop test procedure produces shock loads representative of slamming-induced repeated shocks experienced by high speed craft occupants, and that some seats could amplify deck level shock inputs [29]. In 2016, a comparison of laboratory drop test seat data and seakeeping trial seat data in the United Kingdom concluded that the correlation was “in good agreement” and that “drop testing was a useful approach for down selecting seats for further testing” (at-sea) [33].

U.S. Navy seat test requirements were first published in 2015 [26] and revised in 2018 [34]. The requirements were based largely on lessons learned from seat testing at-sea in the U.S. and laboratory drop testing performed in Canada and the United Kingdom [19, 20, 23, 25, 28, 29]. The engineering rationale, assumptions, and criteria for the test requirements were published in 2018 [35].The test requirements were subsequently published as standard test requirements in a Naval Sea Systems Command technical manual in 2019 [36].

In 2016 the U.S. seat test requirements [26] were included in U.S. Navy acquisition requirements for a new high-speed craft (HSC). Seats had to undergo laboratory testing to be considered for installation in the craft. Seat manufacturers conducted successful laboratory drop tests that were submitted in test reports as part of the acquisition program.

When invoked by acquisition documents, completion of laboratory testing and successful demonstration of reduced shock inputs to seat occupants is a first step toward integration into a boat design. Many other seat design attributes (e.g., comfort, weight, size, arrangements, adjustability, cost, safety) must also be considered to determine which seat design is most appropriate for different high-speed craft applications.

Purpose

The purpose of this report is to present a comparison of the shock mitigation performance of a shock isolation seat recorded during laboratory tests with the mitigation performance of similar seats installed and tested in a high-speed craft during at-sea seakeeping trials. The purpose of the comparison is to evaluate the efficacy of the laboratory test requirements as an indicator for successful mitigation at-sea.

Rigid Body Accelerations

Raw acceleration data includes acceleration signals caused by local structural vibrations in the vicinity of the gauge as well as rigid body accelerations. Quantifying and comparing differences in shock pulse severity requires that the vibration portion of the signal be removed by low-pass filtering [21]. All acceleration data presented in this report is the rigid body vertical acceleration obtained by using a 20 Hz low-pass filter as specified by the laboratory test requirements.

SEAT TESTS

Laboratory Drop Tests

In 2017 a shock isolation seat was subjected to vertical drop tests by the seat manufacturer in accordance with the HSC acquisition documents and reference [26]. The documents specified testing at four test severities (100 msec half-sine pulses with 3 g, 4 g, 5 g, and 6 g peak rigid-body amplitudes)[1]. Three inert seat payloads (109 pound (lbs), 184 lbs, and 248 lbs) simulating the weight of seat occupants were tested with each test repeated three times. Vertical accelerometers were installed to record shock inputs at the base of the seat. Vertical response accelerations were recorded by gauges mounted on the seat pan and on the cushion between the payload and the cushion.

Figure 1 shows an example of the vertical rigid body accelerations[2] recorded at the base of the seat for the heaviest payload at the 6 g test severity level. Each test severity level is repeated three times. The dotted lines specify the allowable envelopes for each shock pulse to be considered a valid test. The three different colors show the results of the three repeated drop tests. The 3 g, 4 g, 5 g, and 6 g peak rigid body accelerations specified for this craft were achieved by adjusting the drop height of the test apparatus.

The mitigation performance of the seat for each drop test was computed using the shock response spectrum (SRS) mitigation ratio (MR). It is a ratio that divides the severity of the shock pulse measured on the seat (cushion and pan locations) by the severity of the shock pulse measured on the deck below the seat. The severity of an acceleration shock pulse depends upon its direction, the rate of application (i.e., jerk), peak amplitude, pulse shape, and pulse duration [36]. The shock response spectrum calculation inherently accounts for all of these shock pulse attributes when comparing shock pulse severities [27].

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[1] These amplitudes were selected based on the craft weight and mission profile.
[2] The rigid body acceleration recorded during an impact event characterizes the shock pulse force.

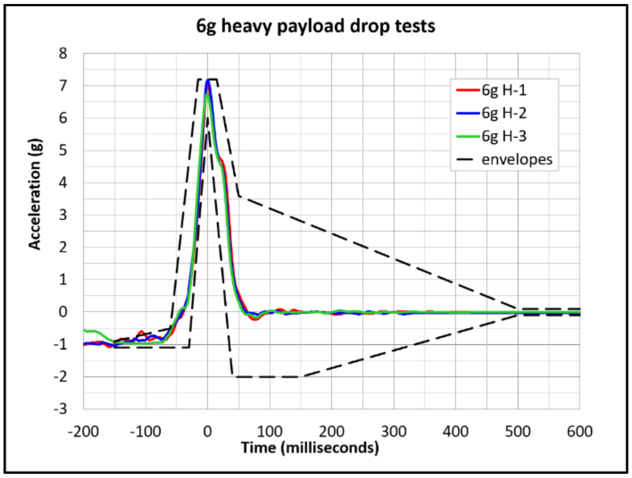

Figure 1. Example Drop Test Acceleration Pulses

The MR is a measure of a seat's shock mitigation performance during an impact event. As an example, a computed value of MR equal to 0.7 indicates the seat response severity was seventy percent of the deck input shock pulse (i.e., a thirty-percent reduction of the shock input severity). If MR is equal to 1.0 it indicates zero mitigation. If MR is greater than 1.0 it indicates the seat amplified the deck shock input. The computational method and rationale for its use are presented in Appendix A.

Figure 2 is a plot of the computed mitigation ratios for different deck peak accelerations achieved during the laboratory drop tests. The MR values for the pan acceleration varied from 0.45 to 0.76 depending upon the input shock pulse severity. On the seat cushion the acceleration data yielded MR values from 0.55 to 0.96 depending upon payload weight. The results show that the seat pan and seat cushion MR values are all less than 1.0, so the seat did not amplify the deck inputs. Analyses of the time history data indicated that seat bottom impacts did not occur during the drop tests.

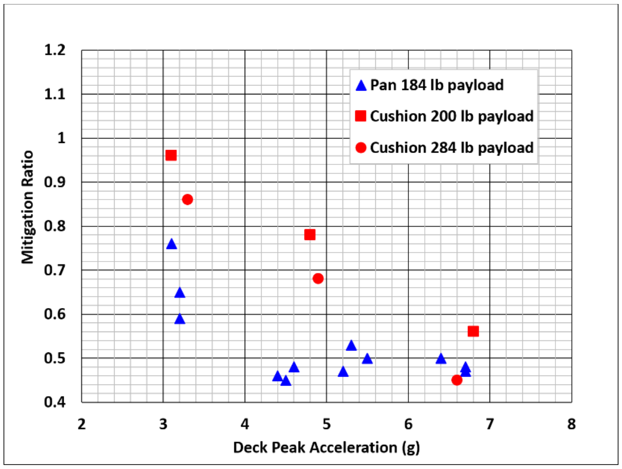

Figure 2. Laboratory Drop test Mitigation Ratios

Craft Seakeeping Trials

The new craft was tested by the Combatant Craft Division (CCD) of Naval Surface Warfare Center Carderock (NSWCCD) during at-sea seakeeping trials. Two craft of the same design were tested side-by-side during the trials. Craft 1 was configured to a Normal Load displacement. Craft 2 was configured to a Full Load displacement weighing 4,500 lbs more than Craft 1. Acceleration data from three head sea runs was used to evaluate seat mitigation performance. Table 1 lists the craft average speeds obtained from global positioning satellite data, as well as significant wave heights and average wave periods obtained from wave buoy data.

Table 1. Seakeeping Trials

Run	Average Speed knots		Significant Wave Height	Average Wave period
	Craft 1	Craft 2	feet	seconds
1	29.4	29.6	3.6	5.4
2	19.4	20.5	5.7	4.7
3	33.4	31.6	3.9	5.2

Five shock isolation seats were installed in each craft[3]. Two of the seats in each craft were instrumented with vertically oriented accelerometers: the coxswain (cox) seat and an aft passenger (pax) seat. The passenger seat was positioned approximately three feet aft of the longitudinal center of gravity (LCG). It had accelerometers on the seat cushion below a 175-lb inert payload weight, on the seat pan, and on the deck at the base of the seat. The coxswain seat was positioned approximately 3 feet forward of the LCG. It had accelerometers on the seat pan below the cushion and on the deck at the base of the seat. For Craft 1 the coxswain weighed roughly 210 lbs. The coxswain in Craft 2 weighted roughly 170 lbs. During the trials there was not sufficient time to test all three payload weights tested in the laboratory.

Figures 3 and 4 show example 20 Hz low-pass filtered data recorded during the at-sea trials in Craft 2. The black curves are the rigid body deck vertical accelerations. The red curves are rigid body vertical seat pan accelerations. The green curve in Figure 4 is the vertical seat cushion acceleration recorded on the passenger seat. Each spike in the acceleration record corresponds to an individual wave impact. Figures 3 and 4 show the coxswain seat is exposed to higher wave impact peak accelerations because it is forward of the LCG where it is exposed to the effects of larger downward pitch accelerations. The coxswain seat position experienced eight impacts with peak vertical accelerations greater than 3 g. The passenger seat is subjected to only one impact with a peak greater than 3 g because it is aft of the LCG.

[3] Each seat had a switch with two settings for manual adjustment based on payload weight (i.e., position 1 for greater than 200 lbs and position 2 for less than 200 lbs).

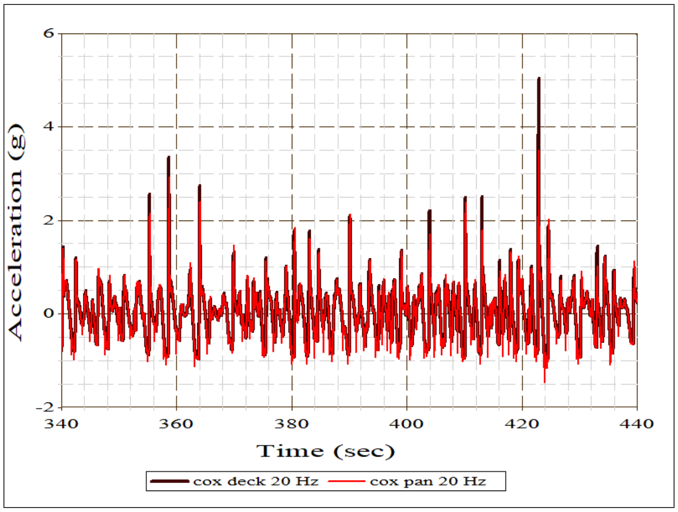

Figure 3. Deck and Pan Accelerations on Coxswain Seat

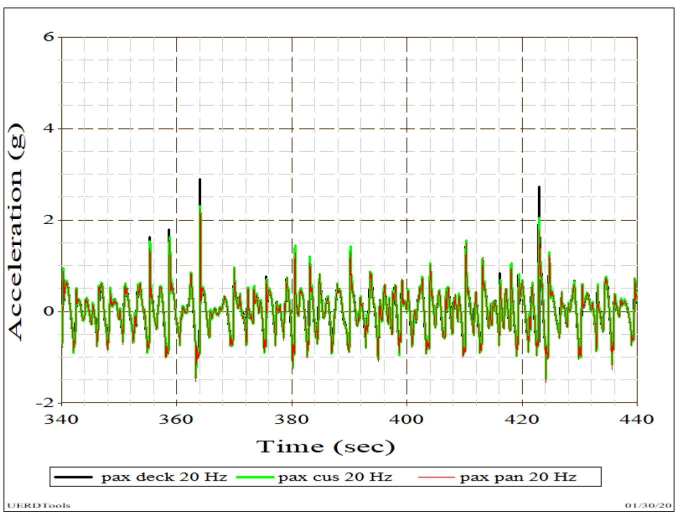

Figure 4. Deck, Pan, and Cushion Accelerations on Passenger Seat

Seat Data Analysis Process

The mitigation performance of each seat is determined by comparing the severity of the acceleration time history recorded at the deck (i.e., base of seat) with the severity of the seat response accelerations recorded on the pan and cushion. Figure 5 shows example data for a wave impact that occurred at approximately 5.3 seconds in the time history. The plot on the left shows the deck input acceleration (black curve) and the seat pan response acceleration for the coxswain (cox) seat. The plot on the right shows the deck input acceleration (black curve), the seat pan response acceleration (green curve), and the seat cushion response acceleration (blue curve) for the passenger (pax) seat. The higher peak acceleration amplitude at the coxswain deck (black curve) location is due to its position farther forward of the LCG.

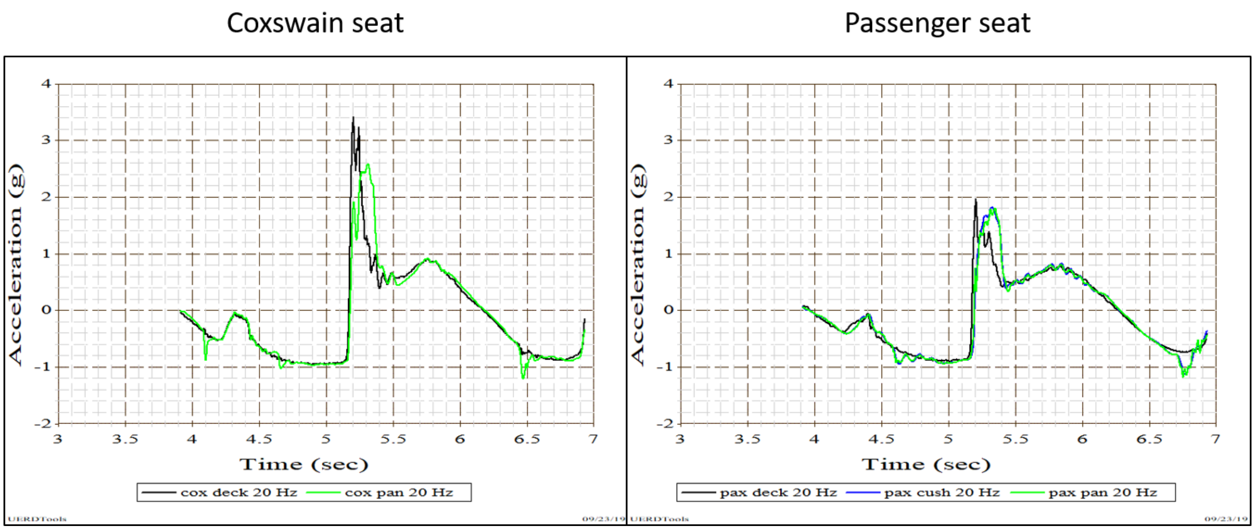

Figure 5. Example Accelerations for an Individual Wave Impact

The measure used to quantify the mitigation performance of a shock isolation seat is the mitigation ratio (MR). The MR is computed by dividing the relative displacement shock response spectrum (DSRS) for the seat response acceleration divided by the DSRS of the deck input acceleration [35]. When the seat cushion acceleration data is used to compute MR, as shown by equation (1), it is a measure of the mitigation performance of the entire system, including the shock absorbers, the seat pan, and the seat cushion.

$$MR_{cushion} = \frac{DSRS_{cushion\ accel}}{DSRS_{deck\ accel}} \qquad \text{Equation (1)}$$

When the seat pan acceleration data is used to compute the MR, as shown by equation (2), it is a measure of the mitigation performance of the partial system that includes only the shock absorbers and the seat pan (i.e., without the seat cushion). The reason for computing the pan MR is discussed later in the report.

$$MR_{pan} = \frac{DSRS_{pan\ accel}}{DSRS_{deck\ accel}} \qquad \text{Equation (2)}$$

Appendix A summarizes the MR computational process and the rationale for its use. The computed mitigation ratios for the seats on both craft will be presented for all three runs in a later section of the report.

Figure 6 shows example MR plots for a wave impact recorded on the coxswain and passenger seats in craft 2. The acceleration time histories are in the upper plots, and the corresponding mitigation ratio curves are in the lower plots.

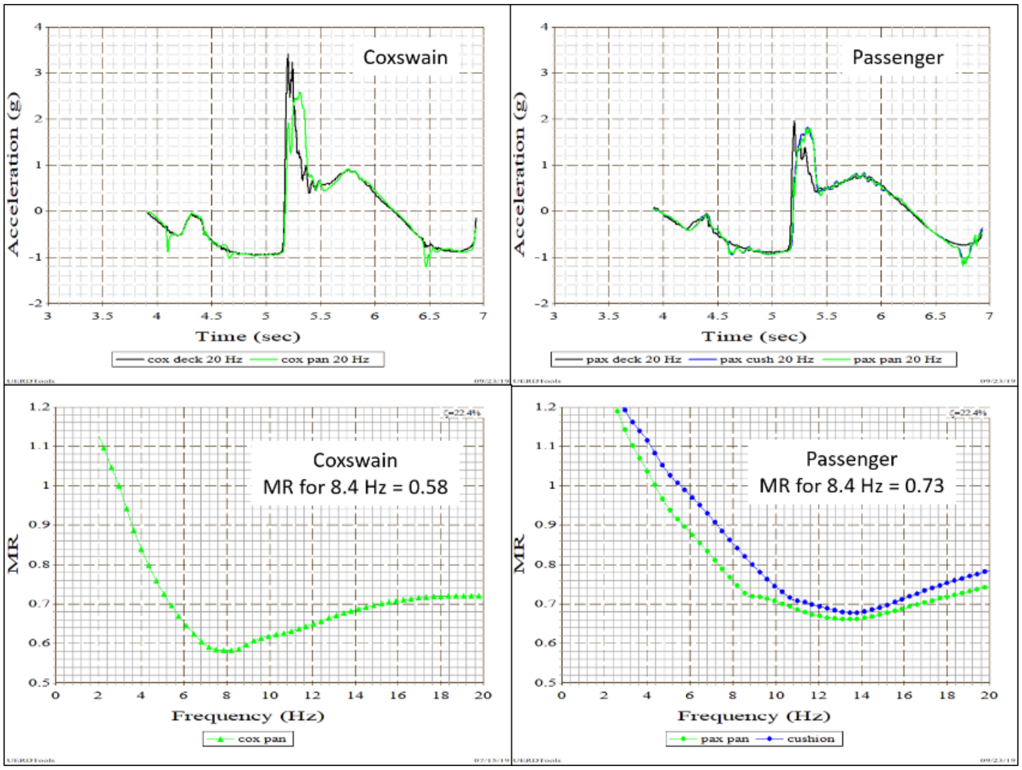

Figure 6. Example Acceleration and Mitigation Ratio Plots

The MR value for a natural frequency of 8.4 Hertz (Hz) is used to quantify the mitigation performance of the seat pan and cushion [35]. In Figure 6 the computed MR values for the pan are 0.58 (cox) and 0.73 (pax), indicating a 42-percent reduction on the coxswain pan and 27-percent reduction on the passenger pan. The MR value for the passenger cushion is 0.82, indicating an 18-percent reduction.

Craft 1 Seat Performance

Computed MR values for the seat pan and seat cushion locations in craft 1 are shown in Figure 7. For both seats all impacts with a peak acceleration of 2 g and higher were analyzed. Only a few impacts with peaks from 1 g to 2 g were analyzed. The left plot is for the seat pan data. The right plot is for the cushion data. The red circles are for the passenger seat. The blue triangles are for the coxswain seat pan. The yellow symbols are the mitigation ratios computed using the laboratory drop test acceleration data.

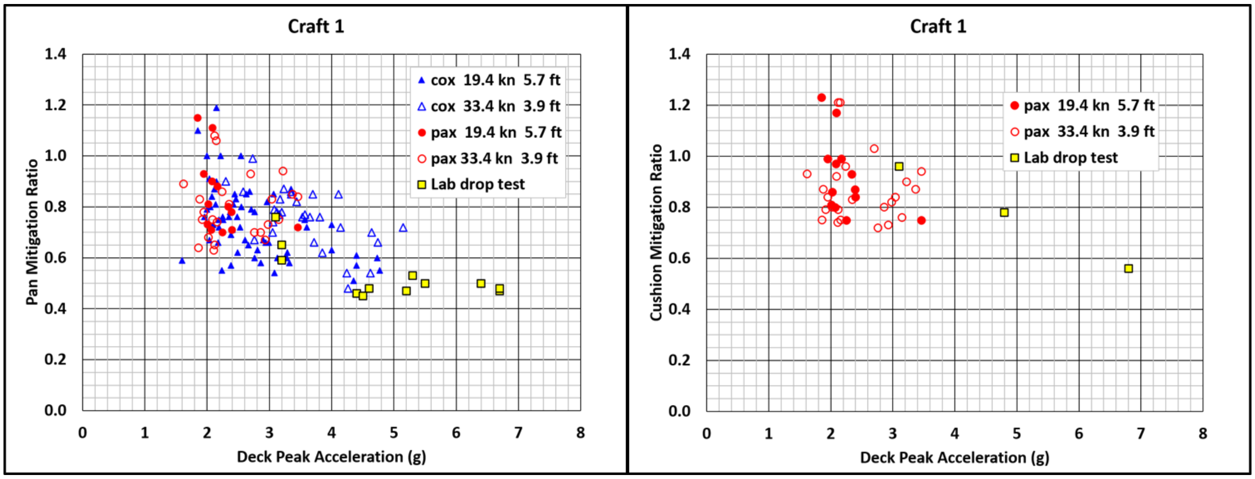

Figure 7. Craft 1 Seat Mitigation Ratios

The scatter in the MR values is attributed to the presence of non-vertical forces[4] and rotations[5], as well as longer duration input shock pulses not simulated in the laboratory tests. The left plot in Figure 7 shows that the coxswain seat was subjected to deck input accelerations with peaks as high as 5.15 g. The plot on the left shows that as deck input severity increases from 1.6 g to 5.15 g, the pan MR values improve from 1.19 to 0.48. As the deck input severity increases the MR values decrease to the range of MR values for the laboratory drop test data. The seat cushion MR values on the right improve from 1.23 to 0.75 for deck input peak accelerations increase from 1.6 g to 3.46 g. The cushion and the pan MR values both show similar improvement trends (i.e., the light blue dashed lines) exhibited by the laboratory MR values: as deck input severity increases the MR values decrease.

Craft 2 Seat Performance

Computed MR values for the coxswain and passenger seats in craft 2 are shown in Figure 8. The left plot is for the pan data. The right plot is for the cushion data. The red circle and blue square symbols are for the passenger seat. The blue triangle and blue diamond symbols are for the coxswain seat. For both seats all impacts with a peak acceleration of 2 g or more were analyzed. Impacts with peak accelerations from 1 g to 2 g were surveyed to show trends. The trends for craft 2 pan MR values are similar to the trends for craft 1. As deck input severity increases from 1.2 g to 5.3 g the pan MR values improve from 1.19 to 0.45. As the deck input severity increases the MR values decrease to the range of MR values for the laboratory drop test data. The seat cushion MR values on the right vary from 1.02 to 0.65 for deck input peak accelerations from 1.2 g to 3.65 g.

[4] Fore-aft and port-starboard wave impact forces.
[5] Pitch, roll, and yaw rotations.

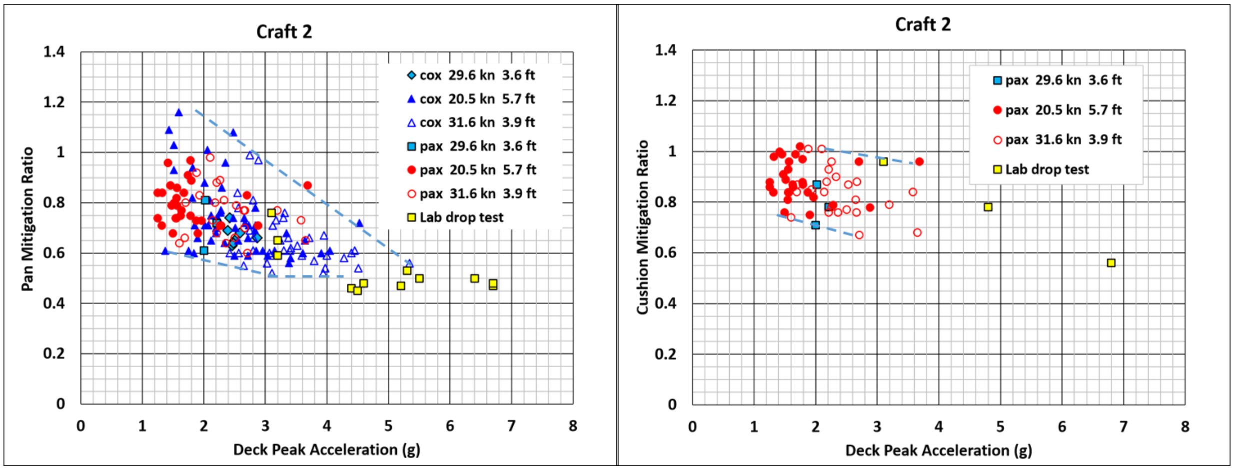

Figure 8. Craft 2 Seat Mitigation Ratios

Craft 1 and Craft 2 Data

Figure 9 shows all the MR values for craft 1 seats (red symbols) and all MR values for craft 2 (blue) seats. Pan values are on the left and cushion values are on the right. The MR values show similar results, both in amplitude and improved mitigation with increasing severity. The relatively small differences between the distributions of blue and red MR values are likely attributed to three factors: different craft displacements, coxswain throttling, and different coxswain weight. Craft 2 weighed 4,500 lbs more than Craft 1. Typically lighter craft experience larger peak accelerations than heavier craft, but during run 2 and run 3 the coxswain were throttling (i.e., reducing speed) when anticipating a very severe wave impact. The purpose of throttling is to reduce crew exposure to the potential higher peak accelerations. It is therefore not possible to clearing identify craft weight trends because different coxswains have different reaction times and different throttling skills. The third factor is coxswain weight. The coxswain in craft 1 weighed on the order of 50 lbs to 75 lbs more than the coxswain in craft 2. The manual switch on the coxswain seat was therefore set for greater than 200 lbs, and the passenger seat was set for less than 200 lbs.

Figure 10 combines MR values for both craft to show the overall seat performance trends for coxswain and passenger seat locations. The pan MR values are on the left, and cushion MR values are on the right. All MR values and deck peak accelerations are tabulated in Appendix B. The dotted blue lines for the pan data on the left clearly show the general trend of improving mitigation performance (i.e., decreasing MR values) as deck peak acceleration increases. A similar trend is observed on the right for the cushion MR values for deck peak accelerations less than 3 g.

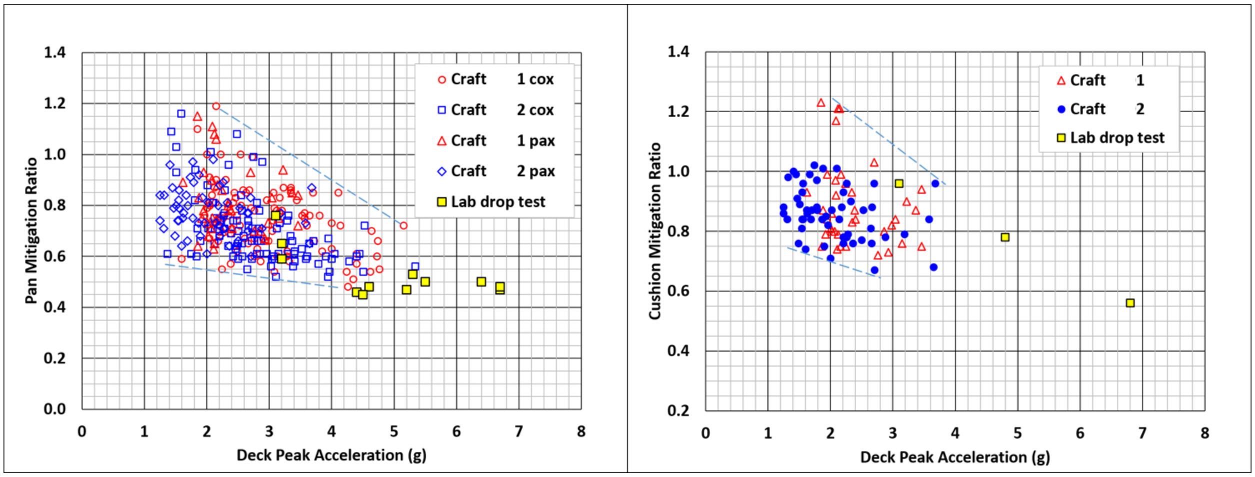

Figure 9. Craft 1 MR Compared to Craft 2 MR

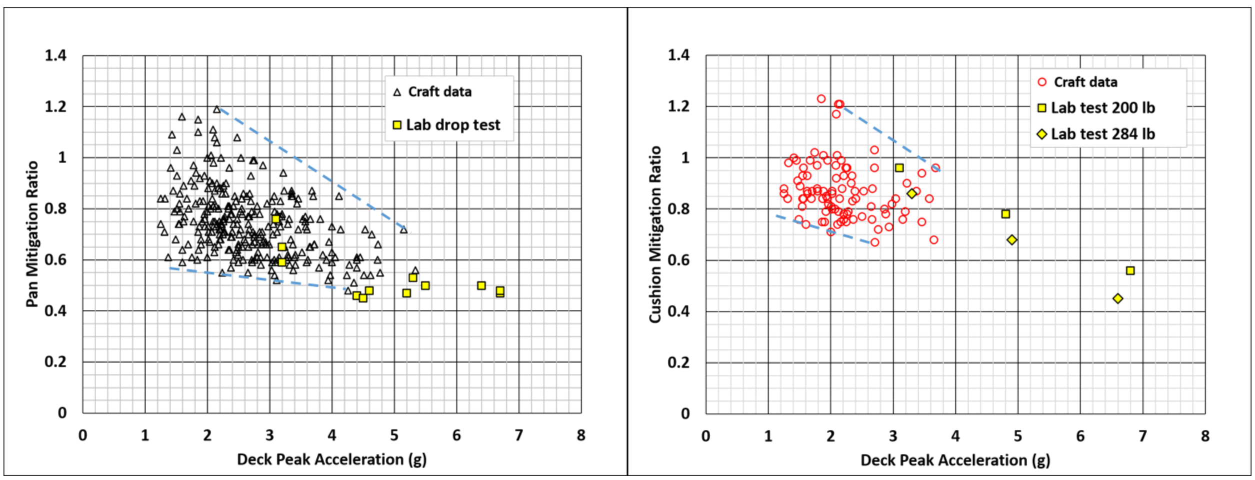

Figure 10. Seat Pan and Seat Cushion MR Value Trends

For deck input peak accelerations greater than 3 g, the MR values are all less than 1.0, indicating mitigation was achieved by varying amounts. The values range from 0.46 to 0.94 for pan data (i.e., 6-percent to 54-percent shock reduction) and 0.68 to 0.96 for cushion data (i.e., 4-percent to 32-percent shock reduction). The range of the variations and the decreasing height of the range as deck peak acceleration increases is believed to be caused primarily by the occurrence of larger shock pulse durations as deck impact severity decreases. Appendix C explains observed trends in shock pulse duration and presents theoretical calculations that explain why MR values increase (less effective mitigation) as shock pulse duration increases.

The data points plotted in Figure 10 for deck input accelerations from 1 g to 2 g are a small sampling of the hundreds of wave impacts in this amplitude range. It is therefore not possible to describe the trends of the full data set in this range. The analysis process did, however, include analyzing all impacts with deck peak accelerations equal to or greater than 2 g, so the plot in Figure 10 in the 2 g to 3 g range is fully populated. In this range there are five pan MR values and three cushion MR values greater than 1.0, and the same general trend is observed in this range: as the deck peak acceleration decreases, the largest MR values increase. This trend appears to be related to the occurrence of larger shock pulse durations for lower severity wave impacts. See Appendix C.

Mitigation Ratio Statistics

Figures 11 and 12 show statistical plots for all mitigation ratios for the passenger seat and the coxswain seat. In the data set there are 91 MR values for the passenger seat, and 193 values for the coxswain pan.

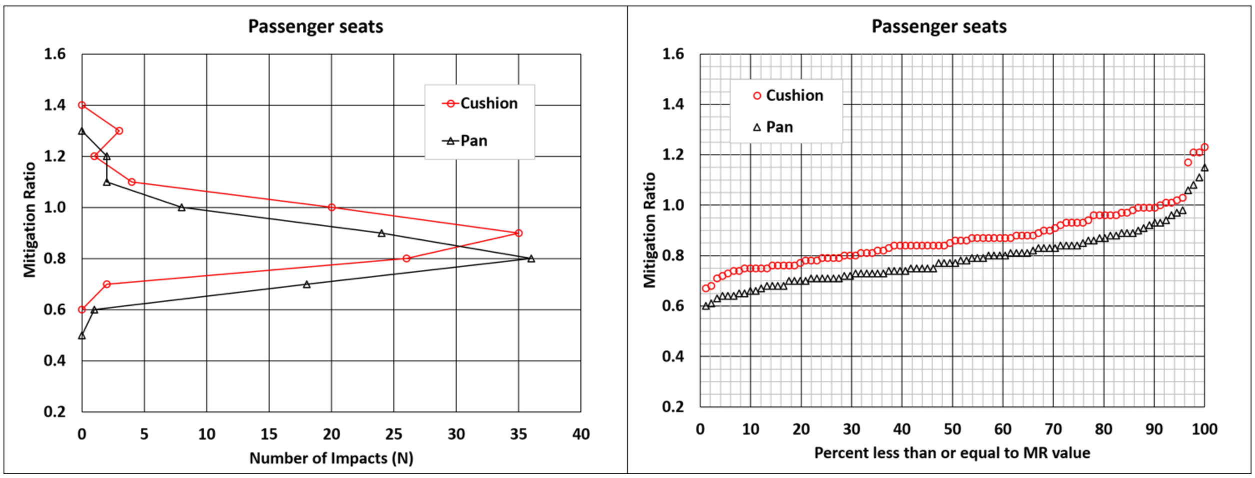

Figure 11. Passenger Seat Mitigation Ratio Statistics

The plot on the left in each figure is a histogram showing the number of MR values that fall in 0.1 bins. The number of values is plotted at the upper end of each bin. The plot on the right is a cumulative distribution showing the percent of values less than or equal to an MR value.

Table 2 presents the statistics for the craft pan and cushion MR values for all wave impacts shown in Figure 10. The table shows the number of MR values (N), the minimum MR, the MR quartiles (i.e., 25th, 50th, and 75 percentiles), the MR maximum, and the percent of MR values less than 1.0.

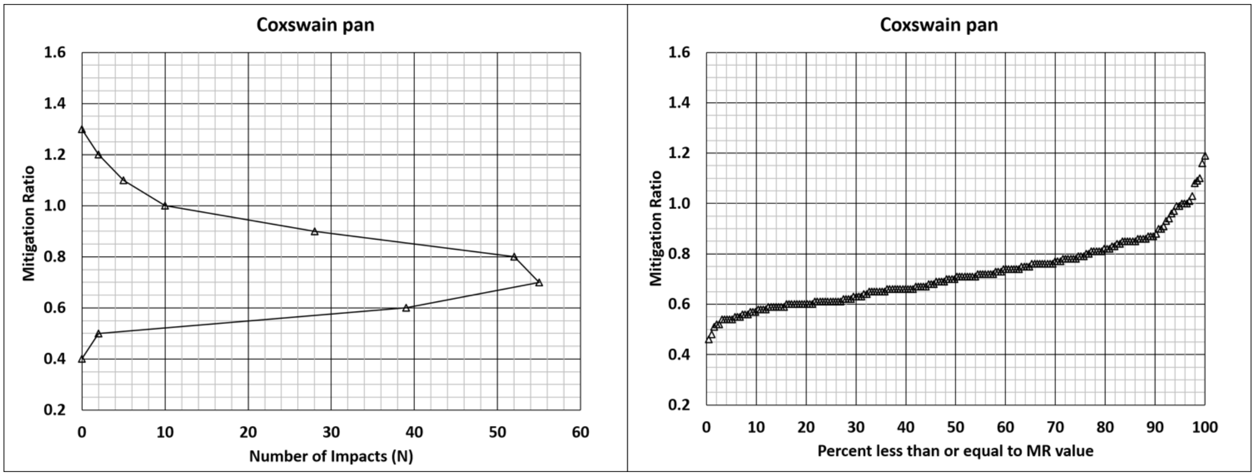

Figure 12. Coxswain Seat Mitigation Ratio Statistics

Table 2. Mitigation Ratio Statistics for All Data

Position	N	Mitigation Ratio Statistics					
		Min	Quartiles			Max	% MR < 1.0
			Q1	Q2	Q3		
Pan	284	0.46	0.65	0.73	0.82	1.19	95
Cushion	91	0.67	0.79	0.85	0.93	1.23	90

OBSERVATIONS

Low Severity Cushion Data

During the at-sea trials it was only feasible to install an accelerometer on the cushion of the aft passenger seat below the inert payload weight. The position of the seat aft of the LCG resulted in only 10 peak accelerations out of 91 surveyed with deck peak accelerations equal to or greater than 3 g. The largest deck peak acceleration for the passenger seat was 3.7 g, thus the cushion MR for peak accelerations in the range of 4 g to 6 g could not be determined.

Extrapolation of the laboratory test data suggests it would be expected that larger deck peak accelerations in the craft from 4.8 g to 6.6 g would result in cushion MR values on the order of 0.55 to 0.78. During future trials it would be beneficial to attempt to instrument seat cushions on seats at locations forward of the LCG to obtain larger deck input peak accelerations.

Seat Payload Weight

The seat test requirements for this craft design required that laboratory tests be performed with inert seat payloads of 109 lb, 184 lb, and 248 lb. The seakeeping trials were only able to record data for a 175-lb inert weight. During future trials it would be beneficial to record acceleration data for all seat payloads required by the laboratory test requirements.

Laboratory to At-Sea Comparisons

The requirements for the craft specified that 3 g to 6 g were the peak vertical accelerations to be achieved during the laboratory tests. In other words, this was the range of interest for shock isolation seat performance for this craft. Figure 13 shows the cumulative distribution curves for the at-sea pan (blue triangle) and at-sea cushion (red circle) MR values for all seats and all wave impacts with peak deck accelerations equal to or greater than 3 g (i.e., 3 g to 5.3 g).

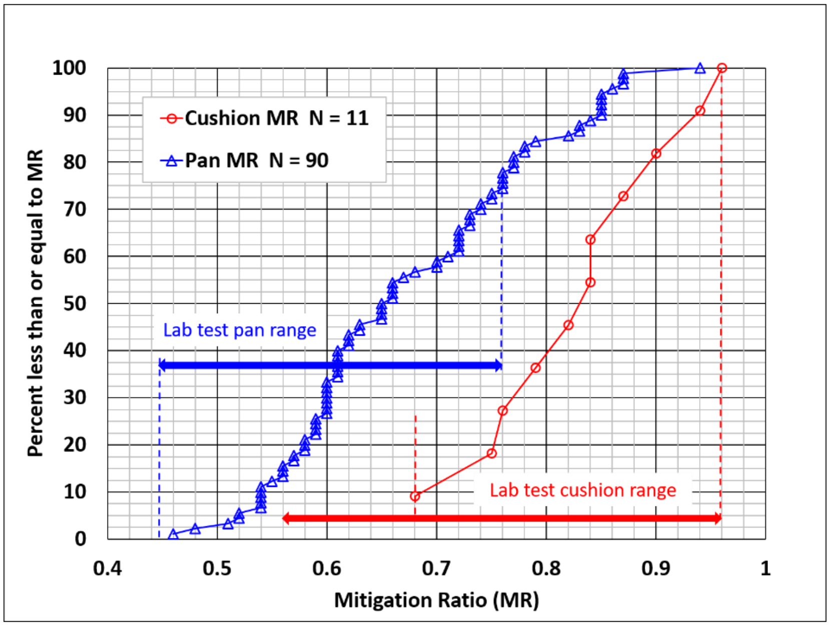

Figure 13. Laboratory and Craft Seat MR Values for 3 g to 6 g Impacts

The solid arrows in Figure 13 show the ranges of MR values for the laboratory drop test data. The figure shows that: (1) 78 percent of the at-sea pan data falls within the range of pan MR values from the laboratory tests, and (2) 100 percent of the at-sea cushion MR values fall within the range of cushion MR values from the laboratory tests.

Table 3 presents the statistics for the craft pan and cushion MR values for all wave impacts shown in Figure 13. The table shows the number of MR values (N) for 3 g or higher, the minimum MR, the MR quartiles (i.e., 25^{th}, 50^{th}, and 75 percentiles), the MR maximum, and the percent of MR values less than 1.0. Table 4 summarizes the results of comparing the craft MR values in Table 3 with the MR values for the laboratory drop tests. Seat bottom impacts did not occur during the laboratory tests or the at-sea trials, and dynamic amplification of deck inputs did not occur in either tests in the 3 g to 6 g range of interest.

Table 3. Mitigation Ratio Statistics: 3 g to 6 g Deck Input Range

Position	N	Mitigation Ratio Statistics					
		Min	Quartiles			Max	% MR < 1.0
			Q1	Q2	Q3		
Pan	90	0.46	0.59	0.65	0.76	0.94	100
Cushion	11	0.68	0.76	0.83	0.88	0.96	100

Table 4. Laboratory Test and At-Sea Test Result Comparison

Lab Test Goals	In the 3g to 6g vertical shock input range of interest	
	Laboratory Drop Test	**At-Sea Trials**
Avoid seats that bottom out	No seat bottom impacts	No seat bottom impacts
Avoid dynamic amplification	No dynamic amplification	No dynamic amplification
Demonstrate mitigation - pan	MR = 0.45 to 0.76	MR = 0.46 to 0.94 in 3g to 5.3g range
Demonstrate mitigation - cushion	MR = 0.56 to 0.96	MR = 0.68 to 0.96 in 3g to 3.7g range

The purpose of the laboratory tests was to demonstrate effective mitigation performance prior to installation in a craft and to avoid installation of an ineffective seat that bottoms out or amplifies shock pulses in the impact severity range of interest. Table 3 shows that the seats did not bottom out or demonstrate dynamic amplification, and that shock mitigation was achieved in an impact severity range from 3 g to 5.3 g. The at-sea testing did not achieve wave impact severities up to the 6 g threshold value for pan and cushion locations, but the at-sea MR values do overlap the ranges of the laboratory test MR values. This overlap, and the lack of seat bottom impacts during at-sea testing, provides an interim, partial validation that the goals of the laboratory tests were achieved. Continued laboratory testing is therefore recommended. During future trials it would be beneficial to attempt to achieve deck input peak accelerations that overlap the range of interest (e.g., 3 g to 6 g for this craft) for seat pan and seat cushion data.

Seat Cushion Dynamics

It has been shown that soft seat cushions can amplify the magnitude of a relatively long duration shock pulse [18, 30, 37 to 40]. In other words, the seat cushion MR computed using equation (1) may be larger than the pan MR value computed using equation (2) depending upon the material properties of the cushion design. When cushion amplification occurs, the ratio of the cushion MR divided by the seat pan MR can be greater than 1.0 (i.e., the seat cushion amplifies the seat pan shock severity). Shock isolation seat design as a total system is therefore a balance between seat cushion comfort over long periods of time in calm seas and impact protection during sprints in rough seas [38 to 40].

The dynamic effects of the cushion for each wave impact is quantified by dividing the cushion MR (total system performance) by the pan MR (partial system performance). The ratio yields the performance of the seat cushion relative to the seat pan. In other words, does the cushion provide additional mitigation relative to the pan, or does it amplify the seat pan shock severity? The cushion-to-pan ratio is plotted in Figure 14 versus the deck peak acceleration. Two values are less than 1.0 (0.95 and 0.97); the other 89 values fall in the range from 1.0 to 1.27. A large percentage of the relative values (93.4 percent) fall between 1.0 and 1.20.

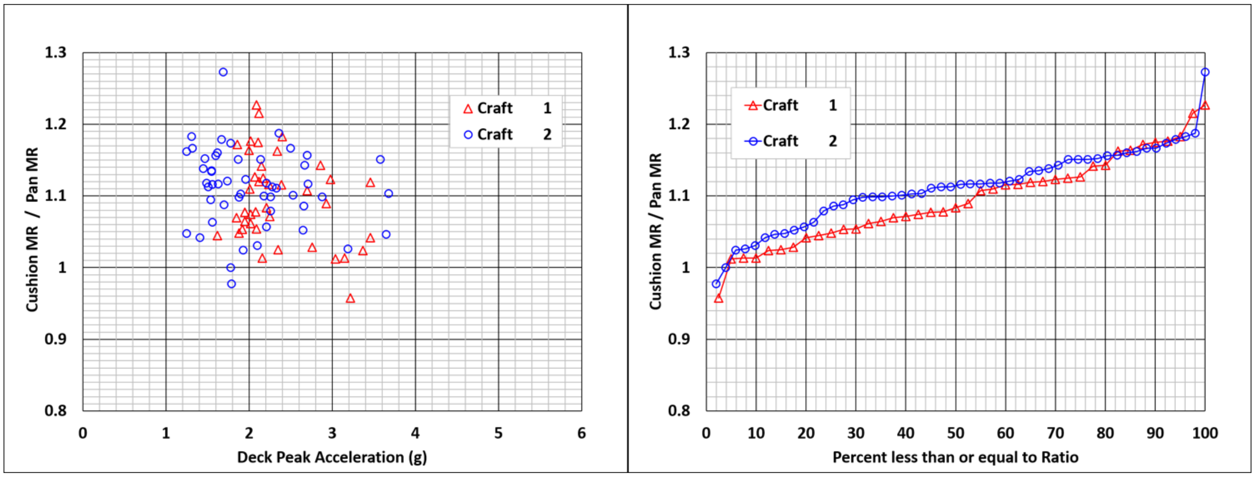

Figure 14. Cushion Mitigation Ratio Divided by the Pan Mitigation Ratio

The dynamic performance of a seat cushion is unique for each cushion design. A more firm seat cushion could result in lower amplification or even some additional mitigation depending upon the seat pan shock severity, but a more firm cushion may have a negative effect on seat comfort over time. Seat cushion design/selection is therefore a balance between comfort and dynamic performance.

Low Severity Dynamic Amplification

The data plots in Figures 10 and 11 include a sampling of wave impacts with peak deck accelerations less than 2g and all wave impacts with deck peak accelerations from 2 g to 5.3 g. The plots show that below a deck input of approximately 2.5 g (i.e., below the 3 g to 6 g seat testing range of interest) 14 of the 284 pan mitigation ratios (4.9%) and 9 of the 91 cushion mitigation ratios (10%) are equal to or greater than 1.0. In this lower severity range the shock pulse durations typically show the greatest variation, from 100 msec up to 450 msec [31]. Shock isolation theory indicates that as pulse duration increases for a given isolation system design the mitigation ratio increases and can exceed 1.0 [41]. This is shown in Appendix C. It is hypothesized that MR values greater than 1.0 in Figure 10 are attributed to the longer pulse durations observed when the impact severity is less than 3 g.

The at-sea test results demonstrate that low severity impacts (i.e., less than 3 g) may or may not be mitigated, but the impact severities are low, so the amplified severity (up to roughly 20% higher) is still relatively low. The higher severities from 3 g to 6g were all successfully mitigated with no amplification.

CONCLUSIONS AND RECOMMENDATIONS

The shock isolation seat laboratory drop test data showed that the seat design reduced the severity of the simulated wave impact shock pulses during laboratory testing[6]. Shock mitigation was achieved on the pan and on the cushion. The seat did not amplify any of the drop test shock pulses, and seat bottom impacts did not occur within the rigid body 3 g to 6 g range of interest.

Two seats of the same design as tested in the laboratory were subsequently installed in two craft and tested during at-sea seakeeping trials. This was the first time a shock isolation seat was required to be tested first in the laboratory before installation in a U.S. Navy craft. Although large amounts of seat data were obtained during the at-sea trials, not all required seat payloads tested in the laboratory were tested at-sea, and shock inputs for evaluating seat cushion performance could only be evaluated for deck inputs up to 3.7 g rather than the full range of 3 g to 6 g. The acceleration data recorded during at-sea testing shows that the four seats reduced the severity of the vertical shock inputs. The seats in the craft did not amplify any of the deck shock input pulses within a rigid body range of 3 g to 5.3 g, and seat bottom impacts did not occur for seat payloads from roughly 170 lb. to 210 lb. The range of shock mitigation performance achieved by the four seats at-sea is similar to the range of shock mitigation performance achieved during laboratory testing. These results, and the lack of seat bottom impacts during at-sea testing, provide an interim, partial validation that the goals of the laboratory tests were achieved. Continued laboratory testing is therefore recommended.

Additional at-sea testing with instrumentation installed on other seats is recommended whenever laboratory test requirements are invoked for a craft acquisition program. All attempts should be made to install seat cushion accelerometers on seats located as far forward as possible to record vertical deck input accelerations that overlap the entire shock severity range of interest, and all attempts should be made to record acceleration data for all required seat payload weights.

It is recommended that seat cushion design parameters be investigated further to better understand the tradeoffs between long-term cushion comfort and short-term dynamic performance. This includes seat cushion dynamic responses during lower severity impacts (e.g., (e.g., 1 g to 3 g) and higher severity impacts (e.g., 3 g to 6 g or higher, as required).

Seakeeping trials with instrumented shock isolation seats have relied on inert payloads to simulate the weight of seat occupants. It is recommended that future trials include accelerometer pads on the seat cushion below seat occupants to investigate and correlate the response of shock isolation seats with human occupants and shock isolation seats with inert payloads[7].

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[6] 100-millisecond (msec) half-sine pulses with 3 g to 6 g rigid-body peak vertical acceleration amplitudes
[7] This applies for seats with foot rests that preclude the use of the seat occupant's legs for absorbing shock.

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APPENDIX A. SHOCK RESPONSE SPECTRUM

The shock response spectrum (SRS) is a computational tool used internationally to compare the severity of different shock motions [A1 to A10]. It is also referred to as a maximum response spectrum that can be used to analyse any dynamic event, even vibration signals [A7]. 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 A1 to compute the effects of an input motion X (t) on the SDOF system. The system has a base attached to a mass (m) by a spring with stiffness k and a damper with damping coefficient c. For a prescribed time varying shock input motion X (t) at the base of the system the resulting response of the mass (m) is Y (t). The relative displacement Z (t) between the base and the mass is X (t) minus Y (t). The equation of motion of the system given by equation (A1) is obtained by summing the inertial force of the mass and the forces within the spring and damper.

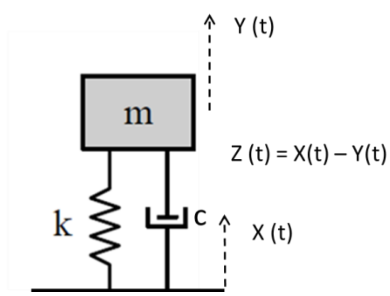

Figure A1. Single-degree-of-freedom Mathematical Model

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

Where t is time and:

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

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

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

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

An SRS is the maximum response of a set of single-degree-of-freedom (SDOF), spring-mass-damper oscillators to an input motion. The input motion is applied to the base of all oscillators, and the calculated maximum response of each oscillator versus the natural frequency make up the spectrum [A7].

The relative displacement SRS is often used as a parameter to compare shock severity when two input shock motions are being compared. It is an intuitive engineering measure of severity because the relative displacement is proportional to the strain in the spring in Figure A1. 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 A2 shows three vertical acceleration time histories recorded at different locations on a craft. The plot on the right is the computed maximum relative displacement SRS (DSRS) for each 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.

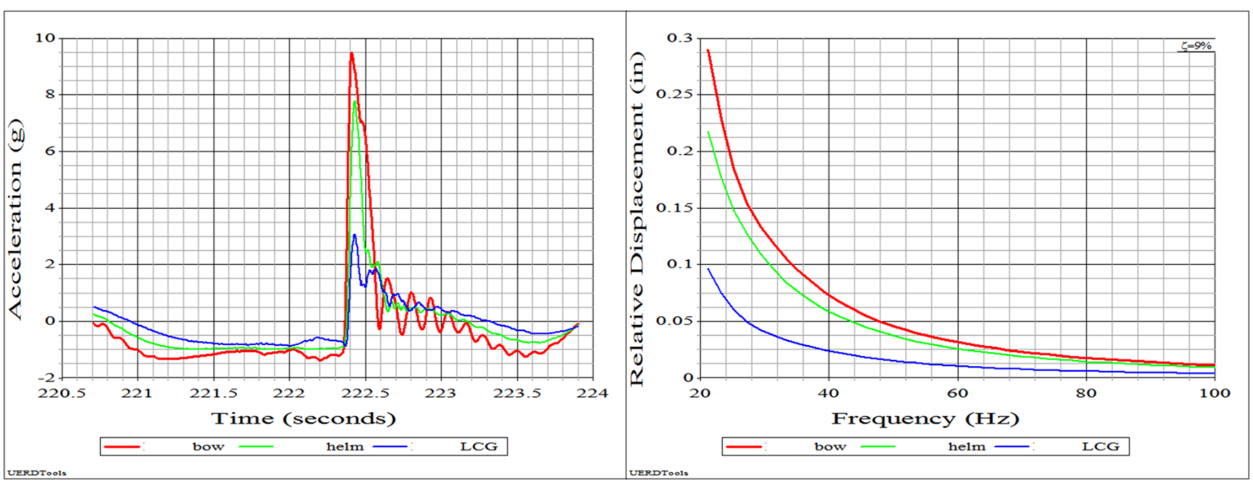

Figure A2. Three Wave Slam Shocks (left) and Relative Displacement SRS (right)[8]

[8] 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 A3. In this figure the spectra compare the severity of a 3 g, 100-msec half-sine pulse to the severity of a 2 g, 150-msec 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).

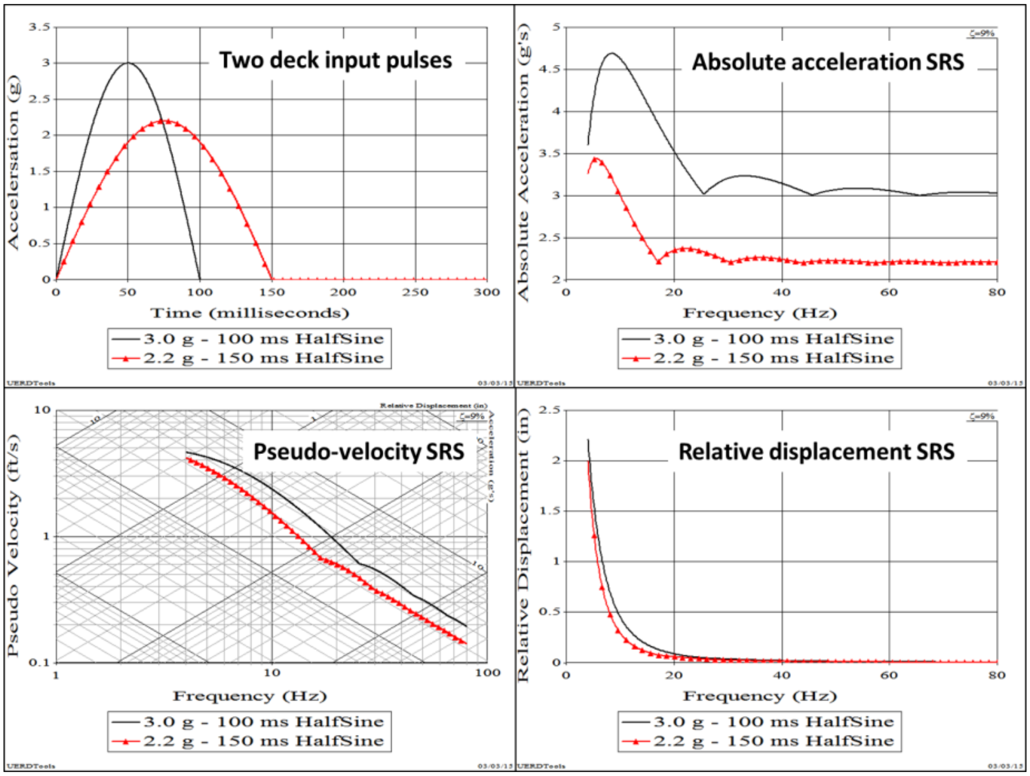

Figure A3. Different Types of Shock Response Spectra

The lower right plot in Figure A3 is the relative displacement SRS for each input pulse, and the lower left plot is the pseudo-velocity SRS (VSRS) for each pulse. Logarithmic scales are used on all four axes of the VSRS. The horizontal lines are the pseudo-velocity scale. Vertical lines are the system natural frequency scale. Lines sloping downward to the left show the predicted maximum relative displacement scales. Lines sloping downward to the right show the predicted maximum response accelerations. The log-log VSRS is a useful format because it provides a measure of the shock severity in units of maximum displacement, velocity, and acceleration. The acceleration scale is referred to as the pseudo-acceleration (A_{MAX}) for damped systems and the velocity scale is referred to as the pseudo-velocity when the maximum values are calculated using equations (A5) and (A6), which applies for lightly damped or zero damped systems [A1]. Z_{MAX} is the maximum relative displacement.

$$A_{MAX} = (2\pi f)^2 Z_{MAX} \tag{A5}$$

$$\mathrm{V_{MAX}} = (2\,\omega f)\,\mathrm{Z}_{MAX} \tag{A6}$$

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 [A1]. 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 A7. 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.

$$\text{Mitigation Ratio} = \frac{\mathrm{SRS}_{\text{Response}}}{\mathrm{SRS}_{\text{Input}}} \tag{A7}$$

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 A4 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 A5 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 [A11]. 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 [A12].

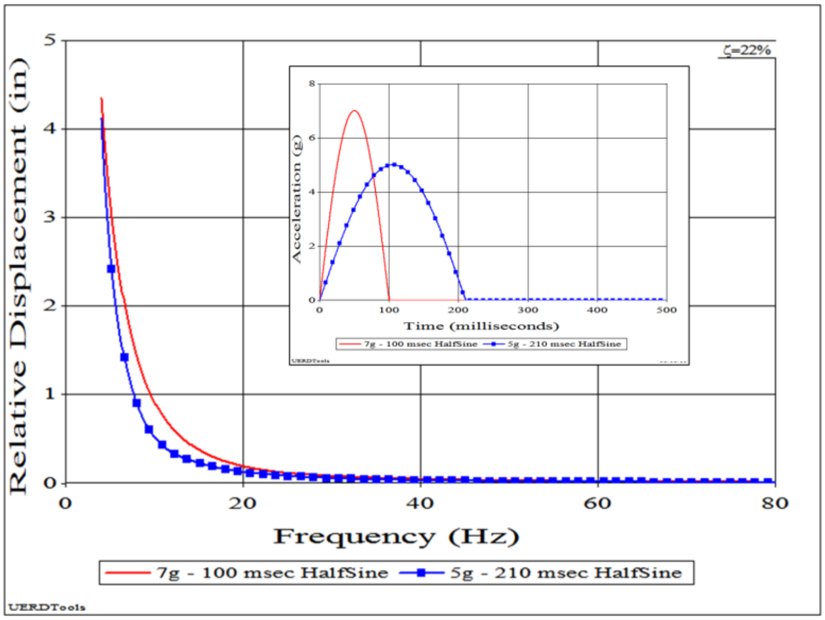

Figure A4. Comparison of Hypothetical DSRS

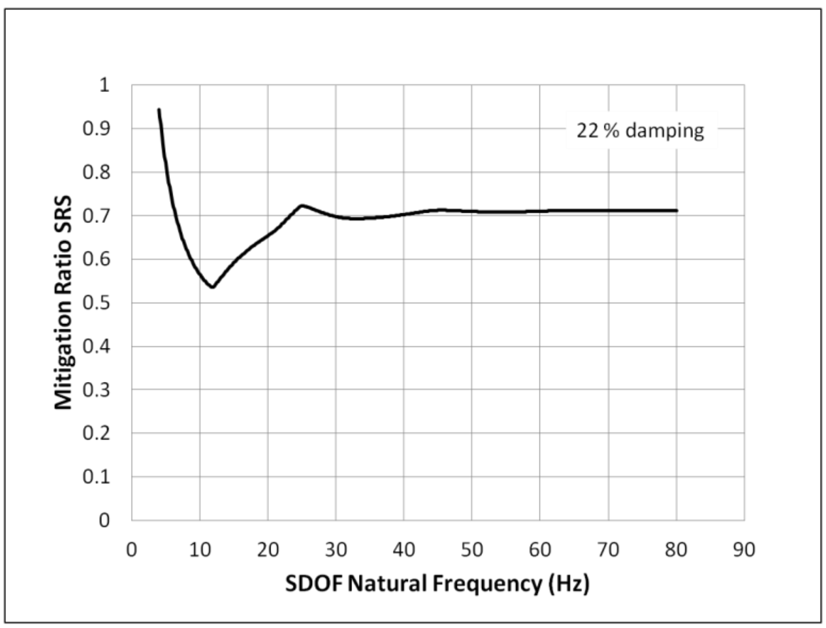

Figure A5. Mitigation Ratio for 5 g and 7 g Half-sine Pulses

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 [A13] 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 [A15]. 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 (A1). Since it is a single degree of freedom model as shown in Figure A1, 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 (A7) 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.

Table A1 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 [A16]. 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 [A17, A18]. It has been used as a shock isolation seat design criterion for individual severe wave impacts in a high speed craft [A19], and it has been used to quantify the severity of different individual wave impacts recorded during high speed craft tests [A20]. 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 A1. 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 B. TABULATED AT-SEA TEST RESULTS

Tables B1 thru B8 list the deck peak accelerations, the peak seat response peak accelerations, and the seat mitigation ratios computed using deck and seat vertical acceleration data recorded during runs on three different dates. The slam number in column 1 is the approximate time in seconds at which the wave impact occurred.

Table B2. Run 2 Passenger Seat Data Craft 1

8 June Slam Number	Peak Acceleration (g)			Mitigation Ratio	
	Deck	Pan	Cushion	Pan	Cushion
1-14	2.01	1.48	1.70	0.73	0.81
1-44	2.25	1.63	1.67	0.70	0.75
1-58	2.08	2.10	2.21	0.90	0.97
1-107	1.95	1.78	1.86	0.93	0.99
1-168	1.85	2.12	2.17	1.15	1.23
1-176	2.09	2.02	2.11	1.11	1.17
1-209	2.07	1.25	1.37	0.71	0.80
1-222	2.34	2.17	2.37	0.80	0.93
1-432	2.40	1.84	1.95	0.71	0.84
2-173	2.02	1.97	2.00	0.81	0.86
2-197	2.39	228.00	2.42	0.78	0.87
2-236	2.17	2.20	2.14	0.88	0.99
3-227	3.46	3.00	3.05	0.72	0.75

Table B1. Run 2 Coxswain Seat Craft 1

8 June Slam Number	Peak Acceleration (g)		Pan MR
	Deck	Pan	
1-7	2.00	2.43	1.00
1-14	2.96	2.82	0.82
1-23	2.40	1.80	0.71
1-36	3.32	1.66	0.58
1-44	3.08	2.11	0.54
1-58	2.94	2.63	0.66
1-64	2.22	2.69	1.00
1-87	2.55	2.61	0.80
1-107	3.29	2.89	0.62
1-161	2.42	2.58	0.81
1-168	3.60	3.41	0.72
1-176	3.35	3.83	0.87
1-195	2.19	1.94	0.75
1-209	2.76	1.69	0.60
1-222	4.73	3.89	0.60
1-253	2.63	2.74	0.85
1-286	2.54	2.95	1.00
1-294	2.68	2.72	0.86
1-366	2.61	2.06	0.67
1-392	2.44	2.55	0.85
1-411	2.10	2.00	0.73
1-432	4.44	2.74	0.46
1-442	2.25	2.08	0.76
1-467	2.12	2.37	0.87
1-474	2.14	2.21	0.81
2-32	2.76	2.69	0.78
2-43	2.49	2.09	0.62
2-47	2.26	1.94	0.75
2-84	3.13	2.56	0.60
2-95	2.15	2.49	0.90
2-110	3.07	2.71	0.85
2-116	2.00	1.46	0.79
2-125	2.08	2.23	0.84
2-129	2.66	2.30	0.65
2-147	2.18	1.97	0.66
2-173	2.86	1.96	0.58
2-197	4.35	2.89	0.51
2-211	4.40	3.08	0.57
2-222	4.00	3.27	0.73
2-236	3.28	2.40	0.60
2-250	2.90	2.30	0.67
2-266	2.15	3.03	1.19
2-278	4.77	3.27	0.55
2-284	2.35	2.61	0.76
2-298	2.48	2.49	0.76
2-324	2.81	2.33	0.63
2-326	2.71	2.82	0.79
2-338	2.99	2.54	0.66
2-345	2.38	1.61	0.57
2-348	1.60	1.06	0.59
3-16	2.04	1.59	0.67
3-78	2.05	1.99	0.80
3-85	1.96	2.12	0.76
3-95	2.46	2.59	0.83
3-98	4.00	3.16	0.63
3-106	2.37	2.04	0.78
3-136	3.57	3.22	0.75
3-151	2.53	2.51	0.72
3-169	2.04	2.43	0.91
3-195	1.85	2.36	1.10
3-209	2.38	2.23	0.69
3-227	4.40	3.74	0.61
3-247	2.24	1.15	0.55
3-279	2.19	1.90	0.72

Table B3. Run 3 Coxswain Seat Data Craft 1

13 June Slam Number	Peak Acceleration Deck (g)	Peak Acceleration Pan (g)	Pan MR
4	3.20	2.80	0.78
143	4.26	2.22	0.48
145	2.73	3.25	0.99
157	2.58	3.05	0.86
179	2.30	3.04	0.90
181	2.76	2.37	0.67
191	3.65	3.43	0.76
221	3.35	2.53	0.85
228	3.57	3.21	0.77
358	3.70	2.76	0.85
436	3.08	3.29	0.79
456	4.14	3.54	0.72
528	5.15	4.69	0.72
586	3.05	2.73	0.70
593	4.64	3.97	0.70
637	3.17	2.82	0.83
652	3.85	3.27	0.62
711	3.06	2.67	0.74
718	4.11	4.02	0.85
731	3.53	3.56	0.76
744	3.72	3.46	0.66
747	4.24	3.45	0.54
760	3.35	3.62	0.86
766	3.44	3.69	0.82
770	3.12	2.97	0.78
782	4.74	4.08	0.66
804	3.81	4.05	0.76
869	3.23	3.19	0.87
937	4.62	3.48	0.54
949	3.16	3.33	0.77

Table B4. Run 3 Passenger Seat Data Craft 1

13 June Slam Number	Peak Acceleration			MR	
	Deck (g)	Pan (g)	Cushion (g)	Pan	Cusion
4	1.86	1.51	1.51	0.64	0.75
102	3.22	2.99	2.95	0.94	0.9
143	2.09	1.66	1.67	0.75	0.92
228	2.16	2.08	1.98	0.74	0.75
230	2.15	2.20	2.18	1.06	1.21
354	3.04	3.19	2.88	0.83	0.84
415	3.46	2.71	2.93	0.84	0.94
436	1.95	2.12	2.09	0.78	0.84
457	1.88	2.39	2.35	0.83	0.87
511	2.24	2.30	2.19	0.86	0.96
528	2.70	3.13	3.07	0.93	1.03
539	1.92	1.65	1.65	0.75	0.79
593	3.15	2.96	2.93	0.75	0.76
637	2.02	1.87	1.84	0.68	0.8
652	2.12	1.92	1.80	0.65	0.79
711	2.11	1.77	1.73	0.63	0.74
718	2.35	2.43	2.43	0.81	0.83
731	3.37	2.67	2.64	0.85	0.87
744	2.86	2.56	2.55	0.70	0.8
747	2.93	2.63	2.59	0.67	0.73
760	1.62	2.11	2.19	0.89	0.93
782	2.98	2.75	2.70	0.73	0.82
804	2.12	2.56	2.57	1.08	1.21
937	2.76	2.71	2.63	0.70	0.72

Table B5. Run 1 Coxswain Seat Data Craft 2

13 May Slam Number	Peak Acceleration (g)		Pan MR
	Deck (g)	Pan (g)	
156	2.39	2.14	0.69
175	2.46	1.18	0.63
232	2.5	1.7	0.65
247	2.59	2.02	0.68
415	2.42	2.04	0.74
454	2.87	2.26	0.66
549	2.48	2.06	0.64

Table B6. Run 1 Passenger Seat Data Craft 2

13 May Slam Number	Peak Acceleration (g)			MR	
	Deck	Pan	Cushion	Pan	Cushion
20	2.21	1.39	1.47	0.72	0.78
118	2.02	1.28	1.33	0.81	0.87
681	2.00	1.03	1.08	0.61	0.71

Table B7. Run 3 Passenger Seat Data Craft 2

13 June Slam Number	Peak Acceleration (g)			MR	
	Deck (g)	Pan (g)	Cushion (g)	Pan	Cushion
32	3.65	2.58	2.64	0.65	0.68
40	3.58	2.96	3.3	0.73	0.84
71	2.53	2.19	2.26	0.79	0.87
110	1.93	1.76	1.74	0.83	0.85
161	2.26	1.70	1.77	0.71	0.78
223	1.88	1.66	1.83	0.92	1.01
250	2.10	1.89	2.01	0.98	1.01
278	1.70	1.73	1.85	0.80	0.87
324	3.19	2.47	2.47	0.77	0.79
382	2.67	2.40	2.43	0.77	0.88
401	1.69	1.49	1.48	0.66	0.84
424	2.33	1.96	2.11	0.81	0.90
460	2.21	1.95	2.08	0.68	0.76
495	2.66	2.15	2.31	0.70	0.76
501	1.60	1.03	1.13	0.64	0.74
539	2.18	1.96	2.12	0.80	0.88
627	2.36	1.88	1.89	0.64	0.76
721	2.65	2.14	2.13	0.77	0.81
726	2.50	2.04	2.15	0.66	0.77
809	2.14	1.93	2.10	0.73	0.84
877	2.71	2.03	2.11	0.60	0.67
894	2.21	1.96	2.08	0.88	0.93
902	2.26	2.22	2.36	0.89	0.96

Table B8. Run 3 Coxswain Seat Data Craft 2

13 June Slam Number	Peak Acceleration		Pan MR
	Deck (g)	Pan (g)	
32	4.51	3.25	0.54
40	3.71	3.24	0.66
61	2.57	1.68	0.6
71	3.29	2.93	0.74
83	2.75	2.48	0.69
110	3.31	2.52	0.76
133	2.55	2.34	0.84
155	2.42	2.03	0.60
161	3.41	2.54	0.62
176	2.56	2.65	0.78
194	2.65	1.96	0.55
226	3.11	1.77	0.52
250	2.80	2.87	0.81
278	2.81	2.46	0.66
306	2.75	2.83	0.99
324	2.89	3.08	0.97
332	3.12	2.83	0.71
382	5.34	2.98	0.56
401	2.80	2.31	0.61
424	3.52	2.84	0.63
438	4.45	2.84	0.61
460	4.00	2.96	0.59
465	3.79	1.91	0.57
495	3.40	2.87	0.61
501	3.30	1.92	0.61
539	3.17	2.93	0.73
562	3.24	2.51	0.65
586	3.03	2.38	0.56
627	3.94	2.97	0.52
660	3.07	2.67	0.60
671	3.09	2.31	0.59
689	3.97	2.90	0.54
721	4.28	3.03	0.58
726	3.95	2.81	0.67
750	3.24	2.39	0.65
803	3.37	2.71	0.66
809	3.59	3.10	0.59
877	4.40	3.06	0.60

APPENDIX C. SHOCK PULSE DURATION

Figure C1 shows the general trend observed in many high-speed planing craft during head-sea runs in rough seas. The plot includes data for craft with three different displacement ranges, and other data sets of the maximum severity wave impact for three different locations in different craft. Each data point plots the shock pulse duration versus the deck peak acceleration experienced during individual wave impacts. The shock pulse duration (T) and the range (i.e., scatter) of durations tend to decrease as the deck peak vertical acceleration increases [C1].

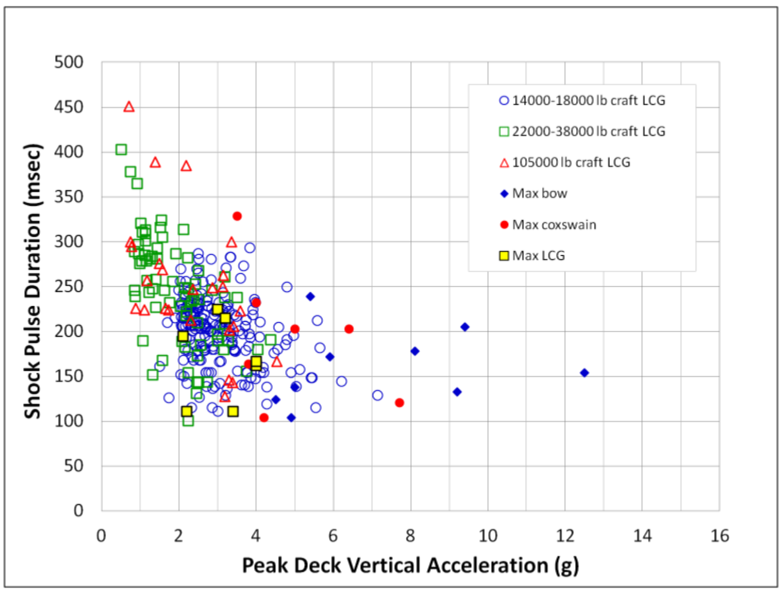

Figure C1. Shock Pulse Duration Trends (Ref. C1, Figure 3)

The theoretical principles for equipment shock isolation also apply to shock isolation seats, so the general trends shown in Table C1 and Figure C2 for equipment isolation are useful for understanding shock isolation seat responses as shock pulse duration increases.

Table C1 was created during an earlier investigation of shock isolation mounts for protecting equipment [C2]. Six spring-damper shock mounts with natural frequencies from 2 Hz to 4 Hz and damping ratios from 20 percent to 40 percent were investigated. The shock input pulses were assumed to be vertical half-sine acceleration pulses with peak amplitudes and pulse durations that vary in amplitude as shown in the table. For a constant peak acceleration, the calculations for each mount design shows that as pulse duration increases the mitigation ratio increases and the mount excursion space increases in order to avoid mount bottom impact. .

Table C1. Predicted Shock Mount Maximum Relative Displacements [C2]

Mounts	Pulse Duration	MR	Mount Relative Displacement (inches)						
	msec		2 g	3 g	4 g	5 g	6 g	7 g	8 g
2 Hz 20% damped	70	0.41	2.96	4.45	5.93	7.41	8.89	10.37	11.85
	100	0.58	4.18	6.26	8.36	10.45	12.54	14.63	16.72
	150	0.83	6.08	9.12	12.16	15.2	18.25	21.29	24.33
	200	1.03	7.77	11.66	15.55	19.44	23.32		
	300	1.28	10.37	15.55	21.74	25.92			
2 Hz 30% damped	70	0.36	3.13	4.69	6.26	7.82	9.39	10.95	12.52
	100	0.51	4.42	6.64	8.84	11.07	13.28	15.5	17.71
	150	0.74	6.49	9.73	12.97	16.22	19.47	22.72	25.97
	200	0.92	8.38	12.58	16.27	20.97	25.16		
	300	1.14	11.56	17.34	23.12	28.9			
3 Hz 20% damped	70	0.6	1.94	2.92	3.87	4.85	5.81	6.81	7.78
	100	0.83	2.7	4.05	5.39	6.75	8.11	9.44	10.81
	150	1.12	3.79	5.68	7.58	9.47	11.37	13.26	15.16
	200	1.28	4.61	6.91	9.22	11.51	13.83		
	300	1.37	5.49	8.23	10.98	13.72			
3 Hz 30% damped	70	0.54	2.06	3.09	4.12	5.15	6.18	7.22	8.25
	100	0.74	2.88	4.32	5.77	7.21	8.65	10.08	11.53
	150	0.99	4.11	6.17	8.23	10.29	12.35	14.41	16.47
	200	1.14	5.13	7.7	10.27	12.84	15.41		
	300	1.24	6.56	9.84	13.12	16.4			
4 Hz 30% damped	70	0.69	1.52	2.28	3.04	3.8	4.55	5.32	6.09
	100	0.92	2.09	3.14	4.19	5.24	6.29	7.34	8.39
	150	1.14	2.89	4.33	5.78	7.22	8.67	10.11	11.56
	200	1.23	3.46	5.2	6.93	8.67	10.4		
	300	1.22	4.23	6.35	8.47	10.59			
4 Hz 40% damped	70	0.62	1.62	2.44	3.25	4.06	4.87	5.69	6.5
	100	0.83	2.26	3.39	4.52	5.66	6.79	7.92	9.06
	150	1.03	3.2	4.8	6.41	8.01	9.61	11.22	12.82
	200	1.12	3.98	5.98	7.97	9.97	11.96		
	300	1.14	5.25	7.89	10.53	13.16			

Appendix C References

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