Shock Mitigation for the Human on High Speed Craft: Development of an Impact Injury Design Rule

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SUMMARY

Occupants of U. S. Special Operations high speed craft are exposed to severe and repeated shock loads during operation in heavy seas, leading to an alarming incidence of reported chronic and acute musculoskeletal injuries. Traditional craft design rules for craft seakeeping qualities are assumed to account for spinal impact injury during the acquisition process. Supplemental design rules, based on spinal impact injury models, are being evaluated in an effort to reduce the incidence of injury. NSWC-PC and its academic partner, the University of Virginia Center for Applied Biomechanics, have identified several supplemental models that show promise, and have performed an initial evaluation of their performance by applying them to conventional and suspension seat acceleration data. The rationale, method, and initial results of this comparative evaluation are presented.

1.0   INTRODUCTION

Advancements in high speed craft (HSC) construction and powering technology have led to ever-increasing craft speed and increasing numbers of reported impact injuries. The military HSC impact injury problem is particularly insidious since, unlike their high speed pleasure craft and offshore racing counterparts, military crewmen *must* operate their craft at high speed in rough seas to fulfill their mission and, at times, to survive. Further, as military craft crewmen are quick to remind us, they must "train as they fight." A critical objective within a human-centered approach to HSC acquisition is to reduce the incidence of impact injury.

Figure 1. U. S. Naval Special Warfare Rigid Inflatable Boat

In 2000, the U. S. Naval Health Research Center conducted a comprehensive study of U. S. Special Operations craft crewmen. (Ensign 2000) Of those surveyed, 65% reported one or more injuries that required hospitalization, with 95% of these injuries attributed to craft operation. The reported injury rate was nearly six times that of the overall U. S. Navy average. While the injury sites are numerous, trauma to the lumbar spine, at 34% of the reported injuries, is believed to be the most deserving of attention. A spinal injury is painful, highly debilitating, costly, and its victim often suffers for the remainder of his life.

Clearly the process for designing HSC craft deserves intense scrutiny and -- if an improved approach is identified -- modernization. The traditional approach taken by the naval architecture design community for assessing HSC seakeeping qualities is to apply various criteria to motion and acceleration data obtained from seakeeping simulations, tow tank tests, or full-scale prototype sea tests, as shown in Figure 2 The STANAG 4154 guideline for seakeeping, for example, defines "motion response criteria" such as the RMS of six motion degrees of freedom (6-DOF) and their derivatives, and "derived criteria" such as slamming, sonar emergence, wetness, propeller emergence, motion-induced interruptions (MII), motion-induced seasickness (MSI), and whole-body vibration (WBV) [STANAG 2000].
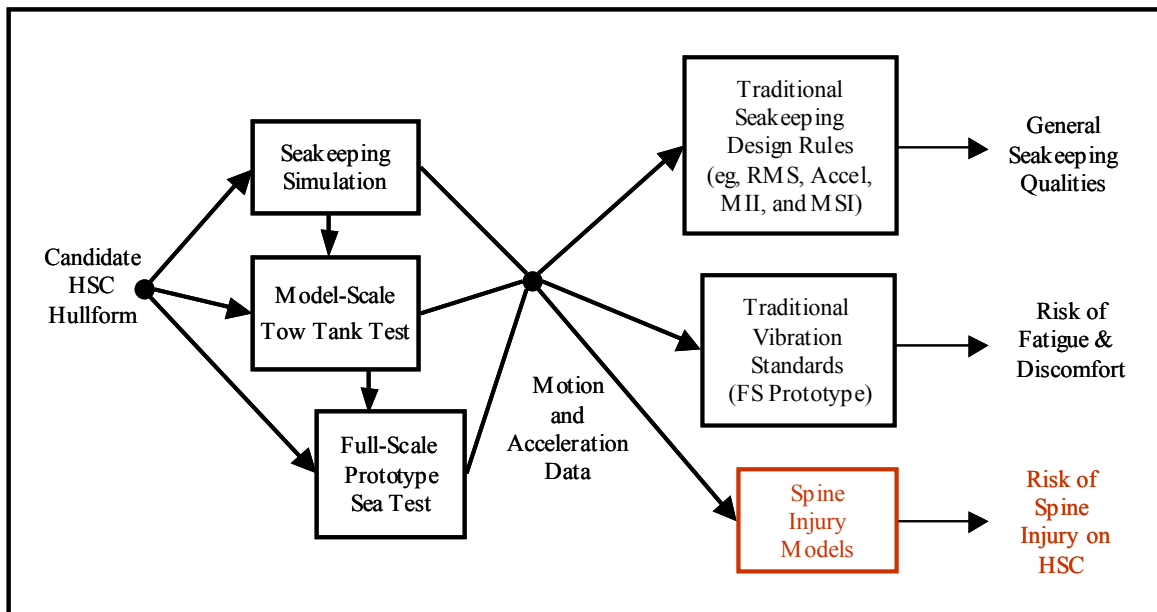

Figure 2 Introduction of New Design Rules to Reduce Injury

The thrust of the present investigation is to identify a *supplemental* design rule for reduction of human impact injury on HSC. The traditional design rules most often used currently by the naval architecture community, assumed applicable to impact injury, include the RMS of the vertical acceleration and the 1985 ISO 2631 Part 1 whole-body vibration standard [ISO 2631 P1 1985], as shown in the right hand of Figure 2. We are obliged to ask whether these current design criteria capture the human dynamics phenomena associated with impact-related spinal injury, and therefore whether these design rules alone serve to minimize the risk of such injury when invoked during the craft design and acquisition process.

NSWC-PC and its research partner, the University of Virginia Center for Applied Biomechanics (UVA CAB), are conducting a quantitative investigation of several candidate supplemental design rules in an effort to improve the HSC design process and reduce injuries sustained by HSC occupants. Design rules and injury models currently under investigation include the design rules in current practice, and a number of candidate injury models that may be introduced in the near-term. Follow-on mid- and far-term candidate injury models are also briefly described.

2.0   CURRENT AND CANDIDATE SUPPLEMENTAL DESIGN RULES

2.1   Current Design Rules

2.1.1   Root-Mean-Square (RMS)

The acceleration root-mean square,

$$\text{RMS} = \sqrt{\frac{1}{T}\int_0^T a^2(t)dt}$$

where a(t) is acceleration time history and T is the period over which the RMS is computed, is the most commonly used criterion to assess seakeeping characteristics, and has been used for many years to evaluate alternative hullforms. Many within the naval architecture community have historically assumed the RMS is also useful for predicting the incidence of impact injury. The designer or analyst typically computes the RMS of the vertical deck acceleration time history, and compares the results to established limits. Various limits are published in the literature, such as 0.2 g rms [STANAG 2000] and 0.3 g rms [Mandel 1979]. Most of the published RMS limits, however, are for ships, passenger craft, and generally low Froude-number applications. The application of these limits to human injury onboard HSC operating at high Froude numbers has been questioned [Savitsky 1992, Bass 2002]. The basic RMS is an indication of power within the entire signal bandwidth, and may not adequately assess human spine dynamics, nor reflect the effect of individual severe events within an acceleration time history.

The NSWC RMS algorithm currently low-pass filters the acceleration signal at 80 Hz, prior to computing the RMS, with a phase-corrected, three-pole Butterworth digital filter.

2.1.2 ISO 2631 Part 1 (1985)

Many naval architects have used the 1985 version of the ISO 2631 Part 1 WBV Standard [ISO 2631 Part 1 1985] to complement the RMS and acceleration methods to assess fatigue and discomfort [e. g., Haupt 1996] and some craft designers have assumed that the standard is also suitable for repeated impacts. The 1985 standard defines two basic approaches:

1. Compute the RMS of an acceleration time-history of the vibration source (deck for standing, seat for seated) within one-third octave bands between 2 and 80 Hz, and to compare the resulting multiple values to threshold contours defined in the standard.

2. Frequency-weight the signal within one-third octave bands, compute the RMS value of the frequency-weighted signal, and compare the result to a threshold. This method is stated in the standard to be preferable for signals with a crest factor greater than three. The crest factor is defined as the ratio of the peaks of the frequency weighted signal, to the rms of the frequency-weighted signal.

The crest factor of high speed craft acceleration data is much higher than three for moderate-to-high craft speeds in moderate-to-high seas; therefore the second method was chosen by NSWC-PC for the present investigation. The 1985 standard was designed principally to predict fatigue and discomfort limits in the presence of vibration, and its ability to predict probability of injury from severe repeated impacts, as with the RMS method, has been questioned [Village 1995, Bass 2003, Payne 1978].

2.1.3   Acceleration Statistics

Another criterion found in the literature and frequently used for assessing the seakeeping characteristics of various hull forms is the "1/Nth highest acceleration." [Fridsma 1971, Savitsky 1992]. Developers of suspended seats often assume that simple reduction of the maximum acceleration amplitude corresponding to an impact event is a valid and sufficient figure of merit. Craft designers also often assume that amplitude reduction is a suitable figure of merit for hull design. When dealing with sea test data or irregular seas tow tank test data, the acceleration time history must be dealt with statistically. The 1/Nth highest acceleration is defined as the average of the highest 1/Nth of the peak acceleration magnitudes within the time history. Traditionally, every peak within the time history is considered in the calculation of the 1/Nth highest. This method was not chosen for the present analysis because of lack of established methods to account for high frequency characteristics within the signal that may vary with the method of measurement, and that can bias the 1/Nth highest calculation.[Zselecsky 1992]

2.2   Near-Term Candidate Supplemental Design Rules

Near-term candidate supplemental design rules are defined here as candidate design rules, injury models, or standards that have not been used routinely by the naval architecture community, and that do not require development but rather require only coding of the published procedures and algorithms. NSWC-PC and UVA CAB have identified and begun detailed evaluation of certain injury models as candidates for impact injury HSC design rules. These alternative injury model candidates are described individually in the next sections.

2.2.1   Impact Acceleration Amplitude Statistics

As discussed in Section 2.1.3, motion data corresponding to irregular seaway conditions requires statistical analysis. For this investigation, NSWC-PC chose to compute the statistics of the individual acceleration maxima that correspond to each impact event (wave encounter), rather than the statistics of every acceleration peak within the time history. This method, although becoming more common, is considered an alternative method relative to the traditional acceleration statistics method of Section 2.1.3. The NSWC-PC algorithm first low-pass filters the raw acceleration data at 10 Hz to locate the time window corresponding to the maximum within each impact event. All filtering is performed with a phase-corrected, three-pole Butterworth digital filter. Next the raw data is low-pass filtered at 80 Hz, and the maximum amplitude is computed within each event . Events with a maximum acceleration level of 0.25 g or less are not included. Finally, the average of the highest $1/10^{th}$ of the acceleration maxima is computed.

2.2.2   ISO 2631 Part 1 Standard (1997)

The 1997 ISO 2631 Part 1 standard was developed, in part, to improve the applicability of the earlier 1985 standard to vibration exposure with high crest factor -- for example, vibration mixed with repeated moderate impacts. First, the vertical acceleration time history is frequency-weighted with a digital filter specified in the standard for the vertical seated case. Next, the crest factor is computed, as with the 1985 standard, as the ratio of the maximum amplitude of the weighted acceleration divided by the RMS of the weighted acceleration. For a crest factor less than 9, the RMS of the weighted acceleration time history is computed. For a crest factor greater than 9, the Vibration Dose Value (VDV), which is the root-mean-quad of the weighted acceleration, is computed. The battery of NSWC-PC injury assessment algorithms includes code for computing the weighted acceleration, the crest factor, and both the RMS and VDV of the weighted acceleration.

2.2.3   Dynamic Response Index Statistics (DRI)

The DRI [e. g., Payne 1978] was developed by the U. S. Air Force for single-event, seated-posture, human vertical impacts, such as jet aircraft seat ejections. The DRI is computed by measuring the seat pan acceleration time history, computing the maximum lumbar strain based on the published single-degree-of-freedom (SDOF) model of the lumbar spine, non-dimensionalizing the strain to form the DRI value, and comparing the DRI value associated with each impact to thresholds based on seat-ejection spine injury data. To provide a statistical parameter required to assess stochastic

acceleration time history data, the NSWC-PC DRI algorithm first computes a running DRI value within a given acceleration time history. The double-integration from acceleration to displacement leads to a highly smoothed signal, so that the resulting individual DRI maxima generally correspond to individual impact (wave encounter) events. The algorithm then computes the $1/10^{th}$ highest DRI (average of the highest $1/10^{th}$ values) for the time segment. While the DRI considers spine dynamics in the prediction of injury, its simplistic SDOF model has been questioned. [Village 1995, Bass 2002]

2.2.4 Onset-Rate Statistics

Several early investigators identified the onset-rate (also called "jerk", in g/sec) of the leading edge of the source acceleration impact waveform as an indicator of extreme discomfort and injury. [e. g., Eiband 1959] In a manner similar to that of the DRI, the NSWC-PC onset rate algorithm computes the rate for each impact event within a statistical acceleration time history, and then computes the $1/10^{th}$ highest onset rate. The acceleration raw data is first low-pass filtered at 10 Hz to locate the time window corresponding to each individual impact event. Next the raw data is low-pass filtered at 80 Hz, using a phase-corrected, three-pole Butterworth digital filter. The onset rate is then computed for each impact event using the 10% and 90% values relative to the minus 1.0 g baseline. Finally the $1/10^{th}$ highest onset rate for the entire time history is computed.

2.2.5 ISO 2631 Part 5 Standard

The recently established ISO 2631 Part 5 standard was developed by the U. S. Army Aeromedical Research Laboratory at Fort Rucker, Alabama to assess extreme discomfort and spinal injury for Army ground vehicle occupants exposed to repeated impacts and vibration. [Village 1995] The dynamics concept within the standard is similar to that of the DRI, except that the injury model within the standard is based on spinal tissue fatigue failure data, and not on seat ejection statistics. Further, the vertical lumbar spine dynamics model within the Part 5 standard is represented by a nonlinear neural net developed from measured seat and human acceleration measurements during tests of human volunteers seated on a motion simulator. The method is questionable for impacts greater than 4 g, since that is the approximate limit of the human volunteer tests. The parameter within the Part 5 standard chosen by NSWC-PC for the present application is the "daily equivalent static compressive dose", or S_{ed}, normalized to a daily exposure dose of 8 hours, in units of MPa.

2.2.6 Power Spectral Density (Bandwidth-Limited)

The PSD algorithm developed by NSWC-PC computes the PSD [$10 \log_{10}(g^2/Hz)$] of the unfiltered acceleration time history over the 0.1 to 100 Hz bandwidth, then computes the average PSD value within the 4 to 8 Hz bandwidth. The algorithm uses a 4096 point Hamming window with 50% overlap. This candidate design rule is not seen in the literature, but is intuitive, given that the 4 - 8 Hz bandwidth is generally associated with human torso dynamics and discomfort. [ISO 2631 Part 1 1985, ISO 2631 Part 1 1997]

2.3 Mid-Term and Far-Term Supplemental Design Rules

Mid-term supplemental design rules are defined here as modifications of existing injury models, the development of which is expected within the next year or two. Among the most prominent candidates identified by NSWC-PC and UVA-CAB is a modification of the ISO 2631 Part 5 standard with a more accurate and computationally fast spine dynamics model, and a more accurate spine injury model. Another mid-term candidate is a waveform-based injury model with multiple waveform parameters where the injury model might be defined, for example, as a combination of amplitude and onset rate criteria.

A candidate far-term model, requiring intensive laboratory investigation, has for several years been considered by NSWC-PC and UVA CAB. The proposed approach is to develop a fundamentally new model for lumbar spine dynamics and injury based on a laboratory investigation of on- and off-axis fatigue loading and failure characteristics of cadaver and porcine spine segments.[Bass 2003]

3.0   EVALUATION OF CURRENT AND NEAR-TERM DESIGN RULES

The following sections summarize the initial NSWC-PC comparative evaluation of both current design rules and candidate supplemental near-term design rules. This effort, when completed, is expected to lead to the recommendation of a improved method to predict HSC spine injury and an approach for integration within the HSC design process.

3.1 Model Performance Evaluation Method

Three general methods for evaluating candidate impact injury design rules are: 1) immediate application of the candidate methods to two sets of actual craft or craft-seat acceleration data, one with a known improvement in discomfort and/or injury, to evaluate their relative performance; 2) a comprehensive, long-term epidemiological study of SWCC impact exposure to correlate dynamic exposure with injury statistics, coupled with a parallel application of the candidate injury models; and 3) inputs from the body of knowledge and expertise of the impact biomechanics community and their decades of investigating the various methods. The U. S. Navy has in fact begun the second approach with a modest, initial epidemiological study. However, at least several years of exposure investigation will be required before its results may be brought to bear on the problem.

For the immediate task of identifying an interim impact injury design rule, the first method is being applied by NSWC-PC and UVA-CAB. That is, the Navy is initially evaluating the relative performance of current and candidate supplemental design rules by applying the various methods to acceleration data obtained during a controlled sea test involving simultaneous measurement of a baseline craft-seat configuration, and a modified craft-seat configuration with a substantial and documented improvement in performance.

This initial investigation is not without limitation because a single controlled sea test, during which injuries are extremely unlikely, cannot provide sufficient statistical injury data with which to fully evaluate relative injury model performance. That is the role of an epidemiological investigation. Further, the results are interpreted based primarily on operator feedback related to comfort. For example, the whole-body vibration standards that are one of the candidate methods are expected to show sensitivity to a suspended seat relative to a conventional "rigid" seat, but this does not necessarily indicate reduced probability of spine injury. Positive sensitivity of a candidate model to two craft-seat configurations is viewed as a necessary but not sufficient condition for indication of the particular model for use as an impact injury design rule. Thus, the results of this initial model performance assessment, that is based on specific craft-seat sea test measurements, must be tempered with the body of impact biomechanics knowledge and experience.

The initial comparative design rule evaluation, performed by NSWC-PC and UVA CAB, was based on acceleration data obtained by NSWC-PC during a sea test of a U. S. Navy MK V Special Operations Craft (SOC) during October 2003. The MK V SOC was outfitted with two types of seats: 1) the baseline, non-suspended Stidd Systems Inc. Model 800-101V4 (hereafter called the V4 seat), and 2) the new Stidd-Taylor V5 equipped with an optimized passive spring-damper suspension system (hereafter called the V5 seat). Feedback from U. S. Navy Special Warfare Combatant-craft Crewmen (SWCCs), over the course of many hundreds of hours in the new V5 suspension seats, have proven their superior performance relative to the original non-suspended V4 seats. [Klembczyk 2003]

The V4-V5 seat acceleration data were obtained in seas with a significant wave height of approximately 4 ft, for varying craft headings relative to the seaway direction, in the area between Norfolk, Virginia and the Chesapeake Light Buoy in the Atlantic Ocean, 25 miles east of Norfolk. The initial performance evaluation summarized here includes the comparison of the injury model predictions based on three-axis acceleration data obtained from the deck, the seat frame, seat cushion, and human back (L4 lumbar position). The acceleration data were sampled with a 12-bit D/A converter at 750 Hz and low-pass filtered (for anti-aliasing) at 250 Hz.

Two types of data from the sea test have been, or are being, investigated. First, NSWC-PC analyzed two principal short time history segments, a 30-second segment and a 45-second segment, both corresponding to the worst-case bow-quartering craft direction in 4-ft seas at approximately 40 kt. The short time segments included only about 80 to 100 impact events. UVA-CAB also analyzed these short time segments as a cross-check of the NSWC-PC and UVA-CAB

injury model algorithms. Second, UVA-CAB is analyzing longer time segments of the acceleration data including various craft directions all with the craft speed at about 40 kt. The parallel UVA-CAB investigation, in progress, is expected to provide much greater statistical confidence with the analysis of thousands of impact events over the longer periods of impact exposure. The results of the NSWC-PC analysis of the 30- and 45-segment are reported here.

While the values for the deck, seat frame, seat cushion, and back were generally computed for all of the various design rules and injury models, the seat frame and seat cushion are the anticipated positions for application of the selected injury model to the HSC craft design process. The craft design process, particularly where seakeeping models and tow tank tests are involved, is expected to produce principally deck acceleration data. This data may however be processed with a measured or predicted transfer function to represent the seat frame and seat cushion, thus forming the bridge necessary to apply the selected injury model or design rule to the seat frame or seat cushion. Alternatively, in the case of full-scale prototype craft-seat configurations, the seat frame or seat cushion acceleration data may be measured directly.

3.2 Performance of Current Design Rules

3.2.1 Root-Mean-Square (RMS)

Table 1 summarizes the results of the traditional vertical acceleration RMS calculation (in g units) with the raw 250 Hz bandwidth V4-V5 data low-pass filtered further at 80 Hz. The design rule was applied to the 30-sec and 45-sec data segments, for the case of the deck, seat frame, seat pan, and back (L4 lumbar) positions. Note that the deck acceleration RMS is the same for both the V4 and V5 seats. Of interest is the generally increasing RMS value from the deck, through the seat frame, cushion, and lumbar positions. This result, that is seen for most of the various injury models, suggests that a "rigid" seat, that is of course not truly rigid, is in fact a dangerous place to sit.

The principal entries of interest in Table 1 (and in the following tables), corresponding to the percent improvements for the seat frame and seat cushion, are bolded. The results show no consistent trend in reduction of the RMS value for the V5 relative to that of the V4 seats. Thus these initial results do not demonstrate ability of the basic acceleration RMS parameter to distinguish between the performance of the two seats.

Table 1. Calculation of RMS for V4 vs. V5 Seats (g)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	0.50	0.50	0.00	0.62	0.62	0.00
Seat Frame	0.51	0.52	**0.80**	0.63	0.66	**4.37**
Seat Cushion	0.62	0.63	**1.89**	0.76	0.75	**-1.09**
Back (L4)	0.63	0.55	-12.45	0.66	0.69	4.82

3.2.2 ISO 2631 Part 1 (1985)

The initial results for the ISO 2631 Part 1 (1985) evaluation are shown in Table 2 for the two seats, and for the deck, seat frame, seat cushion, and back. For each case, the 250 Hz bandwidth vertical acceleration signals were frequency-weighted in accordance with the standard, and the RMS was computed. The resulting values for the V5 seat are consistently lower than those of the V4 seat. Therefore this standard is a candidate for further consideration.

Table 2. ISO 2631 Part 1 (1985) RMS of Frequency-Weighted Acceleration (m/sec^2)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	1.98	1.98	0.00	2.23	2.23	0.00
Seat Frame	2.01	1.62	**-19.3**	2.49	1.96	**-21.1**
Seat Cushion	3.01	2.19	**-27.1**	4.15	2.58	**-37.7**

3.3 Performance of Near-Term Candidate Supplemental Design Rules

3.3.1 Impact Acceleration Amplitude Statistics

The initial results for the 1/10th highest acceleration maxima (with a single maximum computed for each impact event) are shown in Table 3. The 1/10th highest acceleration maxima for the V5 seat, relative to those of the V4 seat, show an inconsistent trend for the seat frame and seat cushion positions.

Table 3. 1/10th Highest Acceleration Maxima (g)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	3.83	3.83	0.00	4.90	4.9	0.0
Seat Frame	3.55	3.40	**-4.16**	4.83	4.97	**3.01**
Seat Cushion	4.12	4.59	**11.4**	6.53	5.58	**-14.5**
Back (L4)	7.16	4.20	-41.4	5.40	5.43	0.50

3.3.2 ISO 2631 Part 1 Standard (1997)

Tables 4 and 5 summarize the results of the 1997 ISO 2631 Part 1 evaluation. Both the RMS and VDV of the frequency-weighted acceleration data are shown. The crest factor for each of the vertical acceleration signals was computed, and in no case was the crest factor less than 9; therefore the preferred indicator for this standard is the VDV.   Substantial reduction in the V5 RMS and VDV values, relative to those of the V4, are seen for both the seat frame and seat cushion.

Table 4. ISO 2631 Part 1 (1997) RMS of Frequency-Weighted Acceleration Data (g)

Direction	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	1.98	1.98	0.0	2.33	2.33	0.0
Seat Frame	2.01	1.62	**-19.3**	2.50	1.96	**-21.1**
Seat Cushion	3.01	2.19	**-27.1**	4.15	2.58	**-37.8**

Table 5. ISO 2631 Part 1 (1997) VDV of Frequency Weighted Acceleration (g)

Direction	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	5.89	5.89	0.0	6.12	6.12	0.0
Seat Frame	5.38	3.48	**-35.4**	6.26	4.17	**-33.4**
Seat Cushion	9.22	6.24	**-32.3**	11.8	7.02	**-40.26**

3.3.3 Dynamic Response Index Statistics (DRI)

The results of the DRI calculation for the two time segments and two seats are summarized in Table 6. For each impact event, the DRI was computed for the deck, seat frame, and seat cushion. Then the 1/10th highest DRI values within each time segment were computed. The DRI method was intended by its developers to be applied to the seat cushion acceleration, and in fact the seat cushion DRI values appear to indicate sensitivity to the known difference between the V4 and V5 seats.

Table 6. 1/10th Highest DRI (non-dimensional)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	2.26	2.26	0.0	3.03	3.03	0.0
Seat Frame	1.83	1.85	**0.9**	2.67	2.87	**7.59**
Seat Cushion	2.95	2.30	**-22.0**	4.66	3.44	**-26.2**

3.3.4 Onset Rate Statistics

The results of the onset rate calculation for the two time segments and the V4 and V5 seats are summarized in Table 7. The onset rate for each impact event, in units of g/sec, with the data low-pass filtered at 80 Hz, was computed for the V4 and V5 seats for the deck, seat frame, seat cushion, and human back. Then the 1/10th highest onset rate was computed for each time segment. The resulting onset rates for the V5 seat, relative to those of the V4 seat, appear to be consistently lower for the seat frame, but the results are inconsistent for the seat cushion.

Table 7. 1/10th Highest Onset Rate (g/sec)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	59.7	59.7	0.0	77.6	77.6	0.0
Seat Frame	59.3	46.1	**-22.3**	80.6	38.7	**-52.0**
Seat Cushion	45.2	47.5	**5.1**	103.9	52.4	**-49.6**
Back (L4)	152.7	38.2	-75.0	54.2	48.2	-11.1

3.3.5 ISO 2631 Part 5 Standard

The results of the ISO 2631 Part 5 calculation are summarized in Table 8. The S_{ed} values, normalized to an average eight-hour exposure, were computed for each seat and each time segment, for the deck, seat frame, and seat cushion. The S_{ed} values for the V5 seats are consistently lower than those of the V4 seats, for both the seat frame and seat cushion positions.

Table 8. ISO 2631 Part 5 S_{ed}, Normalized to 8 Hour Exposure (MPa)

Position	V4-30sec	V5-30sec	% Diff	V4-45sec	V5-45sec	% Diff
Deck	5.47	5.47	0.0	5.51	5.51	0.0
Seat Frame	5.23	3.57	**-31.8**	5.80	5.57	**-4.0**
Seat Cushion	7.93	6.58	**-17.0**	11.0	8.35	**-23.7**

3.3.6 Power Spectral Density (Bandwidth-Limited)

The results of the PSD-BL calculation are shown in Table 9, for the two time segments, the V4 and V5 seats, and for the deck, seat frame, seat cushion, and human back. The values shown are in dB; thus a difference of 3 dB is a factor of two in the power. The PSD-BL values, for the seat frame and seat cushion positions of the V5 seat, are consistently lower than those of the V4 seat.

Table 9. PSD-BL Comparison

Position	V4-30sec	V5-30sec	db Impr	V4-45sec	V5-45sec	db Impr
Deck	-32.5	-32.5	0.0	-33.0	-33.0	0.0
Seat Frame	-32.7	-37.0	**-4.3**	-32.5	-38.4	**-5.9**
Seat Cushion	-28.1	-34.3	**-6.2**	-26.0	-33.5	**-7.5**
Back (L4)	-26.4	-36.5	-10.1	-32.0	-34.6	-2.6

3.4 Conclusions from Model Evaluation

The results of the initial comparative performance evaluation are summarized in Table 10. The limited statistics of the 30- and 45-second time segments allow only a qualitative indication of the relative model performance. The investigation summarized is at this point principally a *demonstration of an approach* for identifying improved design rules to reduce impact injuries within the HSC acquisition process.

Table 10. Initial Qualitative Performance of Alternative Impact Injury Design Rules

Alternative Impact Injury Design Rule	Seat Frame	Seat Cushion
Current (Traditional) Design Rules		
Root-Mean Square	Poor	Poor
ISO 2631 Part 1 (1985)	Good	Good
Near-Term Alternative Design Rules		
Acceleration Statistics (1/10th Highest)	Poor	Poor
ISO 2631 Part 1 (1997) (VDV)	Good	Good
Dynamic Response Index (1/10th Highest)	Poor	Good
Onset Rate (1/10th Highest)	Fair	Fair
ISO 2631 Part 5 (S_{ed}, 8 Hour)	Good	Good
Bandwidth Limited PSD (average over 4-8 Hz)	Good	Good

Clearly, additional experimental data, obtained from specific side-by-side tests of both craft and seats with known improvements in discomfort and injury, and from long-term epidemiological studies, are needed to finalize the selection of a supplemental impact injury design rule.

4.0 APPLICATION OF SELECTED SUPPLEMENTAL DESIGN RULE

Figure 3 illustrates a recommended application approach for the example of the ISO 2631 Part 5 S_{ed} (8 hr) as the basis of the selected design rule for assessing impact spine injury. Table 8 shows that the seat cushion S_{ed} performs well, and the seat cushion is the position intended by the developers application of the standard. The data shown in the table indicate that a reasonable S_{ed} limit, corresponding to SS 4 and 40 kt, is about 5.0.

The example of Figure 3 assumes that a catamaran hullform, to be ultimately outfitted with suspension seats, is being tested in the tow tank in irregular head seas conditions such as Pierson-Moskowitz SS 3. The contractor would be responsible for developing a model of the suspended seat, including the seat cushion, and would process the deck acceleration with the seat model. Next, either the U. S. Navy or the contractor would process the modified vertical acceleration time history with the algorithm to produce the S_{ed} value, and would then compare this value with the specified limit. If the limit is exceeded, the contractor would be required to modify either the seat or the hullform, and repeat the process.
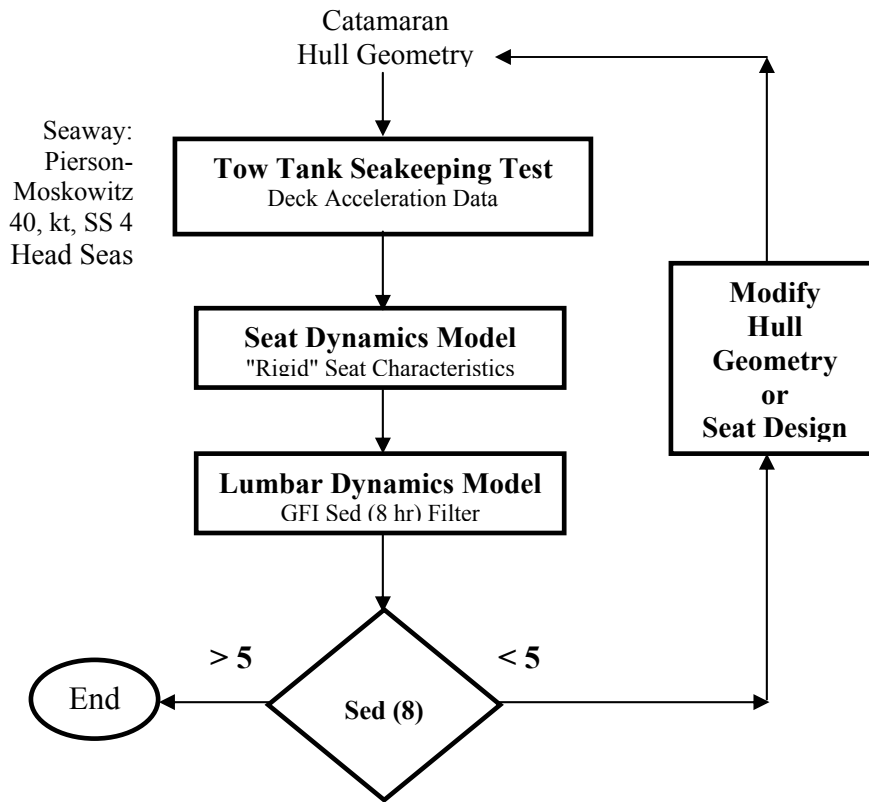
Catamaran
Hull Geometry

Seaway:
Pierson-
Moskowitz
40, kt, SS 4
Head Seas

Tow Tank Seakeeping Test
Deck Acceleration Data

Seat Dynamics Model
"Rigid" Seat Characteristics

Lumbar Dynamics Model
GFI Sed (8 hr) Filter

**Modify
Hull
Geometry
or
Seat Design**

> 5

End

< 5

Sed (8)

Figure 3. Example Application of Design Rule: Model-Scale Catamaran Tested in Tow Tank

5.0 REFERENCES

[Bass 2003] C. Bass, S. Lucas, R. Salzar, L. van Rooij, W. Pilkey, R. Peterson, and S. Martin, "Human Biodynamic Response to High Speed Planing Boat Shock Loading," presented at SAVIAC 03, 74th Shock and Vibration Symposium, San Diego, CA, October 2003.

[Eiband 1959] M. Eiband, "Human Tolerance to Rapidly Applied Accelerations," NASA Memo 5-10-59E, National Aeronautics and Space Administration, 1959.

[Ensign 2000] W. Ensign, J. Hodgdon, K. Prusaczyk, S. Ahlers, D. Shapiro, and M. Lipton, "A Survey of Self-Reported Injuries Among Special Boat Operators," NHRC Technical Report 00-48, Naval Health Research Center, San Diego, 2000.

[Fridsma 1971] G. Fridsma, "A Systematic Study of the Rough-Water Performance of Planing Boats (Irregular Waves – Part II), Report SIT-DL-71-1495, Davidson Laboratory, Stevens Institute of Technology, March 1971.

[Klembczyk 2003] A. Klembczyk and M. Mosher, "Analysis, Optimization, and Development of a Specialized Passive Shock Isolation System For High Speed Planing Boat Seats," presented at SAVIAC 03, 74th Shock and Vibration Symposium, San Diego, CA, October 2003.

[Haupt 1996] K. Haupt, "MK V SOC 951 Craft Motions Test Results," CRDKNSWC-TM-20-96-42, Carderock Division, Naval Surface Warfare Center, 1996

[ISO 2631 Part 1 1985] Guide for the Evaluation of Human Exposure to Whole-Body Vibration, International Standards Organization, 1985.

[ISO 2631 Part 1 1997] Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration,] International Standards Organization, 1997.

[ISO 2631 Part 5 2003] Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole Body Vibration, International Standards Organization, 2003.

[Mandel 1979] P. Mandel, "Seagoing Box Scores and Seakeeping Criteria for Monohull SWATH, Planing, Hydrofoil, Surface Effect Ships, and Air Cushion Vehicles," DTNSRDC/SDD-79/1, 1979.

[Savitsky 1992] D. Savitsky and J. Koelbel, "Seakeeping of Hard Chine Planing Hulls," prepared for Technical and Research Panel SC-1 (Power Craft), Society of Naval Architects and Marine Engineers, November 1992.

[STANAG 2000] Common Procedures for Seakeeping in the Ship Design Process, Edition 3, NATO Standardization Agreement, STANAG 4154, 2000

[Payne 1978] P. Payne, "Method to Quantify Ride Comfort and Allowable Acceleration," *Aviation, Space and Environmental Medicine*, January 1978.

[Village 1995] J. Village, et al., "Development of a Standard for the Health Hazard Assessment of Mechanical Shock and Repeated Impact in Army Vehicles," USAARL Contract Report No. CR 95-1, U. S. Army Aeromedical Research Laboratory, Ft. Rucker, AL, May 1995.

[Zseleczky 1992] J. Zseleczky, B. Nehrling, and R. Compton, "Side-by-Side Testing of Hard Chine and Round Bilge Semiplaning Models in Waves," Intersociety High Performance Marine Vehicles Conference and Exhibition, Arlington, VA, June 1992.

Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P31   R. Peterson, E. Pierce, B. Price 'Shock Mitigation for the Human on High Speed Craft: Development of Supplemental Design Rules' , (Naval Surface Warfare Centre, US)

Again a very interesting paper that privilegiates the Human-centered approach of the ship design in order to reduce the damage caused by the shocks generated by the high speed of ships operating in adverse environmental conditions. The references to the ISO 2631-1, 5 have been discussed by the proposal of design rules aiming at the amelioration of the comfort: the author concluded on the necessity to get more experimental data.

Discussor's name: B. Masure
Q. First, congratulation for your presentation. I make now a remark: I think that your presentation demonstrates that, for the ship that you have chosen for your study of shock and injuries induced by waves, the velocity of 40 knots must be avoided, even in the relatively small sea state index corresponding to the significant wave height of 1 to 1.5m. Other types of ships must be envisaged for high velocities such as: hydrofoil ships, SES ships, SWATH ships. Could you comment on this remark?
R. For a conventional mono hull in sea states of 3 and 4, 40 knots is probably too fast (depending on size). We are investigating the possibility of "operational guidelines" to constrain the speed/sea state envelope at least during training missions. We have also found that the crews, sitting in our new suspension seats, tend to operate their craft faster. Advanced hull forms can have their own limitations, such as cost, sea-keeping, and payload capacity.

Discussor's name: S. Smith
Q. What crest factors are you seeing in your measurements? How do the crest factors compare between the two seat designs? Thank you, nice presentation!
R. We are seeing crest factors between 15 and 20, for traditional seats, where CF = (max of weighted acceleration) / (runs of weighted acceleration), as defined in ISO 2631 Part 1(1997). The crest factors for the passive suspended seats run approximately 10-15.

Discussor's name: M. Nieuwenhuis
Q. Can you give an indication of the acceleration value where above injuries will appear?
R. As a very general rule, we become concerned where levels exceed 3-4 g over extended period of exposure. However, the entire thrust of our work is to identify parameters that are a better predictor of injury than simply acceleration magnitudes.

Discussor's name: P. Ksiazek
Q. What's the structure of a dynamic model of a "rigid" seat? What's the structure (including values of the parameters) of the lumbar dynamics model?
R. The structure has not been identified in detail, but could be a set of linear and nonlinear stiffness and damping parameters, as determined by laboratory tests. The structure of the lumbar dynamics model depends on which model is considered. The DRI (Dynamic Response Index Statistics) for example is described in Payne, 1978, Aviations Space, and environmental Medicine, January 1978. The ISO 2631 Part 5 standard includes a description of its lumbar spine model within the standard itself. The DRI is a vertical spine model, and is linear. The ISO 2131 Part 5 spine model is 3-DOF, with the vertical direction nonlinear and the horizontal direction linear.