METHODS FOR SHOCK AND VIBRATION EVALUATION APPLIED ON OFFSHORE POWER BOATS

PAHANSEN DE ALWIS
METHODS FOR SHOCK AND VIBRATION EVALUATION
APPLIED ON OFFSHORE POWER BOATS

By
Watuthanthirige Manudul Pahansen de Alwis

Supervised by
Dr. Karl Garme (PhD) – KTH Royal Institute of Technology Sweden
Dr. Jerzy Matusiak (DSc) – Aalto University Finland

This thesis is submitted to KTH Royal Institute of Technology Sweden and Aalto University Finland
in partial fulfilment of the requirements for the Nordic Master in Maritime Engineering.

KTH Royal Institute of Technology
Sweden
July 2014
ABSTRACT

Vibration is a part of human life. People use vibrations in many useful ways but eventually human exposure to vibration has become an impediment to human life. Health problems due to exposure to vibration and shock are common among the crew operating high speed craft (HSC). Whole body vibration and repeated shocks have been identified as one of the major causes for health effects among HSC crew. Whole body vibration can affect health, comfort and performance depending on the magnitude, waveform and time of exposure. Therefore it is prudent the significance of consideration of human exposure to vibration and shock when deciding the operational envelope of an offshore HSC. This report addresses this question in two correlated parts where it identifies the interrelationship between the human exposure to vibration and shock and the operational envelope of HSC. The first part consists of a state of the art review on methods and measures for evaluation of workplaces exposed to vibrations containing multiple shocks and select a suitable method to be used in the second part. The second part is a case study of a Swedish Coast Guard HSC, KBV 476, which describes crew exposure to shock and vibration using the method selected from the state of the art review, and discusses the results in relation to the risks involved with the crew in the perspective of short and long term exposure. Nature of the vibration exposure and the corresponding risk involved is then discussed with respect to the operational envelope of the craft.

Keywords: Vibration, Shock, Human Exposure, High Speed Craft
## CONTENTS

1. **INTRODUCTION** .......................................................... 1

2. **STATE OF THE ART REVIEW ON METHODS AND MEASURES FOR EVALUATION OF WORKPLACES EXPOSED TO VIBRATIONS CONTAINING MULTIPLE SHOCKS** .......................................................... 3


   2.4. Statistical analysis of acceleration data (exceedance of 1% of the time or 1/N\(^{th}\) highest acceleration values) ................................................. 19

   2.5. Dynamic Response Index (DRI) ........................................... 20

   2.6. Vibration Ride Quality Index (VRQI) and Impact Ride Quality Index (IRQI) ................................................. 21

   2.7 Impact Count Index (ICI) ................................................... 23

   2.8. Extreme value analysis (Most probable largest, MPL value of acceleration or probability of exceedance) ................................................. 24

   2.9. Evaluation of Shock and Vibration on Human ................................................... 25
3. EVALUATION OF ADVERSE HEALTH EFFECTS ON HUMAN LUMBAR SPINE OF THE CREW OF SWEDISH COAST GUARD RIB KBV476

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1. KBV476 Swedish Coast Guard RIB</td>
<td>28</td>
</tr>
<tr>
<td>3.2. Method</td>
<td>29</td>
</tr>
<tr>
<td>3.3. Instrumentation</td>
<td>29</td>
</tr>
<tr>
<td>3.4. Analysis</td>
<td>32</td>
</tr>
<tr>
<td>3.5. Results</td>
<td>33</td>
</tr>
<tr>
<td>3.6. Discussion</td>
<td>36</td>
</tr>
<tr>
<td>4. SUMMARY AND CONCLUSION</td>
<td>43</td>
</tr>
<tr>
<td>ACKNOLEDGEMENT</td>
<td>48</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>49</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Method of evaluation and assessment of vibration and repeated shock in BS 6841:1987.</td>
<td>9</td>
</tr>
<tr>
<td>2.2</td>
<td>Method of evaluation and assessment of vibration and repeated shock in ISO 2631-1:1997.</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Method of evaluation of vibration containing multiple shocks ISO 2631-5:2004.</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>Major steps to evaluate effect of shock and vibration on human.</td>
<td>26</td>
</tr>
<tr>
<td>2.5</td>
<td>Categorization of types of oscillatory motion.</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Swedish Coast Guard RIB KBV476</td>
<td>28</td>
</tr>
<tr>
<td>3.2</td>
<td>Location of the accelerometers as fitted on the RIB KBV476.</td>
<td>29</td>
</tr>
<tr>
<td>3.3</td>
<td>Arrangement of the accelerometer on the side frame of the coxswain seat.</td>
<td>30</td>
</tr>
<tr>
<td>3.4</td>
<td>Wiring diagram for Hull Crew Load Monitoring System (HCL system).</td>
<td>30</td>
</tr>
<tr>
<td>3.5</td>
<td>Daily equivalent static compression dose ($S_{eq}$) for each exposure day.</td>
<td>34</td>
</tr>
<tr>
<td>3.6</td>
<td>Behaviour of $R$ factor over 25 year of work life.</td>
<td>35</td>
</tr>
<tr>
<td>3.7</td>
<td>Z-axis acceleration signals at the seat and the deck (low pass filtered at 100Hz).</td>
<td>37</td>
</tr>
<tr>
<td>3.8</td>
<td>Dependency of the risk for an adverse health effect.</td>
<td>38</td>
</tr>
<tr>
<td>3.9</td>
<td>Annual operational profile (for 45 exposure days).</td>
<td>40</td>
</tr>
<tr>
<td>3.10</td>
<td>Daily operational profile and $S_{eq}$.</td>
<td>42</td>
</tr>
</tbody>
</table>
LIST OF TABLES

3.1 Structure of data storing at 600Hz .......................................................... 31
1. INTRODUCTION

Vibration is a part of human life. People use vibrations in many useful ways but eventually human exposure to vibration has become an impediment to human life. In day-to-day life people are primarily exposed to either localized vibration, vibration that affects the whole body or vibration that causes motion sickness [1]. Nowadays exposure to vibration has become a serious problem in the field of occupational health. Health problems due to exposure to vibration and shock are common among the crew operating high speed craft (HSC). Spinal injuries are the top most adverse health effect category reported among the HSC community. In addition to that, mental fatigue effects on the performance of the operators which may lead to greater disasters. Whole body vibration and repeated shocks have been identified as one of the major causes for health effects among HSC crew. Whole body vibration can affect health, comfort and performance depending on the magnitude, waveform and time of exposure [1]. Therefore it is prudent the significance of consideration of human exposure to vibration and shock when deciding the operational envelope of an offshore HSC. This report addresses this question in two correlated parts where it identifies the interrelationship between the human exposure to vibration and shock and the operational envelope of HSC.

The first part consists of a state of the art review on methods and measures for evaluation of workplaces exposed to vibrations containing multiple shocks. The state of the art review, which is Section 2 of this report, discusses about some of the available evaluation methods that could be used to assess effects of human exposure to shock and vibration on HSC. In the past few decades plenty of studies have been carried out on human exposure to vibration and shock in many aspects. As a result of that there are many standards, legislations and methods available for quantification and evaluation of human exposure to vibration. When it comes to evaluation methods for vibration and shock on high speed craft the subject is still in debate. Most of the standards available to assess human exposure to vibration are based on the experimental results and studies carried out in relation to automobile communities. Vibration environments exposed by HSC operators are different (mainly vibration type, magnitude and time of exposure) from the vibration environments exposed by automobile operators. HSC vibration environments contain more transient vibration and shocks than automobile vibration environments. HSC operators are exposed to very high magnitude of vibration compared to automobile operators. Daily exposure time, number of exposure periods with different vibration magnitudes per day and number of exposure days per year are also different between these two types of operators. All the available standards present methods for measuring and evaluating whole body vibration and repeated shock. Neither these standards provide vibration limits (accepted levels of magnitude and time of exposure) nor the probability of occurrence of any specific injury that may cause due to excessive exposure to vibration. Some of the standards provide general...
indication of vibration levels with regard to the different effects those vibration environments induce on human. This is because, there is a lack of data for incontrovertible evidence relating specific injuries to definite vibration exposure level. Therefore no standard provide a definitive dose-effect relationship between whole body vibration and specific type of injury. There are statistical methods available to evaluate vibration environments, which have been developed using the data obtained from experiments carried out on HSC. These methods do not have specific criteria for evaluation of human exposure to vibrations. This is due to most of those methods have been developed for other purposes such as for assessment of seakeeping characteristics of hull, design of HSC structures and design of shock mitigation seats. Common vibration limits used in the legislations have also been taken from the standards mentioned above and doubtful whether these limits are appropriate for assessment of shock and vibration on HSC. Therefore it is important to carefully select the best method or combination of methods or standards when evaluating human exposure to vibration and shock on HSC. The objective of the first part is to deliberate the modus operandi of each evaluation method and to select a suitable method which could be used in the second part. At the same time this review provides an insight of future possibilities for utilization of different methods in different ways to evaluate human exposure to vibration environments on HSC.

The second part, Section 3 of the report is a case study of a Swedish Coast Guard HSC, KBV 476, which describes crew exposure to shock and vibration using the method selected from the first part, i.e. the state of the art review, and discusses the results in relation to the risks involved with the crew in the perspective of short and long term exposure. Nature of the vibration exposure and the corresponding risk involved is then discussed with respect to the operational envelope of the craft.
2. STATE OF THE ART REVIEW ON METHODS AND MEASURES FOR EVALUATION OF WORKPLACES EXPOSED TO VIBRATIONS CONTAINING MULTIPLE SHOCKS

Vibration is a complex phenomenon where it has different magnitudes, contains number of frequencies, occurs in many directions and varies over time. The characteristics of vibration (magnitude, frequency and axis) vary with the environment. The response of the human body to vibration is basically the same in all environments [23]. This nature of behaviour provides a very good prospect for developing methods for evaluation of vibration and shock based on human response to different vibration environments. There are many intrinsic and extrinsic variables which influence the human response to vibration. Still studies are being carried out for developing methods to incorporate these effects with the available vibration evaluation methods.

Throughout many decades number of national and international institutions have been working on the standards for quantifying mechanical vibration and repeated shocks and developing methods for evaluation of such measurements in relation to human health, performance, comfort, the probability of vibration perception and the incidence of motion sickness. Some of the institutions are International Organization for Standardization (ISO), European Committee for Standardization (CEN), British Standards Institute (BSI), American National Standards Institute (ANSI), Deutsches Institut fur Normung, Germany (DIN) and Japanese Industrial Standards Committee (JISC). Apart from those standardization bodies mentioned above, many universities and laboratories have been studying the effects of vibration on human body. Widely used standards for measurement and evaluation of human exposure to whole-body vibration are BS 6841:1987 Guide to Measurement and Evaluation of Human Exposure to Whole-Body Mechanical Vibration and Repeated Shock, ISO 2631-1:1997 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration Part:1 General Requirements and ISO 2631-5:2004 Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration Part:5 Method for Evaluation of Vibration Containing Multiple Shocks. In addition to those standards, there are other statistical methods for evaluation of human exposure to vibration and shock such as statistical analysis of acceleration data (exceedance of 1% of the time or 1/Nth highest acceleration values), Dynamic Response Index (DRI), Impact Count Index (ICI) and extreme value analysis (Most probable largest, MPL value of acceleration or probability of exceedance). ISO 2631-1:1997 standard has been used in the legislation, Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002, for the assessment of the level of human exposure to vibration.

Most of these standards and methods are currently being used for assessment of vibration environments on HSC. Some methods are obsolete though they provide good concepts for
evaluating human exposure to shock and vibration which can be reconsidered with some modifications. Therefore this state of the art review discusses about the methods those are currently being used and recaptures the methods presented in those obsolete methods. Then the most suitable method which could be used for the case study is selected.


The scope of the standard [2] is to provide methods for quantifying vibration and repeated shocks in relation to human health, interference with activities, discomfort, the probability of vibration perception and the incidence of motion sickness. According to the standard, transducer of the accelerometer should be mounted between the human body and the source of its vibration. Magnitude of the vibration is expressed as weighted root-mean-square acceleration in \( \text{ms}^2 \) for translational vibration and \( \text{rads}^2 \) for rotational vibration. Even though it is not considered in this context this standard also provides guidance for evaluating vibration measured at seat back and at the foot rest. Vibration occurs in many directions and makes different effects on human body. Therefore use of frequency weighted signals provides the opportunity of uniform reporting of vibration conditions and possibility of predicting the relative severity of different vibration environments. Frequency weightings amplify the frequencies those are hazardous for human health and suppress the non-hazardous frequencies from the acceleration time history. This provides better opportunity for the evaluation method to capture the accelerations of hazardous frequencies. Different frequency weightings are used for the different axes of vibration. Special frequency weightings are used for evaluation of low frequency vibration affecting motion sickness. The manner which vibration affects human is dependent on the vibration frequency content. Health, discomfort and perception are assessed using the vibration over the frequency range 0.5 Hz to 80 Hz. Human performance assessment is only applicable to vibrations with dominant motions in the frequency range 1.0 Hz to 80 Hz and frequency range 0.1 Hz to 0.5 Hz is used for motion sickness assessment.

There is no clear definition for the health in the standard but gives an implication of the health effect as an injury to any part of the body during exposure to vibration. As illustrated in the standard, for evaluating the effect of vibration and repeated shock on human health, root-mean-square \((r.m.s.)\) values of the frequency weighted acceleration signal are calculated. If the crest factors \([\text{Crest factor} = (\text{weighted peak acceleration})/(\text{weighted r.m.s. acceleration})]\) are less than 6 i.e. the acceleration signals are of constant magnitude or the signals are stationary, the estimated vibration dose value \((eVDV)\) in each translational axis is calculated as; [2]
Methods for shock and vibration evaluation applied on offshore power boats

\[ eVDV = [(1.4 \times a)^4 \times b]^{1/4} \]  \hspace{1cm} (1)

where

\( eVDV \) is the estimated vibration dose value
\( a \) is the r.m.s. value (in ms\(^{-2}\))
\( b \) is the duration (in s)

or if the crest factors are greater than 6, then vibration dose value \((VDV)\) in each translational axis is calculated as; [2]

\[ VDV = \left( \int_0^T a^4(t) \, dt \right)^{1/4} \]  \hspace{1cm} (2)

where

\( VDV \) is the vibration dose value (in ms\(^{-1.75}\))
\( a(t) \) is the frequency weighted acceleration
\( T \) is the total period of the day (in s) during which vibration may occur

The fourth root of the sum of the fourth powers of the vibration dose values \((eVDVs\) or \(VDVs)\) in each axis is determined to get the total vibration dose value for the particular vibration environment.

The standard states that the vibration magnitudes and durations which produce vibration dose values in the region of 15ms\(^{-1.75}\) will usually cause severe discomfort. Since the standard clearly states that "there is currently no consensus of opinion on the precise relation between vibration dose values and the risk of injury", it implies that this 15ms\(^{-1.75}\) threshold dose value does not interpret the limits of the risk of injury and is only a general indicator.

When it comes to the effects of vibration on human activities this standard mainly deals with the specific effects of vibration on the coordinated control of hand movements and vision. The standard does not involve with quantification of fatigue, possible concerning effects on activities such as speech, postural control, cognitive processes and attention or any consequent effects on performance which may occur during or following prolonged vibration exposures [2]. According to the standard, vibration effect on human performance is evaluated using weighted r.m.s. values and states that "the weighted acceleration magnitude in any axis should not exceed 0.5 ms\(^{-2}\) r.m.s." for accurate hand manipulation and/or for precise vision. As stated in
the standard the guidance is primarily intended for environments with low crest factor motions and for predicting the effects on activities which occur during vibration exposure. For the vibration environments such as HSC operations where the crest factors exceed 6 in most of the cases, additional guidance has to be obtained from scientific literature as stated in the standard.

Comfort is a highly relative effect, however, the standard is only concern about a uniform and convenient method of indicating subjective severity of the vibration. This standard provides methods to assess comfort level of a seated, standing or recumbent person using translational accelerations as well as comfort of a seated person affected by rotational vibration on the seat, by vibration of the backrest or by vibration at the feet. When the crest factors are below 6 assessment is based on the weighted $r.m.s.$ value and when the crest factors exceed approximately 6 ($\approx 6$), root-mean-quad ($r.m.q.$) value is used. Because in these situations, $r.m.s.$ methods underestimate the discomfort produced by the vibration. The $r.m.q.$ value provides more accurate prediction of relative discomfort of motion of similar duration than that of the $r.m.s.$ value provides. If vibration exposures consist of periods of high and low vibration throughout variable periods of time i.e. for high crest factor (>6) which contains shocks or transient vibration events, the vibration dose value ($VDV$) as defined for health assessment is used. Standard does not provide any limits for comfort assessment but shows very approximate indications of the likely reactions to various magnitudes of frequency-weighted $r.m.s.$ acceleration which may also varies and depends on the vibration environment. Perception of vibration on seated, standing or recumbent person is also assessed using $r.m.s.$ methods described in the standard. As stated in the standard fifty percent of alert fit persons can just detect a weighted vibration with a peak magnitude of approximately $0.015 \text{ ms}^{-2}$ [2]. Ability to perceive vibration may vary largely between individuals. It can also be seen that these indications have been given for low crest factor (<6) events.

In this standard, incidence to motion sickness is used to assess the low frequency vibration. The standard provides guidance for assessment of only the $z$-directional vibration (vertical) and no $x$ and $y$ axis translational motions are considered. Adaption to the motion is not taken in to account. Guidance is only applicable to persons in sitting and standing postures. Also no guidance is given for the effect of rotational motion which gives a large impact on $z$-axis translational motion. The standard itself states that “The incidence of motion sickness is affected by many factors such as age, sex, motion experience, head movements and other activities, the visual environment, odours and anti-motion sickness drugs. The precise importance of these factors is not yet sufficiently known for their effects to be quantified in this standard” which
implies that the actual effects of the low frequency vibrations on human might be more complex than those are predicted by this method.

Motion sickness is evaluated using the motion sickness dose value ($MSDV$) in $\text{ms}^{1.5}$ which then can be interpreted as a percentage of persons who may vomit. This vomit percentage may vary according to the exposed population. It has been found that females are more prone to motion sickness than males and that the prevalence of symptoms declines with increasing age [2]. A simplified flow chart describing the BS 6841:1987 can be seen in Figure 2.1.

BS 6841 uses $r.m.s.$ as the basis for measurement of signals. Different methods are used to evaluate the effect of vibration and repeated shock on health, performance, comfort, perception and incidence of motion sickness. When evaluating effects on health it uses a common platform for evaluating periodic and non-periodic signals (crest factor below 6 and above 6 respectively) by introducing fourth root of the fourth power analysis where for $eVDV$ for crest factors below 6 and $VDV$ for crest factors above 6. The preferred method of vibration evaluation has been indicated in the standard as the $VDV$ method and the $eVDV$ method has been given as an alternative method of estimating vibration dose value in the case of the crest factor is below 6. The standard states that “The preferred method, given in A.3, may be used with all types of vibration and repeated shock. The approximate method, given in A.4, may be used with low crest factor vibration”. No direct evaluation method using $r.m.s.$ values has been provided to evaluate health. For vibration environments containing repeated or occasional shocks which is the case in high speed marine craft, this $VDV$ and $eVDV$ methods provide better approach for evaluating the severity of the vibration environment. It is doubtful how much the threshold level $15\text{ms}^{-1.75}$ given in the standard is applicable for HSC. It is clear that this method can be used to compare quality of two rides. It is the author’s personal view that this method can be further improved with long term experimental data and statistical methods to provide better indication of the quality of ride. There is an ambiguity in the word “health”. This is because the standard does not define health with respect to any pathological aspect. Therefore it simply gives an implication of the health effect as an injury to any part of the body during exposure to vibration. This method does not provide any quantified relationship between the vibration environment and the type of injury.

The vibration could reduce human performance and induce activity interference. This standard provides guidance to evaluate a very important aspect of HSC which is the effect of vibration on human activities. This is a unique feature of this standard. Human performance is evaluated with respect to hand manipulation and vision which are the most important human performance
parameters in HSC nature. This is especially important in military sector which will be discussed later in this report where optimal performance of the individuals is required in potentially challenging environmental conditions. In this case comfort is of no interest. Similarly in the case of power boat racing, riders try to reach the maximum possible speed where no other effect comes into mind or feels other than the eagerness of winning the race. So hand control activities and the human vision described in the standard are very important aspects where any error occurs in a hundredth of a second can be fatal. The standard uses $r.m.s.$ as the basis for evaluating effect of vibration on human performance. It can clearly be seen that $r.m.s.$ does not capture the impacts or repeated shocks experience in HSC vibration environment. The performance evaluation guidance has been given only for the vibration environments where the crest factor is below 6, i.e. for the periodic signals (sinusoidal). Therefore, even though the effect is very important, there is no chance to use this standard to evaluate HSC vibration environment with respect to human performance. Unfortunately this is the only standard or method that can be found which discusses about the effect of vibration on human performance.

The standard does not properly define the word ‘comfort’ and does not provide guidance to evaluate effect of impacts or repeated shocks on human comfort. Even though the standard propose to calculate $VDV$ for high crest factor events it does not provide any means of comfort evaluation base on $VDV$. As mentioned under the section of health evaluation, this method can also be used to give a combined index to compare the quality of rides.

Incidence of motion sickness is a better approach for evaluating low frequency vibration environments on HSC since it provides a quantitative relationship between the vibration environment and the effect that is concerned. Unfortunately motion sickness (kinetosis) is not a sever effect when comparing to the common injuries reported in HSC operations such as spondylosis deformans, osteochondrosis intervertebralis, arthrosis deformans, etc. Motion sickness dose value ($MSDV$) described in the standard is also equivalent to calculating $r.m.s.$ value by true integration over the time of exposure and multiplying by the root of time. Therefore it is doubtful how much this method is capable of capturing transient vibrations and repeated shocks.

When using this standard, selection of correct frequency weighting is very important. It is still debatable as to what extent it provides reasonable results for the high speed marine craft.
Figure 2.1 Method of evaluation and assessment of vibration and repeated shock in BS 6841:1987.

The scope of this standard [3] is to define methods for the measurement of periodic, random and transient whole-body vibration and to provide guidance on the possible effects of vibration on health, comfort and perception and motion sickness. This standard does not provide any limits but indicates factors that combine to determine the degree to which a vibration exposure will be acceptable.

The primary quantity of vibration magnitude is acceleration and expressed as frequency weighted root-mean-square (r.m.s.) values where translational and rotational accelerations are expressed in m/s² and rads⁻² respectively. Vibration is measured on the surface between the body and the surface. Locations of measurement as indicated in the standard for a seated person are the supporting seat surface, the seat-back and the feet. 0.5 Hz to 80 Hz acceleration signals are used to evaluate health, comfort and perception and for evaluation of motion sickness 0.1 Hz to 0.5 Hz range is used. In this standard effect of the frequency content of vibration on health, comfort, perception and motion sickness is considered to decide and define different weighting factors for different axes of vibration. In addition to the weighting factors, multiplying factors are used for each axis to maintain the order of magnitude of x, y and z axis vibration.

Basic evaluation of vibration in this standard is based on the measurements of the weighted root-mean-square (r.m.s.) acceleration. Evaluation method is decided using the crest factor, which in this standard is defined as the modulus of the ratio of the maximum instantaneous peak value of the frequency weighted acceleration signal to its r.m.s. value. This r.m.s. based basic evaluation method is used to evaluate vibration with crest factor below or equal to 9. Additional methods have been introduced viz. the running r.m.s. method where the running r.m.s. is a measure of the acceleration magnitude in the previous second and the fourth power vibration dose method to evaluate the vibrations having crest factor greater than 9. Because it is understood that the peak values influence health disorders and the basic method underestimates the effects of vibration containing occasional shocks and transient vibration. Running r.m.s. method is used to determine the maximum transient vibration value (MTVV) which is the highest running r.m.s. reading during the measurement period. Running r.m.s. and MTVV are determined using the equations given below; [3]
where
\( a_w(t) \) is the instantaneous frequency weighted acceleration
\( \tau \) is the integration time for running averaging
\( t \) is the time (integration variable)
\( t_0 \) is the time of observation (instantaneous time)

\[
MTVV = \max[a_w(t_0)]
\] (4)

Fourth power vibration dose method is used to determine the vibration dose value (VDV) which uses fourth power of the acceleration time history as the basis for averaging. The VDV is expressed in ms\(^{-1.75}\) and determined using the equation;[3]

\[
VDV = \left\{ \int_0^T [a_w(t)]^4 dt \right\}^{\frac{1}{4}}
\] (5)

where
\( a_w(t) \) is the instantaneous frequency weighted acceleration
\( T \) is the duration of measurement

Standard also recommends to use and report evaluations using these additional methods even for crest factors less than or equal 9 in case of a doubt. The standard clearly states that “It is recognized that the crest factor is an uncertain method of deciding whether r.m.s. acceleration can be used to assess human response to vibration”. In case of doubt the standard recommends to use ratios between magnitudes evaluated by the additional methods and the basic method to decide the method of evaluation. If these ratios are exceeding the values indicated in the standard, it is suggested that to use additional methods for the judgement of the effect of vibration on human beings. Recommended ratios are given below;[3]

\[
\frac{MTVV}{a_w} = 1.5
\] (6)
\[
\frac{VDV}{a_w T^{1/4}} = 1.75
\] 

Guidance to evaluate the effect of vibration on human health has only been provided for seated persons even though there is no clear indication of the definition of health. Weighted r.m.s. acceleration for each x, y and z axis of translational vibration is determined. Evaluation is carried out with respect to the highest frequency weighted r.m.s. acceleration (including multiplying factor) found in any axis. Resulted r.m.s. value is compared with the health guidance caution zones indicated in the standards. Frequency weighted acceleration measured or calculated for eight hours is used to distinguish daily occupational vibration exposure. No clear guidance has been given for evaluation of MTVV and VDV obtained for high crest factor events or vibration with occasional shocks and transient vibrations. Apart from that the standard indicates another value called estimated vibration dose value (eVDV) which has been included in the health guidance caution zones.

Guidance has been provided to evaluate effect of vibration on human comfort for seated, standing and recumbent postures. Comfort is evaluated on a seated person using vibration which occurs in all six directions on the seat span i.e. three translational and three rotational axes of vibration. Only the three translational axes are considered for seat-back and feet of seated persons. Vibration occurring in the three translational axes on the principal surface supporting the body is used to evaluate the comfort level of standing and recumbent persons. The weighted r.m.s. acceleration for each axis of vibration is determined. If there is vibration in more than one direction the root-sum-of-squares summation of weighted r.m.s. acceleration in each point is used to determine the point vibration total value. If there is vibration in more than one point overall vibration total value is then obtained by the root-sum-of-squares summation of the point vibration total values. Standard provides approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport to evaluate weighted r.m.s. acceleration values obtained using the basic evaluation method for low crest factor vibration events but no appropriate evaluation method for evaluating vibration environments with high crest factors (i.e. MTVV and VDV) is provided in the standard.

For the perception of vibration, only periodic and random vibration occurring in the three translational axes are evaluated for sitting, standing and recumbent postures. Perceptibility is evaluated with respect to the highest weighted r.m.s. acceleration determined in any axis at any point of contact at any time. The standard indicated the median perception threshold as approximately 0.015ms\(^2\).
Motion sickness is assessed using the vibration at frequency below 0.5 Hz and only with respect to the overall frequency weighted acceleration in the z-axis. The content of this clause and the relevant annexures is exactly similar to that of BS 6841. It provides guidelines to determine approximate percentage of people who may vomit using the motion sickness dose value \((MSDV_z)\) where the motion sickness dose value is determined from motion measurements (frequency weighted acceleration in the z-direction) throughout the full period of exposure. A simple flow chart which describes the ISO 2631-1 can be found in Figure 2.2.

The methods of acquiring acceleration data, locations for measurements and the basis for measurement of signals of ISO 2631-1 are similar to that of BS 6841. There are some differences in the evaluation methods. Limit of the crest factor is considered as 9. The \(r.m.s.\) values are used for the vibration with crest factors below 9 when evaluating effect of vibration on health. Standard itself has identified the uncertainty of using crest factor for deciding of \(r.m.s.\) or \(VDV\) method for evaluating health effects. Therefore it has proposed the ratios given in Equations (6) & (7) for deciding the method of evaluation. Vibration evaluation method based on \(r.m.s.\) cannot be used when there are series of impacts or impulsive velocity changes, spikes [13]. Even though theses spikes do not have much effect on the \(r.m.s.\) value they might be the most injurious acceleration one can experience in the ride. Therefore the author contemplates that the comparison of \(r.m.s.\) and \(VDV\) methods is a waste of time and it is better to use \(VDV\) method for vibration evaluation on HSC. Now the question is the relationship between \(VDV\) and human health. There is no direct quantitative relationship between the level of vibration and shock and the probability of injury and level of severity to be found in this standard. It can be found in [5] that the \(r.m.s.\) and \(VDV\) values as described in ISO 2631-1 have been referred to for the assessment of the level of exposure to vibration under whole body vibration evaluation. The limit and the action values indicated in the legislation [5] are still in debate since it has been found that the \(VDV\) levels in HSC operations often exceed not only the action value but also the limit value. Therefore one might think it is a matter of deciding the action and limit values. According to the author it is a matter of deciding whether to evaluate the quality of the ride or to obtain a quantitative measure on the probability of specific injury or probability of severity based on specific type of injury or injuries. When the latter is concerned the methods provided by ISO 2631-1 do not provide a direct approach for evaluating effect of vibration on human health. The standard talks about maximum transient vibration value \((MTVV)\) which is of no use without a proper criterion for evaluation. Proper studies may guide to use this \(MTVV\) with probability of occurrence and extreme value distributions to develop a better method of evaluating effect of impact acceleration on human health.
Figure 2.2 Method of evaluation and assessment of vibration and repeated shock in ISO 2631-1:1997.

Scope of this standard [4] is to define a method of quantifying whole-body vibration containing multiple shocks in relation to human health. In the standard the major health risk of short term and long term exposure to vibration is considered as the adverse health effects on the lumbar spine, resulting from a material fatigue process. The evaluation method is based on the response of the bony vertebral endplate (hard tissue) to vibration containing multiple shocks. Since different responses in the spine can be resulted by different postures it is presumed that the person involved is in a seated upright and unsupported posture and does not rise from the seat during the exposure. As indicated in the standard the person should be in good physical condition with no reported spinal pathology. However, the methods have still not been validated epidemiologically.

Vibration is measured in the three translational axes with the correct sign (positive or negative) of the acceleration signal. Spinal response in the $x$ and $y$ axes is determined using the single degree of freedom (SDOF) lumped-parameter model and the $z$ – directional spinal response is determined using the recurrent neural network (RNN) model provided in the standard. Peaks of the spinal response accelerations (maximum absolute value of the response acceleration between two consecutive zero crossings) in desired direction are then determined. Acceleration dose ($D_k$) in ms$^{-2}$ is calculated using the peak accelerations and expressed as; [4]

$$D_k = \left[ \sum_i t A_{ik}^6 \right]^{1/6} \quad (8)$$

where

- $A_{ik}$ is the $i^{th}$ peak of the response acceleration
- $k = x, y$ or $z$

Standard provides guidelines to assess health effects using the average daily acceleration dose ($D_{kd}$) which is calculated for the duration of the daily exposure. This method can be used when the total daily exposure is represented by a single measurement period and determined by; [4]

$$D_{kd} = D_k \left[ \frac{t_d}{t_m} \right]^{1/6} \quad (9)$$
where
\[ t_d \] is the duration of the daily exposure
\[ t_m \] is the period over which \( D_k \) has been measured

The equivalent static compressive stress (\( S_e \)) which provides the relationship between compressive stress part of biomechanical model experiments results and the peak acceleration response in the spine is used to calculate the daily equivalent static compression dose (\( S_{ed} \)) for the average daily exposure time and is expressed in MPa. \( S_{ed} \) is expressed as [4]

\[
S_{ed} = \left[ \sum_{k=x,y,z} (m_k D_{kd})^6 \right]^{1/6}
\]  

(10)

where
\( m_k \) are the direction weighting factors
\( m_x = 0.015 \text{ MPa/ms}^{-2} \)
\( m_y = 0.035 \text{ MPa/ms}^{-2} \)
\( m_z = 0.032 \text{ MPa/ms}^{-2} \)

Evaluation of short term effect of human response acceleration dose with respect to human health is based on a factor denoted by \( R \) which relates the \( S_{ed} \) with number of years of exposure and the ultimate strength of the lumbar spine. \( R \) factor is given by [4]

\[
R = \left[ \sum_{i=1}^{n} \left( \frac{S_{ed} \cdot N^{1/6}}{S_{ul} - c} \right) \right]^{1/6}
\]  

(11)

where
\( N \) is the number of exposure days per year
\( i \) is the year counter
\( n \) is the number of years of exposure
\( c \) is a constant representing the static stress due to gravitational force
\( S_{ul} \) is the ultimate strength of the lumbar spine for a person of age \((b + i)\) years
\( b \) is the age at which the exposure starts
$R$ below 0.8 is considered as low probability of an adverse health and $R$ above 1.2 is considered as low probability of an adverse health. Adverse health effect at lifetime exposure is evaluated based on $S_{cd}$. If $S_{cd}$ is below 0.5MPa it is considered as low probability of an adverse health and high probability of an adverse health is considered above 0.8MPa.

The standard clearly states that “The RNN for the z-axis was trained using vibration and shocks in the range of $–20ms^{-2}$ and $40ms^{-2}$ and 0.5 Hz to 40 Hz. As the model is non-linear, this constitutes the range of applicability of this part of ISO 2631” which means that this standard is valid only for accelerations up to approximately 4g level. Flowchart as given in the standard can be seen in Figure 2.3.

This method provides a quantitative relationship between the vibration environment and the risk of injury. The basis of evaluation is lumbar spine response to vibration containing multiple shocks. Annex B to the standard describes the limitation of this method with respect to the posture in the lumbar spine. The method is valid only for upright unsupported seated posture. In addition to posture in the lumbar spine there are more other factors which influence this method such as population type (age, sex, size, fitness, etc.), experience, application (public transportation, naval craft, racing power boats, etc.), body posture (standing, recumbent, etc.), supporting of hand and foot and other environmental influences (noise, heat, light, etc.). Also intervals between two rides might heal the stress and the effect resulted due to impacts up to some extent. This healing effect is not taken into consideration in this model. As a whole it is a good measure for the risk of injury. An important feature in this method is that it can predict short term as well as long term adverse health effects on human spine.

At the moment this standard is being developed [24] by combining multiple important variables into single parameter $R$, associated with probability of failure. It combines the number of cycles, effect of impact stress at spine and design population. Then this parameter $R$ is modified by modelling separately for males and females. With the available epidemiological data then the $R$ value is linked to risk of fracture.

Still these methods have to be further developed to address the healing effects, disc injury and the effect of posture.
Figure 2.3 Method of evaluation of vibration containing multiple shocks ISO 2631-5:2004.
2.4. **Statistical analysis of acceleration data (exceedance of 1% of the time or 1/Nth highest acceleration values)**

This method is widely used by designers and classification societies for assessment of seakeeping characteristics of hulls. As described in [18], in this method positive peak accelerations, including those that are wave induced and resulted due to impacts are sorted, grouped and processed. The mean value of the crests and the troughs of the acceleration signal is determined. The crests and troughs are then determined relative to the mean value and are sorted in ascending order. The sorted data are grouped in known intervals and the proportion \( r \) of negative maxima or minima is calculated where \( r \) is the proportion of negative crests or troughs. Number of motion values in each interval is also determined. The cumulative frequency and corresponding probability that a maxima or minima is less than or equal to the interval value is then calculated. Semi-log graph is then plotted for probability of exceeding acceleration \( \eta \) vs. acceleration \( \eta \). As found in [18] the statistical distribution of the impact accelerations is in exponential form. 1/Nth highest acceleration which is the average of the highest 1/Nth of peak acceleration magnitudes within the time history is then calculated as follows [18] [19].

\[
\bar{\eta}_{1/N} = \bar{\eta}(1 + \ln N) \tag{12}
\]

where \( \bar{\eta} \) is average peak acceleration.

Most of the time designers and the classification societies are concerned with the 1/3 or 1/10 highest values which can be expressed as follows; [18]

\[
\bar{\eta}_{1/3} = 2.1 \bar{\eta} \tag{13}
\]

\[
\bar{\eta}_{1/10} = 3.3 \bar{\eta} \tag{14}
\]

The probability of exceeding a specified acceleration level is given by; [18]

\[
P[\eta > \eta_{specified}] = e^{-\left(\eta / \bar{\eta}\right)} \tag{15}
\]

Probabilities of exceeding the 1/3 highest and 1/10 highest average accelerations are 12 percent and 4 percent respectively.
HSC designers and classification societies have been using this method mainly for hull structural designing work. This can also be used to assess the accelerations on HSC crew but there is no evaluation criterion available. Therefore it will be a future development to combine this method with an appropriate evaluation criterion.

2.5. Dynamic Response Index (DRI)

This method has been developed by the U.S. Air Force to assess single event human vertical impact exposures in seated posture especially seat ejection of air craft [12] [13]. The DRI is representative of the maximum dynamic compression of the vertebral column of the human body [21]. Dynamic response of the human spine is determined using a single degree of freedom lumped parameter mechanical model consisting of a mass, spring and damper. DRI is calculated using the equation given below; [21]

\[
\frac{d^2\delta}{dt^2} + 2\zeta\omega_n \frac{d\delta}{dt} + \omega_n^2 \delta = \frac{d^2Z}{dt^2}
\]

\[
DRI = \frac{\omega_n^2 \delta_{max}}{g}
\]

where

- \(\delta\) is compression of the spring (ft)
- \(\zeta\) is damping ratio of the model = 0.224
- \(\omega_n\) is un-damped natural frequency of the model = 52.9 rad s\(^{-1}\)
- \(\frac{d^2z}{dt^2}\) is z axis output acceleration from the seat pad (ft.s\(^{-1}\))
- \(t\) is time (s)
- \(g\) is acceleration due to gravity (32.2 ft.s\(^{-2}\))

Substituting given numerical values, then the equation becomes; [21]

\[
\frac{d^2\delta}{dt^2} + 23.7 \frac{d\delta}{dt} + 2798 \delta = \frac{d^2Z}{dt^2}
\]

\[
DRI = 86.9 \delta_{max}
\]
This model can be fed by any complex acceleration time history and the output is a single value called DRI. This value is proportional to the peak load in the spine of the model (spring) during the exposure. Then the percentage of the vertebral fractures corresponds to the particular DRI is obtained from the available DRI-Spinal Injury correlations.

This seems a very good model for evaluating vibration environment on HSC. It clearly provides a quantitative relationship between the vibration exposure and the risk of injury. The type of injury is clear i.e. vertebral fracture. This method also has the same restraint as in the ISO 2631-5 since it used SDOF spinal response model. Unfortunately still this is being used only in the aircraft ejection seat design. This method uses a similar SDOF lumped parameter mechanical model as is used in the ISO 2631-5 but much simpler. May be this is why the DRI method is not used by HSC community since more advance dynamic response models are available such as the one used in ISO 2631-5. The evaluation techniques of the two methods are different. When carefully studying the new developments of ISO 2631-5 mentioned in the previous section it can be seen incorporation of spinal fracture percentage evaluation criteria similar to the evaluation criteria that has been used in the DRI method but more advanced. The DRI method has been developed for single event human vertical impact exposures. Therefore this method can be further developed by combining with the extreme value analysis. The largest possible impact that could be experienced by the crew can be determined using the extreme value analysis methods described in Section 2.8. This maximum probable largest impact could be assessed using the DRI method to indicate the probability of risk of an adverse health effect i.e. vertebral fracture based on DRI-Spinal Injury correlations (a thought form the author).

2.6. Vibration Ride Quality Index (VRQI) and Impact Ride Quality Index (IRQI)

This is a method introduced in [13] to measure roughness of the ride. This method has been introduced keeping well motivated naval crews in mind. In this method two dynamic response models have been introduced. One is for the frequencies above 1 Hz and the other one is for the frequencies below that. These methods evaluate only the vibrations experienced in z translational axis. The dynamic response model consists of three different systems namely spinal model, visceral model and body vibration model. Vibration quality index is determined in terms of $r.m.s.$ mass acceleration. Each $r.m.s.$ mass acceleration has to be less than the critical value specified in the method. There are four limits described on this method limit A, B, C and D, which correspond to sever less than one hour, tolerable less than one hour, long-term sever and long-term tolerable respectively. The critical values have been selected based on the
vibration tolerance limit curve provided in the ISO 2631:1974 for sinusoidal vibration. As stated in [13] a given ISO limit curve roughly corresponds to one of the r.m.s. mass accelerations $\ddot{Y}_1$, $\ddot{Y}_2$, $\ddot{Y}_3$ being equal to the appropriate critical value. e.g.

$$\ddot{Y}_1 = \ddot{Y}_{n\text{crit}} \text{ and } \ddot{Y}_2 \leq \ddot{Y}_{n\text{crit}}, \ddot{Y}_3 \leq \ddot{Y}_{n\text{crit}}$$

Vibration ride ratio for each degree of freedom in the model is expressed as; [13]

$$VRR = \frac{\ddot{Y}_n}{g}$$ (20)

where

$\ddot{Y}_n$ is r.m.s. mass acceleration of $n^{th}$ system (spinal, visceral or body)

$g$ is the gravitational acceleration

The highest value among the three systems is selected as the Vibration Ride Quality Index (VRQI).

Impact ride quality index (IRQI) is obtained based on the DRI output of the spinal model of the system. In this method spinal model is used to count the number of times the output DRI value exceed a given threshold. Threshold levels are decided based on the number and the magnitude of shocks that can be tolerated in unit time [13]. Then the IRQI is defined as; [13]

$$IRQI = \frac{E(N)}{L(N)_{\text{MAX}}}$$ (21)

where

$E(N)$ is the DRI at a particular frequency

$L(N)$ is the DRI limit at that frequency

In the [13] there is a model to assess the low frequency vibration environments i.e. below 1 Hz. Motion sickness indices has been described as a function of frequency and acceleration for different combination of pitch, roll and heave and for individual pitch, roll and heave motions. Then it defines separately the motion of importance to a crew member located at $x$ and $y$ axis and the same is expressed as a local heave acceleration. Because this method considers the local heave as the most important parameter for the kinetosis.
Methods for shock and vibration evaluation applied on offshore power boats

Since the evaluation criteria of ISO 2631:1974 have been completely changed the above method might not have been further developed or might be because nobody has given any attention for further developing this method afterwards. The concepts is more relevant and applicable for HSC vibration environments than *r.m.s.* and *VDV* methods described in BS and ISO standards and can be further developed with the latest available methods in future.

### 2.7. Impact Count Index (ICI)

Main objective of this method is to provide a simple but sensitive and informative measure of repeated shock exposure, compatible to the high-speed craft vibration environment. This method is suggested for analysing the effect of shock mitigating methodologies in HSC. It is thought helpful for designers, operators and owners when deciding the shock mitigation (suspension) seats for their HSC. In the ICI method only band limited accelerations are used. No frequency weightings are used. As explained in [7], the vertical accelerations are measured at the surface that needs to be assessed. Then the peak acceleration reading of each shock is assigned to a ‘bin’ which covers a narrow range of peak acceleration value (in this case the range is 0.2g i.e. 1.0000g to 1.1999g, 1.2000g to 1.3999g….etc.). Acceleration signal of the entire exposure time history is analysed in the same manner in order to obtain the cumulative sum of impacts (i.e. impact count) in each bin. Since the low magnitude accelerations represent the general boat motions which are not counted under shocks, only the acceleration data above 1.6g are selected to present the impact count index. Cumulative sum of the impacts as a percentage of the total number of impact is plotted against the impact magnitude (g). Then the ICI criteria is defined as the percentage of impact count less than a specified percentage such as 95% (ICI_{95%}) or 99% (ICI_{99%}) of the total impact count.

This is a different interpretation of the statistical method described in Section 2.4. Also in this method there are no clear limits for vibration as well as no known relationship found between the impacts and the risk of injury. This method can be used for comparing quality of two rides or behaviour of two shock mitigation seats. In [7] it states that the “Further work is ongoing to link the IC/ICI analysis methodology to indices of Motion Induced Fatigue (MIF) and acute and chronic musculoskeletal injury”.

---

*Further work is ongoing to link the IC/ICI analysis methodology to indices of Motion Induced Fatigue (MIF) and acute and chronic musculoskeletal injury*.
2.8. Extreme value analysis (Most probable largest, MPL value of acceleration or probability of exceedance)

This method is basically used for quantifying the extreme values of accelerations experienced in short term and long term or lifetime exposure. There is no set method of evaluating the impact with respect to human health, performance, comfort and perception or incidence of motion sickness.

The acceleration signal is conditioned by a low pass filter in order to reduce influence from structural vibration and noise. The peak values of the acceleration time history are identified and expressed as an empirical distribution function as given below; [8]

\[ F(x) = \frac{\text{number of } x_i \leq x}{n} \]  \hspace{1cm} (22)

where

\( x_i \) is the \( i^{th} \) peak value

\( n \) is the total number of peaks.

The empirical distribution function is then fitted to a Weibull distribution, [8]

\[ F(x) = 1 - e^{-\left(\frac{x}{a}\right)^b} \]  \hspace{1cm} (23)

where

\[ F(x) = P(X \leq x) \]  \hspace{1cm} (24)

The coefficient \( a \) and \( b \) are determined and the peak value distribution is set from which the most probable largest (MPL) and the largest with 1% probability of exceedance are then calculated. The most probable largest value during \( N \) events is expresses as; [8]

\[ X_{MPL} = a \left( \ln N \right)^{1/b} \]  \hspace{1cm} (25)

The MPL during a 100 times longer period of time than the time for \( N \) events which is the largest with 1% probability of exceedance is expressed as; [8]
\[ X_{1\%} = a \left( \ln \frac{N}{0.01} \right)^{1/c} \]  

(26)

The extreme value analysis can be used with some other appropriate evaluation methods to interpret very good quantitative relationships between impacts and the risk of injury, hence limits for impacts or vibration exposure. The largest possible acceleration (impact) that a crew member can experience within a particular period of time can be determined with the extreme value analysis method and then the effect of that impact on human can be evaluated using another appropriate evaluation method.

It is found that no standard or method addresses the effect of vibration on mental fatigue which is a major problem in HSC. ISO 2631-1: 1985 consisted of a method called Fatigue-Decreased Proficiency (F-DP) which was replaced by the ISO 2631-1: 1997 and can be further considered in future to develop methods to evaluate mental fatigue of the HSC crew.

Human tolerance to vibration is still debatable. Reactions are different between individuals and even vary for an individual based on the environment and other facts (posture, seated or standing, physical and psychological conditions, etc.). Acceleration environment will completely change from one ride to another. Within the same ride, acceleration environment can change due to various reasons (changes in wave period, changes in course, etc.). It can even changes with the form of the hull. So it can be seen that the vibration and shock environments are complex to be evaluated.

2.9. Evaluation of Shock and Vibration on Human

When evaluating the effects of shock and vibration on human, it is important to understand, first the vibration environment in terms of the fundamentals of physics underlying the engineering, then the responses of human which are basically biomechanical and psychological. Finally the biological, anatomical, physiological and psychological effects on human have to be understood. Methods addressing the above mentioned three aspects are suitable for evaluating shock and vibration on human. A simple illustration can be seen in Figure 2.4.
Methods for shock and vibration evaluation applied on offshore power boats

If vibration is defined as oscillatory motion, then it can be divided into two different categories namely deterministic and random based on their characteristics as shown in Figure 2.5 [1] [23]. Vibration that humans are exposed to is categorized as the random motion. That means it can be stationary where the statistical properties do not vary over time or it can be non-stationary where the statistical properties vary over time. When considering stationary random vibration, a sample vibration averaged over an adequately long period is independent of the time over which the sample is measured. This behaviour of random motion has been used in most of the available vibration evaluation methods to assess human exposure to vibration. These methods assume that the motion of the vibration is stationary and then a representative average value is used to indicate the severity of the vibration over the total exposure time. In HSC, vibration environments are non-stationary. Therefore it is evident the requirement of a method which capture non-periodic i.e. shock and transient vibration as well as non-stationary vibration.

Figure 2.4 Major steps to evaluate effect of shock and vibration on human.

![Diagram of Vibration Environment, Response of Human, and Effects on Human](image)

Figure 2.5 Categorization of types of oscillatory motion [1].
When considering the evaluation methods described in the previous sections ISO 2631-5:2004 addresses the three major aspects i.e. identify the vibration environment, determine the corresponding human response and then determine the effect of particular vibration environment on human, mentioned in the beginning of this section. It does not assume the vibration exposed by human as stationary and uses a different approach to calculate the acceleration dose. The method determines response of the human spine using SDOF lumped parameter dynamic model in three translational axes and acceleration dose is calculated using the acceleration peaks of the spinal response. Then it provides a quantitative relationship between the vibration environment and the risk for spinal injury. Even though there is no clear indication about the type of spinal injury at least the method specify limits for probability of risk for a spinal injury in terms of short term and long term exposure. Therefore this method is selected for evaluation of crew exposure to shock and vibration on Swedish Coast Guard RIB KBV 476 discussed in the next section.
3. EVALUATION OF ADVERSE HEALTH EFFECTS ON HUMAN LUMBAR SPINE OF THE CREW OF SWEDISH COAST GUARD RIB KBV476

In this case study acceleration raw data signals collected from accelerometers connected to the coxswain seat and the deck of the Swedish Coast Guard RIB KBV476 are evaluated using the method described in ISO 2631-5:2004.

3.1. KBV476 Swedish Coast Guard RIB

![Swedish Coast Guard RIB KBV476](image)

**Figure 3.1 Swedish Coast Guard RIB KBV476.**

**Main Particulars**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Overall</td>
<td>12.50 m</td>
</tr>
<tr>
<td>Length between perpendiculars</td>
<td>10.70 m</td>
</tr>
<tr>
<td>Beam (Moulded)</td>
<td>2.92 m</td>
</tr>
<tr>
<td>Max. Breadth moulded (fully loaded)</td>
<td>2.57 m</td>
</tr>
<tr>
<td>Depth (Moulded)</td>
<td>1.46 m</td>
</tr>
<tr>
<td>Draught (fully loaded)</td>
<td>0.70 m</td>
</tr>
<tr>
<td>Block coefficient</td>
<td>0.62 m</td>
</tr>
<tr>
<td>Deadrise (at LCG)</td>
<td>23.00 degrees</td>
</tr>
<tr>
<td>Displacement (fully loaded)</td>
<td>6.31 tonnes</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>45.00 knots</td>
</tr>
<tr>
<td>Max. Power</td>
<td>740 hp</td>
</tr>
</tbody>
</table>
3.2. Method

Acceleration data on the coxswain seat and the deck of the Swedish Coast Guard RIB KBV476 were collected. The collected data represent the exposure of the coxswain to shock and vibration throughout the year 2013. Days of the year where the RIB had been used for more than 30mins per day were selected for this case study and found to be 56 exposure days from April to December 2013. Working time, or the exposure time in each day, is different from day to day. In this case study each individual daily exposure time is separately considered to analyse individual daily equivalent static compression dose ($S_{eq}$). Acceleration data collected from the accelerometers fitted on the seat and the deck are evaluated using the method given in ISO 2631-5:2004 for adverse health effects at work life ($n$ number of years) as well as lifetime exposure. Results of the data measured at the seat are then compared with the results of the data measure at the deck to get an overview of the effect of shock and vibration on the crew. Since the highly sophisticated shock mitigation seats fitted in this craft act themselves as filters, no additional filters are used to condition the data collected from the accelerometers. Most of the high frequency vibrations due to structural, engine and other machinery vibrations are normally filtered out by the seat. Raw acceleration data signals are directly fed in to the spinal response model and the lumped parameter dynamic response model also acts as a filter. Sampling rate of the acceleration signals is 600Hz. Therefore to comply with the ISO standard, data signals are resampled at the rate of 160Hz.

3.3. Instrumentation

Triaxial accelerometer, mounted on the side of the frame of the coxswain seat was used to measure the three translational axis accelerations experienced by the coxswain, Figure 3.2 and Figure 3.3.

![Figure 3.2 Location of the accelerometers as fitted on the RIB KBV476.](image-url)
This arrangement of the accelerometer which is completely different from the commonly used semi-rigid disc originally specified by the Society of Automotive Engineers (SAE pad in accordance with ISO 10326-1:1992), eliminates the effect of the seat cushion on the acceleration data, hence the spinal response.

Figure 3.3 Arrangement of the accelerometer on the side frame of the coxswain seat.

Apart from the acceleration data on the seat pad, the data collection system which is called Hull Crew Load monitoring system (HCL) installed in the craft (Figure 3.4) measures acceleration data on the deck where the coxswain keeps his or her legs on and acceleration data of the hull at two locations aft and forward of the coxswain post.

Figure 3.4 Wiring diagram for Hull Crew Load Monitoring System (HCL system).
Motion sensor fitted on the console measures three rotational axes angular velocity, hence the acceleration data on pitch, roll and yaw. To get an overview of the data, saving memory space and provide guiding information to the driver most signals are processed by the HCL system as they are collected. This applies to computations which can be performed on vectors of samples (sometimes frequency-weighted), peak, rms, rmq and $rm6^6$ (root-mean-sixth power). From these values, other parameters such as $MTVV$, $VDV$ and $VDV_6^6$ (vibration dose value calculated using $rm6^6$) based on ISO 2631-1:1997 can be determined. The system starts measuring data as soon as the craft’s ignition switch is on. Then the display indicates the driver’s current vibration environment and how the hull is loaded. Driving conditions are described with the highest $MTVV$ value for the last two seconds of the accelerometers Acc-1 or Acc-2 (Figure 3.2), depending on whether the operator is standing or sitting. The $MTVV$ value is based on frequency weighted running r.m.s. calculated over 1 second. Hull load is indicated by the accelerometer Acc-3 and the value $MTVV$ for the last two seconds of which in this case is based on running r.m.s. calculated over a hundredth of a second. However the above mentioned data are not used for this study. Only the raw data signals from Acc-1 and Acc-2 are used.

Acceleration raw data signals are directly stored through 19 channels at the rate of 600Hz as shown in Table 3.1. Speed data for each individual run are recorded by the GPS system. Longitudes, latitudes, course over the ground and the heading of the craft are also recorded by the GPS system. GPS data are registered at the rate of 1Hz.

Table 3.1 Structure of data storing at 600Hz

<table>
<thead>
<tr>
<th>Channel No.</th>
<th>Data Signal</th>
<th>Data Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Time</td>
<td>Unsigned 32 bits integer</td>
</tr>
<tr>
<td>2</td>
<td>x - axis acceleration (Acc-1)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>3</td>
<td>y - axis acceleration (Acc-1)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>4</td>
<td>z - axis acceleration (Acc-1)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>5</td>
<td>x - axis acceleration (Acc-2)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>6</td>
<td>y - axis acceleration (Acc-2)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>7</td>
<td>z - axis acceleration (Acc-2)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>8</td>
<td>x - axis acceleration (Acc-3)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>9</td>
<td>y - axis acceleration (Acc-3)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>10</td>
<td>z - axis acceleration (Acc-3)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>11</td>
<td>x - axis acceleration (Acc-4)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>12</td>
<td>y - axis acceleration (Acc-4)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>13</td>
<td>z - axis acceleration (Acc-4)</td>
<td>Signed 32 bits integer</td>
</tr>
<tr>
<td>14</td>
<td>x - axis acceleration (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
<tr>
<td>15</td>
<td>y - axis acceleration (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
<tr>
<td>16</td>
<td>z - axis acceleration (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
<tr>
<td>17</td>
<td>Pitch (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
<tr>
<td>18</td>
<td>Roll (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
<tr>
<td>19</td>
<td>Yaw (Motion sensor)</td>
<td>Signed 16 bits integer</td>
</tr>
</tbody>
</table>
3.4. Analysis

Acceleration data, collected from channel 2 to 7 were evaluated using the method provided in ISO 2631-5:2004. Acceleration dose \(D_k\) in \(x\), \(y\) and \(z\) translational axes of each exposure event of each exposure day are determined using Equation (8). Since each exposure day contains a number of different exposure events (periods) with different magnitudes the daily acceleration dose \(D_{kd}\) is then calculated using the equation; [4]

\[
D_{kd} = \left[ \sum_{j=1}^{n} D_{kj}^6 \frac{t_{dj}}{t_{mj}} \right]^{1/6}
\]  

(27)

where
\[t_{dj}\] is the duration of the daily exposure to condition \(j\)
\[t_{mj}\] is the period over which \(D_{kj}\) has been measured
\(n\) is the number of exposure events per day
\(k\) = \(x\), \(y\) or \(z\)

Daily equivalent static compression dose \(S_{ed}\) for each exposure day is calculated using Equation (10). To determine the \(R\) factor, \(S_{ed}\) is averaged over the annual exposure time (number of exposure days per year) using the equation; (proposed by author)

\[
S_{edM} = \left[ \frac{1}{M} \sum_{i=1}^{M} (S_{edi})^6 \right]^{1/6}
\]

(28)

where
\(S_{edM}\) is averaged daily equivalent static compression dose (MPa)
\(S_{edi}\) is daily equivalent static compression dose of the \(i^{th}\) day of the year (MPa)
\(M\) is number of exposure days
\(i\) is the day counter

Then the \(R\) factor is determined using Equation (11) given in Section 2.3. When evaluating the adverse health effect at lifetime exposure to shock and vibration, the lower and the upper limits of \(S_{ed}\) are determined using the equations given below. [4]
Methods for shock and vibration evaluation applied on offshore power boats

\[ \text{Lower limit} = 0.5 \left( \frac{240}{N} \right)^{\frac{1}{6}} \quad (29) \]

\[ \text{Upper limit} = 0.8 \left( \frac{240}{N} \right)^{\frac{1}{6}} \quad (30) \]

where

\[ N \] is the number of exposure days per year

\[ S_{edM} \] values at the seat and the deck are then compared to get an understanding of the behaviour of the shock mitigation seat used in this RIB on the adverse health effect on lumbar spine. Also the effect of the operational profile of the craft on health of the crew is examined.

3.5. Results

The number of days that the craft has been used for more than 30mins is 56 days. Proper acceleration raw data signals are available only for 45 days out of the total 56 days. Therefore the analysis is carried out using the available acceleration data for 45 exposure days, but the number of operational days per year was considered as 56.

It was found that the averaged daily equivalent static compression dose \( (S_{edM}) \) at the seat frame as given in Equation (28) for the total 45 exposure days is 1.88MPa and that at the deck is 1.36MPa. Lower limit and the upper limit of the \( S_{edM} \) were determined for 56 working days and are 0.64MPa and 1.02MPa respectively. The resultant \( S_{ed} \) values for each exposure day can be seen in Figure 3.5.
Figure 3.5 Daily equivalent static compression dose ($S_{ed}$) for each exposure day.
The $R$ factor was calculated for 25 year of continuous work life. A person starting his or her work life at the age of 20 years reach the $R$ factor value of 1.52 at the age of 45 years if acceleration data at the seat are considered. Notably the $R$ factor reaches only up to 1.10 after 25 years if acceleration data at the deck are considered. The resultant $R$ factor values and its behaviour over the 25 years of work life can be seen in Figure 3.6.

**Figure 3.6** Behaviour of $R$ factor over 25 year of work life.
3.6. Discussion

It can be seen from Figure 3.6 that a person who operates this RIB has low probability of an adverse health effect till the age of 22 years and reaches the limit for high probability of adverse health effect at the age of 33 years. However based on the $R$ factor calculated using the acceleration data collected at the deck, the low probability of an adverse health effect continues till the age of 29 years before the risk exceeds the lower limit and it does not reach the high probability limit within the 45 years of work life. Therefore it can clearly be seen that there is an amplification of risk of being harmed by the shocks and vibration by omitting any positive effect of the seat cushion.

Similar results can be observed in the behaviour of daily equivalent static compression dose ($S_{ed}$) over the 45 exposure days. From Figure 3.5 it can be seen that, in each exposure day, $S_{ed}$ value at the seat is greater than at the deck. $S_{ed}$ value at the seat of 18 days out of the total 45 exposure days exceed the upper limit for the high probability of adverse health effect at the lifetime exposure but only $S_{ed}$ at the deck in 11 days out of those 18 days exceed the upper limit. Even though both the averaged $S_{ed}$ values at the seat and the deck exceed the upper limit for the probability of high risk it is important that the $S_{ed}$ value at the seat is greater than that of the deck. As mentioned earlier, in this case, the amplification of the risk of an adverse health effect at the seat is clearly observed.

This phenomenon was further investigated by comparing the z-axis acceleration data signals measured at the seat and the deck. When calculating the acceleration dose value in $x$ and $y$ translational axes, both positive and negative acceleration peaks are taken into consideration, but only the positive peaks are considered in the $z$ translational axis. Therefore the accumulation of acceleration dose is comparatively lower in the $x$ and $y$ translational axes than that in the $z$ translational axis. Because of that it can be presumed that the $z$-translational axis acceleration is the dominant parameter when determining the acceleration dose, hence $S_{zed}$. Comparison of $z$-axis acceleration data signals of the seat and the deck of the 14th exposure day low pass filtered at 100Hz can be seen in Figure 3.7. This day was selected because it has the maximum difference between seat and deck $S_{zed}$ values and at the same time maximum $S_{zed}$ at the seat can also be found on the same day.

It is clear in Figure 3.7 that the seat amplifies the impact accelerations of the deck signal instead of mitigating them. It was found that the transmissibility i.e. the ratio of the vibration on the seat surface to the vibration at the seat base (in this case the deck) as a function of
frequency, is greater than unity. It means that the acceleration of the seat is greater than that of the deck. It is also visible that after every impact the seat keeps on oscillating at about 5Hz which generates more number of peaks which results in increasing the acceleration dose ($D_k$). Acceleration dose is a function of number of peaks of the spinal response acceleration signal. It is observed that increasing number of peaks of the seat acceleration signal at lower frequencies increases the number of peaks of the spinal response acceleration signal. Therefore in this case the seat not only amplifies the deck impact accelerations but also increases the number of impacts, hence acceleration dose.

![Figure 3.7 Z-axis acceleration signals at the seat and the deck (low pass filtered at 100Hz).](image)

Normally shock mitigation seats are designed such that they provide isolation from the frequencies transmitted through the deck. It seems that in this case the deck vibrates around the resonance or natural frequency of the seat which then amplifies the receiving deck signal instead of isolating or mitigating it. Still it is not appropriate to conclude that this seat increases the risk of adverse health effects on the lumbar spine. The reason is, as mentioned in Section 3.3 the accelerometer had been located on the side frame of the coxswain seat. This arrangement disturbs capturing the actual seat-person combined dynamic behaviour of the system. Effect of the seat cushion on the shocks and vibration is completely disregarded. Therefore one can argue that the acceleration data recorded by the seat accelerometer are not the exact shocks that are experienced at the ischial tuberosities of the seated person. Furthermore, because of positioning the transducer forward to the centre of rotation of the seat the effect of the rotational vibration on the recorded translational vibration is much higher than
that at a conventional SAE pad (especially on $z$-translational axis vibration which is the dominant in this case).

Shock mitigation seats are tuned by adjusting the dynamic response of the seat such that it minimizes the most important adverse health effect. Principally it can be expressed that the seat should be designed with a resonance frequency less than the frequency of the repeated shocks or impacts experienced by the craft or transmitted to the seat through the deck. This means that the high energy zones of the deck vibration power spectrum has to be coincided with the low energy zones of the seat vibration transfer function. Now the question is how the shock mitigation seat designers decide on the resonance frequency or the highest power spectral density of the suspension system. To decide this, the vibration power spectra of the deck at different operating conditions (may be different sea states) are required. This implies that the seat has to be tuned with respect to different vibration environments. This can be attained only if the vibration environment is known. Similarly, to state whether a shock mitigation seat is suitable for a particular application in different vibration environments the frequency spectra and the amplitude distributions of vibration in those environments are required. These vibration environments depend on various parameters such as sea wave spectrum, geometry of the hull, speed of the craft and heading. A simple flow chart to represent the relationship of the above parameters with the adverse health effect at lifetime exposure to shock and vibration can be seen in Figure 3.8.

![Flow chart](image)

**Figure 3.8** Dependency of the risk for an adverse health effect.
From Figure 3.8, it can be seen that if the daily operational time is fixed, $S_{ed}$ can be manipulated by controlling the vibration environment. Similarly vibration environment can be manipulated by varying the sea state, hull form, speed and heading. There are many methods (semi empirical and simulation) to generate vibration environments using above mentioned parameters. It is evident that when considering real situations sea state, speed and heading are not constant parameters. It is difficult to register the actual wave conditions experienced by a craft when moving at very high speeds. Sea state recorded by the relative reciprocating motion of a stationary wave buoy and the relative motion or sea state experienced by a HSC are different. If a wave buoy is positioned in the area of trials a good picture of the sea state can be obtained (in statistical terms, wave spectrum). The difficulty is first to do the wave measurement and secondly that the craft, especially HSC, move over a quite large area and since the sea state changes both in time and location, the measured sea state might not be the same as what the craft experiences. In the case of KBV 476 it is impossible to measure sea state since it is in operational duty. Therefore it is difficult to get the real view of the sea conditions experienced by HSC.

Since there are number of Swedish Coast Guard craft are fitted with these HCL data acquisition systems this study can be further developed to examine the interrelationship of speed and the vibration environments. As the first step in that direction, this case study is moved one step forward by examining the influence of the speed when evaluating the shock and vibration environments with respect to human health using the available speed and acceleration data.

The operational profile of the craft is divided in to three speed categories namely high, medium and low based on the speed limits, speed above 40knots, speed between 40knots and 25knots (including 40knots and 25knots) and speed below 25knots respectively. Percentage operational time of each individual speed range can be seen in Figure 3.9.
Figure 3.9 Annual operational profile (for 45 exposure days).

The craft has been operated below 25 knots within 62% of the total operational time. Only within 3% of the annual operational time the craft has been operated above 40 knots and in the remaining 35% of time it has been operated between 25 and 40 knots. This annual exploitation can be interpreted in many ways. For instance that the 62% of slow speed operation follows from too severe sea conditions but the actual reason might be that there was no requirement for operating the craft at higher speeds. Similarly crew might have operated the craft at higher speeds in severe sea state conditions due to insistent demands. Figure 3.10 provides daily operational time of the craft at each speed category and the $S_{ed}$ at the deck. Since the seat amplifies the deck impacts in this case, it was decided to use the deck acceleration data to examine the influence of speed on the probability of adverse health effect. This is because, if the seat does not provide shock mitigation then at least the transmissibility should be unity. This means that the seat should have the same impact acceleration as the deck. If we consider the 41st exposure day, the craft has been used 53 mins at high speeds, 128 mins (2 hrs & 8 mins) at medium speeds and 214 mins (3 hrs & 34 mins) at low speeds and the corresponding $S_{ed}$ is 1.0 MPa. On the 22nd exposure day a $S_{ed}$ of 2.3 MPa corresponds to 5 mins and 26 sec at high speeds, 67 mins (1 hrs & 7 mins) at medium speeds and 188 mins (3 hrs & 8 mins) at low speeds. Operational time at each speed category on the 22nd exposure day is lesser than that of the 41st exposure day but the $S_{ed}$ of the 22nd day is greater than that of the 41st day. On the 14th exposure day the $S_{ed}$ is 1.87 MPa where the craft has not been used at high speeds at all and only 44 mins & 40 sec at medium speeds and 172 mins (2 hrs & 52 mins) at low speeds. Furthermore, on the
23rd exposure day the craft has been used only at low speeds for 351mins (5hrs & 51sec). From these results, significance of the influence of sea state and the heading of the craft on the vibration environment in addition to the operational time at each speed limit is evident.

The time dependency of \( S_{\text{ed}} \) occurs at the stage of determining daily acceleration dose, \( D_k \) (Figure 3.8). Therefore the author contemplates that the influence of the sea state and the heading on the vibration environment can be investigated by spectral analysis of acceleration data corresponds to each speed category.

Power spectral density of the acceleration time histories at each speed category can be analysed to find out how the energy is dispensed at different frequency ranges. Since the speed is considered constant within the specified category, sequences of energy transmission at different frequencies can be examined. Similarly, the response spectrum of the deck can be generated using the available acceleration time history data. Relationship between the transmitted energy and the response in different frequencies at each speed categories can then be studied.

At the same time it can be seen in Figure 3.5 that 40% of the time i.e. 18 days out of total 45 exposure days \( S_{\text{ed}} \) at the seat is above the upper limit of risk and 22% of the time (10 days) ranges within the lower and upper limits. An important fact is that 22 days i.e. 49% of the time \( S_{\text{ed}} \) at the deck is above the lower risk limit. This shows that the probability of risk of adverse health effect is around 50% in each case. Still Figure 3.9 shows that the craft has been operated at high speed only about 3% of the total time. Time that the craft has been operated above low speed is 38% i.e. around 1/3rd of the total time. Therefore the doubt is still there whether the limits given in the standard is appropriate for marine HSC community, especially for the military operations. This can be further studied using data collected from the Swedish coast guard boats for investigating better risk limits for marine HSC community.
Methods for shock and vibration evaluation applied on offshore power boats

Figure 3.10 Daily operational profile and $S_{ed}$.
4. SUMMARY AND CONCLUSION

Vibration is a complex phenomenon with varying characteristics which depend on various intrinsic and extrinsic parameters. Because of its complex nature evaluation of vibration environments has become a greater challenge. There are plenty of methods available for evaluation of vibration environments. Evaluation of human exposure to vibration is one method of evaluating vibration environments which is widely being used in the field of occupational health. Vibration environments exposed by human are different from one occupational environment to another. Therefore using a common method or standard for evaluating human exposure to vibration has to be done with a great understanding, especially when selecting the limits. This report mainly looks into methods for evaluating vibrations containing multiple shocks with regard to marine high speed craft (HSC). Marine HSC operators belong to a well-motivated and physically fit community, who are exposed to extreme levels of vibration compared to the other communities those who deal with speed and vibration. There are very few methods available for evaluation of vibration environments on marine HSC. All these methods can be used only to assess the ride quality between different rides of the same craft or of different craft. There are lots of complaints about health effects and injuries from the HSC operators. Therefore availability of a method for evaluation of human exposure with respect to probability of risk for those identified health hazards is important. Unfortunately there is no such method currently available to assess the vibration environment exposed by HSC community. Section 2 to this report described some of the selected methods those have been developed to evaluate vibration environments containing multiple shocks experienced by different communities and also used by HSC community. Some of the methods are currently being used and some of them are obsolete. As mentioned earlier the problem of these methods is that they have failed to provide quantitative relationship between the vibration environment and the risk of adverse health effects. When carefully reading through Section 2 it is evident that some of them provide reasonably good methods to evaluate exposure of human to HSC vibration environments but the limits provided are doubtful whether they are suitable for the community in question. Some methods are good but no specific limits have been established. There is another set of methods which have very good methods to quantitatively analyse the vibration environment but no evaluation method or criterion with respect to human exposure. All these methods have been discussed in Section 2 as a state of the art review. As a conclusion to Section 2 it can be seen that the methods discussed are better not to be used directly for assessment of vibration environments experienced by HSC operators. These methods can be modified or further developed to become more suitable for the required task. As discussed in Section 2 some of the methods can be combined together to develop more versatile methods and to improve their appropriateness.
BS 6841:1987 presents the $VDV$ as their preferred method for evaluation of all types of vibration and repeated shocks when human health is concerned. The $eVDV$ has been given as an alternative for the vibration events of the crest factor below 6. The limits provided by the standard are doubtful for HSC since the limits are based on experimental data carried out on automobiles. Therefore it could be further improved by reconsidering the limits using experimental and statistical data on HSC. Author identifies that this method is appropriate for comparison of ride quality between different rides. This is because the standard does not provide precise relationship between vibration dose values and the risk for specific injury. ISO 2631-1:1997 uses weighted root-mean-square (r.m.s.) acceleration as their basic evaluation method i.e. vibration with crest factor below or equal to 9 for assessment of health effects on human. Vibration environments on HSC contains with series of impacts or impulsive velocity changes, spikes. These impacts do not have much effect on r.m.s. value though they can cause acute injuries. Therefore for vibration with non-periodic motion (transient and shocks) r.m.s. method is not recommended. The standard proposes $VDV$ and $MTVV$ for evaluating effects of vibrations with non-periodic motion on human health even though no criteria for evaluation are provided. Similar to BS standards $VDV$ can be used for ride quality comparison with appropriate validations with HSC data. Author contemplates that there are two methods to use $MTVV$ for evaluation human exposure to vibration. One method is that $MTVVs$ can be treated as acceleration peaks and determine the spinal response for those peaks. Then the spinal response acceleration peaks can be evaluated using a similar method as described in ISO 2631-5:2004. The other method is, the maximum possible $MTVV$ for a particular period of exposure can be determined using extreme value analysis. Then that value can be evaluated using DRI method.

Single event human vertical impact exposures in seated posture can be evaluated using DRI method. This method uses SDOF lumped parameter dynamic response model to determine maximum dynamic compression of the vertebral column of the human body. Then the response is evaluated to determine the percentage of the vertebral fractures corresponds to the particular DRI using the available DRI-Spinal Injury correlations. This shows that this model contains second and third steps, i.e. determination of human response to a particular vibration environment and the corresponding effect on human, of the three steps for evaluation of shock and vibration on human as mentioned in Section 2.9 (Figure 2.4). The first step i.e. identifying the vibration environment can be modified to be suitable for HSC. Extreme value analysis can be used to determine the most severe impact exposed by the operator i.e. the most probable largest (MPL) impact that could be experienced by the operator. This is assumed as the most injurious impact experienced by the operator. Then the MPL can be evaluated using DRI method to determine the probability of risk for a vertebral fracture. Furthermore, DRI-Spinal Injury correlations can also be updated with experimental and statistical
HSC data. This way DRI method can be utilized to predict the probability of risk for spinal fracture caused by exposure to shock and vibration environments on marine HSC.

VRQI and IRQI can again be looked into where it provides a relevant and an appropriate approach for quantifying the roughness of a ride. This method can further be developed with the adoption of more appropriate evaluation methods. Similarly proper evaluation criteria can be introduced for statistical analysis of acceleration data (exceedance of 1/Nth highest acceleration value) and Impact Count Index (ICI) methods (Sections 2.4 and 2.7).

ISO 2631-5:2004 is the most appropriate available method for evaluating human exposure to vibration environments containing multiple shocks. The method has no community specific approach and it provides common limits as indications of high and low probability of an adverse health effect i.e. spinal injury. There are numerous spinal injuries that could be caused by exposure to different types of motion. As mentioned in Section 2.3, updating of this method is now in progress. Effect of different intrinsic and extrinsic parameters such as shape of the spine (C or S shape), movement of spine (twist), population type (age, sex, size, fitness, etc.), experience, application (public transportation, naval craft, racing power boats, etc.), body posture (standing, recumbent, etc.), supporting of hand and foot and other environmental influences (noise, heat, light, etc.) can be incorporated into this standard. Type of spinal injury can be more specific (e.g. vertebral fracture). Limits for short term and long term adverse health effect can also be updated and validated for HSC. Then this will become the most appropriate and mature method for evaluating vibration environments experienced by HSC operators.

BS 6841 and ISO 2631-1:1997 present methods to evaluate effect of vibration on human comfort, perception and incidence of motion sickness. Comfort is a highly relative effect and dependent on the motivation and the physical fitness of the operator. For HSC, especially military craft, comfort is not particularly important. Because tolerance limits of highly motivated physically fit military HSC operators are comparatively higher than normal high speed pleasure craft operators and passengers. Motion sickness in high frequency vibration environments is a complex phenomenon. As discussed in Sections 2.1 and 2.2, motion sickness is a very good measure that could be used for evaluating low frequency vibration environments but too simple comparing to the complex nature of the actual kinetosis experienced onboard. A person could adapt to motion sickness with time. Therefore incidence of motion sickness can also be neglected when evaluating risk for health hazards in HSC. Vibration perception on HSC is more important compared to comfort and motion sickness. Both BS 6841 and ISO 2631-1 use peak magnitude of weighted r.m.s. acceleration for the prediction of the perceptibility of vibration. For very short acceleration duration, a person is sensitive to velocity
change of $\frac{1}{2} a_{\text{max}} t$ (where $t$ is the duration of the impact) rather than the magnitude of $a_{\text{max}}$ [13]. This shows that the rise time ($t/2$) of a peak is very important when evaluating impact acceleration. This implies that even the magnitude of the impact is lethal if the rise time is very short then a person might fail to perceive it i.e. the person will not feel the impact but finally the pain of the injury. Similarly if the rise time is high then person might feel discomfort even though the impact is not lethal. High speed marine craft acceleration time history contains much higher frequencies than the upper limit of 80Hz indicated in BS and ISO. In many occasions high speed marine craft experience high impact slamming or pounding in which the acceleration time history shows a great impulsive velocity change which is difficult to be analysed spectrally [13] when using low pass filters (weightings) as of BS 6841 and ISO 2631-1. Because, filtering acceleration signals normally ends up with reducing the amplitude and increasing the duration of an impact.

As a common approach all the methods could be revalidated for HSC community with latest experimental, statistical and epidemiological data.

Last part of Section 2 (i.e. Section 2.9) of the report discusses the selection of ISO 2631-5:2004 method for the case study which is described in Section 3. Since the author identifies the most appropriate available single method for evaluating human exposure to shock and vibration experienced by HSC operators is the ISO 2631-5:2004 it was used as the evaluation method in the case study. Even though this is the most mature method available there are many restrictions and doubts in this method too. Some of them are ambiguity in type of spinal injury, restrictions in body posture and spinal shape and the limits.

Case study in Section 3 was mainly carried out first to identify the risk involved with the HSC operations and then to discuss the importance of consideration of vibration environments at the stage of deciding the operational envelope of the craft. Normally when deciding the operational envelope the main concern is that the capability of the hull structure to withstand for different vibration environments at different speeds and then the machinery configurations and the capabilities to match with the defined operational envelope. No consideration to the exposure of human to vibration environments is given.

A common problem in the HSC is the difficulty of identifying the correct sea conditions experienced by the crew at different speeds. This matter was discussed under Section 3.6 and the author proposed a future study to identify the sea conditions with respect to speed limits for particular hull shapes based on spectral analysis of data collected from the high speed craft currently deployed in Swedish Coast Guard.
As a result of the case study it was identified that the seat fitted on board amplifies the accelerations transmitted by the hull. This can be further studied to investigate whether these results are due to the uncommon mounting position of the accelerometer or whether it really amplifies the acceleration signal received from the hull. If it amplifies the acceleration signal then these results might warn the HSC designers, builders, seat designers and manufacturers that it is their responsibility to ensure the safety of the crew by providing the safest seat and proving the same by evaluating the performance after installing. It is also evident that even though reducing risk for injuries caused by impacts does not solve the health hazard of HSC operations. If seat generates number of peak accelerations while reducing the magnitudes of impact and if the number of acceleration peaks of the spinal response signal increases because of that, the accumulation of peaks i.e. the increasing of dose increases the probability of short term and long term risk for health issues. Therefore it is another important aspect which has to be looked into.

So far this report has only been about the effect of shock and vibration on human health. Mainly risk involved with the spinal injuries. There are many more other important aspects those are effected by shock and vibration environments which are very important in HSC operations. Performance is one of the important aspects when considering HSC operations. Effect of shock and vibration on performance can also be divided in short term and long term effects. Concerning military and racing craft short term human activities are very important. Especially effect on the visual performance of drivers as well as navigators in these craft is crucial. Navigational and communicational equipment are used in these craft while operating at very high speeds. Similarly weapons are also used while chasing after an enemy craft. When chasing after another HSC, sometimes the chaser has to run over the wake of the other craft which results sever impacts which disturbs human activities as well as causes risk for severe injuries. Clear vision is important for drivers to maintain the course and the targets and for the navigators to follow the maps and charts. In HSC operations attention is also an important aspect which is greatly influenced by shock and vibration. Loss of attention for a millisecond might end up in a lethal accident.

Mental fatigue is another important parameter which has to be considered. Mental fatigue slowly builds up with time and effects human performance as well as health. Another important characteristic of this, mental fatigue, can occur due to very low frequency vibration as well as high frequency vibration. This aspect is equally important as spinal and muscular fatigue when considering HSC operations.

The state of the art review and the case study aims to put light on a new dimension of the evaluation methods of vibration environments on offshore high speed craft.
ACKNOWLEDGEMENT

Special thanks given to Dr. Karl Garme (PhD) the supervisor of this master’s thesis project at KTH Royal Institute of Technology Sweden, for giving me this opportunity to work in this project and guiding me throughout the project to make it a success. Katrin Olausson (MSc) is acknowledged for providing reference literature and the cooperation provided with the discussions and feedback. Sincere thanks to Professor Dr. Jerzy Matusiak (DSc) the supervisor of this master’s thesis project at Aalto University Finland, for his support in completing the project. Thankfully mention Dr. Johan Ullman (MD) for directing and recommending me for this project.
REFERENCES


