KTH Engineering Sciences

On Evaluation and Modelling of Human Exposure to Vibration and Shock on Planing High-Speed Craft

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Licentiate Thesis
Stockholm, Sweden
2015

Academic thesis with permission by KTH Royal Institute of Technology, Stockholm, to be submitted for public examination for the degree of Licentiate in Vehicle and Maritime Engineering, Thursday the 12th of February, 2015 at 10.00, in D3, Lindstedtsvägen 5, KTH - Royal Institute of Technology, Stockholm, Sweden.

TRITA-AVE 2015:01
ISSN 1651-7660

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Abstract

High speed in waves, necessary in for instance rescue or military operations, often result in severe loading on both the craft and the crew. To maximize the performance of the high-speed craft (HSC) system that the craft and crew constitute, balance between these loads is essential. There should be no overload or underuse of crew, craft or equipment. For small high-speed craft systems, man is often the weakest link. The human exposure to vibration and shock results in injuries and other adverse health effects, which increase the risks for non-safe operations and performance degradation of the crew and craft system. To achieve a system in balance, the human acceleration exposure must be considered early in ship design. It must also be considered in duty planning and in design and selection of vibration mitigation systems.

The thesis presents a simulation-based method for prediction and evaluation of the acceleration exposure of the crew on small HSC. A numerical seat model, validated with experimental full-scale data, is used to determine the crew's acceleration exposure. The input to the model is the boat acceleration expressed in the time domain (simulated or measured), the total mass of the seated human, and seat specific parameters such as mass, spring stiffness and damping coefficients and the seat's longitudinal position in the craft. The model generates seat response time series that are evaluated using available methods for evaluation of whole-body vibration (ISO 2631-1 & ISO 2631-5) and statistical methods for calculation of extreme values.

The presented simulation scheme enables evaluation of human exposure to vibration and shock at an early stage in the design process. It can also be used as a tool in duty planning, requirements specification or for design of appropriate vibration mitigation systems. Further studies is proposed within three areas: investigation of the actual operational profiles of HSC, further development of seat models and investigation of the prevailing injuries and health problems among the crew of HSC.

Keywords: Whole-body vibration, high-speed craft, working conditions, seat modelling, apparent mass, ergonomics, human factors, ISO 2631-1, ISO 2631-5

Sammanfattning

Hög fart genom vågor är nödvändigt under exempelvis räddningsuppdrag eller militära operationer men innebär ofta svåra belastningar på såväl båt som människa. För att maximera prestandan av det tekniska system som en högfartsbåt och dess besättning utgör, krävs att dessa belastningar balanseras. Båt, utrustning eller människa ska varken överbelastas eller underutnyttjas. På små högfartsbåtar utgör människan ofta den svagaste länken. Stötar och vibrationer resulterar i skador och andra negativa hälsoeffekter som också ökar risken för nedsatt säkerhet såväl som försämrad prestanda av det tekniska systemet. För att uppnå ett system i balans är det nödvändigt att ta hänsyn till människans vibrations- och stötexponering tidigt i utvecklingen av nya högfartsbåtar. Likaså vid planering och schemaläggning av tjänst samt vid val och design av dämpningssystem.

Avhandlingen presenterar en simuleringsbaserad metod för prediktering och utvärdering av accelerationsexponeringen för besättningen på små högfartsbåtar. En numerisk stolsmodell som validerats mot experimentell accelerationsdata används för att modellera besättningens accelerationsexponering. Modellens indata är båtens acceleration uttryckt i tidsplanet (simulerad eller experimentell), förarens totala massa samt stolsspecifika parametrar såsom massa, fjäder- och dämpkonstant samt stolens longitudinella position i båten. Stolsmodellen genererar tidsserier av stolsresponsen som utvärderas med hjälp av tillgängliga metoder för utvärdering av helkroppsvibrationer (ISO 2631-1 och ISO 2631-5) och med statistiska metoder för beräkning av extremvärden.

Simuleringsschemat som presenteras möjliggör utvärdering av människans stöt- och vibrationsexponering tidigt i designskedet men kan också användas som ett verktyg vid planering av tjänst, kravställning eller för utformning av lämpliga dämpningssystem. Vidare studier föreslås inom tre områden: kartläggning av högfartsbåtars verkliga operationsprofil, vidareutveckling av stolsmodell samt kartläggning av skador och hälsoproblem bland personal på högfartsbåtar.

Nyckelord: Helkroppsvibration, högfartbåt, arbetsmiljö, stolsmodellering, skenbar massa, ergonomi, mänskliga faktorn, ISO 2631-1, ISO 2631-5

Preface

The work presented in this thesis has been performed at the Centre for Naval Architecture at the Department of Aeronautical and Vehicle Engineering at KTH Royal Institute of Technology, from November 2012 to January 2015. The work was initiated and supported by Dr. Karl Garme, Prof. Jakob Kuttenkeuler, Dr. Anders Rosén and Dr. Ivan Stenius. The research has been financially supported by Sjöfartsverket (Swedish Maritime Administration), the Lundeqvist Foundation (promoting scientific research within the field of Naval Architecture at KTH) and FMV (Swedish Defence Materiel Administration).

I would like to sincerely thank my supervisors Karl Garme and Jakob Kuttenkeuler for their eminent support, guidance, and help during this work. To you and to all my colleagues at KTH Centre for Naval Architecture - it has been a pleasure to work with you. I also would like to thank Stefan Andersson (Swedish Coast Guard), Gustav Kjellberg (Swedish Armed Forces) and Carl-Magnus Ullman (Ullman Dynamics) for their valuable contributions and for putting my work into a wider context. To my colleagues at the department, thank you for giving me energy and motivation during lunch breaks and jam sessions.

Finally, a special thank to my family and friends for always being there in times of joy and doubt. To my husband Lars, words cannot express how grateful I am to you, and how much I appreciate your never ending support and your ability to always make me laugh.

Katrin Olausson

Stockholm, 12th January 2015

Dissertation

This thesis consists of two parts: The first part gives an overview of the research area and work performed. The second part contains the following research papers (A-C):

Paper A

K. Olausson and K. Garme. Prediction and evaluation of working conditions on high-speed craft using suspension seat modelling. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, published online before print, January 2014.

Paper B

K. Olausson and K. Garme. Simulation-based assessment of HSC crew exposure to vibration and shock. In *Proceedings of the 12th International Conference on Fast Sea Transportation (FAST2013)*, December 2013.

Paper C

M. Razola, K. Olausson, K. Garme and A. Rosén. On High-Speed Craft Acceleration Statistics, preprint paper, January 2015.

Publications not included in this thesis

Conference paper: M. Razola, A. Rosén, K. Garme and K. Olausson. Towards Simulation-Based Structural Design of High-Speed Craft. In *Proceedings of the Fourth Chesapeake Powerboat Symposium*, Annapolis, Maryland, June 2014.

Division of work between authors

Paper A

Olausson developed the presented methods and validated the seat model using experimental data provided by Garme. Olausson wrote the paper supervised by Garme.

Paper B

Olausson determined the seat response to boat accelerations, which were numerically simulated by Garme. The disposition of the paper is a result of a collaboration between Olausson and Garme. Olausson wrote the major part of the paper.

Paper C

Olausson developed the descriptive statistics methods and Razola developed the inferential statistics methods. Olausson and Razola planned the study, performed the analysis and wrote the paper in collaboration. Garme performed boat simulations used in the analysis. The study was initiated and supervised by Garme and Rosén.

Contents

Part I

OVERVIEW

1 Introduction

1.1 Background

Over the years, advanced high-strength and lightweight materials have been developed, resulting in stronger and faster high-speed craft (HSC). However, the loads acting on the crew cause tiredness, muscle damage [1] and injuries [2] and limit the utilization of the craft's performance. In order to achieve efficient HSC systems, balance between loads on the hull, crew and equipment is necessary. It is therefore essential to improve working conditions on HSC, both from human and technical point of view.

The thesis adresses measures for improved working conditions with focus on the crew's exposure to vibration and shock. Three different approaches to reduce the acceleration exposure are discussed: techniques for vibration mitigation, human factors based ship design and operational acceleration reductive actions. The latter may for example be related to duty planning or installation of decision support systems onboard. To maximize the possibilities of achieving safe and efficient high-speed craft operations, all these measures need to be addressed. Adoption of any of these ways of action, however, presupposes that working conditions can be properly predicted and evaluated; a procedure that is everything but straightforward. The conditions in terms of sea state, speed and heading are stochastic and constantly changing. In addition, the relation between working on HSC and effects on health and work performance is unclear.

1.2 Objective

The long term goal is to achieve safe and efficient high-speed craft. The thesis aims to contribute to the development of methods for prediction and evaluation of working conditions on HSC. In other words, methods that can be used when evaluating working conditions on both existing and future HSC.

One of the main objectives of the presented work is to enable human factors to be introduced as a parameter in ship design. However, prediction of working conditions also enables requirements specification and planning of the crew's duty to be performed with respect to human health risk. Therefore, the presented work is supposed to be useful not only for the naval architect, but also for the seat designer or employer, who wants to reduce the acceleration levels transmitted to the human body.

1.3 Thesis overview

A simulation-based method for prediction of HSC crew vibration and shock exposure is presented in Paper A & B [3, 4] and is further elaborated in Chapter 3 - *Modelling the acceleration exposure of HSC crews*. An introduction to the prevailing health problems among HSC operators is given in Chapter 2 - *Health effects of whole-body vibration and shock*. As will be seen, the most severe injuries are caused by severe impact events rather than vibration. In order to appropriately analyse extreme values of HSC acceleration exposures, two different statistical approaches applicable to HSC acceleration is presented in Paper C [5]. These methods are discussed and compared with other acceleration based evaluation methods in Chapter 4 - *Evaluation of whole-body vibration and shock exposure*. As a complement to these detailed analysis methods, an additional approach for evaluation of HSC crew's exposure to health risks is introduced in Chapter 5 - *Risk analysis based on injury statistics*. The suggested approach is not a complete evaluation method but may become useful in the future if more statistical data on injuries and health problems among HSC operators are available. Chapter 6 - *Summary & conclusions* summarizes the work and suggests future studies.

1.4 Vibration mitigation techniques

Suspension seats are common on high-speed craft and can be effective in order to reduce the vibration transmitted to the human body. Generally, suspension seats have a spring unit that absorbs energy, and a damper unit, which dissipates energy. The spring can for example be a coil spring or a pneumatic spring, but other solutions also exist. For example, the suspension seat displayed in Figure 1.1 designed for use on HSC has a type of leaf spring system.

Figure 1.1: Example of suspension seat designed for use on HSC [6].

When operating small high-speed craft in waves, suspension seats can reduce the acceleration levels by 50 % [7, 8] in some situations and can be a necessity in order to avoid immediate injuries, as concluded by Garme et al [7]. The seat's mitigating performance depends on its *transmissibility*, in relation to the prevailing acceleration exposure. A seat's transmissibility is defined as the ratio of the vibration on the seat surface to the vibration at the seat base as a function of frequency,

$$T(f) = \frac{a_{seat}(f)}{a_{floor}(f)} \tag{1.1}$$

where $T(f)$ is the transmissibility, $a_{seat}(f)$ is the amplitude of the acceleration on the seat and $a_{floor}(f)$ is the amplitude of the acceleration at the seat base at frequency f [9]. Essentially, a suspension seat is a low pass filter, which has resonance frequency at around 2 Hz [9] and thus amplifies acceleration at this frequency, but mitigatets at larger frequencies. When designing a suspension seat, it is therefore essential to consider the frequency spectrum of the acceleration exposure for which the seat is supposed to provide isolation. For marine high-speed craft, this is a non-trivial task since they are operated in stochastic waves and with speed, heading and sea conditions being constant only for very short time periods. This naturally complicates the process of designing suitable mitigation systems, as these generally are tuned for one type of exposure. This is the case for suspension seats and other *passive* mitigation systems, although the occupant of a suspension seat sometimes has the possibility to adjust the damper before or during ride. As an example, consider the acceleration signal in Figure 1.2.

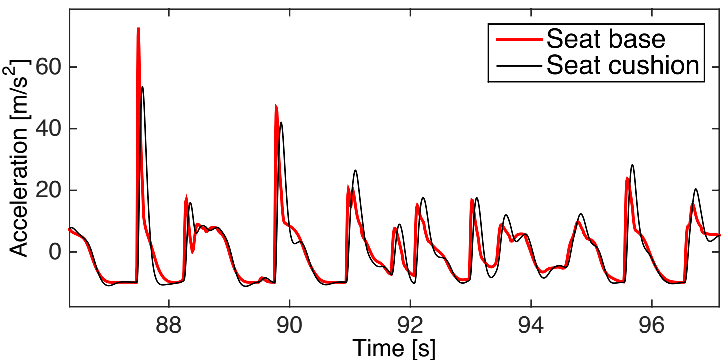

Figure 1.2: Illustration of mitigating effect of a suspension seat. The boat and seat accelerations are simulated according to the methods proposed in Paper B [4].

The signal displayed in Figure 1.2 is a sequence of a simulated acceleration signal for a high-speed craft equipped with a suspension seat that is assumed to be occupied by a 85 kg human (see further Chapter 3 and Paper A & B [3, 4]). As seen, the seat provides mitigation for the two largest impacts, but amplifies most of the impacts of lower magnitudes. Similar observations have been made also for full-scale experiment data, for example by De Alwis [10]. One explanation to the effects seen in Figure 1.2

is the discussed seat transmissibility, which varies with frequency (see Equation 1.1). Since severe impact events are related to very short time scales (see Paper C [5]), the seat mitigates these better than acceleration of lower frequencies. However, the seat transmissibility is not the only factor influencing the performance of the seat in terms of mitigation. For instance, the human body is flexible and interacts with the seat. The seat model used to generate the time series shown in Figure 1.2 includes a human representation in order to capture these effects. Furthermore, the seat cushion is also likely to influence the seat's transmissibility (see De Alwis [10]), although the model in Paper A [3] has been successfully validated with experimental data without describing the properties of the seat cushion.

It should be noted that the transmissibility of the seat-human system is not the only important factor that needs to be considered when designing a suspension seat. Human sensitivity to vibration at different frequencies should also be considered, as well as the risk for the suspension mechanisms to bottom out. In Paper B [4], the influence of seat design (in terms of spring stiffness and damping) on crew vibration exposure is investigated using methods for evaluation of whole-body vibration. These methods account for the human sensitivity to vibration of different frequencies by a frequency weighting filter that is applied before quantifying the acceleration. In the study, it is demonstrated that the acceleration exposure decrease if the spring stiffness is reduced, but also that a lower spring stiffness requires a larger motion stroke (vertical displacement). If the available motion stroke of the seat is too short with respect to the current spring stiffness, bottoming-out events may occur and subject the occupant to severe impacts. Thus, it is crucial to design the seat with a sufficient motion stroke. In practice, however, there is limitation on stroke length with respect to practical aspects as well as comfort. Concluding, designing a suspension seat is always a trade off between stroke and mitigating effect.

To meet the demands for reduced acceleration on HSC, developing and adopting complementary and/or more advanced methods for vibration mitigation may be necessary. There are several advantages of mitigation systems reducing acceleration not only for the crew, but for whole compartments or the entire craft. Such systems can limit the need of isolation mountings for sensitive equipment on board, and allow the crew to be standing behind the seats, which is often impossible during HSC transits [7]. Townsend et al [11] investigated the effects of using various flexible hull systems by simulating and comparing three different flexible hulls; a suspended hull design, an elastomer coated hull and a hull with reduced stiffness, to a regular aluminium hull. Of the three hull designs, only the suspended hull showed potential in shock mitigation. It is thus likely that suspending not only seats, but also larger compartments of the craft (e.g. cockpit) may be a suitable way of reducing the acceleration exposures for both the crew and equipment on HSC.

Since passive mitigation systems tuned for one type of exposure cannot perform equally well in all situations, active and semi-active suspension systems can be advantageous. Such systems are controlled using sensors that read the environment conditions [12]. For semi-active systems, the damper is typically adjusted to best dissipate energy, whereas active systems exert a force that controls the motion, e.g. using hydraulic, magnetic or electric actuators [12]. On HSC, active or semi-active suspension systems are rare; probably due to the difficulty of predicting the craft motion when speed, heading and waves change more or less randomly. In addition, these systems are associated with high costs, power resource dependency and need for maintenance. This may further explain why passive systems, which are more robust, are the most commonly used mitigation systems on HSC.

1.5 Human factors based ship design

Numerous decisions in the design process influence the acceleration levels that the crew and craft will be exposed to during high speed operation. Such design decisions are related e.g. to hull shape, displacement, design speed and running attitude [13]. With current design rules (e.g. [14, 15]), these parameters are chosen with respect to hull structural loads, and with little or no consideration of human factors before the boat is built, launched and tested. This may result in boat designs where the human acceleration exposure is limiting the performance of the technical system and/or the crew is exposed to health risks. That is, the performance of the craft cannot be fully utilized due to the severe levels of vibration and shock that the crew is subjected to while operating at high speed in waves. To improve the balance between loads on the crew and the craft and thereby achieve efficient high-performance systems, the key is to consider human factors continuously in the design process. As a part of the refined design methods currently being developed with the goal to achieve more efficient HSC hull structures, see for instance Razola et al [16, 17, 18], it is essential to develop methods for working condition assessment that can be introduced into the design process. Although several authors have proposed such methods [19, 20], there is none yet established. In Paper B [4], a simulation-based method aiming for a rational approach for introducing measures for working condition evaluation as requirements in HSC design is presented. The method is summarized in the simulation scheme displayed in Figure 1.3.

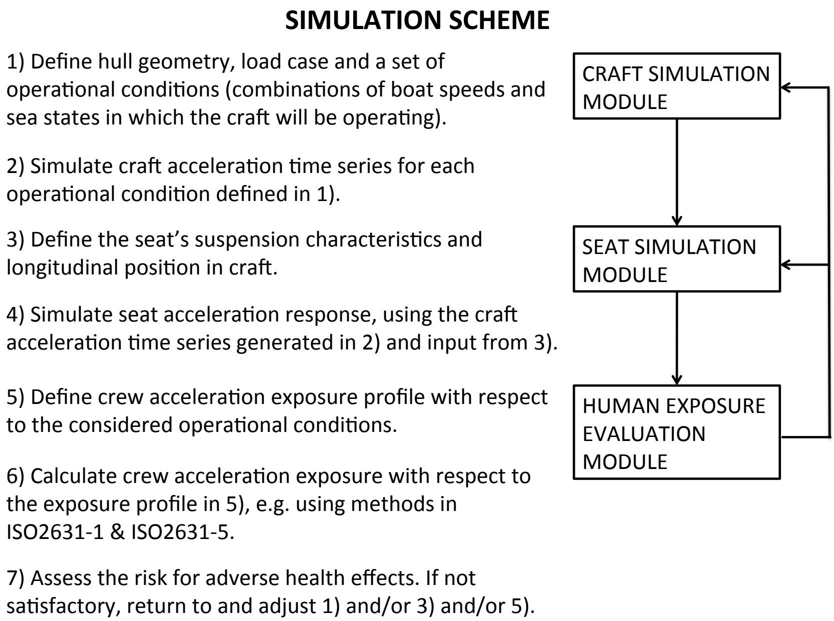

Figure 1.3: Simulation scheme as proposed in Paper B [4].

As can be seen, the simulation scheme consists of three modules. In the first module, the craft acceleration time series for operation at constant speed in head seas are generated. Input data are sea state and craft specific details such as hull geometry, load case and speed. The output of the first module is used in the second module to generate the seat acceleration time series. In this module, the seat's spring and damping characteristics are specified, as well as the seat's longitudinal position in the craft. Finally, the crew exposure to vibration and shock is assessed in two steps in the third and the last module. First, the crew exposure profile is formulated as the time spent per day in each of the conditions defined by the operational profile. Then, the seat acceleration time series are used together with the information in the exposure profile to assess the working conditions using the evaluation methods described in Chapter 4.

The simulation scheme is applicable at many stages both in the design and operation of HSC, e.g. when investigating the effect of changing the seat configuration (stiffness and damping) or its longitudinal position in the craft. In that case, the craft design, operational profile and crew exposure profile is held constant. However, if all parameters related to the craft and the seat are held constant, the simulation scheme can be used to assess different working schedules for a given system. This may be of interest for the employer, who is legally responsible to reduce the mechanical vibration and attendant risks for the empolyees to a minimum (EU Directive 2002/44/EG [21]). Concluding, the simulation tool can be used for various purposes; by the seat designer, naval architect and the employer, in requirements specification, ship design and operation of HSC.

1.6 Operational actions to reduce acceleration exposure

High-speed craft operations often result in physical and mental fatigue [22], which both increase the risk of injuries and reduce the crew's working capacity. For safe and efficient operations, it is thus essential to understand the mechanisms that cause fatigue. As an example, working night shift is more fatiguing than working day shift. This is partly due to the added concentration required when navigating at night. Other factors that impact on fatigue are physical performance and the access to periods of rest [22]. Thus, planning the duty appropriately, with physical training and periods of rest considered, the negative effects of fatigue can be limited.

In addition to adequate duty planning, health risks may also be reduced by installing a decision support system. For example, a configuration where real-time acceleration measurements continuously give feedback on the current loading situation (both on hull structure and human) to the coxswain may prevent acceleration criteria to be exceeded. Such systems are currently being developed and tried out by the Swedish Coast Guard in cooperation with KTH. A difficulty arising with the implementation of such a system is the definition of limits that are both safe and trustworthy.

2 Health effects of whole-body vibration and shock

The effects of whole-body vibration (WBV) on human health have been frequently discussed since the 1950's, as a consequence of the rapidly increased use of machines in industries and transportation. Although there is a wide range of health effects often being associated with WBV, it is generally difficult to link these effects to WBV exposure specifically. However, there seems to be an existing relationship between WBV exposure and health effects such as blood pressure, heart rate and respiration rate, due to increased muscular activity or psychological stress [23]. People exposed to whole-body vibration and shock have reported tiredness and headache in connection to duty [2, 7], as well as motion sickness, which is known to be caused by vibration of low frequencies [23]. Such *temporary* effects of WBV may result in reduced safety in any technical system operated by human exposed to vibration.

Due to the difficulty of distinguishing health effects caused by WBV from those caused by other factors, e.g. prolonged sitting, poor sitting posture or heavy lifting, there is little evidence indicating that WBV itself increases the risk of acute and/or chronic injuries or other *permanent* effects [24]. Nevertheless is it of importance to identify the most common and most problematic health effects, related to both vibration and shock, among the crew of HSC. Otherwise, appropriate actions to improve the working situation cannot be taken, nor is it possible to assess the working conditions, or finding the adequate parameters for doing so.

2.1 Injuries and health problems among HSC operators

Although the attention to the risks related to HSC crews' acceleration exposure has increased significantly in recent years (see for example [25]), there is little documentation of the prevalence of injuries and health problems among the operators of small HSC. Stevens and Parsons [26] presented a survey on effects of motion at sea on crew performance. Several aspects are discussed, although effects related to sea sickness are in focus. Ensign et al [2] presented a survey of self-reported injuries among high-speed boat operators within the US Navy. The result gives an idea of the variety of injuries that can occur while operating HSC; see Table 2.1 where the number of injuries reported at different anatomical locations is summarized. The table also presents the number of injuries that required medical attention.

Table 2.1: Distribution of reported injuries (149 in total) and medical attention frequency according to Ensign et al. [2]. The medical attention frequency refers to the number of persons that answered yes to the question if they sought for medical attention in relation to the number of injured persons that responded to the question.

Anatomical Location	**No. injuries**	**Sought medical attention**	
Head	3	3(3)	(100 %)
Neck and upper back	9	6(9)	(67 %)
Shoulder	21	15(20)	(75 %)
Elbow	2	1(2)	(50 %)
Wrist	1	1(1)	(100 %)
Hand	1	1(1)	(100 %)
Trunk	2	1(1)	(100 %)
Low back	50	40(48)	(83 %)
Hip/Buttocks	6	6(6)	(100 %)
Thigh	2	1(2)	(50 %)
Knee	32	24(32)	(75 %)
Leg	7	5(7)	(71 %)
Ankle	10	9(10)	(90%)
Foot	3	1(2)	(50 %)

According to Table 2.1 it is clear that injuries to the lower back are the most common, accounting for 34% of the total number of reported injuries (149) [2]. This result is consistent with other studies on health effects caused by whole-body vibration and shock exposure, for example Wikström et al [27] and Burström et al [24]. However, the diversity of injuries to different anatomical locations seen in Table 2.1 shows that HSC crews are exposed to a great variety of health risks. Not only the location, but also the type of injury varies. According to Ensign et al. [2], the most common type of injuries were sprain/strain (46 %), trauma (7 %), disc problems (7 %), dislocation/separation (6 %), stress fracture (5 %) and chronic pain (5 %). The study gives no details regarding what injury type is the most common for each anatomical location.

In addition to the acute and chronic injuries found in Ensign et al [2], symptoms such as headache and tiredness have been reported to be common in connection to duty among HSC operators, for instance within the Swedish Coastguard [7]. Several studies also show that high-speed craft transits can result in reduced physical capacity, muscle damage and fatigue [8, 22]. In Myers et al [8], the physiological consequences of a three hours high-speed boat transit were investigated. It was found that the occupants' physical performance, assessed by a number of performance tests such as exhaustive shuttle-run, handgrip, vertical-jump and push-up, were reduced after the transit. In addition, the creatine kinase activity was increased, which is an indication of muscle damage [8]. Stevens and Parsons [26] refer to tests performed on a ship motion simulator from which it was found that the maximum capacity for oxygen for an individual was significantly reduced when performing physical excercises on the moving platform, compared to when the tasks were performed in a stationary motion simulator.

Although muscle damage and fatigue are probably consequences of muscle contractions following when occupants try to compensate for and attenuate the mechanical shocks they are exposed to [8, 28], acceleration exposure is not necessarily the only reason to the health effects associated with HSC operation. Fatigue for example, can be both physical and mental, although Stevens and Parsons [26] suggest that mental fatigue is a manifestation of physical fatigue. Still, it is reasonable to believe that some health effects (e.g. tiredness and headache) may be a result of mental fatigue caused for example by demanding tasks such as high-speed navigation or navigation at night, as well as a result of physical fatigue caused by whole-body vibration and shock exposure.

To conclude, there is limited statistical data of the prevalence of injuries among HSC operators available. More data are needed in order to enable appropriate risk mitigation. To understand the risks of injuries among HSC operators, it is essential to study also other health effects, such as muscle damage and fatigue. These are factors that most likely increase the probabilities of both acute and chronic injuries, if the exposure to vibration and shock continues.

3 Modelling the acceleration exposure of HSC crews

Predicting the crew's acceleration exposure is fundamental to enable improvement of working conditions onboard HSC. However, stochastic waves and constantly varying boat speed and heading make the prediction difficult. To predict the acceleration exposure, these random conditions need to be identified and described. In addition, acceleration time series need to be collected either through experimental measurements or numerical modelling. Since experimental data acquisition is time consuming and restricted to existing vessels, numerical methods are desirable, especially in a design or planning process. Numerical modelling facilitates evaluation of various operational situations, such as different seat configurations, sea states and craft designs.

Previously, several authors have presented work on modelling of planing craft in waves, for example [29, 30, 31, 32]. By combining one of these models with a numerical seat model, the crew's acceleration exposure can be predicted and later evaluated. This approach can be utilized to evaluate an existing working situation on a HSC. It can also be used to determine an adequate crew exposure profile, in order to minimize the risks for adverse health effects for the crew on a particular craft with a given operational profile.

In Paper A [3] a seat model is introduced and validated using full-scale experiment data. The seat model is also included in Paper B [4], as part of a simulation-based approach for assessment of working conditions on

HSC. The following sections elaborate further on what is needed to predict and evaluate working conditions on HSC using numerical methods.

3.1 Modelling the seat response

Although the configuration of various HSC suspension seats may differ (see Chapter 1, Section 1.4), they can usually be described mechanically using a combination of springs, masses and dampers as illustrated in Figure 3.1. Numerically, the equation of motion for a single degree-of-freedom (DOF) system as in Figure 3.1 is given by

$$m\ddot{z} + c\dot{z} + kz = F \tag{3.1}$$

where m is the mass, c is the damping coefficient, k is the spring stiffness coefficient and F is the external forces. For a suspension seat, m is the mass of those parts of the seat that move relative to the seat base, whereas k and c describe the seat's spring stiffness and damping, respectively.

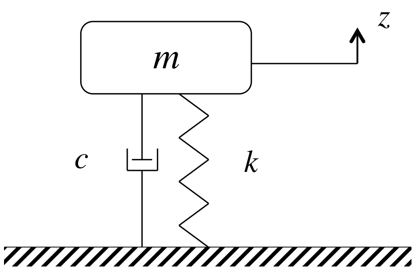

Figure 3.1: Single degree-of-freedom mass-spring-damper system.

Depending on the application (and purpose of the analysis) different degrees of complexities of the seat model may be required. A wide range of models is therefore found in previous research; from single DOF systems to more refined models including end-stop units [33, 34, 35, 36]. Although a number of studies on seat modelling have been performed for the application of marine, high-speed craft [28, 37, 38], most of the published studies are applied to on-land vehicles [34, 35, 36], for which the acceleration exposures differ significantly from those of HSC.

In Cripps et al [28], an improved seat design for a high-speed rescue craft using a single DOF seat and human interaction model is proposed. A similar model, but for three directions, is used in Coe et al [37] to study seat isolation system designs for use on HSC. Both these studies focus on seat modelling as a tool to investigate the influence of seat parameters on human acceleration exposure. In Paper A [3], however, the presented seat model aims for prediction and evaluation of HSC crew working conditions and experimental full-scale acceleration data are used to validate the model. A further description of the seat-human interaction model is given in Section 3.3.

3.2 Modelling the human response

Human response to acceleration plays a significant role in seat modelling since the human body is flexible and therefore interacts with the seat when excited. The feedback from the human body varies with frequency and can be described by the mechanical impedance of the human body, which is also called the *apparent mass*, defined as

$$M(f) = \frac{F(f)}{a(f)} \tag{3.2}$$

where $F(f)$ is the excitation force and a the seat acceleration. The apparent mass at zero frequency, $M(0)$, corresponds to the static weight on the seat. Griffin [23] exposed 60 seated humans to vertical vibration of frequencies between 0.5 and 20 Hz and found that the apparent mass, $M(f)$, varies greatly between individuals. However, he also found that the normalized apparent mass, $M(f)/M(0)$, vary considerably less between individuals and can be well predicted by a lumped parameter model as the one illustrated in Figure 3.2. Figure 3.3 shows the normalized apparent mass obtained with a model as the one in Figure 3.2. For a detailed description of how to calculate the apparent mass, see Paper A[1] [3].

[1]Figure 3.3 is the correct graph for the normalized apparent mass as proposed by Griffin. In Paper A [3] the corresponding figure is unfortunately errenous with resonance at 5 Hz.

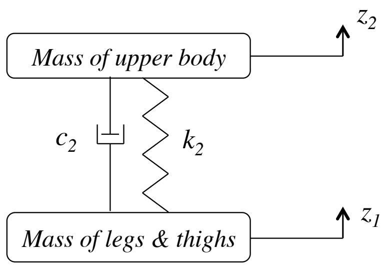

Figure 3.2: According to Griffin [23], the normalized apparent mass for a seated human exposed to vertical vibration ($0.5 < f < 20$Hz) can be well predicted by a mass-spring damper system as displayed.

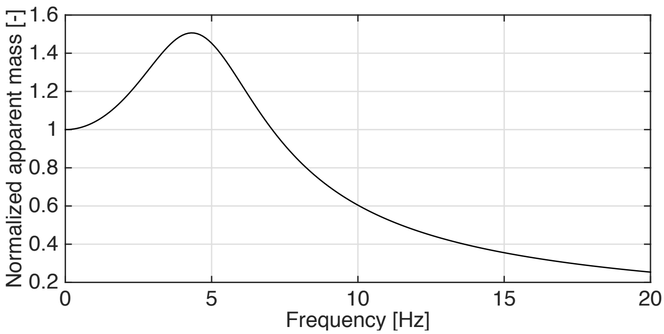

Figure 3.3: Normalized apparent mass for a single DOF system, determined according to the procedure described in Paper A [3]. The resonance frequency is 4.3 Hz.

3.3 Seat and human interaction model for HSC

Several authors have utilized the findings of Griffin [23] to define a numerical seat and human interaction model [3, 28, 37], but validation with experimental, shock-dominated HSC acceleration data is only provided in Paper A [3]. The seat model as of Paper A [3] is displayed in Figure 3.4 and the input data that need to be defined by the user are shown in Table 3.1.

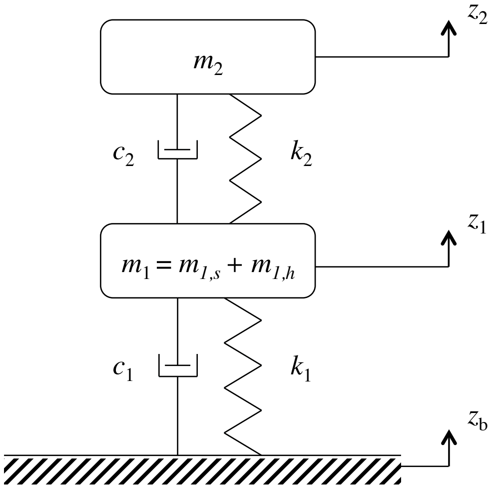

Figure 3.4: Seat model presented in Paper A [3].

Table 3.1: Seat model input defined by user.

m_h	Human body mass	kg
$m_{1,s}$	Seat mass (moving parts)	kg
c_1	Seat damping coefficient	Ns/m
k_1	Seat spring stiffness coefficient	N/m
$\ddot{z}_b(t)$	Seat base acceleration time series	m/s^2

As seen in Table 3.1, the only input required to obtain time series of the seat response, except from the exciting acceleration (which can be either measured or simulated), are the mass of the moving parts of the seat, the seat's spring stiffness and damping coefficients and the total mass of the seated person. Based on these data, the seat model calculates the upper body mass m_2 as well as the spring stiffness k_2 and damping coefficient c_2 of the human response model based on the Griffin normalized apparent mass curve. The following assumptions are made:

- The normalized apparent mass transfer function is constant for all human bodies and can be approximated by a single DOF system as previously displayed in Figure 3.2 (see [23])
- The apparent mass for a seated human is linear with respect to vibration magnitude and has a resonance frequency at 5 Hz (see [39, 40])
- The mass of the upper body, thighs and legs (including the feet) is 72%, 18% and 10% of the total body mass respectively (i.e. $m_2 = 0.72m_h$ and $m_{1,h} = 0.18m_h$) (see [3])
- The thighs move with the seat and thus the mass of the thighs can be added to the mass of the seat, m_1, in the lumped parameter model (see [3])
- The feet are supported on a footrest and the total mass of the legs and the feet can therefore be neglected as they do not influence the seat or human response (see [3, 23])

The assumption that the normalized apparent mass of a seated human is well represented by a single DOF system enables the spring stiffness and damping coefficients c_2 and k_2 to be calculated for various human body masses (see Paper A [3] for further details). However, it should be noted that the spring stiffness and damping coefficients, c_2 and k_2, as well as the z_2 degree-of-freedom have no clear physical interpretation. The model representing the human body is a "construction" with the purpose of reproducing similar feedback to the seat model as the seated human gives to the seat in reality. Concluding, the purpose of the human representation is to achieve time series of the seat acceleration ($\ddot{z}_1$) that accurately describe the working environment onboard HSC and that can be used for further evaluation.

Validation of the seat model in Paper A [3] is performed using acceleration time series collected during sea trials of a 10-meters HSC, which was equipped with high-standard suspension seats for which data in terms of mass, spring stiffness and damping coefficients were provided by the manufacturer. Also the coxswain's mass, occupying the instrumented seat, was known. The seat acceleration were measured using a 3-axial seat pad mounted accelerometer and the craft acceleration by accelerometers mounted on two bulkheads (for further details, see [3, 7]). Data from the latter two measurement points were used to calculate the seat base acceleration, using linear interpolation. A representative example from the validation is displayed in Figure 3.5, where the measured seat acceleration is compared with the seat acceleration generated by the seat model, when fed by experimental (interpolated) seat base acceleration. As can be seen, the acceleration passed through the seat model correlates well with the measured seat acceleration, although the peak values are generally higher for the measured signal.

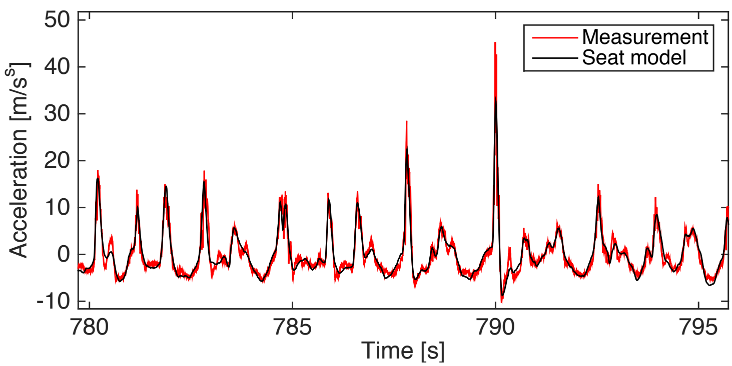

Figure 3.5: Measured and predicted (using seat model) seat acceleration.

The lumped parameter apparent mass model is of course a simplification and a generalisation of the seated human body. Parameters such as body composition (physique), posture and eventual use of arm or back rests influence the apparent mass, but are not considered here. Despite this, the single DOF model (which parameters are set based on the total human weight) appears to have a sufficient level of detail for the purposes of the present work. The lumped parameter model describing the seat seems to be sufficient as well. Nevertheless, there is potential in developing the model to capture the effect of bottoming-out events. Currently, the risk for bottoming-out is determined by studying the time series for the seat displacement generated by the model, and by identifying eventual time instants where the displacement exceeds the available motion stroke of the seat. This is a reasonable approach since the ambition should be to completely eliminate the risk for such events in order to ensure safety for the occupant.

Concluding, connecting two single DOF systems in series allows the seat acceleration to be repeated with good accuracy when the system is excited by shock-dominating acceleration. The proposed model, with one mass-spring-damper system each to describe the seat and the human responses, seems to have a sufficient level of detail to generate acceleration time series that agree well with experimental data. The current model is defined for the vertical direction since vertical accelerations are clearly dominating on HSC [3, 7, 10, 41, 42]. However, if future investigations show that acceleration in several directions have significant influence on human health, comfort and performance, the model can be expanded to several degrees-of-freedom (as in Coe et al [37]) in order to enable design and evaluation of more complex mitigation systems.

3.4 Crew and craft exposure profile

Defining a craft's operational profile is crucial in order to properly describe and evaluate the loads acting both on the human and on the craft. Nevertheless, the task is not straight-forward, as high-speed craft operation is highly non-homogeneous and associated with random variations of sea state, loading condition, heading and forward speed. In addition, the knowledge about the craft's actual operation is very often limited and would benefit from further research.

In Paper B [4], a simplified but nevertheless useful approach is proposed to tackle the difficulty of evaluating the acceleration exposure when the conditions are stochastic and constantly changing. A simulation-scheme in three steps is presented (see also Chapter 1) and used to evaluate two different seat configurations and two load cases with respect to crew working conditions. A set of operational conditions is defined as a number of combinations of speeds and sea states. These combinations form the basis for the craft operational profile, defined as a percentage of the total operational time spent in each of these conditions, as illustrated in Figure 3.6. The crew exposure profile is defined as percentage of the day spent in each condition, resulting in a characteristic day of exposure. By generating acceleration time series for the craft and coxswain seat, based on the conditions in the operational profile, working conditions can be evaluated with respect to a characteristic daily dose. The long-term evaluation is performed based on a number of characteristic days a year and number of years in service.

		Sea state		
Speed	Calm	Mod.	Severe	
High	12%	6%	2%	**20%**
Med	30%	15%	5%	**50%**
Low	18%	9%	3%	**30%**
	60%	**30%**	**10%**	

Figure 3.6: Example of operational profile. The sea state is divided into three categories; calm, moderate and severe. Similarly, three speed regimes are defined; low, medium and high speed.

The generalized operational profile in Paper B [4] and Figure 3.6 describes a craft's operation in a lifetime perspective, using a limited number of operational conditions, and for craft simulated in head seas only. Although this is a simplification of reality, the approach is useful from many aspects. For example, operation in head seas is known to cause the most severe acceleration impacts [42], which is relevant when evaluating loads on craft and human (even though loads in other directions should not be considered as unimportant). Furthermore, by defining the craft operational profile (and the crew exposure profile) with respect to a limited number of conditions, a collection of time series can be generated for each craft and/or seat design and used in many analyses. That means, as soon as a set of craft and seat acceleration time series once is established, different seat designs, craft operational profiles or crew exposure profiles can be evaluated without generating or collecting new data. In addition, the resolution of the exposure profile can easily be varied in order to suite the current analysis by refining the condition matrix in Figure 3.6. This is an important aspect, as the level of details required depends on the purpose of the analysis. For the naval architect, who is interested in determining the design loads, the most severe condition(s) that the craft will be operated in is of primary interest. For the employer or seat designer on the other hand, who aims for minimizing the health risks for the crew, a more detailed exposure profile may be relevant. For example, severe injuries may not only be the result of a single heavy impact; a wide range of injury types and health risks also arise from accumulated vibration and shock exposure (see further Chapter 4). In addition, it may be of interest to include details such as posture (standing or sitting) and pattern of work (day or night shift), when evaluating a crew's exposure to WBV and shock.

4 Evaluation of whole-body vibration and shock exposure

There are at least two important factors deciding whether the risk for injuries can be determined appropriately or not. Firstly, the evaluation methods must be defined in a stringent way so that the entire procedure, from data acquisition to post processing and interpretation of result, can be repeated regardless of where or by who the analysis is performed. As will be seen later in this chapter and in Paper C [5], this is one of the disadvantages with many of the statistical measures being used to date. Secondly, to express the risk for human injuries, the evaluation measures must be related to human endurance. Furthermore, it is important to note that acute and chronic injuries can be the result of a single, severe high-acceleration event or a large quantity of smaller acceleration events, as well as a result of long-term exposure. Therefore, these different types of exposures must be evaluated separately, and probably with a set of different methods.

In the following sections, the evaluation methods that are available to date are presented, and their pros and cons discussed.

4.1 Measures in international standards

To date, the most common methods to assess the risk of adverse health effects are those defined in the International Standards ISO 2631-1 [43] and ISO 2631-5 [44], not least since EU legislation refers to these standards. Similar methods are used in the British Standard BS 6481-1987 [45]. In the EU Directive 2002/44/EG [21], action and limit values are stated with reference to the root mean square (RMS) value and the vibration dose value (VDV) defined in ISO 2631-1 [43] as

$$RMS = \left\{ \frac{1}{T} \int_0^T [a_w(t)]^2 \, \mathrm{d}t \right\}^{1/2} \qquad [\mathrm{m/s^2}] \tag{4.1}$$

$$VDV = \left\{ \int_0^T [a_w(t)]^4 \, \mathrm{d}t \right\}^{1/4} \qquad [\mathrm{m/s^{1.75}}] \tag{4.2}$$

but evaluated for an 8-hour time period

$$RMS(8h) = RMS(T) \cdot \left[\frac{8}{T} \right]^{1/2} \tag{4.3}$$

$$VDV(8h) = VDV(T) \cdot \left[\frac{8}{T} \right]^{1/4} \tag{4.4}$$

where $a_w(t)$ is the frequency weighted acceleration signal and T is the measurement time period. Since the RMS value porly displays the effect of shock in an acceleration signal, the VDV has been defined for signals having a significant shock content and should be used if the *crest factor*, defined as the maximum instantaneous peak value of the signal divided by its RMS value, exceeds a value of 9. The VDV is commonly used within the HSC community.

The EU directive 2002/44/EG [21] states that the employer must *take immediate action* to reduce the acceleration levels if the daily exposure, $VDV(8h)$, exceeds the limit value (21 $\mathrm{m/s^{1.75}}$) and *take action* to reduce the acceleration to as low as reasonably possible if the action value (9.1 $\mathrm{m/s^{1.75}}$) is exceeded. However, there is an exception for the legislated limit value that applies for sea transport. The background to this exception is that the methods of ISO 2631-1 [43] initially were developed for evaluation of whole-body vibration under homogeneous conditions. Therefore, the applicability of these methods and limits when evaluating impact dominating, non-homogeneous exposures may be dubious. Within the HSC forum, the ISO 2631-1 methods are therefore sometimes criticized to be inadequate. The scepticism can be understood, as the legislated limit value is often exceeded only after tens of minutes of high speed operation [7, 46]. Of course, the crew of high-speed craft can, and do, operate the craft for much longer time periods.

Scepticism is also directed to the action and limit values because they are based on subjectively determined comfort criteria for human exposed to vibration. Although pain and discomfort are generally considered as indicators of prevailing health risks, i.e. *"if it feels bad, it probably is bad"*, the link between discomfort and risk for injuries is not obvious [23, 47]. Mansfield [9] explains that the physiological receptors adressing pain or discomfort when exposed to WBV, not necessarily are located where injury may occur. Nevertheless, there is no doubt that the acceleration levels on HSC can be severe. Thus, it is not obvious that a higher limit value should apply for HSC, even though the legislated levels may not be perfectly tuned for non-homogenous, peak dominating acceleration exposures.

Before criticising any measures it is relevant to reflect on what the purpose of the analysis is. Perhaps is the VDV measure itself not the problem, but rather the interpretation of its magnitude. In Annex B of ISO 2631-1 [43], *Guide to the effects of vibration on health*, it is stated that since there are not sufficient data to show a quantitative relationship between vibration exposure and risk of adverse health effects, it is not possible to assess whole-body vibration in terms of the probability of risk at various exposure magnitudes and durations. Nevertheless, VDV captures the effects of both vibration and shock [4, 7], which is relevant when evaluating acceleration exposures on HSC, which contain both types. As pointed out in the beginning of this chapter, different types of exposures and health problems may require different evaluation methods. Since VDV is formulated as a daily dose measure and the relation between dose and health effects is not yet clear, it is considered as a useful comparative measure for short-term analyses. However, for assessement of the risk for acute injuries, additional methods are needed.

As discussed in Chapter 2, one of the most common health problems for people exposed to high acceleration events is injuries to the lumbar spine [2]. In order to enable estimation of the risk for adverse health effects due to such injuries, the ISO 2631-5 [44] method has been developed. In contrast to the ISO 2631-1 [43] method, which considers only daily exposure, the ISO 2631-5 [44] method also has a long-term perspective. This is achieved by accounting for the number of days and years an employee is exposed to vibration of a daily equivalent static compression dose S_{ed}. The S_{ed} is calculated using a lumbar spine model, which considers the ultimate strength of the lumbar spine and thus also adds a link to human endurance to the analysis. From the dose S_{ed} the risk factor R, which indicates if the risk for an injury to the lumbar spine is high or low, can be calculated as function of years of duty.

It should be noted that the lumbar spine model included in the standard ISO2631-5 [44] is applicable only for peak acceleration up to 40 m/s^2 [44, 48], a level that is routinely exceeded on small high-speed craft. It is of course highly desirable to develop the method to be valid also for larger acceleration levels. The American standard ASTMF1166-07 has, based on Peterson et al [19], defined a maximum limit for the $S_{ed}(8)$ (4.7 MPa) below which the probability of risk for adverse health effects can be considered as low for exposures where "impacts routinely exceed 4 Gs". However, as stated by Bass et al [48], the neural network dynamics model in ISO 2631-5 should clearly not be used outside its range of applicability. Therefore, the authors present a refined human response model that is validated with experimental data from sea trials and can be used for acceleration exposures up to 14 g.

Except from being valid only up to 4 g with the present lumbar spine model, the ISO 2631-5 evaluation method is considered as promising for evaluation of risks for long-term adverse health effects on HSC [7, 19]. Concluding, there is relevance in the standardized ISO 2631 methods, but the purpose of the analysis must be carefully considered before any measure is applied. The ability of VDV to predict the risk for injuries is dubious, but can be useful as a comparative measure, which also S_{ed} can. Perhaps, the ISO 2631-1 with corresponding evaluation limits can be linked to exposure duration and magnitude variations in order to be better suited for sea transport, where the conditions vary over time. In addition, the procedures from data collection (or simulation) to interpretation of the result must be unified and clearly defined.

4.2 Statistical measures

When aiming to determine the most severe loads that the crew is subjected to, which may be of interest in the ship design process for example, a statistical measure is preferable. The measure should typically describe the peaks in terms of quantity and magnitude, in order to be useful for injury risk assessment. It is also advantageous to express the measure in units of m/s^2 or 'g', since these units are communicated more easily than for instance VDV, which is expressed in the non-intuitive unit $m/s^{1.75}$. Finally, as highlighted in the beginning of this chapter, it is crucial that evaluation measures are clearly defined, so that the outcome of the analysis does not rely on the analyst's judgement.

Historically, a number of attempts to formulate a single-figure statistical measure for quantification of acceleration exposures with significant shock content have been made. For example, peak fraction averages such as the average of the 1/10th or 1/100th largest acceleration peak values ($a_{1/10}$ and $a_{1/100}$) are common in structural design but have also been used to evaluate ride comfort, for example by Riley et al [49]. A similar approach is the Impact Count Index, proposed by Dobbins et al [50]. However, these measures give no information regarding the top magnitudes or statistical distribution of peak values. Neither are they defined with respect to sample duration nor the number of peaks included in the analysis. This makes the results ambiguous and difficult to interpret and reduces the possibilities to successfully compare results. As an example, consider the acceleration signal in Figure 4.1. The acceleration sample was measured on the HSC unit of the Swedish Coast Guard displayed in the same figure.

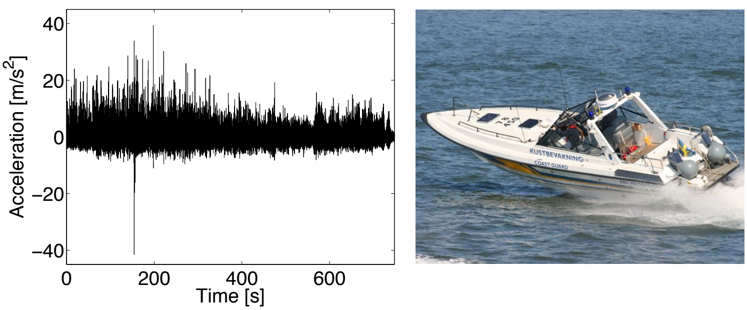

Figure 4.1: Acceleration signal measured upon the coxswain seat onboard the 10 meters HSC shown in the figure. Photo: Jonas Andersson, The Swedish Coastguard.

In order to calculate fractional peak value averages, the peak values of the acceleration signal must first be identified. In this example, the predefined Matlab command *findpeaks* is used, with an acceleration threshold equal to the standard deviation of the signal and a minimum peak distance equal to 0.85 times the sampling frequency, which was 800 Hz. The result is 630 identified peaks. By sorting these peaks in order of magnitude, the cumulative distribution of the observed data can be drawn; see Figure 4.2.

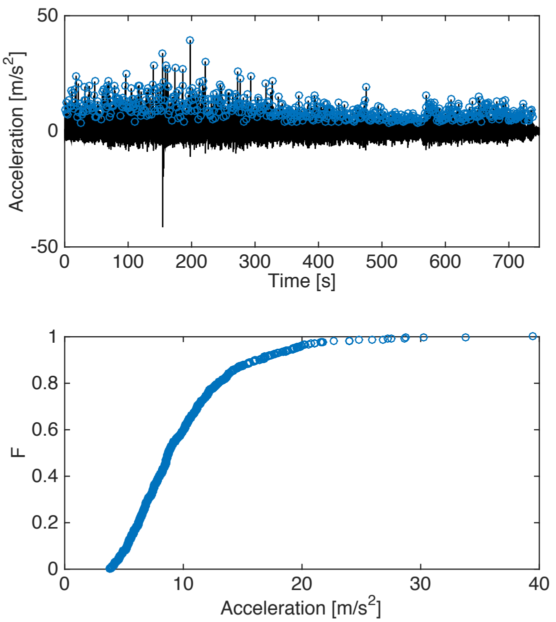

Figure 4.2: Acceleration signal with 630 identified peaks and the corresponding empirical cumulative distribution.

The $1/N$th fractional peak value average is then calculated as the mean value of the $1/N$ largest peaks in the collection. Thus, in this particular case, the $a_{1/10}$ and $a_{1/100}$ is the mean value of the largest 63 and the largest 6 peaks respectively, which is 20.6 m/s^2 and 30.8 m/s^2. The accuracy of a measure such as $a_{1/100}$, calculated based on only 6 points, is of course doubtful. To be accurate, a significantly larger amount of peaks is needed. In addition, the peak value averages do not capture any effects of variations in the signal. As an example, consider the acceleration signal in Figure 4.1 again. As seen, the magnitude is on average higher in the first half of the signal. However, if the second half of the signal had the same level as the first, as illustrated in Figure 4.3, the number of identified peaks would have been 620 and the peak fraction averages $a_{1/10}$ and $a_{1/100}$ would have been 23.5 m/s^2 and 33.7 m/s^2. Thus the difference between the two signals in Figure 4.2 and Figure 4.3 is very small if the $a_{1/10}$ and $a_{1/100}$ are considered. However, any crew exposed to the two signals would most likely experience the accelration of Figure 4.3 more severe than the acceleration of Figure 4.2. Hence, it is clear that the acceleration peak fraction average gives information neither regarding the largest peak value in the data collection, nor the quantity and magnitude (i.e. the statistical distribution) of large peaks; information that is of particular interest when assessing loads that the craft or human are subjected to.

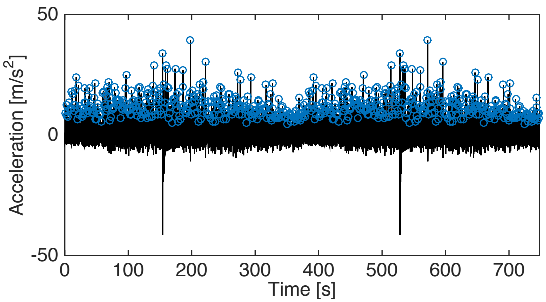

Figure 4.3: Acceleration signal with 620 identified peaks.

A powerful method when searching for the largest loads that the crew will be subjected to during a certain exposure time period, is to fit a statistical distribution to the empirical collection of peak values. This enables extreme values such as the most probable largest value during X hours or the largest value to be exceeded within 1% of probability to be determined, even for a time period longer than for the available data set (extrapolated extreme values). The accuracy of the calculated extreme value will naturally depend on the accuracy of the fitting. The selection of distribution function is therefore critical. In addition, decisions related to the collection and processing of acceleration data, e.g. sampling rate and duration, filtering and peak identification, influence the final result.

When analysing acceleration of planing high-speed craft, the procedure of determining extreme values is not obvious. HSC acceleration impacts are caused by different physical mechanisms and generally belong to several statistical distributions. To perform an analysis of good accuracy, these mechanisms must be understood. In Paper C [5], an extensive amount of simulated craft acceleration time series for systematically varied speeds and sea states are investigated in order to improve the understanding of the complex acceleration process that high-speed craft operation is associated with. The investigations result in important conclusions regarding sample size, sampling rate, filtering and peak identification. For example, it is concluded that low-pass filtering below 20 Hz will adversely affect the results; see Figure 4.4 where the effect of low-pass filtering with cut-off frequency 20 Hz and 10 Hz is illustrated.

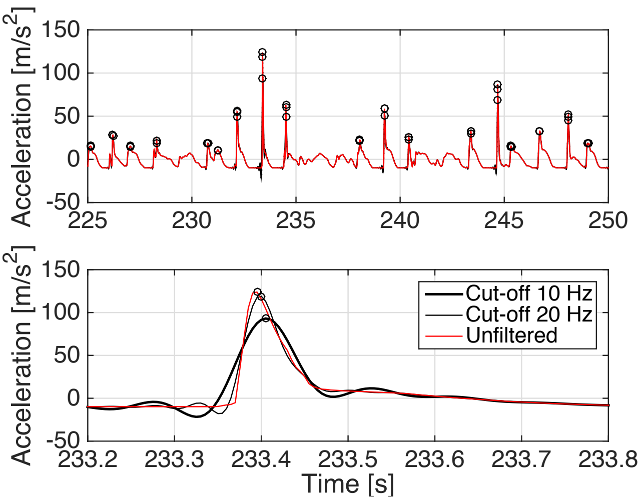

Figure 4.4: Illustration of the effect of low-pass filtering with cut-off frequency 10 Hz and 20 Hz, using a Butterworth filter of 8th order. The studied acceleration signal corresponds to a 10.5 meter high-speed combat boat of 6500 kg, simulated at constant speed (21.7 m/s) in rough sea (1.0 m significant wave height and 3.58 s wave period). The peak fraction average $a_{1/100}$ for the three signals are: 96.5 m/s^2 (unfiltered), 93.4 m/s^2 (cut-off 20 Hz) and 75.3 m/s^2 (cut-off 10 Hz).

The paper also presents two stringently defined methods for determination of extreme values. A Weibull and a Generalized Pareto distribution are fitted to the empirical data set using automated fitting threshold selections. Both two methods work well and enable analysis of large data sets with good reproducibility and almost completely removes subjective analyst judgement. An overview of these methods are given in the following section. Further details are found in Paper C [5].

4.2.1 Extreme value predictions using the Weibull and Generalized Pareto Distributions

According to Ochi [51] the short-term cumulative distribution function for a sample of independent and identically distributed data, $F(x)$, is related to the cumulative distribution of the extreme values, $F_e(x)$, as

$$F_e(x) = F^n(x) \tag{4.5}$$

where n is the number of identified peaks and related to the exposure time T. The probability α that an extreme load X_e exceeds a certain value of x can then be formulated as

$$P(X_e > x) = \alpha = 1 - F(x)^n \tag{4.6}$$

Using Taylor expansion and assuming $\alpha << 1$, Equation 4.6 can be expressed as

$$1 - F(x) = \frac{\alpha}{n} \tag{4.7}$$

Ochi [51] also shows that the most probable largest value (MPL) for a sample of independent and identically distributed data can be estimated by solving

$$1 - F(x) = \frac{1}{n} \tag{4.8}$$

given that n is large. Consequently, the extreme value with a certain probability of being exceeded as well as the MPL value can be calculated if the cumulative distribution function for the short-term responses can be determined.

When aiming for extreme value predictions, modelling of the largest values, i.e. the tail of the distribution, is of particular interest. This is typically done by fitting all values above a certain threshold, in this text referred to as the fitting threshold, to a given family of distributions. According to the extreme value theorem (Fisher & Tippett [52], Gnedenko [53]), the maximum of a sample of independent and identically distributed variables can only converge to one of the three Generalized Extreme Value (GEV) distributions; the Gumbel, Fréchet or Weibull distribution. For high-speed craft responses the preferred distribution has been the Weibull distribution (see e.g. [42, 54, 55]), which cumulative distribution function is given by

$$F(x) = 1 - \mathrm{e}^{(-x/a)^b} \tag{4.9}$$

where a and b is the scale and shape parameter respectively.

The choice for the Generalized Pareto Distribution (GPD) in Paper C [5] derives from the peak over threshold method (POT). The POT-method is based on Pickand's theorem, stating that if the parent distribution $F(x)$ is in the domain of attraction of one of the GEV distributions, the distribution of peaks exceeding a threshold, i.e. the conditional excess distribution function, is well approximated by the Generalized Pareto Distribution if the threshold is high enough. The cumulative GPD is given by

$$G(x;c,\lambda) = \begin{cases} 1-(1+cx/\lambda)^{-1/c} & \text{if } c \neq 0 \\ 1-e^{x/\lambda} & \text{if } c = 0 \end{cases} \tag{4.10}$$

where c and λ is the shape and scale parameter, respectively. The distribution of the tail of $F(x)$ is given by $G(x;c,\lambda)$ if

$$F_u(x) = \frac{F(x) - F(u_{gpd})}{1 - F(u_{gpd})}, \qquad x > u_{gpd} \quad \text{and} \quad u_{gpd} \to \infty \tag{4.11}$$

where u_{gpd} is the fitting threshold. By rewriting Equation 4.11 the unknown CDF can be expressed as

$$F(x) = F_u(x)(1 - F(u_{gpd})) + F(u_{gpd}) \tag{4.12}$$

A large benefit of the POT method is that the mathematical properties of the GPD can be used to guide the threshold selection. These properties are used to formulate an automated threshold selection algorithm in Paper C [5] and listed below.

Properties of GPD
Given that the sampled peak values follow a Generalized Pareto Distribution, for increasing threshold u_{gpd}

- the shape parameter remains constant,
- the scale parameter develops linearly as a function of u_{gpd}, and
- the mean of the peaks above the threshold u_{gpd} develops linearly with a slope of $c/(1-c)$.

No similar properties exist for the Weibull distribution, which explains the difficulty of selecting an appropriate fitting threshold when using the Weibull approach. In Paper C [5], an automated algorithm is defined by formulating an optimization problem that minimizes the $1-R^2$ statistic. Both the Weibull and GPD approach result in good fits of the distributions to the observed data and predict the extreme values well. The GPD approach, however, requires larger samples in order to achieve the same level of uncertainty as the Weibull approach. It is concluded that sample durations of 1200 s is required for convergence of the most probable extreme values, based on the studied conditions.

Figure 4.5 shows the most probable largest values (MPL) based on the POT method and the Weibull approach compared with the acceleration peak value averages $a_{1/10}$ and $a_{1/100}$. Also the influence of the threshold selection for the peak identification is illustrated, with the standard deviation of the signal as starting point, as suggested by Riley et al [56]. As can be seen, the average of the 1/10th and 1/100th largest acceleration peak values are significantly lower than the MPL values. Based on the data set in Paper C [5], it is concluded that the relation between the extreme values and the peak fraction averages is consistent for all conditions. This is important since it makes this type of measure less ambiguous. The fact that the acceleration peak fraction averages converge fast and are straight-forward in their derivation makes the measures powerful for instance in ship design, despite the discussed weaknesses related to the measure. However, as seen in Figure 4.5, the acceleration peak fraction averages is strongly related on the peak identification threshold. This implies that a common standard for the peak identification procedure, as suggested by Riley et al [56], is a prerequisite. Finally, to be suitable for evaluation of risk for injuries, the measures have to be related to the human endurance and to exposure duration.

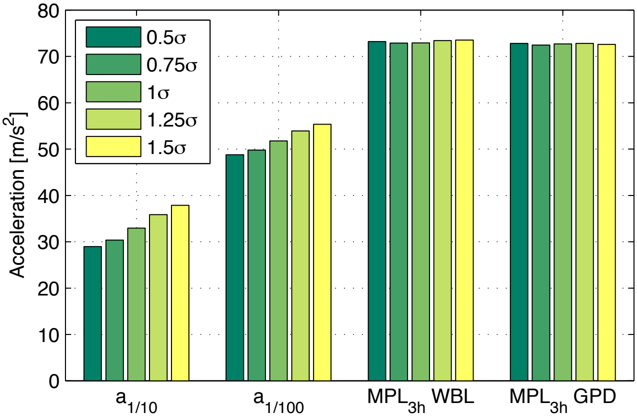

Figure 4.5: Peak fraction averages ($a_{a/10}$ and $a_{a/100}$) and extreme values (MPL_{3h}) based on Weibull and GPD approach. The acceleration threshold used for peak identification is varied between 0.5σ and 1.5σ, where σ is the standard deviation of the acceleration.

5 Risk analysis based on injury statistics

This chapter elaborates on a concept, i.e. not a complete method, for an alternative approach to estimate risks for adverse health effects among the crew of high-speed boats. The approach is based on injury (health problem) statistics, and may become a useful complement to simulation-based assessment of working conditions. Evaluating working conditions using statistical data has the advantage of actually enabling *risks* to be determined. As discussed in Section 4.1, there is yet no quantitative relationship between vibration exposure and risk of adverse health effects. The following approach may therefore be of particular interest in organizational planning, e.g. when aiming to identify, reduce and/or eliminate potential health risks.

5.1 Preliminary Hazard Analysis

Risk analysis is a concept used within a large variety of fields and applications. It can be used to estimate the risk of a failure in a system, project or organization, or to estimate the risk of accidents in a tunnel or at a certain workplace. In such cases, risk is usually defined as a function of the likelihood of an unwanted event to occur and the consequences of the same event. As a first step in the risk analysis process, a Preliminary Hazard Analysis (PHA) can be used (see for example [57]). In principle, the PHA is based on identification of all potential unwanted events in a system, and ranking of the corresponding risks. Risks can be ranked by grading the likelihood and the consequence of each event using a scale from 1-5, for example as in Table 5.1, and calculating the risk as a function of probability and consequence. Note that risk can be mitigated both by reducing the likelihood and the consequences of the unwanded event.

Table 5.1: Grading levels for estimation of probability and consequence of an event.

Probability	**Consequence**
1. Very unlikely	1. Minor
2. Unlikely	2. Moderate
3. Possible	3. Significant
4. Likely	4. Severe
5. Very likely	5. Very severe

The aim of the PHA is to identify the largest risks in a system, in order to find out how to focus the proceeding steps of the analysis and to select appropriate means of controlling or eliminating the risks. According to [57], a PHA should include:

- experience data
- a list of known hazardous events
- measures taken to eliminate/minimize hazardous events
- requirements as a result of identified hazardous events
- recommended countermeasures, in order to eliminate/minimize hazardous events

Here, a simplified PHA is performed in order to illustrate the methodology. Table 5.2 shows an example where a number of injury risks for HSC operators have been ranked using the injury statistics presented in Ensign et al [2] (see also Chapter 2). The risk r is here defined as the product of the estimated probability p and consequence c. As can be seen, the largest risks are found for low back disorders. Based on this knowledge, it is reasonable to proceed the risk analysis with a refined analysis of this particular injury. However, the results also show clearly that the personnel of HSC are exposed to several significant injury risks. The probability of acute and chronic injuries to the head, knees, neck and upper back are for example estimated to be either *very likely* (head, chronic) or *possible* with reference to Table 5.1. Although the consequences of these injuries are perhaps not as severe as an injury to the lower back may be, they are of importance for the safety onboard as they influence the crew's working performance and/or working capacity.

Table 5.2: Ranking of potential injuries for operators of HSC, based on data from [2].

Injury location	**Probability,** p	**Consequence,** c	**Risk,** $p \cdot c$
Knee	3	3	9
Low back	4	5	20
Shoulder	2	3	6
Leg	2	3	6
Head (chronic)	5	2	10
Head (acute)	1	5	5
Neck and upper back	3	3	9

The following section aims to illustrate how the risk analysis can proceed after a first coarse analysis. A refined analysis of the risk for low back injuries is performed using the injury statistics of Ensign et al [2]. The results are compared with those achieved using the methods of ISO 2631-5 [44].

5.2 Risk of low back injuries

The solid line in Figure 5.1 shows the percentage of the participants in the study of Ensign et al [2] that were injured at least once after x years in duty. Out of the 154 participants, only 30 were still working on HSC after six years. This may be an explanation to the decrease in injury occurrence after six years of duty seen in Figure 5.1. Another explanation to this decrease may be increased working experience and habituation, although it is more likely that the occurence of injuries increases in average with the time of duty. The dashed line in Figure 5.1 shows an exponential function fitted to the empirical data of Ensign et al [2]. Based on this curve fitting, the likelihood for a HSC crew member to be injured can be expressed analytically as

$$P_{injury} = 1 - 0.73^{x} \tag{5.1}$$

where x is the number of years in duty.

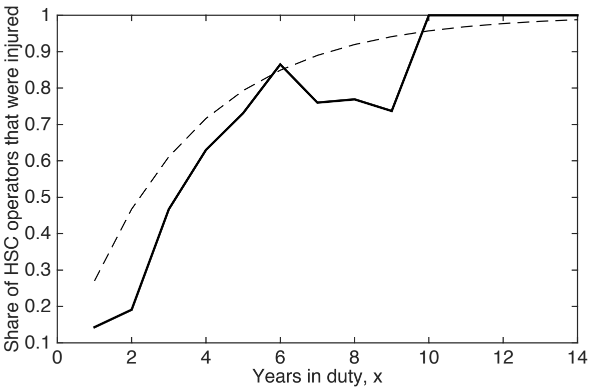

Figure 5.1: Share of HSC operators that were injured at least once as function of years in duty. Statistical injury data (solid line) and analytical estimation (dashed line).

Out of the 149 reported injuries, 33% (50) were low back injuries. Thus, the probability of low back injury can be estimated as

$$P_{lowbackinjury} = 0.33 \cdot P_{injury} \tag{5.2}$$

Among the 149 reported injuries, 11 were of the type *disc problems*. Assuming that all these are connected to the low back (which is not certain), a rough but reasonable estimation is that 20% of the low back injuries are acute and 80% are chronic. Based on this assumption, the risk of acute and chronic lowback injury is given by

$$\begin{aligned} P_{lowbackinjury,acute} &= 0.2 \cdot P_{lowbackinjury} \\ P_{lowbackinjury,chronic} &= 0.8 \cdot P_{lowbackinjury} \end{aligned} \tag{5.3}$$

Figure 5.2 shows the probability of acute and chronic injuries to the low back as function of years in duty, calculated using Equation 5.3. After five years, the probability for an acute injury is 5 %, which must be considered as high risk (since acute injuries to the back have severe consequences).

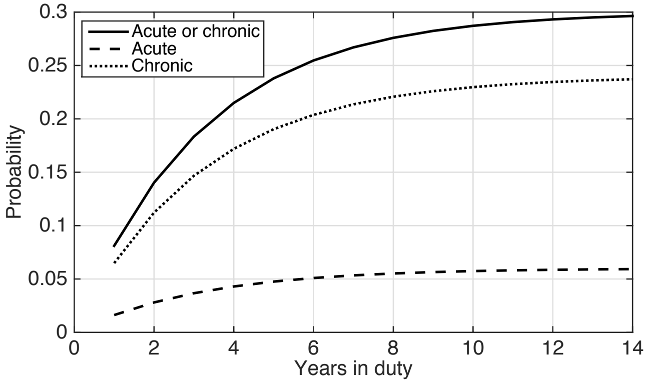

Figure 5.2: Probability of low back injury for personnel on HSC.

For comparison, Figure 5.3 shows the risk factor R defined in ISO 2631-5 [44] for evaluation of risk for acute lumbar spine injury. The R factor is calculated for a person initiating duty at the age of 20 and travelling at 45 knots in relatively rough sea conditions (H_s = 0.65 m, T_z = 3.5 s) 12.5 minutes a day, 45 days a year. 10 combinations of seat configurations and running attitudes are compared (see Paper B [4] for further details).

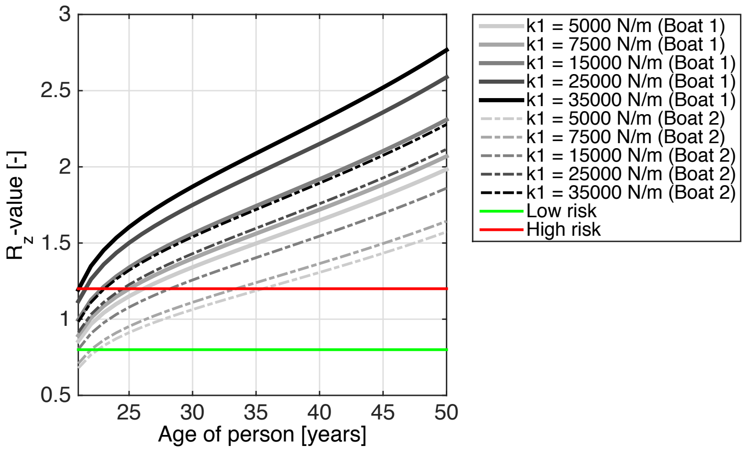

Figure 5.3: Risk of lumbar spine injury according to ISO 2631-5 [44] for a person initiating HSC duty at the age of 20 and travelling at 45 knots in relatively rough sea conditions (H_s = 0.65 m, T_z = 3.5 s) 12.5 minutes a day, 45 days a year. Red line indicates high risk, green line low risk. For further details, see Paper B [4].

As can be seen, the risk for acute injuries to the lumbar spine is high after 1-15 years of duty, depending on load case and seat configuration. Assuming that HSC suspension seats have a spring stiffness coefficient around 25000 N/m (which was the case for the instrumented seat in Paper A [3]), then high risk is reached after only 1-5 years. This result is comparable with the results in Figure 5.2, which indicated a 5 % probability of acute low back injury after 5 years in duty.

In addition to the refined analysis of the risks for lumbar spine injury, a refined consequence analysis may be desirable in order to enable implementation of suitable risk management. For an employer within the field of HSC, it may for instance be of interest to evaluate the probability for sick leave or reduced working performance for the employees, as function of years of duty. Given that the probabilities for these consequences can be estimated, either based on statistics or expert opinion, the likelihood for different consequences can be estimated as function of years of duty using the probability of injury, P_{injury}. However, for health effects or consequences from which *recovery* is possible, for instance through periods of rest, it is not relevant to evaluate for a longer horizon than perhaps a day.

The present chapter illustrates the principles of an alternative approach for evaluation of HSC crews' risks for adverse health effects. The examples given are based on a very limited amount of statistical data, and the reader should rather pay attention to the presented methodology than to the absolute values obtained. The concept of performing risk analysis based on injury statistics can be advantageous and may be a useful complement to the presented simulation-based approach, which requires specification of for example craft operational profile, load case and seat configuration to generate acceleration time series. In addition, the possibility to estimate risks for injuries and adverse health effects based on this acceleration data is currently limited.

To achieve accurate and useful results using the presented risk analysis approach, extensive and adequate statistical data are required. The best results will be achieved if the statistical data are based on the same type of operation as is in question for the HSC system being assessed. Thus, to introduce the risk analysis approach in practice, more statistical data on injuries, health problems (e.g. fatigue, motion sickness) and other consequences (e.g. reduced working performance) are needed.

6 Summary & conclusions

The thesis adresses the need for a simulation-based method for prediction and evaluation of HSC crew acceleration exposure. The main contributions of the work are:

- Development of a numerical seat model validated using full-scale, acceleration data (Paper A [3]).
- Development of a simulation-scheme that enables prediction and evaluation of working conditions on HSC (Paper B [4]).
- Development and evaluation of clearly defined methods for characterization and statistical analysis of the vertical acceleration process for planing HSC (Paper C [5]).
- Recommendations related to the acquisition of acceleration data for HSC, such as sample size, sampling rate and cut-off frequency (Paper C [5]).

6.1 Conclusions

A single-degree of freedom, mechanical seat model, consisting of a seat representation and a representation of the seated human body, can be used to predict the seat acceleration time series with high accuracy. A generalized apparent mass model considering the human body mass but neglecting other variations between individuals appear to be detailed enough to reflect the feedback of the human response to the seat.

Numerous evaluation measures appropriate for HSC acceleration exposures are available. What the most suitable measure is, depends on the purpose of the analysis. For instance, the craft designer may be interested in extreme values, wheras the employer may be more interested in long-term doses. The VDV has the advantage of capturing the effect of both vibration and shock, which is relevant for HSC where the conditions vary over time. The interpretation of the levels, however, is not clear since there is yet no dose-effect relationship linking the measure to the risk for adverse health effects. Nevertheless, VDV is a useful comparative measure and may in the future be better linked to the risk for injuries. To increase the credibility and in order be more appropriate for applications where the exposures vary significantly, the measure with corresponding evaluation limits may possibly be defined with respect to exposure duration.

The S_{ed} measure evaluates the risks of lumbar spine injuries, but is only valid for acceleration levels up to 4 g. However, with reference to ongoing research, the method is expected to be developed for higher acceleration levels in a quite near future. In addition to S_{ed}, extreme values predicted using e.g. the Weibull or Generalized Pareto distribution is likely to be useful for evaluation of risk for acute injuries, given that human endurance can be linked to the measures. The two alternative approaches proposed in Paper C [5] are clearly defined and describe the distribution of peak values well. In addition, the dependence on analyst judgement is reduced. Since the methods are applicable when evaluating loads on both human and hull structure, they are particularly suitable when aiming to introduce human factors in HSC design. Extreme values can also be used in requirement specification or to describe the performance of e.g. a HSC or a suspension seat.

The accuracy of the results of the evaluation of crew acceleration exposure is strongly dependent on the accuracy of the operational profile. A realistic, although generalized, operational profile enables determination of efficient and suitable craft designs, mitigation systems and operational actions. To properly specify the operational profile, good knowledge of how HSC actually is operated is necessary; however, this knowledge is today often lacking.

Introducing a simplified approach for evaluation of working conditions based on traditional risk analysis methodologies and injury statistics may be useful as a complement to the simulation-based approach. Risk analysis based on injury statistics can be performed without defining details regarding e.g. craft design or operational profile, but naturally requires statistical data of health problems among HSC personnel. To date, there is not sufficient data for such an approach to be useful, but as soon as more data are available, the approach may be useful to help focusing future actions to improve working conditions and to develop appropriate assessment methods. As the crew of HSC may experience health problems caused by vibration and shock as well as other factors eventually causing physical or mental fatigue (e.g. navigation at night), it is recommended that the prevalence not only of acute injuries, but of all types of health problems, is investigated. This should also be kept in mind when choosing and developing evaluation methods.

Finally, it should be remembered that the work within this thesis aims for improved working conditions on HSC with the focus of reducing acceleration exposures. To reach the long-term goal of safe and efficient HSC, all means to improve the working conditions are needed. A holistic approach is desirable, meaning that measures to evaluate and actions to improve the crew's situation in a broader perspective, with focus not only on (reduced) acceleration levels, are needed. As an example, limiting the crew's time of operation in darkness may result in reduced risks for mental fatigue. Similarly, the risks of physical and mental fatigue (which can cause injuries in the long term) may be reduced by preparation, health examination, physical training and periods of rest. Furthermore, other measures to evaluate the performance of the technical system than those covered by this thesis may be useful; for example measures for estimating the risk for motion sickness or motion induced interruptions.

6.2 Future work

With reference to the conclusions, the following three research areas have been identified to be of particular interest when aiming for safe and efficient HSC by improved working conditions.

HSC's actual use
The better description of the craft actual operational profile, the better

decisions are possible to make regarding craft design, mitigation systems and operational actions. By collecting long-term measurements of craft acceleration, e.g. using permanent measurement systems, knowledge about the actual use of different HSC can be gained. With this purpose as well as for real-time feedback to the crew, the Swedish Coast Guard in cooperation with KTH is since 2013 continuously collecting data from several HSC units. This data will be used in coming research and will improve the picture of the actual conditions at sea. Data from the first instrumented unit is presented in De Alwis [10].

Seat model development
Bottoming-out events can result in severe acceleration peaks that are hazardous for the occupant. Modelling the seat's end-stop is therefore highly recommended in order to improve the accuracy of the predicted acceleration exposure for the crew.

As several experimental studies have indicated that suspension seats in some situations amplifies the acceleration levels, investigating the effect of the seat cushion would be of great interest. Depending on the outcome, it may become relevant to include the seat cushion in the seat model.

Due to the practical aspects limiting the lowest possible spring stiffness of the seat, it may be of interest to expand the seat model to a larger suspension system, isolating not only the crew, but also larger compartments, from accleration. It is likely that a larger motion stroke may be allowable for a larger suspension system, which increase the possibilities to mitigate acceleration of a wider range of frequencies or magnitudes.

Prevalence of health problems among HSC operators
Examining the prevailing health problems on HSC, caused by vibration, shock or other factors, is a key factor in order to succeed in reaching improved working conditions. Research cooperation initiatives for a prevalence/incidence survey on musculoskeletal pain and the related risks to personnel at sea, is now taken by KTH and Karolinska institutet. The research includes development and validation of a web-based questionnaire and is expected to enable identification of risk factors for; injuries or adverse health effects, performance impairment or for jeopardizing safety at sea. Based on this knowledge, risk reducing actions can be focused appropriately. A questionnaire study may also improve

the knowledge about a crew's actual exposure, which enables the crew exposure profile to be defined with better precision.

Finally, there is a need to link current evaluation measures to human endurance. For measurable health effects, simultanous measurements on craft and human may be a viable way to link the effects to various exposure types and levels.

7 Summary of appended papers

Paper A - Prediction and evaluation of working conditions on high-speed craft using suspension seat modelling

K. Olausson and K. Garme, Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, published online before print, January 2014

Severe working conditions on board high-speed craft adversely affect not only the safety, health and performance of the crew but also the performance of the vessel as a technical system. Human factors–based ship design combined with appropriate vibration mitigation techniques and work routines for the crew can improve the working conditions and reduce the risks for performance degradation and adverse health effects. To enable development and use of such means, methods for prediction and evaluation of working conditions are needed for both existing high-speed craft and craft under design. This article presents a 2-degree-of-freedom seat model compatible with both measured and simulated input data. The interaction between seat and human is treated using the concept of apparent mass. The model is validated against experiment data collected on board a 10-m, 50-knot high-speed craft equipped with high-standard suspension seats. Evaluation measures defined in ISO 2631-1 and ISO 2631-5 are used to compare experiment data to modelled data. The seat model slightly overestimates the experiment S_{ed} dose by a mean of 6.5% and underestimates the experiment vibration dose value (8 h) by 4.0%. It is concluded that model data correlate well with experiment data.

Paper B - Simulation-based assessment of HSC crew exposure to vibration and shock

K. Olausson and K. Garme, In Proceedings of the 12th International Conference on Fast Sea Transportation (FAST2013), Amsterdam, Netherlands, December 2013.

A simulation-based method for assessment of HSC crew vibration and shock exposure is presented. The simulation scheme includes three modules: Craft response module, Seat response module and Human exposure evaluation module. The first module computes the craft acceleration in the time-domain by a non-linear strip method and delivers input to the second module, where a crew seat model determines the human acceleration exposure time history. The crew's acceleration exposure is assessed in the third module, which includes a strategy to describe the operational profile. The human vibration exposure is evaluated using international standards (ISO 2631-1, ISO 2631-5). In addition, statistical extreme value analyses are used to evaluate the human exposure to shock. The potential to reduce the vibration and shock level is discussed and exemplified using the simulation-based evaluation method to analyse how different seat designs and running attitudes influence the crew vibration exposure.

Paper C - On High-Speed Craft Acceleration Statistics

M. Razola, K. Olausson, A. Rosén and K. Garme, preprint paper, January 2015.

This paper presents an extensive set of acceleration data for a small high-speed craft that is generated using a nonlinear strip method. Craft speeds and sea states are systematically varied and simulations extend to three hours. The data set is used to establish and evaluate methods for calculation of acceleration statistics, for example used in design load prediction and crew safety evaluation. The Standard-G approach for identification of peak values is evaluated and two alternative methods for fitting of analytical distribution functions to the acceleration data is established and evaluated. The Weibull distribution and the Generalized Pareto distribution are used. The established methods are applied on the simulation data and a number of aspects are clarified and discussed, such as the general characteristics of high-speed craft accelerations, slamming time scales, statistical convergence, and the relation between the peak fraction averages and the actual extreme values. It is for example concluded that calculation of the average of the largest 1/10th and 1/100th peak acceleration values converge for 300 and 600 acceleration peaks respectively. Further, it is shown that scaling of the average peak acceleration using the exponential distribution is erroneous. The most probable largest acceleration values require significantly larger samples to converge. For the conditions studied in this paper 2400 s of nonlinear simulations are required. Important results related to sampling and filtering of the vertical acceleration process are also presented. It is for example concluded that for craft of similar size as that studied in the paper sampling should be performed with a period of less than 0.01 s and low-pass filtering with cut-off frequency of no less than 20 Hz.

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Part II

APPENDED PAPERS A-C