On Evaluation of Working Conditions aboard High-Performance Marine Craft

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Licentiate Thesis in Vehicle and Maritime Engineering
School of Engineering Sciences
KTH Royal Institute of Technology
Stockholm, Sweden 2018
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TRITA-SCI-FOU 2018:02

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Abstract

High-Performance Marine Craft (HPMC) is a complex system confronted by the stochastic nature of the waves challenging the safety of life at sea. The personnel aboard these craft are vulnerable to detrimental conditions, in fact, limiting the system’s performance evoking the significance of the Human Factors Integration (HFI) in the design and operation of these craft. The risks related to the work environments at sea have inadequately been investigated. A consistently identified fact is that the exposure to work environments containing vibration and repeated shock elevates the risk of adverse effects on human health and performance. In the event that the exposure risk is known, the situation can be managed by the operators and the legislated health and safety demands can be achieved by the employer. Moreover, when quantification of the exposure–effect relationships is potential, human factors, in terms of health and performance, can be integrated into HPMC design and operation. However, the knowledge is limited about the adverse health and performance effects among the High-Performance Marine Craft Personnel (HPMCP), the factors causing these effects and their relationships.

The thesis presents a holistic approach for the integration of human factors, in terms of health and performance, into HPMC design and operation. A research program has been designed branching the design and operational requirements of HPMC concerning HFI. A method is introduced for a real-time crew feedback system, which monitors and characterizes vibration and shock conditions aboard HPMC, enabling determination of the risk of acute injuries due to the high-intensity instantaneous impact exposure and the acquired risk of adverse health and performance effects due to the accumulated vibration exposure. This brings forth the requirement of epidemiological studies in order to strengthen the exposure–effect relationships. Therefore, web-based questionnaire tools are developed, validated and pilot tested for cross-sectional and longitudinal investigation of health and performance in HPMC. The work exposure is measured aboard HPMC in terms of vibration and investigated in relation to the adverse health and performance event onsets, and the ride perception of the personnel aboard.

The introduced method for the real-time crew feedback is capable of informing the exposure risk in terms of human health and performance. The questionnaire tools are feasible for epidemiologically surveying HPMCP and similar populations providing data for investigating adverse health and performance effects, risk factors and their relationships. Promising trends are observed between the quantified work exposure and the health and performance onsets, and the human perception.

The work will be continued to identify the exposure–effect relationships facilitating better use of the existing standards, supporting ongoing development of the existing standards and providing information to draw appropriate design and operational limits in rules and regulations.

Keywords:
high-speed marine craft, human factors integration, whole-body vibration, epidemiology, musculoskeletal pain, fatigue
Sammanfattning

Högprestandafortyget (HPMC) utgör komplexa tekniska system där sjösäkerheten i den stokastiska vågmiljön är en utmaning. Besättningen ombord utgör många gånger den begränsande faktorn för systemets prestanda vilket betonar betydelsen av att integrera olika aspekter av människan som systemkomponent (Human factors integration, HFI), vid så väl projektering, konstruktion som under driftsfasen. Riskerna vid arbete till sjös är inte fullt ut kartlagda. Vad som står klart är dock att exponering för vibrationer och upprepade stötar ökar risken för att hälsan såväl som arbetets kvalité påverkas menligt. Om riskerna med exponeringen var kända skulle besättning i sitt handhavande kunna agera så att riskerna hålls på acceptabla nivåer och att arbetsgivaren uppfyller kraven i arbetsmiljö- och säkerhetslagstiftning. Dessutom, om riskrelationen mellan exponering och följder för hälsan och arbetsförmågan kan kvantifieras så öppnas en reell möjlighet att integrera human factors i både konstruktions- och driftsfasen. För närvarande är dock kunskapen begränsad om vilka negativa effekter på hälsa och arbetsförmågan som förekommer hos besättningar till HSMC, vilka faktorer som leder till dessa effekter och hur relationen mellan dessa ser ut.

Avhandlingen presenterar ett holistic angreppssätt för att integrera human factors, i termer av hälsa och arbetsförmåga, vid konstruktion och drift av högprestandafortyget. Ett forskningsprogram har utformats för att klargöra konstruktions- och driftskrav för HPMC avseende HFI. En metod för att övervaka och i realtid karaktärisera stötpåverkan vid vibrationsförsändringar ombord introduceras för att möjliggöra bedömning av risken för akuta skador till följd av enstaka kraftiga genomslag, risken för nedsatt arbetsförmåga under pågående verksamhet samt risken för negativa hälsoeffekter till följd av ackumulerad stötpåverkan och vibrationsexponering.


Det fortsatta arbetet siktar mot att identifiera och kvantifiera relationerna mellan exponeringen och dess påverkan på hälsa och prestation. Därmed kan man bättre utnyttja befintlig standard, stödja den pågående utvecklingen av befintlig standard och bidra till att sätta relevanta gränser i regelverk och lagstiftning som styr konstruktion och handhavande av högprestandafortyget.

Nyckelord:
höghastighetsfartyg, human factors, HFI, helkroppsvibrationer, epidemiologi, muskuloskeletal smärta, utmattning
Preface

The research work presented in this thesis has been performed at the Centre for Naval Architecture, Department of Aeronautical and Vehicle Engineering, School of Engineering Sciences, KTH Royal Institute of Technology Sweden. The work was initiated and supervised by Karl Garme. Anders Rosén backed the work by being the main supervisor. The research was financially supported by the Gösta Lundeqvist foundation for ship research (Gösta Lundeqvists stiftelse för skeppsteknisk forskning) and the Swedish Maritime Administration (Sjöfartsverket).

I would like to extend sincere gratitude to my supervisors Dr. Karl Garme and Dr. Anders Rosén for the support and guidance they gave throughout the research. It was a privilege working with Karl who navigated me through all the stochastic conditions by setting up the correct sails reaching the destination with a smooth voyage. Karl, kindly accept my hearty cheers for being a mentor not only in research but also in personal life. Thank you Anders for the valuable time spent sharing knowledge about the research work as well as life.

Special thanks to Riccardo Lo Martire for sharing the experiences throughout the journey and being a diligent peer. Riccardo, the time spent with you was a life lesson. I would take this opportunity to thank Stefan Andersson of the Swedish Coast Guard for coordinating the research work with the Swedish Coast Guard and accompanying me while travelling around the coast guard stations having fruitful discussions. Thank you my colleagues at the Centre for Naval Architecture for making the work environment inspirational and challenging.

Shereena, the one who shapes my shadow, this work would have been a nightmare without you and your love. Thank you and love you. My two little angels, Vaiduray and Dularu, your love and spirit bridge the two banks making it so easier for me to move between the work and family lives.

Stockholm, April 2018
Pahansen de Alwis
Dissertation

The thesis presents an overview of the work contributed to the field of research based on the following appended papers.

**Paper A**

**Paper B1**

**Paper B2**

**Paper C**
Division of work between authors

Paper A
de Alwis together with Garme developed the method. de Alwis analyzed the acceleration time histories numerically simulated by Garme. de Alwis authored the manuscript and Garme co-authored and reviewed it.

Paper B1
The four authors de Alwis, Lo Martire, Garme and Äng, constituted the consensus panel. de Alwis together with Lo Martire outlined the questionnaire and updated it following the expert raters’ suggestions and the consensus panel’s decisions. de Alwis and Lo Martire supported the web implementation. de Alwis, Lo Martire and Garme performed the pilot test. de Alwis is the main author, co-authored by Lo Martire and Garme. Äng outlined the study design and contributed by repeated reviews of the manuscript. Garme and Äng supervised the research students de Alwis and Lo Martire. Garne is leading the research programme of which this study is a part. All authors contributed to the editing and have read and approved the final manuscript.

Paper B2
Garme is leading the research programme of which this study is a part. All authors Lo Martire, de Alwis, Garme and Äng, conceived and designed the study, and constituted the consensus panel. Lo Martire and de Alwis outlined the questionnaire and refined it in accordance with the experts’ feedback. Lo Martire implemented the questionnaire online and drafted the manuscript. de Alwis, Garme and Äng reviewed and contributed to the manuscript’s development. All authors read and approved the final manuscript.

Paper C
de Alwis and Lo Martire developed the web-based questionnaires together with Garme and Äng. All authors, de Alwis, Garne, Lo Martire, Kåsin and Äng designed the pilot study. Kåsin coordinated the pilot study with the subjects and helped out with calibrating the vibration measurement systems. de Alwis and Lo Martire installed the vibration measurement systems on the high-performance marine craft with the support of Kåsin. de Alwis, Garne, Lo Martire and Äng, designed the cross-sectional study. de Alwis and Lo Martire visited eighteen coast guard stations in Sweden collecting epidemiological data on Swedish Coast Guards. de Alwis analyzed the objective and subjective data collected during the pilot and cross-sectional studies and wrote the manuscript. Garne, Lo Martire and Äng reviewed the manuscript. All authors read and approved the final manuscript.
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Chapter 1
Introduction

High-Performance Marine Craft (HPMC) is a complex man-machine system demanded with high level of performance not only the craft but also the personnel aboard. Craft need to have high level of design and operational characteristics, such as strength and propulsive power required for high-speeds in different sea states. These craft are often deployed by navies, coast guards, customs, marine pilots, special military operations and rescue units for maritime interdiction and intervention, seizure operations, search and rescue, rapid insertion and extraction of crews and surveillance. Usually, HPMC crews as well as passengers, i.e. High-Performance Marine Craft Personnel (HPMCP), are demanded for psychophysical fitness in order to successfully complete their missions. A HPMC in operation can be seen in Figure 1.1. HPMC crews are expected to efficiently manoeuvre the craft and safely reach the destination whereas the passengers are required to execute post-transit activities, such as, boarding on to a larger vessels travelling at high speeds, rescuing personnel and fire-fighting. The craft are operated day and night. Unlike their counterpart high-speed marine craft operators, such as, pleasure and off-shore racing, they are demanded to operate their craft at high speed in rough seas to accomplish their mission. The personnel, i.e. crew and passengers, aboard these craft often wear heavy operational equipment, including body armor, helmets and sometimes night vision goggles.

Figure 1.1 A High-Performance Marine Craft in action
1.1 High-Performance Marine Craft Design and Operation

HPMC design and development mainly focus on the performance and the structural aspects of the craft. Due to the fact that the state of the art HPMC design has expanded its boundaries developing stronger and faster craft with higher performance characteristics, humans have become the factor limiting the overall performance of these man-machine systems, particularly in waves. These craft are used under various operational envelopes with different speeds, sea states and ranges. It is worth considering that even though the designers develop unbreakable craft, they are operated by the humans with fragile structures. Craft designed and built for high operational demands, such as, operated at high sea states at elevated speeds for longer durations, could be under used due to the human limitations. When designing HPMC, human response to the working conditions is a crucial input that designers must consider for the next generation of high-performance craft. Is human the weakest link? Are the personnel go aboard aware of it and their limits?

1.2 Working Conditions aboard High-Performance Marine Craft

Working conditions aboard HPMC result from the interaction of stochastic environmental conditions and the craft’s design and operational characteristics. Personnel on board these craft are not aware of the actual severity of the exposure conditions and what could exactly happen except their perceptive ride comfort. Risk of being exposed to harmful conditions are unknown and the level of which is important in order to decide the operational limits. These limits, in return, decides the design limits.

The work aboard HPMC is usually demanded with high level of operational requirements (Cohen et al. 1986, Dobbsn et al. 2016, Parsons 2002, Vickers et al. 1997) and the personnel experience work related psychophysical health disorders which require medical assistance during their career and degrade their work performance (de Alwis et al. 2017, Ensign et al. 2000, McMorris et al. 2009, Myers et al. 2011, Raby and McCallum 1997, Stevens and Parsons 2002, Townsend et al. 2012, Wadsworth et al. 2008). These detrimental effects are believed to be due to complex multiple interactive factors related to environment, human and craft. However, the knowledge is limited about these factors and their association with the adverse health and performance effects.

Exposure to work environments containing vibration has been identified as a factor negatively affecting human health and performance (Bazrgari et al. 2008, Bovenzi and Hulshof 1999, Burström et al. 2015, Conway et al. 2007, Johanning 2015, Lings and Leboeuf-Yde 2000, Wikström et al. 1994). The marine personnel have been exempted from the legislated occupational vibration exposure levels due to the fact that given the current state of the art it is not possible to comply, in all circumstances, with those levels (Directive 2002). It means that the knowledge in the respective discipline, i.e. how humans are affected by the exposure conditions aboard marine craft is limited, which is also true for HPMC. Nevertheless, studies have indicated that working environments aboard HPMC regularly exceed these limits during typical high-speed operations, even when accounting for shock-mitigation systems (Allen et al. 2008, Garme et al. 2011).

There are many HPMC deployed in the field and many personnel work aboard these craft. It is critical to let them aware of their work exposure and take necessary precautionary actions to reduce the work related injuries and health consequences. There will be many more HPMC coming into the field and the designers must aware of the human limitations in order to design a balance man-machine system. Therefore it is important to consider human factors from both the design and operational perspectives.

1.3 Searching for Balance

From an engineering point of view the balance is sought between the craft’s ability and the human’s capability to make the most out of the technical resources. Consideration of the human factors in HPMC design and operation facilitates integration of the involved risk, risk levels and risk factors in terms of human health and performance while knowledge about the association between the risk factors and the adverse effects supports defining the limits. These limits in return can be used for optimizing craft design, hence the operation.
The research work presented in this thesis aims to integrate human factors into HPMC design and operation searching for balance between the man and the machine concerning the effects of exposure to the working conditions aboard HPMC on human health and performance. Following sections outline the main objectives, research questions and the methods directing to this main goal of the research.

1.3.1 Research Objectives

a) To inform HPMC crews about their exposure conditions during regular high-speed operations in terms of the risk of adverse effects on human health and performance.

b) To find and quantify the relationships between the working conditions aboard HPMC and the adverse effects on human in terms of health and performance, hence the acceptable levels of exposure.

c) To find the factors affecting human health and performance due to working conditions aboard HPMC.

1.3.2 Research Questions

a) Is it possible to inform HPMC crew about the working conditions in terms of risk of adverse health and performance within a sufficiently short time frame in real-time operation?

b) What measures can be used for the real-time assessment of the working conditions aboard HPMC?

c) What are the tolerable and acceptable levels of exposures in terms of the measures determined in b)?

d) Are there any relationships between the working conditions aboard HPMC and adverse effects on human in terms of health and performance?

e) How to quantify these relationships?

f) Which are the factors, in the working conditions aboard HPMC, negatively affecting human health and performance?

g) How to identify and quantify these factors?

1.3.3 Research Methodology

a) Development of a method to continuously analyze the exposure conditions aboard HPMC in order to feedback the crew indicating the risk of acute injuries due to severe impacts and the risk of adverse effects due to accumulated vibration exposure. Bring-forth the requirement of severity limits in order to setup the operational limits.

b) Development and validation of web-based questionnaires for surveying the health and working conditions and for longitudinal investigation of work exposure, musculoskeletal pain and performance impairments in HPMC personnel.

c) Conduct an epidemiological survey in order to determine the prevalence and incidence of work related adverse health effects and performance impairments in HPMC personnel. Determination of the factors and the extent of exposure causing incidence of adverse health effects and performance impairments.
1.4 Research Contribution

The four publications contributed to the research field demonstrate how the research questions are addressed in order to achieve the stated objectives.

**Paper A: Monitoring and characterization of vibration and shock conditions aboard high-performance marine craft**

*Manudul Pahansen de Alwis, Karl Garme*

In Paper A, a method is developed for a decision support feedback system for HPMC crews. A set of simulated acceleration time histories are investigated for the correlations between their acceleration characteristics based measures and statistical measures. The objective is to select suitable measures for real-time analysis of working conditions aboard HPMC, thus to determine the severity of exposure due to high-intensity instantaneous impacts and accumulated vibration during regular high-speed operations. The level of severity is computed every second using immediate 60 seconds vibration exposure history and communicated to the crew by means of a color code; green, yellow and red representing the intensity low, medium and high respectively. The feedback method presented in this work assists to keep HPMC operators within tolerable and acceptable level of severity while raising the requirement of quantified exposure-effect relationships and appropriate severity limits directing the work towards Paper B.

**Paper B:**

This section consists of two publications named as Paper B1 and Paper B2.

**Paper B1: Development and validation of a web-based questionnaire for surveying the health and working conditions of high-performance marine craft populations**

*Manudul Pahansen de Alwis, Riccardo Lo Martire, Björn O Ång, Karl Garme*

The objective of the study is to develop, validate and pilot test a web-based questionnaire for the assessment of occupational exposure risk associated with health and performance conditions in High-Performance Marine Craft Personnel (HPMCP). The comprehensive web-based questionnaire tool measures demography, life-style, work-exposure, health and performance data on seaborne personnel allowing the quantification of prevalence of adverse health and performance effects and their association with the work exposure.

**Paper B2: Construction of a web-based questionnaire for longitudinal investigation of work exposure, musculoskeletal pain and performance impairments in high-performance marine craft populations**

*Riccardo Lo Martire, Manudul Pahansen de Alwis, Björn O Ång, Karl Garme*

This is an extended work of Paper B1 where the study develops, validates and pilot tests a web-based questionnaire for longitudinal investigation of work exposure, musculoskeletal pain and performance in HPMCP. This is a complementary, more succinct, questionnaire tool with higher resolution in order to isolate the causal effects of work-exposure on health and performance in HPMCP.

This work fulfilled the requirement of such tools in order to conduct epidemiological surveys in the field of HPMC.
Paper C: Crew acceleration exposure, health and performance in high-speed operations at sea

Manudul Pahansen de Alwis, Karl Garme, Riccardo Lo Martire, Jan Iva Kåsin, Björn O Ång

Paper C summarizes the development and validation of web-based questionnaires for cross-sectional and longitudinal investigation of health and performance in HPMCP presented in Paper B. It also presents a comprehensive work on the pilot test of the questionnaires in a population of military personnel and the first cross-sectional investigation of musculoskeletal pain and performance among a selected population of seaborne personnel. The pilot test is specially designed to correlate physical and perceived working conditions identifying performance and health related risk factors by collecting objective and subjective work-exposure data and subjective performance indicators and health data. The pilot test confirms the feasibility of the set-up and the method for collecting data in order to determine the prevalence and incidence of work related adverse health and performance effects among HPMC personnel. Study results demonstrate the ability of the questionnaires for the determination of the factors and the extent of various components of the objective measures of acceleration such as levels, frequencies and content of shocks causing incidence of adverse health effects and performance impairments. The cross-sectional study shows that musculoskeletal pain and mental fatigue are prevalent among the study population. Musculoskeletal pain prevalence is comparatively higher than that of the general population and similar populations signifying the consideration of the human factors in terms of health and performance in HPMC design and operation.
1.5 Thesis Organization

The thesis is organized into five different chapters as described below.

Chapter 1: Introduction

HPMC is introduced as a complex man-machine technical system, while stating the requirements of a holistic approach for a balanced system based on the human factors, mainly on human health and performance. Objectives, questions and methodology of the research is briefed while summarizing the contribution to the research field.

Chapter 2: A method for real-time crew feedback

This chapter presents the development of a method for decision support crew feedback system for the personnel aboard HPMC in order to continuously indicate the risk of adverse health and performance effects by being exposed to the working conditions containing vibration and shock (Paper A: de Alwis and Garme 2017). This section describes the vibration environments containing shock aboard HPMC and requirement of design and operational vibration exposure limits which leads the study to the next chapters.

Chapter 3: Development of web-based questionnaires


Chapter 4: Epidemiological data collection

This chapter demonstrates the pilot test of the questionnaires outlining the set-up and major findings. The chapter also delineates the first cross-sectional investigation of a selected population of seaborne personnel (Paper C: de Alwis et al. 2017).

Chapter 5: Conclusions and future work

The final chapter of the thesis concludes the research work against its objectives and discusses about the requirements and possibilities for further extensions.
Chapter 2
A Method for Real-Time Crew Feedback

A method is developed in order to determine the severity of expected high-intensity short-duration impacts and accumulated vibration exposure aboard HPMC, and to continuously update the crew during real-time operations.

2.1 Introduction

Personnel aboard HPMC experience various detrimental conditions caused by multiple interactive factors, among which the exposure to Whole-Body Vibration (WBV) containing Repeated Shock (RS) has been identified as a distinctive factor elevating the risk of adverse health effects (Bazrgari et al. 2008, Bovenzi and Hulshof 1999, Burström et al. 2015, Conway et al. 2007, Johanning 2015, Lings and Leboeuf-Yde 2000, Wikström et al. 1994). The vibration environments during regular high-speed operations are characterized by random and transient vibrations. The association of vibration exposure with human health and performance impairments is dependent on time. The adverse effects such as musculoskeletal disorders caused by WBV are expected to follow a time frame of months to years of exposure while WBV related psychophysical fatigue, presumably influencing work performance, develops in hours. The high level impacts caused by RS, typical for HPMC, might cause acute injuries within seconds. If HPMC crews are aware about the hazardous conditions to be expected because of being exposed to these work environments, it could be possible for them to manage the situation in order to reduce the risk, for instance, by changing the speed, course or posture. Moreover, employers could meet the legislated health and safety demands by educating the operators about the exposure levels at which the necessary precautionary actions must be taken. These can be supported by having an onboard monitoring system which analyze real-time vibration environments aboard the craft and feedback the crew concerning risk of adverse health and performance effects.

2.2 Vibration Measures

Vibration is a complex phenomenon characterized by magnitude, axis of occurrence and frequency content which varies over time. Effect of vibration on human health is highly dependent on these characteristics as well as the duration of exposure.

Vibration as an oscillatory motion, the magnitude can be measured by many possible means among which acceleration is the most commonly used measure to evaluate the working conditions containing vibration and shock. Although vibrations act on human body in all three translational and rotational axes in various ways (Griffin 1990), adverse effects due to vertical (z-axis) translational vibrations are found to be the most common and calamitous among the personnel aboard HPMC (Dupuis et al. 1991). Therefore it is prudent using vertical translational acceleration in order to analyze and assess vibration environments aboard these craft. The heterogeneity of these environments mainly due to the interaction of random and transient vibrations evokes the necessity of a method that is capable of capturing this dual character of the exposure conditions as can be seen in Figure 2.1. Then the situation can be evaluated in terms of adverse health effects potential of high-intensity shock profiles and random vibrations containing repeated shock. This concept is used to feedback the crew about the severity of the exposure conditions in Paper A (de Alwis and Garme 2017).

The severity of the momentarily operational state is required to be communicated to the crew. Therefore measures are desired that support the crew in their judgment of the acceleration exposure that can continuously characterize and state the situation in short time lapses, in the order of tens of seconds to a few minutes, i.e. of the time scale of constant conditions during HPMC operations.
The magnitude of acceleration can be expressed in terms of basic measures such as peak-to-peak, peak, Root-Mean-Square (RMS) (BS 1987 and ISO 1997), Maximum Transient Vibration Value (MTVV) (ISO 1997), Vibration Dose Value (VDV) (ISO 1997), Daily Equivalent Static Compression Dose ($Se_d$) (ISO 2004), Dynamic Response Index (DRI) (MIL-SPEC 1967), Impact Ride Quality Index (IRQI) and Vibration Ride Quality Index (VRQI) (Payne 1976), and statistical measures, for instance, average $1/n$ highest acceleration peaks (Fridsma 1971, Savitsky and Brown 1976, Razola et al. 2016), Most Probable Extreme Acceleration Peak (MPEAP) and extreme acceleration peak values having $\alpha$% probability of exceedance ($MPEAP_{\alpha%}$) during a defined period of time (Ochi 1981 and Razola et al. 2016).

For very short acceleration duration, a person is sensitive to impulsive acceleration change, i.e. jerk, rather than the magnitude (Payne 1976) which shows the significance of the rise time of a peak when analyzing impact acceleration. This implies that a person might fail to perceive an impact having a short rise time even if the magnitude is destructive, i.e. the person will not feel the impact but finally experience the harmful health consequences. Therefore it is important to select a measure for analyzing high-intensity instantaneous shock events, i.e. isolated shocks with considerably short exposure times, which are common in HPMC vibration environments causing discrete adverse consequences such as acute injuries. Exposure to comparatively low magnitude random vibration for prolonged durations is also equally important where the high amount of energy transmitted to human body over a period of time causes accumulated adverse health effects such as musculoskeletal pain and psychophysical fatigue.

![Figure 2.1 Example of vibration exposure aboard HPMC. A portion of a vertical (z-axis) acceleration time history extracted from an actual HPMC in operation at about 50 knots, filtered at 100Hz.](image)

Therefore it is crucial to select measures that are capable of capturing this duplex nature of exposure within a short period of time, considering the diminutive time scale of constant conditions during high-speed operations, and are low in real-time computational complexity.

Although acceleration peaks are commonly used to analyze vibration exposure, the time varying nature of the exposure conditions aboard HPMC does not allow capturing sufficient amount of peaks within a short time interval, which corresponds to the constant condition during HPMC operations, in order to deliver crew feedback using the existing assessment methods based on acceleration peak statics. Convergence of statistical peak measures such as average fractional highest acceleration peak and extreme values requires considerable amount of time, in the order of 20-40 minutes or above, as indicated by Razola et al. 2016. Beside the real-time computational complexity of acceleration peaks based statistical analysis methods is comparatively high.

Acceleration peaks based measures using biodynamic models such as DRI, IRQI and VRQI are suggested for analyzing and assessing short duration shocks likely to cause acute injuries. The ambiguity of the peak and impact profile definitions, overshoot characteristics of the models, poor agreement between the incidence of spinal fracture and DRI (Anton 1986) and the effects of signal processing on the amplitudes of peak and the duration of the impact together with the real-time computational complexities limit the selection of these measures for real time feedback.
Vibration evaluation methods based only on RMS cannot be used when there are series of impacts or impulsive velocity changes, i.e. spikes, which is the case in HPMC operations (Allen et al. 2008, Garne et al. 2011, Payne 1976). Even though these spikes do not have much effect on the RMS value they might be the most injurious acceleration one can experience during the ride. It is suggested that RMS or energy based measures underestimate the severity of high-magnitude short-duration motions. Although the peaks based measures estimates the severity of a single cycle of motion, they increasingly underestimate severity as the number of cycles of motion increases (Griffin 1990).

The time averaging cumulative measures, commonly known as dose, for instance, VDV, can be applied to a single shock, a mixture of vibration and shock as well as prolonged exposure to vibration of various types (Griffin 1990). Since in a real-time feedback system exposure conditions are analyzed for very short discrete time lapses, behavior of these dose measures are analogous to that of RMS based measures.

The vibration and shock exposures aboard HPMC result from the stochastic nature of the waves. Therefore a measure must be selected to correctly identify the characteristics of this random process although only a snap shot of the process is considered for analysis. The method should be able to determine the upcoming severe impact events at a given point in time, if continued in the same exposure conditions, together with another measure that determines the cumulative effect of the vibration exposure indicating the exposure severity.

2.3 Feedback Mechanism

The crew vibration exposure conditions are assessed in terms of the accelerations occurring in the defined vertical axis (z-axis) (ISO 1997). The method analyses immediate 60 seconds vibration exposure history, as 60 seconds acceleration bins, every second. Then it determines the severity of expected high-intensity instantaneous impacts while separately computing the acquired severity due to the accumulated vibration exposure. The exposure severity is then communicated to the crew by means of a color code; green, yellow and red representing the intensity low, medium and high respectively, using two indicators as can be seen in Figure 2.2.

![Figure 2.2 Illustration of the exposure severity display mounted on HPMC console. Severity of expected high-intensity instantaneous impacts by blinking colored lights (left) and the accumulated risk by a dose meter (right)](image)

2.2.1 Signal Processing

The method processes the input acceleration signal using the frequency weighting for z-direction ($W_z$) related to health, comfort and perception as recommended in ISO (1997), since the effect of vibration on human body is dependent on its frequency content. The frequency weightings are designed including band-limiting filters of 0.4Hz high-pass and 100Hz low-pass.
2.2.2 Impact Analysis

The high-magnitude short-duration impact characteristics causing acute injuries in the vibration exposures are captured by a measure called Transient Factor (TF) computed for vertical accelerations measured over a period of 60 seconds, which is the ratio between MTVV and RMS, given in ISO (1997) and expressed as

\[
\text{Transient Factor} = \frac{\text{MTVV}}{\text{RMS}} \tag{2.1}
\]

where

\[
\text{MTVV} = \max[a_w(t_0)]
\]

\[
a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} [a_w(t)]^2 \, dt \right\}^{\frac{1}{2}} \tag{2.2}
\]

where

- \(a_w(t_0)\) - instantaneous frequency weighted acceleration
- \(\tau\) - integration time for running averaging
- \(t\) - time (integration variable)
- \(t_0\) - time of observation (instantaneous time)

The RMS of an acceleration signal signifies the amount of energy transmitted to the human body while MTVV catches the information about the impact magnitudes. The TF indicates the influence of the impacts on the signal, i.e. the spikiness of the signal or bumpiness of the ride, as shown in Figure 2.3 (a).

![Figure 2.3](image)

Figure 2.3 (a) Transient Factor (Eq. 2.1) computed using RMS and MTVV for an acceleration time history simulated for 3 hours. RMS and TF has been computed for 60 seconds time window moving over the acceleration time history in 60 seconds time steps resulting 180 windows. Integration time for MTVV (Eq. 2.2) is 1 second \( (\tau = 1s)\). (b) Unpredictability Factor (Eq. 2.3) computed for the same acceleration time history using 10 seconds micro time window and 6 micro time windows (\(\Delta t = 10s\) and \(N = 6\)).
The deviation of TF from RMS is represented by a measure called *Unpredictability Factor (UF)* given by

\[
Unpredictability \ Factor = \sqrt{\frac{1}{N} \sum_{n=1}^{N-1} \left( \frac{MTVV}{RMS} \Delta t_{n+1} - \frac{MTVV}{RMS} \Delta t_n \right)^2}
\]  

(2.3)

where

\( \Delta t \) - size of micro time window  
\( N \) - number of micro time windows  
\( n \) - micro time window number

This measure, UF, levels the scattered TF as can be seen in Figure 2.3 (b). In order to compute UF, the acceleration exposure history considered for real-time analysis, in this method 60 seconds, is further segmented into micro windows of time \( \Delta t \) and the ratio between \( MTVV \) and RMS for each micro window is computed.

The *Severity Index (SI)*, an indicator of the exposure severity, is computed using the RMS and UF of the 60 seconds acceleration bin formulated as

\[
Severity \ Index \ (SI) = RMS \times Unpredictability \ Factor
\]

(2.4)

There is a desire for a meaningful measure interpreting the SI in order to be able to rank the exposure severity.

### 2.2.3 Severity Reference

The Most Probable Extreme Acceleration Peak (*MPEAP*) is used to rank the vibration exposure, characterized by SI, according to the severity order. The *MPEAP* can be interpreted as the statistically determined largest acceleration peak being the most probable to occur during an observation period. In Paper A, *MPEAP* values are used representing a set of 27 three-hour acceleration time histories numerically simulated for a HPMC in nine different sea conditions at three speeds previously determined at KTH (Razola et al. 2016). The *MPEAPs*, of the 27 cases, sorted in the ascending order, \( 3.68 \text{ms}^{-2} \) to \( 146 \text{ms}^{-2} \), are considered as the reference scale for determining the exposure severity due to high-intensity short-duration impacts.

### 2.2.4 Severity Limits and Predictive Indicator

There is no sufficient scientific evidence available on direct quantitative relationships between the levels of vibration containing shocks and the probability of acute injuries for HPMC personnel, hence acceptable vibration and shock exposure levels.

As a feasible solution to this matter, the relationship between shock loads and ultimate strength of Functional Spinal Units (FSU), human tolerance levels to impact acceleration or a similar measure that directly related to acceleration magnitudes can be used to indicate the severity of the exposure. Based on such impact-injury relationships the reference severity scale, in this study *MPEAPs*, can be divided into different severity zones using tolerable and destructive limits.
In this work the MPEAP severity scale is divided into three severity zones, low, medium and high using arbitrarily selected limits. The correlation between SI and MPEAP is determined by fitting the data into a function of the form \( y = Ax^b \). The coefficients of the function are numerically determined by least squares fitting procedure for the power law functions yielding,

\[
\ln y = \ln A + b \ln x
\]

\[
b = \frac{n \sum_{i=1}^{n} (\ln x_i \ln y_i) - \sum_{i=1}^{n} (\ln x_i) \sum_{i=1}^{n} (\ln y_i)}{n \sum_{i=1}^{n} (\ln x_i)^2 - (\sum_{i=1}^{n} \ln x_i)^2}
\]

(2.5)

\[
a = \frac{\sum_{i=1}^{n} (\ln y_i) - b \sum_{i=1}^{n} (\ln x_i)}{n}
\]

where

\[
A = e^a
\]

\( n \) - number of data points

The method computes SI every second, as described above using 60 seconds acceleration bins, and identify the process which it belongs to by looking at the corresponding MPEAP value. Based on the MPEAP severity scale, the method determines the severity of expected high-intensity instantaneous impacts and update the crew every second. The exposure severity is displayed to the crew as a predictive indicator in terms of a color code green, yellow and red indicating the level low, medium and high respectively.

**2.2.5 Cumulative Vibration Exposure**

In this work, the severity gained by the accumulation of vibration exposure is computed using an established measure, i.e. Vibration Dose Value (VDV) (ISO 1997). It is the time average of the fourth power of the frequency weighted acceleration defined by

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

(2.6)

where

\( a_w(t) \) - instantaneous frequency weighted acceleration

\( T \) - duration of the measurement

Daily equivalent static compression dose \( (Se_d) \) is another potential measure that could also be used for analyzing the accumulation of vibration exposure (ISO 2004). It was found, during the pilot test presented in Chapter 4, that this measure is analogous to VDV. Furthermore, the single degree of freedom lumped-parameter model used for the determination of human lumbar spine response, when computing \( Se_d \), manifests the same complications typical for the peaks based measures using biodynamic models, such as, DRI, IRQI and VRQI.

Sufficient epidemiological data is required in order to categorize the dose-effect relationships into different severity levels.
2.4 Verification and Validation

The method for HPMC crew feedback system is verified using the 27 simulated acceleration time histories and actual acceleration time histories measured aboard three HPMC having different applications, i.e. patrolling, special operations and racing. The method computes SI and determines the severity of expected high-intensity instantaneous impacts based on the SI-MPEAP correlation and communicates to the crew every second as a color coded predictive indicator. The method continuously computes the acquired severity in terms of VDV and communicates to the crew every second.

The method is validated using the same 27 simulated acceleration time histories by computing SI for 60 seconds acceleration bins every second and it shows that the method is able to identify the corresponding simulation based on SI-MPEAP correlation confirming the validity with an acceptable level of accuracy. Which means that, SI computed only for 60 seconds acceleration data identifies corresponding MPEAP, which is a statistical measure having high computational complexity that requires considerable amount of time for convergence, i.e. above 40 minutes (Razola et al. 2016).

2.5 Application

A sample application of the method on a HPMC in operation is shown in Figure 2.4.

![Figure 2.4 Application of the method on a HPMC used for special military operations. Exposure duration is one hour. Sampling frequency is 600Hz. Signal has been low-passed at 100Hz. Lower and upper severity limits are 2g and 6g respectively. (de Alwis and Garme 2017)
Chapter 3
Development of Web-Based Questionnaires

In the absence of clearly defined relationship between working conditions and the adverse health effects among personnel aboard HPMC it remains desirable to define an appropriate method of quantifying work exposure which in turn facilitates comparing severity of different HPMC work environments. Knowledge about the factors causing these adverse conditions and the causal effects of these factors on human health and performance enables setting up the design and operational limits of these craft. Linking measured or computed quantities to adverse effects or their risk factors are crucial from both the perspectives, feedback during operations as well as setting up the design boundaries. However, there is limited epidemiological data available for the assessment of working conditions aboard HPMC. Although questionnaire surveys are widely used for identifying exposures, outcomes and associated risks with high accuracy levels, validated and feasibility tested epidemiological survey tools were lacking for surveying HPMC personnel. To fill this gap, web-based questionnaire survey tools are developed, validated and pilot tested in Paper B1 and B2. The aim is to collect data on working conditions aboard HPMC and the work related health disorders and performance impairments in order to investigate the risk factors causing these adverse effects and the association between them.

3.1 Conceptual Models and Selection of Questionnaire Items

The questionnaires are developed for the collection of multivariate data on marine populations in order to investigate the prevalence and incidence of adverse health and performance effects. In epidemiology prevalence is defined as the proportion of a selected population with a particular characteristic or an effect at a given point in time. In this study population is the personnel aboard HPMC and the characteristics under investigation are adverse health and performance effects. Incidence can be described as the number of new cases of these characteristics or effects occurring in a certain population during a specific time period. Appropriately designed regular follow up investigations allow identifying the factors causing the effects and their relationships.

To understand the complex interrelations between the multiple variables under study, Structural Equation Modeling (SEM) is used to analyze the data (Ditlevsen et al. 2005). The multivariate data analysis techniques included in SEM combine aspects from multiple regression and factor analysis. This facilitates simultaneously solving series of interrelated dependencies while enabling definition of aimed consequences and directly incorporating measurement errors into the model (Ditlevsen et al. 2005). An important feature of SEM is its augmentation for estimating measurement errors by using factors or latent variables. This allows inclusion of variables that are not directly measurable, but through their effects or their observable causes. The content representation of the questionnaire items is decided on the basis of their sensitivity to reflect, sample and measure the respective variables of the SEM. The conceptual SEM depicted by a path diagram constructed for developing the questionnaire in order to determine the prevalence of adverse health and performance effects among marine personnel is shown in Figure 3.1.

The questionnaire items are developed under four basic sub-domains viz. demography, lifestyle, work-exposure and health. Although the comorbidities, fatigue and stress are illustrated as indicators, in the model, they are actually latent variables, i.e. non-measurable variables, containing set of other indicators. A structural sub model for performance as a construct will later be introduced for analyzing the overall performance of the HPMC as a system and is not included in this thesis. This sub model will consider fatigue symptoms, duration of work at sea, subjective severity of working conditions aboard different types of craft, reasons for reducing craft speed in rough sea conditions, availability of shock mitigation techniques and ergonomics of the craft as the indicators for system performance.
Functioning and impairments can be examined as a complex interaction between the health condition of the individual and the contextual factors of the environment as well as personal factors by mapping the questionnaire items into the International Classification of Functioning, Disability and Health (ICF) framework (ICF 2001) as shown in Figure 3.2. This is important not only from the point of rehabilitation but also for prevention, for instance, appropriate training, rest and shift scheduling.

Figure 3.1 Path diagram of the SEM for studying incidence of adverse health and performance effects among marine personnel.
Another more concise questionnaire tool is developed in order to isolate the factors causing adverse health and performance effects in marine populations enabling quantification of the exposure-effect relationships. The requirement of this questionnaire is to longitudinally investigate these populations by collecting data on their work-exposure, health and performance. So that, it provides data on the occurrence of new cases of the studying health and performance consequences during an investigation period. The questionnaire items are designed based on the conceptual SEM illustrated by a path diagram in Figure 3.3. The model measures incidence of adverse health and performance effects among marine personnel.
The questionnaire items are generated under three sub-domains; work-exposure, health and performance covering their comprehensiveness by increasing the resolution. An additional construct with two indicators is introduced to capture the missingness of data.

In addition to the performance construct showed in Figure 3.3, a fatigue symptoms based aggregated score system is developed considering the correlation of performance indicators: tiredness, concentration difficulties, decision-making complications, headache, memory-recalling issues, mission status, human and craft performance, and motion sickness with the perceived ride quality. Performance degradation index is presented as the number of performance indicators per subject for a selected period of exposure.

As web-based surveys, these questionnaires have dynamic, responsive and active interactions with the respondent such as ability of skipping and routing by delivering questions based on the answers provided to the previous question(s) and indicating the missed questions.

Figure 3.3 Path diagram of the SEM for studying incidence of adverse health and performance effects among marine personal.
3.2 Validation of Questionnaires

The questionnaires are systematically validated by a set of experts for their content relevance and simplicity in three consecutive stages, each iteratively followed by a consensus panel revision. Each questionnaire item is assessed by rating on two ordinal Likert rating scales quantized by four points as 1=not relevant, 2=somewhat relevant, 3=quite relevant and 4=highly relevant, and 1=not simple, 2=somewhat simple, 3=quite simple and 4=very simple. The scale is dichotomized into agreed (rating of 3 and 4) and disagreed (rating of 1 and 2) and the Item Content Validity Index (I-CVI) is determined as the proportion of experts giving a rating of 3 or 4 (agreed) with I-CVI ≥0.78 as the acceptable level. The Scale Content Validity Index (S-CVI/Ave) is computed by averaging the I-CVIs for the assessment of the questionnaire as a tool. The detail validation processes of the two web-based questionnaires can be found in Paper B1 and B2 (de Alwis et al. 2016, Lo Martire et al. 2017). It shows that the web-based questionnaires fulfil previously published validity acceptance criteria (Polit and Beck 1997) and are therefore considered valid for the empirical surveying of epidemiological aspects among HPMC personnel and similar populations.
Chapter 4
Epidemiological Data Collection

The working environment aboard HPMC has rarely been investigated. It is characterized by complex time varying multiple interactive factors, where the crew is often at the mercy of natural forces and circumstances beyond their control. The High-Performance Marine Craft Personnel (HPMCP), i.e. crew and passengers, aboard these craft are vulnerable to many detrimental health and performance consequences, where the causal factors have still not clearly been identified (de Alwis et al. 2017, Ensign et al. 2000, McMorris et al. 2009, Myers et al. 2011, Raby and McCallum 1997, Stevens and Parsons 2002, Townsend et al. 2012, Wadsworth et al. 2008). Vibration containing repeated shock have been suggested as a factor causing these adverse effects, however, the scientific basis for this is weak and present legislation (Directive 2002) and related international standards (ISO 1997) are still in debate. Experience and earlier studies (Ensig 2000) indicate that the prevalence of musculoskeletal disorders is high among HPMC. Furthermore, high prevalence of fatigue symptoms such as headache, tiredness, concentration difficulties, decision making impairments and effort of thinking can be added as related risks for work performance hazardously influencing safety of life at sea. Types of occupant debilitation related to repeated shock have been identified as on-route and on-arrival performance degradation produced by shock related fatigue and discomfort, chronic injuries from sever shocks or repeated moderate shocks and acute injuries from sever isolated shocks (Gollwitzer and Peterson 1995). The lack of knowledge in the discipline of human-machine interaction clarifying the exposure to the working conditions and potential risk of negative health consequences and reduced work-performance has made a void causing uncertainty which delays further prevention of hazardous conditions and development of efficient work environments at sea, for instance, warning levels for crew feedback system or design of shock mitigation systems. Therefore an epidemiological study has been commenced in order to collect data, by means of web-based questionnaire surveys, on health and performance outcomes among marine populations due to the exposure of various working environments. The study has been approved by the Regional Committee for Medical Research Ethics (Dnr.2015/576-31), Stockholm, Sweden (Ethics 2015).

4.1 Feasibility of Questionnaire Tools

The questionnaire tools developed and validated as described in the previous chapter are pilot tested for its fit for purpose characteristics and the item properties before conducting the epidemiological data collection. The pilot test is also designed to correlate physical and perceived working conditions identifying performance and health related risk factors by collecting objective and subjective work-exposure data and subjective performance indicators and heath data. One objective of this set-up is to search the feasibility of using subjective data in order to level the severity of exposure data and subjective performance indicators and heath data. The former will support on setting up the operational limits in the method for real-time crew feedback described in Chapter 2 while the latter provides a platform to draw design operational limits as a function of working conditions, human health and performance.

The pilot test is designed as a cohort study in a sample of military seaborne personnel during a period of eight weeks of a marine exercise. Craft acceleration and GPS data is objectively recorded by vibration measurement systems installed onboard while work related exposure, performance and health data is subjectively collected via the two web-based questionnaires described in Chapter 3.

The subjective health and performance impairments are assessed in terms of prevalence and incidence of musculoskeletal pain using the SEM suggested in Figure 3.1 and 3.3.
Musculoskeletal pain data is collected using a high-resolution pain areas scheme having 18 different zones shown in Figure 4.1 and analyzed under ten major body areas. Results are expressed as the number of subjects having pain during the past six months and past seven days, i.e. prevalence, and the number of subjects incurred new pain events during the entire investigation period, i.e. incidence. The objective vibration exposure, measured as acceleration, is quantified by daily equivalent static compression dose \((S_{eq})\), (ISO 2004) as the method considers adverse effects on the lumbar spine as the dominating health risks because of exposure to vibration containing repeated shocks. This will also help understanding exposure severity limits in the onboard decision support crew feedback system. The study, in detail, can be found in Paper C.

![Figure 4.1 Pain areas scheme, with 18 zones, merged into ten major body areas inspired by Kuorinka et al. (1987).](image)

The amount of data collected during the pilot test is limited to draw direct conclusions on the correlation of objective exposure conditions with subjective perception, thus, identification of related risk factors. The pilot test shows promising trends between the objective and subjective data as can be seen in Figure 4.2 and confirms the feasibility of the questionnaires, test set-up and method for collecting such data.

![Figure 4.2 Trends of the correlations between objective and subjective vibration measures. Objective data is presented in terms of daily equivalent static compression dose \((S_{eq})\) and the subjective data as four ride quality levels very smooth, smooth, rough and very rough together with the aggregated fatigue symptoms score.](image)
4.2 Baseline Data Collection: A Cross-Sectional Study

A cross-sectional study is conducted targeting the whole population of Swedish Coast Guard (SCG). SCGs are selected as the study population since they are mainly involved with sea going activities and the other activities affecting their health and performance are comparatively less. The questionnaire developed in Paper B1 is anonymously completed by 342 coastguard officers providing data about their demography, lifestyle, work-exposure and health.

The most prevalent pain event among the subjects is low back pain which is 165 subjects concerning past 6 months and 81 for past 7 days. The results also indicate that 95 subjects have sought for health care and 115 have received treatments for the pain during the past 6 months. Eleven subjects (3.2% of the study population) have answered that the pain during the past 6 months reduced their workability for a large extent while for 122 (35.7%) up to some extent. Seven subjects (2.0%) have permanently changed their work task. Thirty-two subjects (9.4%) believe that the pain is due to work at sea.

In addition to the common mental fatigue symptoms, headache and tiredness, 132 (38.6%) subjects have experienced memory-recalling issues at least once per week considering past 6 months while 100 (29.2%) subjects having concentration difficulties and decision-making impairments once per week.

It is evident, from the cross-sectional study that musculoskeletal pain and mental fatigue are prevalent among the study population and the percentage musculoskeletal pain prevalence is comparatively higher than that of the general population and similar populations (Ensign et al. 2000 and Hoy et al. 2012).
Chapter 5
Conclusions and Future Work

The thesis presents the contribution of work at this milestone during the expedition on evaluation of the working conditions aboard HPMC in order to incorporate human factors into the HPMC design and operation considering the involved risk, risk levels and risk factors in terms of human health and performance. It sets-up the cornerstones of the holistic approach in the consideration of human factors inside the HPMC design and operations by

- Developing a method for real-time monitoring and characterization of vibration and shock conditions aboard high-performance marine craft, in order to determine the risk of adverse health and performance effects and feedback the crew with upcoming hazardous events (Paper A), to address the research questions a) and b), by

- Developing web-based questionnaires for surveying the health and working conditions and for longitudinal investigation of work exposure, musculoskeletal pain and performance impairments in HPMC personnel (Paper B1 and B2), in order to facilitate answering the research questions d), f) and g), and by

- Conducting an epidemiological survey in order to determine the prevalence and incidence of work related adverse health effects and performance impairments in HPMC personnel (Paper C), addressing the research questions d), e), f) and g),

aiming to gain knowledge about the factors causing adverse health and performance effects and the association between these factors and the adverse effects in order to set-up design and operational limits, finally by answering the research question c).

5.1 Conclusions

The method developed for a decision support crew feedback system captures instantaneous shock conditions involved in the stochastic process of working conditions aboard HPMC using the introduced measure, Severity Index. It determines the severity level of expected high-intensity instantaneous impacts with an acceptable level of accuracy, at a given point in time, during high-speed operations by analyzing exposure data of only 60 seconds. Simultaneously, the method continuously evaluates the gained exposure severity due to the accumulated vibration exposure. Then both the severity levels are updated to the crew every second. The method uses acceleration characteristics based measures Root-Mean-Square, Maximum Transient Vibration Value and Vibration Dose Value to analyze the vibration exposure while using a statistical measure the Most Probable Extreme Acceleration Peak as the severity reference for high-intensity instantaneous impacts fulfilling the need of the measures in the real-time assessment of the working conditions as stated in the research question b). The method is feasible for continuously informing HPMC crews about their working conditions within a sufficiently short time frame in real-time operations partially meeting the requirements in the research question a).

The questionnaire validation process confirms that the questionnaire items are relevant concerning the representation of the content domain and are simple to understand. The pilot study and the cross-sectional data collection suggest that the questionnaires are fit for their intended purpose. These questionnaires can be used for the collection of epidemiological data on seaborne personnel allowing the quantification of prevalence and incidence of adverse health and performance effects and their association with the work exposure. The questionnaire described in paper B2 enables identification of the factors negatively affecting human health and performance, thus quantification of their
relationships with the working conditions aboard HPMC. This work provides necessary tools for addressing the research questions d), f) and g).

The promising trends observed in the correlations of perceived ride quality with the performance indicators and measured vibration exposure show the possibility of using perceived ride quality to grade the exposure severity as well as performance degradation, in the absence of measured vibration data. This confirms feasibility of the set-up and procedure for the quantification of exposure-effect relationships as questioned in e). The cross-sectional study reveals the prevalence of musculoskeletal pain and fatigue among marine populations still keeping the hopes for the research question d).

5.2 Future Work

The method developed for a crew feedback system (Paper A) analyzes the exposure conditions aboard HPMC during real-time operations and communicates the exposure severity to the crew every second. If the MPEAP-injury and the VDV-effect relationships are known then the severity can be communicated to the crew in terms of human health and performance. Since MPEAP and incidence of adverse health and performance effects are probabilistic parameters, it will be possible to express the exposure severity in terms of risk. For this, further investigations are required on the MPEAP-injury and VDV-effect relationships.

The MPEAP values used as the severity reference, in Paper A, were not uniformly distributed over the range 3.68ms$^2$ to 146 ms$^2$ and all the possible distributions have not been covered. Therefore this real-time analysis method can further be improved by increasing the number of simulated acceleration time histories, thus more and equally distributed data points representing the whole range of MPEAPs and various distributions.

The results of the pilot study indicate a considerable level of pain incidence and high level of vibration exposure ($Se_d$) exceeding the upper limit for the lifetime exposure, i.e. 0.8 MPa considering 240 annual exposure days, (ISO 2004). This confirms that there is a relationship between vibration exposure and the health impairments in personnel aboard HPMC. This relationship could further be investigated using a summary score of weekly vibration exposure with pain incidence or pain intensity data. A summary score method can be introduced for the assessment of weekly vibration exposure in order to analyze the correlation of weekly vibration exposure levels with the musculoskeletal pain incidence and intensity. This will facilitate quantification of tolerable and acceptable levels of vibration exposure, especially in terms of the measures used in the feedback method, for personnel aboard HPMC.

KTH in collaboration with Karolinska Institutet (KI) and the Swedish Coast Guard (SCG) has started investigating work exposure, health and performance of HPMC personnel and quantifying their association using measured vibration environments. The first cross-sectional data collection has been completed and presented in Paper C. The study continues with another round of data collection using the questionnaire developed in Paper B1 with one year interval. A selected population from the SCGs working aboard HPMC will be investigated using the questionnaire developed in Paper B2 for the incidence of health and performance impairments. This whole study will provide sufficient epidemiological data about work-exposure, health and performance of personnel aboard HPMC in order to identify and quantify the exposure-effect relationships and the factors negatively influencing human health and performance, facilitating better use of the existing standards (BS 1987 and ISO 1997), supporting ongoing development of the existing standards (ISO 2004) and providing information to draw appropriate operational limits in the legislations (Directive 2002).

Researchers have long been working on different methods for reducing shock exposure on HPMC by introducing various shock mitigation techniques such as shock mitigation seats, suspended-cockpits and hulls. The human musculoskeletal response to a particular vibration environment differs with the body posture. It was found that HPMC operators change their body posture, sitting and standing, frequently due to various reasons which has a significant effect on the incurred adverse health and
performance effects. The relationship exposure-posture-effect could further be investigated using the information collected during this study. The relationship between the vibration exposure magnitudes and the adverse effects will provide essential information for seat modelling when deciding the end-stops, progressive and active suspension mechanisms. Generally shock-mitigation seats are installed onboard HPMC to reduce the acute injuries caused by severe isolated shocks. Although these seats control propagation of high level impacts, their continuous vertical reciprocating motion keeps the occupants’ body muscles active throughout the transit. These unnecessary prolonged muscular workouts consume energy, thus, largely contribute to the performance degradations found among the HPMC occupants. The muscular activity of these seat occupants during high-speed operations can be investigated using EMG studies on HPMC personnel on actual craft or simulators.

In future the investigations related to exposure-effect relationships can further be improved by introducing test modules such as cognitive and physical performance tests, electromyography (EMG) testing and biomarker screening. These modules will provide objective data regarding health and performance effects caused by working environments aboard HPMC strengthening the epidemiological data collected by KTH together with KI and SCG.
References


Appended Papers