The Impact of Wave Slamming Induced Vibration on Human Factors and Equipment on-board the S.A. Agulhas II

by
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Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering (Mechanical) in the Faculty of Engineering at Stellenbosch University

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March 2016

Declaration

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Date: March 2016

Abstract

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Hamza Omer
Thesis: MEng (Mechanical)
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An investigation of wave slamming phenomenon was performed in the context of human factors on-board the S.A. Agulhas II, a South African Polar Supply and Research Vessel. Full scale vibration measurements were conducted during the vessel's voyage to Marion Island in 2014 and Antarctica in 2014/15. The measurements captured vibrations in the vertical direction as per the directives of ISO 2631-1 (1997). A questionnaire survey was conducted on both voyages to acquire the human response to wave slamming. The study for the Marion Island voyage focused on measurement and analysis of vibration due to slamming using the metrics recommended by ISO 2631-1 (1997). The analysis revealed that slamming events produce impulsive accelerations of high magnitude resulting in broad band excitation of the vessel. The weighted r.m.s acceleration levels resulting from slamming exceeded the comfort threshold provided by the standard. The qualitative analysis of human response indicated that slamming not only caused discomfort on-board but also affected work and equipment. The study performed during the Antarctic voyage was designed to identify and correlate measured slamming vibration data with human response and to investigate their association. Statistical analysis, performed using Kendall's coefficient, indicated that slamming vibration was correlated to human complaints on-board the S.A. Agulhas II. The highest correlation found was the cumulative Vibration Dose Values (VDV) which proved to be the best metric amongst all others to represent slamming vibration for human factors. In addition to that, the study evaluated the effects of some environmental factors such as swell height and wind speed on wave slamming. It was concluded that even moderate sea states can lead to heavy incidences of slamming. Finally, operational deflection shapes were calculated for the visualization of the structural response of the vessel during bow and a stern slamming event. Time domain response and frequency response was calculated to observe the motion of the ship as it undergoes a slamming event. The analysis indicated that the area of impact (bow or stern) comes under severe loading immediately. Both slamming events produce bending and twisting of the entire structure. It was also noted that the long duration of heavy oscillations produced by slamming may affect human comfort and performance on-board the vessel.

Uittreksel

Die Impak van Branderklap Vibrasie-opwekking op Menslike Faktore en Toerusting aanboard die S.A. Agulhas II

Hamza Omer
Tesis: MIng (Meganies)
Maart 2016

Ondersoek is ingestel oor die menslike impak van ‘n branderklap-verskynsel aan boord die S.A. Agulhas II, ’n Suid-Afrikaanse Voorraad-en-navorsingskip. Volskaal vibrasie-metings is op die skip uitgevoer tydens vaarte na Marioneiland in 2014 en Antarktika in 2014/15. Die metings het vibrasies opgeneem in die vertikale rigting soos per die aanwysings van ISO 2631-1 (1997). ’n Opname was ook uitgevoer op beide vaarte om die menslike reaksie tot branderklap te verkry. Die studie vir die Marioneiland-vaart het gefokus op die meting en analise van vibrasie as gevolg van branderklap deur gebruik te maak van die maatstawwe soos aanbeveel deur ISO 2631-1 (1997). Die analise het getoon dat branderklap impulsiewe versnellings van beduidende grootte produseer wat lei to breë-band opwekking van die skip. Die geweegde w.g.k. vlakke versnellings veroorsaak deur branderklap het die standaard se ongemak drumpelwaarde oorskry. Die kwalitatiewe analise van menslike reaksie het aangedui dat branderklap nie net ongemak aan boord veroorsaak het nie, maar ook werk en toerusting geaffekteer het. Die studie uitgevoer tydens die Antarktiese vaart is ontwerp om die gemete branderklap vibrasiedata te identifiseer en te korreleer met menslike reaksie en die verband daartussen te ondersoek. Statistiese analise, uitgevoer met behulp van Kendall se koeffisiënt, het aangedui dat branderklap vibrasie gekorreleer is met menslike klagtes aan boord die S.A. Agulhas II. Die hoogste korrelasie wat gevind is, was die kumulatiewe Vibrasie Dosis Waarde (VDW) wat die beste maatstaf van almal was om die branderklap vibrasies vir menslike faktore te verteenwoordig. Daarby het die studie die effek van omgewingsfaktore soos deining-hoogte en windspoed op branderklap evalueer. Die gevolgtrekking dat selfs matige seetoestande kan lei to beduidende insidensies van branderklap is gemaak. Operasionele defleksie vorms is uitgewerk vir die visualisering van die strukturele reaksie van die skip tydens ’n boeg en agterboeg branderklap gebeurtenis. Tyddomein respons en frekwensie respons is apart uitgewerk om die beweging van die skip waar te neem wanneer dit ’n branderklap beurtenis ondergaan het. Die analise het aangedui dat die area van impak (boeg of agterboeg) onmiddelik onder belasting verkeer. Beide branderklapgebeure lei tot buiging en verwringing van die golbale struktuur. Daar word ook waargeneem dat die lang duur van ossilasies geproduseer deur branderklap menslike gemak en uitvoering prestasie op die skip kan affekteer.

Acknowledgements

I would like to start by thanking the Almighty, as nothing is possible without His will. After that, I would extend my deepest gratitude to my Supervisor Dr Annie Bekker for providing the incredible opportunity to undertake this project. She is one of the most passionate and ambitious women I have ever met. Her constant encouragement, support and appreciation has helped me immensely to grow as a researcher and I owe her the most, for the knowledge and wisdom that I have gained during this academic journey. Every meeting with her has left me motivated, challenged and inspired.

I also acknowledge my debt of thanks to my colleagues, Keith Soal, Brendan Boulle, Kim McMahon, Rosca de Waal and Hannes Swart for their help throughout the course of my masters. This work would have never been possible without their insightful arguments and regular guidance. I would specially like to thank my organization SUPARCO for funding and allowing me to take on this study. I would like to thank the Department of Environmental Affairs of South Africa for the opportunity to conduct measurements on their ship, as well as the project partners namely STX Finland, Aalto University, the University of Oulu, Aker Arctic, Rolls-Royce, DNV and Wärtsilä. And last but not the least, a heart-warm thanks, to my family for their infinite love and prayers and to all my friends here in South Africa who have made this place a second home to me.

Dedication

This thesis is dedicated to all the beautiful people of South Africa, who have enriched my life with eternal colours of love and wisdom.

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1 Introduction

Human factors are becoming increasingly important as the interaction between man and machine tends to rise. Ship design, like all other vehicles, revolves around human comfort, safety and performance. With technological advances reducing crew members every year, the comfort and wellbeing of the crew is becoming ever more critical (Dobie, 2000). In particular, polar vessels operating in Antarctica and the Southern ocean offer a challenging and harsh dynamic environment for the people on-board. Such vessels often have a hybrid design enabling them to operate both in open water and through pack ice. In order to break ice, they have thick rounded keels with no protuberances for stability, which can result into severe rolling even in light seas (Kujala, 2011). The habitability of polar vessels also becomes a vital concern as the passengers, scientists and crew often spend months on-board, living and working in this environment (Soal & Bekker, 2013).

(a) (b)

Figure 1.1: The hybrid design of the S.A. Agulhas II a) rounded bow b) flat stern

The S.A. Agulhas II is a Polar Supply and Research Vessel (PSVR) built by STX Finland. It was commissioned in April 2012 and is the backbone of South African research program in Antarctica and the Southern oceans. The vessel was built to Polar Ice Class PC 5 and was classified by Det Norske Veritas (DNV) with a comfort class notation of COMF-V(2)C(2). She is fully equipped with laboratories for the scientists to conduct on-board research. The vessel is designed to operate both in open water and ice and some design tradeoffs have been made in this regard. It has a thick rounded keel to break the ice and a flat aft section to accommodate container laboratories. Table 1.1 describes the main features of the vessel.

Table 1.1: Main features of the S.A Agulhas II

Length, bpp	121.8 m
Beam	21.7 m
Draught, design	7.65 m
Speed, service	14 kn

Wave slamming is one of the consequences of this hybrid design which can be critical for both the structure and well-being of the people on-board. It can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). This event occurs when the vessel's bow or stern emerges from a wave and re-enters the water with a heavy impact (ABS, 2011). Slamming loads are considered to be higher than any other wave loads and the impacts can damage the ship structure (Bertram, 2012). Besides the harmful effects on the structure, slamming can also affect human comfort and performance as well as cause damage to the equipment on-board (Constantinescu *et al.,* 2009). However, this phenomenon has remained understudied especially in terms of human factors.

This topic got the attention of the Sound and Vibration Research Group when it was approached by the South African Department of Environmental Affairs to perform slamming measurements on the S.A. Agulhas II in 2013. This request was motivated as a result of complaints from the captain and crew. During her voyage to Marion Island in 2013, S.A. Agulhas II experienced severe slamming incidents. The captain and the crew complained that these incidents affected the performance and comfort of the people on-board. The research work was said to be adversely affected by heavy slamming at the stern. After these complaints, the issue of stern slamming became the subject of a warranty claim between the Department of Environmental Affairs and the ship manufacturers.

A brief study done by Bekker (2013) captured and analysed induced slamming events during a trial run. This investigation found high acceleration levels due to slamming and recommended that a thorough study should be performed in operational conditions to measure the real time slamming incidents and analyse them with respect to human factors.

The aim of this research was to investigate wave slamming phenomenon in context of human factors. The focus was kept to probe the complaints and issues on-board the S.A. Agulhas II which are claimed to be caused by wave slamming. By carrying out field measurements and human response surveys, an attempt was made to answer the underlying questions about slamming effects on human comfort, performance and equipment safety. Measurements were performed during the vessel's voyage to Marion Island in 2014 and Antarctica in 2014/15. The Marion Island study, which was a pilot study, focused mainly on getting a better understanding of the phenomenon in operational conditions. This was done by performing measurement and analysis of the vibrations captured during vessels operation in rough sea, while encountering heavy slamming events. Human survey was also conducted to acquire the subjective response during these events in the context of comfort, performance, equipment use and damage. The Antarctic voyage was designed to identify and correlate measured slamming vibration data with human response and investigate their association. The study also examined these correlations to find an appropriate vibration metric to effectively quantify slamming vibrations. In addition to that, the study evaluated the effects of some environmental factors such as swell height and wind speed on wave slamming. Finally, operational deflection shapes were calculated for visualization the response of the vessel during a slamming event. A bow and a stern slamming event was analysed separately using both time and frequency domain response.

The main body of this thesis (chapter 2 to 5) is presented in an article format. Hence, each chapter has its own introduction, discussion, presentation of results and conclusion. Maintaining the stand alone character of each article has also resulted into some unavoidable repetition amongst the chapters. Chapter 2 presents a comprehensive review of the existing literature on wave slamming phenomenon and its impact on ship structure and human factors. Current comfort evaluation standards have also been reviewed in order to gauge their applicability to access slamming vibration. Chapter 3 presents the measurement and analysis of slamming vibrations encountered by the S.A Agulhas II during her voyage to Marion Island in 2014. Chapter 4 presents a detailed investigation of slamming vibration for the Antarctica voyage in 2014/15. The earlier draft of this chapter was published and presented by the author at the proceedings of the 50th United Kingdom Conference on Human Responses to Vibration, held at ISVR, University of Southampton, Southampton, England, 9 - 10 September 2015 (Appendix A). In chapter 5, operational deflection shapes are calculated and analysed for a bow and a stern slamming event. Chapter 6 and 7 contain the summary of conclusions of all the studies and recommendations for future work respectively.

2 A review of wave slamming phenomenon in ships in the context of human factors

This study reviews the existing literature in view of slamming effects on human factors. Gaps were indicated as the current literature focuses mainly on the low frequency whole body vibration and motion sickness on the ships in respect of humans. Essential evidences were provided, including the slamming influence on sleep, perceptual performance and ship environment (noise, vibrations etc.) to support the hypothesis that slamming effects human comfort and performance on-board. Available standards were discussed for the evaluation of severity of motion for slamming vibrations. It was concluded that appropriate evaluation methods to measure slamming for comfort do not exist.

2.1 Introduction

A lot of questions have been raised in the past few decades in order to take wave slamming and its effects into account. Since Von Karman, who was the first to look into slamming loads in 1929 (Karman, 1929), this phenomenon has been the focus of many studies. Researchers have studied methods of assessing slamming loads and the impacts of these loads on ship structures. Slamming has drawn some attention since it has been reported as the cause of unfortunate accidents, such as *Estonia 1994*. According to the investigation report, *Estonia* lost its bow visor due to heavy slamming which led to its sinking (Kapsenberg, 2011). This incident is still considered one of the worst peacetime disasters in maritime history. Slamming is thought to be one of the compounding factors that led to the breaking down of four container vessels in the past four decades (Storhaug, 2014).

Slamming is a random, dynamic and non-linear process involving two different responses. *Local* response focuses on the impact site which is under severe loading and is prone to damage. The *global* response of the ship, due to slamming, results in large oscillations and bending moments (Constantinescu *et al.,* 2009). According to Kapsenberg (2011), the high magnitude accelerations due to slamming cause increased loads on the container ships, which can eventually lead to a loss of containers overboard. For the same reason slamming can be troublesome for bulk carriers as well as vessels with flat stern designs.

Besides the harmful effects on the ship's structure, slamming can also affect human factors such as comfort and performance as well as cause damage to the equipment on-board (Constantinescu *et al.,* 2009). However, not much focus has been placed to conduct studies specifically to recognise the effects of slamming vibration on humans. With regards to comfort and human performance, current literature focuses mainly on the effects of low frequency whole body vibration or motion sickness on the people on-board. A lot of work has been done in determining the methods for evaluating low frequency whole body vibration or motion sickness and finding its correlation with human factors.

This study reviews the current literature related to human factors on ships and objectifies the questions that need to be answered about slamming from a human perspective. Different studies have been reviewed to provide evidence of how slamming can effect comfort and performance of the vessel occupant. Existing standards have also been compared and analysed in order to gauge their applicability to assess human comfort and health when exposed to slamming vibration.

2.2 Understanding slamming

Slamming is a complex topic vexing shipbuilders and designers alike. It can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). Figure 2.1 depicts a bow slam as the bow of the S.A Agulhas II hits the water surface during a slamming incident.

According to American Bureau of Shipping (ABS, 2013), this event occurs when the vessel's bow and stern may emerge from a wave and re-enter the wave with a heavy impact or slam as the hull structure comes in contact with the water. This results in the development of high impact loads within the structure. Due to their transient and impulsive nature, these loads can cause severe damage to the ship.

Slamming loads are generally categorized into three types (ABS, 2013).

- Bottom slamming
- Bow-flare slamming
- Stern slamming

Figure 2.1: The S.A. Agulhas II during a bow slamming incident (Soal K, 2014)

The influence of these load types depends upon different design and operational conditions of the vessel. A flat bow design may cause heavy fore-body slamming.

Flat aft designs are said to be affected by stern slamming even when the swell height is less than 1m. Such events cause heavy excitation that is felt throughout the structure. The impact of stern slamming can be reduced by increasing the speed of the ship, while bow-slamming is not influenced by this factor (Carlton & Vlasi´c, 2005). The reason is that the wave system of the ship interrupts the environmental wave system as the speed increases and serves as protection from the slamming. Slamming loads are considered to be higher than any other wave loads and the impacts can damage the ship structure (Bertram, 2012). Figure 2.2 shows a vibration signal recorded during a slamming event on a fighter ship (Swartz *et al*., 2009). The impulsive nature of slamming is evident from the signal. This is explained by the high velocity impacts that occur between the surface of the ship and water. The response of this impulse is experienced throughout the ship structure as heavy oscillations, which take a long time to die out completely. Hence, slamming vibration signal contains shock which excites a range of frequencies below 15 Hz (Bekker, 2013).

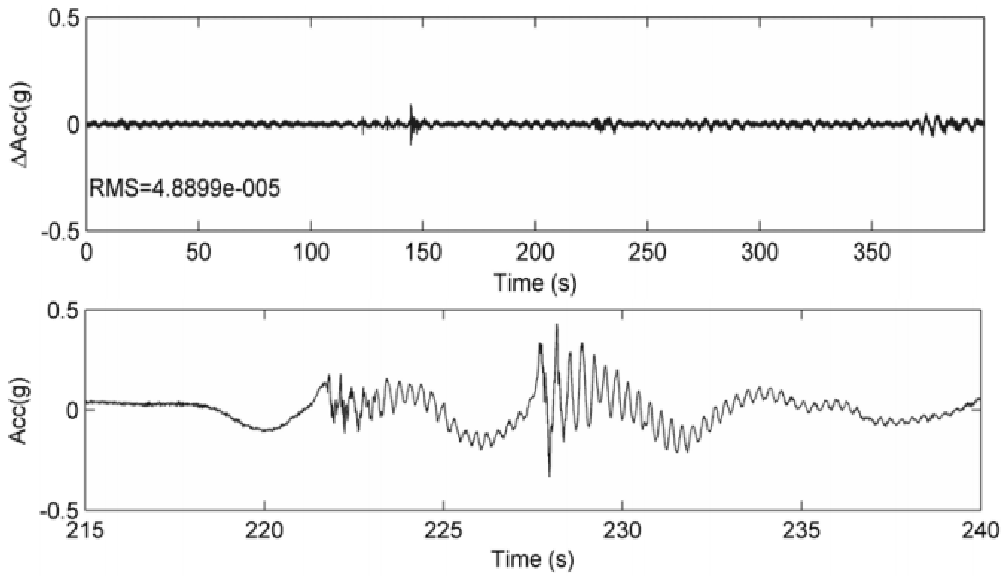


Figure 2.2: Response of the Sea Fighter measured during a slamming event on the ship bow (Swartz *et al*., 2009)

2.3 Slamming in view of human factors

According to International Ergonomics Association (IEA, 2016), human factors or ergonomics is a study that is concerned with the evaluation and improvement of the human-machine interaction. It mainly focuses on designing machines and equipment that are suitable to humans in terms of their physical and cognitive abilities. Ship design also revolves around certain factors involving human comfort, safety, performance and health. With technological advances reducing crew members every year, the comfort and wellbeing of the crew is becoming ever more critical. (Dobie, 2000)

The frequencies in the range of 2 to 12 Hz are said to affect the human performance in general (Von Gierke *et al.,* 1991). Wave slamming can generate vibrations in this range (Bekker, 2013). Samson and Parsons (2002) state that slamming can impair perceptual tasks. Additional impediments such as blur vision may occur during slamming incidents. The severity of hull/sea interaction can also be a factor that affects gross motor skills (Dobie, 2000). Bekker (2013) mentions that wave slamming interfere with the fine motor skills of the crew on-board. Tasks such as writing were said to be effected during slamming events.

Wave slamming phenomenon is considered as one of the sources that contribute to the noise on a ship (Carlton & Vlasi´c, 2005). Noise produced in such event not only adds to discomfort but also hinders tasks involving verbal communication. With context to human performance, noise can have a definite effect on verbal communication that can be distracting and irritating (Dobie, 2000). A study by Haward *et al.,* (2009) describes slamming as an environmental issue on-board. Slamming was found to be one of the major reasons for sleep interruption and tiredness. The study goes on reporting that some crew members were unable to work due to lack of sleep and tiredness. Bekker (2013) also reports complaints by the captain and the crew about sleep interference due to wave slamming.

Studies performed by Pisula *et al.,* 2012 and Haward *et al.,* 2009 investigated the effects of low frequency rigid body ship motion on crews performance, health and sleep impairment. Subjective response was collected in the form of a daily diary questionnaire for several months. The crew had to respond by answering questions such as the rating of physical and mental tasks difficultly due to ship motion. r.m.s values were calculated throughout the voyage and compared with the human response to find correlation of the ship motion with human factors. It was concluded that difficulties with physical tasks, sleep disturbance, fatigue and cognitive problems were associated with motion magnitude.

Consideration of these influences of slamming on human performance and comfort led Shigehiro & Kuroda (2001) to propose anti-pitching fins as a design feature. These fins were designed to reduce the pitching motion of the ship during slamming. The comfort of the crew was calculated using these fins and compared with the survey done with using these fins. Another method was proposed by Mosleh & El-Kilani (2005), who designed a control system to isolate certain areas of ship from vibration. The purpose of the study was to control the local oscillations from slamming in order to minimize structure fatigue and equipment damage. Same approach can also be utilized keeping human comfort in mind.

2.4 Evaluation methods of slamming

How to correctly evaluate wave slamming vibrations with respect to human comfort is the next big question. The severity of slamming acceleration, which is random, non-stationary and impulsive, should be evaluated to calculate its impact on comfort, performance and health. BS 6841 (1987) and ISO 2631-1 (1997) are two principle international standards for evaluation of whole body vibration in relation to human response (Patelli *et al.,* 2013). Guidance is provided for the measurement, reporting and evaluation of vibration. Both BS 6841 (1987) and ISO 2631-1 (1997) recommend using the root-mean-square (r.m.s) metric as the basic method to evaluate whole body vibration comfort. However, r.m.s tends to provide an inaccurate estimate of discomfort produced by shocks, as in case of slamming vibrations. This is explained by the fact that r.m.s is an averaging metrics and its time dependency deems it inappropriate for a non-stationary signal (Griffin & Whitham, 1980).

$$r.m.s = \left[1/T \int_0^{\mathrm{T}} a_w^2\ (t)\mathrm{dt}\right]^{1/2} \tag{2.1}$$

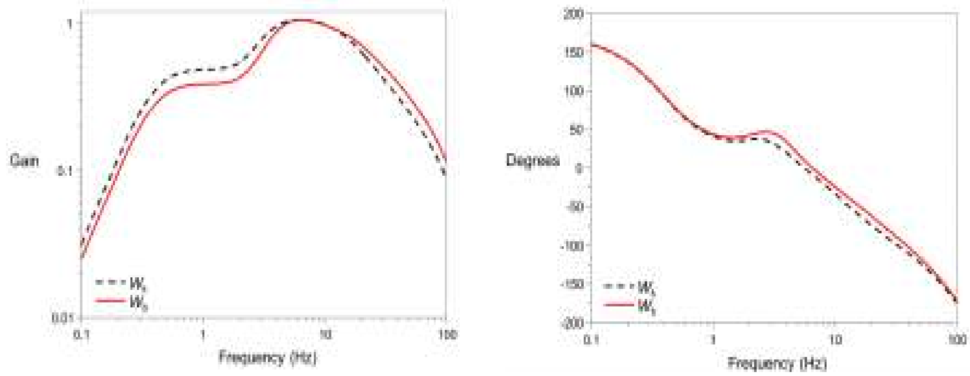
Vibration Dose Value (VDV) is recommended to estimate vibration when a mixture of shocks and vibration are present in vibration exposure. VDV accrue vibration exposure over the measurement period and therefore provides better predictions for the severity of motion for impulsive vibrations.

$$VDV = \left[\int_0^{\mathrm{T}} a_w^4\ (t)\mathrm{dt}\right]^{1/4} \tag{2.2}$$

Crest Factor (CF) is defined as the ratio between peak and r.m.s acceleration. It is provides a measure of the impulsiveness of an acceleration signal. ISO 2631-1 (1997) suggests calculating VDV to evaluate vibration exposure when the CF value is or above 9.0. On the other hand, BS 6841 (1987) suggest calculating VDV only when the crest factor reaches 6.0.

$$CF = \frac{peak\ acceleration}{r.m.s\ acceleration} \tag{2.3}$$

As human comfort is highly dependent on the frequency of vibration (Griffin, 1990), both standards provide the frequency weightings for all six axes of oscillation in the frequency range 0.5 to 80 Hz. However, the standards have different frequency weighting filters. It can be observed from Figure 2.3 that the gains of ISO 2631 (1997) vertical frequency filter W_k affords a bit more weightage to lower frequencies than the BS 6841 (1987) vertical frequency filter W_b. Also, both filters have slightly different phases. According to Patelli *et al.,* (2013), these two factors can lead to different estimations of severity of motion by both standards in case of a shock waveform.



(a) (b)

Figure 2.3: Comparison of human weighting frequency filters for vertical vibration W_b and W_k given by ISO 2631 (1997) and BS 6841 (1987) respectively, a) Gains of frequency weighting W_b and W_k b) Phases of frequency weighting W_b and W_k, (Patelli *et al.*, 2013)

It is important to note that the information for implementing these filters provided by the standards is only applicable to the data recorded in frequency domain. However, most of the data acquisition devices used for measuring vibration for human exposure record data in the time domain. Rimell & Mansfield (2007, 2010) proposed a method to apply the weighting filters provided by the standard for digital signals. This method uses digital Infinite Impulse Response (IIR) filters to implement the weighting filters given by the standards.

To account for single or multiple shocks solely in relation to human health, ISO 2631-5 (2004) was developed. Unlike the other two standards, ISO 2631-5 (2004) employ a spinal method to estimate the impact of motion in the lower lumbar spine. The lumbar spine is believed to be affected the most by shock; this method calculates the fore aft, lateral and vertical accelerations in the spine of a seated person. Health risk is estimated by calculating a daily exposure value which is used to determine an equivalent daily stress. This is the representation of the static compressive stress in the spine, in mega-pascal (*MPa)*. The standard provides limiting values for the probable adverse health effects using these stress values. Vibration Directive (2002/44/EC) by the European commission also provides a vibration exposure limit value and daily action value for health risk and safety of the workers. The whole-body-vibration limits can be calculated using VDV for an 8-hour reference period.

Besides these whole body vibration evaluation standards, Det Norske Veritas (DNV) 2003 Comfort Class Rules also provides vibration limits for single frequency components between 5 and 100 Hz. It also specifies the acquisition, processing and reporting of the vibration measurements. International standard ISO 6954 (2000) is also used to evaluate the human exposure to vibrations on-board ships by providing guidelines for habitability. However, the overall shipboard vibration is also calculated in terms of an overall frequency-weighted r.m.s. value, in the range from 1 Hz to 80 Hz (Savreux K *et al.,* 2007).

2.5 Discussion

Literature has hinted at the effects of slamming on comfort and human performance. Slamming has been regarded as the cause of disturbance and lack of sleep (Haward *et al.,* 2009). This can prove challenging on a bad night in rough seas. It has been observed that workers cannot perform adequately when they are tired and sleepless. Evidence suggests that vision is distorted as well as the motor skills. In the case of a research vessel, where experiments are to be executed on-board, slamming can adversely affect the task performance of the scientists. Noise produced by slamming is found to be an issue on-board. This not only contributes to discomfort but can also cause sleep interruptions.

Until now, there appears to be a gap in the literature concerning slamming effects on humans. It is suggested that field measurements should be performed in order to capture slamming events along with the human response. This subjective response can be acquired from the passengers and crew on-board in the form of a daily dairy as done by previous studies on ship motion sea sickness (Pisula *et al.,* 2012 and Haward *et al.,* 2009). The statistical data from the subjective response should be correlated to the measurements performed on the ship for slamming throughout the voyage. This can prove effective to determine the effect slamming has on human performance and comfort. Systematic studies could be conducted through vibration reconstruction in a laboratory environment to analyse how motor skill and cognitive and perceptual tasks are affected during the event of slamming. The same can be done for understanding the relationships between slamming and the performance of physical tasks.

BS 6841 (1987) and ISO 2631-1 (1997) are two principle international standards for the evaluation of whole body vibration in relation to human response. According to a comparison done by Marjanen (2005), there is an agreement that ISO 2631 (1997) and BS 6841 (1987) underestimate transient shocks. Patelli *et al.,* (2013) also states that both ISO 2631-1 (1997) and BS 6841 (1987) are not satisfactory for determining the discomfort produced by shock waveforms. This study also states that using frequency weightings defined in these two standards may not be appropriate for evaluating discomfort for impulsive and transient signals. r.m.s. is an averaging metric and provides a non-robust quantification when the acceleration signal is impulsive. VDV on the other hand, tends to estimate the severity of motion in a cumulative way which results in the same magnitude irrespective of the measurement time. However, it is critical to note that no comfort threshold is provided by the standard to relate VDV values to human comfort. It is vital to notice that r.m.s and VDV values do not correlate with each other as well, because they emphasize amplitudes differently (Marjanen, 2005).

Despite the fact that ISO 2631-5 (2004) provides comprehensive insight for calculating shock severity with respect to health, some inadequacies are also present. This method cannot be used with any posture other than sitting. Also, the standard assumes that the subject is in an upright position and will not leave the seat during vibration exposure. This method is strictly for the use of assessing health risk. It cannot be used for evaluating discomfort as discomfort does not originate from the motion in lumbar spine Patelli *et al.,* (2013). Hence it may be concluded that the existing methods for analysing severity of slamming vibrations with respect to comfort are insufficient. There is a need for improved methods for calculating human comfort because of the weaknesses of the available metrics in estimating the impacts of transient shocks.

2.6 Conclusion

Wave slamming can prove to be perilous to humans, equipment and ship structures. The need has been identified to look into the matter with respect to human comfort, performance and equipment safety as no specific study has ever been conducted in this regard. Evidence on these issues such as slamming interference with sleep, motor skills and perceptual tasks is provided from the available literature. This leaves a potential to study human comfort, health, performance and equipment safety which is observed to be on a risk during slamming events. This can be done by performing a survey substantiated by field measurements of actual slamming incidents. Similarly, if these factors are to be found critical, suggestions to enhance the ship design can be made. Some useful techniques like vibration isolation and use of anti-pitching fins could be implemented to mitigate the slamming. Systematic studies are needed to fill the information gap in the desired areas such as slamming effects on motor or perceptual skills. As such, it has also been concluded that appropriate evaluation methods to measure slamming for comfort do not exist. There is a need to improve the existing standards to encompass slamming shock with respect to human comfort and safety such that the potential complaints can be predicted by a robust metric.

3 Slamming vibration analysis in context of human comfort on the S.A. Agulhas II during a voyage to Marion Island

Wave slamming vibration can be critical for ships. Besides the harmful effects on the ship structure, slamming is also said to affect humans on-board. However no detailed studies have been done to investigate wave slamming effects on human comfort and performance. Full scale measurements were conducted on the S.A. Agulhas II, a South African Polar Supply and Research Vessel, during a 35 day voyage to Marion Island in 2014. Subjective responses were acquired through a questionnaire survey. Slamming vibration was captured and analysed using ISO 2631-1 (1997). The low response rate to the survey resulted in a solely qualitative evaluation of the subjective response. The r.m.s acceleration levels resulting from slamming were high and exceeded the comfort threshold given by ISO 2631-1 (1997). The signals were found to have crest factors greater than 9.0. The qualitative analysis of human response revealed that slamming not only caused discomfort on-board but also affected work and equipment.

3.1 Introduction

Ship environments can be subjected to many sources of vibration induced by surrounding sea conditions, engine, shaft line and machinery on-board (Dobie, 2000). Wave slamming is considered as one of the sources that contribute to the vibration on a ship (Carlton & Vlasi´c, 2005). It can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). This event occurs when the vessel's bow or stern emerges from a wave and re-enters the water with a heavy impact (ABS, 2011).

Bekker (2013) describes slamming response as an impulsive phenomenon. This is explained by the high velocity impacts that occur between the surface of the ship and water. The response of this impulse is experienced throughout the ship structure as heavy oscillations which take a long time to die out completely. The same study also reports that slamming vibration excites a range of frequencies below 15 Hz. Slamming loads are considered to be higher than any other wave loads and the impacts can damage the ship structure (Bertram, 2012).

In addition to the harmful effects on the ship's structure, slamming can also affect human factors such as comfort and performance as well as cause damage to the equipment on-board (Constantinescu *et al.,* 2009). A study by Haward *et al.,* (2009) describes slamming as an environmental issue on-board as it was found to be one of the major reasons for sleep interruption and tiredness. The study proceeded to report that this fact made some crew members unable to work. Another study claims that the severity of slamming vibration can possibly affect the motor skills of the vessel occupants and can cause blurring of vision and difficulties with cognitive skills such as interpretation (Dobie, 2000). Stevens and Parsons (2002) also state that slamming can impair the perceptual tasks of the ship occupants. It is also considered as one of the sources that contribute to the noise on a ship (Carlton & Vlasi´c, 2005).

None of the reviewed studies were specifically investigating slamming and its impacts on humans. At present, literature focuses on either the effect of low frequency whole body vibration or motion sickness on human factors. Hence it is safe to say that not much has been done in order to investigate the effects of slamming regarding human comfort, performance and equipment on-board.

In this regard a full scale vibration measurement was performed on the SA Agulhas II during her 35 day voyage to Marion Island in 2014. Continuous measurements at two different locations recorded the vibration during the vessels operation in rough seas and slamming encounters. The data was recorded and evaluated according to the vibration metrics recommended ISO 2631-1 (1997). The standard describes the methods to measure and analyse whole body vibration. It also provides guidelines to access human comfort, health, perception and motion sickness. A human response survey was conducted to relate the vibration analysis to the subjective response.

3.2 Methodology

3.2.1 Voyage description

The S.A. Agulhas supports research in Marion Island through an annual voyage from Cape Town, South Africa. This voyage comprises of three legs. The first leg entails the transport and off-loading of cargo and personnel at the Marion Island base from Cape Town. The second leg serves as an oceanographic leg as it includes sampling of sea water and deployment and retrieval of oceanographic data measurement systems at certain locations further south of the island. The final leg involves a return voyage to the island to reload cargo and personnel for the return to Cape Town.

3.2.2 Measurement plan and instrumentation of the ship

Full scale measurements were performed on the S.A. Agulhas II during a voyage between Cape Town and Marion Island. Vibration was measured continuously in the vertical direction at two different locations on the ship. Two previous studies done on the S.A Agulhas II indicate that the vertical acceleration levels are dominant (Bekker, 2013; Soal & Bekker, 2013).

The relevant locations were selected for the placement of the two accelerometers. One sensor was placed on Deck 8 which is an accommodation area of the officers and the other sensor was placed on Deck 3, at the stern, where the laboratory containers are located (Figure 3.1). Deck 8 data represents the accommodation space whereas Deck 3, which is also close to the impact site, represents the working space for the scientists. Hence these two sensors captured the vibration of the locations where the vessel occupants were likely working or relaxing.

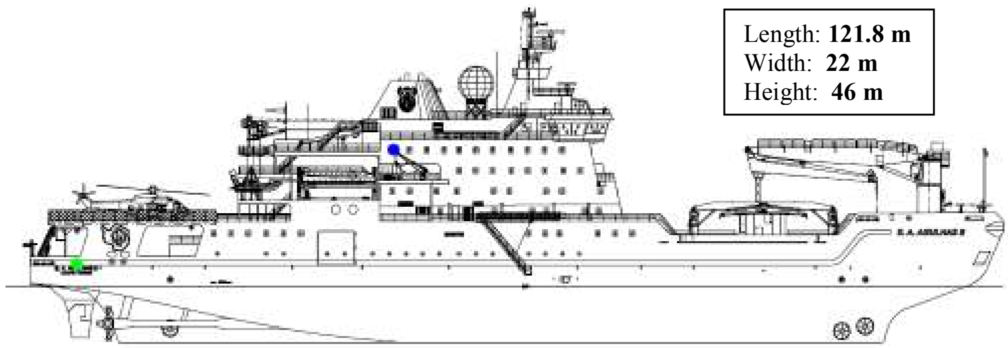


Figure 3.1: Location of the accelerometers on Deck 3 and Deck 8

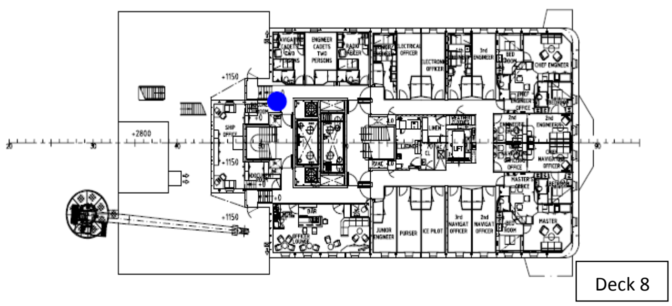


Figure 3.2: Location of accelerometer on Deck 8

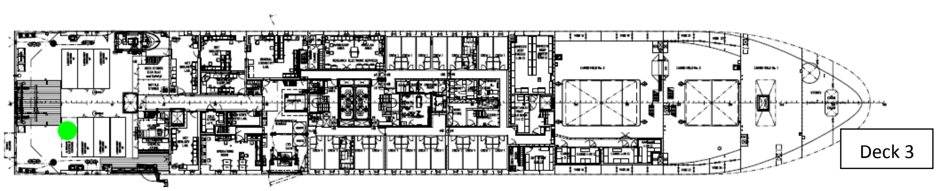


Figure 3.3: Location of accelerometer on Deck 3

Two LMS SCADAS mobile data acquisition units were used in a master slave configuration to capture the vibration data in the two locations. Furthermore, PCB piezoelectric ICP accelerometers *(Model no 333B32)* were used for this study as they have an appropriate frequency range of 0.5 to 3000 Hz and average sensitivity of 100mV/g. A sample rate of 2048 Hz was selected and measurements were recorded continuously with a record length of 5 minutes.

3.2.3 Vibration data processing

The ship set sail on 4 April 2014 and returned on 8 May 2014. During the total 35 day voyage, the ship operated in open water and vibration data was recorded continuously. The post processing and analysis of the vibration data was done using *MATLAB* and *LMS Test.Lab Turbine Testing13A* according to ISO 2631-1 (1997). Each 5 minute measurement was human weighted using the W_k filter for vertical vibration (ISO 2631-1, 1997) in the time domain using the methodology proposed by Rimell & Mansfield (2007, 2010). The Matlab code developed for this purpose is presented in Appendix B.

Throughout the voyage, the roughest weather and heaviest slamming events occurred between 16 April 2014 and 23 April 2014. During this time the ship was south of the Marion Island to perform oceanographic research. The results presented in this study are from these eight days. According to ship log book, extreme pitching and heavy swells were encountered during this period leading to severe slamming. The wave height reached a maximum value of 12 m while the average wave height for this period was 5.6 m.

Vibration data for these eight days was analysed by calculating the vibration metrics recommended by ISO 2631-1 (1997). These include weighted peak and *r.m.s* values for all the 5 minute data records. Weighted r.m.s values were used to investigate if the vibration exceeded the comfort threshold provided by ISO 2631-1 (1997). To verify the impulsive nature of slamming, Crest Factor (CF) was also calculated. According to ISO 2631-1 (1997), crest factor is the measure of impulsiveness of a signal. The standard recommends that if the CF value is greater than 9.0 then the Vibration Dose Value (VDV) should be calculated. According to Griffin (1990), VDV is the cumulative measure of the vibration and shock experienced by a person during the measurement period. Hence, VDV values were also plotted and analysed.

3.2.4 Human response survey

Human comfort and performance is considered to be a subjective issue. While effects of slamming on human comfort and performance still remain understudied, a survey was planned to gather subjective response from the vessel occupants. A questionnaire (presented in Appendix C) was prepared as a daily dairy. The questionnaire included a rating for slamming events and its impacts on sleep, comfort, task performance and sensitive equipment use. The design of the questionnaire was based on the methodology by Haward *et al.,* (2009) which investigated the effects of ship motion on the crew of an oil production and storage vessel. However, for the current study, subjects were asked to respond in context of wave slamming and they were to fill in only if slamming was experienced for that day. The survey was anonymous and was distributed amongst the 50 crew members and the 96 passengers aboard, with instructions before the departure of the vessel.

3.3 Results

3.3.1 Peak values of acceleration

Figure 3.4 presents the weighted peak acceleration values, for each of the 5 minute recordings on Deck 3 and Deck 8. Peak values for Deck 3 are much higher than Deck 8; however, there is consistency in the trend of the acceleration values for both decks. The highest values for both sensors are recorded between 17 and 20 April. The transmissibility of the ships super structure may cause the reduction of vibration levels as Deck 3 is very close to the site of impact of wave slamming.

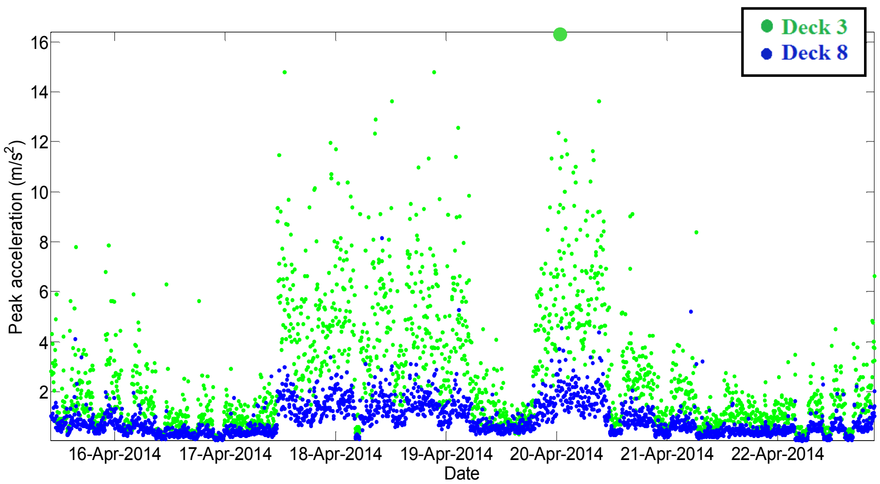


Figure 3.4: Peak values of weighted vertical acceleration on Deck 3 and Deck 8

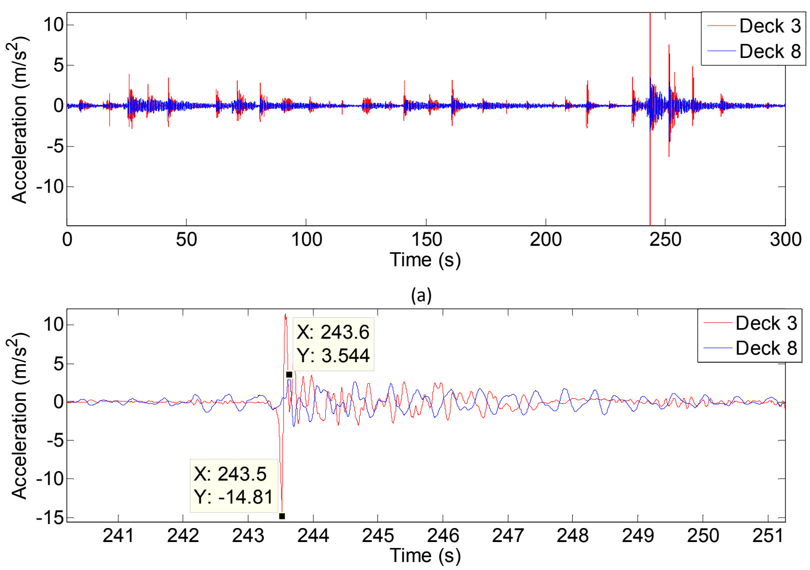
The high levels of vibration are clearly evident in Figure 3.4. However, there is still a need to prove that these levels are caused by slamming as the ship may be exposed to different vibration environments. Hence the investigation of the maximum vibration acceleration signal was performed to validate that high vibration levels are caused by wave slamming.

3.3.2 Investigation of the maximum acceleration event

The maximum acceleration event was recorded on 20 April 2014 at 12:49:34 GMT at the stern of the vessel. The average wave height was recorded to be 7 m reaching up to 12 m according to the ship log book. The wind direction was WSW and the ship heading was 065^{o} i.e. the ship almost sailed perpendicular to the swell for some time. Significant pitching motion was encountered and the worst slamming incident was recorded during these conditions. Later on the ship heading was changed to sail into the swell to avoid heavy pitching.

Figure 3.5 shows the time history of the weighted maximum acceleration signal on Deck 3 and Deck 8. Looking at the time history of the signal four important observations can be made.

- The time history indicates high magnitudes of acceleration.
- The vibration signal is impulsive, transient and non-stationary in nature.
- The peaks occur almost at the same time on both decks referring to the vibration as an event which was experienced globally throughout the ship.
- The oscillatory response post the slamming event, also referred to as whipping (Dessi D, 2014), continuous for several seconds and does not die down immediately.



(b)

Figure 3.5: Time plot of weighted peak acceleration a) 300 s time history of the peak signal b) time history of the peak event (zoomed in)

These facts indicate that vibration is impulsive and transient impact which is felt throughout the ship. Also, slamming impact generates high levels of acceleration which resonate for some time before dying out. The power spectral density (PSD) of the event was calculated using *pwelch.m* command in MATLAB with 50 % overlap, *Hanning* window and a frequency resolution of 0. 25 Hz (Figure 3.6). The PSD plot shows that the vibration signal excites a broad range of frequencies from 1 to 12 Hz including peaks from the resonant responses and harmonic excitations. Hence it can be concluded that the peak acceleration can be attributed to the slamming vibrations. A similar procedure was carried out for the dominant peak acceleration signals to confirm that the vibrations under consideration were caused by wave slamming phenomenon.

After establishing this fact, analysis can be can carried out in context of wave slamming and the resulting effect on human comfort.

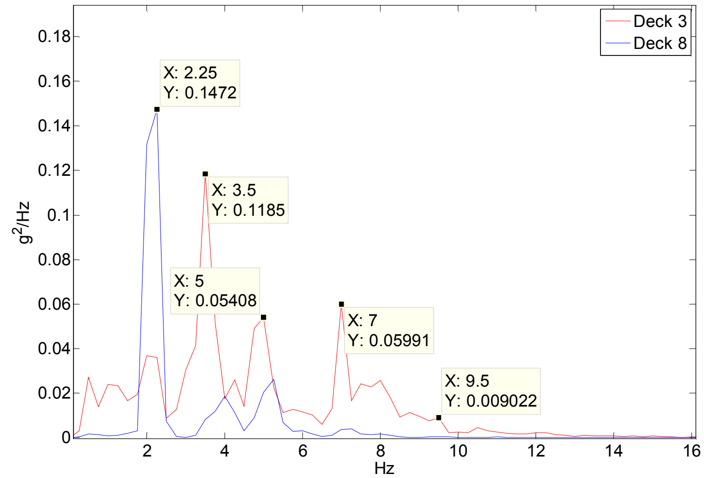


Figure 3.6: The PSD plot of the peak slamming event

3.3.3 ISO 2631-1 (1997) comfort metrics

The r.m.s values for each 5 minute recording of the acceleration follows the same trend as peak values. The highest values are found between 17 to 20 April 2014, same as the peak values. Once again, Deck 3 has the higher values of acceleration compared to Deck 8, however the difference between the maximum r.m.s values amid both decks is reduced as compared to the peak acceleration values. This is noticeable from Table 3.2. These weighted r.m.s values are used for the evaluation of comfort according to ISO 2631-1 (1997).

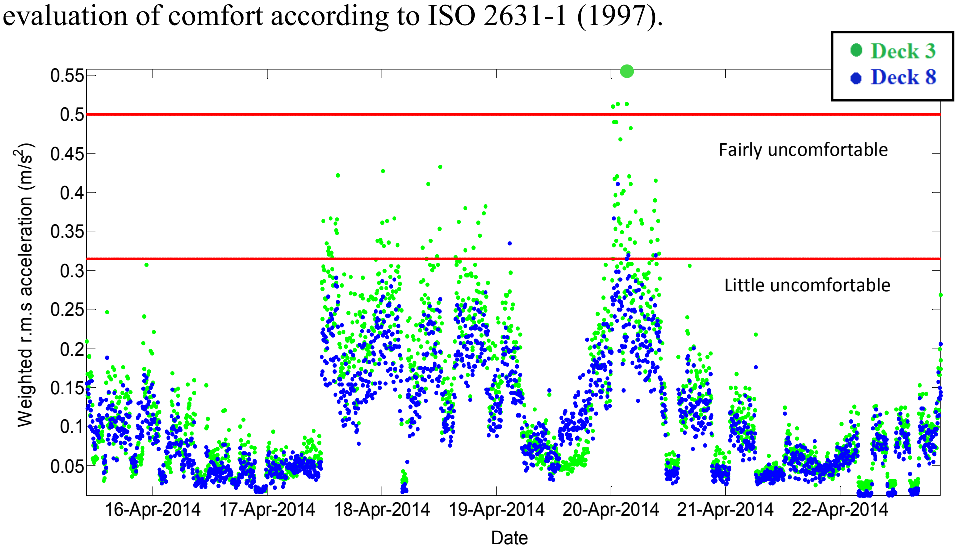


Figure 3.7: Comfort evaluation for Deck 3 and Deck 8 according to ISO 2631-1 (1997)

ISO 2631-1 (1997) provides threshold of the r.m.s values for the perception of human comfort. Figure 3.7 shows the weighted r.m.s values for both decks. It can be seen that the vibration levels during these eight days exceeded the comfort threshold on both decks on several occasions. Levels for Deck 3, being higher, were considered as "Fairly uncomfortable".

Table 3.1: Comfort threshold evaluation

r.m.s. vibration level	Perception	Number of times threshold exceeded on Deck 3	Number of times threshold exceeded on Deck 8
0.315 m/s^2 to 0.63 m/s^2	Little uncomfortable	84	6
0.5 m/s^2 to 1.0 m/s^2	Fairly uncomfortable	4	0

The plots in Figure 3.8 show the CF for both decks using human weighted peak and r.m.s values.

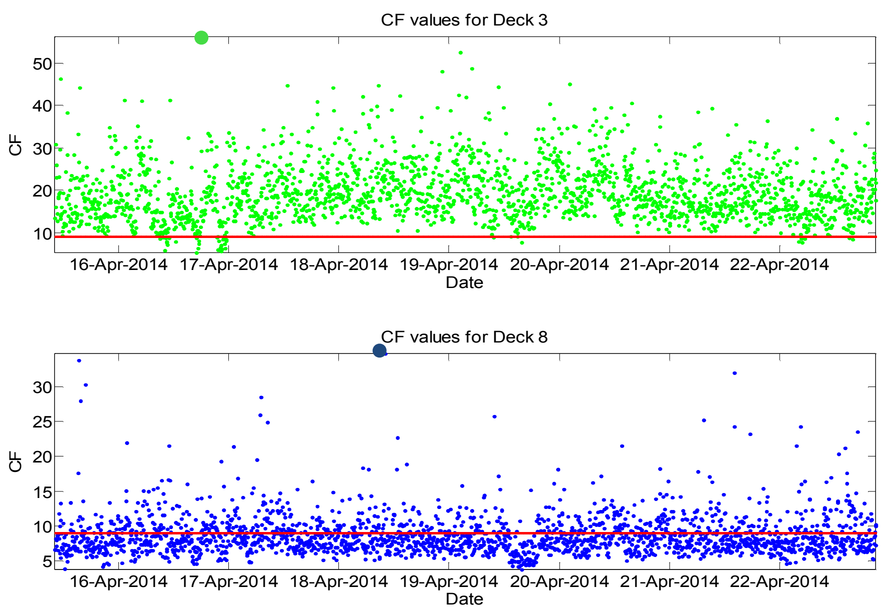


Figure 3.8: CF values on Deck 3 and Deck 8

For Deck 3, almost all (98.4 %) CF values are above 9.0, and the mean value is calculated to be 19.5. On Deck 8, 35.2 % of the CF values exceed 9.0. This clearly reveals the impulsive nature of wave slamming vibration. A considerable difference between the values on both decks is also noticeable. This can be explained by keeping the peak value signal analysis in mind. The time plot of the peak signal showed very high peaks for Deck 3 acceleration unlike Deck 8. Also the difference between the r.m.s is lower than the difference in the peak values.

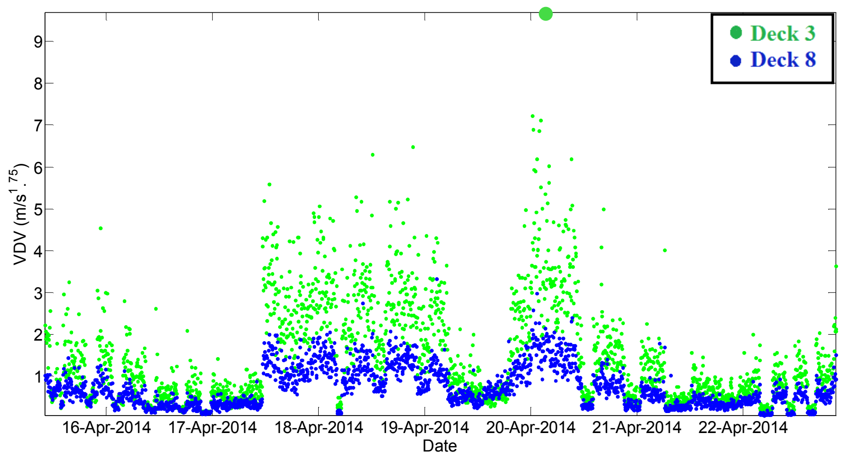


Figure 3.9: VDV values for vertical acceleration on Deck 3 and Deck 8

As CF values are quite high, the calculation of VDV is performed as recommended by ISO 2631-1 (1997). Figure 3.9 presents weighted VDV's for Deck 3 and Deck 8. Again, the higher values are found between 17 to 20 April 2014, as predicted by other metrics. However, it can be observed that the mean VDV values for Deck 3 are twice as high as for Deck 8. This is different than predicted by r.m.s values.

Table 3.2: Maximum and Mean values for each deck

Metrics	**Deck3**		**Deck8**	
	Max	Mean	Max	Mean
Peak	16.4	2.67 ± 2.47	8.17	0.9 ± 0.67
r.m.s.	0.56	0.13 ± 0.09	0.41	0.1 ± 0.07
CF	56.4	19.5 ± 6.6	35.0	8.9 ± 4.19
VDV	9.7	1.48 ± 1.22	3.33	0.72 ± 0.48

3.4 Questionnaire response

The survey conducted through the questionnaire did not receive the expected participation. The response rate of 40 % for the first 8 days dropped to 12 % after a week. This factor limited the planned use of the survey for quantitative analysis and comparison with the measured data. However some mentioned comments and reported incidents do provide useful insight as to the discomfort and possible equipment damage caused by slamming. Some of these comments are presented below.

Subject M59 revealed herself as the chief scientist and wrote:

"I have spent 35 days on-board this vessel and not one day went by where the ship did not slam or shudder! The slamming not only affects our instrumentation but sleep + mood patterns. The dairy will not do justice to the problem. Please use this note as further motivation to your study on the need to rectify this problem"

Subject M49 commented that:

"Firstly, the semi-predictable slamming of the ship has the potential to damage the deployment of expensive scientific equipment/instruments (e.g. CTD /winch systems and Sea Gliders). Secondly , the slamming of the ship also prevents some oceanography from being done since aft deck activities become extremely dangerous/impossible during serious sessions of slamming …,… and thirdly, slamming does not specifically prevent me from sleeping , but severe slamming more often than not wakes me up "

Subject M40 reported *"equipment malfunction for three times and lack of sleep during events of heavy slamming.*

Subject M15 reported that he *"snapped his CTD cable twice, due to slamming".*

Subject M30 on several occasions, reported sleeplessness, lower back pain and task delay (reading writing physical work etc.) due to slamming interference.

These comments indicate the severity of the wave slamming issue aboard the S.A. Agulhas II during her operation in open water. This brief subjective response from scientists on-board highlights the following aspects of slamming in terms of human factor:

- Slamming affects human comfort and causes sleep interruptions
- Slamming can be hazardous to sensitive equipment
- A heavy slamming session can be perilous and prevents the performance of scientific activities at the aft of Deck 3 where container laboratories are mounted

3.5 Discussion

Measurements on-board the S.A. Agulhas II reveal high peak levels of acceleration as a result of slamming events, which can be regarded as fairly uncomfortable. The stern section of Deck 3, which hosts the container laboratories for scientists, was highly affected by stern slamming as it is located in a close proximity to the wave impact site. The accommodation space on Deck 8 was also affected but the extent was less than Deck 3 due to the structural transmissibility between the impact site and the officer's accommodation in the super structure. The qualitative assessment of the subjective response showed that slamming not only disturbs the comfort and performance but can be a safety hazard. Heavy slamming incidents cause the suspension of activities on Deck 3 as a result of high pitching motion and violent wave activity. Slamming also caused sleep interruptions and interfered with fine motor tasks such as writing and perceptual tasks like reading, watching TV etc. Finally, there were reports of sensitive equipment malfunction and damaging of the cables that were used to deploy and recover the oceanographic equipment in the ocean.

The predisposition of the vessel to stern slamming can be explained due to raised and flat design of the hull in this area. During high swells and rough weather, the waves strike this large surface area which results in stern slamming. Flat aft designs are said to be affected by stern slamming even when the swell height is less than 1m (Carlton & Vlasi´c, 2005). These impacts cause heavy excitation that is felt throughout the ship structure. The other significant factor that contributes towards making slamming a critical issue on-board the S.A. Agulhas II is performance of the oceanographic operations. Throughout these eight days of the voyage the ship was required to stop at certain locations. The oceanographic equipment was deployed and recovered to obtain sea water samples specific sites. This operation takes 1 to 5 hours depending on the depth of the cast and the ship remains on station for the entire time. According to Carlton & Vlasi´c (2005), stern slamming is highly dependent on ship speed. If stationary, the aft of the ship is more prone to wave slamming whereas increasing the speed can reduce the effect by interrupting the environmental wave system.

From the analysis of the vibration data, it can be seen that peak acceleration values for Deck 3 are almost twice as high as on Deck 8. This is in agreement with the fact that Deck 3 is fairly close to the location of the impact whereas Deck 8 is situated in the super-structure. However when r.m.s values are considered, it is observed that the difference for the values between both decks has been greatly reduced. This indicates the fact that r.m.s metric subdues impulsive vibration by averaging over the measurement duration. The analysis of the calculated VDV values on the other hand show similar tendency as peak value results. The mean VDV values for Deck 3 are almost twice as high as for Deck 8. Calculating VDV seems to work better as ISO 2631-1 (1997) recommends its use if the crest factor is high. However it is critical to note that no comfort threshold is provided by the standard to relate these VDV values to human comfort. Vibration

Directive (2002/44/EC) by the European commission which provides limits for VDV are only in the context of human health and not comfort.

Wave slamming vibrations are impulsive and non-stationary random in nature. According to Patelli *et al.* (2013), existing standards such as ISO 2631-1 (1997) and BS 6841 (1987) are not satisfactory for determining the discomfort produced by shock waveforms. This study also states that using frequency weightings defined in these two standards may not be appropriate for evaluating discomfort for impulsive and transient signals. Hence it may be concluded that the existing methods for analysing severity of slamming vibrations with respect to comfort are insufficient. The r.m.s. metric which is well calibrated for the assessment of comfort is not robust for the assessment of high crest factor vibration caused by slamming. Alternatively, VDV is robust, yet not well calibrated to the onset of discomfort.

3.6 Limitations and future recommendations

The present work was carried out through an unmanned measurement and surveying effort. The ship was instrumented before departure and the questionnaires were handed out with instructions to the vessel management. This fact resulted in a few challenges. One of the main disadvantages was not being able to personally experience, observe and note the slamming incidents. This would have provided a better insight of the problem on-board the S.A. Agulhas II. The participation rate for the survey could have been increased by personal presence and the motivation of other passengers towards filling the questionnaire every day. Besides this factor, it was realised that the design of the questionnaire was very complicated. The majority of the respondents found the questionnaire difficult and filling it daily was a cumbersome task. The vibration comfort levels were only measured at Deck 8 whereas the accommodations spaces are allocated in lower levels of the vessel such as Deck 4. The reason was that the connection-cables for the placement of the sensor are routed throughout the ship were only available on Deck 8. It is speculated that the levels of vibration would be higher than Deck 8 on the lower decks. Located closer to the site of impact, the comfort of the passengers on these decks would have been increasingly affected.

There is a need to design a comprehensive method of identifying a slamming event from the measured vibration data. Future work should include a method to isolate slamming vibrations in the measurement data and hence only use these events to correlate with human factors. It is suggested that a manned study should be carried out which involves a survey with a simplified questionnaire. The statistical data from the subjective response should be correlated to the measurements performed on the ship for slamming throughout the voyage. Different metrics such as peak, r.m.s and VDV can be correlated to the human response to determine their suitability for evaluating the effects of slamming on vessel occupants. Systematic studies can be conducted in the laboratory to further validate these finding. Slamming vibrations can be recreated in a laboratory environment to perform systematic studies of human response to slamming stimuli. Experiments can be designed specifically on how motor skills and perceptual tasks are affected during the event of slamming. The same could be done for understanding the relationship of slamming to the performance of physical tasks.

3.7 Conclusion

Evaluation of measured data and subjective responses confirm that slamming is a problem in terms of human factors on-board the S.A. Agulhas II. The analysis of the vibration levels captured during the oceanographic leg of the Marion Island voyage exceeded the comfort threshold on Deck 3 and Deck 8, according to ISO 2631-1 (1997). Crest factors exceed the value of 9.0 and therefore VDV is deemed an appropriate metric. However, the standard does not contain guidelines for the onset of discomfort as a result of impulsive vibration. The hybrid design of the ship is believed to be a contributor towards making slamming an issue during open water operations. Slamming at the stern gets worse when the ship operates on station to perform oceanographic tasks. Subjective response also highlights the criticality of this phenomenon in terms of safety of humans and equipment due to high levels of vibration and violent wave action at Deck 3. There is a need to improve the existing standards to encompass slamming with respect to health and comfort. Systematic studies are also deemed to be useful for providing potential insight into the effects of slamming on human performance and comfort.

4 A study of wave slamming vibrations and analysis in the context of human factors on the S.A Agulhas II during a voyage to Antarctica

Polar vessels operating in Antarctica and the Southern Ocean often have a hybrid design due to their operation in both ice and open water. Wave slamming is one of the consequences of these hybrid design attributes such as a rounded keel or a flat stern section. As critical as these impulsive vibrations due to slamming can be, no detailed studies have been performed as to how they affect human comfort and performance on-board. This study analyses slamming vibration in the context of human factors. Full scale measurements were performed on the S.A. Agulhas II during a voyage to Antarctica according to the ISO 2631-1 (1997). A survey was also conducted to gather the human response. The vibration caused by wave slamming was found to be strongly correlated with human problems on-board the S.A. Agulhas II. The highest correlation found was the cumulative Vibration Dose Value (VDV) values which proved to be the best metrics amongst all others to represent slamming vibration. Sleep and equipment use was found to be the most affected parameters by slamming. There was a marked increase in the reports of respondents considering a slamming event to be 'severe' when the cumulative VDV acceleration exceeded 6.0 $m/s^{1.75}$ at the stern of the vessel. Finally, an investigation was also done to determine the effects of some environmental factors such as swell height and wind speed on the wave slamming phenomenon. It was concluded that even moderate sea states can lead to heavy incidences of slamming.

4.1 Introduction

Polar vessels operating in Antarctica and the Southern oceans are exposed to a harsh dynamic environment. Such vessels often have a hybrid design enabling them to operate in both open water and pack ice. In order to break ice, they have thick rounded keels with no protuberances for stability, which can result into severe rolling even in light seas (Kujala, 2011). The habitability of polar vessels is important as passengers, scientists and crew often spend months on-board, living and working in this dynamic environment (Soal & Bekker, 2013).

Wave slamming is one of the consequences of these hybrid design attributes that can be critical for both the structure and well-being of the people on-board. It can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). This event occurs when the vessel's bow or stern emerges from a wave and re-enters the water with a heavy impact (ABS, 2011). Constantinescu *et al.*, (2009) describe slamming as a random, dynamic and non-linear event affecting the structure of the vessel, both globally and locally. *Local response* refers to the area of the impact site which is under severe loading and is prone to damage in case of repetitive impacts. The *global response* refers to the large oscillations and bending moments felt throughout the vessel. As a result, the high impact loads can damage the structure of the vessel (ABS, 2011).

Besides the harmful effects on the ship's structure, slamming can also affect human factors such as comfort and performance as well as cause damage to the equipment (Constantinescu *et al.,* 2009). However, impacts of slamming on humans have been under-studies. As such it remains to determine how slamming correlates to human factors. There is a need to develop a better understanding of methods to evaluate slamming vibration which is impulsive and transient in nature. BS 6841 (1987) and ISO 2631-1 (1997) are two principle international standards for the evaluation of vibration in relation to human response but they are unsatisfactory for the determination of discomfort produced by shock waveforms (Patelli *et al.,* 2013). A comparison done by Marjanen (2005) also concludes that both of these standards underestimate transient shocks.

To this end an investigation was conducted to analyse slamming vibration in the context of human factors. Full scale vibration measurements were performed on the S.A. Agulhas II during her voyage to Antarctica in the Southern Ocean. A survey was conducted in the form of a daily diary to be completed by the passengers on-board. The survey questionnaire was prepared in order to acquire the human response to the effects of slamming on comfort, performance, equipment use and safety. The vibration measurements and human response were then compared to investigate how slamming can be correlated to human factors. These correlations were benchmarked to find the most appropriate vibration metric to effectively quantify slamming vibrations. In addition to that, the research also evaluates the effects of some environmental factors such as swell height and wind speed on wave slamming.

4.2 Methodology

4.2.1 Voyage description

The S.A. Agulhas II sailed from Cape Town on 4 December 2014 on a 76 day voyage to Antarctica. More than 50 % of the time was spent either breaking pack ice or standing stationary at the Antarctic shelf for logistical reasons. Only the open water data was used for slamming measurements which is divided into three legs:

- Leg 1 – 5 Dec 2014 to 12 Dec 2014 (departing Cape Town until reaching pack ice)
- Leg 2 – 31 Dec 2014 to 19 Jan 2015 (leaving the Antarctic shelf (Akta Bukta) for South Georgia)

- Leg 3 – 8 Feb 2015 to 15 Feb 2015 (return trip to Cape Town from Akta Bukra, along the Greenwich Meridian)

The measurements from Leg 2 and Leg 3 were used for the analysis as the data from Leg 1 was incomplete due to data acquisition problems. The oceanographic research was continuously performed during all the three legs. This included the sampling of sea water and deployment and retrieval of oceanographic data measurement systems at certain locations.

4.2.2 Full scale Measurements

A total of six accelerometers were placed throughout the vessel to capture vibration at relevant locations (Figure 4.1). Acceleration was measured in the vertical direction only as it was found to be dominant during the slamming trial study and full scale measurements throughout her Antarctic voyage in 2013/14 (Bekker, 2013 and Soal & Bekker, 2013)

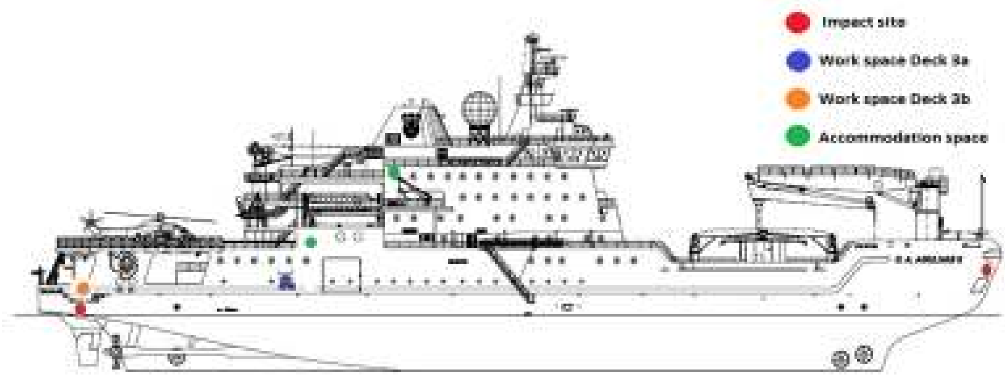


Figure 4.1: **Location of the accelerometers on the S.A. Agulhas II**

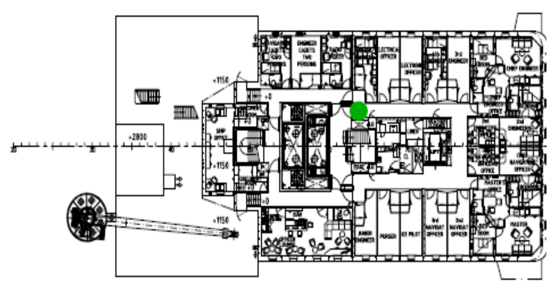


Figure 4.2: Location of the accelerometers on Deck 8 (accommodation)

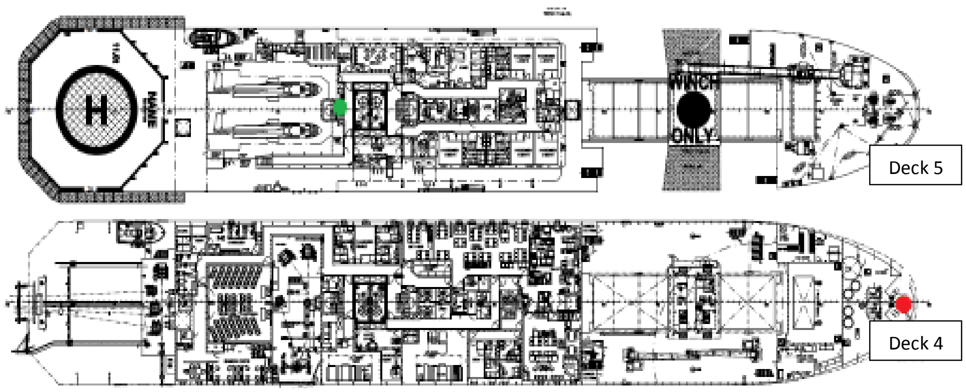


Figure 4.3: **Location of the accelerometers on the Deck 5 (accommodation), Deck 4 (slamming identifier at the bow)**

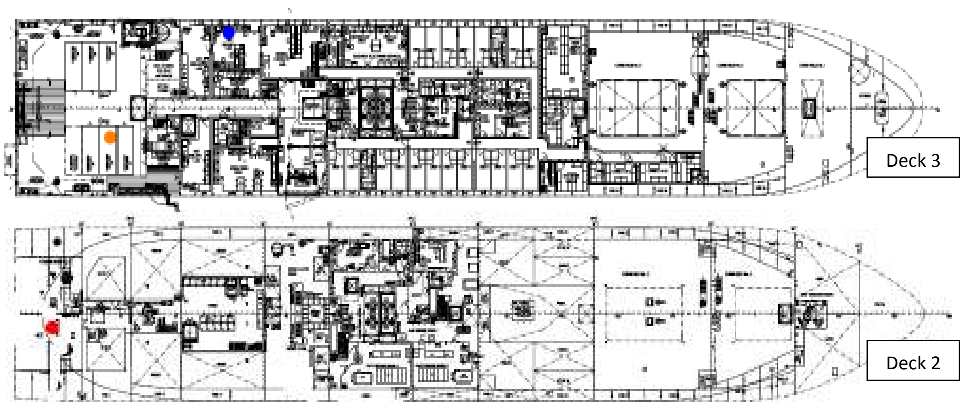


Figure 4.4: **Location of the accelerometers on the Deck 3 (work space), Deck 2 (slamming identifier at the stern)**

Accelerometers at the stern (Deck 2) and bow (Deck 4) were used for identifying slamming events as they were closest to the impact sites for bow and stern slamming (Figure 4.3 and 4.4). The accommodation space on the vessel comprises of Deck 4 to Deck 8. One accelerometer was placed at Deck 5 and one at Deck 8 (Figure 4.2 and 4.3). Two accelerometers were placed on Deck 3 close to the research laboratories that served as the working area for the scientists. Hence, a total of six accelerometers were used to identify slams and represent the working and accommodation areas where passengers spent most of their time.

LMS SCADAS mobile data acquisition units were used in a master slave configuration to acquire acceleration measurements. Furthermore, PCB piezoelectric ICP *(Model no 333B32)* accelerometers were used for this study as they have an appropriate frequency range of 0.5 to 3000 Hz and average sensitivity of 100mV/g. A sample rate of 2048 Hz was selected and measurements were recorded continuously with a record length of 5 minutes throughout the voyage.

4.2.3 Questionnaire survey

A key component of the study was to conduct a questionnaire survey to gather human responses. The survey was anonymous and was distributed after delivering a comprehensive presentation which explained slamming phenomenon, the aim of research and filling instructions. The questionnaire (Figure 4.5) was prepared in the form of a daily diary. The respondents had to start the questionnaire by answering if a slamming event occurred that day or not. Only in the cases where slamming was deemed present, they were required to proceed with replying to the subsequent questions. This included rating of the worst slamming event for that day based on a subjective judgement (on a scale of 1 to 10) and then mentioning if slamming had affected their sleep or task performance.

It was also enquired if the use of equipment had been disturbed or if any equipment damage had occurred. A section was also left for comments. The questionnaires were distributed on the first day and were collected two days before returning to Cape Town (15 Feb 2015).

Encountered slamming	*No*	*Occasionally*	*Regularly*
Worst slamming incident rating *(1= nothing, 3 = slight, 10 = severe)*	*1 2 3 4 5 6 7 8 9 10*		
Tasks affected by slamming *(tick the appropriate boxes)*	*No*	*Typing/writing*	*Visual tasks (reading/TV)*
	Equipment use	*Equip. damage*	*Sleeping*
Comments:			

Figure 4.5: The daily diary slamming questionnaire

4.3 Post processing

4.3.1 Vibration measurements

The post processing and analysis of the vibration data was done using *MATLAB* and *LMS Test.Lab Turbine Testing* according to ISO 2631-1 (1997). Each 5 minute measurement was human weighted using the W_k filter for vertical vibration (ISO 2631-1, 1997) in the time domain with the methodology proposed by Rimell & Mansfield (2007, 2010). The weighted data was then used to calculate the peak value, r.m.s., Crest Factor (CF) and Vibration Dose Value (VDV) metrics for each 5 minute data record.

4.3.2 Statistical methods

Statistical analyses were performed using the *Statistica* software. The methodology for those analyses was guided by the studies of Pisula *et al.,* (2012) and Haward *et al.,* (2009). Both studies are relevant to the current research as they also correlate human response to vessel vibration albeit for the purpose of motion sickness. A Shapiro-Wilk statistical test of normality was conducted. The distribution was found to be non-normal; hence a non-parametrical analysis was performed. Kendall's correlation was used as a statistical tool to estimate the correlation of the slamming measurements with the human response.

4.3.3 Data analysis

The data analysis was performed in five stages.

Stage 1: Identifying slamming events

To keep the study specific to slamming vibration, finding and selecting only slamming events was vital. An algorithm was developed to investigate each 5 minute recording of vibration for the 26 days in open water. Accelerometers at the stern and the bow were used for the investigation as they were close to the impact sites. As slamming is considered to be impulsive, the algorithm started with calculating the CF for every file and only selected the files with a CF higher than 9.0 either at the bow or stern. This criterion was imposed using the definition of impulsive vibration as described by ISO 2631-1 (1997) which considers vibrations above 9.0 to be non-stationary random. After these files were segregated, each file was analyzed individually.

Time history and power spectral density (PSD) plots were inspected to ensure that the signal adheres to the properties of a slamming event. The time history of the signal at the bow and stern were plotted together along with other accelerometers to see if the peaks for the impulsive signal occurred at virtually the same instant on all the channels. This check was performed to confirm whether the event was global or not, as slamming vibrations would be experienced throughout the entire vessel. In addition to this, PSD plots of the same signals were analyzed to investigate the frequency content. PSD plots were developed using *pwelch.m* command in *MATLAB* with 50 % overlap, a *Hanning* window and a block size of 8192 with a resolution of 0.0625 Hz. This was done to further confirm that the vibration signal represents a slamming event. After all the files were individually scanned, only those with slamming events were selected and processed for further analysis.

Stage 2: Calculation of vibration metrics

Vibration data was evaluated using three different metrics namely peak, r.m.s. and VDV. These metrics were correlated to the human response to slamming. As the human response data had a resolution of 24 hours, the vibration data was also transformed accordingly. For these three metrics, a daily average and a maximum value were calculated from the measurement records that contained slamming for each day.

The daily maximum values for peak, r.m.s and VDV were the highest values for the day of a 5 minute measurement. The daily average values for peak and r.m.s were estimated by averaging all the 5 minute slamming records for the day. However for VDV, it was calculated differently by accumulating the exposure of slamming events for each day. According to Griffin (1990), VDV is a cumulative measure of the vibration and shock experienced by a person during a measurement period. Hence a cumulative VDV was calculated for each day by integrating the record instances during which wave slamming was encountered. For example, if 40 measurement records (out of 288 files) contained slamming events for a day i.e. 200 minutes, then a cumulative value was calculated using the following procedure:

$$\mathrm{VDV} = \left\{\int_{t=0}^{t=200\ \mathrm{min}} a_w^4(t)\, dt\right\}^{1/4} \tag{4.1}$$

$$\mathrm{VDV} \cong \left\{\left(\sum_{i=1}^{i=614400} a_i^4 + \sum_{i=614400\times1+1}^{i=614400\times2} a_i^4 + \cdots + \sum_{i=614400\times39+1}^{i=614400\times40} a_i^4\right)\Delta t\right\}^{\frac{1}{4}} \tag{4.2}$$

The sample rate was kept to be 2048 Hz and the recording time was 300 seconds. The total number of points for one measurement was 614400.

Stage 3: Finding correlation between human response and slamming measurements

Kendall's coefficient was used to correlate the six vibration metrics (three average/cumulative metrics and three maximum metrics) with the daily human responses. This not only provided the correlation of slamming with the human factors but also the information on selecting a vibration metric which effectively quantifies slamming vibration in the context of the human factors.

Stage 4: Human response as a function of slamming acceleration magnitude

To demonstrate how human perception of slamming severity is linked to slamming magnitude, the cumulative distributions of the rating responses were plotted as a function of slamming acceleration magnitude. The technique used to generate these plots was according to the study by Pisula *et al.,* (2012) and Haward *et al.,* (2009). Based on a similar method, the human factors were also plotted against slamming acceleration to demonstrate how the response is affected by magnitude.

Stage 5: Effects of Environmental factors on wave slamming

Environmental factors such as wind speed and swell height are considered and their effect on wave slamming is determined. As rough sea states are often linked with wave slamming incidences (ABS, 2011 and Bertram, 2012), an attempt is made to correlate these factors with slamming induced vibration and human response on-board the S.A. Agulhas II. Sea state data is regularly recorded in the ship log book daily. Swell height is logged every 4 hours whereas wind speed is logged every hour. The data for swell height is estimated using visual observations and compared to the wind speed which is calculated using anemometer. A daily average value of swell height and wind speed was calculated and correlated to the daily vibration magnitude, human response and slamming count using Kendall's tau coefficient. The analysis was done in order to investigate the extent of the inter-dependence of these variables.

4.4 Results and discussion

4.4.1 Identifying slamming events

Slamming events were identified using a verification algorithm. A total of 7488 files comprising of 5 minute recordings were analyzed in accordance with slamming properties mentioned in literature. Approximately half of the files were found to contain a total of 9473 slams. Figure 4.6 and 4.7 present an example of how the investigation was conducted for each file. It shows the time histories and PSD plots of an acceleration signal taken from a 5 minute run recorded on Day 68. The time signals of the nearest impact sites (bow and stern) were plotted against other sensors which reveal that the vibration signal is indeed impulsive and that the peaks occur at the same time instant.

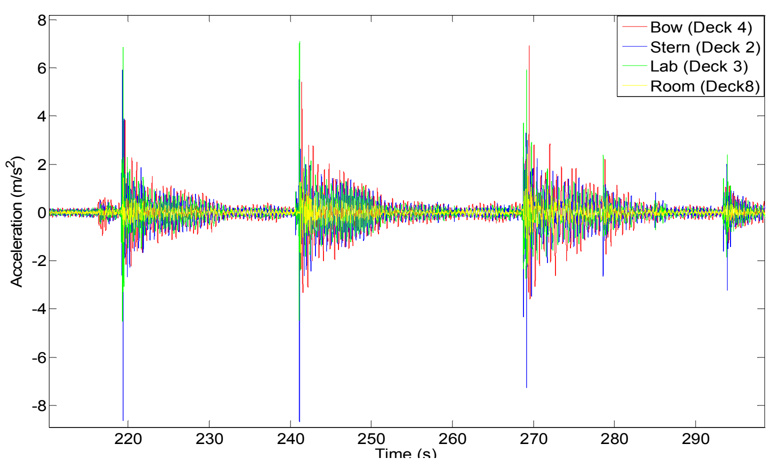


Figure 4.6: Time history of the weighted acceleration vibration signal from 9 Feb 2015

Both these facts indicate a slamming phenomenon as it always leads to an impulsive and transient impact which is felt throughout the vessel. Also, slamming impact can generate high forces producing high levels of acceleration.

Further insight is provided by looking at the PSD plot of the event as shown in Figure 4.7. Slamming phenomenon is known to excite a range of frequencies, as can be observed from the plots. Figure 4.7 show that slamming excites a broad range of frequencies from 2 to 15 Hz including the modes and the harmonic excitation for which the peaks can be seen. Hence it was concluded that the file contained slamming events. The number of slams was also counted from the time history of all the files (four slams can be observed from Figure 4.6). Slamming count per day was also calculated as shown in Figure 4.8.

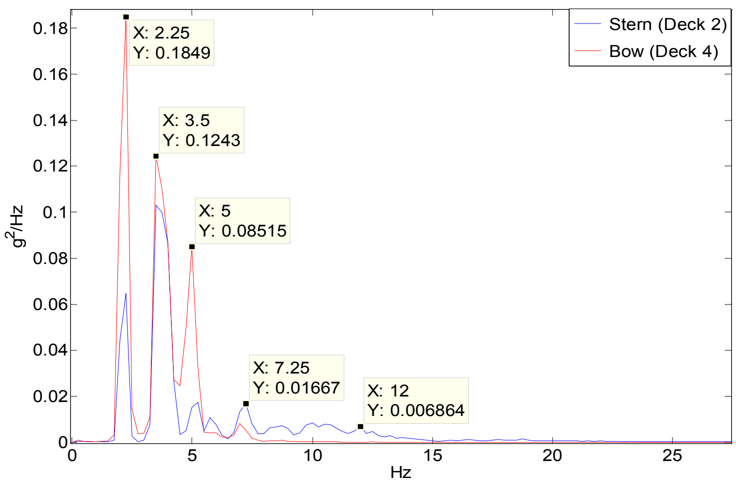


Figure 4.7: PSD plot of the weighted acceleration vibration signal from 9 Feb 2015

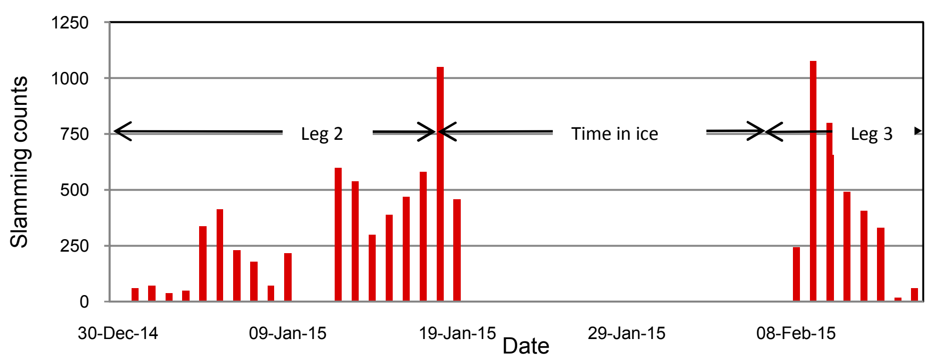


Figure 4.8: Slamming count distribution for Leg 2 and Leg 3 data

Figures 4.9 to 4.12 present the weighted values of vibration calculated at the stern on Deck 2 for the 26 days of open water data (also includes time in ice). The distribution of slamming events can be seen along with the vibration generated from other sources. It is noted that most of the higher values of acceleration are attributed to slamming. This is due to the fact that slamming impact produces high loads on the structure. Also, the hybrid design of the ship, i.e. the flat and raised stern and a big rounded keel offer a large surface area for the impact. The situation is worsened during oceanographic activities when the vessel is stationary.

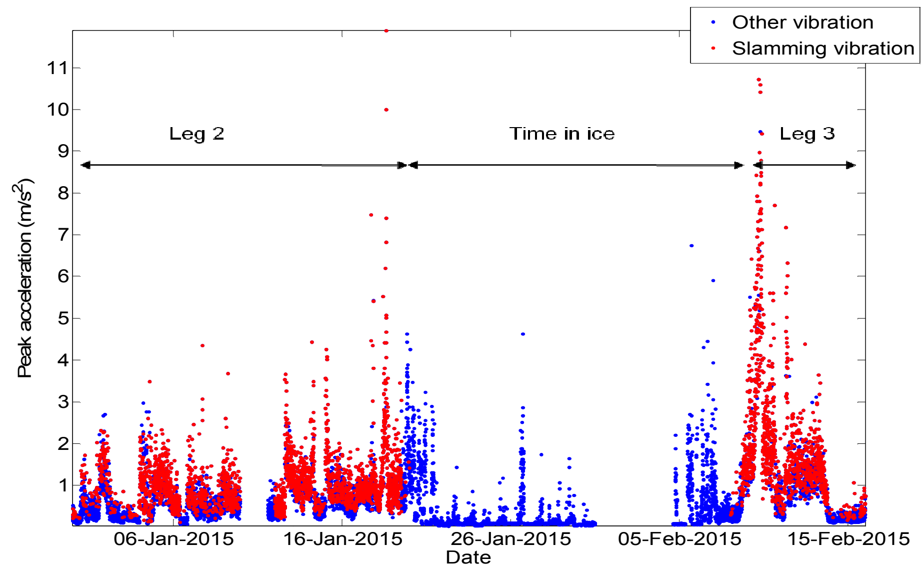


Figure 4.9: Slamming vs. non slamming events for the peak values of all the 5 minute files

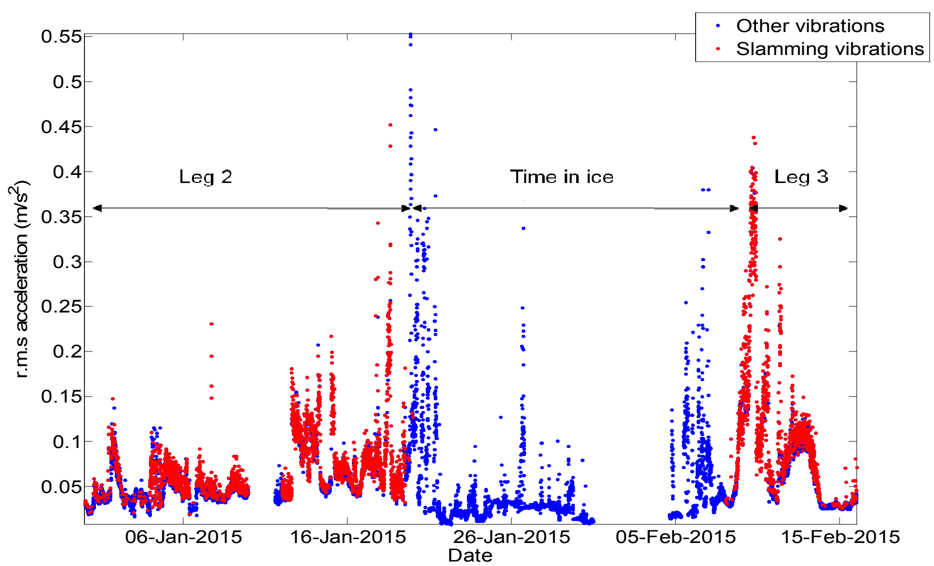


Figure 4.10: Slamming vs. non slamming events for the r.m.s values of all the 5 minute files

Carlton & Vlasi´c (2005) mentions that stern slamming is highly dependent on ship speed. If stationary, the aft of the vessel is more likely to be effected by wave slamming whereas increasing the speed can reduce the effect by interrupting the environmental wave system. However, some of the higher values as seen from the plots do occur which are not a result of slamming. These are mainly due to the high vibrations recorded by only one sensor as a result of some local excitation.

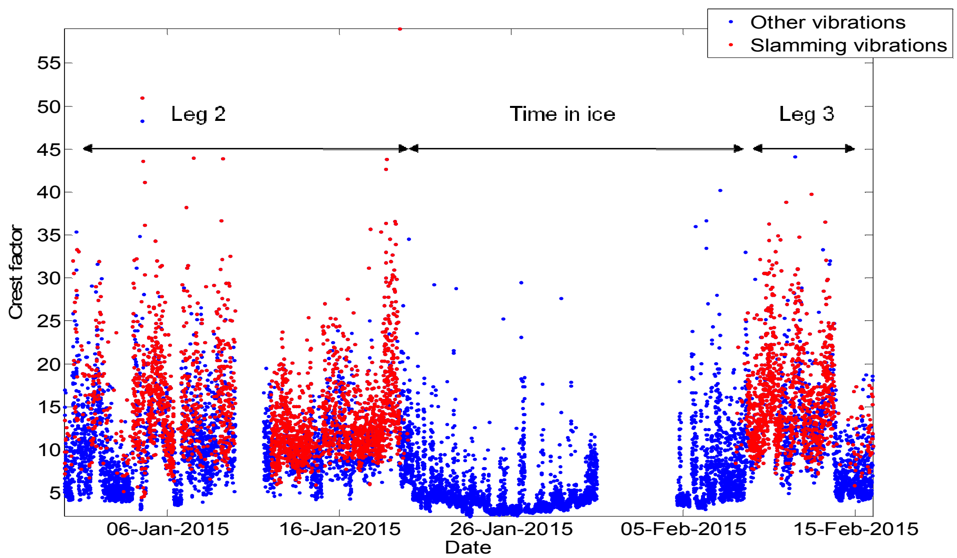


Figure 4.11: Slamming vs. non slamming events for the CF values of all the 5 minute files

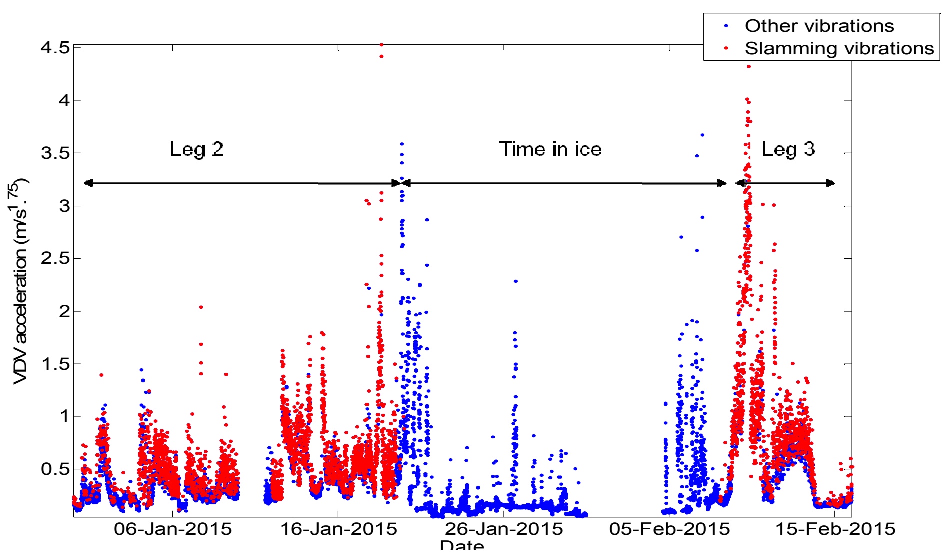


Figure 4.12: Slamming vs. non slamming events for the VDV values of all the 5 minute files

4.4.2 Vibrations metrics

Figure 4.13 to 4.15 presents the calculated values for the three vibration metrics. It can be observed that the daily average values for peak and r.m.s. are lower than the maximum values. However, in the case of VDV it is different. Cumulative VDV is much higher than the maximum VDV values per day as this metric directly depends on the duration of the period for which it is estimated.

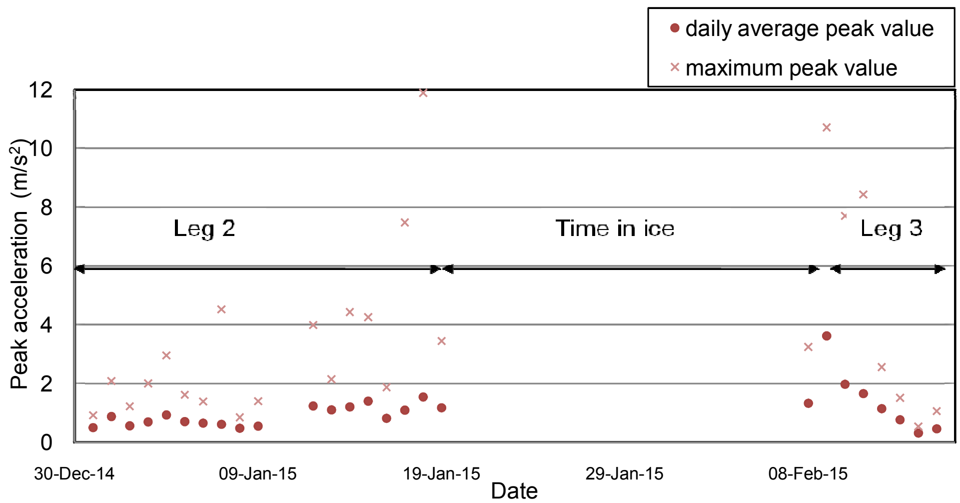


Figure 4.13: The daily average and maximum values for peak acceleration

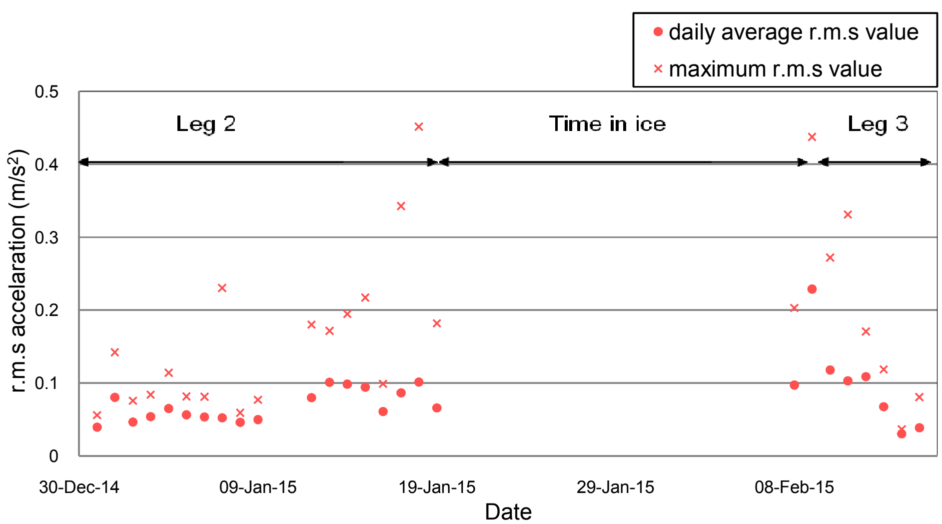


Figure 4.14: The daily average and maximum values for r.m.s acceleration

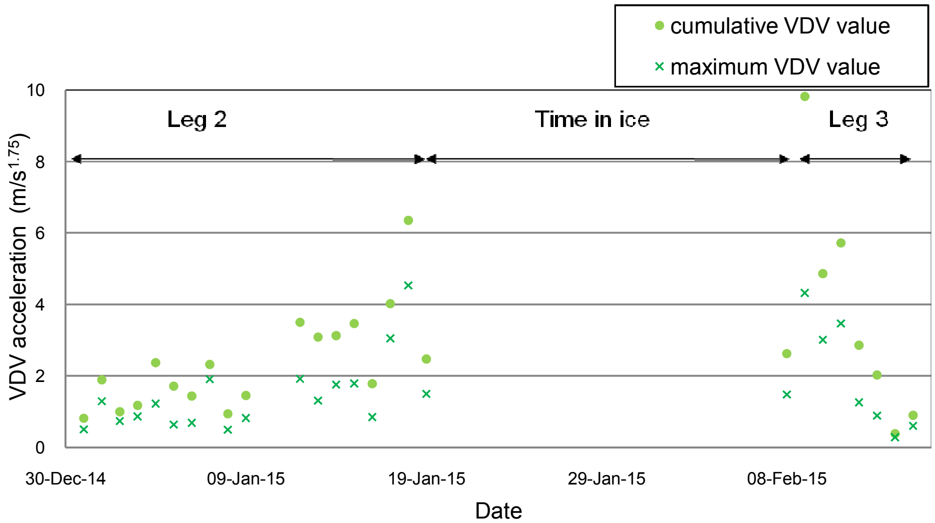


Figure 4.15: The daily average and maximum values for VDV acceleration

4.4.3 Human response

The vessel hosted 98 passengers ranging between the ages of 21 to 65 and included a fair mix of both genders. A quarter of the passengers were involved in research activities on the vessel throughout the voyage. The human response survey was conducted strictly in view of wave slamming vibration. Passengers only responded if they encountered slamming events. They were instructed to rate the severity of the worst slam on a scale of 1 to 10. Figure 4.16 presents the distribution of the human rating for the 26 days of the voyage. It is interesting to observe a similar trend in the rating distribution as from the slamming events indicator plot (Figures 4.9 to 4.12) and the slamming count distribution (Figure 4.8). This is an indication that if the frequency of slams increases, the perception of the severity of the worst slam also increases for that day.

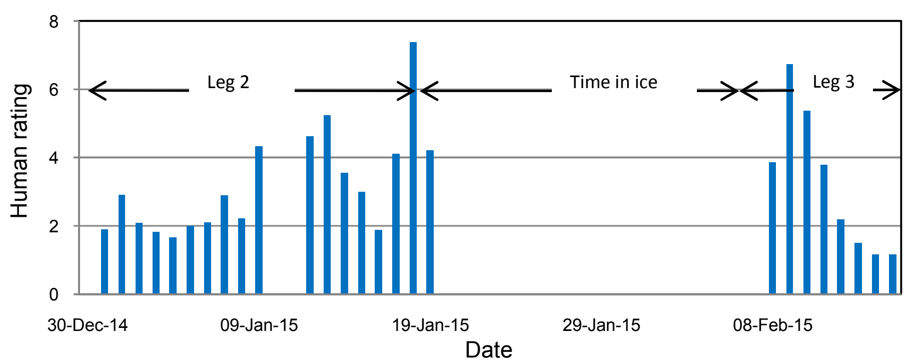


Figure 4.16: Human rating distribution for Leg 2 and Leg 3 data

A total of 427 complaints were logged throughout the voyage with a response rate which varied from 34% to 88%. Figure 4.17 presents the distribution of the complaints with sleep being reported as the most affected factor. Visual tasks and writing/typing both were reported 63 times each, however they were not always reported during the same slamming incidents. Equipment use was the second most logged complaint. Several incidents were noted where using equipment was said to be affected but no typing/writing or visual task complaints were mentioned. As such, it suggests that the research passengers were more sensitive towards reporting equipment use problems. During the course of the voyage, equipment damage was reported ten times.

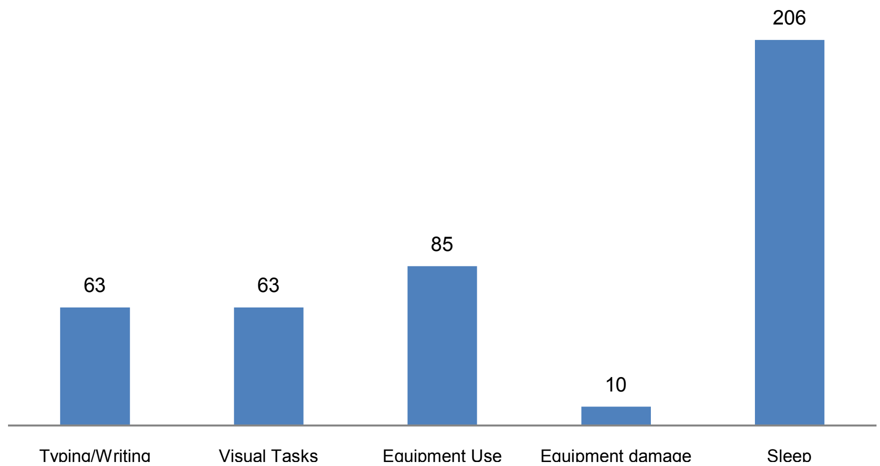


Figure 4.17: Distribution of complaints for the entire voyage

Oceanographic research was performed throughout the voyage. This included the daily sampling of surface water through the bow intake after every few hours. The main activity however was to collect deep water samples which included the deployment and retrieval of equipment into the ocean at certain locations. Wave slamming was reported to interfere with such activities regularly. Excessive vibration was reported to often cause the sampling tap pipe to disconnect. Slamming vibration was also said to effect the deployment and retrieval of the equipment. The filtering and measurement activities were also affected in the clean container laboratory which was located outside on Deck 3. However, this may also be affected by the rolling of the ship.

Finally, the percentage of complaints was plotted as a function of human rating to understand the relationship between the two. A general rise can be observed in the percentage of complaints with the increase of human rating of slamming from Figure 4.18. It can also be seen that equipment damage complaints are only reported when the rating was 7, which is the maximum daily average rating that has been recorded. Also, this rating affects the sleep of almost half of the population. Visual and typing/writing tasks show almost a similar trend.

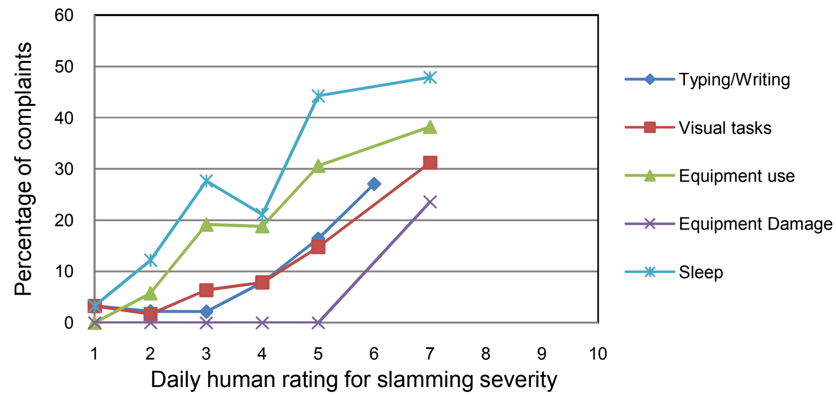


Figure 4.18: Percentage complaints as a function of human rating

4.4.4 Correlations between slamming vibration and human factors

The daily average rating of the worst slamming event and percentage of complaints were found to be highly correlated to slamming vibration. For human rating, data from both work space and accommodation accelerometers was used. Also Deck 2 accelerometer data was correlated to see how the impact site vibration associates with human response. Correlation was highly significant ($p<0.01$) between all the vibration metrics and the average human rating. However, cumulative VDV was found to show the best correlation as indicated in Table 4.1 (strongest correlations indicated in red).

Table 4.1: Kendall's correlation coefficient between daily average rating and slamming vibration metrics (p< 0.01, *p>0.05)**

Location	Average/Cumulative values			Maximum daily values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.526**	0.428**	0.582**	0.557**	0.458**	0.508**
Deck 5	0.397**	0.378**	0.538**	0.397**	0.514**	0.477**
Deck 3a	0.489**	0.440**	0.569**	0.575**	0.551**	0.588**
Deck 3b	0.415**	0.446**	0.551**	0.483**	0.495**	0.545**
Deck 2	0.514**	0.477**	0.575**	0.526**	0.502**	0.557**

For factors such as typing/writing and visual tasks, the daily percentage of complaints was correlated with vibration data from all the accelerometers as above. However, Deck 3b accelerometer data was not used for typing/writing as it was placed at the container laboratory where no such activities was taking place. Both cumulative VDV and maximum r.m.s showed the best correlation and significance according to Tables 4.2 and 4.3.

Table 4.2: Kendall's correlation coefficient between typing/writing complaints and slamming vibration metrics (p< 0.01, *p>0.05)**

Location	Average/Cumulative values			Maximum daily values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.341*	0.355*	0.413**	0.341*	0.442**	0.399**
Deck 5	0.276*	0.290*	0.406**	0.297*	0.428**	0.370**
Deck 3a	0.334*	0.334*	0.384**	0.326*	0.348*	0.334*
Deck 2	0.355*	0.341*	0.392**	0.326*	0.370**	0.355*

Table 4.3: Kendall's correlation coefficient between visual task complaints and slamming vibration metrics (p< 0.01, *p>0.05)**

Location	Average/Cumulative values			Maximum daily values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.310*	0.338*	0.366**	0.338*	0.401**	0.373**
Deck 5	0.234*	0.248*	0.352*	0.269*	0.345*	0.345*
Deck 3a	0.282*	0.282*	0.331*	0.276*	0.331*	0.324*
Deck 3b	0.234	0.289*	0.338*	0.380**	0.359*	0.359*
Deck 2	0.310**	0.310**	0.324**	0.338**	0.352**	0.345**

For sleep disturbance complaints, accommodation accelerometer data was correlated with the slamming vibration metrics. Table 4.4 shows that all metrics were significantly correlated with sleep disturbances, whereas cumulative VDV demonstrated the strongest correlation. Table 4.5 shows the correlation between equipment usage complaints and slamming vibration.

Work space accelerometer data was used as the equipment was only located and used on Deck 3. Similarly, all metrics are significantly correlated, with cumulative VDV being the most correlated metric. Equipment damage complaints were not evaluated as the incidences were not sufficient to make a significant correlation.

Table 4.4: Kendall's correlation coefficient between sleep complaints and slamming vibration measurements (p< 0.01, *p>0.05)**

Location	Average/Cumulative values			Maximum daily values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.429**	0.411**	0.454**	0.429**	0.355**	0.392**
Deck 5	0.367**	0.373**	0.435**	0.342*	0.417**	0.423**
Deck 2	0.429**	0.417**	0.435**	0.361**	0.348*	0.379**

The analysis of the correlation between human response and vibration data reveals that the human factors are associated with wave slamming vibration. All the selected metrics are found to be significantly correlated with human response. Cumulative VDV showed the best correlation in most of the cases along with average r.m.s in some cases (typing/writing and visual tasks).

VDV is presented as more suitable evaluation metric when the vibration is impulsive according to ISO 2631-1 (1997) and BS 6841 (1987) (Griffin, 1990). It can be noted that VDV is sensitive to include the effects of peaks in the acceleration signal. This is the reason why it appears to be a robust metric for evaluating slamming vibration and shows strong correlation with human response.

Table 4.5: Kendall's correlation coefficient between equipment usage complaints and slamming vibration metrics (p< 0.01, *p>0.05)**

Location	**Average/Cumulative values**			**Maximum daily values**		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 3a	0.415**	0.327*	0.502**	0.484**	0.452**	0.528**
Deck3b	0.333*	0.371**	0.502**	0.421**	0.440**	0.465**
Deck 2	0.433**	0.383**	0.515*	0.484**	0.446**	0.509**

4.4.5 Human response as a function of slamming acceleration magnitude

To illustrate how the human factor is affected by slamming vibration magnitude, a cumulative human response distribution was plotted as a function of acceleration magnitude. The vibration metric used was the cumulative VDV as it was found to show the best correlations consistently. The data from Deck 2 stern accelerometer was used. This sensor was chosen to reflect the acceleration magnitude of the closest point to the impact of the slamming force.

The method to plot the distribution was based on ideas presented by Pisula *et al.,* (2012) and Haward *et al.,* (2009). The acceleration scale was divided into bands of 2.0 $m/s^{1.75}$. The cumulative distribution of percentage of average human rating has been plotted against VDV acceleration in Figure 4.19. A strong correlation is noted from the plot as shown in Table 4.1. This plot provides useful information about the trends of human ratings with an increase in acceleration. For example, only 15 % of the passengers considered slamming events to be severe when the acceleration level was between 4.0 to 6.0 $m/s^{1.75}$, however there is a distinct increase in this percentage (up to 68%) when the acceleration magnitude exceeds 6.0 $m/s^{1.75}$.

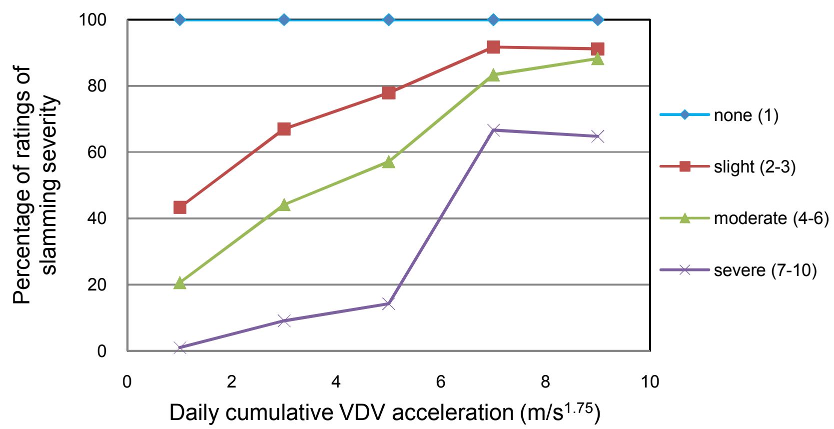


Figure 4.19: Cumulative distribution of human rating as a function of slamming magnitude

The distribution of complaints was plotted against the cumulative VDV calculated from the stern accelerometer on Deck 2 as shown in Figure 4.20. The distribution was not cumulative as complaints were not logged in as ratings. The percentage of complaints was used to see how they varied with the increase in acceleration magnitude at the impact site for stern slams. The distribution of sleep complaints was generally higher throughout, reaching more than 50 % when the acceleration value exceeded 8.0 $m/s^{1.75}$. A rise in the equipment use complaints can be observed as the magnitude of acceleration is increased above 6.0 $m/s^{1.75}$. It can also be noted that even at the lowest magnitudes, sleep and equipment usage complaints were reported. Typing/writing and visual tasks complaints show a similar pattern at the lower magnitudes. Typing/writing complaints increase linearly with an increase in cumulative VDV. However, the trend for visual tasks complaints is less predictable.

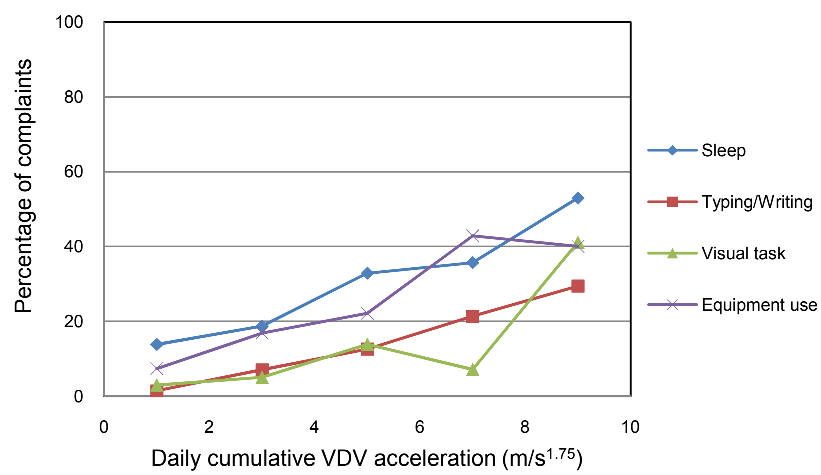


Figure 4.20: Human factor as function of slamming magnitude

4.4.6 Effects of Environmental factors on wave slamming

Table 4.6 shows the Kendall's correlation of swell height and wind speed with respect to slamming response. Slamming response defines both the objective and subjective data measured for slamming events. A daily cumulative VDV value from the stern sensor is used again, along with the daily slamming count as the objective response, whereas the human rating is used to represent the subjective response. From Table 4.6 it can be seen that both environmental factors correlate well with slamming response. This is in accordance with the general association of rough seas leading to greater slamming response. However, to validate that the values of these correlations are sufficient, some further investigations were performed.

Table 4.6: Kendall's correlation coefficient between environmental factors and slamming response (p< 0.01, *p>0.05)**

Environmental factors	Slamming response		
	Human rating	VDV	Count
Swell Height	0.531**	0.505**	0.524**
Wind Speed	0.559**	0.545**	0.538**

The slamming response data was plotted against the environmental variables to see if only high sea states lead to elevated slamming response. Figure 4.21 and 4.22 reveal that even at low swell heights and wind speeds; an above average slamming response is recorded. A significant slamming response is seen both objectively and subjectively at the average swell height of 1m and wind speed of 13 kn. This suggests that the design of the vessel makes it prone to the effect of wave slamming even at low sea states.

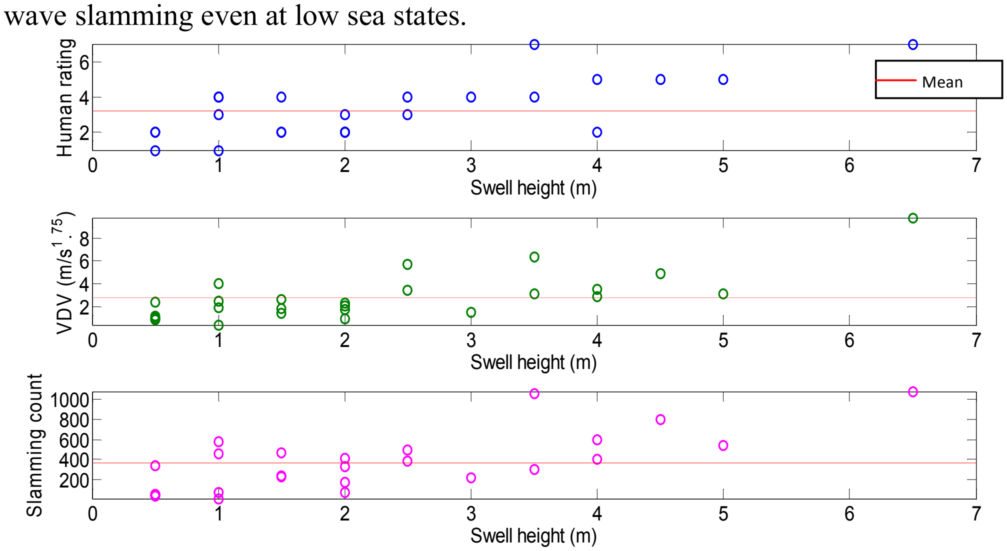


Figure 4.21: Swell height vs slamming response

According to Carlton & Vlasi´c (2005), vessels with flat aft designs are said to be affected by stern slamming even at well height of 1 m. It is appropriate to note that slamming incidents that led to the breaking of four container vessels also took place in moderate seas (Storhaug, 2014).

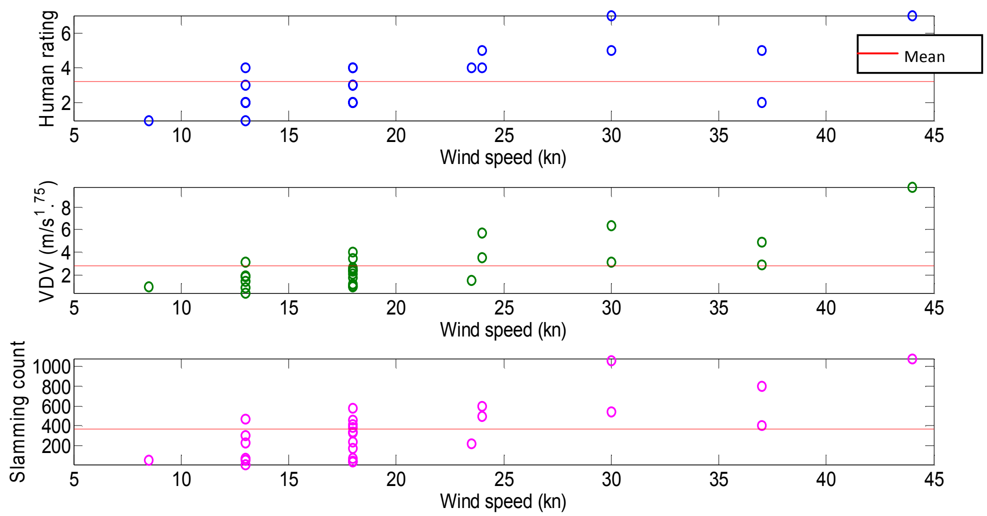


Figure 4.22: Wind speed vs slamming response

4.5 Limitations

The study was limited due to the low participation rate from the passengers. Some of the daily diaries were left incomplete where others were not returned. One of the reasons for low response rates can be the overall long duration of the voyage and the large response gaps that occurred due to vessel operations in ice. This may have reduced the motivation of passengers to keep filling in the diary. Another factor could be the involvement of some passengers in long hours of work shifts throughout. There was also no way to verify the authenticity of the claims which were reported in the human response. Measurement of slamming vibration was only conducted at certain locations. Not all locations facilitated the routing of cables for sensor placement. For instance, the sensor used to capture slamming at the bow was placed at Deck 4, unlike the sensor at the stern which was placed at Deck 2. The accommodation space for passengers starts at Deck 4 but the closest measurement sensor was placed at Deck 5. It is thought that measuring acceleration at locations closer to the wave impacts and human activity points could provide more accurate insight into the relationship between slamming vibrations and the human response. The low resolution of data due to 24 hour human response intervals may also distort the correlation results. This also prevented the use of some other important environmental factors, such as ship heading relative to swell and wind. Finally, all the measurements used in this study were in the vertical direction. Slamming is a three dimensional event and tri-axial measurements would likely to improve the representation of the phenomenon.

4.6 Conclusion

The vibration caused by wave slamming was found to be strongly associated with human responses on-board the S.A. Agulhas II. The highest correlation was found to be between the cumulative VDV values from slamming events which proved to be the best metric. Vibration analysis revealed that most of the high levels of acceleration recorded by the sensors were impulsive and occurred as a result of wave slamming. This is due to flat stern and rounded keel of the S.A. Agulhas II, which makes it prone to high wave slamming impacts. Sleep disturbance was the most frequently reported complaint. Slamming vibration was also reported to affect equipment use and interfere with oceanographic research activities. There were 4 days during which incidences of equipment damage were reported. There was a marked increase in the reports of respondents considering slamming events to be ‘severe’ when cumulative VDV acceleration exceeded 6.0 $m/s^{1.75}$ at the stern. Similarly for complaints of slamming effects, a correlation is demonstrated with an increase in acceleration magnitude. Consideration of environmental factors such as swell height and wind speed revealed that the vessel is prone to slamming even at low sea states.

5 Operational deflection shapes for bow and a stern slamming on the S.A. Agulhas II, Polar Supply & Research Vessel

Operational deflection shapes (ODS) provide useful information about the dynamic behavior of a vibrating structure. Analysis of the vibration pattern of the structure at specific frequencies or time instances can effectively answer many questions related to the design and performance of that structure. In this study, ODS technique is implemented to visualize wave slamming excitation on the S.A Agulhas II, a South African polar supply and research vessel .Due to the operation in both ice and open water, the vessel has a hybrid design which makes it prone to wave slamming phenomenon. The study uses real time vibration signals, produced by slamming events, during a voyage to Antarctica in 2014/2015, to calculate the ODS. Time and frequency domain responses were measured for both bow and a stern slams. ODS provides a visual impression of the vessel's response at the moment of the impact of the slam and also shows how the excitation propagates throughout the structure. Results reveal that slamming vibrations cause twisting and bending of the entire structure. The vessel undergoes oscillation which takes 20 to 40 seconds to die out completely which may cause human comfort and performance issues on-board. It is suggested that an investigation must be carried out to determine if slamming may lead to the structural fatigue of the vessel.

5.1 Introduction

The S.A. Agulhas II is a Polar Supply & Research Vessel (PSRV) and is the backbone of South African research program in Antarctica and the Southern oceans. The vessel is designed to operate both in open water and ice and some design tradeoffs have been made in this regard. It has a thick rounded keel to break the ice and a flat aft section to accommodate container laboratories. The aft of the vessel is also raised to let the ice pass between the propellers and the hull.

The demanding ice and open water voyage profiles of the Antarctic research voyages necessitated a hybrid design pre-disposes the ship to wave slamming. Omer & Bekker (2015) investigated slamming issue in the context of human factors on-board S.A. Agulhas II and found a correlation between slamming vibration data and human comfort and task performance complaints. The study also defined a method of isolating slamming vibrations from other sources of vibration on-board. However, none of the studies performed in regards of wave slamming on the S.A. Agulhas II provide any information about the dynamic response of the vessel as it undergoes a slamming impact. As yet no distinction has been made in terms of identifying and categorizing the difference between bow and stern slamming events in operational conditions. By identifying and isolating a bow and a stern slam, further research can be done to investigate their impacts on human factors and the vessel structure.

In this regard, a study was planned to visualize the response of the S.A. Agulhas II, during slamming events, using ODS techniques. ODS can prove to be a useful method for understanding ship motion under different vibration conditions. Current work utilized this technique to identify and analyze both a bow and a stern slamming event from real time vibration measurements. Time domain and frequency response was calculated to observe the motion of the ship as it undergoes slamming.

5.2 Background

5.2.1 Wave slamming phenomenon

Wave slamming is considered as one of the sources that contribute to vibration and noise on a ship (Carlton & Vlasi´c, 2005). This phenomenon can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). Slamming loads are higher than any other wave loads and the impacts can damage the ship structure (Bertram, 2012). Constantinescu *et al*., (2009) describe slamming as a random, dynamic and non-linear event affecting the structure of the vessel, both globally and locally. Local response refers to the area of the impact site which is under severe loading and is prone to damage in case of repetitive impacts. Besides that, slamming can also affect human factors such as comfort and performance as well as cause damage to the equipment on-board (Constantinescu *et al*., 2009).

5.2.2 Operational deflection shapes (ODS)

Operational defection shapes (ODS) are used to visualize the vibration response of a structure under real operating conditions (Inman, 2014). It provides insight to the overall vibration pattern, which contains both forced and resonant responses. This is different from modal analysis which only provides information about the inherent resonant behavior of the structure (Heaton & Hewitt, 2006).

These deflection shapes and structural movements relative to certain points can be analyzed using either the time domain response or the frequency response. Time domain response provides information of the behavior of the structure at certain instances in real time. Whereas frequency domain response uses many different types of frequency and time domain measurements, including linear spectra (FFTs), cross and auto power spectra and Frequency Response Functions (FRFs) to help visualize the response at a particular frequency (Ganeriwala & Richardson, 2011). Hence ODS is recognized as a useful industry tool for the solution of vibration related problems in machines and structures.

Some studies have used ODS to analyze the structural ship responses under operational conditions (Swartz *et al*., 2009 and Salvino *et al*., 2009). However, that was done as a part of developing a ship structure monitoring system for naval a combat vessel.

5.3 Methodology

5.3.1 Measurement setup

Full scale measurements were performed on the S.A. Agulhas II during her voyage to Antarctica in 2014/15. Fifteen accelerometers were placed throughout the vessel to capture the global sense of vibration as shown in Figure 5.1. The sensors measured acceleration in the vertical axis. Three LMS SCADAS mobile data acquisition units were used in a master-slave configuration. Furthermore, both ICP *(Model: 333B32*) and DC *(Model: 3711B111OG)* accelerometers were used for this study. ICP sensors have a sensitivity of 100 mV/g and they measure vibration in the frequency range of 0.5 Hz to 3000 Hz, whereas DC sensors have a sensitivity of 200 mV/g and they measure frequency in the range of 0 Hz to 1000 Hz. A sample rate of 2048 Hz was selected and measurements were recorded continuously and saved in 5 minutes data records.

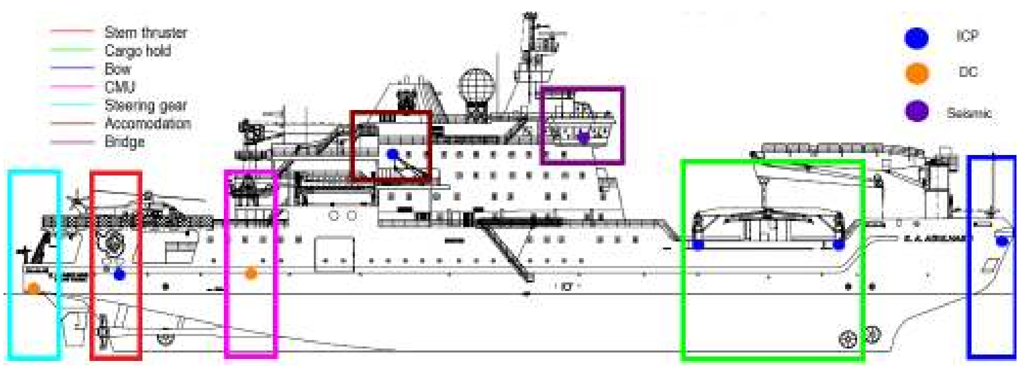


Figure 5.1: Location of the accelerometers on the S.A. Agulhas II

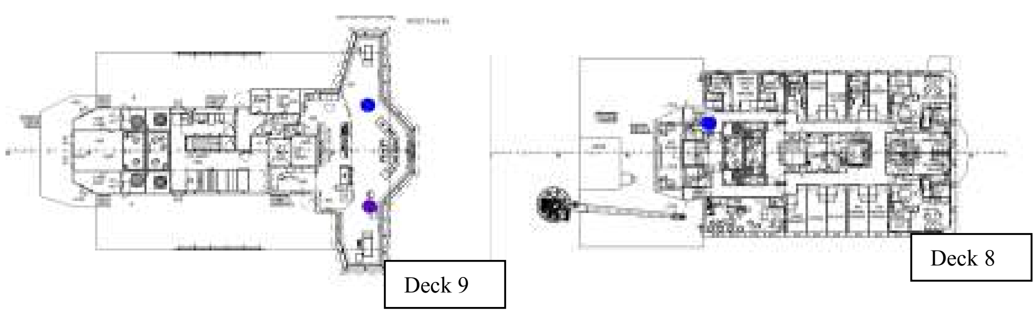


Figure 5.2: Location of the accelerometers on the bridge (Deck 9) and accommodation space (Deck 8)

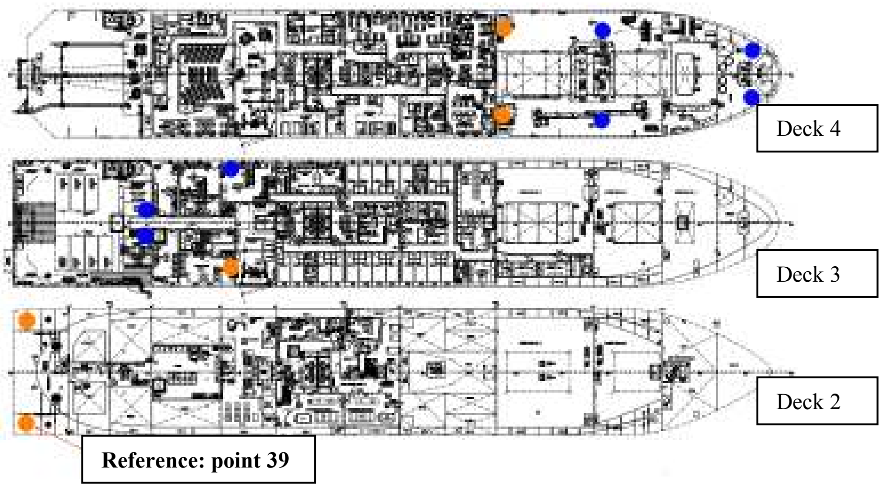


Figure 5.3: Location of the accelerometers on the steering gear (Deck2), CMU, stern thruster (Deck 3) , cargo hold and bow (Deck 4)

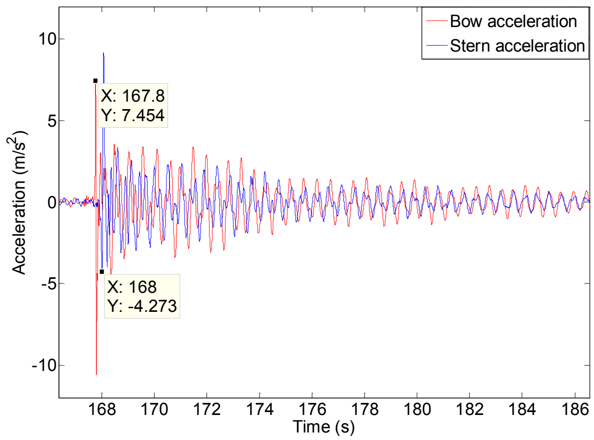
5.3.2 Slamming events

From the full scale vibration data, two different slamming events were selected. One represented a bow slam and the other represented a stern slam. These slams were identified using the methods described by Omer & Bekker (2015) which suggests analyzing the time history and PSD plots of the signals. However the distinction between a bow slam and a stern slam was made by looking at the time difference between the peaks as a result of wave impacts. Figure 5.4a shows the plot of a slam recorded the voyage. By plotting the time history from the sensor placed at the stern and the bow together, it can be seen that the peak for the stern sensor occurs prior to the peak captured at the bow. This is an indication that wave impacted the vessel closer to the sensor at the stern of the ship.

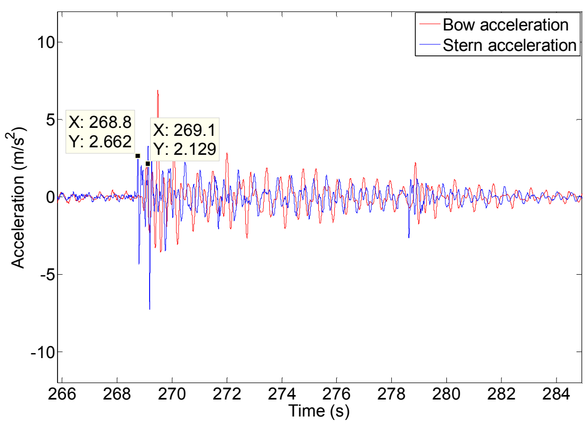
The same is true for the identification of a bow slam as presented in Figure 5.4b. Both of these events are selected and processed to be used for the calculation of ODS. Table 5.1 provides the parameters for the environmental condition at the time of the occurrence of the slamming events. It can be noted that the bow slamming event happened in a low sea state opposite to the stern slamming event.

Table 5.1: Environmental parameters at the time of occurrence of the slams

Parameters	Bow Slam	Stern Slam
Swell height	2.5m	8.0m
Swell direction	ESE	SW
Wind speed	30kn	52kn
Wind direction	SE	W
Ship heading	96°	303°



(a)



(b)

Figure 5.4: Time history of acceleration measurement for (a) bow slamming event and (b) stern slamming event

5.3.3 Signal processing for ODS

Signal processing was conducting in *MATLAB* and *LMS Test.Lab Turbine Testing* software. Raw acceleration measurements were decimated from 2048 Hz to 512 Hz. This resulted in a signal cut-off frequency of 256 Hz. Finally the signals were passed through high-pass filters to remove the rigid body vibrations. Rigid body vibrations are low frequency vibrations generally below 1 Hz (Griffin, 1990). These vibrations normally depend on the sea state. Hence it was necessary to remove them for a better visualization of the flexure of the ship as a result of the excitation. Two different high-pass filters were designed to attenuate the low frequency vibration measured by the ICP and DC accelerometers respectively.

A Chebyshev high-pass filter with an order, N = 800, and a cut-off frequency F_c = 1 Hz, was used to filter the ICP data. A higher order filter was required for the DC accelerometers which can measure below 0.5 Hz vibrations. A Chebyshev high-pass filter with an order, N = 1400, and a cut-off frequency, F_c = 1.6 Hz was used to filter the DC data.

5.3.4 Operational deflection shapes

ODS were calculated using *LMS Test. Lab 10A Operational Deflection Shape and Time Analysis*. Time animation and frequency response animation was performed to calculate the ODS of the bow and the stern slams. Time signals from Figure 5.5 were used as input for the time animations whereas the PSD plots from Figure 5.6 were used to visualize the motion of the vessel at certain frequencies.

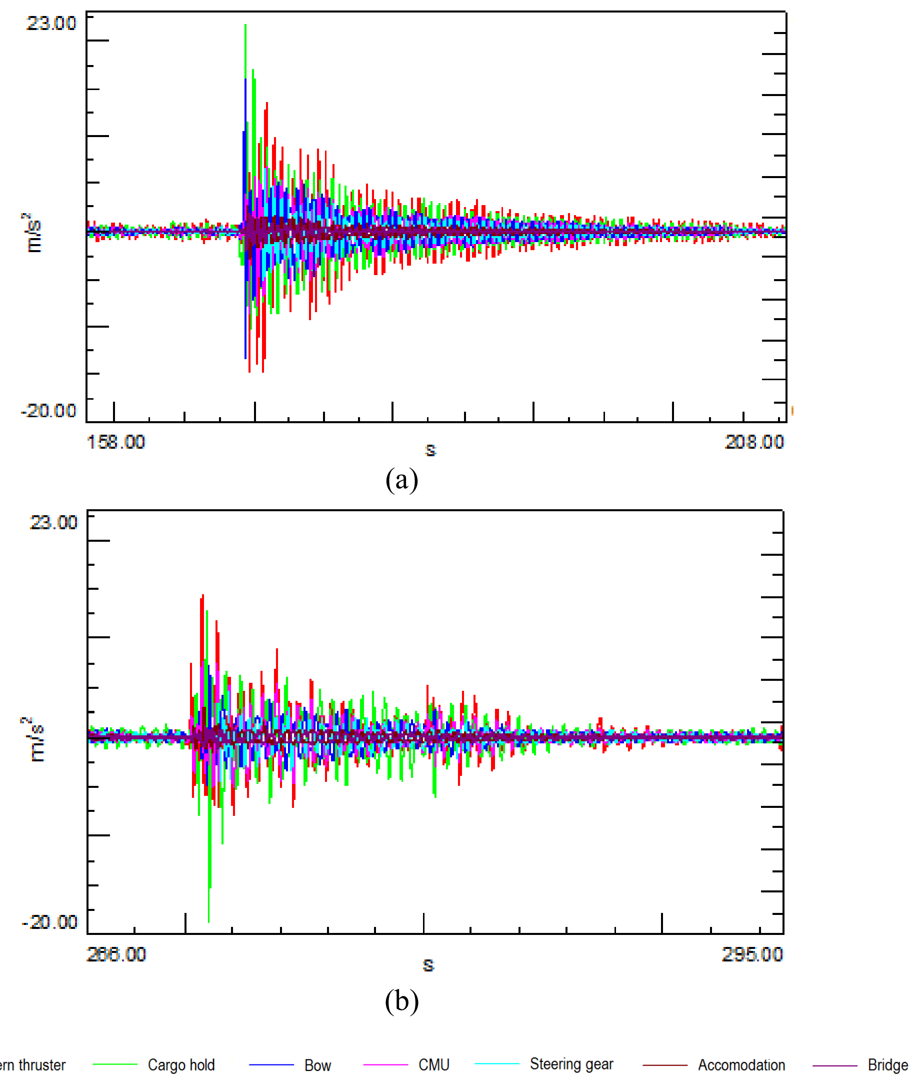


Figure 5.5: Input signals used for ODS time domain response (a) time signal for the bow slam (b) time signal for the stern slam

The PSD plots are calculated using an *Exponential* window, 8192 NFFT points and a resolution of 0.0625 Hz. The exponential function decayed to 1 % before the end of the time record (Fladung, 1997).The amplitude correction was done as exponential window introduces damping in the response. First two peaks were identified by the PSD plots and were used to calculate the shapes for the frequency response. It is noted that the PDS plots (Figure 5.6a) also indicate the peaks from the harmonic excitation of the propulsion system of the vessel (Soal & Bekker, 2013).

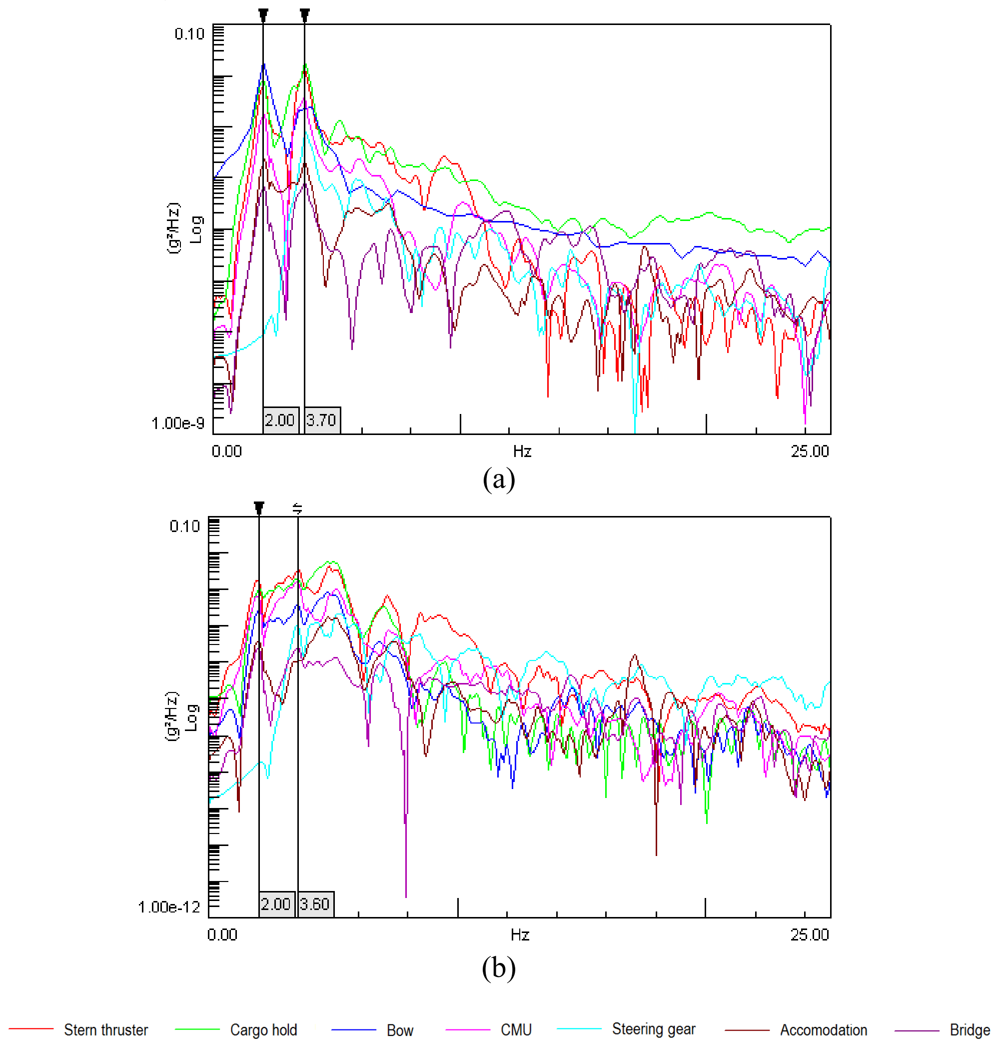


Figure 5.6: PSD plots used for calculating the frequency domain response (a) PSD plot for bow slamming (b) PSD plot for stern slamming

5.3.5 Geometry for ODS

Figure 5.7 shows the 3D Geometry of the vessel to calculate ODS. The geometry was created using the *LMS Test. Lab 10A* module *Operational Deflection Shape and Time Analysis*. Fifteen sensors along the total length and width of the vessel from Deck 2 up to Deck 9 have been modeled to represent the actual vessel. The starboard DC sensor (Point 39) at the stern has been taken as a reference for rest of the dimensions.

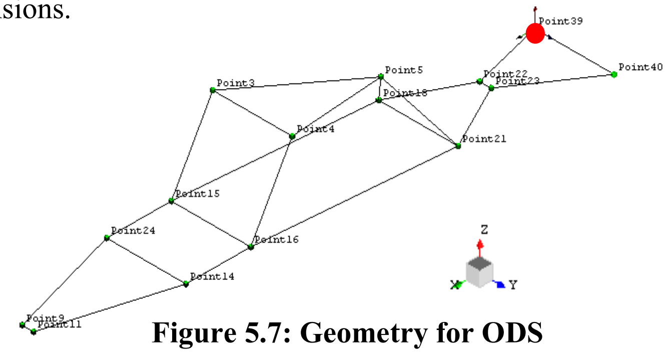


Figure 5.7: Geometry for ODS

5.4 Results

5.4.1 Time domain responses

Figure 5.8 indicates the progression of the vessel deflection state for a bow slamming event. The bow is seen to be displaced upwards at the instance of the slam hitting the vessel (Figure 5.8b). This vertical motion of the bow is followed by a twisting on the starboard side and then at the portside. The vibrations then travel throughout the vessel in less than a second.

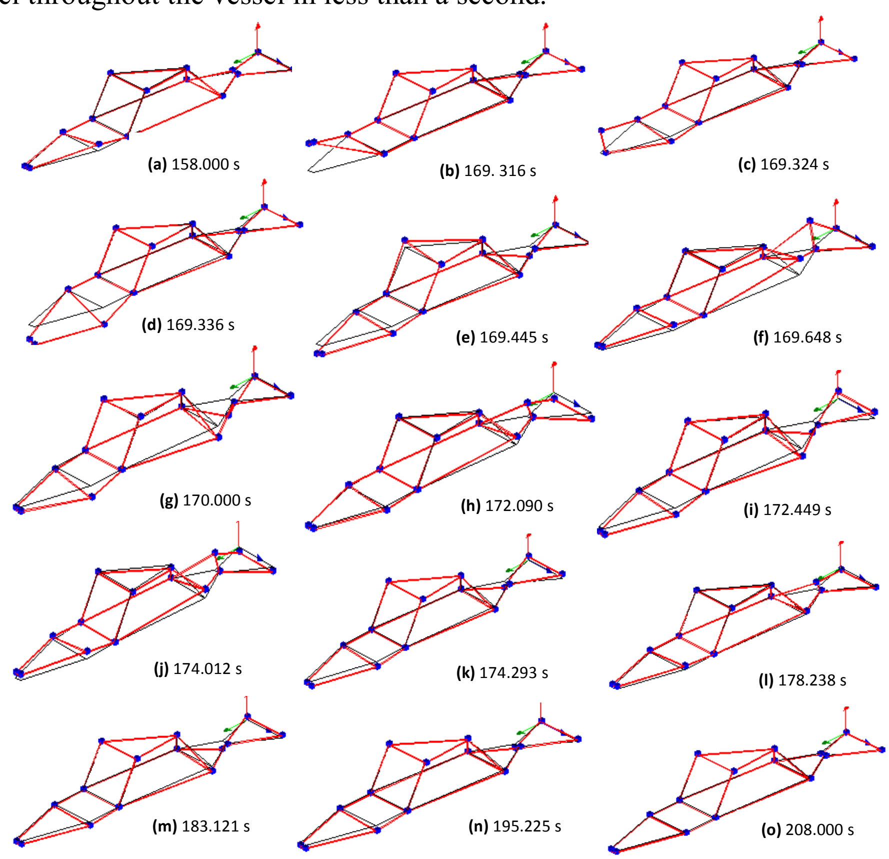


Figure 5.8: Time domain ODS for the bow slamming event

The Bridge and the Stern thruster region are also loaded (Figure 5.8e). The oscillations finally reach the stern after a few seconds and some bending motion is observed (Figure 5.8h). The starboard side of the stern and the port side of the cargo hold experience twisting and bending throughout the remainder of the event. The amplitude of the motion decreases until, after approximately 40 seconds, the excitation dies out.

Figure 5.9 shows the time animation of a stern slam event. It can be seen that the slam hit the aft of the vessel at 270.352 s (Figure 5.9b), causing twisting of the aft of the ship. At the instance of the impact, both stern thruster room and operations are loaded. As the slam propagates through the vessel, it causes the bow to twist as well (Figure 5.9c). It is noted that even though the slam impacted the vessel at the back, but the front region also reacts to the excitation by oscillating. Bending at the stern can also be seen a few seconds after of the impact. Much like the bow slam response, the port side of the bow and the starboard side of the stern also exhibit twisting. The excitation takes approximately 15 seconds to die out completely.

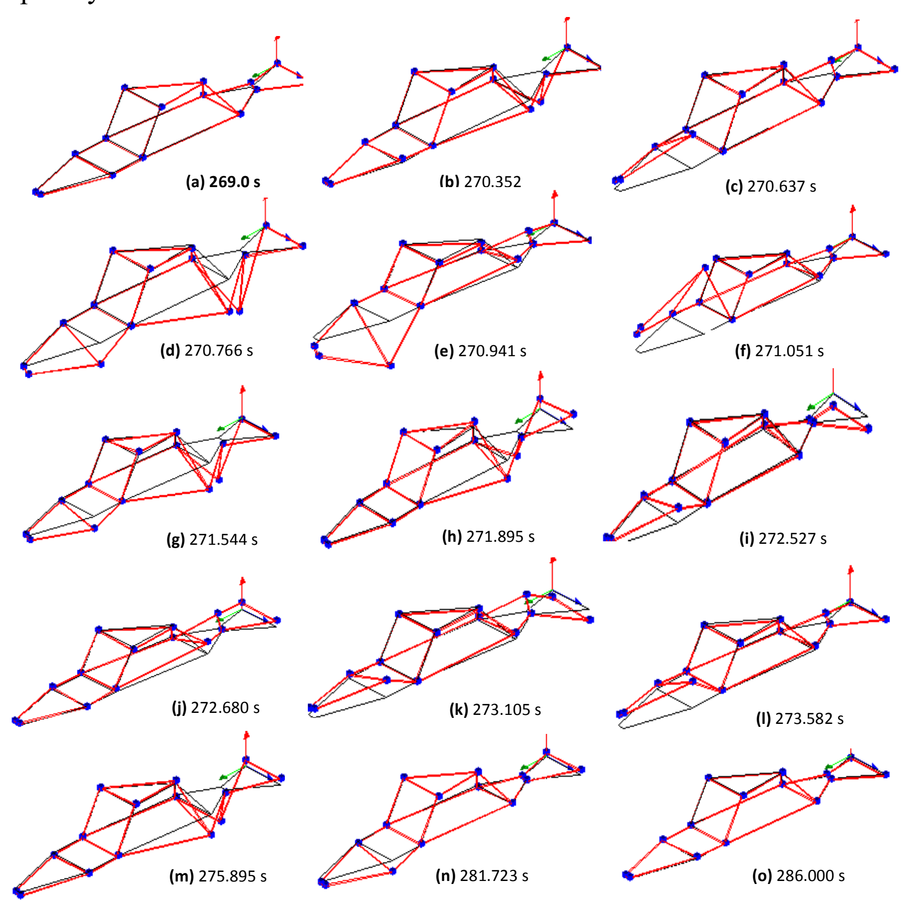


Figure 5.9: Time domain ODS for the stern slamming event

5.4.2 Frequency domain responses

Figure 5.10 and 5.11 show the frequency domain response of the bow and the stern slam respectively. For the bow slamming event, a coupling of modes at the 2.0 Hz and 3.70 Hz are observed. This means both bending and torsion are present. Similar is the case for the stern slamming frequency response.

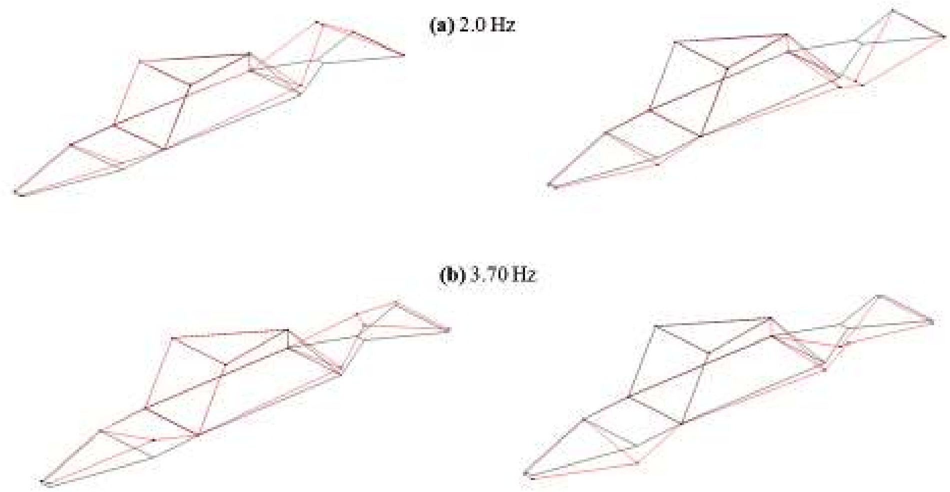


Figure 5.10: Frequency domain ODS for the bow slamming event

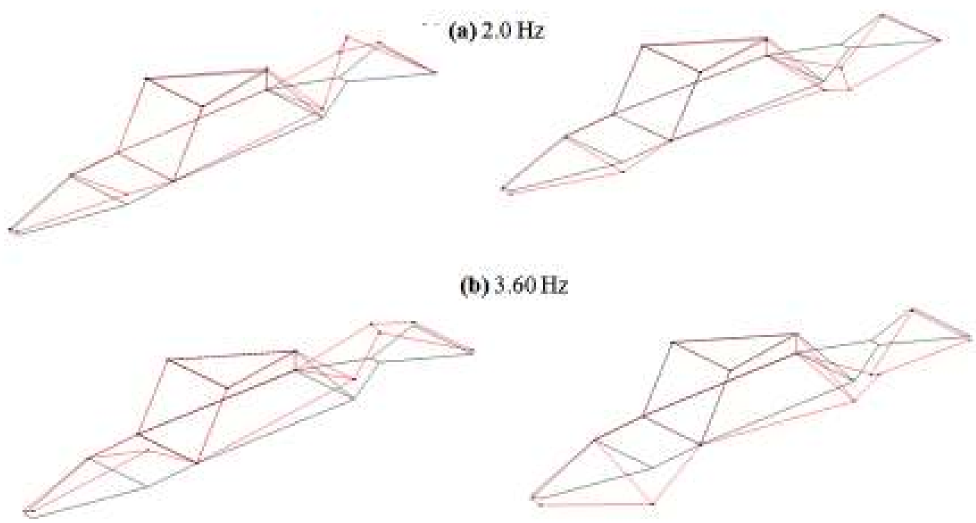


Figure 5.7: Frequency domain ODS for the stern slamming event

It is noted that the vessel behavior and the peak values of the frequencies are slightly different for both excitations. This can be explained by the change in mass properties and the operational conditions of the vessel between the incidences of these two events i.e. burning of fuel and change in draught etc. These reasons may have affected the resonant response of the vessel. It may be concluded from Figure 5.10 and 5.11 that these peak frequency responses may not represent any of the pure bending or torsion modes of the vessel.

5.5 Discussion

Time domain response proves to be useful in determining the slamming site and further revealing the behavior of the vessel due to the excitation produced as a result. ODS analysis indicates that oscillations due to slamming take a long time to die out completely. In case of bow slamming event, the vessel continued to vibrate for almost 40 seconds. Such long durations may lead to human comfort and performance issues. This is indicated by a study done by Omer & Bekker (2015) which concluded that wave slamming effects human comfort and performance on-board the S.A. Agulhas II. The study also reported scientific equipment usage and damage complaints due to slamming. This may be due to the bending and twisting of the vessel at the stern thruster and CMU region which hosts all the scientific laboratories. (Figure 5.3)

The analysis of the shapes for both events shows that the vibration travels throughout the ship and results in bending and twisting of the entire structure. It is to be investigated if this bending and twisting may result in structural fatigue and cause damage to the vessel, especially at the impact site. Soal *et al.,* (2015a) performed structural vibration analysis on the S.A Agulhas II and concluded that the bow and the stern region of the ship are at risk of damage due to structural fatigue. This fatigue was a result of the vibration encountered during vessel operation in the Southern ocean. The study also mentioned the occurrence and welding of cracks on the ship hull in the cargo hold. From the current ODS analysis, it is suggested that slamming leads to bending and twisting of the vessel which could contributes towards causing structural fatigue of the S.A. Agulhas II.

Soal *et al.,* (2015b) conducted an operational modal analysis (OMA) study on the S.A. Agulhas II and found the first 2 bending modes at 1.94 Hz and 3.40 Hz respectively. The study also compared the operational modal frequencies with the FE model natural frequencies provided by the manufacturers STX Finland. The modes found by the study were lower than the ones predicted by the FE model. The reason was the difference in the draught and boundary conditions. The difference between the resonant frequencies found by Soal *et al.,* (2015), and the current study is due to the fact that ODS may or may not reveal the modes of the structure. While modal analysis calculates only the resonant response of the structure, ODS determines both the forced and resonant response of the structure.

5.6 Conclusion

ODS techniques were used to visualize the dynamic response of the S.A Agulhas II during wave slamming events. Shapes are calculated for both bow slam and a stern slam to observe the vessel's behavior under different slamming excitations. The analysis revealed that the impact site (bow or stern) comes under severe loading immediately. The excitation propagates throughout the vessel which results into heavy oscillations that last for a considerable amount of time, depending on the impact. Both slamming events produce bending and twisting of the entire structure. It is noted that the long duration of heavy oscillations produced by slamming may affect human comfort and performance on-board the vessel. The likelihood of wave slamming causing structural fatigue or local damage to the vessel is to be investigated. Finally, frequency domain response suggested that at the peaks calculated from the PSD plot, the modes were coupled. Also, the resonant frequencies changed for both slamming events due to the change in mass properties and draught of the vessel.

6 Conclusion

Full scale measurements and human response survey was performed during the S.A. Agulhas II voyage to Marion Island in 2014 and Antarctica in 2014/15. The vibration caused by wave slamming was found to be strongly correlated with human problems on-board the S.A. Agulhas II. The levels exceeded the comfort threshold provided by ISO 2631-1 (1997) and interfered with activities such sleeping, writing/typing and visual tasks. Slamming not only affected the use of scientific equipment but in some cases even caused damage. ODS technique was used to determine the slamming impact site. ODS analysis of the impacts also revealed that slamming causes bending and twisting of the entire structure and the excitation takes a long time to die out.

Existing literature was reviewed in the context of wave slamming phenomenon. Gaps were identified in terms of slamming effects on human factors. Evidence has been provided from the present literature to support the hypothesis that slamming effects human comfort and interferes with activities and performance on-board. It was concluded that the evaluation methods to measure slamming for comfort are insufficient and that no dedicated study has been conducted in this context. The available metrics, as suggested by the standards, are not appropriate to estimate the severity of motion caused by slamming vibration for the prediction of comfort complaints in vessels that are disposed to slamming.

Measurements and analysis of vibration was performed on the S.A. Agulhas II during her voyage to Marion Island in the context of human factors. Along with full scale measurements at two different locations (Deck 3 and Deck 8) on the vessel, a human survey was also conducted to acquire subjective response of the issues caused by slamming. Vibration was measured and analysed by calculating different metrics during vessels operation in rough seas where heavy slamming was reported. The vibration displayed high crest factors (exceeding 9.0) and resulted in high magnitudes of acceleration. The r.m.s values calculated for the slamming vibrations exceeded the comfort threshold on the vessel and were considered to be "Fairly uncomfortable", according to ISO 2631-1 (1997). The hybrid design of the ship is believed to be a contributor towards making slamming an issue during open water operations. Subjective response also highlighted the criticality of this phenomenon in terms of safety of humans and equipment due to high levels of vibrations at Deck 3.

A method was described to isolate slamming events from other vibration on the vessel using analysis of the time history and PSD. A total of 9473 slams were found to have occurred during the voyage. Kendall's coefficient analysis indicated that slamming vibration was associated with human responses aboard the S.A. Agulhas II. The VDV for the slamming instances was accrued on a daily basis. These cumulative VDV values were proven to correlate the best with human complaints and rating of slamming severity. Sleep disturbance was the most frequently reported complaint followed by equipment use complaints. Ten incidences of equipment damage were also reported. There was a marked increase in the reports of respondents considering slamming events to be ‘severe’ when cumulative VDV acceleration exceeded 6.0 $m/s^{1.75}$at the stern. Similarly for complaints of slamming effects, a correlation is demonstrated with an increase in acceleration magnitude. Consideration of environmental factors such swell height and wind speed revealed that the vessel is prone to slamming even at low sea states.

ODS technique was been implemented to visualize the dynamic response of the S.A Agulhas II during wave slamming events. The analysis of the shapes show that the impact site of the slamming event can be determined using the time domain response. It was also noted that the area of impact comes under loading immediately. This impact results into a broad band excitation of the entire structure. The excitation propagates throughout the vessel producing oscillations that last for 20 to 40 seconds approximately, depending on the impact. Both slamming events produced global bending and twisting of the vessel. It was suggested that the long duration of heavy oscillations produced by slamming may affect human comfort and performance on-board the vessel.

7 Recommendations for future work

The present work investigated slamming as a result of vertical vibration. Wave slamming is a three dimensional phenomenon (Bertram, 2012), hence a tri-axial measurement is recommended to improve the representation of the impact. There is potential to conduct an in-depth study on the causes and effects of bow and stern slamming events. A better response rate and data resolution for the subjective response is also suggested for an improved correlation study. Vibration metrics like root-mean-quad (r.m.q) and maximum transient vibration value MTVV can also be included in the considered metrics.

A thorough investigation is needed to understand the influence of environmental and operational factors on wave slamming. Environmental factors such as swell and wind direction and operational parameters like ship speed, heading and draught can be correlated to the slamming response. This can lead to the development of a regression model for the prediction of the slamming response using the environmental and operational factors. It can also be investigated if slamming can result in structural fatigue and damage to the vessel, especially at the impact site.

Systematic studies can be conducted in the laboratory to further validate these finding. Slamming vibrations can be recreated to perform systematic studies of human response to slamming stimuli. Experiments can be designed specifically on how motor skill and perceptual tasks are affected during an event of slamming. The same could be done for understanding the relationship of slamming to the performance of physical tasks. A study can also be executed to investigate the effects of noise produced by slamming on discomfort. A robust data acquisition system is needed to prevent the loss of data during full scale measurements.

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Appendix A

A.1 Conference paper

This paper was published and presented at the proceedings of the 50th United Kingdom Conference on Human Responses to Vibration, held at ISVR, University of Southampton, Southampton, England, 9 - 10 September 2015. This paper and the feedback provided the basis for the work presented in Chapter 4.

A STUDY OF WAVE SLAMMING VIBRATIONS AND ANALYSIS IN THE CONTEXT OF HUMAN FACTORS ON THE S.A. AGULHAS II DURING A VOYAGE TO THE SOUTHERN OCEAN

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Abstract

Vessels operating in Antarctica and the Southern Ocean have a hybrid design due to their operation in both ice and open water. Wave slamming phenomenon is one of the consequences pertaining to these design considerations of a flat and raised aft and a rounded keel to break ice efficiently. As critical as these impulsive vibrations due to slamming can be, no detailed studies have been performed as to how they affect human comfort and performance on-board. To this end a study was done to analyse slamming vibration in the context of human factors. Full scale measurements were performed on the S.A. Agulhas II during a voyage to Antarctica. A survey was also conducted to gather the human response. The vibration caused by wave slamming was found to be strongly correlated with human problems aboard the S.A. Agulhas II. The highest correlation found was the average VDV values which proved to be the best metrics amongst all others. Sleep and equipment use was found to be the most affected parameters by slamming. There was a marked increase in the reports of respondents considering a slamming event to be ‘severe’ when the average VDV acceleration exceeded 6.0 $m/s^{1.75}$ at the stern of the vessel.

1 Introduction

Wave slamming, also referred to as whipping, can be described as the exposure of a vessel structure (bow, stern or hull bottom) to large forces due to wave impacts for a short duration of time (Kapsenberg, 2011). This event occurs when the vessel’s bow or stern emerges from a wave and re-enters the water with a heavy impact (ABS, 2011). Constantinescu *et al*. (2009) describe slamming as a random, dynamic and non-linear event affecting the structure of the vessel, both globally and locally. Local response refers to the area of the impact site which is under severe loading and is prone to damage in case of repetitive impacts. The global response refers to the large oscillations and bending moments felt throughout the vessel. As a result, the high impact loads can damage the structure of the vessel (ABS, 2011).

Bekker (2013) describes slamming vibration to be highly impulsive in nature. This is explained by the high velocity impacts that occur between the surface of the ship and water. The response of this impulse is experiences throughout the entire ship structure as heavy oscillations which take a long time to die out completely. The same study also reports that slamming vibration excites a range of frequencies below 15 Hz. Slamming is said to be the cause of several maritime accidents including the sinking of the *Estonia* in

1994 (Kapsenberg, 2011). It is also considered as one of the compounding factors that led to the breaking down of four container vessels in the past four decades (Storhaug, 2014).

Besides the harmful effects on the ship's structure, slamming can also affect human factors such as comfort and performance as well as cause damage to the equipment on-board (Constantinescu *et al*., 2009). It is considered as one of the sources that contribute to the noise on a ship (Carlton & Vlasi´c, 2005). A study by Haward *et al.* (2009) describes slamming as an environmental issue on-board as it was found to be one of the major reasons for sleep interruption and tiredness. The study proceeded to report that this fact made some crew members unable to work. Another study claims that the severity of slamming vibration can possibly affect the motor skills of the vessel occupants and can cause blurring of vision and difficulties with cognitive skills such as interpretation (Dobie, 2000). Stevens and Parsons (2002) also state that slamming can impair the perceptual tasks of the ship occupants.

The above mentioned studies provide hints as to how wave slamming can affect human comfort and performance. However, none of these reviewed studies were specifically investigating slamming and its impact on humans. At present, literature focuses on either the effect of low frequency whole body vibration or motion sickness on human factors. Hence it is safe to say that not much has been done in order to investigate the effects of slamming regarding human comfort, performance and equipment on-board. As such a detailed study is required to determine how slamming correlates to human factors. There is a need to develop a better understanding of methods, to evaluate slamming vibration which is impulsive and transient in nature. BS 6841 (1987) and ISO 2631-1 (1997) are two principle international standards for evaluation of vibration in relation to human response but they are unsatisfactory for the determination of discomfort produced by shock waveform (Patelli *et al*., 2013). A comparison done by Marjanen (2005) also concludes that both of these standards underestimate transient shocks.

To this end a study was done to analyse slamming vibration in the context of human factors. Full scale vibration measurements were performed on the S.A. Agulhas II, a South African Polar Supply and Research Vessel (PSRV) during her voyage to Antarctica in the Southern Ocean. A survey was also conducted in the form of a daily diary to be completed by the passengers on-board. The survey questionnaire was prepared in order to acquire the human response to the effects of slamming on comfort, performance, equipment use and safety. The vibration measurements and human response was then compared to investigate how slamming can be correlated to human factors. The study also examined these correlations to find an appropriate vibration metric to effectively describe slamming vibrations. In addition to that, the research also provides insight into the effects of slamming on oceanographic research work.

2 Background

The S.A. Agulhas II is a PSRV built by STX Finland. It was commissioned in April 2012 and is the backbone of South African research program in Antarctica and the Southern oceans. The vessel was built to Polar Ice Class PC 5 and was classified by DNV with a comfort class notation of COMF-V(2)C(2). She is fully equipped with laboratories for the scientists to conduct on-board research. The vessel is designed to operate both in open water and ice and some design tradeoffs have been made in this regard. It has a thick rounded keel to break the ice and a flat aft to accommodate container laboratories. The aft of the vessel is also raised to let the ice pass between the propellers and the hull.

During her voyage to Marion Island in 2013, S.A. Agulhas II experienced severe slamming incidents. The captain and the crew complained that these incidents affected the performance and comfort of the people on-board. The research work was also said to be affected due to heavy slamming at the stern. In this regard the Sound and Vibration Research Group of Stellenbosch University was approached to perform slamming measurements. A brief study was done which captured the induced slamming events during a trial run and analysed the measurements (Bekker, 2013). This investigation found high acceleration levels due to slamming and recommended that a thorough study should be performed in operational conditions to measure the real time slamming incidents and analyse them with respect to human factors. The current study is therefore undertaken to specifically investigate slamming in context of human factors.

3 Methodology

3.1 Voyage description

The S.A. Agulhas II sailed from Cape Town on 04/12/14 for a 76 day voyage to Antarctica. More than 50 % of the time was spent either breaking pack ice or standing stationary at the Antarctic shelf for logistical reasons. Only the open water data was used for slamming measurements which is divided into three legs:

- Leg 1 – day 1 to day 9 (departing Cape Town until reaching pack ice)
- Leg 2 – day 28 to day 47 (leaving Antarctic shelf for buoy run)
- Leg 3 – day 67 to day 74 (return trip to Cape Town)

The measurements from leg 2 and leg 3 were used for the analysis as the data from leg 1 was incomplete due to software crash. The oceanographic research was continuously performed during all these legs. This included sampling of sea water and deployment and retrieval of oceanographic data measuring systems at certain locations.

3.2 Full scale Measurements

Full scale measurements were performed on the S.A. Agulhas II during a voyage between Cape Town and Antarctica for 76 days. A total of six accelerometers were placed throughout the vessel to capture vibration at relevant locations. The acceleration was captured in the vertical direction only as it was found to be dominant during the slamming trial study and full scale measurements throughout her Antarctic voyage in 2013/2014 (Bekker, 2013) and (Soal & Bekker, 2013)

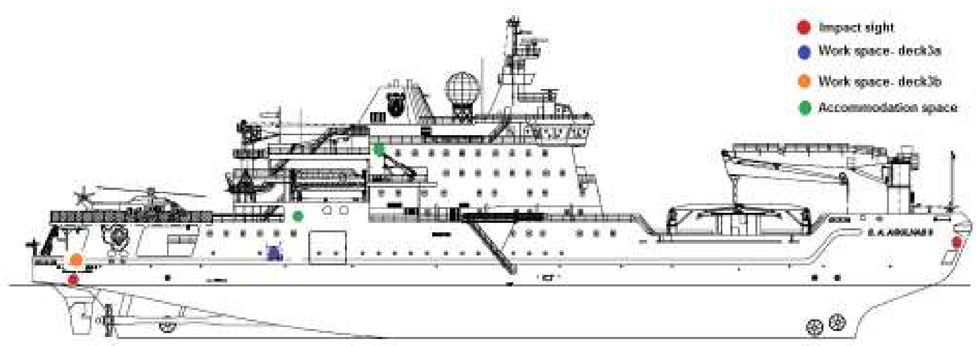

Figure 1: Location of the accelerometers on the S.A. Agulhas II

Accelerometers at the stern (deck 2) and bow (deck 4) were used for identifying slamming events as they were closest to the impact sites. The accommodation space on the vessel runs from deck 4 to deck 8. Hence one accelerometer was placed at deck 5 and one at deck 8. Two accelerometers were placed on deck 3 which was the working area for the scientists containing research laboratories both inside and outside. Hence, a total of six accelerometers were used to identify slams and represent the working and accommodation areas where passengers spent most of their time.

LMS SCADAS mobile data acquisition units were used in a master slave configuration. Furthermore, ICP accelerometers were used for this study as they have an appropriate frequency range of 0.5 to 3000 Hz and average sensitivity of 100mV/g. A sample rate of 2048 Hz was selected and measurements were recorded continuously with 5 minute intervals.

3.3 Questionnaire survey

The key component of the study was to conduct a questionnaire survey to gather human response. A questionnaire (attached as Annex -A) was prepared which was required to be filled in as a daily diary. The respondents had to start the questionnaire by answering if a slamming event occurred that day or not. Only in the cases when it happened, could they proceed with replying to the subsequent questions. This included rating of the worst slamming event for that day (on a scale of 1 to 10) and then mentioning if slamming had affected their sleep or task performance. It was also inquired if the equipment use had been disturbed or if any damage had occurred. A section was also left for comments. The questionnaires were distributed on the first day and were collected two days before returning to Cape Town (day 74). The survey was anonymous and was distributed after delivering a comprehensive presentation which explained the phenomenon, aim of research and filling instructions.

3.4 Post processing

3.4.1 Vibration measurements

The post processing and analysis of the vibration data was done using *MATLAB* and *LMS Test.Lab Turbine Testing* according to ISO 2631-1 (1997). Each 5 minute measurement was human weighted using the W_k filter as described in ISO 2631-1 (1997).

The weighted data was then used to calculate the peak, *r.m.s*, Crest Factor (CF) and Vibration Dose Value (VDV) values.

3.4.2 Statistical methods

The statistical analysis was done using the *Statistica* software package. A similar method was followed as by the studies of Pisula *et al*. (2012) and Haward *et al.* (2009). Both studies are relevant to the current research as they also correlate human response to vessel vibration. A Shapiro-Wilk statistical test of normality was conducted on the data. The distribution was found to be non-normal; hence a non-parametrical analysis was performed. Kendall's correlation was used as a statistical tool to estimate the correlation of the slamming measurements with human response.

3.4.3 Data analysis

The data analysis was performed in three stages.

3.4.3.1 Stage 1: Finding slamming events

To keep the study specific to slamming vibration, finding and selecting only slamming events was vital. An algorithm was developed to investigate each 5 minute recording of vibration for the entire 26 days in open water. Accelerometers at the stern and the bow were used for the investigation as they were close to the impact site. As slamming is considered to be impulsive, the algorithm started with calculating the CF for every file and only selecting the files with a CF higher than 9.0 either at the bow or stern. This criterion was imposed using the definition of impulsive vibration as described by ISO 2631-1 (1997) which considers vibrations above 9.0 as impulsive. After these files were segregated, each file was analyzed individually.

Time history and power spectral density (PSD) plots were inspected to ensure that the signal adheres to the properties of a slamming event. The time history of the signal at the bow and stern were plotted together along with other accelerometers to see if the peaks for the impulsive signal occurred at the same instant. This check was performed to confirm whether the event was global or not, as slamming vibrations would be experienced throughout the entire vessel. In addition to this, PSD plot of the same signal was analyzed. PSD plots were developed using *pwelch.m* command in *MATLAB* with 50 % overlap and a *hanning* window resulting in a resolution of 0.25 Hz. After all the files were individually scanned, only those with slamming events were selected and processed for further analysis.

3.4.3.2 Stage 2: Finding correlation between human response and slamming measurements

The next step was to calculate the correlation between the slamming vibration and human response. As the human response data had a resolution of 24 hours, the vibration data was transformed accordingly. Vibration data was evaluated using three different metrics namely peak, r.m.s., VDV. The calculation was further performed to estimate the daily average and the maximum value per day for each metric. Kendall's tau was used to correlate these six vibration metrics (three average metrics and three maximum metrics) with the daily human response. This not only provided the correlation of slamming with the human factors but also the information on selecting a vibration metric which effectively describes slamming vibrations in the context of the human factors.

3.4.3.3 Stage 3: Human response as a function of slamming acceleration magnitude

To demonstrate how human perception of slamming severity is linked to slamming magnitude, the cumulative distributions of the rating responses were plotted as a function of slamming acceleration magnitude. The technique used to generate these plots was according to the study by Pisula *et al.* (2012) and Haward *et al.* (2009). Based on a similar method, the human factors were also plotted against slamming acceleration to estimate how the response is affected by magnitude.

4 Results and discussion

4.1 Identifying slamming events

Slamming events were identified using a verification algorithm. A total of 7488 files of 5 minute recording were analyzed in accordance with slamming properties mentioned in the literature. Approximately half of the files were found to contain a total of 9473 slams. Figure 2 and 3 presents an example of how the investigation was conducted for each file. It shows the time histories and PSD plots of an acceleration signal taken from a 5 minute run recorded on day 68. The time signals of the nearest impact sites (bow and stern) were plotted against other sensors which reveal that the vibration signal is indeed impulsive and that the peaks occur at the same time instant. Both these facts indicate a slamming phenomenon as it always leads to an impulsive and transient impact which is felt throughout the entire vessel. Also, slamming impact can generates high forces producing high levels of acceleration.

Further insight is provided by looking at the PSD plot of the event as shown in Figure 3. The plot shows that slamming excites a broad range of frequencies from 2 to 15 Hz including the modes for which the peaks can be seen. Hence it was concluded that the file contained slamming events. The number of slams was also counted from the time history of all the files (4 slams can be observed from Figure 2).

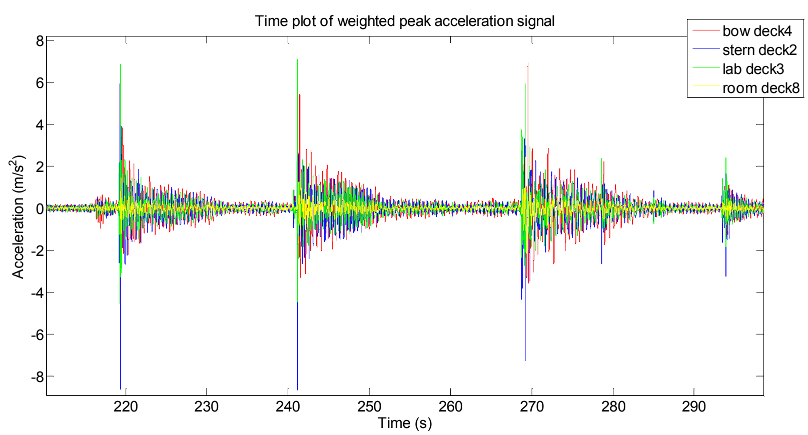

Figure 2: Time history of the weighted acceleration vibration signal from day 68

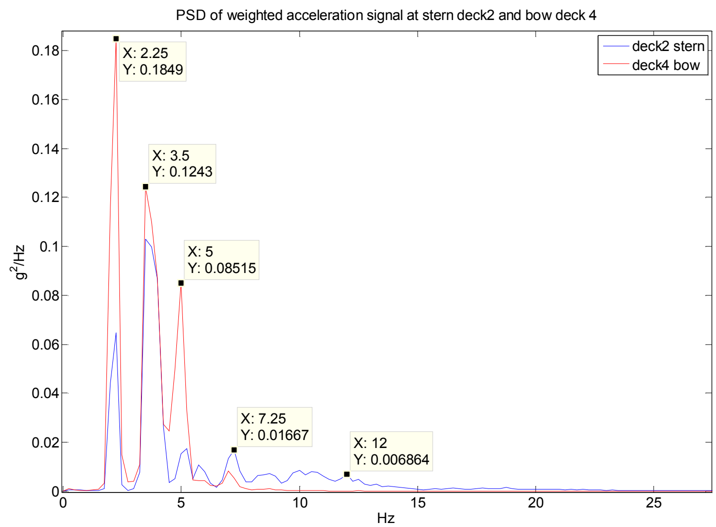

Figure 3: PSD plot of the weighted acceleration vibration signal from day 68

Figure 4 shows the peak values of vibration calculated at stern deck 2 for the 26 days of open water data (also includes sometime in ice). The distribution of slamming events can be seen along with the vibration generated from other sources. It can be noted that most of the higher values of acceleration are due to slamming. This is caused by the hybrid design of the ship. The flat and raised stern and a big rounded keel offer a large surface area. This makes the vessel prone to wave slamming not only during rough weather but even during low sea states. Flat aft designs are said to be affected by stern slamming even when the swell height is less than 1m (Carlton & Vlasi´c, 2005). The situation is worsened during oceanographic activities when the vessel is stationary. Carlton & Vlasi´c (2005) also mention that stern slamming is highly dependent on ship speed. If stationary, the aft of the vessel is more likely to be effected by wave slamming whereas increasing the speed can reduce the effect by interrupting the environmental wave system.

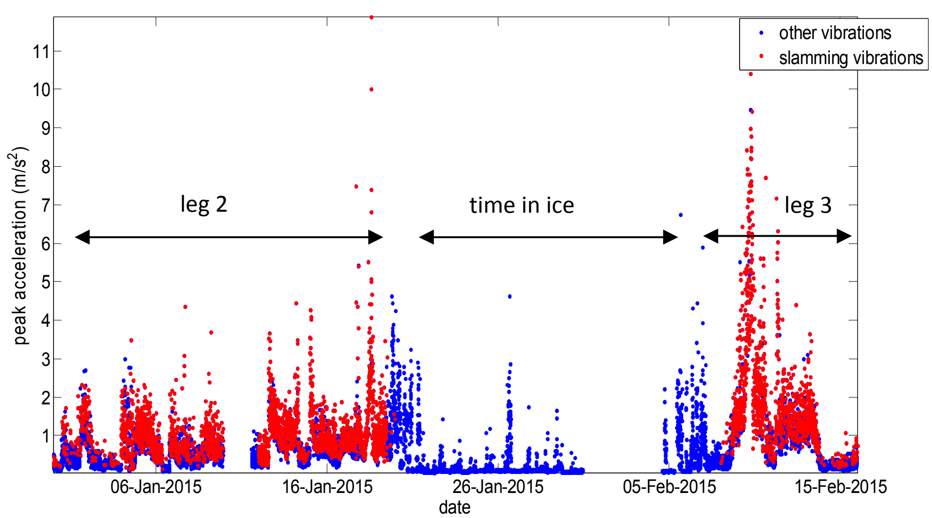

Figure 4: Slamming vs. non slamming events for the peak values of all the 5 minute files

4.2 Human response

The vessel hosted 98 passengers ranging between the ages of 21-65 and included a fair mix of both genders. A quarter of the passengers were involved in research activities on the vessel throughout the voyage. The research included using oceanographic equipment for collecting deep ocean water samples. The human response survey was conducted strictly in view of wave slamming vibrations. Passengers only responded if they encountered slamming events. They started with rating the severity of the worst slam on a scale of 1 to 10. Figure 5 shows the distribution of average human rating (mentioned at the top for each day) along with the number of slams.

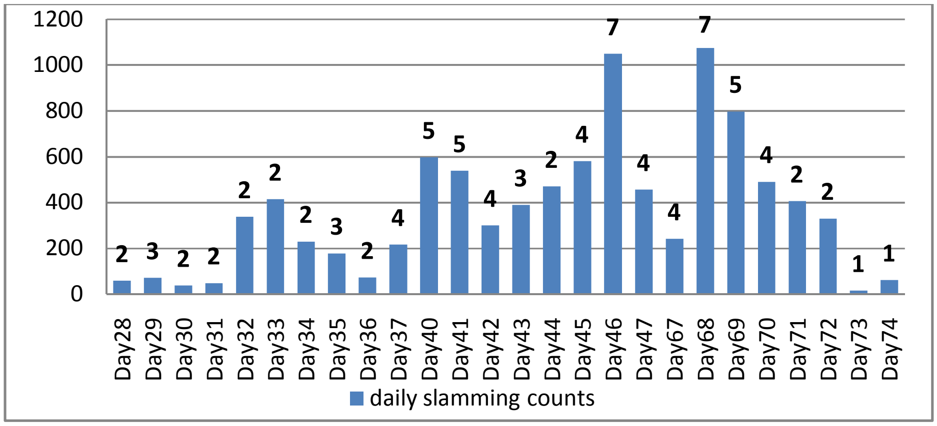

Figure 5: Slamming count with average human rating per day

A total of 427 complaints were logged throughout the voyage with a response rate which varied from 34% to 88%. Figure 6 shows the distribution of the complaints with sleep being reported as the most affected factor. Visual tasks and writing/typing both were reported 63 times each, however they were not always reported during the same slamming incidents. Equipment use was the second most logged complaint. Several incidents were noted where using equipment was said to be affected but no typing/writing or visual task complain was mentioned. As such, it suggests that the research passengers were more sensitive towards reporting equipment use problems. During the course of the entire voyage, equipment damage was stated 10 times.

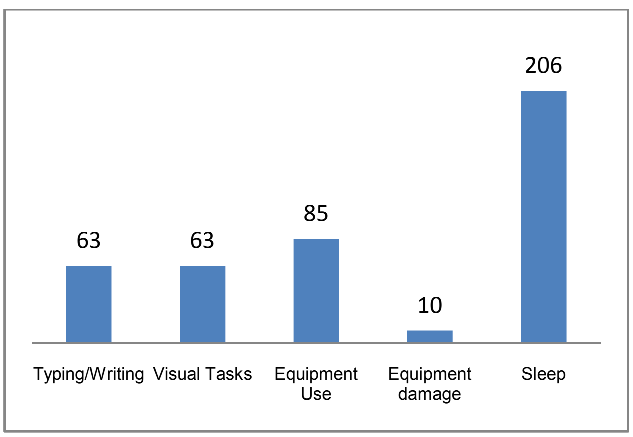

Figure 6: Distribution of complaints for the entire voyage

Oceanographic research was continuously performed throughout the voyage. This included the taking of surface water samples through the bow intake after every few hours daily. The main activity however was to collect deep water samples which included deployment and retrieval of equipment into the ocean at certain locations. Wave slamming was reported to interfere with such activities regularly. The vibrations were reported to often cause the sampling tap pipe to disconnect. Slamming vibration was also said to effect the deployment and retrieval of the equipment. The filtering and measurements activities were also affected in the clean container laboratory which was located outside on deck 3. However, this may also be affected by the rolling of the ship.

4.3 Correlations between slamming vibration and human factors

The daily average rating and percentage of complaints were found to be highly correlated to the slamming vibration. For human rating, data from both work space and accommodation accelerometers was used. Also deck 2 accelerometer data was correlated to see how the impact site vibration associates with human response. Correlation was highly significant ($p<0.01$) between all the vibration metrics and the average human rating. However, average VDV was found to show the best correlation.

Table 1 Kendall's correlation coefficient between daily average rating and slamming vibration measurements. (**$p< 0.01$)

Location	Average values			Max values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.526**	0.428**	0.582**	0.557**	0.458**	0.508**
Deck 5	0.397**	0.378**	0.538**	0.397**	0.514**	0.477**
Deck 3a	0.489**	0.440**	0.569**	0.575**	0.551**	0.588**
Deck 3b	0.415**	0.446**	0.551**	0.483**	0.495**	0.545**
Deck 2	0.514**	0.477**	0.575**	0.526**	0.502**	0.557**

For factors like typing/writing and visual tasks, daily percentage of complaints was correlated with vibration data from all the accelerometers as above. However, deck 3b accelerometer data wasn't used for typing/writing as it was placed at the container laboratory where no typing/writing activity was taking place. Both average VDV and maximum r.m.s showed the best correlation and significance according to Table 2 and 3.

Table 2 Kendall's correlation coefficient between typing/writing complaints and slamming vibration measurements (**$p< 0.01$, *$p>0.05$)

Location	Average values			Max values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.341*	0.355*	0.413**	0.341*	0.442**	0.399**
Deck 5	0.276*	0.290*	0.406**	0.297*	0.428**	0.370**
Deck 3a	0.334*	0.334*	0.384**	0.326*	0.348*	0.334*
Deck 2	0.355*	0.341*	0.392**	0.326*	0.370**	0.355*

Table 3 Kendall's correlation coefficient between visual task complaints and slamming vibration measurements (**p< 0.01, *p>0.05)

Location	Average values			Max values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.310*	0.338*	0.366**	0.338*	0.401**	0.373**
Deck 5	0.234*	0.248*	0.352*	0.269*	0.345*	0.345*
Deck 3a	0.282*	0.282*	0.331*	0.276*	0.331*	0.324*
Deck 3b	0.234	0.289*	0.338*	0.380**	0.359*	0.359*
Deck 2	0.310**	0.310**	0.324**	0.338**	0.352**	0.345**

For sleep disturbance complaints, accommodation accelerometer data was correlated with the slamming vibration metrics. Table 4 shows that all metrics were significantly correlated with sleep, whereas average VDV demonstrated the strongest correlation. Table 5 shows the correlation between equipment usage complaints and slamming vibration. Work space accelerometer data was used as the equipment was only located and used on deck 3. The result here is also similar as in above cases. All metrics are significantly correlated with VDV being the strongest metric once again. Equipment damage complaints were not evaluated as the incidences were not enough to make a significant correlation.

Table 4 Kendall's correlation coefficient between sleep complaints and slamming vibration measurements (**p< 0.01, *p>0.05)

Location	Average values			Max values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 8	0.429**	0.411**	0.454**	0.429**	0.355**	0.392**
Deck 5	0.367**	0.373**	0.435**	0.342*	0.417**	0.423**
Deck2	0.429**	0.417**	0.435**	0.361**	0.348*	0.379**

The analysis of the correlation between human response and vibration data reveals that the human factors are associated with wave slamming vibration. All the selected metrics are found to be significantly correlated with human response. Average VDV showed the best correlation in most of the cases along with average r.m.s in some cases (typing/writing and visual tasks). VDV is presented as a better evaluation metric when the vibration is impulsive according to ISO 2631-1 (1997) and BS 6841 (1987) (Griffin, 1990). It can be noted that VDV is sensitive to peaks in the acceleration signal. This is the reason why it appears to be a good metric for evaluating slamming vibration and shows strong correlation with human response. According to Griffin (1990), VDV is the cumulative measure of the vibration and shock experienced by a person during the measurement period. It is given by the formula

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

$a_w(t)$ is the human weighted acceleration T is the total measurement period in seconds. Average VDV for the study was calculated for the entire duration of time for which slamming was encountered. This way a cumulative VDV was obtained for each day. However the maximum VDV was the maximum value amongst all those calculated for a 5 minute run.

Table 5 Kendall's correlation coefficient between equipment usage complaints and slamming vibration measurements (**p< 0.01, *p>0.05)

Location	Average values			Max values		
	Peak	r.m.s	VDV	Peak	r.m.s	VDV
Deck 3a	0.415**	0.327*	0.502**	0.484**	0.452**	0.528**
Deck3b	0.333*	0.371**	0.502**	0.421**	0.440**	0.465**
Deck 2	0.433**	0.383**	0.515*	0.484**	0.446**	0.509**

4.4 Human response as a function of slamming acceleration magnitude

To illustrate how the human factor is affected by slamming vibration magnitude, human response distribution was plotted as a function of acceleration magnitude. The vibration metric used was the average VDV as it was found to show the best correlations consistently. The data of deck 2 stern accelerometer was used. This sensor was chosen to reflect the acceleration magnitude of the closest point to the impact of the slamming force. The method to plot the distribution was based on the idea presented by Pisula *et al.* (2012) and Haward *et al*. (2009). The acceleration scale was divided into a band of 2.0 $m/s^{1.75}$. The cumulative distribution of percentage of average human rating has been plotted against VDV acceleration in Figure 7. A strong correlation can be noted from the plot as shown in Table 1. This plot also provides useful information about the trend of human rating of severity along with the increase of acceleration. For example, only 15 % of the passengers considered slamming event to be severe when the acceleration level was between 4.0 to 6.0 $m/s^{1.75}$, however there is a distinct increase in this percentage up to 68% when the acceleration magnitude exceeds 6.0 $m/s^{1.75}$.

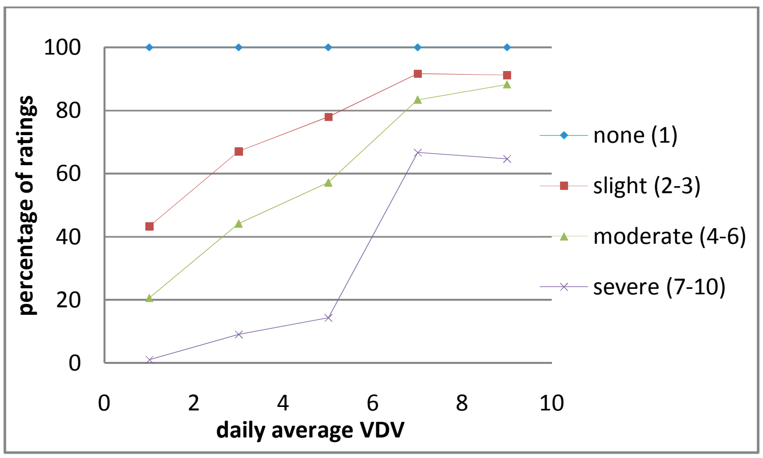

Figure 7: Cumulative distribution of human rating as a function of slamming magnitude

The distribution of complaints was also plotted against the VDV acceleration of the deck 2 stern accelerometer as shown in Figure 8. The band size was kept the same, however this time the distribution was not cumulative as complaints were not logged in as ratings. The percentage of complaints was used to see how they varied with the increase of acceleration magnitude. Sleep complaint distribution was generally higher throughout reaching more than 50 % when the acceleration value exceeded 8.0 $m/s^{1.75}$. A rise in the equipment use complaints can be observed as the magnitude of acceleration is increased above 6.0 $m/s^{1.75}$. It can also be noted that even at the lowest magnitudes, sleep and equipment usage complaints were reported. Typing/writing and visual tasks complaints show a similar pattern at the lower magnitudes. Typing/writing complaints increase linearly throughout, whereas a fluctuation can be observed in the visual tasks complains beyond 6.0 $m/s^{1.75}$.

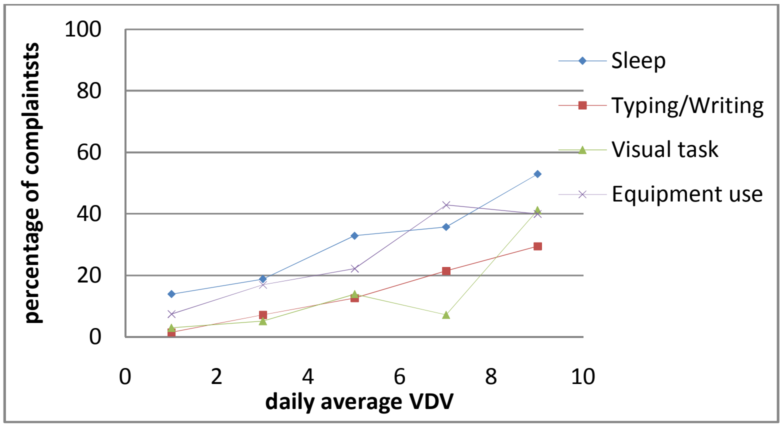

Figure 8: Human factor as function of slamming magnitude

4.5 Study limitations

The study was limited due to the low participation rate from the passengers. Some of the daily diaries were left incomplete where others were not returned. One of the reasons for low response rates can be the overall long duration of the voyage and the large response gaps that occurred due to the vessel operation in ice. This may have reduced the motivation of passengers to keep filling in the diary. Another factor can be the involvement of some passengers in long hours of work shifts throughout. There was also no way to verify the authenticity of the claims that were reported in the human response. Measurement of slamming vibration was only conducted at certain locations. Not all location had the facility to be used for placing a sensor. For instance, the sensor used to capture slamming at the bow was placed at deck 4, unlike the sensor at the stern which was placed at deck 2. The accommodation space for passengers starts at deck 4 but the sensor was placed at deck 5. It is thought that measuring acceleration at locations closer to the wave impacts and human activity points will provide greater insight into the relationship between slamming vibrations and the human response. The low resolution of data due to 24 hour human response averages may also distort the correlation results.

5 Conclusion

The vibration caused by wave slamming was found to be strongly associated with human responses aboard the S.A. Agulhas II. The highest correlation was found to be between the average VDV values which proved to be the best metric. Vibration measurement analysis revealed that most of the high levels of acceleration recorded by the sensors were impulsive and occurred as a result of wave slamming. This is due to flat stern and rounded keel of the S.A. Agulhas II, which makes it prone to high wave slamming impacts. Sleep disturbance was the highest logged complaint. Slamming vibration was also reported to effect equipment use and interferes with oceanographic research activities. There were 4 days during which incidences of equipment damage were reported. There was a marked increase in the reports of respondents considering slamming events to be 'severe' when average VDV acceleration exceeded 6.0 $m/s^{1.75}$ at the stern. Similarly for complaints of slamming effects, a correlation can be seen with the increase in acceleration magnitude.

6 Acknowledgement

The authors would like to thank The Department of Environmental Affairs, South Africa and the S.A. Agulhas II represented by Captain G. Syndercombe for letting us conduct measurements and questionnaire survey. Furthermore, we would also like to thank Mr. Keith Soal, Mr. Brendan Boulle and Ms. Gillian Trollope for providing assistance and guidance throughout the different phases of this study.

7 Appendix A. Slamming questionnaire

Slamming

Encountered slamming	No	Occasionally	Regularly
Worst slamming incident rating (1 = nothing, 3 = slight, 10 = severe)	1 2 3	4 5 6 7	8 9 10
Activity/equipment affected by slamming	No	Typing/writing	Visual tasks (reading/TV)
(tick the appropriate boxes)	Equipment use	Equip. damage	Sleeping
Did you find slamming to be uncomfortable?	Yes	No	
Comments:			

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Appendix B

B.1 Matlab Code for IIR weighting filter W_k

```
 %code for IIR weighting filter Wk ISO 2361
 clc

npoints = 100000;

 % Impulse signal

xf = ones(npoints,1); % impulse in frequency domain
x = ifft(xf);

 % Random signal
 x = randn(npoints,1);

 % defining f and t Vector

 fs= 2048; % sample frequency
 tmin = 0;
 tmax = tmin + (npoints-1)/fs;
 t = linspace(tmin,tmax,npoints);
 f = linspace(0,fs/2,npoints/2);

% defining variables
 w1 = 0.4*2*pi/fs;
 Q1 = 1/sqrt(2);
 w2 = 100*2*pi/fs;
 Q2 = 1/sqrt(2);
 w3 = 12.5*2*pi/fs;
 w4 = 12.5*2*pi/fs;
 Q4 = 0.63;
 w5 = 2.37*2*pi/fs;
 w6 = 3.3*2*pi/fs;
 Q5 = 0.91;
 Q6 = 0.91;


%% High Pass Filter

    w1h = 2*tan(w1/2);

    a0 = 4*Q1 + 2*w1h + w1h^2*Q1^2;
    a1 = 2*w1h^2-8*Q1;
    a2 = 4*Q1 - 2*w1h + w1h^2*Q1^2;

    b0 = 4*Q1;
    b1 = -8*Q1;
    b2 = 4*Q1;

    ah = [a0, a1, a2];
    bh = [b0, b1, b2];
  Xh = filter(bh,ah,x);


%% Low Pass Filter
```

```
    w2l = 2*tan(w2/2);

    a0 = 4*Q2 + 2*w2l + w2l^2*Q2;
    a1 = 2*w2l^2*Q2 - 8*Q2;
    a2 = 4*Q2 - 2*w2l + w2l^2*Q2;

    b0 = w2l^2*Q2;
    b1 = 2*w2l^2*Q2;
    b2 = w2l^2*Q2;

    al = [a0, a1, a2];
    bl = [b0, b1, b2];
    Xl = filter(bl,al,Xh);

%% Acceleration-Velocity Transition Filter

    w3t = 2*tan(w3/2);
    w4t = 2*tan(w4/2);

    a0 = 4*Q4 + 2*w4t + w4t^2*Q4;
    a1 = 2*w4t^2*Q4 - 8*Q4;
    a2 = 4*Q4 - 2*w4t + w4t^2*Q4;

    b0 = w4t^2*Q4 + 2*(Q4*w4t^2)/(w3t);
    b1 = 2*w4t^2*Q4;
    b2 = w4t^2*Q4 - 2*(Q4*w4t^2)/(w3t);

    at = [a0, a1, a2];
    bt = [b0, b1, b2];
    Xt = filter(bt,at,Xl);


%% Upward Step Filter

    w5s = 2*tan(w5/2);
    w6s = 2*tan(w6/2);

    a0 = (4*Q6 + 2*w6s + w6s^2*Q6)/Q5;
    a1 = (2*w6s^2*Q6 - 8*Q6)/Q5;
    a2 = (4*Q6 - 2*w6s + w6s^2*Q6)/Q5;

    b0 = (4*Q5 + 2*w5s + w5s^2*Q5)/Q6;
    b1 = (2*w5s^2*Q5 - 8*Q5)/Q6;
    b2 = (4*Q5 - 2*w5s + w5s^2*Q5)/Q6;

    as = [a0, a1, a2];
    bs = [b0, b1, b2];
    Xs = filter(bs,as,Xt);

%% FFT's

fftx = fft(x)/npoints;
```

```
fftx = fftx(1:npoints/2);
fftXs = fft(Xs)/npoints;
fftXs = fftXs(1:npoints/2);

ampx = abs(fftx);
ampXs = abs(fftXs);

%% ISO 2631 frequency domain filter

 w1 = 0.4;
 w2 = 100;
 w3 = 12.5;
 w4 = 12.5;
 w5 = 2.37;
 w6 = 3.3;

s= j*f;
Hhs=abs(s.^2./(s.^2 + (w1/Q1)*s +w1^2));
Hls= abs(w2^2./(s.^2 + ((w2/Q2)*s) + w2^2));
% Hls= abs(sqrt(100^4/f.^4 + 100^4))
Hts= abs( ((w4^2/w3)*s + w4^2)./(s.^2 + (w4/Q4)*s +w4^2));
Hss= abs((s.^2 +(w5/Q5)*s+ w5^2)./(s.^2 + (w6/Q6)*s + w6^2));
Wk=Hhs.*Hts.*Hss.*Hls;
```

Appendix C

C.1 Marion Island Study Questionnaire

Daily Diary for Slamming

1. Did you encounter any slamming incidents in the past 24-hours? Yes ☐ No ☐

************If ‘No’ ignore the remaining questions on this page***********

2 How frequent were the slamming incidents?

Once or twice ☐ Occasionally ☐ Regularly ☐ Always ☐

3.a How would you rate the worst slamming incident on the scale of 1 to 10?

1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10 ☐

Just noticeable Mild Heavy Severe Bouncing

b. What part of this slamming incident seems to make it worst? (you can choose more than one option)

Noise ☐ Vibration ☐ Shock Impact ☐ Other ☐ ________________

c. What was your location in the vessel at the time of the worst slamming incident? (Please refer diagram) ______

4. Do you consider these slamming to be unpredictable? ***Yes*** ☐ ***No*** ☐

If yes, do you feel this factor contributes towards making slamming uncomfortable? ***Yes*** ☐ ***No*** ☐

5. ***Human Performance***

Which of the following tasks were you performing during the last 24-hours when slamming occurred and how were they affected?
Please select the appropriate tasks and for each, please circle a number which most closely relates to any performance problems listed, according to any difficulties experienced, using codes 0 - 4 as follows: 0 = none, 1 = slight, 2 = some, 3 = great, 4 = severe (Task wasn't completed)

	Task / Activity	***Location***	***Balance / Moving***	***Carrying/ Lifting***	***Hand / eye co-ordination***	***Vision***	***Attention / concentration***	***Task delay?***	
☐	Physical work (lifting, lab work, etc.)		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	Typing / Writing		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	Using Electronic Equipment		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	Operating machinery (crane, lifter, etc.)		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	Visual activities (Watching TV / Reading)		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	Eating/ walking/sitting		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
	Other Activities (Please specify)								
☐	___________		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time
☐	___________		0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	0 1 2 3 4	Same time	More time

6. **Equipment Performance**

a. Did slamming affect the functioning of your instrument/equipment? Please describe the experience.

No☐ Physical damage ☐ Malfunctioning ☐ Knocked out ☐ Cannot operate ☐ Others ☐ ___________

Description: ____

7.	**Symptoms** *(Please record any symptoms experienced during the last 24-hour period due to slamming for activities using the following headings).*					
	Symptoms	***None***	***Slight***	***Some***	***Great***	***Severe***
a.	Headache	☐	☐	☐	☐	☐
b.	Tension / Anxiety	☐	☐	☐	☐	☐
c.	Aches and pains	☐	☐	☐	☐	☐
d.	Low Back pain	☐	☐	☐	☐	☐
e.	Depression	☐	☐	☐	☐	☐
f.	Other: Please specify ____________	☐	☐	☐	☐	☐
8.	**Interference with sleep**					
a.	Did slamming incidents interfere with your sleep last night? No☐ Slight unease ☐ Sleep interruptions ☐ Kept you up for some time ☐ Others ☐ ____________					

Figure C.1: The daily diary questionnaire for Marion Island study