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Condition based maintenance on board, vibration & shock pulse monitoring

Diploma thesis in the Marine Engineering Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Cover: FW pumps in an engine room.

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Abstract

To achieve continuity in the operation of machinery and systems, maintenance is required. Nowadays focus is to attain more effective maintenance strategies and to move away from the old-fashioned maintenance philosophy of Corrective Maintenance, CM in favour of Preventive Maintenance, PM (Johansson, 1997). While shore based industries have been developing their maintenance further by implementing Condition Based Maintenance, CBM, shipping has continued to utilize less refined maintenance approaches (Lazakis, 2010).

The purpose of this thesis was to investigate why CBM and vibration monitoring seem to be rare aboard ships, what obstacles there are and to some extent see if they can be managed and also to examine what means of maintenance are used in industrial as well as maritime applications.

The data for this thesis was gathered through semi-structured interviews with personnel from ships, shipping companies, industries and vibration experts to ensure a broad spectrum of knowledge and thoughts.

The results of this thesis show a distrust towards vibration monitoring, while other means of condition monitoring such as lube oil and thermal analysis is common on board. This distrust can be related to the complexity of the subject of vibration monitoring as well as a lack of training, thus, lack of knowledge. Vibration monitoring is also regarded as an expense whence there is little to gain due to critical systems on board having redundancy.

Keywords: vibration monitoring, shock pulse, condition based maintenance, maritime sector

Sammanfattning

För att uppnå kontinuitet i driften av maskineri och system krävs underhåll. Idag ligger fokus på att uppnå mer effektiva underhållsstrategier samt att gå ifrån gammalmodigt haveriorienterat underhåll till förmån för förebyggande underhåll (Johansson, 1997). Medan landbaserad industri har utvecklat sitt underhåll ytterligare genom att införa tillståndsbaserat underhåll har sjöfarten fortsatt att nyttja mindre raffinerade underhållskoncept (Lazakis, 2010).

Syftet med denna studie är att undersöka varför tillståndsbaserat underhåll och vibrationsmätning tycks vara ovanligt ombord på fartyg, vilka hinder det finns och i viss utsträckning ta reda på om de kan hanteras samt att undersöka vilka underhållskoncept som nyttjas i industriella såväl som maritima applikationer.

Informationen för denna studie samlades in genom semistrukturerade intervjuer med personal från fartyg, rederier, industrier och vibrationsexperter för att få ett brett spektrum av kunskap och tankar.

Våra resultat har visat på en misstro mot vibrationsmätning, medan andra former av tillståndsövervakning såsom olje- och temperaturanalys är vanliga ombord. Denna misstro kan härledas till komplexiteten hos vibrationsmätning över lag samt brist på utbildning i ämnet, alltså, brist på kunskap. Vibrationsmätning ses även som en kostnad vilken ger lite nytta tillbaka då kritiska system ombord är försedda med redundans.

Nyckelord: vibrationsmätning, stötpuls, tillståndsbaserat underhåll, förebyggande underhåll, sjöfart

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Table of contents

List of figures

List of images

List of equations

Abbreviations

ABS – American bureau of shipping
BPF - ball passing frequency
BPFI - ball passing frequency inner
BPFO - ball passing frequency outer
CBM - condition based maintenance
CM - corrective maintenance
CPM - cycles per minute
DNV - Det Norske veritas
FEM - finite element method
Hz - hertz
IACS – International association of classification societies
LO – Lubricating oil
PLM – Planned maintenance
PM - preventive maintenance
PMS – planned maintenance system
RCM - reliability centered maintenance
RMS - root mean square
RPM - revolutions per minute
RPS - revolutions per second
SPM - shock pulse monitoring

1 Introduction

The introduction of more technical solutions in ship operation has increased over the last decades. More automated solutions and more equipment has been installed on board and has contributed to create a demanding and complex technical plant on board to operate and maintain on a day-to-day basis.

With an ever-increasing competition on a global market, the demand for more efficient plants and processes increases as well (Lazakis, 2010). One way of reducing costs and increasing the availability of equipment is to put more focus on new maintenance strategies. This has been accomplished before by introducing preventive maintenance (PM) as a replacement for corrective maintenance (CM) (Johansson, 1997). The philosophy of PM is to counteract breakdowns and downtime as a result of insufficient maintenance. One common way of utilizing PM is to overhaul machinery equipment according to a fixed running time basis, known as planned maintenance, PLM. CM is focused on repairing broken-down machines rather than preventing the breakdowns of happening. This type of maintenance is considered somewhat obsolete in the highly efficient world of today. CM might however still be of use where cheap components are available, and preventive actions might be more expensive than simply replacing a broken piece of equipment.

While PM is commonly preferred over CM, there is a third option. Condition-based maintenance (CBM) which offers another way of potentially streamlining the maintenance organization even further. PM means less unexpected downtime in the form of breakdowns, but still, results in unavailability of machinery while maintenance is being performed (Xiao, 2015). With CBM the numbers of unplanned maintenance actions can be reduced to a minimum due to the knowledge of the current component (mainly bearing) condition. This also provides for more precise maintenance planning since deterioration of bearings can be monitored and remaining lifespan estimated (Samarasekera, 2005; El-Thalji, 2015).

CBM incorporates several techniques for the determination of machinery health. One of these is vibration monitoring, which has been used for some time in the shore-based industry. However, Storm (2012) suggests that the shipping industry has fallen behind regarding CBM, especially concerning vibration analysis and the International association of classification societies, IACS (2001) suggests that maintenance management on board is somewhat neglected in the shipping industry. Ships today mainly use PM (and CM to some extent) being conducted based on planned maintenance systems (PMS) such as AMOS, STAR etc. (Spectec, 2017; Star information systems, 2017). Shipping seems, in some respects, to be lagging behind the shore-based industry as new technical equipment and concepts might be mistrusted or misunderstood. This could be due to tradition and excessive vibrating from various equipment found on board that is spread through machine foundations and piping (Turan, 2011).

Low-frequency vibrations originating from outside of the machine in question can nevertheless be filtered out (Tandon, 1999). Another delusion is that equipment used to monitor roller bearing health is difficult to handle but this isn't necessarily the case, and the analysis can even be automated where large quantities of data are collected (Tandon, 1999). Combining low and high pass filters means one can achieve a "clean" signal that is easier to analyse (White, 1996), not entirely different from an old-fashioned radio where a frequency width is chosen when selecting a channel, known as a band-pass filter.

The PM and CBM methods raised in this thesis are focused on rolling element bearings. Rolling element bearings are some of the most important components in rotating machinery, thus, important to maintain and supervise to ensure reliable operation of a plant or vessel (Tandon, 2007). These bearings consist of either rollers or balls which in combination with lubricants minimize friction of rotating parts. Rolling element bearings give rise to vibrations (as further described in the background chapter of this thesis) which can be used to oversee their state of deterioration (Tandon, 2007).

Det Norske Veritas (DNV) has seen the problems excessive vibrations might cause and produced a notation to assess and minimize these hazards (DNV, 2011). With DNV: s notation kept in mind, vibration and shock pulse analysis should offer a surety concerning machinery damage and unexpected downtime. As ships these days often sail with a minimal crew, avoiding unexpected downtime and off-hire due to machinery breakdowns should lie in every shipping company's interest. These aspects create a basis for this thesis' focus on trying to understand why CBM with vibration analysis has not made as big of a breakthrough in the shipping industry as in industries ashore.

1.1 Purpose

This paper aims to investigate why CBM and vibration monitoring is, seemingly, rare on board ships, what obstacles there are when implementing such methods, and to some extent investigate how they can be managed. The study also seeks to examine what means of maintenance are used in industrial as well as maritime applications.

1.2 Questions

Primary question: Why is vibration monitoring not used to a greater extent aboard seagoing vessels? What are the possible obstacles comprised of? How can they be overcome?

Secondary question: What differences, if any, are present between shore based and shipping industry concerning maintenance? Which type(-s) of maintenance are favoured in both fields?

1.3 Delimitations

This study narrows down to CBM and vibration analysis in the engine room on board ships. However, due to the scarce information available, shore-based industrial knowledge and information will be included. On board, interviews will be limited to engineers. Interviews will be conducted in Sweden and limited economically by scholarship contributions. Interviewing will take place between seventh of January and continue until the middle of April 2017. Writing will proceed until twenty-ninth of April. The focus of this study is rolling element bearings.

2 Background and theory

To keep a machinery operation going with minimum downtime and high reliability, an effective maintenance organization is required. To maintain this effectiveness, maintenance policies and standards must at all times be kept up to date (Johansson, 1997). To further develop the maintenance organization, condition monitoring and CBM is introduced (Jardine, 2006). Figure 1 displays the progress of maintenance in the shore-based industry. To obtain an optimal maintenance organization, all personnel, under the entire lifetime of machinery, from installation to operation and service must be involved in the process (Johansson, 1997; Manzini, 2015).

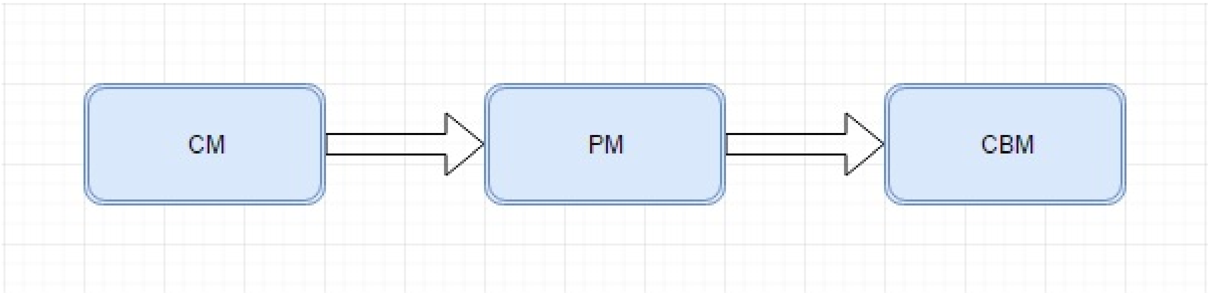


Figure 1 Evolution of maintenance

The shipping industry has considered maintenance operations as a necessity rather than a possibility to increase availability (IACS, 2001; Lazakis, 2010). By neglecting the development of maintenance strategies, the shipping industry has fallen behind and has of late started to look into other more delicate maintenance philosophies, such as CBM (Lazakis, 2010). This problem might be rectified by the acquisition of new tools, equipment (for instance, portable or fixed vibration monitoring equipment) and philosophies (Ölcer, 2016). By implementing these tools and philosophies, availability increases and maintenance costs can be reduced. There are flaws in the industrial maintenance organizations as well, as approximately 30% of maintenance time where spent on unplanned activities as suggested by Alsyouf (2009) in his study of manufacturing industries with a minimum of 100 employees.

The classification societies take an interest in maintenance and IACS (2001) refers to seven different ways of determining maintenance intervals listed below:

- Manufacturers recommendation (running hours)
- CBM
- Experience based on frequency of failure and trends based on inspections
- Purpose and usage of machinery (normally running, stand-by, emergency operation)
- Obstacles preventing regular maintenance actions (maintenance requiring dry-docking)
- Maintenance intervals required by the classification societies, international conventions and similar
- The necessity in testing of stand-by systems

2.1 Routine maintenance

Routine maintenance is part of the day-to-day work in maintaining a vessel, such as jobs appearing in the vessels PMS as painting, overhauling of minor components, minor repairs, cleaning of filters and separators etc. These are maintenance actions that do not interfere with the daily operation of the ship (Turan, 2009). CM, PM and CBM (described below) undertaken by the crew of a vessel is routine maintenance as long as it does not require dry-docking nor putting the vessel off-hire (Turan, 2009). Even corrective work or other maintenance concerning main engine(s), thus disabling the ship temporarily must be considered routine maintenance as long as it can be performed by the crew and within an arbitrary period of time, thus not putting the ship off-hire (Turan, 2009). Such maintenance activities are usually planned to be undertaken while in port.

2.2 Periodic maintenance

This is the type of maintenance actions that requires dry-docking or to go off-hire, thus, require the ship to be put out of operation (Turan, 2009). Dry-docking a vessel is expensive and usually done for work such as cleaning and painting of the hull, removal, and inspection of the propeller shaft or similar, repairs that cannot be undertaken at sea or in port etc. A lot of other maintenance activities that isn’t considered periodic maintenance can be planned for and undertaken on the same occasion as dry-docking for periodic maintenance. Completing several maintenance actions at the same occasion means better utilization of time and personnel.

2.3 Corrective maintenance, CM

CM is to repair machinery and equipment when a breakdown occurs and has, traditionally, been the primary form of maintenance (Johansson, 1997, Al-Najjar, 2016). That is, keep a machine running until failure occurs, then, restore the machine in question to an acceptable state (Jardine, 2006; Stenström, 2016). This method has been practically relinquished in favour of PM, which is deemed a better maintenance strategy (Ölcer, 2016). The benefits of CM are that certain machines and equipment might be cheaper to replace rather than to repair and maintain. The downsides with CM are the difficulty in planning and scheduling maintenance actions. Unexpected breakdowns of machinery could result in expensive downtime, or hazardous accidents (Johansson, 1997). These are mainly the reasons why CM is being abandoned.

2.4 Preventive maintenance, PM

PM has the distinguished advantage over CM because of the planning potential it offers, where the focus is to counteract failures and downtime (Stenström, 2016). Maintenance actions are usually performed following a schedule, known as PLM, where certain measures are performed on a running hour basis (Ölcer, 2016; Stenström, 2016). Maintenance intervals have been improved by logging failures that occur (Martin, 1994), to either utilize more of the operational time of a piece of equipment by prolonging the interval or to ensure that failures will not occur by shortening it. PM does not take the actual condition of a machine into account, which means unnecessary and costly maintenance actions, such as replacing bearings are conducted (Jardine, 2006). This is commonly the case at sea. Even when PM is utilized, breakdowns cannot be avoided completely since here is a limit between how many PM measures that should be undertaken versus how many CM actions that might be allowed (Johansson, 1997). Exceeding this limit will result in a maintenance organization becoming less efficient, as seen from an economical point of view.

2.5 Condition based maintenance, CBM

CBM is an umbrella term for several methods for determining the condition of machinery. CBM is sometimes considered a part of PM, but will in this thesis be treated as a separate maintenance philosophy. Vibration monitoring is common in the shore-based industry, but other methods such as SPM, oil analysis, and temperature measurement are available (Lazakis, 2016). CBM is the philosophy of conducting maintenance actions based on the actual condition of a machine, and predicting the remaining lifespan of the same (Jardine, 2006; Heng, 2009; Al-Najjar, 2016). CBM is PM essentially, undertaken when necessary rather than on a fixed time basis (Jonge, 2016). By maintaining a machine or induction motor using CMB, maintenance-related downtime can be scheduled to when it acts as a disturbance to normal vessel operation the least, since entire machine systems could become unavailable during maintenance. It is also possible to see whether a machine is able to operate until the next dry-docking for periodic maintenance for ships. Another great advantage of CBM in favour of CM and PM is that the progression of a failure can be monitored, thus avoiding unexpected breakdowns but also minimizing excessive maintenance (Samarasekera, 2005; Jardine, 2006; Al-Najjar, 2016). Failures such as those, failures whose progress can be monitored are called soft failures, whereas a hard failure is when a breakdown occurs abruptly (Martin, 1994).

Condition monitoring and/or CBM can be used as a basis for reliability centered maintenance (RCM) to improve a plant for safety or economic reasons, where downtime could entail major losses regarding mentioned aspects (Johansson, 1997). A form of CBM that is common aboard ships is the earlier mentioned temperature measurement taken using infrared meters.

2.6 Proactive condition based maintenance

As an extension to CBM, there is proactive CBM. The aim of this maintenance strategy isn't only to avoid unscheduled breakdowns of engines and equipment but to use any information at hand to enhance the lifespan and/or efficiency of such equipment. For instance, if a pump with an electric motor as prime mover gets fretting marks in a radial dimension on its bearings, one might suspect that the pump and motor aren't properly aligned. A precision balancing and alignment of the pump equipment in a combination of careful vibration monitoring may prolong the lifespan of the bearings. Studies have shown that precision alignment has prolonged the lifespan of rotating machinery by a factor of 8 and made them 11% more energy efficient in average (White, 1996). Proactive maintenance strategies usually incorporate follow-ups of failures, breakdowns and similar unplanned activities. By doing this, maintenance actions can be directed where needed and when. It is also a way of determining why a failure occurred and what might be done to prevent it from happening again (Hagberg, 2016). Thus, the number of equipment failures can be reduced. Either to a minimum or to keep a balance between CM and PM actions depending on what is desired (Hagberg, 2016).

2.7 Training

The Chalmers University of Technology offers a course in maintenance technology (Underhållsteknik) for the students enrolled in the marine engineering program. The course discusses different types of maintenance and concepts such as maintainability, reliability engineering and availability (Jarlros, 2003; SJO845, 2015). The focus of this course is the concepts of maintenance in general and how availability and reliability etc. are affected by different designs, engineering as well as other aspects alike. Condition monitoring is presented in form of cooling/boiler water analysis as well as oil analysis. However, no vibration monitoring or analysis is present in this course, which could aggravate implementation of vibration monitoring on board, since theoretical training as well as experience is considered important (Johansson, 1997). DNV (2008) stresses the necessity of having crew members trained in condition monitoring on board at all times when following the machinery condition monitoring survey method.

Another course included in the program is an engine and workshop technology course (LNB660, 2015). This is more directly focused on practical maintenance in the form of dismantling engines and other machines. Alignment of electrical motors and pumps/fans are taught as well, both using a dial indicator and laser alignment equipment. Alignment between machines such as pumps or fans with their prime mover affects coupling and transmission life span as well as vibrational levels.

2.8 Maintenance-associated costs

There are several financial aspects of maintenance which is important to recognize:

- Downtime and unavailability of machines and systems (loss of trade)
- Spare parts
- Oils and lubricants
- Maintenance workforce
- Scrapping of replaced parts
- Waste oil and detergents

CM requires fewer resources, both economically and personnel wise than that of PM and CBM on a day-to-day basis. A benefit of this is a cheap maintenance organization. But more expensive maintenance such as PM and CBM isn’t as financially burdensome as loss of production or going off-hire. This is because these factors could induce loss of income as well as repair costs (assuming a suitable level of PM/CBM is utilized) and greater risk of costly breakdowns (Turan, 2009; Verma, 2012; Ölcer, 2016). Unplanned downtime could result in ships being delayed, as can only be made up for with increased speed resulting in more fuel oil being consumed. There is an upper limit to the amount of PM and CBM actions that is economical to perform on a given plant. There is also a limit to a number of PM actions in relation to CM, as illustrated in figure 2 and as mentioned by Johansson (1997). The level of maintenance actions should be based on the criticality of the system/component where economic and safety aspects are considered, but also the function of the same as well as operating surroundings (Al-Najjar, 2016). Stenström (2016) suggests that an arbitrary ratio of 80/20 concerning PM and CM. This means to aim at accomplishing 80% PM and 20% CM to achieve an economically effective maintenance organization. The very same study suggests that the sections with the highest levels of PM had the lowest maintenance costs in total concerning railway lines.

With the introductory list above of maintenance associated costs in mind, especially concerning downtime and unavailability, the gathering of maintenance tasks within the same system is a way to make maintenance more effective (Jonge, 2016). This is usually done to some extent in PM based on running hours, where several maintenance tasks such as oil change, bearing replacements and cleaning is undertaken at one occasion to minimize downtime for a given machine or piece of equipment. What this means is that if several maintenance actions are undertaken at the same occasion, downtime can be reduced due to fewer separate shutdowns of a given plant.

An article by Marais (2013) discusses repair versus replacement of a component, which is two variants of CM. One single repair of this component could very well be less costly than that of a replacement of this component, as illustrated in figure 2. However, one should take maintenance history into account to get a deeper insight of which action is most cost-efficient, repair or replacement. Seen over time, replacement of a machine or component could be the better option as figure 2 suggests. This is important to keep in mind with older equipment, as aging machines could have an increasing maintenance or failure intensity and increasing operating costs (Johansson, 1997).

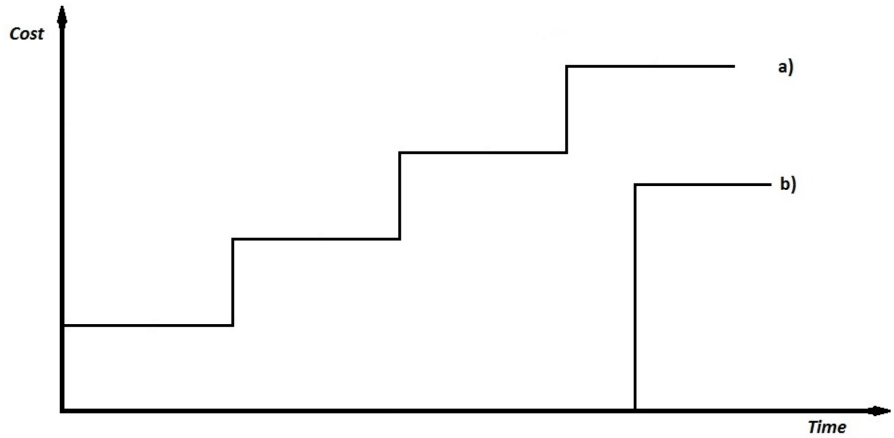


Figure 2 Arbitrary ratio of cost of repair (a) and replacement (b) of components over time

The study by Jonge (2016) shows that the fixed part of relative maintenance costs of a series of identical pumps is 50% of the total maintenance costs. The remaining 50% is varying between each pump, where the factors influencing this variation the most is materials (20%) and man hours (20%). About 25% of employees in the process industry are working with maintenance (Marais, 2013). This indicates the vastness of such a maintenance organization and the major financial impact this brings. Ölcer (2016) points out that up to 30% of a vessel operating cost is due to maintenance, where downtime and unavailability stand for a majority of these actions. The fact that unavailability is such a large portion of operating expenses makes PM and CBM in particular attractive as maintenance strategies. Johansson (1997) proposes a case involving 18 vessels that reduced their preventive maintenance actions undertaken by 43% and saved up to 700’000 SEK annually by implementing RCM based on condition monitoring on refrigeration plants.

2.9 Rolling element bearings

Rolling element bearings is comprised of two main categories of bearings: roller bearings and ball bearings, which in turn have subcategories of their own. Image 3 displays two types of ball bearings: radial and spherical ball bearings from an oil separator. Other types of bearings are plain bearings (which is excluded in this thesis), thrust bearings and needle roller bearings. Rolling element bearings are critical components of rotating machines and electrical motors (Zhen, 2008; Nguyen, 2015).

The number of rolling elements in a given bearing varies with size and price. A greater number of rolling elements, for a given bearing, makes the revolving motion smoother since the bearing material is giving way somewhat to mechanical stresses (Wardle, 2015). The number of rolling elements also makes a given bearing more robust, but generally, more expensive as well. Bearings with different clearances between the outer race and rolling element are also available. This is of importance in machines that becomes hot while running as heat causes the material to expand.

Image 1 Radial ball bearing (left) and spherical ball bearing (right)

2.9.1 Ball bearings

Ball bearings consist of balls running between an inner and outer race, held together by a cage. Ball bearings are usually made of steel or ceramic materials for high-precision bearings (Wardle, 2015). Ball bearings can be found in a wide variety of machines such as pumps, fans, pneumatic tools, and electrical motors. Figure 3 shows the basic difference between a ball and a roller bearing.

- Radial ball bearings
- Axial ball bearings
- Spherical ball bearings

2.9.2 Roller bearings

Roller bearings are like ball bearings, but use cylindrical rollers instead of balls. Roller bearings are typically used in bigger machinery than ball bearings and heavy-duty applications (e.g. gearboxes). Roller bearings are generally more suited to heavy loads than ball bearings because of the greater contact surface between races and rollers, as illustrated in figure 3, where contact surface between rolling elements and bearing races are coloured red. Both types of bearings are usually lubricated with oil or grease.

- Needle roller bearings
- Spherical roller bearings
- Conical roller bearings

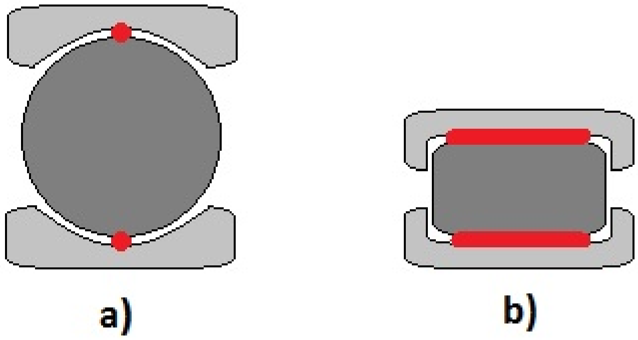


Figure 3 Contact surface differences between ball bearing (a) and roller bearing (b) as seen from a cross-section perspective

2.10 Failures in rolling element bearings

A thesis by Hellström (2011) suggests that up to 6% of bearing damages originates from an incorrect assembly, from transportation and manufacturing. This offers an explanation to why maintenance organizations spend some 30% of their time on unplanned activities (Alsyouf, 2009). Room for improvement is demonstrably present. Defects in bearings such as pits and chips commonly originate from the exhaustion of bearing material, resulting in irregularities causing vibrations that might stress the materials even further (Tandon, 2003). Exhaustion of bearing material can also be caused by a too high tension when fitting the bearing onto the shaft or misalignment of the bearing (Hellström, 2011). This might cause the pressure between rolling elements and bearing races to become too great for the lubricant, which is dispersed locally. An abnormally high tension in the bearing might even force the rolling elements out of the cage, as image 4 shows. This spherical roller bearing has been subjected to a too high axial pressure (observe the arrow in image 4, which points at the vibration measuring point of this component). Defects induced by incorrect assembly can be caused by too much force, or force applied incorrectly. The result of this is that forces from the assembling tools have to go from the outer race (assuming that the inner bearing race is fixed on the shaft), trough the rolling elements and finally to the inner race. This might cause damage to the outer race and the rolling elements themselves. Incorrect assembly of bearings as mentioned above can cause cracks to arise in the material that might cause spalling or chip of the races over time (Tandon, 2003; Hellström, 2011). A connection between unplanned maintenance actions and incorrect assembly cannot be drawn straight away since Hellström (2011) offer more causes to bearing damage than incorrect assembly. Furthermore, these researchers point out that 90% of scrapped bearings could have continued in operation. A study by Nguyen (2015) suggests that 50% of rotating machinery failures is due to failure in bearings.

Damages in roller bearings originate from a number of sources. Improper assembly and misalignment are two examples of handling errors. Damages can also be created by dirt, lack of lubrication or contaminated lubricant (Mitrovic, 2016). In bearings lubricated with grease, oversupplying the bearings with grease increases friction and temperature that could ruin the grease, thus damaging the bearings (Lansdown, 1982). Motors that are operated with a variable frequency could produce a current going through the bearings, which might create grooves in the axial direction of the bearing races by this (Prudhom, 2017). Figure 4 is a tree diagram displaying the common fates of rolling element bearings where it can be seen that 10% of all bearings develop a failure before being replaced and that this 10 % cause 50% of overall breakdowns of rotating machinery (Hellström, 2011; Nguyen, 2015).

Image 2 shows a ball bearing that has been subjected to water and is therefore corroded. There are lubricants that can handle water, but as can be seen, this has not been the case. Corrosion can cause cracking of the material and/or spalling (Hellström, 2011). Lubrication related issues can occur due to various factors such as oxidation, water/moisture and direct defects in the lubricant used (Lansdown, 1982). A photography showing a roller bearing that has been run with no or too little lubricating oil is shown in image 3. Fatigue in rolling element bearings could cause cracks to develop in the bearing raceways or rolling elements which could progress beneath the metal surface, thus a defect is developed resulting in spalling or pitting over time (Tandon, 2003).

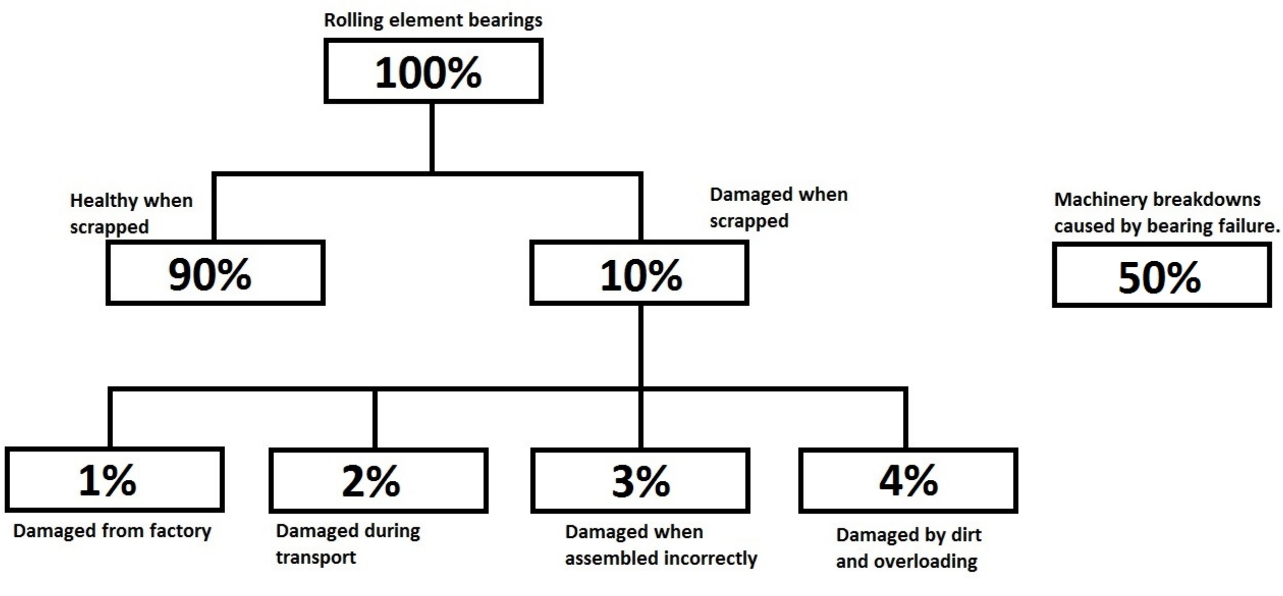


Figure 4 Tree diagram showing causes of bearing failures

Image 2 Ball bearing subjected to water (with permission from Royne Hedlund, 2017)

Image 3 Roller bearing that has been in operation with insufficient lubrication (with permission from Royne Hedlund, 2017)

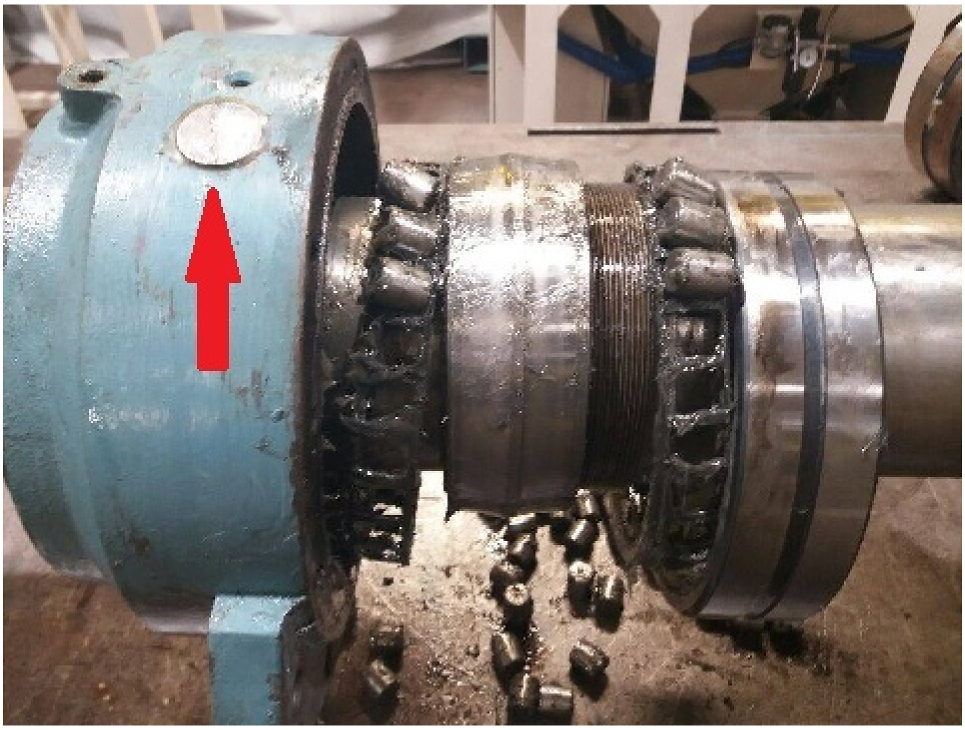


Image 4 Roller bearing subjected to a too high axial pressure (with permission from Royne Hedlund, 2017)

2.11 Provenance of vibrations in rolling element bearings

Vibrations on board ships are an uninterrupted process affecting all supports, foundations and decks (SAN, 2008) that can arise from various defects and operating conditions and influences both man and machine. Vibrations are affected by machine RPM and load, though a lot of machinery has a fixed RPM and little variations in load, such as fresh water pumps and fuel transfer pumps not regulated by frequency converters. There are nevertheless other factors causing vibrations around the machinery at sea. Such factors include background vibrations from other machinery, tools, the roughness of the sea and the weight of cargo/ballast/bunkers carried.

Vibrations can be defined as oscillations of a mass around its state of equilibrium (White, 1996), which is illustrated in figure 5. If one imagines a line passing through the centre of each mass, a sinusoidal curve is formed. This is the simplest form of vibration in one direction along a supposed y-axis (vertically). A vibration as shown in figure 5 is in reality finite. The motion will be smaller and smaller until the mass is stationary in its state of equilibrium. If the sinus curve in figure 5 is observed, one finds that a) represents the period of the curve. The period can be used to find the frequency of oscillations by determining the number of periods per second (Gustavsson, 1996; White, 1996). Equation 1 shows a basic definition of frequency, where it is the quota of 1 and the period of which an item or a mass is oscillating (see figure 5 a) for an illustration of the period). Equation 2 is frequency defined as the quota of RPM and 60. This gives revolutions per second or RPS. Both of these definitions give a quota in Hz.

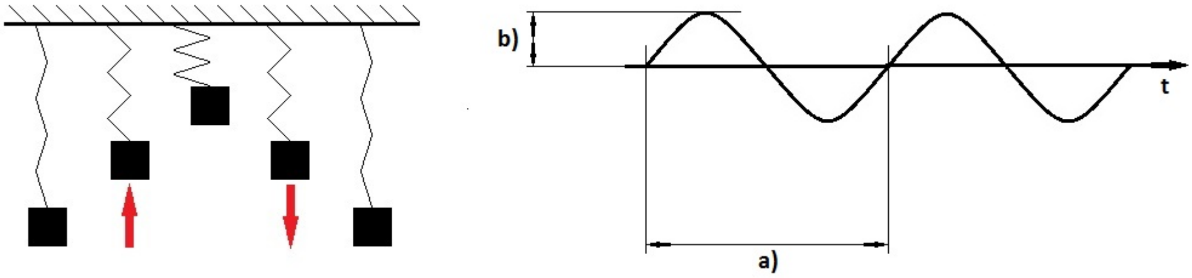


Figure 5 An oscillating mass in a spring and sinus curve with period (a) and amplitude (b)

$$Frequency = \frac{1}{T}(Hz)$$

Equation 1 Frequency defined as the quota of 1 and the period of an oscillation

$$Frequency = \frac{RPM}{60}(Hz)$$

Equation 2 Frequency defined as the quota of RPM and 60

2.12 Condition monitoring techniques

The condition of a machine can be monitored in two general ways. Either by utilizing senses of an operator or crewmember (subjective) or by using sensors and transducers to record condition parameters (objective) (Johansson, 1997). In this thesis, the focus lies with objective monitoring.

2.12.1 Lubricating oil, LO analysis

The condition of machinery and components such as propeller shaft bearings, gears, and diesel engines can be assessed by analysing a sample of the lubricating oil (LO) used for the machinery in question. With an LO analysis, it is possible to determine wear of machine parts, quality, and condition of the oil itself and the content of impurities (Lansdown, 1982; ABS, 2016). By monitoring the condition of the LO, failures related to an inadequate lubricant can be minimized as for instance changes in viscosity can be detected (Kuiken, 2012). It is common to monitor the contaminant level in scraped-down cylinder LO on two-stroke engines since these have separate cylinder lubrication (some four-stroke engines have separate cylinder lubrication as well) (Kuiken, 2012). By analysing the cylinder LO, excessive wear of cylinder liners can be detected. LO systems can be cleaned with filters which have to be replaced over time. Larger LO systems can be cleaned with automatic filters or separators that require less maintenance. Depending on what material the wear particles consists of, it is possible to determine what part of for instance a diesel engine is being excessively worn (Johansson, 1997). This is due to different parts being manufactured from different materials.

2.12.2 Thermal analysis

It is possible to detect the initial stage of certain types defects as well as to monitor deterioration of bearings by measuring temperature and log values to create trends. An increase in temperature is commonly caused by worn/damaged parts or lubrication failure (ABS, 2016). While vibration monitoring is more commonly used to determine bearing condition, thermal analysis is, as mentioned by ABS (2016), a useful condition monitoring technique (Lazakis, 2016). There are several different methods and pieces of equipment such as infrared thermocameras, paints/crayons that change colour depending on temperature (colour change when a predetermined temperature is exceeded) and thermocouples (Johansson, 1997; ABS, 2016). Infrared thermography is one of the best techniques for monitoring temperatures and finding hot spots on machines and electrical installations (Jeffali, 2016). An image of the surface in infrared is presented where hot spots are easily distinguishable from surrounding surfaces (ABS, 2016; Jeffali, 2016).

2.12.3 General vibration monitoring

Defects in bearings are closely related to failures in rolling element bearings. Defects cause vibrations that escalate with time, why vibration monitoring is a way of minimizing breakdowns related to these failures (Tandon, 2003; El-Thalji, 2015; Lazakis, 2016). Clearances in bearings are in some applications necessary as thermal compensation. Clearance is also related to vibrations since there is excess space for the inner race to move around between rolling elements and outer race (Cui, 2016), with influence such as shown in image 5. The dimensions of a rolling element bearing are slightly altered as the rolling elements rotate past the direction of the force the rolling elements carry since the number of elements is finite (White, 1996; Wardle, 2015). Increasing the number of rolling elements for a given bearing means more material, more often to conduct forces from machine shaft to bearing housing and foundation. This can be understood by studying figure 3, which illustrates contact surface of a ball- and a roller bearing. Fluids processed by the machine could cause vibrations due to cavitation in the fluid and turbulence etc. (Mobley, 1999).

There are several causes to vibrations related to rolling element bearings in machinery. Some of these are mentioned above.

- Defects in bearing races
- Clearance between bearing races and rolling elements
- Finite number of rolling elements

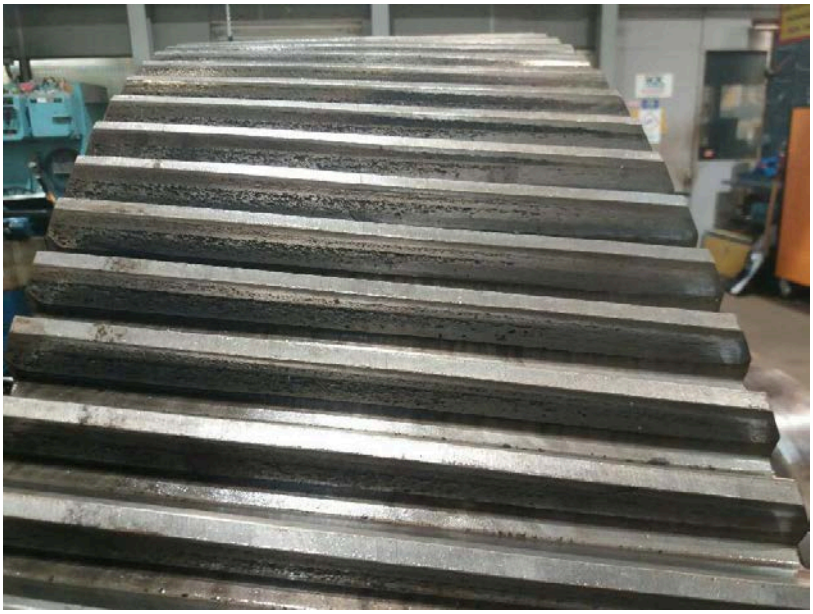


Image 5 Gear unevenly worn due to excessive bearing clearance (with permission from Royne Hedlund, 2017)

Figure 6 illustrates a ball bearing with an anti-clockwise direction of rotation and a defect represented by an arrow. Each time a rolling element passes the defect, oscillations are emitted through the bearing. The result of this is a vibration frequency dependent on the number of rolling elements and rotational speed, but other factors as well such as rolling element contact angle (White, 1996; Niu, 2015). A technique based on this is the ball passing frequency (BPF), which makes it possible to determine if a fault of a rolling element bearing is located in the outer (ball passing frequency outer, BPFO) or inner (ball passing frequency inner, BPFI) races of the bearing, see equation 3 and 4 (Niu, 2015).

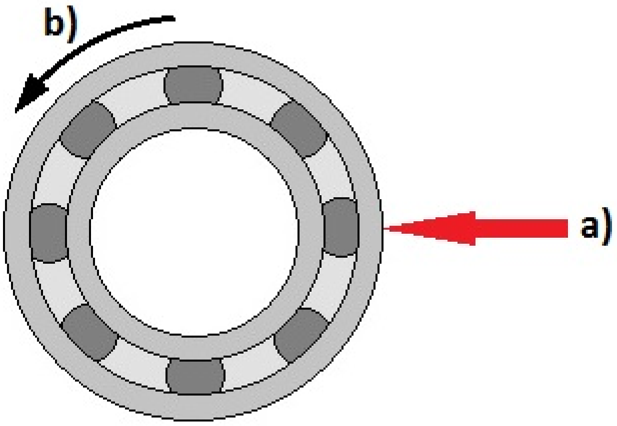


Figure 6 Illustration of a ball bearing with a defect (a) and rotational direction (b)

Vibrations can be measured either by handheld or fixed measuring equipment. Vibration measuring devices commonly use an accelerometer transducer to gather bearing vibrations.
Measurements are commonly taken using a piezo-electric accelerometer (White, 1996; Johansson, 1997; Murer, 2015) that measures acceleration in three dimensions (X, Y and Z axis’s). Unit for vibration measurement should according to DNV (2011) be mm/s (velocity), mm/s2 (acceleration) or mm (displacement). White (1996) on the other hand suggests µm for velocity and RMS (root mean square of acceleration) for acceleration as units of choice. Frequency is usually measured in Hertz (Hz), cycles per minute (CPM) or revolutions per minute (RPM) (White, 1996; Mobley, 1999). The accelerometer sensor should be placed as close as possible to the bearings when measurements are taken to reduce noise from the surroundings, as the vibrations of interest originate from the bearings (Murer, 2015). The geometry does however not always permit the sensor to be placed at an optimal location of the machine in question. Mitrovic (2016) suggests a correlation between vibrations and elevated temperature of a bearing which can be used to determine the condition of the bearing, as briefly mentioned in section 2.5 (Lazakis, 2016). White (1996) on the other hand suggests that vibration levels decrease with an increase in friction, which absorbs vibrations and converts it into heat.

It is important to recognize the fact that different machines and equipment will have different vibration characteristics (Brandt, 2011). This isn’t limited to the machines themselves, but also to the type of bearings used, for instance, further described in section 2.11. If the fitted bearing specifications are not known, there is a great risk of inaccurate prediction of the condition. Other factors such as the number of fan blades and pump shovels are also mentioned in section 2.11.5 (White, 1996).

2.12.4 Shock pulse monitoring, SPM

Damped impulses in short sequences are generated when a rolling element rotates past a defect, such as, a crack or a spall located in any of the bearing components, which can be seen in figure 7 (White, 1996; Tandon, 2003). SPM relies on one single value in the form of an impulse, known as, normalized shock value (amplitude, measured in decibel, dB). The normalized shock value is obtained by removal of the initial shock value that healthy bearings have, to be able to monitor deterioration of the bearing (Tandon, 2003; Zhen, 2008). In essence, the normalized shock value will increase as the bearing condition deteriorate. This can be used to assess the grade of failure of the bearing. The shock generated by a rolling element passing a defect in raceways, or in the rolling element itself, is measured using a piezo-electric sensor (Butler, 1973; Tandon, 2003; Zhen, 2008).

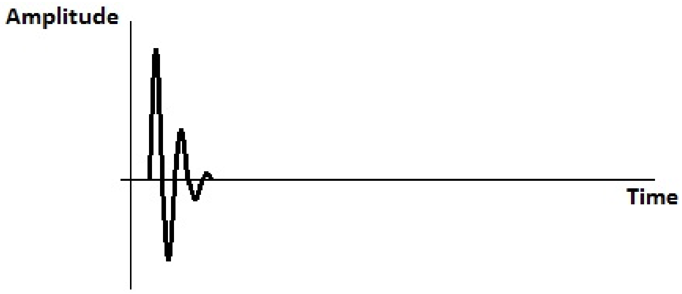


Figure 7 Simplified shock pulse in the time domain

Since SPM relies on a single shock value in contrast to vibration monitoring that measures “waves”, or oscillations in a bearing, less rendering of data is required (Zhen 2008).
SPM is according to Tandon (2003) a more reliable method of detecting bearing defects since the method offers a larger margin between a healthy and a defect bearing than that of vibration monitoring.

2.12.5 Spectral analysis, time and frequency domains

Oscillations of a mass give rise to a sinusoidal curve as illustrated by figure 5 in section 2.11. This sinus curve is displayed in what is known as the time domain, where the x-axis is time and the y-axis is the amplitude of the oscillations, as more clearly illustrated in figure 8 (top) (De Silva, 2005). If one sets the x-axis as frequency instead, the curve is shown in the frequency domain, also depicted in figure 8 (bottom), where it appears as a single peak. This is because the periods of the vibration are constant resulting in a single frequency, thus appearing as a single peak in the frequency domain (White, 1996; De Silva, 2005). The same frequency spectrum would have several peaks in reality, as measured vibrations are composites of other vibrations, usually making up complex wave patterns (White, 1996). Figure 7 illustrates a simple shock pulse in the time domain for comparison to a vibration. It can be seen that the shock pulse is of shorter duration and relatively high amplitude, whereas a vibration is more stretched out. These figures (7 and 8) are however simplified to give a basic understanding of the mechanisms and theory behind vibration response, as vibrations measured in reality are composites of several different vibrations combined into one signal (White, 1996).

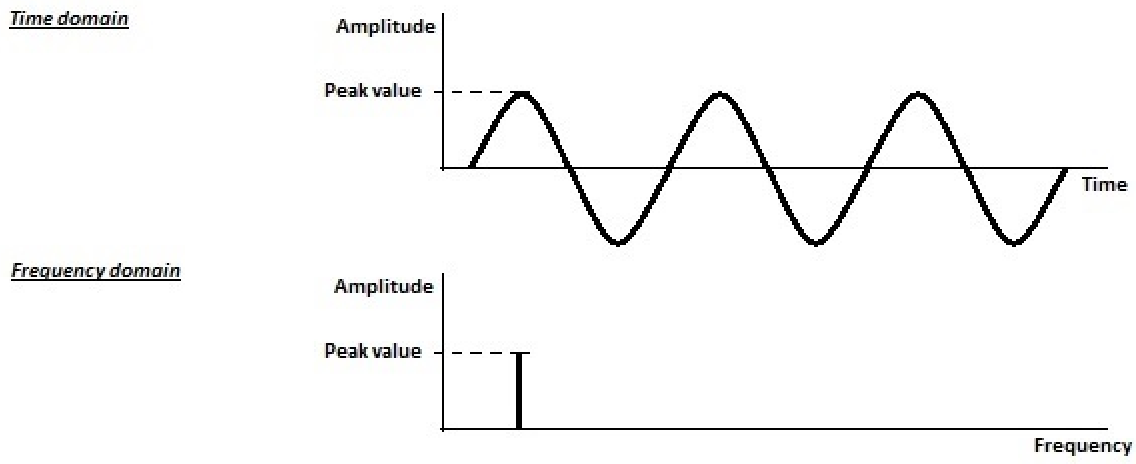


Figure 8 Sinus curves in the time respectively frequency domains

An oscillation caused by a bearing defect gives rise to different frequency responses due to the location of the defect. This is described by the BPFO respectively BPFI equations below, as explained by both Niu (2015) and Hellström (2011). Equations 3 and 4 shows a method of calculating the frequency generated by both inner and outer races of a rolling element bearing. This is used to determine where to look in a spectrum, to detect and monitor potential failures in these races (see appendix list for BPF in spectra). These differences originate from different parts of the bearing rotating in different motions (Tandon, 2003). The inner race rotates with the same RPM as the machine shaft, the outer race is stationary and the rolling elements rotate around their own axes as well as rotating around the inner race as illustrated in figure 9 (assuming the inner race is the fixing part of the bearing). This provides an explanation for the complexity of bearing defect monitoring using vibration measurement. The movement of the rolling element cage in a bearing gives rise to a frequency of its own as well. The effects of mentioned parameters are affected by machine load, lubrication etc. (Niu, 2015).

$$BPFO = \frac{n * RPM}{2}\left(1 - \frac{R_d}{D_d} * cos\alpha\right)$$

Equation 3 Frequency calculation for BPFO

$$BPFI = \frac{n * RPM}{2}\left(1 + \frac{R_d}{D_d} * cos\alpha\right)$$

Equation 4 Frequency calculation for BPFI

- n = number of rolling elements
- R_d = rolling element diameter
- D_m = pitch diameter (distance between centre of opposing rolling elements)
- α = contact angle

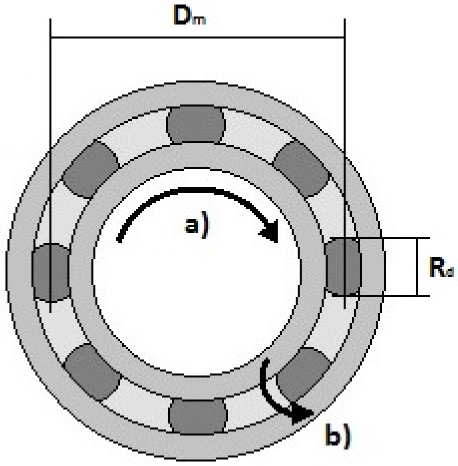


Figure 9 Rotational direction of shaft (a) and rolling elements (b)

While time domain analysis could be useful to determine the change in overall vibration amplitude, there is a difficulty in distinguishing individual vibration-causing components in the spectrum (Mobley, 1999). Therefore, frequency analysis is common as vibration sources within a machine are dependent on RPM, thus, is calculable, as mentioned above as well (White, 1996; Mobley, 1999).

Figure 10 displays three sinus waves, where a combination of these three waves gives the frequency spectra as depicted at the bottom of the figure. Different parts of the same machine generate vibrations of different frequency with different amplitude based on balance, condition, the number of rotating elements etc. (White, 1996). When the frequency of a component is known, the amplitude can be supervised to see if it is increasing over time which gives an indication of the condition of the component. That is, by monitoring the increase in the amplitude of a peak in the spectrum, the deterioration can be supervised as for instance a spalled outer race of a bearing will increase in amplitude over time (assuming operational parameters remains the same). The progression of a defect can be monitored in this manner by determining which frequency “peak” is generated by which part of the machine. A specific component can be isolated in the spectrum by calculating the frequency it is producing (see equation 3 and 4). Factors for the determination of what component is producing what peak in the spectrum includes, RPM, the number of rolling elements for a rolling element bearing, number of shovels for a pump or number of blades in the case of a fan as well as gear ratio in a gearbox etc. (White, 1996).

The frequencies b) and c) are known as harmonics to a) in figure 10 in this case.

- a) Has the amplitude 1 and frequency 1 Hz.
- b) Has the amplitude 1/3 and frequency 3 Hz.
- c) Has the amplitude 1/5 and frequency 5 Hz.

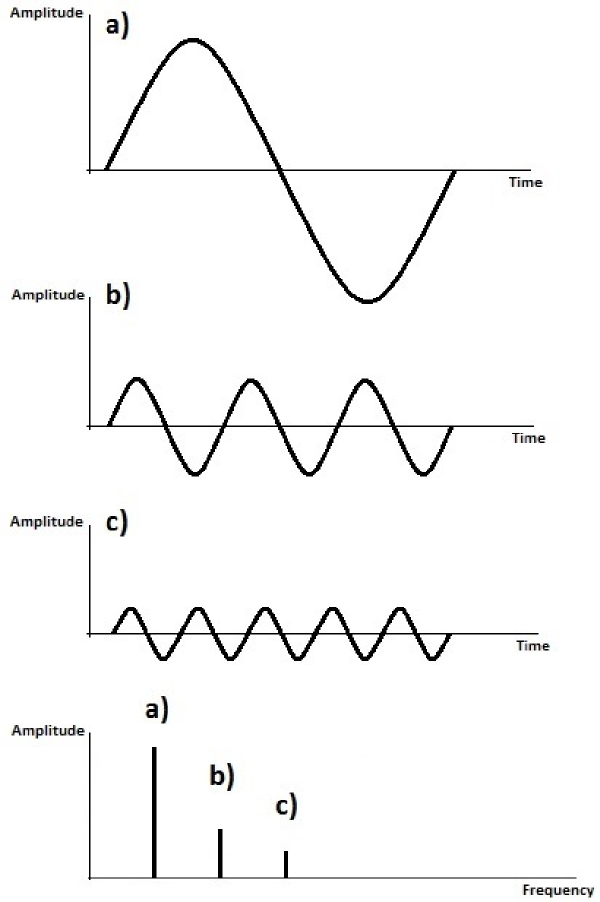


Figure 10 A series of sinusoidal waves combined in a frequency spectra

2.12.6 Order normalization

It is common to normalize the obtained spectrum to simplify analysis (White, 1996). This is achieved by determining the peak of the rotational frequency in the spectrum. That is the frequency generated by the rotating shaft of the machine. This peak is defined as 1X, accordingly one times the rotational frequency (White, 1996; Brandt, 2011). 2X (second order), 3X (third order), 4X (fourth order) and so on is known as multiples to the rotational frequency 1X (Brandt, 2011). 1X is used as a reference point to find other spectral components of interest (BPFO, BPFI, gear mesh frequencies etc.). If one considers a directly driven fan, with 5 blades, a spectral peak in a close proximity of 5X will be found in the normalized spectrum (an example is featured in the following section below). Orders are not limited to integer numbers as proposed in the above example (Brandt, 2011). A distinct advantage of order normalizing is that spectrum components generated by the machine in question become independent of machine RPM (Mobley, 1999). That is, an alteration in RPM between measurement occasions becomes irrelevant to the location of a specific peak in the frequency spectrum. Alterations in RPM could, however, affect the amplitude of the same peak even when order normalizing has been performed (Mobley, 1999). Equation 2 in section 2.11 suggests a means of calculating the shaft rotational frequency (1X).

Appendix 1 shows four order normalized frequency spectra provided by Mikael Lorentzson at ABB. These images show a high range and a low range version of the same two spectra (1.1

and 1.2 are from one motor, 1.3 and 1.4 are from another). In essence, there are more orders (higher frequencies) in the high range spectra. BPO and BPI are ball passing frequency outer race respectively ball passing frequency inner race (in this thesis called BPFO and BPFI). These two (appendix 1.1 and 1.2) is measurements taken at an electrical motor which has a supposed defect believed to have originated from a current going through the bearing since a frequency converter is installed in the machine operation. Appendix 1.3 and 1.4 shows spectra from also from an electrical motor, but in this case in good condition.

2.12.7 Fast Fourier transform, FFT

A Fourier transform is a transform used to transfer signals between time and frequency domains (De Silva, 2005; De Silva, 2006), see figure 10. This is how a sinusoidal wave pattern is converted, transformed into a peak in a frequency spectrum. This might simplify analysis of a vibration spectrum due to the relative ease to differentiate different sources of vibrations. This is known as FFT-analysis as well as spectrum analysis, which is the most common method of analysing vibration signals (White, 1996).

2.12.8 Resonance

Resonance is a phenomenon that when occurring amplifies vibrational energy, consequently, increasing its amplitude in the frequency spectrum (Mobley, 1999; De Silva, 2006). Resonance occurs when a vibration coincides with the natural frequency of a machine, where the machine structure acts as an amplifier to another vibration frequency and could be fatal to the machine in question (White, 1996; Mobley, 1999). This is known as static resonance, where static components such as piping, fundaments, and beams are the provider of the natural frequency which is excited. Some machines or machine fundaments have a critical range of RPM’s where resonance occurs under influence of other components, and should, therefore, be avoided due to the risk of damage or breakdown, known as dynamic resonance (Mobley, 1999).

Mobley (1999) suggests that a rotating machine should not be operated within ±10% of the RPM conjuring its natural frequency to avoid resonance. Accordingly, a machine with a natural frequency occurring at 1400 RPM should not be operated between 1260 and 1540 RPM. This phenomenon isn’t limited to electrical machines and equipment but occurs in large marine diesel engines as well, why certain ranges of RPM should be accelerated past quickly (Kuiken, 2012).

2.12.9 Filtering

Filtering is to differentiate unwanted information and noise from useful data in a signal before analysis. There are numerous sources of unwanted information in a vibration signal known as noise (Akishita, 2005; Zarei, 2014). Noise originates from sources such as gears, misalignment, unfastened bearing housings etc. (assuming vibrations from bearings is of primary interest). When conducting a spectrum analysis, the width of the spectrum is a case of filtering. Due to the excessive amount of information present in a vibration signal, practically, very low and very high frequencies must be filtered out, somewhat similar to the illustration in figure 11 (Mobley, 1999). A too wide spectrum might have a negative impact on the resolution of the spectrum, which may result in increased difficulty in the analysis (Mobley, 1999).

Some components emit a low-amplitude peak in the frequency spectrum and thus are difficult to detach from noise in the spectrum (White, 1996; Mobley, 1999; Zarei, 2014). Low-pass filters allow low frequencies to pass through; cuts off high-frequency noise (Brandt, 2011). High-pass filtering allows high frequencies to pass and blocks off low-frequency noise (Brandt, 2011). Band-pass filtering is to select a part of the spectrum to analyse and discard all other frequencies not within this band (White, 1996), as shown in figure 11. When filtering a signal, a term to keep in mind is cut-off frequency. The cut-off frequency is commonly defined as where the signal has decreased by 3 dB (Brandt, 2011). Zarei (2014) proposed a method of utilizing intelligent filtering that relies on artificial neural networks.

DNV (2008) argues that vibrations from surrounding equipment can be identified by narrow-band filtering, which is necessary in the case of resonance.

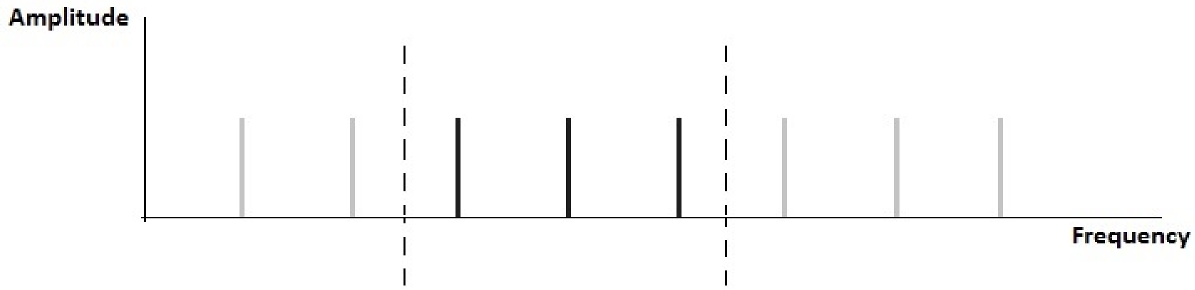


Figure 11 Simplified theory of band-pass filtering; grey is filtered-out frequencies

2.13 Criticality analysis

A criticality analysis should be performed before undertaking any new maintenance approaches to ensure it is justified (Lind, 2017). This is somewhat mentioned in section 2.4, as the number of maintenance actions should not exceed a given limit to be economically justified (Johansson, 1997). Highly critical components might justify vibration monitoring and CBM to reduce the risk of unexpected breakdowns that could compromise safety or induce a financially burdensome outcome (Johansson, 1997). Less critical machines such as B-class components are not likely to be critical enough to motivate condition monitoring on their own Lind, 2017. DNV (2012) proposes a failure modes and effects analysis (FMEA) be performed on redundant systems to assess criticality.

The criticality of a component is dependent on several factors. These include the function of a given component in a system, redundancy, economical aspects etc. Typical components that have high criticality on board a vessel could be gears and propeller shaft bearings, depending on constructional arrangements. Less critical components commonly include low-temperature fresh water pumps, fans, and generators due to overcapacity. The difference between these components is that gearboxes and shaft bearings usually have a higher significance with propulsion in mind than water pumps and fans and because the latter usually is redundant. This is where RCM might become interesting due to safety and loss of production (off-hire or costly spare parts) is considered (Johansson, 1997). IACS (2001) suggests that on board maintenance has a low priority management wise, which in itself is a safety hazard.

Criticality of a component or system can be categorized using a simple ABC-system (see the list below).

- A - Highly critical component
- B - Moderately critical component
- C - Non-critical component

A-class systems are systems or components such as gearboxes, main engines or propeller shaft bearings depending on arrangement on board. If there is only one main engine, a single reduction gearbox or shaft bearing where only one propeller shaft is fitted, these could be considered highly critical. This is due to a single failure of any of these components will render the vessel stationary. Consider a pump arrangement with two identical pumps fitted parallel to each other in order to achieve a redundant system. This system could be considered a B or C-class system due to the redundancy depending on the importance of the system in general. However, if one pump running were to fail and the remaining pump starts, the criticality of the system will increase. This means that a B-class system could become an A-class system during events such as breakdown, maintenance or similar that render the stand-by pump unavailable (Lind, 2017). C-class systems or components are non-essential to the progression of the ship. Failure of C-class components could be an inconvenience but not endanger the ship or its progression. As mentioned, failure of a single component could increase the criticality class of the system or remaining components that the system is comprised of.

What maintenance strategy that is chosen for a given piece of machinery should be motivated by aspects such as criticality, cost and economic effects of downtime. Other factors such as failure intensity and periodicity of failures should be considered. If breakdowns of an asset occur regularly at intervals with small alteration, PLM might be justified (Hagberg, 2016). If failures occur without any significant periodicity, it becomes difficult to implement a PLM strategy due to a varying time between failures. If an average time to failure can be estimated that is similar for several machines/components, a basis for PLM can be developed that is shorter than the average time to failure. In the case of insignificance in the periodicity of failures, condition monitoring and/or CBM could prove suitable (Hagberg, 2016).

2.13.1 Redundancy and diversification

Redundancy is a machine configuration where multiple like or similar components are installed to ensure continuous operation of a system (Jarlros, 2003; DNV, 2012; Öner, 2013). Naturally, this enables maintenance of one unit during operation and increases system availability. This is common aboard ships. A system is redundant if a complete failure only occurs if all components that make up the system fail (Öner, 2013). An option to redundancy is diversification. Diversification is another way of increasing availability of a system, much like redundancy but by other means (Jarlros, 2003). For instance, instead of having two identical pumps side by side (redundancy), a gravity tank might be fitted instead to maintain a pressure albeit temporarily. A simple redundant system with two identical pumps is shown in figure 12. This type of system configuration allows for further operation of the system even if one pump were to fail (Jarlros, 2003). The amount of redundancy is limited by factors such as the economy since this is expensive (Xie, 2014). In some redundant system applications, one pump is running normally and one is kept in standby (DNV, 2012). If a failure were to occur on the pump in operation, the system should only suffer a short pressure drop before recommencing normal operation. It is common practice to alter between pumps. By doing this running hours is evenly distributed between the pumps of the system. The risk of standstill damage is also reduced (DNV, 2008).

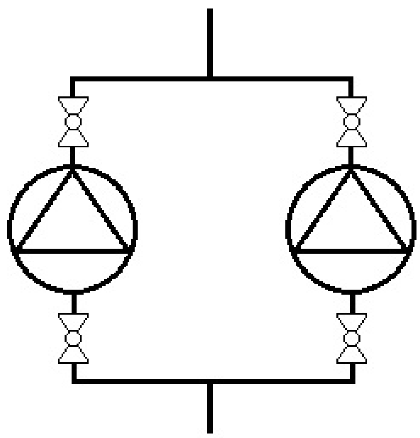


Figure 12 A simple redundant pump arrangement

It is sometimes assumed that machinery only has two states: normal functioning and broken down. However, for a system, in reality, there are gradations of failure. This means that a machine does not necessarily have to fail instantly, but rather deteriorate over time (Tandon, 2007). When there is, an audible noise originating from a bearing in a machine, not related to the normal operation, there is usually still some time left before complete failure. This allows for switch-over to the stand-by machine in a redundant system which means that complete failure can be avoided. Thus, the process which a given system is maintaining does not have to be affected by a single failure at all. This could be vital since DNV (2012) points out that a single failure must not cause a ship to lose its position.

3 Method

To obtain a further understanding of maintenance philosophies on board and ashore, semi-structured interviews were carried out (Kallio, 2016). The choice of semi-structured interviews is based on obtaining as much information as possible from persons participating, as it is a method suitable for follow-up questions (Kallio, 2016). The interviews were structured in order that one person primarily asked questions and the other person taking notes. All interviews were recorded for transcription. Interview participants were contacted by email or telephone. Email addresses were found on respective company's web pages in most cases. Some of the respondents answered our inquiry with a telephone number which was used to establish further contact.

3.1 Collection of data

Place of interviews were offices of the participants, Chalmers facilities, conference rooms and a café.

The interviews were undertaken following a theme of questions with backup questions as well. Several different themes were prepared, and theme of choice for each interview was based on background and present employment of the interviewees. The interviewees that were asked to participate in this thesis were selected on common themes such as relations to the shipping/shore-based industry, vibration monitoring, and analysis. To ensure a wide perspective of knowledge of the subject of vibration monitoring and CBM of interviewees, vibration /analysts and technicians, vibration technology office personnel, shipping company office personnel and marine engineers were interviewed.

3.2 Ethics

All persons interviewed for this thesis has agreed to their participation, to be recorded during interviews as well as to be mentioned by name. The thesis will be sent for approval to all participants before the final deadline. A consent form used before the start of every interview is found in appendix 2.

Interviewees:

- 3 chief engineers
- 3 vibration technicians
- 2 maintenance technicians
- 1 technical superintendent
- 1 technical operations director
- 1 senior technical manager
- 1 product manager
- 1 vice president

The interviewees were all familiar with maintenance procedures, with technical knowledge. Participants have to this study relevant (experience of vibration monitoring, industrial work and/or seagoing experience) experience ranging from approximately 7 to 40 years, with a mean experience of 23.6 years.

3.3 Data processing

The interview conversations were recorded using an Olympus VN-7800 Dictaphone.

3.4 Analysis of data

Recordings from interviews were transcribed and assessed using a matrix together with notes to find answers to our questions as well as common denominators. Backups of the finished transcriptions were taken as a precaution.

We chose to transcribe all raw data as our purpose with this thesis incorporates investigation of underlying structures (Denscombe, 2014). Notes were taken while transcribing and compared with notes from the interviews themselves to uncover patterns and common denominators. Due to interviewees not always answering in complete and logical sentences, some rearrangement to the sentence structures were required to ensure an understandable context (colloquial language was avoided as far as practicable, swearing was not included etc.) (Denscombe, 2014). The analysis was performed through coding and categorization of data obtained during interviews. Themes and common denominators formed the categories within our research questions.

4 Results

The following results are based on a total of ten interviews (incorporating thirteen persons in total) compiled to incorporate relevant answers in a comprehensible format. Two meetings were held as to gain knowledge and background information on the subjects of vibration monitoring/analysis, maintenance, and criticality. The answers are presented anonymously to ensure confidentiality of the participants of this thesis.

How common is vibration monitoring aboard in shipping applications?

Our results reveal that all participants of this study are familiar with vibration monitoring/SPM and CBM. Out of ten interviewees, seven of them have been in contact with vibration monitoring in maritime applications. One of them uses vibration monitoring today. Three interviewees know other shipping companies that use vibration monitoring. Many ships have performed trials with vibration monitoring and SPM. It is shown that SPM was more common in the past and has been widely replaced by vibration monitoring. Few ships have continued to use vibration monitoring and/or SPM today even though there are indications in the results that there might be an increase in the usage of this in maritime applications.

Why is vibration monitoring not used to a greater extent in shipping applications?

The results showed distrust to the technology and/or data analysts. Maintenance personnel on board consult the manufacturer's manuals and documents rather than different vibration monitoring/SPM technologies regarding the need for service/ service intervals for machinery. The crew on board trust manufacturers of their equipment. Trials with vibration monitoring and SPM have been conducted by many ships/shipping companies, but haven't caught on. This in combination with the fact that regular PLM works well for its users feeds the disbelief in the technology, according to our results.

> *"What should you believe in? What you have measured or the manufacturer? In the end, you trust the manufacturer"*

Economic factors such as equipment cost in combination with redundant systems that ships have means that many see no need for supervision of component condition, as vibration monitoring could provide. An uncertainty is present to whether an investment in vibration monitoring/SPM equipment will actually result in any savings. An issue related to investment contra savings emerges.

> *"I think it is important somehow, I believe the installation cost of a system is somewhere around 300'000 SEK. For that reason, you want to see that you get something in return one way or another. There are a lot of ball bearing failures that have to occur to make up 300'000 SEK."*

The shipping industry is conservative. Redundancy is, like conservatism related to an experienced lack of need for vibration monitoring and SPM. Several interviewees replied that the use of a screwdriver held against one’s ear protectors is sufficient to monitor the bearing condition. This is common practice and has been done a long time according to our results.

Our study has found that vibration monitoring requires an enthusiast to be effective. This is problematic since ships commonly use a relief system, thus rotating the crew. By having changes in the crew on board, different interpretations of the same data might be problematic. Vibration monitoring requires training as well as experience to be effective.

How can these obstacles be overcome?

To overcome the distrust of vibration monitoring, better information to the crews and shipping companies is required. Training is also important, be it school based and/or commercial vibration monitoring/analysis training from certified trainers. To gain trust among the crew, vibration monitoring needs to be proven that it works. The handling of vibration monitoring should be simplified as far as reasonable. Fixed sensors can be installed on equipment considered critical. To be financially effective, the equipment subjected to monitoring must be relevant. As far as analysis is concerned, experts should be consulted since it is difficult to become experienced on board and analysis of vibration data requires experienced analysists to ensure effectiveness. Easy to understand reports made by an expert is important as well. If the person receiving a report doesn’t understand what is written in it, it has no use.

> *“The experience, one machine is never the same as the next one, never. However, all patterns seen in the readings are recurrent. So that is what one have seen before”*

According to the results, if surveys undertaken by classification societies can be simplified by the usage of vibration monitoring, this can help motivating the implementation of vibration monitoring and CBM. Thus, if machine diagnostics protocols can be used to prove the condition of machinery to a surveyor, a clear advantage of using vibration monitoring arise.

Preferred maintenance type(s) in shipping?

The dominant maintenance strategy on board is PLM, as six of the interviewees answered that that PLM is favoured on board. Vibration monitoring is, while uncommon, used in maritime applications, as one of our interviewees currently uses vibration monitoring on selections of their machinery. CM proved to be unfavourable at sea generally. Crew and shipping companies do not want equipment to break down. Despite this, the usage of CM cannot be eliminated completely. A small amount of CM is considered acceptable. Condition monitoring in the form of LO analysis is common aboard ships, as most maritime related participants answered that their shipping company uses it. Thermal analysis is also quite common on board. Samples are taken on board and sent ashore for analysis. Many ships have infrared thermocameras on board as well.

Preferred maintenance type(s) in land based industry?

The results indicate a common presence of CMB in shore-based industrial applications. Seven of our interviewees responded that CBM is common among industries. This is somewhat dependent on the type of industry and size of the plant in question. Paper mills have proven to be the most extensive users of CBM as downtime is highly burdensome financially. Preventive maintenance is in general preferred as a maintenance strategy. Generally, condition monitoring and CBM is used parallel to PLM in industrial applications. CM is usually unfavourable due to many industries having PLM stops annually, which is difficult to match with machine failures. Thus, if utilizing CM extensively, maintenance planning becomes close to impossible. However, in some cases of cheap and quick-to-repair machinery, CM has the advantage of being the more economic maintenance strategy.

5 Discussion

Vibration monitoring has proven to be rare on board ships according to our results. But the results also show that vibration monitoring/SPM are known subjects that the majority of the participants of this thesis has been in contact with. Nevertheless, vibration monitoring in maritime applications seems to be an area fairly unexploited. It is probably not the case of a single aspect of our results that prevent the implementation of vibration monitoring on board ships. Neither is it likely that any individual aspect of our "overcome" section that, on its own, could reverse the trend of vibration monitoring on board. It is likely to be a combination of these aspects. For instance; our results show, if surveys can be simplified by presenting machine diagnostics protocols to a surveyor, implementation of vibration/condition monitoring might become easier. But there is already a class notation called "machine condition monitoring", which enables this form of survey (DNV, 2008). Thus, something more must change for vibration monitoring to become common at sea.

The results showed distrust to the technology and analysis of vibration monitoring, as does Turan (2011). This can be traced back somewhat to training, or the lack of training concerning the subject of vibration monitoring in general. School-based training does not incorporate vibration monitoring, as a part of the training (SJO845, 2015). The importance of training when handling vibration analysis is further described by DNV (2008). Training is highly important, especially, if the analysis is to be undertaken on board. As vibration analysis is a difficult subject which requires enthusiastic personnel as mentioned by several interviewees and illustrated by images 1.1-1.4 in the appendix list (White, 1996; Johansson, 1997). By studying certain background literature used for this thesis, especially the vibration monitoring and analysis introduction literature, it becomes obvious how wide and complex the subject actually is (Mobley, 1999; De Silva, 2005; Akishita, 2005). As can be seen in image 1.1-1.4 of the appendix list, it can be very complex to tell different frequency peaks apart from each other or to tell which ones are interesting without formal training. The untrained eye seems to primarily look at the largest peaks in the spectra rather than at what is of actual interest due to BPFO and BPFI peaks not standing out in an obvious way (assuming bearing frequencies is of primary interest). It is important that all parts of the shipping company have knowledge about the subject in question, even if the analysis isn't performed on board, but sent ashore to a contracted vibration analysis company. Personnel in the company office might otherwise regard vibration monitoring on board their vessels as an unmotivated expense and crewmembers might see it as "just another job that must be performed". If the technology cannot be trusted, maintenance actions may still be performed based on running hours rather than based on condition. Naturally, an important aspect of vibration monitoring might be lost this way, with a risk of the equipment invested in ending up on a shelf or in a locker. Despite these negative factors, White (1996) states that the technologies surrounding CBM and vibration analysis should be as possible to implement at sea as in shore-based industry.

One of the technicians interviewed pointed out that the main financial advantage of vibration monitoring isn't that it allows for full exploitation of bearing lifespan, but allow maintenance personnel to perform maintenance when suitable as well as the avoidance of unexpected downtime. While downtime might be more financially burdensome to shore-based industry, it is a fact that cannot be ignored in maritime aspects either. This might not be considered a major interference in shipping due to the common presence of redundancy which reduces the risk of failure (Jarlros, 2003; Öner, 2013). Clustering of maintenance actions could prove economically sound if the actions taken would have resulted in the unavailability of certain machinery at separate occasions, as well as to enable better utilization of time spent in dry-dock.

The maritime industry seems to be a bit conservative concerning vibration monitoring according to our results. This could once again be traced back to training as cadets and new crewmembers are taught a lot from more experienced crewmembers during internships or introduction to the new vessel. If training received in school don't incorporate vibration monitoring or too little of the subject, cadets become heavily dependent on knowledge from experienced crewmembers. This way conservatism can be spread from one generation of engine crew to the next as cadets have little or no other knowledge to rely on.

The current situation on board, with little crew and circulation of the crew, may not allow for accurate and consistent vibration analysis. Many Swedish-flagged vessels have on board periods ranging from approximately two to six weeks. When a crewmember has completed his weeks on board, a reliever takes over. Thus, there is room for differences in interpretation of vibration data. This opens a risk that one crewmember relies on vibration analysis and his/her reliever on the manufacturer's suggested running hours, which would eliminate one of the benefits of vibration monitoring and CBM (Jonge, 2016). Another circumstance contributing to the difficulties is that on board personnel tend to move to other vessels every so often and this makes it difficult to establish knowledge within the company, as it is unlikely that a company would send the entire crew for training. This means that there are a limited number of people within the company who hold sufficient training in the subject, why knowledge is unlikely to be gained in the same manner as concerning regular maintenance. There is also a risk that the enthusiasts that our results suggest are of great importance are lost in the same way.

> *"They have their own personnel who are measuring, but I have to attend the problem anyway. So, it is of utmost importance that you measure at the very same location and that is a bit difficult if you change technician, who measures in his own way."*

One of the overall difficulties with vibration monitoring is the machines themselves. Even if two similar machines are manufactured by the same company, they are different. Every machine has its own characteristics and minor alterations compared to other machinery (Brandt, 2011). While the machinery plant on board is relatively small compared to that of an average shore based industrial plant, the crew is also numerically small. This leaves a benefit and a drawback in relation to vibration monitoring. According to some of our interviewees, the maritime crews have a high level of oversight of their equipment, somewhat related to the size of the onboard plant. A normal workday usually comprises of engine room routines, usually performed by an oiler/motorman. This way the motorman gains experience of the normal condition of the on-board machinery plant and knowledge to tell when something is different.

The knowledge that could help determine possible sources of error such as, for instance, cavitation, which might affect the result of vibration data. The drawback with a small plant, is primarily, that it is difficult to gain experience regarding vibration monitoring/analysis for the person responsible. As DNV (2008; 2015) stresses, the analysis should be performed by qualified personnel. What is suggested by "qualified" is likely to be formal training, but it is difficult to tell if not experience of vibration monitoring/analysis is as important. Thus, a formally trained crewmember might still not be considered qualified. Fixed monitoring equipment and analysis outsourced to a contractor could help easing this problem, as this minimizes the requirements on the crew. A downside of having the vibration analyst in a different location is that he/she cannot see the machine physically. Factors such as rapid change in temperature of the sensor, badly attached sensor (looseness of the sensor) and changed operating conditions can affect the analysis and therefore requires the analyst to be informed of these factors, to be able to take necessary counteractions (White, 1996). It can be difficult to assess an issue if the symptom cannot be observed and it can be difficult for the crew to describe this symptom to an analyst if they don't know what they are looking for. There is also a risk that maintenance personnel on board replaces a used bearing with what is considered an equivalent bearing, but this new bearing, while similar concerning the operation of the machine might have different vibration characteristics (Brandt, 2011).

> *"Taking readings is one thing, but then you have to analyse the data recovered as well. They are likely not to have any experience of measuring, nor of analysis."*

Trials with cheap and simple equipment might have had a negative impact on those involved in the testing, since, this kind of equipment isn't as refined as more expensive equipment generally. If one compares a yardstick with calipers, the theoretical difference becomes clear. The less refined piece of equipment can still be used to determine lengths and thicknesses, but a great deal of precision is lost. This is a problem that a deeper understanding of vibration technology and technique have the potential to change. Once again, is this an issue related to training.

This study has suggested a significant difference in the approach to maintenance strategies on board versus ashore. Shore based industries such as chemical plants, combined heat and power plants and paper mills are extensive users of vibration monitoring and CBM (Lazakis, 2016). The results revealed only one confirmed case of vibration monitoring being used at sea today among the interviewees of this thesis. One of the major differences between shore-based and shipping industry concerning maintenance approach is the criticality of equipment. Ships are required, by classification societies, to have redundant systems depending on the society and class notation (DNV, 2012). The fact that ships have redundant systems means that on board and office personnel can't see any need for vibration monitoring. For instance, if there is a failure or a pump, the standby pump can readily be started. Redundancy is, however, an expensive way of ensuring a safe and reliable operation of a plant (Xie, 2014), why the shore based industry has chosen CBM in favour of redundancy to a greater extent. Nevertheless, shore based industries still apply redundancy when deemed necessary, but due to the plant usually being much more extensive is this economically unfavourable, unless the criticality of a system is very high (Johansson, 1997). Shore based industries such as paper mills usually have planned shut-downs of the mill annually to perform maintenance (Lind, 2017). Vibration monitoring is in this sense an important factor to know in advance whether a machine can continue to operate until this planned stop as downtime can be very costly (Johansson, 1997).

IACS (2001) suggests that poor maintenance management endangers the crew to some extent and increases the risk of port state controls resulting in detainment. These factors could motivate a maintenance approach such as RCM, which is based on vibration monitoring inter alia (Johansson, 1997). As our results have indicated, benefits concerning classification from condition monitoring based on vibration analysis could prove to be a step forward to overcome

the disadvantages. As DNV (2008) suggests, with condition monitoring the need to open up certain machinery partly or fully is eliminated. Combining these aspects with other benefits of vibration analysis such as simplified maintenance scheduling and a reduced number of excessive maintenance actions (Samarasekera, 2005; Al-Najjar, 2016). The opportunity of rescheduling maintenance activities to a more appropriate time becomes a reality. This means that there is a possibility to see if the running time of a machine can be prolonged until the next visit to a dry-dock, or if an activity planned for the dry-docking has to be undertaken in advance.

Our results have shown that condition monitoring in terms of LO and thermal analysis is common on board. Oil from propeller shaft bearings, propeller sleeves and diesel engines used for propulsion or power generation. LO analysis can be used to detect wear and deterioration of machine parts or the oil itself (ABS, 2016). Thermal analysis is used to find hot spots and increased friction, indicating worn components (mainly bearings) and lubrication failures (ABS, 2016). Some of these methods are relatively simple and cheap when compared to vibration monitoring and require little training. Locating hot spots using a basic thermocamera is for instance very simple and require no real training at all. Most of our interviewees utilize one or both of the techniques of thermal and/or LO analysis. It could be that these methods combined with a functioning PLM strategy mean vibration monitoring have little to contribute with. Oil samples are commonly sent ashore for analysis, why there is little risk of error in the interpretation of the results.

Consider an offshore support vessel that requires DP-2 (dynamic positioning, class 2). This vessel is dependent on the redundancy of critical components. If one critical component is lost, it is no longer a DP-2 vessel, as might be required based on the type of operation being conducted. By implementing CBM, unexpected failure of critical components could be avoided thus minimizing this operational safety hazard.

Another example for the above-mentioned demand of extra reassurance might be autonomous vessels. If a machinery failure strikes a crewless vessel out at sea, there is no one to redress this until the vessel arrives in port. Here it is reasonable to consider vibration monitoring as a basis for CBM. Both since these vessels are supposed to be monitored from locations ashore, as well as to make the planning of maintenance actions easier and possibly enable clustering of maintenance actions to minimize the number of maintenance crews sent to the vessel annually.

It isn’t as simple as selecting the most sophisticated type of maintenance strategy. There must be a balance between criticality of a machine and what reasonable expenses on that machine, in particular, are as our results indicate and stated by Johansson (1997). For instance, a fluorescent tube isn’t worth replacing on a fixed basis due to the minimal criticality. A lubricating oil pump, however, might cause a shutdown of main engine(s) and subsequently grounding, collision etc. in the event of a failure during operation. Due to the amount of redundancy aboard ships, the criticality of those systems is reduced (Jarlros, 2003). This means that vibration monitoring might be more of an expense rather than a tool to increase the availability of the vessel.

5.1 Method discussion

It was assessed that the information received would be easier to validate when aspects such as atmosphere and reaction to questions asked during interviews when having a conversation face to face (Denscombe, 2014). It was deemed easier to get the interviewees to explicate their answers further this way as well.

Our interviewees have a wide variety of knowledge and backgrounds. By having knowledge diversity like this we considered any possible common denominators to be more reliable and more valid. That is, if someone working on board has the same thoughts and ideas as a technician working ashore, we consider this type of correlation as significant. All participants of this thesis are experts in their own fields. What they have said should be considered reliable, though at some occasions our questions were outside their areas of expertise.

5.1.1 Background literature

To gain a further understanding of maintenance in general, different maintenance types and basic vibration and analysis, subject relevant literature such as scientific articles, books, and course literature were reviewed. This information helped to benefit further from technical and analytical terms and demonstrations served by our interviewees. A lot of written information is available on both subjects of maintenance and vibration monitoring/analysis. However, little information was to be found combining these subjects and applying them to the shipping industry. Despite this, a lot of scientific information has been read, assessed and presented in our own words in the background chapter. This information has been further validated by persons working with some of the methods and technology presented, as to make sure a connection with reality was present.

5.1.2 Collection of data

Establishing contact with relevant persons is a difficult thing. A lot of those persons with the kind of knowledge our thesis required are very busy people with little or no time to spare. We explicitly stated upon contacting our persons and companies of interest that we would come to them when suitable for them. Despite this, about 3 out of 10 persons or companies contacted responded, where the majority of those responding wanted to participate. Nevertheless, the more interviews we did the more replies we got as well as advice on other persons to contact. This lead to a potentially too high workload in relation to the information obtained, as a theoretical saturation had started to emerge (Denscombe, 2014).

The experience of our participants might have had an effect on the final result. If we had more interviewees with no experience or less technical knowledge of vibration monitoring, our result might have been either more in favour of the subject, or against. The results could have been affected in the same way if our participants had formal training in the subject and/or practical experience. If we had interviewed more active onboard personnel from different types of vessels, we might have received different results concerning thoughts and ideas related to vibration and condition monitoring. In essence, our results could be somewhat shaped after individual participants of our study.

By having some width in our selection of participants we concluded that the overall quality of our study was enhanced and achieving a more thorough answer to our main research question. The question templates were structured as not to lead interviewees into by us pre-determined thoughts or ideas. Thus, not forcing or deceiving interviewed persons into answering as we wanted. Some leading questions were used if we thought that a reasoning of an interviewee had some deficits. This way we could find out not just what an interviewee thought, but also why.

Even though semi-structured interviews were assessed as a suitable method to our research questions, it has a very high workload. This workload took shape as traveling, transcription of recordings, a rough analysis and finally compilation of the results. A questionnaire could have been used to achieve a wider range of answers since the lack of time limits the number of interviews that can be undertaken for a thesis. But semi-structured interviews were considered more qualitative than a questionnaire and the frequency of replies to a questionnaire has a potential risk of not being satisfactory. One must, first of all, read up on the current subject before undertaking any interview, writing any questionnaire or writing a template of questions to ensure the relevant questions are asked.

6 Conclusions

Why is vibration monitoring not used to a greater extent aboard seagoing vessels? What are the possible obstacles comprised of? How can they be overcome?

Our results have indicated that there are two main aspects to why vibration monitoring isn't more common in maritime applications; economic reasons, it is expensive to implement and distrust to the technology and analysis. Few participants of this study can identify any significant areas of application for vibration monitoring on board since ships have redundancy on critical components. Essentially, the need for further operational safety and reliability cannot be seen, why vibration monitoring is regarded as something highly expensive and unnecessary. The distrust of vibration monitoring is related to the general conservatism of seafarers as our thesis has shown. Onboard crew rather follow manuals from the manufacturers regarding maintenance intervals than a piece of equipment that they haven't had any need for before. This is where conservatism comes in, as it is commonly believed that a screwdriver held against one's ear protectors is good enough to monitor the bearing condition.

To remedy the issue of distrust towards vibration monitoring, better training is required. The subject should be incorporated into the maintenance course that is offered in school to give cadets and new engineers a basic understanding of the subject and its uses. Vibration monitoring must be seen as a tool rather than simply an expense to overcome the economic factor. This can be achieved by using vibration monitoring to simplify surveys performed by the classification societies. It can also be applied to critical machinery which requires dry-docking to enable maintenance. That is periodic maintenance (Turan, 2009).

Which differences if any are present between shore based and shipping industry? Which type(s) of maintenance are favoured in both fields?

PLM is the primary maintenance strategy used on board ships, as our thesis has shown. This form of maintaining the condition of the machinery installations on board usually works very well with little unforeseen failures. In essence, PM based on PLM is considered adequate in the shipping industry. In shore-based industry, especially in bigger plants such as paper mills is it important to have an effective maintenance organization to minimize downtime and enable scheduling of maintenance actions to planned stops of the plant. As discussed, unavailability is more financially burdensome than failures, spare parts and repair personnel themselves in shore based industries. This is the primary difference between maritime and industrial applications of CBM and vibration monitoring uncovered in this thesis.

6.1 Further studies

The authors of this thesis suggest a study identifying critical components on board, as this thesis has pointed out that the criticality of a component is what a maintenance strategy should be based on. This could provide interesting and useful information regarding reasonable maintenance and inspection actions to be performed on these components, as well as identify potential hazards, both operational and concerning safety.

7 References

ABS (2016) *Guidance notes on equipment condition monitoring techniques* https://maritimecyprus.files.wordpress.com/2016/05/abs-equipment_condition_monitoring.pdf [2017-04-14].

Akishita, S. (2005) *Source of Noise: Vibration and shock handbook*, edit. De Silva, C.W, pp. 41-1. Boca Raton: Taylor & Francis Group.

Al-Najjar, B. (2016) *Determination of potential failure Initiation Time using Cumulative Sum Chart*, IFAC-PapersOnLine, vol. 49-28 pp. 43-48.

Alsyouf, I. (2009) *Maintenance practices in Swedish industries: Survey results*, International journal of production economics, vol. 121 pp. 212-223.

Brandt, A. (2011). *Noise and vibration analysis: signal analysis and experimental procedures*. Chichester: John Wiley & Sons, Ltd.

Butler, D.E. (1973) *The shock-pulse method for the detection of damaged rolling bearings*, Non-Destructive Testing, vol. 6 pp. 92-95.

Cui, L. et al. (2016) *Vibration response mechanism of faulty outer race rolling element bearings for quantitative analysis*, Journal of Sound and Vibration, vol. 364 pp. 67–76.

Denscombe, M. (2014). *Forskningshandboken: för småskaliga forskningsprojekt inom samhällsvetenskaperna*, Lund: Studentlitteratur AB.

De Silva, C.W (2005) *Time-domain analysis: Vibration and shock handbook*, edit. De Silva, C.W, pp. 2-40. Boca Raton: Taylor & Francis Group.

De Silva, C.W (2005) *Frequency-domain analysis: Vibration and shock handbook*, edit. De Silva, C.W, pp. 27-67. Boca Raton: Taylor & Francis Group.

De Silva, C.W (2006) *Vibration: fundamentals and practice*. Boca Raton: CRC/Taylor & Francis Group.

DNV (2008) *Guidance for condition monitoring* https://rules.dnvgl.com/docs/pdf/DNV/cn/2008-10/CN10-2.pdf (2017-03-26).

DNV (2011) *Vibration class* https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2011-01/ts615.pdf (2017-01-18).

DNV (2012) *Failure mode and effect analysis (FMEA) of redundant systems* https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2012-01/RP-D102.pdf (2017-03-26).

DNV (2015) *Survey arrangement for machinery condition monitoring* https://rules.dnvgl.com/docs/pdf/DNVGL/CG/2015-12/DNVGL-CG-0052.pdf (2017-04-08).

El-Thalji, I. Jantunen, E. (2015) *A summary of fault modelling and predictive health monitoring of rolling element bearings*, Mechanical systems and signal processing, vol. 60-61 pp. 252-272.

Gustavsson, A. (1996) *Praktisk elkunskap*. Lund: Studentlitteratur AB.

Hagberg, L. Henriksson, T. (2016) *Underhåll i världsklass*. Lund: OEE Consultants AB.

Hellström, S. Lindberg, A. (2011) *Tillståndsanalys av tvättpress inom pappers- och massaindustrin*. Karlstad: Karlstads universitet (Examensarbete vid maskiningenjörsprogrammet).

Heng, A. et al. (2009) *Rotating machinery prognostics: State of the art, challenges and opportunities*, Mechanical Systems and Signal Processing, vol. 23 pp. 724-739.

IACS (2001) A guide to managing maintenance http://www.iacs.org.uk/document/public/Publications/Guidelines_and_recommendations/PDF/REC_74_pdf214.pdf (2017-04-08).

Jardine, A.K.S. Lin, D. Banjevic, D. (2006) *A review on machinery diagnostics and prognostics implementing condition-based maintenance*, Mechanical Systems and Signal Processing, vol. 20 pp. 1483-1510.

Jarlros, M. (2003) Driftsäkerhetsteknik Göteborg: Institutionen för sjöfart och marin teknik.

Jeffali, F. (2016) *Thermal diagnostic of a rotating machine using the non-destructive technique of infrared thermography*, Journal of Nature Science and Sustainable Technology, vol. 10 pp. 219-234.

Johansson, K. E. (1997). *Driftsäkerhet och underhåll*. Lund: Studentlitteratur AB.

Jonge, B. et al. (2016) *Reducing costs by clustering maintenance activities for multiple critical units*, Reliability Engineering and System Safety, vol. 145 pp. 93–103.

Kallio, H. et al. (2016) *Systematic methodological review: developing a framework for a qualitative semi-structured interview guide*, Journal of advanced nursing, vol. 72 pp. 2954-2965.

Kuiken, K. (2012) *Diesel engines part 1*. Onnen: Target global energy training.

Lansdown, A.R. (1982) *Lubrication, a practical guide to lubricant selection*. Swansea: Pergamon Press.

Lazakis, I. Turan, O. Aksu, S. (2010) *Increasing ship operational reliability through the implementation of a holistic maintenance management strategy*, Ships and offshore structures, vol. 5 pp. 337-357.

Lazakis, I. et al. (2016) *Advanced ship systems condition monitoring for enhanced inspection, maintenance and decision making in ship operations*, Transportation Research Procedia, vol. 14 pp. 1679 – 1688.

LNB660 (2015) *Verkstad, motorkurs* https://www.student.chalmers.se/sp/course?course_id=23283 [2017-04-07].

Manzini, R. et al. (2015) *The scheduling of maintenance. A resource-constraints mixed integer linear programming model*, Computers & industrial engineering, vol. 87 pp. 561-568.

Marais, K.B (2013) *Value maximizing maintenance policies under general repair*, Reliability Engineering and System Safety, vol. 119 pp. 76–87.

Martin, K.F. (1994) *A review by discussion of condition monitoring and fault diagnosis in machine tools*, International journal of machine tools and manufacture, vol. 34 pp. 527-551.

Mitrovic, R.M et al. (2016) *Statistical correlation between vibration characteristics, surface temperatures and service life of rolling bearings – artificially contaminated by open pit coal mine debris particles*, Procedia Structural Integrity, vol. 2 pp. 2338-2346.

Mobley, K.R (1999). *Vibration fundamentals*. Boston: Newnes.

Murer, S. et al. (2015) *Determination of loads transmitted by rolling elements in a roller bearing using capacitive probes: Finite element validation*, Mechanical Systems and Signal Processing, vol. 54-55 pp. 306-313.

Nguyen, P. et al. (2015) *Robust condition monitoring of rolling element bearings using de-noising and envelope analysis with signal decomposition techniques*, Expert systems with applications, vol. 42 pp. 9024-9032.

Niu, L. (2015) *A systematic study of ball passing frequencies based on dynamic modelling of rolling ball bearings with localized surface defects*, Journal of Sound and Vibration, vol. 357 pp. 207–232.

SJO845 (2015) *Underhållsteknik* https://www.student.chalmers.se/sp/course?course_id=24198 [2017-04-07].

Prudhom, A. et al. (2017) *Time-frequency vibration analysis for the detection of motor damages caused by bearing currents*, Mechanical Systems and Signal Processing, vol. 84 747–762.

SAN (2008) *Arbetsmiljömanual för sjöfarten*, 2: nd edition. Katrineholm: Hellmans Förlag AB.

Samarasekera, H.S (2005) *Vibration in rotating machinery: Vibration and shock handbook*, edit. De Silva, C.W, pp. 1198-1237. Boca Raton: Taylor & Francis Group.

Spectec (2017) http://www.spectec.net/maintenance-materials-management [2017-04-28].

Star information systems (2017) http://www.sismarine.com/software/software-for-ships/ [2017-04-28].

Stenström, C. et al (2016) *Preventive and corrective maintenance – cost comparison and cost–benefit analysis*, Structure & Infrastructure Engineering, vol. 12 pp. 603-617.

Storm, H. Lundell, S. (2012) *Vibrationsövervakning av Fortums maskinparker*. Karlstad: Karlstad universitet (Examensarbete vid mekatronikingenjörsprogrammet).

Tandon, N. Kumar, K.S (2003) *Detection of Defects at Different Locations in Ball Bearings by Vibration and Shock Pulse Monitoring*, Noise & Vibration Worldwide, vol. 34 pp. 9-16.

Tandon, N. Choudhury, A. (1999) *A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings*, Tribology international, vol. 32 pp. 469-480.

Tandon, N. Yadava, G.S. Ramakrishna, K.M. (2007) *A comparison of some condition monitoring techniques for the detection of defect in induction motor ball bearings*, Mechanical systems and signal processing, vol. 21 pp. 244-256.

Turan, O. et al. (2009) *Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage*, Ships and offshore structures, vol. 4 pp. 107-125.

Turan, O. et al. (2011) *Investigating the Reliability and Criticality of the Maintenance Characteristics of a Diving Support Vessel*, Quality and Reliability Engineering International, vol. 27 pp. 931-946.

Verma, K.A (2012) *Optimization of maintenance scheduling of ship borne machinery for improved reliability and reduced cost*, International journal of reliability, quality and safety engineering, vol. 19 16 pages.

Wardle, F. (2015). *Ultra-precision bearings*, [electronic] Cambridge, Woodland publishing.

White, G. (1996) Vibrationsteori och principer för tillståndskontroll (G. Jonasson, translation). Landskrona: Diatek vibrationsteknik.

Xiao, L. et al. (2015) *Joint optimization of production scheduling and machine group preventive maintenance,* Reliability engineering and system safety, vol. 146 pp. 68-78.

Xie, W. Liao, H. Jin, T. (2014) *Maximizing system availability through joint decision on component redundancy and spares inventory*, European journal of operational research, vol. 237 pp. 164-176.

Zarei, J. Tajeddini, M.A. Karimi, H.R (2014) *Vibration analysis for bearing fault detection and classification using an intelligent filter*, Mechatronics, vol. 24 pp. 151-158.

Zhen, L. et al. (2008) *Bearing condition monitoring based on shock pulse method and improved redundant lifting scheme*, Mathematics and Computers in Simulation, vol. 79 pp. 318-338.

Ölcer, A. Lazakis, I. (2016) *Selection of the best maintenance approach in the maritime industry under fuzzy multiple attributive group decision-making environment*, Journal of engineering for the marine environment, vol. 230 pp. 297-309.

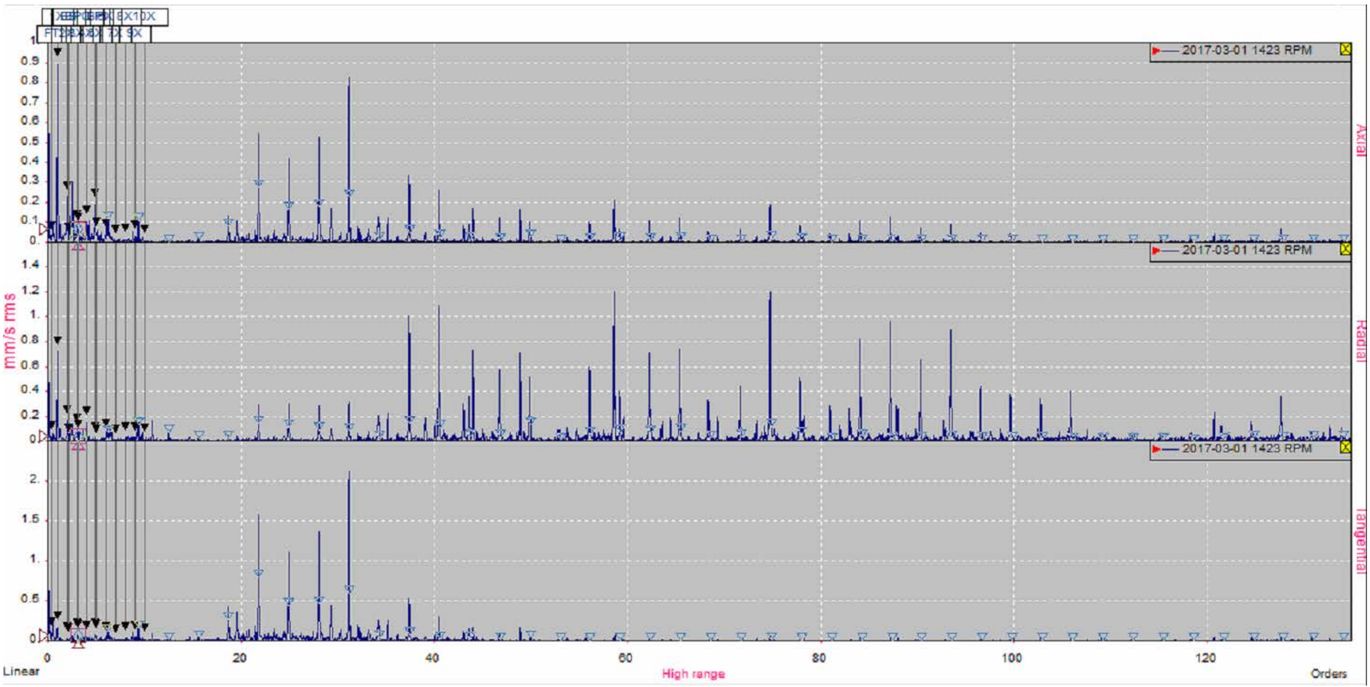
Öner, K.B. Scheller-Wolf, A. Houtum, G-J. (2013) *Redundancy Optimization for Critical Components in High-Availability Technical Systems*, Operations research, vol. 61 pp. 244-264.

Verbal references

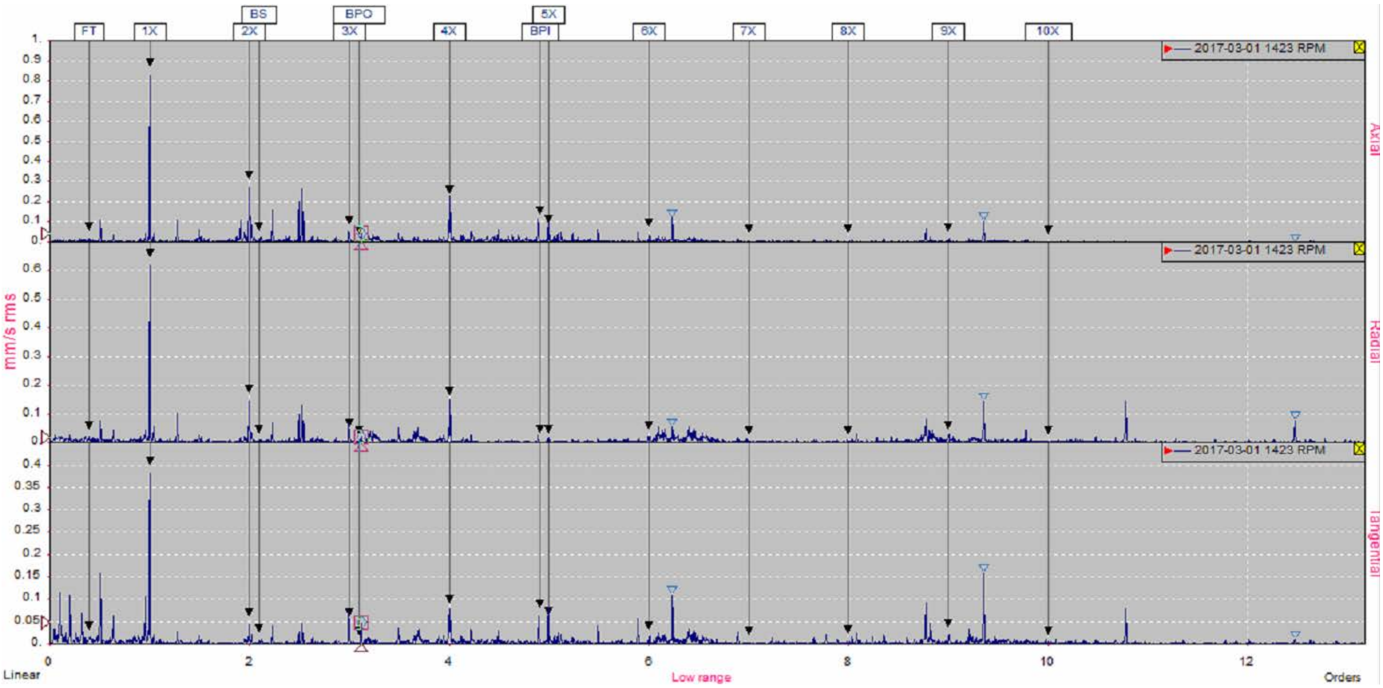
Lind, N. (2017) *Preventive maintenance engineer* [Interview] 2017-03-15.

Welin, A. (2017) *SKF business engineer* [Interview] 2017-03-31.

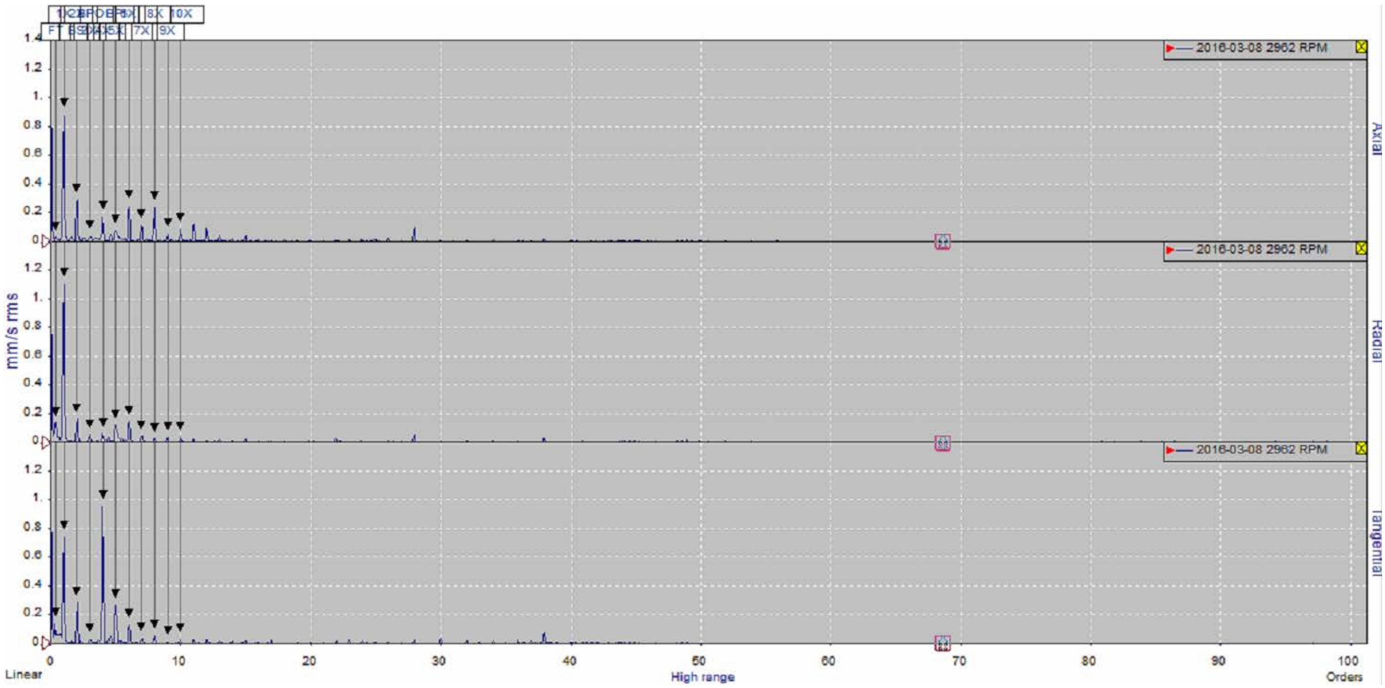
8 Appendix 1



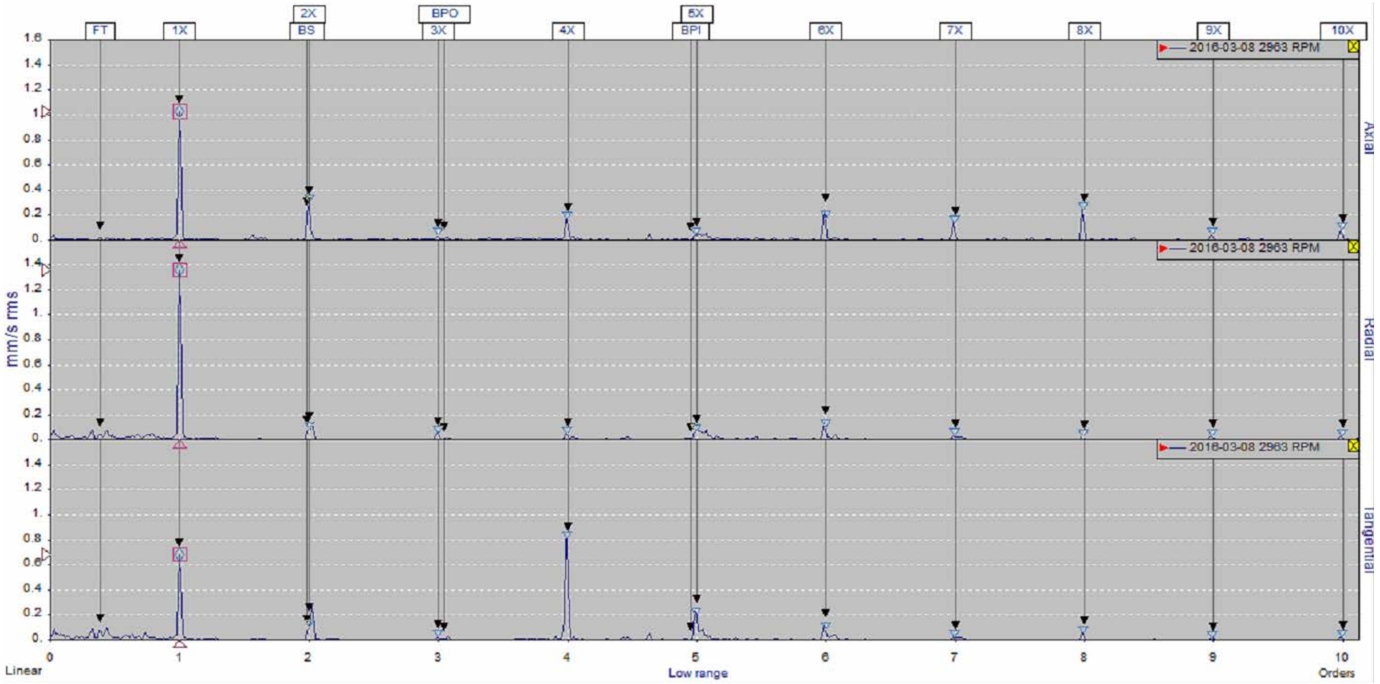
Appendix 1.1: High range spectrum with a probable bearing defect (with courtesy by Mikael Lorentzson, ABB)



Appendix 1.2: Low range spectrum with a probable bearing defect (with courtesy by Mikael Lorentzson, ABB)



Appendix 1.3: High range spectrum with healthy bearings (with courtesy by Mikael Lorentzson, ABB)



Appendix 1.4: low range spectrum with healthy bearings (with courtesy by Mikael Lorentzson, ABB)

9 Appendix 2

Denna intervju är en del i examensarbetet, med syftet att förstå varför tillståndsbaserat underhåll med vibrationsmätning inte används till sjöss i större utsträckning samt kostnaden för införandet av vibrationsmätning ombord. Detta examensarbete är sista delen i vår utbildning till sjöingenjörer. För mer information eller vid frågor, kontakta oss gärna med nedanstående kontaktuppgifter.

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Intervjuad:

Denna intervju är frivillig, medverkan kan ångras, varpå svaren tas bort ur studien. Resultatet är konfidentiellt med möjlighet till granskning innan publicering. <u>Härmed intygas att jag är införstådd med syftet till denna intervju, och har godkänt medverkan.</u>

______________________________ ______________________________

Namnteckning *Namnförtydligande*

______________________________ ____________________ __________

E-mail (frivilligt, för ev. följdfrågor) *Telefon (frivilligt, för ev. följdfrågor)*

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Datum

Härmed godkänner jag att intervjun spelas in, och att materialet används till examensarbete.

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Namnteckning