REDUCTION OF FRICTION

Magnetic bearings

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Summary

This report is about a solution for the problems that exist nowadays in the lubrication of various systems on board a vessel. The traditional systems with mechanical bearings causes a lot of friction and wear. The traditional system therefore needs a lot of maintenance. The maintenance and the large amount of lubrication oil needed, brings a lot of extra costs.

The purpose of this report is to find out if magnetic bearings can solve the problems caused by friction. The main question of the report therefore is: “How can magnetic bearings reduce friction on board vessels?”

In the plan of approach, the sub questions are set up. In chapter three the sub question, “What is tribology and what traditional lubrication systems are used on board of vessels nowadays?” is discussed. It becomes clear that the way how the current systems work comes with a lot of problems and costs.

With answering the sub question “Magnetic bearings; what are they and how do they work?” it becomes clear that nowadays there are three types of magnetic bearings, the passive magnetic bearings and the active magnetic bearings. They both work by the same magnetic principle, i.e. keeping the axis in the right position. The main difference is that the active magnetic bearings work with a controller unit. The controller unit enable the active magnetic bearings to correct itself when it is exposed to external forces. The third bearings discussed in this chapter is the electrodynamic bearing. The electrodynamic bearing is a magnetic bearing in an early state of development, but shows great capabilities when further developed. The working of the electrodynamic bearing is based on the principal of Lorenz and Faraday.

In chapter 5 the sub question “Where on board can magnetic bearings be applied?” is answered. The objective in chapter 5 is to find out if the machinery on board vessels are suitable for magnetic bearings. After research it became clear that magnetic bearings are not suitable for all of the machinery on board vessels. To make magnetic bearings work properly on board vessels a high rpm is needed to compensate for the external forces. Because of the rpms needed the magnetic bearings nowadays will only be useful for the turbo and steam turbine. These systems are better explained in chapter 5.

The next step comes with answering the sub question “Are magnetic bearings retrofittable?” retrofitting can be described as the possibility to install magnetic bearings in existing systems. It becomes clear that it is possible to retrofit magnetic bearing but it is not cost effective.

The final sub question that has been answered is: “What are the effects on maintenance when switching to magnetic bearings?” This is done by comparing the maintenance of the two systems. A lot of things influence the maintenance and costs of the lubrication system and the new system has lower lifecycle costs.

The conclusion describes that the answer to the main question is that the magnetic bearings indeed reduce the friction. However, nowadays it is not yet possible to apply magnetic bearings in all different types of machinery on board of a vessel. Therefore, the research focusses on a turbo compressor, because the characteristics of this system are sufficient to apply them with magnetic bearings. This system could become very interesting after more investigation and research, because it could reduce a lot of maintenance and costs.
Preface

This research project is an assignment for the course Maritime Research Project. Several topics were given in class from which one was chosen by our group. We were looking for a more technical subject and decided to choose the subject about magnetic bearings.

The objective of this project is to do a group assignment and making a plan of approach, doing desk research and writing a desk report and doing field research and implement the results of that research into the final report. After handing in the final report, all groups have to present their research at a maritime symposium, organized by themselves, for other students and experts from the maritime sector.

The learning objectives are applying our skills to organize a project, performing research within the topic of magnetic bearings and managing the group, meetings and progress of the research. For the field research, we had to contact experts from the maritime industry that worked with magnetic bearings and conventional bearings.

It was quite a large assessment and we had a bit of a slow start, because of a change of our subject. When doing desk and field research, we also had to adjust our sub questions to be able to write a more coherent report. The communication within our group didn’t go as planned, resulting in the do-over of our draft final report. After adjusting, we were able to write a cohesive report that describes if magnetic bearings can reduce friction on board of vessels.

We would like to thank our mentor Mister Blankenstein, who gave good advice and helped us shape a good structure for our report. Also, we thank SKF, Siemens, Magnetal and Wärtsilä for the information we received for our field research, making our final report possible.

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1. Introduction

The objective of this research project is to analyze if the use of magnetic bearings in the maritime industry can improve the quality of bearings on board. The system used nowadays on board vessels consists of mechanical bearings and a lubrication system. Although it functions properly, this research will explore if the application of magnetic bearings can reduce friction, wear and lubrication.

The use of a traditional system with mechanical bearings and a lubrication oil system on board of vessels can be expensive. It needs a lubricant, which creates frictions, thus a loss of energy and has to be replaced after a specific amount of running hours. Also, the lubricant contains debris and contaminants when the film of lubricant between two moving surfaces becomes too thin and metallic contact between the surfaces arises. To prevent this, a separate system with a purifier needs to clean the lubrication oil, resulting in more cost and maintenance. Interacting surfaces occur in almost all-rotating machinery, so optimum lubrication can lead to improvement in durability, reliability and safety. The comparison in this project is between traditional lubrication of bearings on board and magnetic bearings that do not need a lubricant and if magnetic bearings need little maintenance and thus can be more cost-effective.

The second chapter describes the research methods used and shortly describes the plan of approach. The third chapter defines the principle of tribology and describes the traditional lubrication methods used nowadays. To prevent friction, a lubricant is used to form a film between two moving parts in the engine. The lubrication system and the problems occurring on existing vessels is the subject of the third chapter. The next chapter explains the working of a magnetic bearing and in the fifth chapter the application of these bearings on board will be discussed. The following chapter describes the retrofitting of magnetic bearings; can they be replaced on board of existing vessels? This report will finish with a comparison between the maintenance of a traditional lubrication system and the maintenance necessary for a magnetic bearing. Finally, a conclusion will be made and recommendations will be given.
2. Plan of approach and research methods

The main lubrication system which is being applied in the shipping sector nowadays creates a loss in engine power and requires a lot of maintenance. Also it requires a separate system to purify the oils and is not very cost effective because one must invest a lot of money in new oils. “A 6500 TEU container vessel has a 12-cylinder Wärtsilä RTA96C main engine with a MCR (Mean Continuous Rate) power of 63,000 kW. The main engine operates 6000 hours per year at an average load of 65% of MCR. Wärtsilä developed the Retrofit Pulse Lubricating System (RPLS). With a specific cylinder lubricating oil (CLO) consumption of 0.8g/kWh the CLO consumption equals 63,000 x 0.65 x 6,000 x 0.8 / 1,000,000 = 197 tons/year. One metric ton of cylinder lubricating oils cost approximately 1750 USD, meaning: CLO operational cost become 197 x 1750 = 345,000 USD/year.” (Wartsila , 2010)

Only replacing cylindrical lubrication oil costs already 345,000 USD a year, not taking into account the other lubrication systems of bearings etc., which would result in even higher costs.

The objective of this report is to analyze if the use of magnetic bearings in the maritime industry improves the quality of the bearings on board. Would it be an improvement relative to the most commonly used system of mechanical bearing systems in the areas of efficiency, maintenance, auxiliary systems and if a system using magnetic bearings is retrofittable.

The main question that followed after mind mapping and several discussions is “How can magnetic bearings reduce friction on board vessels?”. Listed below are the sub questions that go deeper into each subject:

1. What is tribology and what traditional lubrication systems are used on board vessels nowadays?
2. Magnetic bearings; what are they and how do they work?
3. Where on board can magnetic bearings be applied?
4. Are magnetic bearings retrofittable?
5. What are the effects on maintenance when switching to magnetic bearings?

The first two sub questions have been answered doing qualitative research on the web, in several books and asking information from SKF and Magnetel that produce magnetic bearings or engines that use magnetic bearings. The third sub question contains field and desk research: for which machinery is it interesting and could it work to apply magnetic bearings? To find an answer for this question, companies like SKF are approached that make machinery using magnetic bearings or just make magnetic bearings that can be applied in several industries. To find out if magnetic bearings are retrofittable is mostly a desk research question, because almost no companies have applied magnetic bearings on board vessels. For the sub question about a comparison between the maintenance of magnetic bearings and traditional lubrication systems, information came from producers of magnetic bearings (SKF and Magnetel) and the Royal Dutch Navy.
3. Tribology and standard lubrication systems

The scientific term that describes the principles of friction, lubrication and wear is known as tribology. It is defined as the science of interacting surfaces in relative motion. Tribology is all around us in the modern world, in applications from simple to complex and on a large or small scale. Tribology has a multidisciplinary nature and includes different focus groups like chemistry, physics, material science, chemical engineering and mechanical engineering. A successful tribological approach is critical to the cost-effectiveness and sustainability. In this research, the focus will be on the application of tribology in the maritime industry, which is not so much known as in other industries like biometrics, oil & gas industries etc. For example, Imperial College London researches the measurement of wear of explanted hip joints (medical) but also has researches in the automotive industry (Organic Friction modifier behavior) and many others. Like Imperial College’s Tribology group, almost every (technical) university has a tribology department with academics, PhD students and research assistants that perform research in different areas (Imperial College London, 2016).

Tribology fields of study can be individual components, a manufacturing process [polishing, rolling, etc.], construction and exploration [oil drilling rig, Chunnel digging rig, etc.] or natural phenomena [for example water erosion]. While the machine components and lubricants used in the maritime industry are essentially the same as in other applications from other industries, there are some fundamental differences.

Some differences are the acidity of the fuels used, the operating temperatures, the speed ranges of the engines, the forces of waves and swell and the independency that comes with travelling at sea (Shaffer). Marine engines run on heavy fuel oil, which has a high viscosity and needs substantial preheating before it can be used. The average type of a marine engine has an engine-speed somewhere between 120 rpm and 1000 rpm for high speed diesel engines (Maanen p. v.).

For marine applications concerning friction, wear and lubrication, the following components can be found: large thrust loads developed by the propellers shaft(s), cams, gears, pistons and all type of bearings. This research emphasizes only on bearings applied on board.

As stated earlier, the purpose of lubrication is to reduce or minimize friction and wear; to cool and carry away heat from moving parts in close alignment with stationary parts, to minimize oxidation of metals (rust) and to clean the surfaces of the metal by carrying away very small solid deposits. There are different systems of lubrication in this chapter we are going to discuss a few of them.

Friction is the force of resisting relative motion between two surfaces sliding against each other. When the surfaces are in contact with each other and both move in different ways, the friction between these two surfaces converts kinetic energy into thermal energy (heat). Another consequence of many types of friction is wear, which can lead to performance degradation and/or damage to components. These consequences can cause dramatic problems to the materials. There are several types of friction:

(paryleneengineering, n.d.)

- Dry friction occurs between two solid surfaces
- Fluid friction occurs between layers of fluids that are moving in different ways.
- Lubricated friction is a case of fluid friction where a lubricant fluid separates two solid surfaces.
- Skin friction is a component of drag, the force resisting the motion of a fluid across the surface of a body.
- Internal friction is the force resisting motion between the elements making up a solid material while it undergoes deformation.
The wear depends upon various factors like speed of movement between the surfaces, material involved, temperature, load on engine, pressure, maintenance, lubrication, and combustion efficiency.

Most of the machinery is found in the engine room. The few machines that are on deck can be neglected, because these are mostly pumps or electric motors with little wear. Electric motors have little wear because they have small amount of moving parts (most of the time only one moving part). Pumps have little wear, because there is always liquid inside this reduces the wear. So the main focus is the engine room. A few machines that can be found there are the main engine, the generators and the lubrication system.

Taking a look at the main engine, wear occurs in different places because there are a lot of moving parts. There is cylinder, camshaft and cylinder valve wear. The camshaft is able to turn due to bearings. Between the bearings and camshaft lubrication oil is smeared to make sure there is not too much friction. But there will still be friction creating heat and that means a loss of energy. The cylinder wear as well as the cylinder valve wear is not interesting because the wear is created by the fuel combustion.

During the combustion of fuel not all fuel is completely combusted. The not fully combusted fuel can leave with the exhaust gasses, but can also attach to surface of the cylinder. When it attaches to the surface of the cylinder the fuel starts to oxidize to carbon residue. Carbon residue also leads to reduced fuel economy, less power and a rougher surface (axi international, n.d.)

This report is going to focus on lubricated friction because that is the most common sort of friction on board of vessels. As mentioned before lubricated friction is when a fluid separates two solid surfaces. The fluid between the two surfaces is known as the Lubricant. Lubrication allows the two surfaces to run smooth during movement, it also reduces the wear, excessive stresses of the bearings and it allows heat exchange; the dissipation of heat with lubrication oil.

3.1 Greasing

As stated earlier, the purpose of lubrication is to reduce or minimize friction and wear; to cool and carry away heat from moving parts in close alignment with stationary parts, to minimize oxidation of metals (rust) and to clean the surfaces of the metal by carrying away very small solid deposits.

There are different systems of lubrication and in this chapter a few of them will be discussed.

Greasing is the simplest lubrication system of them all. Grease is smeared over the moving parts of the equipment. The grease is usually applied by means of Grease Cups, which are fitted to the casing of the shaft or spindle to be lubricated.

The grease cup is attached to the grease injection point by screws and threads. The cup is given a turn or two at specific intervals. If the cup turns the grease is forced into the injector due to a rising pressure in cup. The injector leads/feeds it to the shaft. Greasing of bearings is simpler the bearing sits in a house. This so called house is filled with grease in which the bearing moves. The quantity of the grease depends on the rotating speed for slow speeds the house is filled up to 90 percent. (SKF, n.d.)

3.2 Lubrication by Oil

3.2.1 Manual Application of Oil

Again, lubrication using oil can be done in some simple/small cases by smearing oil on the surfaces. Oil can also be 'squirted' or injected onto the surfaces by a hand pumped oil can.
3.2.2 Oil bath and Oil pick up ring

In many of the machines there are casings fitted with reservoirs filled with oil in which the shaft passes through. The shaft passes through the oil filled reservoir above the oil level. The machine shaft has a Slinger-ring placed around it which has a larger diameter than the shaft itself. This ring hangs in the oil reservoir.

When the shaft rotates the ring picks up oil. Due to the force of the rotation the oil is thrown off the ring and splashed around and over the shaft and its bearings. The oil then drips down the shaft and bearings back into the reservoir.

Other machine parts such as cam-shafts and crank-cases, have crankcases containing the oil. A scoop attached to the bottom of the connecting rod bearing is used to scoop up oil from the crankcase and again due to the force of rotation the oil splashes around.

The oil bath works almost the same as the pick up ring. The only significant difference is that this method does not use a ring to pick up the oil in the reservoir but the bearing itself. The oil level in the reservoir should reach the lowest turning element of the bearing. Otherwise it cannot pick up the oil.

(SKF, n.d.)

The level of oil in the reservoir or crankcase is maintained by adding oil as required. The oil level can be checked in the sight glass.

3.2.3 Forced Feed Lubrication

Generally reciprocating machines have a built-in pump (which is driven by an electric motor or by a mechanical arm driven by the motion of the machine) and an oil tank which create a lube oil distributor. So the machine has its own lubrication system. The system consists of distribution lines which deliver small portions of oil at intervals to each location in the machine. The delivery of the oil can be seen in the sight glass in each of the lines.

3.2.4 Pressure Lubrication

The bigger the machines get the more oil they need to perform without failing due to the increases of frictional heat, the decrease in the life of the oil and the increases in operating temperatures. The oil is supplied by pumping the oil around the bearings. The oil is filtered, cooled, pumped and controlled at the desired pressure before being fed to bearings. Oil temperature, pressure, flow and level, are monitored constantly and the systems are fitted with alarms to warn of impending problems, and trip systems to shut down the machine at pre-set, undesired conditions.

The supply system consists of a closed circulation system. Which includes a reservoir, pump, filters, coolers and controlling units throughout the system. The shaft of the machine operates some supply systems with an auxiliary pump on standby. Others are independently operated aside from the machine they are feeding oil to.

Lube oil is also necessary when machines have long rotor shafts that are shut down. The rotor and shaft will be warm for a while and, as they cool down, they must be rotated slowly by a 'Turning Gear' to prevent 'bowing' or bending of the shaft. The turning gear and machine bearings will still need lubrication.

(SKF, n.d.) (Maanen p. v.)
3.3 The problems

One of the problems with the traditional lubrication is that all the machinery requires a stand alone lubrication system, meaning a pump, piping and reservoir in most cases. The larger the machine, the larger the lubrication system taking up a large space in the engine room. This is because a lot of machines are necessary to run a lubrication system. For example: pumps, coolers, heaters, purifier, oil tank, oil separation tank and all the pipes needed to transport the oil.

Another problem is that the lube oil needs to be purified because of the small parts of dirt and metal as mentioned earlier. On board of vessels there needs to be a purifier, because no unlimited supply can be taken with when going out to sea. Then there is the problem of the lubrication oil itself. There are various sorts, with each their advantages and disadvantages. Which one to buy natural or synthetic, etc. The lubrication oil is not cheap therefore you need to buy in bulk. Because of the many sorts of lubrication oil it is difficult to make a good choice and easy to make the wrong choice, what leads to unnecessary costs. Last but not least the lubrication of engine parts reduces the friction, but a part of friction still occurs.

So to sum it all up, the traditional lubrication system takes up a lot of space, the oil is expensive, the oil needs to be cleaned and it isn’t the solution for bearings operating without friction.
4. Magnetic bearings

Magnetic bearings are used in many other industries, such as the car-industry. However, in the maritime industry their applications lack behind. To understand how and why they lack behind, the working principle of magnetic bearings are explained in this chapter. In this chapter, the technical details describing the physics behind the working of the magnetic bearing will not be discussed, it will just explain how the system works and describe the basic designs.

Magnetic bearings can be divided into three groups: passive magnetic bearings, active magnetic bearings and a combination of the two called electro dynamic bearings. In this paragraph one will describe the working of passive magnetic bearings and electrodynamic bearings and will go deeper into the working of an active magnetic bearing this is because passive magnetic bearings are not useful for the type of load where we will be using it for. As for why will be described later in the chapter.

4.1 Passive magnetic bearings

Passive magnetic bearings (PMB are used as acronym for the term passive magnetic bearing) get contact-free levitation of an object by the use of the pushing or pulling forces of a permanent magnet. The possible designs of this system are very diverse. These designs can vary from magnets on the shaft as well as the stator, just magnets on the shaft or magnets on only the stator.

Passive magnetic bearings work on a very simple principal. The magnetic forces pulling the shaft up are equal to the magnetic forces pulling the shaft down plus the gravitational forces. (Hillyard, 2006)

The main problem with PMBs is that due to their lack of damping they can become unstable during start up, because of the disturbances of the resonance frequencies. Due to these disturbances, the axial rotor position can become unstable due to Earnshaw’s Theorem. (Linz Center of Mechatronics)

Earnshaw’s theorem states that there is no stable and static configuration of levitating permanent magnets. So if one has a cube and on every corner there are magnets with the same strength, one will expect that a ferrous object resides in the center of the cube. Only this is not the case, the object will not reside in the center due to the fact that the potential of the object is the average of the potentials around the object.

For rotating objects one also must consider angular momentum. Angular momentum is a quantity for the rotational moment of an object. Due to angular momentum fast rotating axis have a form of self-stabilization. This can be compared to a toll which keeps itself upright at high speed but falls down when the speed drops to a certain point. This forces helps to counter the negative forces exerted due to Earnshaw’s theorem. This forces will only negate the effect of Earnshaw’s theorem when the speed is high enough. This speed equilibrium speed is variable per magnetic bearing and might not be achieved depending on the size of the shaft, weight, diameter and the force exerted by the magnets.

This concludes that is does not center itself in the cube and will find no static balance. And it requires an external force to keep it in its place. (mathpages, sd) As seen in figure 4.1 even if the spaces between the three magnets and the middle ferrous object are all the same, the middle object still gets pushed out the center; this is due to Earnshaw’s theorem.
Diamagnetic materials have a relative permeability lower than 1. Relative permeability defines the amount a substance prefers to go through magnetic field lines than through a vacuum. So diamagnetic materials create an induced magnetic field opposite to the externally applied magnetic field. Ant thus are repelled by the applied magnetic field. Also do diamagnetic materials not apply to the theorem of Earnshaw because diamagnetic materials only exhibit only repulsion against magnetic fields and Earnshaw's theorem requires materials which both exhibit repulsion and attraction to a magnetic field. The downside of an application like this is that it has barely any tolerances and is very sensitive for external influences. And not suitable for our application. (Mathpages)

As example, in a study done by NASA with the rig shown in figure 4.2, a passive magnetic bearing system with a rotor of 2.26 kg has been successfully designed and tested and could achieve speeds of up to 5500rpm. With the radial stiffness, the elastic deformation of the bearing expressed with the ratio between load and deflection, within 5 percent of the finite prediction. The axial stiffness, same as radial stiffness but is measured axial, is twice the radial stiffness and within 1 percent of Earnshaw's theorem, the point of center to actual axis position as explained above with figure 4.1. (Siebert, 2002)

The research of NASA proves that it is possible to have passively working magnetic bearings. The factor that makes the use of passive magnetic bearings difficult is that the magnetic forces of a passive magnet can't vary easily and one will have to make sure that no sudden forces will act upon the shaft so it will be brought out of its central position. In the case of the NASA study, only the resonance frequency was taken in to account in the experiment and it was just able to stay stable (with margins of 1 percent) with a specifically designed shaft. In the research NASA has used an air impeller to rotate the shaft and did not put any load on the axis. This combined with the small tolerances makes it unusable to apply on vessels, because of so many external interferences, such as engine vibrations or ship movements caused by waves, which make it very easy for the shaft to get out of the boundaries of the central position.

Another factor that influences the working of PMBs is the temperature; all substances react to temperature change by shrinking or expanding. This also happens in the case of PMBs, because everything has to be designed to such precision that a change in temperature may make the difference if a PMB will work or not. It is possible to design PMB’s with a limited temperature range. Using a visco-elastic supports, a special kind of rubber, will dampen the vibrations made by the rotor, only offer a limited temperature range. These supports only help suspending the axis in periods the magnetic bearing can not suspend the axis.

However, passive magnetic bearing solutions require serious designing. And thus results in high design costs. (Linz Center of Mechatronics)

The passive magnetic bearing is a solution to components that do not react to external forces. They will not provide a solution to components on board, because bearings have to react to significant external forces, for example a crankshaft.
This proves that passive magnetic bearing systems are possible but only in not changing environments and static uses, this is unachievable on board of vessels and such makes passive magnetic bearings unsuitable in the shipping sector.

4.2 Active magnetic bearings

The one property that makes the difference between active magnetic bearings (AMB’s) and passive magnetic bearings (PMB’s) is the use of a controller. AMB’s use controllers to regulate the pull factor of the electromagnets via controlling the amount of current going to the electromagnets. AMB’s use forces created by electromagnets and PMB’s use forces created by passive magnets.

The basic working of an active magnetic bearing is based on the simple concept that an electromagnet, this is a metal core with an electrical coil wound around it, exerts a certain force to a ferrous object. The electromagnet must have a current going through the device. The forces between the electromagnet and the ferrous object are always pulling, never pushing. This is due to the way magnetism affects ferrous objects. (Lucas, 2015)

The pulling force from the magnet depends on two factors: the amount of current going through the electromagnet and the distance between the magnet and the ferrous object. If the current through the electromagnet remains constant and the ferrous object and the electromagnet will be moved closer to each other, the magnetic forces between the two objects will increase. Alternatively if the ferrous object and the electromagnet are kept in the same place and the current through the electromagnet would be increased, the ferrous object and the electromagnet the pulling force increases. (Hawkins, 2013)

The workings of an electromagnet can be compared with the workings of a spring, if an object is suspended. As seen in the figure 4.3, if the object moves up, the force pulling the object up gets weaker; when moving down, the force on the object pulling it up will increase. This is the exact opposite when comparing it to the working of an electromagnet; if the spring was replaced by an electromagnet, as for the parameters mentioned above, when the object gets moved up, the forces pulling the shaft up will actually get stronger. So if one uses one electromagnet an object will only experience pulling forces and no pushing forces, this makes the object only come closer to the electromagnet.

Hereby a conclusion can be made that it is not possible to suspend a ferrous object with one single electromagnet and that it would not be possible for an AMB to be supported by one single electromagnet. Because every movement in the horizontal axis will misalign the axis and the equilibrium between the gravity and the electromagnet. This cannot be reestablished due to the fact that gravity always pulls straight down and the electromagnet won’t pull straight up when the axis is misaligned.

It is necessary to place at least two (or more) electromagnets per axis if an object has to be suspended.

Due to this aspect, most Active magnetic bearing systems mainly have four electromagnets to be able to suspend a shaft in the Z-axis and X-axis, in the longitudinal direction the axis shouldn’t move anyways, so there are only two axes in which the shafts movement is controlled, up and down and left and right (crosswise direction). An Active magnetic bearing system has four main components;
the position sensors, the controller, the amplifier and the electromagnets (which are called electromagnetic actuators). The position sensors measure the distance between the rotor and the stator and send this information to the controller unit. The controller then compares the readings of the position sensors to the programmed value it should be, as for the central or 0 position and calculates the right currents needed for the certain magnets. This information will then be sent to the power amplifier, which will deliver the right current to the specific electromagnet. The electromagnets will, due to the current, exert the force required to pull the rotor back to the central or 0 position. A schematic overview of the system can be seen in figure 4.4.

![Figure 4.4](image)

To give an example in what range active magnetic bearings work; an example of two magnetic bearings with specifications:

<table>
<thead>
<tr>
<th>Model name</th>
<th>Manufacturers/Type</th>
<th>Bearing type</th>
<th>Bore (mm)</th>
<th>Width (mm)</th>
<th>Force range (N)</th>
<th>Speed range (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB-R-130-4660</td>
<td>SKF-Global/Active radial</td>
<td>130</td>
<td>128</td>
<td>50-25,000</td>
<td>1,800-100,000</td>
<td></td>
</tr>
<tr>
<td>NR series</td>
<td>Novaglide/Active radial</td>
<td>4.57-228.6</td>
<td>4,57-224.5</td>
<td>222,4-26,925</td>
<td>13,000-66,000</td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.1 specifications active magnetic bearings (Novaglide, sd) (SKF, sd)*

A very important thing to notice is that Magnetic bearings which can operate at low speeds cannot carry big loads. So to carry a bigger load a higher operational speed is required.
4.3 Electrodynamic bearings

Electrodynamic bearings are mainly still in the research stage but they promise a lot of potential in the coming years and that’s why they will be briefly mentioned in this report.

Electrodynamic bearings are a combination between passive magnetic bearings and active magnetic bearings; They contain passive magnets to induce a magnetic field but the current which gets created is not supplied by a secondary power source but by induction of a conducting rotor. When the shaft is in its central position no induction currents will be created, everything will be in balance. However when the shaft is being moved out of the center, which can be seen in the figure 4.5, induction currents start flowing in the rotor, so called eddy currents, because it is in a magnetic field Lorentz forces will be applied on the rotor, the purple arrows, which move the shaft back into the center position. (Magnetal, 2015)

This effect of which Electrodynamic bearings make use is called “magnetic mirroring”. The big benefit of electrodynamic bearings compared to active magnetic bearings is that they work without a very expensive controlling unit. The downside is that they require a lot of calculations to make them work because the tolerances are so little and everything needs to be in the perfect proportions. And that they work at very high speeds (up to 50,000 rpm) this is necessary because they require enough induced currents to create a big enough Lorentz force to pull the shaft back to its original position. The bigger the speed, the bigger the change in the magnetic field will be and the bigger the induced current will be and so the Lorentz force.

![Figure 4.5 Electrodynamic bearing](image-url)
5. Magnetic bearings on board of a vessel

The question in this chapter will be if it is possible to apply magnetic bearings on board of a vessel. Therefore, it is necessary to look at the characteristics of the system of the magnetic bearings. When this is clear, this information can be compared to the characteristics of several machineries of the engine room. When they show similarities, further research can be done to see if magnetic bearings can be applied.

Through the previous chapters an image of the current systems in the engine room and an image of the magnetic bearings is created. It has become clear that the new systems have several important advantages. Up till now magnetic bearings are quite unknown in marine equipment. Therefore, it’s hard to find out where magnetic bearings could be applied in engine rooms instead of traditional bearings and if they can deal with the ruling conditions on board vessels. What has become clear in the previous chapter is that a good working of the magnetic bearings depends on the rpm and the external forces that work on it. To make it clear which machinery is suitable for the application of magnetic bearings, one has made an overview of the rotations per minute of certain systems in the engine room in table 5.1. In combination with the working forces on the specific machinery it could be possible to find out which ones could be suitable to be applied with magnetic bearings.

<table>
<thead>
<tr>
<th>Machinery</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine</td>
<td>100-2000</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>1500-3000</td>
</tr>
<tr>
<td>Turbocharger</td>
<td>10000-15000</td>
</tr>
</tbody>
</table>

*Table 5.1*

The conditions for the machinery on a vessel are not ideal, because a vessel has to deal with a lot of different motions and external forces. When the above rpms are compared to the ones of the magnetic bearings which are set up in chapter 4 table 4.1. It seems like all of the systems could be applied with magnetic bearings. But, as noticed before, it does not just depend on the rpm. When the rpm of a system that work with magnetic bearings is low, it is more sensitive for external forces. The main engine and the diesel generator are therefore not yet suitable for the magnetic bearings due to the forces that act on it. Therefore, further on in the report the focus will be on the turbocharger. First there will be given some information about a system that works with magnetic bearings. Steam turbines already exist working with magnetic bearings. One of the most well-known examples is the Siemens STT-600 steam turbine.

It is, according to Siemens, the world’s first oil-free steam turbine (Siemens, n.d.). With an active magnetic bearing as the link between the bearing and the rotor, the last is literally floating. It is possible to equip every Siemens turbine with a rotor up to 10 tons and an output up to 40 MW with this system. The Siemens STT-600, part of one of the largest power plants in Germany, is more efficient as the current system because it has almost no losses due to
friction. This means also less maintenance because of the little wear. In table 5.2 some information about this turbine is showed to get a better view of the characteristics.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size(LxBxH)</td>
<td>19x6x5 (m)</td>
</tr>
<tr>
<td>Output</td>
<td>100-150 MW</td>
</tr>
<tr>
<td>Speed</td>
<td>3000 - 18000 rpm</td>
</tr>
</tbody>
</table>

Table 5.2

As noticed earlier, the system that will probably be the most suitable to be applied with magnetic bearings is the turbo charger, or also called turbo compressor. The turbo is a system that does have a rotor with a high rpm, therefore this system will be explained better to look if it is appropriate for the use of magnetic bearings.

A turbo compressor is a machine with very high rpms. It has two wheels that can spin at speeds as high as 25000 rpm. The exhaust gasses from the engine drive the turbo. These gasses make the turbine (one of the wheels) spin. Because the two wheels are connected to each other the compressor wheel spins along with it. The compressor wheel sucks in air which it then compresses.

This means that the density of the air increases. When the air density is higher there is more air in the same volume. The air is then lead into the cylinders of the engine. Because of the higher density of the air the air fuel ratio is better. This means a higher efficiency of the engine. When air is compressed the temperature increases what has a negative effect on the density of the air. This is why there is a cooler in most turbo systems to cool the air before it is lead into the cylinders. A shaft connects the wheels. The shaft turns along with the wheels this means the shaft needs a bearing to turn easily. The goal of a turbo is to improve the air fuel ratio, which improves the efficiency of a motor and will give the motor a little more power. These shaft bearings will always have some friction.

Because a turbo has a very high rpm range, it is possible that the bearings can be replaced with magnetic bearings. A high speed is required if you want to use magnetic bearings, the high speed makes it possible for the shaft to correct itself. This is important on board of vessels, because of the rolling, pitches, vibrations etc. that could cause the shaft to move out of its original position. In this case the rpm of the turbo charger is high enough to take care of the acting forces that act on it. When traditional bearings are replaced with magnetic bearings, the efficiency of the turbo will increase and allow the wheels to spin with negligible friction and so at even higher rpms. Therefore, magnetic bearings will improve the working of the turbocharger (Maanen p. v.).
6. Retrofitting magnetic bearings

In this part of the research the sub question ‘are magnetic bearings retrofittable?’ will be answered. The goal of this chapter is to discover if it is possible to place a magnetic bearing in an existing system and if it is profitable or magnetic bearings are only profitable in new systems and installations.

6.1 Chiller installation

According to a test installation from the Navy technology validation program magnetic bearings have been tested in compressors of a chilling installation. The magnetic bearings where installed in a new compressor and the whole compressor of the chilling installation was replaced. When only the original bearing in the compressor will be retrofitted, it is necessary to adapt the compressor. The compressor must be fitted with electrical wiring, to provide the needed electrical power for the magnetic bearings. The compressor also needs wiring for the controller unit, to fit the wiring in to the compressor it is necessary to adapt the construction of the compressor as well to organize the wiring. All together these adaptions and the cost of installing the controller unit, make that it is not cost effective to retrofit magnetic bearings. The magnetic bearings used in new compressors are specifically designed for this particular compressor and the compressors are already adapted for the magnetic bearings, because the designed magnetic bearing is used in all compressors and the adaptions are already made the costs will be shared over all the units and the cost concerning the adaptions will be shared over the redemption time. This makes the magnetic bearings more cost effective. When the magnetic bearing is retrofitted the redemption time of the compressor will be much shorter and the cost are relatively higher. (Office of Energy Efficiency and Renewable Energy, n.d.)

In January 1994 a patent for a gas compressor with magnetic bearings was requested. In this case the magnetic bearing was again custom made for this particular compressor. In August 1997 a patent for a chilling installation with magnetic bearings in the compressor was requested. In both cases the compressor was new build and the magnetic bearings where not fitted in an existing compressor. (Google, 1994) (Google, 1997)

6.2 Gas turbine

In 2012 a study about flywheel energy storage modules with magnetic bearings in it on board vessels was published. Although in this study the effects of ship motions on magnetic bearings is not mentioned. The study shows that the magnetic bearings where custom made for this particular case. The whole energy storage module had to be replaced. (Herbst, 2012; Herbst, 2012)

6.3 Pros and cons

In this paragraph the advantages and disadvantages of retrofitting magnetic bearings will be displayed in table 6.1. The advantages and disadvantages are based on the system explained in paragraph 6.1.

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>No lubrication oil needed</td>
<td>Adaption of the inner and outer construction of the machinery.</td>
</tr>
<tr>
<td>Less heat losses</td>
<td>Installing the wiring for power and control</td>
</tr>
<tr>
<td>Less maintenance</td>
<td>Installing controller unit</td>
</tr>
<tr>
<td></td>
<td>The costs of the new installation added to the costs of the conventional lubrication system.</td>
</tr>
</tbody>
</table>

Table 6.1 Advantages and disadvantages of retrofitting magnetic bearings
During the research it became clear that retrofitting will not be easy. The magnetic bearings have to be custom made for every piece of machinery that is suitable with magnetic bearings. Nevertheless, it is possible to retrofit magnetic bearings. The only question left is if it is cost-effective to retrofit magnetic bearings. Despite this research does not include a cost calculation, one can conclude that concerning table 6.1 it is not worth the investment to retrofit magnetic bearings. The redemption time of the magnetic bearings will be much longer than the redemption time of the compressor where it is fitted in.
7. Effects on maintenance when switching to magnetic bearings

This chapter makes a comparison between the maintenance of a traditional lubrication system and that of a magnetic bearing.

7.1 Maintenance traditional lubrication system

The maintenance of traditional bearings consists mainly of using the right lubrication oil and enable an uninterrupted supply of clean filtered lubrication oil to the moving parts of an engine or other rotating machinery to reduce friction and wear.

The lubrication oil of general lubrication systems (pressure lubrication) onboard vessels is stored at the bottom of the crankcase, also known as the sump. The oil is drawn into the system via a pump, into a pair of fine filters. These filters remove solid impurities from the lubrication oil system and it is therefore essential that these filters be cleaned according to the manufacturer’s instructions. Cleaning of these filters is done by hand, using a compressed air cleaning gun to blow the filter candles.

Furthermore, the lubrication oil runs through a purifier, which removes impurities from the lubrication oil. The purifier has to be dismantled with care when cleaning, to prevent damage and/or lose the balance of the bowl. It should be examined for corrosion or pitting on any part of the bowl. Any damage, for example corrosion, must be immediately reported (Machinery spaces, n.d.).

The condition of the lubrication oil can be measured by several parameters. One of the most important parameters is the purity, shown in NAS or ISO-code. The NAS-code gives the number of particles in a certain size class [5-15µm], the ISO-code indicates the number of particles larger than a certain value [greater than 5 µm for example]. Counting of these particles occurs with a certain sensor or a laser. Also, the presence of water in the lubrication oil is an important parameter. Water in lubrication oil is undesirable, because it benefits oxidation and increases the electrical conductivity of the oil. Shortly said, the oil ages much faster when water is present and corrosion products can lead to failures. By applying a water sensor, the relative humidity can be determined, combined with temperature and a saturation value, gives the amount of water in parts per million. Furthermore, the relative change of viscosity and conductivity in time needs to be monitored. When a rise or fall in value occurs, something has changed and the cause needs to be determined (Parker Netherlands, 2014).

The results from the field research are that lubrication tasks of bearings of pumps etc. usually are performed after every two thousand operating hours. Measuring the axial clearance of a head thrust bearing only occurs after twelve thousand operating hours. Every system has its own maintenance manual in which all operations are described: from warning the chief engineer, chief of watch and others that maintenance activities are beginning, a list of necessary materials to execute the maintenance to the time intervals in which maintenance has to be done.

7.2 Maintenance of magnetic bearings

As described in the previous chapters, magnetic bearings are non-contact bearings [without mechanical contact] and lubrication systems are no longer necessary. Moreover, oil filters, piping and storage tanks also become otiose and the probability of failure in this type of systems is minimized, because the number of hardware components needed is drastically reduced. Because there is no contact between the rotating and stationary parts, there is no wear and no friction. Failure modes are mostly limited to control electronics, power electronics and electrical windings.
Magnetic bearings use an advanced control system with positioning sensors that measure the position of the rotor up to 15,000 times per second. The lifetimes of these components is greater than those of the conventional bearings (Rama, Magnetic bearing applications & economics, 2012).

The possibility exists to read the important parameters from these magnetic bearings with an Ethernet connection that forwards them to a maintenance management system. These parameters could be the vibration, bearing load, rotor stability, etc. Remote monitoring of the magnetic bearings is offered by several producers. For example, SKF uses a data logger in combination with condition monitoring systems that analyze data through software programs, from which they can write a report offsite [meaning not on board] on the performance of the bearing and communicate this with onboard personnel. They also provide training courses for personnel, service contracts and have a team of field service experts that can provide preventive maintenance and assistance at the customers site (SKF, 2016).

When applying magnetic bearings and after a period of time when all process controls have been fine-tuned, a PPM-program is needed. PPM stands for predictive and preventive management and can extend the smooth running of a system. Such PPM-systems exist for almost all types of machinery in the engine room. The two most important predictive monitoring actions for magnetic bearings are described in this paragraph. A first predictive measurement is the installation of a high temperature alarm and shutdown, as an elevated temperature is harmful for the control system of magnetic bearings. When the heating/cooling unit of the room where the magnetic bearings are placed in fails, especially when navigating in hot and humid areas, the electric components can get overheated. To cool the magnetic bearings and prevent failure in rooms with high temperature (engine room), air flows through controllers. The filters on this cooling system can need occasional cleaning or replacement, depending on the environment they operate in.

The second area that needs monitoring are the clearance checks of the auxiliary bearing system. All industrial magnetic bearings consist of some kind of ‘back up bearing’, a system that provides support for the shaft when the magnetic bearings itself fails or has been overloaded. It is important to check the clearance between the shaft and the auxiliary bearing after they have been in contact. A counter can be placed on the control system of the auxiliary bearing and record all the events where contact took place. Together with visual inspections during overhaul, one can decide when enough damage as occurred and the auxiliary bearing needs to be replaced (Jumonville J.).

Additionally, magnetic bearings have a built-in protection for overload. It gives a signal to the control unit in case of a too excessive load, so that personnel can take action before the system fails. All of the control units do not have an infinite life. The time until a controller fails is about eight to ten years, dependent on the load of the power electronics (T.W., 2006).

### 7.3 Comparison between both systems

The maintenance of a traditional lubrication system consists mostly of replacing the lubrication oil and maintenance on the hardware, such as a purifier and oil filters. Maintenance on these systems consists for the greatest part of physical actions by personnel, for example using a grease gun to lubricate a bearing or measuring the space of a bearing. But one has to take in to account, that a lubrication system is still needed to lubricate the diesel engine, so only the size of the lubrication system is somewhat reduced by taking away bearing lubrication. Every engine still needs lubrication.
Magnetic bearings would only be applicable in steam turbines or turbo compressors, so all the other bearings, for example thrust bearings, bearings in pumps etc. still need lubrication. For both systems, the manufacturer’s recommendations on replacing an item are leading, only the degree to which a system is exposed [for example excessive load] can provide shorter replacement changes. The initial costs of a magnetic bearing system with all its control systems are higher then compared to conventional bearings. Especially the control unit is expensive: it consists of a complex digital controller, sensors that monitor the position of the shaft, cables that carry shaft-position data and cables that move power from the amplifier to the electromagnetic coils. The electromagnetic coils are mostly inexpensive, because they are almost equal to the design of the stator of a motor.

Magnetic bearings’ life cycle costs are very often less when considering all factors of maintenance, see table below. Like an electric motor, magnetic bearings last twenty to thirty years, depending on the environment they operate in. (Synchrony, 2016) (Reitsma T. W., 2006)

<table>
<thead>
<tr>
<th></th>
<th>Traditional Lubrication system</th>
<th>Magnetic bearings</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware</strong></td>
<td>Piping, pumps, fine filters, purifier</td>
<td>Power amplifier, Control unit, electromagnets and position sensors</td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>Replacing lubrication oil after 2000-3000 operating hours, overhaul purifier and pumps equal operating hours, cleaning filters</td>
<td>Clearance checks auxiliary bearing, maintenance electrical components almost negligible, cleaning air filters, certain control diagnostics checks</td>
</tr>
<tr>
<td><strong>Lifetime</strong></td>
<td>Ship’s life when maintenance is performed correctly</td>
<td>Twenty-thirty years, Eight to ten years of electrical components</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td><strong>Initial:</strong> Bearings of expensive material and sophisticated lubrication system with pumps, filters, piping</td>
<td><strong>Initial:</strong> Expensive control system</td>
</tr>
<tr>
<td></td>
<td><strong>Operating:</strong> Around 350,000 a year only for cylindrical lubrication</td>
<td>Other hardware fairly inexpensive</td>
</tr>
<tr>
<td><strong>Overload</strong></td>
<td>Can handle temporary overload, mechanically forces through</td>
<td><strong>Operating:</strong> New air filters and perhaps a new electrical component when overheating/overload</td>
</tr>
</tbody>
</table>

Table 7.1 Comparison Traditional lubrication system and magnetic bearings
8. Conclusion

The main question of the report was “Can magnetic bearings reduce friction on board of vessels?”. This question is answered by the use of multiple sub questions.

- What is tribology and in specific friction and what traditional lubrication systems are used on board vessels nowadays?
- Magnetic bearings; what are they and how do they work?
- Where on board can magnetic bearings be applied?
- Are magnetic bearings retrofittable?
- What are the effects on maintenance when switching to magnetic bearings?

These questions have been answered in the paragraphs above.

Traditional lubrication systems bring a lot of costs and expensive extra machinery (as explained in chapter 3), such as filters to filter out the big contaminants. One also needs pumps to pump around the most important and most expensive part of the traditional lubrication system, the lubrication oil which brings a lot of costs when it has to be replaced or regulated on quality. Mostly the standard systems reduce friction but do not get rid of it and are not a frictionless solution to the problems with friction on board.

In this report research has been done to find out if magnetic bearings are the solution to a frictionless replacement for the traditional lubrication oil systems, the traditional systems are described in chapter three. To comprehend if magnetic bearings can replace the current system the report has researched the workings of magnetic bearings (in chapter four), dividing them into three categories; passive magnetic bearings, active magnetic bearings and electrodynamic bearings. The report has shown that passive magnetic bearings are able to handle lots of forces and have low operational costs. They lack adaptiveness and are thus not suitable for applications on board due to the high influence of external forces.

Active magnetic bearings appear to be the most suitable for application on board due to their ability to handle external forces and high adaptiveness to different constructions by the placing of more or less electromagnets. The downsides of active magnetic bearings are firstly the high operational costs due to the high use of electricity, which can not be used for other purposes on board. Secondly, active magnetic bearings have high design costs and most importantly it requires high speeds to achieve a stable levitation.

Lastly the report has shown that electrodynamic bearings show great potential but lack far behind in research and are thus not useful for application on board of vessels yet.

The most important requirement is a high speed to get a stable equilibrium between the shaft and the bearing. In the report two components, which spin at that high speed, have been chosen to perform research on; the turbo shaft and steam turbines (in chapter five). It has been proven by Siemens that it is possible to apply magnetic bearings in steam generators and thus it should be possible to apply the same system on board.

Speeds of turbo compressors can go up to 25,000 rpm, which is more than fast enough for magnetic bearings to function. The reduced friction and the negligible maintenance make it more cost effective to use magnetic bearings here and makes it possible to get more efficiency out of the compressor. The magnetic bearing technology shows great promise in the near future to make a difference in these parts.
One very important question concerning the application of magnetic bearings is the ability to be retrofittable; the application of magnetic bearings in existing systems. In the report the retrofit-ability has been researched (in chapter 6). It concluded that the design costs of magnetic bearings are extremely high because every piece of machinery need its own hand designed magnetic bearing system. Because the uptime of a magnetic bearing, which is retrofitted, is lower than a new build system it would be harder to get the costs out of the application. The report has also assumed that by designing magnetic bearings in to systems like compressor systems, as done by the American Navy, and sold as complete system, it can become more cost effective due to the fact that the design costs are spread over the product which will be produced in a higher quantity and has more uptime than an existing system.

The effects on maintenance on board of vessels when they use magnetic bearing systems instead of the traditional system has also been researched (in chapter seven). The report concluded that on board the maintenance will switch from hardware maintenance such as cleaning filters or purifiers and replacing lubrication oils to letting a control system give alarms when the bearings are overheating, overloaded or damaged and in need of repair. In both cases the manufacture’s recommendations in replacing parts are leading. When looking over the lifespan of magnetic bearings the costs are less when considering maintenance.

In conclusion, the application of magnetic bearings on board of vessels will reduce friction when compared to the current system only they cannot, in the current state, be applied on every place in the engine room. Application is possible in places where high speeds are achieved such as in steam turbines and turbo compressors. Retrofitting such a system is possible, only it will not guarantee cost-effectiveness and one suggests that buying a newly built system including magnetic bearings is. The application of magnetic bearings will be especially interesting due to the fact that the maintenance costs are lower than the costs in the current system. But all in all it will still need a lot of research before one will see it actively used on board.
9. Recommendation

Before magnetic bearings can be applied on big scale in the maritime sector more research is required. Before magnetic bearings can be applied in low speed components of maritime machinery a lot of research still has to be done, and will probably not be achieved in the near future. In high-speed components of maritime machinery, the application of magnetic bearings on big scale might be achieved in the near future.

The use of magnetic bearings in lower speed components such as crankshafts is not possible yet due to multiple causes; one of the causes is that a high speed is necessary to create enough induced current and Lorentz force to keep the shaft in place. Another cause is that the weight of the crankshaft is so heavy that the system would be expensive to design. Another cause is that there is no damping for the crankshaft if it would fall out of position. This could be damaging to the crankshaft. Therefore, we recommend that more research needs to be done before magnetic bearings can be applied into machinery that operate with low speed. We recommend that there should be done more research into countering the axial momentum at low speeds, to keep the shaft in place. Also, further research has to be done into creating enough induced current to keep the shaft in place with low speeds, in case of applying electrodynamic bearings. We also recommend that there should be done more research into making a design that could be applied on multiple systems instead of designing magnetic bearings to fit one specific component. For example, designing a standardised magnetic bearing system for the propeller shaft, so that it can be modified for different kind of shafts.

The use of magnetic bearings in high-speed components such as turbo compressors and turbines is possible, but few have been built.
To make it able for magnetic bearings to become more mainstream, focus does not have to be on increasing the efficiency of this bearing system, but one has to reduce the production costs. A big factor that makes the production costs high is the fact that every magnetic bearing system has to be specifically designed and modelled for the application and situation it is used for. This drastically increases the designing costs and the manufacturing costs. Therefore, we recommend that if one wants to apply magnetic bearings on high rotating-speed components, more research has to be done in making the production costs lower by researching the possibility to make adaptive magnetic bearing systems which can be produced on a larger scale and be applied in multiple situations and environments. We also recommend that there should be done more research into keeping a shaft in place when there are external forces working on the shaft. By external forces we mean all forces that occur during a vessels voyage like rolling, pitching and yawing.

In conclusion, it is recommended that research has to be done in low speed magnetic bearings to be able to apply it in more places on board of vessels and we recommend that research in the production of magnetic bearings should be done to reduce the costs and scale-up production to a larger scale.
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