Designing a position sensor system for Active Magnetic Bearings

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Abstract

In this thesis report, two sensor systems for measuring the position of a levitated spindle are proposed. An off-the-shelf optical sensor is used and the results of the implementation are discussed. Furthermore a capacitive sensor system is designed, consisting of a capacitive ring, sensor plates and signal conditioning. Testing shows both of these sensor systems can be used with an accuracy of less then 100µm, which can be pushed below 10µm given more development time. The results of these two sensor systems can be used in a later stage to design a full active magnetic bearing setup.

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1 Preface

This report describes the design of a data acquisition system to be used for levitating a spindle in a magnetic field. The system consisting of sensors and coupling to the controller has been built using both newly designed components and preassembled parts.

This work has been carried out by David Beijer and Robert Seepers. David Beijer studies Electrical Engineering at EWI, TU Delft. He has done much outer curriculum work, including a full year being in the board of the student association. Currently his interests lie at control systems, and aerospace and space electronics in particular. Robert Seepers also studies Electrical Engineering at the previously mentioned facility. His interests lie in the more computer based section subjects, in particular embedded systems.

While carrying out this assignment we received a lot of help from several people. For this, we would like to thank:

- Navin Balini (initiator of the project),
- Jeroen Bastemeijer (guide),
- Gerard Meijer (professor, expert on capacitive sensors),
- Martin Schumacher and Leo van Velzen (providing a working space and equipment),
- Liselotte van Dam-Schuringa (coordinator of the Bachelor Final Project)
- Loek van Schie (provided a facility for manufacturing PCB’s)
- Ate Kleijn (Transferred the schematics to a PCB design)
Summary

This Bachelor of Science (BSc) thesis is a report on a project undertaken by David Beijer and Robert Seepers. The assignment of this project was to develop a position sensor system for an AMB test setup. The sensor system has to measure the position of the spindle. This way a control system can control the electromagnets to hold the spindle in the right position. For the position sensing two possible solutions were chosen and implemented, the first being a setup using optics to determine the position, the second a system using capacitive coupling for measuring the position.

The optical sensors use a laser combined with a CCD chip to determine the distance to the object (in this case the spindle). An optimal sensor for this application was found in a sensor from Keyence\(^1\), which was unfortunately too expensive for this project. Fortunately another solution was found at the TU Delft: two less optimal optical sensors could be borrowed. These sensors have a less than optimal resolution, however measurements could be made and these sensors could be used in the test setup for just levitation.

The capacitive setup proved to be much cheaper than all possible optical sensors. However, no off-the-shelf solutions are available, and thus this solution had to be built from scratch. The concept proposed in this project basically works as follows: the spindle of the AMB system is charged capacitively with a high frequency (100 KHz in this case) sinusoid signal by means of a conducting ring around the spindle. The proximity of that spindle to two sensor plates is then determined by measuring the current flowing from that plate as a result of capacitive coupling between the spindle and said plate. Because these currents are very small, a lot of amplification was needed, and to eliminate noise sources, such as other electric devices in the vicinity or the powergrid, filtering was necessary. Unfortunately the sampling rate of the A/D converter that was to be used in the final AMB setup was too slow to detect the 100 KHz signal, so some more signal processing was needed in order to make the signal suitable for the controller. For this reason, a peak-to-peak detector was added to the design. After designing all these modules, they were all tested separately. When these modules worked, they were all integrated in a final setup. After adding another amplification stage, the signal was clearly measurable, with an amplitude varying from 0 V to 10 V, corresponding to a distance of respectively 3 mm and 0 mm.

The question posed in this thesis “What is a good yet affordable way of determining position of a spindle in active magnetic bearings?” has two answers. The optical sensors can be used when a short design time but a high budget is available, as off-the-shelf sensors with specifications similar or much better than those required are readily available. While tests conducted on the capacitive sensors indicated they could be used in a magnetic bearing setup, not enough time was available to estimate the performance of these sensors. The cost of this sensor implementation however is very low, and with more development time it is expected that the capacitive sensors can be an good solution. While not verified, it is expected that both these sensor setups are viable in high-speed applications.

\(^1\)www.keyence.co.uk
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2 Introduction

For many years, ball bearings and similar techniques have been used to allow rotation without putting much stress on the platform. They can be found anywhere: from inline-skates to cars, and from any industrial machine to anti-earthquake technology. While these conventional bearings allow us to use many applications, at higher rotations per minute (rpm) their friction becomes too large to be applied efficiently. Because the stator and rotor in these conventional bearings make contact, their heat generation increases with their speed.

To solve this problem, a new type of bearing has been designed. In order to get close to zero friction, the rotor is levitated in a magnetic field. Bearings of this type of technology are known as Active Magnetic Bearings (AMBs).

The goal of our complete research is to levitate a spindle and test some basic algorithms on, while having a gap between the stator and rotor of only a millimetre. This setup can then be used in a later stage to evolve into a true AMB setup.

In order to succeed, a few problems have to be solved: sensors and actuators have to be designed, providing feedback and steering to and from a controller in order to keep the spindle in place.

In this thesis report, the question "What is a good yet affordable way of determining position of a spindle in active magnetic bearings?" will be answered.

In order to find the answer, the first point of attention has been to gather as much information as possible on potential solutions. These solutions include sensors of the capacitive, optical and magnetic domain. Because of simplicity and the ability of using pre-fabricated parts, a setup using optical sensors will also be created.

With this basic information/theory an optimal solution will be presented, after which the system is created. This system will then be evaluated and optimized, in order to answer the question of the thesis.

In the following chapters several aspects of the design will be discussed. Chapter 3 will explain the need for active magnetic bearings, while chapter 4 will give an overview of the related research in this project. In chapter 5 the demands of the complete setup are presented. Chapter 6 will discuss a design using optical sensors, and some preliminary testing. In chapter 7 the design and an in-depth analysis of the system will be presented, which will be implemented and tested in chapter 8. Finally some concluding remarks and recommendations are given in chapter 9.
3 The need for Active Magnetic Bearings

As mentioned in the introduction, conventional bearings have a downside of friction. To allow the bearings to run at increased speeds lubrication can be used, to reduce the friction and therefore heat in the bearings. In sections 3.1 and 3.2 these two problems will be reviewed briefly, after which a comparison is made between conventional bearings and active magnetic bearings.

3.1 Friction

One of the major problems with conventional bearings is friction, as there is constant contact with the rotating object. This friction is generally dissipated as heat and will generally lower the efficiency of the system. While the problem is not dominant on low frequency application, it becomes a huge problem at higher rotational speeds.

3.2 Lubrication

An indirect problem conventional bearings face is their need for lubrication. As the bearings are generally made of metals, they will be damaged by continuous contact. Lubrication is used to provide the metals some reduced friction, reducing damage taken by the unit while providing a less hot surface. However, lubrication also has its disadvantages: In several high-tech applications (such as clean-rooms and mass-spectrometers) an extreme clean environment is required, while lubrication has a high chance of contaminating its working area.

3.3 Comparing Active Magnetic Bearings with conventional techniques

While AMBs provide zero friction, it is important to relate this to conventional bearings. In this section several implementations will be shown, along with their respective strengths and weaknesses. These strengths and weaknesses will be related to AMBs and provide insight in what area (speed, load etc) AMBs can be used.

<table>
<thead>
<tr>
<th>Type</th>
<th>Lubrication</th>
<th>Cooling</th>
<th>Speed</th>
<th>Gap variation due to changing load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Bearing</td>
<td>Yes</td>
<td>Yes</td>
<td>low / moderate</td>
<td>low, but with slack</td>
</tr>
<tr>
<td>Ball Bearing</td>
<td>Yes</td>
<td>Yes</td>
<td>moderate / high</td>
<td>low, but with slack</td>
</tr>
<tr>
<td>Jewel Bearing</td>
<td>Yes</td>
<td>No</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Flexure Bearing</td>
<td>No</td>
<td>No</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Magnetic Bearing</td>
<td>No</td>
<td>No</td>
<td>infinite</td>
<td>low</td>
</tr>
</tbody>
</table>

In table 1 the main characteristics of several bearings are shown, while table 2 provides their lifetime and special notes.\(^2\) As can be seen in these tables, magnetic bearings provide the highest speed and life time of all bearings. Their downside however is a potential high power needed to overcome gravity: if a rotor of 5kg is to be held in place, the actuators will have to

\(^2\)wikipedia, april 20th 2008
Table 2: Several bearing implementations and their lifetime / special notes

<table>
<thead>
<tr>
<th>Type</th>
<th>Life time</th>
<th>Special notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Bearing</td>
<td>moderate / depends on lubrication</td>
<td>Simple, but high friction</td>
</tr>
<tr>
<td>Ball Bearing</td>
<td>moderate / depends on lubrication</td>
<td>All-round better than plain bearings</td>
</tr>
<tr>
<td>Jewel Bearing</td>
<td>moderate (requires maintenance)</td>
<td>high precision, low load (Clockworks)</td>
</tr>
<tr>
<td>Flexure Bearing</td>
<td>depends on application/stress involved</td>
<td>Simple, but limited movement</td>
</tr>
<tr>
<td>Magnetic Bearing</td>
<td>Infinite</td>
<td>Maintenance free</td>
</tr>
</tbody>
</table>

provide 50N to overcome gravity alone. This problem can be overcome by using both Active and Passive Magnetic Bearings in a single setup: Passive magnets are used to overcome gravity, while sensors and actuators provide the steering to keep the rotor in place. It’s possible to keep objects of several kilograms with just a few milliWatts. ³

In summary, we can conclude that AMBs are highly suited for high-speed applications that will have to provide service for a long time, giving low maintenance as additional benefit. They can also be used in low-speed applications, where lubrication is undesirable. Without passive magnets a lot of energy is required to keep the rotor in place, although by using a combination of both passive and active magnets heavy-load and high-speed can be combined in an efficient piece of machinery.

4 Related Research

The total assignment of designing an AMB test setup was given to a group of six people. The authors of this document researched and developed the sensors and data acquisition necessary for the system. Two others designed the control system and did the modeling of the system. The other two people designed the spindle and framework of the setup. They also designed the actuators.

This first part of this section is dedicated to the work done by the other four group members. A short description of their work will be given in order to get a clearer picture of the total assignment. After this, several sensor system used in AMBs by other engineers will be discussed, in order to estimate which sensor system is most suitable for this particular application.

4.1 Control of AMB’s

Since the bearing might rotate at extremely high speeds, and all kinds of disturbances may arise, it is necessary to actively control the position of the spindle. Passive control (just some fixed magnetic field) wouldn’t be able to compensate for these disturbances. The requirements for this control system are very demanding. This is mainly due to the high rotational speeds, and the wide variety of possible disturbances at those speeds. Some possible disturbances are:

Mass imbalance When the mass of the spindle is not equally balanced around the length axis of the spindle, vibrations arise. These vibrations are due to the centrifugal force of the mass.

Gyroscopic effects When a cylindrical rotating object is relatively short compared to its radius, gyroscopic effects occur at lower rotational speeds compared to when the object is long. These gyroscopic effect cause the spindle to rotate around another axis then is intended.

Forces due to the application A possible application of AMBs is micromilling. In this application the head of the spindle will be used to mill out pieces of the raw material. This will off course cause the spindle to deviate from it’s middle position.

Moving the setup When the setup is accelerated in a certain direction, the bearing will have to compensate for that movement.

To be able to compensate for all the aforementioned possible disturbances, a simple PID controller might not perform satisfactorily. Therefore this group is researching so called robust control.

Robust control is a group of control techniques that is more or less able to compensate for deviations in parameters of the physical system. So when for instance, the mass distribution of the spindle suddenly changes, and is no longer the value as specified in the model of that spindle (and to which the control system was tuned), a robust controller can still control the system in a tolerable way. Off course there are limits to these deviations, but these limits are much less restricting than traditional PID controllers.
4.2 Actuators and mechanical setup

A control system is fairly useless when it has no means to influence the system it is supposed to control. Therefore the control system is equipped with actuators. In this case these actuators will be electromagnets. The actuator system will consist of an electromagnet part and a power amplification section. The electromagnet will be custom designed to meet the requirements of our system. These customisations include the material of the core, the number and thickness of the windings etc. Also thermal properties and energy requirements will be taken into account. Since the electromagnets will probably draw more power than the controller can supply, some form of amplification will have to be implemented. This can be implemented by custom designing a power amplifier for this purpose, but off-the-shelf solutions for this problem are available. Another aspect of this project is the mechanical design of the system. A spindle will have to be designed which will have to possess certain key features. Also a framework will have to be designed to mount the electromagnets and sensors on. This framework will also be designed by this group.

4.3 Choice of sensors

While active magnetic bearings require sensors to allow steering, several types of position sensors are available, in multiple setups. In the following sections optical, magnetic and capacitive sensors will be presented and their up- and downsides discussed.

4.3.1 Optical sensors

The optical domain provides several ways to measure distance. In this section we will have a close look at two possible implementations: light barrier sensors, and light reflection sensors. Both these setups can be used to provide the required technical specifications: other than some alignment issues, the sensors themselves determine the capabilities. Therefore the setups themselves will only be discussed briefly, and the focus of this section will be on the sensors themselves. In particular CCD (charged couple device) and photodiode sensors will be reviewed. CMOS sensors will not be discussed: while they generally require less power, their resolution is inferior to the resolution of a CCD sensor.\(^4\)

**Light barrier sensors** The first type of setup relies on sending out a beam of light on one side of the rotor, and measure the amount of light visible at the other side of the rotor. Such a setup is illustrated in figure 1. As the rotor moves up and down, the light incident on the sensor decreases. Sensors can be implemented in two ways which will be discussed in the sections further down: one implementation relies on arrays of small light sensitive cells, the latter on a large light-sensitive screen of which the properties change depending on the amount of illumination.

One of the main problems to be solved in this setup is to shield the sensor from outside interference, as even regular sunlight will distort the signal to a great degree. This can be a very easy task, as a simple box around the entire system will reduce the outside light enough

\(^4\)howstuffworks, march 2008
to make accurate measurements. However, as the final setup will be developed further into a true AMB system to study the gyroscopic effects of a rotating spindle, it is expected the complete system will not be in a 'black box'. In this case, shielding by physical obstructions hardly generates any profit.

Another, more suitable technique is using specific colors of light: as the light source sends out a specific frequency of light, other frequencies can be filtered out at the sensor side. A final way is modulating the light (for example in frequency, or pulse-width) and demodulating the signal at the sensor. This requires more time, although it renders exterior influences close to zero, especially combined with using only certain frequencies of light.

Light reflection sensors The second type of optical sensor setups relies on reflection. There are two ways to do this. In the first method, light (usually a laser due to a small beam of monochromatic light) is sent to the object, under an angle. The light is reflected on the object, and the reflected light is measured at the sensor. Due to the angle between the light and the object, the measured light changes its 'position' when viewed from the sensor side. The basic operation is pictured in figure 2.

The second method sends out light, but not under an angle. Instead, a small spot of light is projected on the object. Part of the diffuse reflected light is then imaged by the sensor,

\footnote{Schweitzer, Bleuler, Traxler, 1994}
similar as the previous method. This image is the used to calculate the position and/or displacement of the object. This is comparable to a red laser dot in a dark room: the dot can be seen from anywhere thanks to the diffused light. This method is pictured in Figure 3.

![Figure 3: Light Reflection sensor w/o an angle](image)

The object in our research is going to be a round spindle with two degrees of freedom. A system based on a beam under an angle is very susceptible to the alignment of the object, and can therefore easily read out the wrong distance values if the spindle changes in more than one direction. Therefore, the second method is preferred.

As with the light barrier sensor, the system has to be properly shielded. This can be done in the same way as presented at the light barrier sensor, by using a certain frequency of light and possibly modulation. The sensor has to be capable of identifying the location of the beam, rather then the amount of light incident to the sensor. Therefore the sensor can not be made using a large screen which reacts to the amount of light incident, but rather a sensor consisting of numerous small light-sensors.

**Charged Coupled Devices** The first sensor that can be used to measure the incident light is a sensor based on a CCD chip (Charge Coupled Device). In a CCD, there are multiple light-sensitive cells stacked in a matrix / array. These light-sensitive cells become electrically charged when exposed to light: when more light is incident to the cells, a higher charge is induced in the cell. An electro-mechanical shutter briefly activates to expose the cells to light. The charges on these cells are then processed in an electronical circuit to digital signals. These signals are then fed to another processor/platform in order to further process them. Figure 4 shows the basic functionality of a CCD.

In the case of a light-barrier sensor, the arrays of cells can be used to determine the position of the object: very low values of the cells will indicate an object between the light-sensor and

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6Diffuse reflected light is the seemingly random scattering of light when it is incident on a non-uniform plane.

7Vahid/Givargis, 2000
the sensor, whereas high values correspond to a free path. In a similar way a CCD can be used when using reflection to measure the position.

In theory, only a single array of cells can be used to provide the x- and y-coordinates. However, due to manufacturing errors, the cells may have a slight bias to their initial value. As these cells are generally produced row-by-row, the last few cells will be covered in darkness in order to estimate this bias. More cells gives a better estimate for such a bias. The process of measuring the bias and then adjusting the sensor values with it is called zero-bias adjustment. Also, multiple arrays may be used for actual measuring in order to provide a better estimate through averaging. An example is shown in Figure 5.

By using two separate CCDs for the x- and y-position the only calculation to be done is averaging over the various arrays, after which the values can be compared in a lookup table.

Already, CCDs have been created that can throughput information at rates of over 10 kHz\(^8\) and have an accuracy of less than a few micron.\(^9\) The main problem to be solved is making some kind of refraction to have all the possible light fall onto the CCD, as the dimensions of a CCD array are generally different than the dimensions of the incident light. This is much like the way CCDs are used in cameras (in cameras a lens is used to focus the light onto the CCD).

This technique has the required accuracy, but at the cost of speed. The sensors for this setup have a requirement of at least 1 kHz which allows CCDs to be used. As the eventual test-setup is only to study the gyroscopic effects of a rotating spindle, the sensors will provide the service needed. However, it should be noted they will possibly fail at higher rpm, as the sensor may simply be too slow.

\(^8\)eyesonmedia, 26-04-2007
\(^9\)Tom Bruijns, Stueve, Dick, 31-07-2004
Photodiodes  Other then CCDs, an option would also be to use photodiodes. Easily said it can be viewed as one large light-sensitive cell, which generates a current or voltage proportional to the illumination. This property is known as the photoelectric effect. The default schematic symbol to draw a photodiode is given in Figure 6.

![Figure 6: The symbol of a photodiode.](image)

Photo resistors use the same effect, but rather then generating a current, the resistance of the photo resistor decreases with increased light intensity. However, the response time of a photo resistor is inferior to a photodiode, and their output is usually not as linear.\(^\text{10}\) For this reason photodiodes are generally preferred in measurements where time and accuracy are crucial, and photoresistors will therefore not be discussed in more detail in this thesis.

While these photoelectric components can be used in a light-barrier setup, they cannot be applied to light-reflection based setups. As shown earlier, reflection based sensor systems are based on the angular deviation of the reflection, rather then the amount of incident light. A photodiode or photo resistor will therefore continually be lit up with the same light intensity, and will therefore not provide any insight what the position of the rotor is. A potential way to use photodiodes in a reflection setup is by creating an array, similar to the arrays in CCDS. Their main strength is their high speed read out: the electronics don’t have to be built-in as in CCDs (no electric shutters are needed, as the current flowing out of the sensors does not

\(^{10}\text{wikipedia,2008}\)
change with a constant illumination, contrary to CCDs). The main downside of this is that
CCDs may have 10 times as many light-sensitive elements as a photodiode array in the same
area, which causes a high fall in accuracy.\textsuperscript{11} A CCD array is preferred when using a reflection
based system due to its increased accuracy, while a photodiode may be used perfectly in a
light-barrier based system.

4.3.2 Eddy current sensors

Eddy currents are caused when a changing magnetic field intersects a conductor. A time
varying flux causes a magnetic field in the conductor, which in turn causes a current to flow
through the conductor.\textsuperscript{12}

Usually, eddy currents are an undesired effect as they generate losses. In order to reduce
them, the magnetic core is designed to have low electrical conductivity. This can be achieved
by either laminating the core, or using ferrites.\textsuperscript{13} Another way to suppress eddy currents
is by using ferrites. Ferrites are ferromagnetic materials that don’t conduct well. They are
generally used at higher frequencies as the lamination size has to go down when frequencies
go up.

While eddy currents are generally an undesired effect, they can also be used to detect an
object. The changing magnetic field from the object (caused by the eddy currents), interacts
with the coil to change the impedance of the coil. This can be measured by measuring the
current trough the coil.

While measuring the eddy currents on a single coil is not a problem, difficulties arise when
the measurement is done on multiple magnets: All magnets induce their own eddy currents,
which may influence the measurements of the other magnets.

A possible solution is to time-multiplex the magnets: Instead of the maximum sampling
frequency for each magnet, the sampling is divided into 4 equal time slots. This allows the
sampling to still function at high speed (obviously dependant on the maximum sampling
speed).

While relatively hard to implement, eddy current sensors come with very fine accuracy at
good speeds. Commercial available products can go up to 40 kHz, with a resolution less then
a micron.\textsuperscript{14} In a setup created at the TU Delft, eddy currents sensors of 20 kHz work under
a resolution of 25 nm, in order to support a rotating spindle of up to 100,000 rpm.\textsuperscript{15}

The reason eddy currents are not feasible for this research is twofold: Price, and design time.
Commercial stand-alone products cost at least €3,000,- per sensor which is well out of the
budget. On the other hand, designing a complete eddy current sensor system including the
sensors will probably take a lot of time due to the difficulties mentioned above.

4.3.3 Capacitive sensors

The final option to measure the position of the rotor in this setup is by using capacitive
sensors. The formula for a parallel plate capacitor\textsuperscript{16} is given by:

\begin{equation}
C = \varepsilon_0 \frac{A}{d}
\end{equation}

\textsuperscript{11}Tom Bruijns, Stueve, Dick, 31-07-2004
\textsuperscript{12}M.J. Hoeijmakers, 2004
\textsuperscript{13}Ferrites are ferri-magnetic materials with low conductivity.
\textsuperscript{14}Keyence, 2008-04-29
\textsuperscript{15}M. Kimman e.a. 2007
\textsuperscript{16}This is true for a parallel plate capacitor only. However, a spherical capacitor does not apply in this
application, and a cylindrical capacitors do not apply either: As the goal is to measure just the x- and y-
With C the capacitance, $\epsilon_0$ and $\epsilon_r$ the permittivity of respectively freespace and a dielectric, A the area of the plates and d the distance between the plates. As the medium and the area of the capacitor plates do not change, the distance can be measured by measuring the capacitance. By using two capacitive plates on each side of the object, a difference in capacitance can be measured. This method is illustrated in Figure 7, and an example is given in Figure 8.

\[ C = \frac{\epsilon_0 \epsilon_r A}{d} \]  

(1)

Figure 7: Schematic overview of capacitive sensing

A possible idea to measure a the position is by trying to derive the x- and y-position by measuring the capacitance between two plates opposite to each other. However, this is impossible, as the total capacitance is given by

\[ Ct = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \]  

(2)

When writing this out using equation 1, this leads to:

\[ Ct = \frac{maximum\_deviation}{\epsilon_0 \epsilon_r A} \]  

(3)

or in other words: a constant.

In general, capacitive sensors work having two conducting plates connected, and measure the dielectrum between these two plates. Figure 9 shows three of the most common used techniques when applying capacitive sensors.

The left and bottom figures in figure 9 are not applicable, as neither plate will move. The figure on the right can be used to a certain extent, by placing radial disks on the spindle. An alternative would be to charge the object capacitively. A current will start flowing at the positions, very small capacitors will be chosen, which results in a 'flat' area when compared to the curve of the rotor.
sensing plate. This allows the measurement of the capacitances between the object and the plates, which will provide the necessary measurements to work correctly. The main advantages of capacitive sensors over for example eddy current sensors lay on their resolution: Capacitive sensors can achieve less then half the resolution of an eddy current sensor. The sensors can be relatively small. However, their frequency is limited to anything between $15 - 20\, kHz$. Also, they are more influenced by environmental circumstances (for example, the sensors have to be completely dry, and the temperatures they can operate in is possible lower than those of eddy current sensors).\textsuperscript{17} Capacitive sensors can be very cheap to make, as any plate-shaped conductor can be used effectively as a sensor. Some amplification etc. has to be done after receiving, but the solution can be cheaper then optical/eddy current sensors by far.

4.3.4 Concluding remarks on the sensor system

For this particular application, all sensor systems can be used. Having no previous built examples using a capacitive ring, it is very interesting to study the feasibility of capacitive sensors. For this reason the research is conducted into capacitive sensors. However, in order to make sure the final research group setup will function properly, a setup with pre-fabricated optical sensors will be created first. As the optical sensors are almost plug-and-play this can be done in a few days, after which the full focus goes into capacitive sensors. Eddy current sensors are more suitable for high-speed applications and shall therefore not be discussed any further.

\textsuperscript{17}lionprecision, 2008
5 Program of Demands

5.1 Introduction

The goal of this project, to develop a sensor system for a levitated spindle, is meant for technological research on active magnetic bearings. Such a research could be testing various gyroscopic effects of a spindle rotating without contact. In the next few sections the design criteria of such a system will be discussed.

5.2 Technical Demands

2.1 The accuracy of the setup needs to be better than 100µm. As the maximum deviation of the spindle is supposed to be one millimeter, the sensor system needs to provide a very good resolution, being smaller than one percent of the maximum deviation.

2.2 The complete sensor setup needs to have a width smaller than 50 mm. As the spindle is 120mm long and the magnets take up 34 millimeters each, there is about 50mm left on the complete axis. An alternative would be to suspend the sensors on the bottom plate of the setup, which nullifies this criterium.

2.3 Measuring of the position needs to be done in real-time.

2.4 The sensor setup needs to provide values for the position at frequencies of 1 KHz and above. While not strictly needed for counteracting gravity, the setup is expected to work
in a 10,000 rpm environment, in which 1 KHz can provide enough speed to control the system. 18

2.5 Data-acquisition needs to be done in a system compatible to Matlab. This is because the dSpace system used by the controlsystem team uses Matlab/Simulink for interfacing.

5.3 Demands regarding Safety and Environment

3.1 Since lasers might be involved in a optical sensor setup, it is required to be impossible for these lasers to point in the eyes of the user or nearby standing people.

3.2 A voltage will be applied on plates of a capacitive sensor setup. These voltages should be harmless for human beings, or not touchable by anyone. Their positioning should thus be out of reach.

3.3 Whenever possible, the use of materials hazardous for the environment (such as heavy metals, or CFK’s) should be avoided.

3.4 All parts of the system should be processable when the product has reached the end of its lifetime.

5.4 Demands regarding Ease of Use

4.1 The system should be installable in any AMB setup in half a day. This period may seem long, but the mechanical removal of the spindle might be a cumbersome task, since it is often embedded in a lot of rigid parts.

4.2 The system should have no more than one or two setup parameters per sensor that have to be easily adaptable by means of userfriendly software. These parameters might be biasing or tuning parameters.

4.3 The number of wires to connect to outside systems should be as low as possible. The minimum will probably be 3 wires for power plus two wires per sensor.

4.4 However, in a later stage a digital embedded processing system may be developed that lets all sensordata of one system (up to four or eight sensors) be read out by means of a standardised serial protocol (such as i²c, SPI or CAN), that way reducing the number of necessary wires.

4.5 Whenever some part of the system is malfunctioning, the user should be notified of that.

5.5 Demands regarding Manufacturing

5.1 In order to reduce setup time for a factoryline and to eliminate costs, only standardised electronic parts will be used. The PCB will be single layered and not using SMD components, to even further ease the manufacturing and thus reduce costs.

5.2 All CAD files and schematics will be in world standardised format, so that when one factory fails, a manufacturing line can be set up easily in other factories.

18Since 10,000 rpm equals 166.7 rps, the Nyquist criterium defines the double of that frequency as the minimal required sampling speed. So 1 KHz should be more than enough for these speeds
5.6 Demands regarding Marketing and Sales

6.1 The product will be available on the market within 6 months after the starting of development.

6.2 After a customer has placed an order, it should be shipped within 3 working days after payment.

6.3 Demand [6.2] should hold for orders up to 100 units simultaneously.
6 Preliminary testing

This section consists of two parts: the first part is the complete work done on the laser position sensor, the second part shows some preliminary tests of the capacitive sensors. The laser position sensor is tested due to its easy implementation, and it shall be shown only a current-to-voltage conversion is needed (by having the current flow through a resistor) to hook the linear laser position sensor onto the controller. The preliminary testing of the capacitive system is done for two reasons: to give insight in the magnitude of the currents flowing from the sensor plates, and because a lack of certain components early in the project which prevented testing on the more advanced parts of the final setup.

6.1 Testing the laser position sensor

As mentioned several times earlier in this report, laser positioning sensors will be used to create a working setup, before switching to capacitive sensors. While these sensors are too expensive for the final setup (as they cost two to five thousand euros each, while two are needed for just levitating the spindle), they are free to be borrowed from the meetshop at the TU Delft. By first making a setup using these easy to implement sensors, the rest of the total setup (such as the control system and actuators) could be tested before completion of the capacitive sensors. Also, building this easier setup might give more insight in amplification and signal conditioning, in order to provide a signal suitable for the controller when switching to capacitive sensors.

6.1.1 Theoretical principles of the optical sensor system

The borrowed sensors are the Micro-epsilon optoNDCT ILD 1401-200 and the Micro-epsilon optoNDCT ILD 1401-100. The specifications of these sensors are:

- An accuracy of 20 micron when stationary, 100 micron on a moving target @ 1 kHz sampling rate.
- Measuring range between 6-26 cm.
- Sampling frequency of 1 kHz.

In order to get some insights in how this all combines, the sensor is hooked up to a PC environment. As the NI USB-6211 was also available for borrowing and has some good specifications, this device was taken for the data acquisition. The specifications of this card are as follows:

- 250 kSamples/second
- Up to 32 analog inputs, with built-in A/D converter (16 bits).

The setup is sketched in figure 10.

19 The specifications of the ILD 1401-100 are better than the specifications named here but still very similar. More accurate sensors are available off-the-shelf as well, although they could not be borrowed from the meetshop, TU Delft.
The output current is linear over the range of 6 to 26 centimeters and varies between 4 and 20 mA. This means the current changes \( \frac{20-4}{26-6} = \frac{4}{5} \text{mA/cm} \). In the best case scenario the resolution is 20µm, which causes the minimum current difference between two values to be \( 4/5 \times 10^{-6} \times 20 = 16\mu A \).  

As the data acquisition features a 16 bit A/D converter, this minimum current difference needs to be converted to 0.3mV \( (20/2^{16-1}) \). In order to get as much amplification and accuracy to the dSpace system, the distance between the spindle and the sensors is made as small as possible. As the sensors operate completely linear between their starting and ending point, the operating distance can be chosen arbitrary within this region. The minimum needed amplification needed for the sensor is given by the minimum difference in voltage divided by the difference between two values. This leads to a minimum amplification of \( \frac{0.3 \exp^{-3}}{10 \exp^{-10}} = 20 \) times. By setting the distance between the spindle and the sensor to 7 cm, the maximum amplification possible is the maximum output divided by the maximum current, or \( \frac{10}{(4+4/5\times7)\exp^{-3}} = 1000 \) times. The amplification can therefore be anything between 20 and 1000, and can be implemented by simply having the current flow over a resistor as \( U = RI \).

As the sensor’s operating range is larger than needed, scaling is needed to create a signal between zero and one, which is the information required by the controller. While it is possible to do this in both hardware and software, software is preferred due to the simplicity. Along with the manual comes a formula (equation 4) to exactly calculate the range depending on the output current, which simplifies things even more.

\[
x[\text{mm}] = I_{\text{out}} - 4mA \frac{\text{MeasuringRange[mm]}}{16mA}
\]

6.1.2 Testing the optical sensors

As expected, the pre-fabricated sensors were very easy to use. To make sure the specifications given in the manual were correct, several easy tests were performed, including a test for range and comparing the output current to the theoretical output current. This was measured by having the current fall over a 400Ω resistor. Other then a small bias at the output of the sensor of around 1mA, the specifications were an exact match.

\( ^{20} \)In the worst case scenario where the resolution is 100µm, the minimum current difference is 80µA.
After these tests, the sensor was connected to the data-acquisition card and tested in a LabView environment. The output voltage was a good match as expected: The smallest value being around 100 mV, the highest value around 10V (this is measuring the complete range of the sensor). After applying a software scalar, the output was represented by a perfect zero to one in it’s operating range (in this particular case, the sensor was calibrated for the range of 7 cm). The testing of this setup was a succes and was ready to be implemented on the dSpace system.

Implementing the sensors into the dSpace system was as easy as thought. After mounting the sensors onto the test setup, all that was left was creating a scalar in matlab. This proved to be as easy as in LabView, and a signal between zero and one was ready to go to the controller.

6.2 Preliminary testing of the capacitive sensor system

As soon as the spindle and the capacitive ring were available for testing, tests were done to verify the principles on which the system was based. Aim of the test was to verify that the capacitive coupling between the ring and the spindle indeed occurs, and secondly that the capacitive charge on the spindle was measurable. For this test setup, the capacitive ring was connected to a signal generator. The signal generator was set to generate a sinusoid signal at 100 KHz with an amplitude of 30 \( V_{pp} \). The spindle was positioned in the ring in such a way that no contact was made with the ring. Then a probe of an oscilloscope was used to measure whether any signal could be measured on the spindle. This setup can be seen in figure 11.

![Figure 11: Preliminary testsetup for proving the concept should work.](image)

When measuring the voltage present on the spindle, the oscilloscope indicates a 2 \( V_{pp} \) signal. That proves that the capacitive charging of the spindle works. When moving the probe of the oscilloscope in the area of the spindle, the sinusoid is still visible on the scope, albeit with a much smaller amplitude. The amplitude was strongly dependant of the distance between the probe and the spindle, decreasing from a maximum of around 300 \( mV_{pp} \) to 0 V.

The frequency of 100 KHz was chosen arbitrarily at first. Later some measurements were
done to verify if that was a suitable frequency. To check this, the voltage on the spindle was measured while the frequency of the signal on the ring was varied. It appeared that the capacitive coupling started to be measurable at 100 Hz. As frequency increases, the signal grows stronger, reaching maximum strength at 8 KHz. Increasing the frequency further did not have a stronger signal on the spindle as result. However, in order to be sure not to be interfering with the EM field from the electromagnets, and to make faster peak-to-peak detection (and thus faster sampling) possible, it was decided to keep the frequency at 100 KHz. Drawback of this higher frequency is the fact that amplification has to take place in more stages, since the gain-bandwidth of operational amplifiers is an issue at these frequencies.

These measurements prove that the concept of the aimed for sensor setup work. The capacitive coupling occurs and is measurable. However, as expected, further amplification is needed. This is mainly because the control system on which the control algorithm will be implemented has an input voltage range from -10 V to +10 V. Of course it is desirable to use that range as fully as possible, since that will result in the finest resolution possible. The design, building and testing of the amplification system is discussed in the sections 7, 8 and 8.4.
7 Capacitive sensor design

In this chapter the theoretic principles behind the design of the setup are described. In
the first section, several calculations are done to get to the complete design of the sensor and
signal conditioning. This design is then finalized with a practical implementation in chapter 8.
The second section describes the design of the oscillator that is used to charge the spindle
capacitively. In the last section the final design is described, based on the theoretic principles
calculated in section 7.1.4 and potential practical issues.

7.1 Theoretical performance of the capacitive sensor setup

In this section, the theoretical principles behind the required signal conditioning are calculated
and explained. The first two subsections provide calculations in order to estimate the required
amplification, while the last two subsections provide information on the needed filtering and
extra conditioning required to get the required signal to the controller.

7.1.1 The capacitive principles

In this section, the calculations used to estimate the performance under ideal circumstances
are given. The complete setup is sketched in figure 12.

![Figure 12: Sketch of the final setup](image)

The spindle will be charged by the capacitive ring in the middle of the setup. The charge
on this spindle is then used to measure the current on the sensor plate. Assuming a perfect
spread from the middle of the spindle to the sides (where the sensors are), this can be modelled
as a capacitor, with an extra plate (medium) in the middle. A sketch is given in figure 13.

![Figure 13: Simplified representation of the capacitance.](image)
The capacitance between the ring and the spindle is cylindrical, and therefore given by:

\[ C = \frac{2\pi \varepsilon_0 L}{\ln b/a} \]  

with \( L \) the length of the ring, \( b \) the radius of the ring and \( a \) the radius of the spindle. As can be seen, the capacitance does not depend on the distance between the radii of the spindle and ring. In fact, this is something which has been shown in section 4.3.3.

Provided the surface area of the sensors is small enough, the capacitance and spindle can be approximated by a parallel plate capacitor. The capacity of a parallel plate capacitor is given by:

\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]  

In this model, the capacitances can be considered being in series. Therefore, the total capacitance is given by:

\[ C_t = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \]  

When substituting the capacitances from equation 5 and equation 6, equation 7 becomes:

\[ C_t = \frac{1}{\frac{d}{\varepsilon_0 A} + \frac{\ln b/a}{2\pi \varepsilon_0 L}} \]  

From this equation, we can see the equivalent capacitance is large when the capacitance of the plates is large, or when the distance between the spindle and sensorplate is small. The equivalent can be said for a small capacitance value when the distance is large. When calculating the capacitance with MATLAB with a stepsize of 10\( \mu \)m, the lowest capacitance found was 7.8462\( e^{-14} \)F.\(^{21}\) Full deviation (e.g. when the sensor is touching the spindle) has been excluded as the setup would already be destroyed. A plot of this capacitance is given in figure 14.

As the voltage and current are related by

\[ i_c = C \frac{dV_c}{dt} \]  

an expression for the maximum and minimum current can be found. The ring will be charged using a 100kHz sinusoidal signal. Preliminary testing has shown a voltage of 30V can be applied to two parallel plate capacitors to measure small but distinct values. Assuming a perfect sinusoid signal with these properties and putting this into equation 9, the equation for the current flowing from the sensor plate is:

\[ i_c = 30 \cdot 100 exp^{-3} \cdot 2\pi C \]  

A plot of this current is given in figure 15.

\(^{21}\) An area of 3mm\( \times \)6mm has been used for the sensor plates. As the spindle diameter is 12mm, the plate should be small enough to be considered a parallel plate capacitor.
Figure 14: Equivalent capacitance vs distance

Figure 15: Sensor current
7.1.2 Amplification of the signal

The results of this current simulation can be used to further determine the best possible performance of the sensor setup, and examine the amplification properties needed to reach such a performance.

The highest value of the current lies around $6 \times 10^{-5} A$. As the maximum voltage on the input of the dSpace system is $10 V$, this implies the maximum current to voltage amplification is $\frac{10}{6 \times 10^{-5}} = 166k$ times.

To determine the minimum amount of amplification needed, the resolution of the dSpace system and the minimum difference of current between two values need to be known. As the dSpace system has a 16 bits A/D Converter, the resolution of the dSpace system is $0.3mV \left( \frac{10}{2^{16}} \right)$. The smallest two values in the current curve are $1.4863 \times 10^{-6} A$ and $1.4790 \times 10^{-6} A$. Therefore, the minimal difference between the lowest two values is $1.4863 \times 10^{-6} - 1.4790 \times 10^{-6} = 7.3000 \times 10^{-9}$. This difference has to be amplified to provide a minimum difference of $0.3mV$.

The amplification needed for this is $\frac{0.3 \times 10^{-3}}{7.3000 \times 10^{-9}} = 41096$. Thus, an amplification of 41096 times can provide a resolution of 10 micron. When increasing the amplification to the maximum of 166000, it is expected that a resolution of 4 micron and below can be achieved.

The model used in these calculations is very simple, and will most likely be influenced by several factors such as bias, the 50 $Hz$ powergrid frequency, the curvature of the spindle, high frequent noise and imperfections in the production process. The 50 $Hz$ signal and high-frequent noise can easily be removed with a band-pass filter. While imperfections and curvature could be taken into account when setting up the model, it is expected that the capacitance between the plates will not decrease significantly due to the small size of the sensor plates.

The main concern is the low current flowing from the capacitor plate, as it could easily get lost in noise.

7.1.3 Filtering of the signal

The capacitive plates work like an antenna. From the measurements described in section 6.2 it became clear that the high frequency signal could be picked up, however, there were also strong 50Hz components present in the signal. In certain conditions it may occur that the picked up 50Hz signal is stronger than the 100KHz signal. Therefore it was deemed advisable to apply some filtering to the signal, in order to prevent the 50Hz component from appearing in the final signal or it even saturating the further amplification stages.

To filter out these low frequency signals, a high-pass filter is required. Since the main target of this filter is to filter out the 50Hz signal, and since 50Hz and 100KHz are quite far from each other in the spectrum, it was estimated that a first order filter would result in strong enough filtering. However, since the signal coming from the sensor plate is still relatively weak (order of magnitude around 2 to 3 mV), an active filter design was chosen. This is to be sure not to deteriorate the already weak signal any further before final amplification.

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22www.dspaceinc.com, the system used for AD-conversion by the other group is a ds2003
7.1.4 Making the signal suitable for the dSpace system

Since the dSpace has a limited samplerate, it is unable to sample four channels at a rate of 200 KHz. Therefore, it is not possible to simply use the amplified sine wave as an input for the dSpace system and process those signals digitally. Further analog signal processing is thus required. Another advantage of this approach is the fact that no anti-aliasing filter is required to filter out signals above 100 KHz. The amplitude of the 100 KHz sine wave must be converted to a quasi-DC signal. By quasi-DC signal a signal is meant of which the voltage only changes when the position of the spindle changes. For this we need a peak to peak detector. That is an electronic circuit that generates a DC signal based on the amplitude of an AC signal.

7.2 Oscillator circuit

In order to measure the capacitance between the sensors and the spindle, the spindle will be charged capacitively. In order to do so, a high-frequency signal has to be applied over a ring which charges the spindle using the cylindrical capacitance between these two objects. In this section the steps into making this oscillator will be presented. First some basic theory on how oscillators work is presented, in order to be able of understanding how the following oscillators work. After this an already existing, suitable design is chosen. The next step is to build this oscillator circuit and measure its performance. As the charge on the spindle depends on the frequency used, the signal is preferably stable in frequency and amplitude. In addition, the signal has to be strong enough to charge the spindle in order to be detectable by the sensors. Depending on the performance of the circuit alone, an amplifier may be built in order to power up the signal.

7.2.1 Basic oscillator theory

Oscillation circuits are based on feedback: Consider a simple feedback system as in figure 16.

Figure 16: Canonical form of a feedback system

The (classic) transfer function of this system is given by:

\[ \frac{V_{out}}{V_{in}} = \frac{A}{1 + A\beta} \]  

with A the amplifier gain.

The reason oscillators don’t need an input source is because they use a portion of the output signal as the input. The key to oscillation is making the denominator zero (the Barkhausen criterion), in other words making \( A\beta = -1 \).

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23This section is a short summary on oscillation theory found in Guillermo Gonzalez, 2007
In complex algebra, this can be viewed as a 180 degree phase-shift (as -1 is 1 under a 180 degree angle on a unity circle).\textsuperscript{24} Strictly speaking this is an instable system, although it is still limited by the finite supply of energy. When the output voltage heads to either power rail, the gain in the amplifier changes. This causes the value $A\beta$ to change away from the singularity, and eventually causes the increase of the output voltage to halt. When this stop of increase occurs, several things can happen depending on the circuit and amplifier. When the system changes direction and heads to the opposite rail in a linear fashion when the output voltage halts, sinusoid signals can be produced. This type of oscillation is called Harmonic Oscillation. When the system saturates (cut-off) and waits a long time before heading to the other rail, very highly distorted signal waves will be generated, similar to square waves. This type of oscillation is called Relaxation Oscillation. The last thing that can happen causes no oscillation at all: the system becomes 'stable' and hangs at the current power rail.

\subsection{7.2.2 Choice of circuit}

In literature, a lot of standardised oscillators can be found. They all have their specific advantages and disadvantages. A couple of possible solutions are:

- Hartley oscillator
- Colpitts oscillator
- Clapp oscillator
- Armstrong oscillator
- Phase-shift oscillator
- (Wien Bridge) RC oscillator

The schematics of these oscillators can be found in Appendix B. All the above mentioned oscillators are capable of creating a 100 KHz sinusoid signal,\textsuperscript{25} and therefore the easiest circuits can be used. Out of these, the phase-shift and Wien Bridge oscillator seem the easiest to design as they are based on simple RC circuits. As there is much information available on the Wien Bridge oscillator, this oscillator shall be assembled and measured first. The phase-shift oscillator will be assembled in case the Wien Bridge oscillator does not perform as expected.

\subsection{7.2.3 Design of the Wien bridge oscillator}

A Wien bridge oscillator is capable of generating an oscillating signal without an input source. Oscillation is started by either by having a load on the capacitors, or by injecting a pulse into the RC network. It is even possible that the large transient at powering up may kick the oscillation into action.\textsuperscript{26} The basic schematic is given in figure 17. In this circuit, the two RC networks at the positive terminal cause the oscillation. The two resistances at the negative terminal form a feedback network, and thus allow for some basic amplification.

\textsuperscript{24}This is assuming negative feedback. For a positive feedback system, the gain is $\frac{V_{out}}{V_{in}} = \frac{A}{1-A\beta}$, and thus $A\beta$ has to be +1, or a 0 degree phase-shift
\textsuperscript{25}Gonzalez,G(2007)
\textsuperscript{26}ecircuitcenter, 2002
While a harmonic oscillator is preferred for their sinusoid behaviour, they come with their own difficulties which include stabilizing the generated signal (preventing the signal from attenuating down to zero, and clipping). In order to check for these behaviours, the first point of attention is to look at the gain of the circuit. The gain of the complete circuit has to equal one in order to allow oscillation without attenuation. The gain of the complete circuit is:

\[ T(s) = \frac{V_0}{V_t} = \frac{sRCG}{s^2R^2C^2 + 3sRC + 1} \]  

With \( G \) the gain of the gain of the circuit on the negative terminal, which depends on the two resistors connected to this terminal:

\[ G = 1 + \frac{R_2}{R_1} \]

When setting \( s = j\omega \), the total gain becomes:

\[ T(j\omega) = \frac{V_0}{V_t} = \frac{j\omega RCG}{1 - \omega^2R^2C^2 + 3j\omega RC} \]

In order to have the right phase shift, the real part of the denominator has to be 0. This happens when \( 1 - \omega^2R^2C^2 = 0 \). With \( \omega = \frac{1}{RC} \), this simplifies \( T(j\omega) \) to \( \frac{G}{3} \). This also shows that the frequency of the output signal is given by:

\[ f = \frac{1}{2\pi RC} \]

Reflecting on the needed system gain, this implies three things:

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\footnote{Darren De Ronde, May 15 2002}
1. If $G = 3$, perfect oscillation occurs.

2. If $G > 3$, oscillation will occur, but the signal will keep amplifying (unstable).

3. If $G < 3$, oscillation will occur, but the signal will attenuate down to zero.

As resistor values are never perfect it can prove hard enough to find a 'perfect' value of three. As even a minor change of this value can change the behaviour of the oscillator, something in the gain has to be capable of adapting itself in such a way that a value of 3 can be maintained. The first solution (by Hewlett Packard) was to use a incandescent bulb in order to provide a changing gain (see also Appendix B). When the amplitude of the signal becomes higher, the temperature of the bulb increases. This causes the resistance of the bulb to increase, leading to a reduced gain. When the amplitude decreases, a similar process occurs, which ends up in an increased gain. This allows the gain to sweep around the perfect gain of 3 (as long as the right resistor values are used).

An alternative, more practical solution is using diodes instead of a bulb. A circuit using diodes is given in figure 18.

![Figure 18: Wien Bridge oscillator with amplitude stabilization.](image)

When $G = 3$, the diodes are off. However, when $G \neq 3$ diodes are switched on. This caused a resistor to be switched on parallel, causing $G$ to drop. In this configuration the gain must be set a little over three in order to work properly.

In order to provide oscillation of 100 kHz with standard components, $R_1$ and $R_2$ can be 15$k\Omega$, with $C_1$ and $C_2$ being 100$pF$. In the negative feedback network, the gain has to be set a little over three, and as the gain is given as $1 + R_4/R_3$, the choice is made to have $R_4 = 2.2k\Omega$ and $R_3 = 1k\Omega$. This provides a gain that is 3.2, and with a component variation of less then 5 percent guaranteed this should be enough. The equivalent resistance of $R_5$
and R4 should be equal to 1.8kΩ, which causes the gain to be 2.8.\textsuperscript{28} This comes down to a component value of 10kΩ. The diodes can be chosen arbitrary, as long as the reverse recovery time is quick enough. The 1N4148 has been chosen for the diodes, as it is suitable for high frequencies do to a reverse recovery time of no more then 4 ns.\textsuperscript{29}

\subsection*{7.2.4 Spice simulation}

To get a first indication of the Wien Bridge circuits performance, the circuit is simulated in PSpice to get information on attenuation, signal size and frequency. The files in order to run this simulation are enclosed as Appendix A.

The first step has been to use perfect component values computed in the previous section, which causes the resistors and capacitors to have zero variation to their ideal values. In order to determine if the 'ideal' performance can be achieved, perfect components have to be used. In a later stage variations can be added and compared to the perfect values. The results of the perfect values are shown in figure 19.

![Figure 19: Oscillation with component values R=15k and C=100pF. The signal had a peak-to-peak value of 3.5V and oscillates at 106 kHz](image.png)

As can be seen in figure 19, there is no attenuation, nor is there amplification. This shows that under 'ideal' circumstances, the oscillator functions correct. The total frequency is determined by creating a Fourier transform of the signal using the probe function of SPICE. This Fourier transform pointed out the frequency of the signal was a little under the expected value of 106 kHz, but still within range of 100 kHz.

Having the oscillator work as expected under ideal circumstances, it is time to have a look at its performance when the components are under influence of variance. To do this, the maximum variation of each component will be calculated, and the value of the components will be

\textsuperscript{28}this allows a symmetric sweep around three, and allows for the best possible oscillation

\textsuperscript{29}Vishay, 08/04/05
updated to this value. This leads to a worst-case scenario (other than complete breakdown) and will show how the circuit behaves under worst-case circumstances. The first step in this testing was to modify only the RC networks. Taking a 10 percent variance (which is a lot as resistors can have variances below 1 percent) for both networks, a change in frequency of about 5 kHz was measured. When only one of the networks was changed in order to create an imbalance between the two networks (the parallel network shifted to $R = 14k\Omega$ and $C = 90pF$) a maximum shift of 7 kHz was measured.

Next up was changing the amplifying network. A critical point to be measured is when the total gain of this network goes below three. To see the difference, the resistors were first set to make a total gain of 3, where the oscillation still occurred. While the signal power of this oscillation was very low (the voltage of the signal did not pass 100mV), it showed the theory behind the oscillator in practise. As soon as the gain was set below three, the oscillation attenuated down to zero.

All in all, the PSPICE simulation has shown some crucial things:

- The pre-calculated values for generating a 100 kHz frequency were correct.
- The gain of the network connected to the negative port of the op-amp needs to be above three at all times in order to oscillate.
- Small component variations in the RC networks do not matter much for the output frequency.
- The (simulated) generated signal has a peak-peak value of about 3.5V.

### 7.3 Practical system

In this section the practical design considerations of the system are analysed and described. These considerations vary from choice of components to layout of PCBs, when necessary.

#### 7.3.1 The filter module

The final version of this filter circuit can be seen in figure 20. It is loosely based on a circuit that is described in literature as a differentiator. A differentiator is more sensitive to a high frequency signal, and with the values for R and C the filter frequency can be chosen. In this circuit another resistor (R1 in figure 20) was added to tune down the frequency independant gain. Since the gain of the final two amplification stages was already determined at the moment of designing this filter, it was easier to let this filter have a gain of 1 at 100 KHz. First this filter design was simulated using PSpice. A transient AC signal with an amplitude of 1 V was applied to the input in order to obtain the frequency response of the filter. The resultant response can be seen in figure 21.

As can be seen in the frequency plot, the gain approximates 1 around 100 KHz, and as the frequency decreases, the gain decreases by 6dBs per decade, as is to be expected from a first order filter.

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2001, DeCarlo and Lin
7.3.2 The amplification stages

In order to get the required amplification, it was decided to implement the amplification in two stages. The first stage is built onto the sensor PCB in order to reduce interference of cables etc. The second stage can be at any location: it is assumed the signal is strong enough to survive additional noise caused by extra cables.

As the first stage needs to amplify as much as possible in order to reduce overall noise in the output, an op-amp with a large gain-bandwidth product was chosen. The LF357 has a 20M gain-bandwidth product and is therefore capable of amplifying the signal 200 times (assuming a 100 kHz signal as an input). Assuming the calculations in section 7.1 are correct, this should result in a signal in the order of millivolts, which should be strong enough to continue to the next amplification stage. The first stage is a current-to-voltage amplifier, as current flows from the sensor plate directly to the amplifier. The first amplifier stage (including sensor) is given in figure 22.

Having the first stage amplify 200 times, a minimum remaining amplification needed of $\frac{41096}{200} = 205$. To get more signal to the A/D converter (in order to get a better resolution), the remaining amplification has been chosen to be 625, giving a total amplification of 125000 times. This is still below the maximum the A/D converter can handle, yet will give a good resolution. While this could be done by a single op-amp, it has been decided to use a two-stage amplification network as cheaper components can be used. The easiest way to get this amplification is by having two identical voltage-to-voltage amplifier networks which amplify the signal 25 times each. The LF356 has a gain-bandwidth product of 4M and is therefore well suited for this job. The slewrate of this opamp is $12V/\mu s$ and is therefore well suited for a 100 kHz signal, as the needed slew rate is $3V/\mu s$ max.\(^{31}\) The second amplifier stage is pictured in figure 23.

\(^{31}\)This is assuming a signal amplitude of 30 V, which is the maximum power supply the op-amp can handle. The maximum expected voltage is only 10 V peak-to-peak and as such the required slew rate is only $2V/\mu s$
7.3.3 The rectifier

A simple rectifier circuit is based on a diode, with a capacitor in parallel. When the diode is conducting, the capacitor is charged to the input voltage. When the diode is not conducting, the capacitor forms an RC network with the load (in this case, the A/D converter is the load), in which the current drops exponentially with time constant RC. This creates a signal that can be approached to be DC, depending on the ripple size introduced by the RC network. The circuit is given in figure 24. The main downside of this circuit is that the forward bias of the diode is ignored. As the diode needs a certain voltage before it starts to conduct, signals below this voltage will not propagate. However, it is expected that signals will be high enough to 'survive' the voltage drop over the diode, as with an amplification of 125000 (section 7.3.2) the voltage when the sensor and spindle are separated will be around 1 V.

Another downside is that the voltage on the output of the circuit will only ever be as large as the amplitude of the signal. While in the previous sections the peak-to-peak voltage has been mentioned frequently, the output of the rectifier circuit will only go as high as the highest
Figure 23: The second amplifier stage.

Figure 24: The simple rectifier.

positive slope.

It has been decided to first use the simple circuit and measure its performance, before thinking about more advanced AC to DC conversions.
8 Testing the capacitive sensor system

In this section, all steps made to create a working setup using capacitive sensors are presented. First the sensors themselves were tested, after which the filter, amplifiers and oscillator followed. All these components were then connected to test the final setup and finally integrate this into the dSpace system.

8.1 Testing the sensor PCBs using the real setup

When the capacitive ring and the spindle became available, measurements were started on this situation. For testing this setup first a signal generator was used to generate a 100 KHz sinusoid signal. Later in testing this signal generator was replaced by the custom designed oscillator circuit.

8.2 Testing the first amplification stage

Upon powering up the first amplifier (residing on the sensor PCB), severe distortion was detected. While there was no input present in any way, a 1 MHz signal with a voltage of $24 \, V_{pp}$ was detectable at the input. A similar 2 MHz signal was detectable at the output. A possible explanation for this behaviour is the fact that some undesired feedback occurred over the pins of the operational amplifier. This undesired feedback would be caused by crosstalk caused by capacitive coupling between the input and output pins. The high gain-bandwidth of the LF357 would then be able to amplify this capacitive coupled signal, and due to high feedforward, the system would turn instable and start to oscillate. A possible way to eliminate this would be to switch the opamp for a model with a smaller gain factor at high frequencies. After switching the LF357 for the LF356, this distortion disappeared and it was decided to keep this op-amp for the time being. While the amplification is theoretically a factor 4-5 lower, this could possibly be solved by adding an extra voltage-to-voltage amplifier. To test the amplifier, a resistor with value exactly the same as the resistor on the amplifier was soldered to the sensor plate. This changes the circuit to an inverting voltage amplifier with a gain equal to one. This test showed the circuit worked, as the output was the inverse of the input signal, as expected. To test the total amplification, a much smaller resistance was soldered to the sensor plate, which causes the op-amp to reach it’s gain bandwidth product and show the maximum amplification. This test showed out the amplification of the first stage was around 25 times. Other then the strange behavior coming from the LF357, the amplifier worked as expected, and the loss of extra amplification had to be made up by adding a third voltage-to-voltage amplifier to the third stage.

8.3 Testing the filter

Before implementing the full circuit (consisting of the filter, the two final amplification stages and the peak-to-peak detector) a on a PCB, the filter was to be tested in reality. Therefore it was assembled on a breadboard, and tested using a signal generator and an oscilloscope. The method of testing that was used was feeding a steady state sinusoidal signal to the input of the filter, and comparing the resultant output signal strength to it. The used input signal has an amplitude of $240 \, mV_{pp}$. The resultant amplitudes can be seen in table 3. As is clear from these results, the gain at our target frequency of 100 KHz is slightly bigger than 1. To be precise, it can be specified as: $\frac{248 \, mV}{240 \, mV} = 1.03$. 

38
<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Output (mV&lt;sub&gt;pp&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100K</td>
<td>248</td>
</tr>
<tr>
<td>70K</td>
<td>79.5</td>
</tr>
<tr>
<td>50K</td>
<td>71.8</td>
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<td>10K</td>
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</tr>
<tr>
<td>500</td>
<td>10</td>
</tr>
<tr>
<td>100</td>
<td>Noise</td>
</tr>
<tr>
<td>50</td>
<td>Noise</td>
</tr>
</tbody>
</table>

Table 3: Output of filter versus frequency of input

This is a deviation of 3% from specifications. This deviation is most probably due to component variations and measurement errors. However, after the final signal has been digitalised, some post processing such as biasing and (digital) amplification can be applied, so that error can be corrected for in that part of the system.

8.4 Testing the second amplification stage

After designing the circuit for the second amplification stage, it was also tested on a breadboard PCB before designing a dedicated PCB. It was built on the same board as the filter circuit, so it was decided to test both circuits combined. The output of the filter circuit was connected to the input of the second amplification stage. A picture of this experimental setup can be seen in figure 25.

![Figure 25](image)

Figure 25: The experimental breadboard with the filter and two amplification stages.

The used input signal had an amplitude of 72 mV<sub>pp</sub>. The frequency was decreased from 100 KHz down to 5 Hz. However, every input signal with a frequency lower than 100 Hz produced nothing but noise at the output. A total overview of these results can be seen in table 4.

From these results it can be seen that the filter still performs well in cutting frequencies under 100 KHz. The total gain at 100 KHz can be calculated as \( \frac{27.0\text{V}}{72.0\text{mV}} = 375 \). This is lower than
<table>
<thead>
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<th>Frequency (Hz)</th>
<th>Output ($V_{pp}$)</th>
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</thead>
<tbody>
<tr>
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<tr>
<td>50</td>
<td>Noise</td>
</tr>
</tbody>
</table>

**Table 4:** Output of filter and second amplification stage versus frequency of input

the gain of 625 that was calculated to be necessary, and for which this amplifier was designed. Said gain of 625 was to be attained by cascading two op-amp stages with a gain of 25 each. Part of the loss in gain can be explained by the choice of resistors for the feedback network. To get the amplification factor of 25, we wanted to place a 1KΩ resistor as input and a resistor of 25 KΩ as second resistor. Since 25 is not a value of the E24 resistor series, we chose to approximate it by placing two resistors of 47 KΩ in parallel. That already reduces the total resistance to 23.5 KΩ since:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$$

And thus the gain of the amplification stage is reduced to 23.5. Two of these stages in cascade would produce a gain of $23.5^2 = 552.25$. The measured gain of 375 suggests that both amplifier stages deliver a gain of $\sqrt{375} = 19.37$. This calculation is confirmed by measurements on the PCB. The two stages delivered gains of 19 and 20 respectively. Part of this deviation from design specifications can be explained by the fact that for the feedback network resistors were used with a tolerance of 5%.

**8.5 Testing the oscillator circuit**

After building the oscillator using the components described in the previous chapter, the oscillator was connected to a power supply and oscilloscope to measure the output. From this output, a few undesired characteristics can be determined:

1. The signal amplitude is around 2.5 V.
2. The frequency of the oscillation is around 66 kHz.
3. The signal is triangular, with the rising flank being about twice as fast as the lowering flank.

The first point two problems of this signal are easy to correct: the signal can be amplified by an extra voltage amplifier stage, and the signal of 66 kHz can still be used for the capacitive sensors, although more amplification is needed at the sensor side to compensate for the lack of received signal. The last problem, the triangular wave, might pose a bigger problem: triangular waves consist of multiple sine waves of harmonic frequencies added together, which may cause problems when converting the analog signal to a digital signal. A possible reason
this happens may be the slew rate of the op-amp.\textsuperscript{32} The slew rate of the op-amp has not been considered while designing the system before. Due to the availability of the 741, this op-amp has been used. The slew rate of this op-amp is 0.5 $V/\mu s$. The $5 V_{pp}, 100 \ kHz$ signal is simply switching too quick for this op-amp to keep up, which could explain the triangle wave. The required slew rate is 1.3 $V/\mu s$.\textsuperscript{33} The 741 was switched out for a LF356, which has a slew rate of 12 $V/\mu s$. Immediately upon switching on the power, the difference was noticeable: The 60 kHz triangular wave had made room for a clipping sinusoid, with frequency around 140 kHz. While this is still far from perfect (as both the frequency and amplitude were completely different than expected), the LF356 was a clear improvement over the 741.

In an attempt to try and understand at what stage the distortion occurred, several parts of the circuits were measured for the signals present at those particular stages. It was interesting to see that Resistor R3 had a 100 kHz signal at it’s output, without clipping. With no direct cause known, several potential solutions were tried. Switching the resistors for higher values did not change the situation: Clipping still occurred, and the frequency was still not as how it was supposed to be (a frequency of 70 $kHz$ was calculated, however a 110 $kHz$ signal was measured at the output. The gain was set lower and the compensating resistor was increased in size, which in theory should not cause any change on the distortion. As expected, this caused no change on the output signal. However, upon removing the compensating resistor with the power source still on, nothing changed to the output signal, which indicates this entire part of the circuit was not used. After checking if the diodes were still working, a broken connection on the PCB had been discovered. Upon reconnecting, the output signal became a perfect 95 $kHz$ signal, with a peak-peak voltage of 2.1 V.

In order to get as much as possible current running on the sensor plate, the output voltage of the oscillator has to be as high as possible. While the compensating resistance could be changed in order to get a higher voltage, it was decided to use a separate voltage-to-voltage amplifier for this, as the PCB was severely damaged already. This lead to a 26 $V_{pp}$ sinusoid signal of 95 $kHz$, which is almost as good as the ‘ideal’ input. The output of the signal can be seen in figure 26. At this point, the oscillator is ready for use.

### 8.6 Testing the rectifier

To test the rectifier, a 100 kHz signal was put on the input of the rectifier. A capacitance of 100 nF was taken to test the rectifier. As expected, the output signal followed the input amplitude, at around half the input peak-to-peak voltage.

To measure the RC time constant, a 1 k$\Omega$ resistor was placed in parallel to the capacitance. This caused the RC time to be $1exp^{3\times100exp^{-9}} = 100\mu s$, or 10 kHz. To verify this, the signal was changed to a 10 kHz signal. As expected, the signal reached 37% of it’s amplitude at the next slope.

While these tests were completed, it should be noted that the capacitance should get the RC constant to around 10 KHz, in order to be able of following changes of 63% total deviation every 100$\mu s$. If quicker sampling is needed, the RC time should be cut in half.

\textsuperscript{32}The slew rate of an op-amp is defined by the maximum change of voltage over time the op-amp can process.

\textsuperscript{33}For this signal, the complete change is around 13 $V(6.5- > -6.5- > 6.5)$ in 10$\mu s$
8.7 Testing the entire setup

As soon as all the building blocks were completely tested and working, it was time to connect all these subsystems in order to reach the final setup. Testing was started with these blocks despite the fact that it was known that the total amplification was not as large as was calculated. This was done because there was some time-pressure, and it was deemed more desirable to have at least some results of the total system. With these results and when time permitted, the circuit could be improved.

The integration was done by designing a custom made PCB, on which the filter, the second amplification stage and the rectifier were placed. The PCB was designed in such a way that all four channels that would be necessary for a real world spindle (see figure 12 to see why four channels are needed) are realised on one PCB. The result can be seen in figure 27. Also four sensor PCBs were made. They can be seen in figure 28.

The output of these sensor PCBs was connected to the input of the amplification print. The output of the amplification print was then connected to an oscilloscope. The ring was connected to the oscillator, and the sensor was moved into position underneath the spindle. At this point there was no measurable signal. All PCBs and connections were checked for error, but to no avail. The signal coming from the sensor was tracked using oscilloscope probes, and it was found to be too weak. Since the experiment board containing two voltage-to-voltage amplifiers was still available, it was decided to insert one more amplification stage between the sensor PCB and the filter. The gain of that extra amplification stage was the same as the two final stages, around 20. After this addition the signal was clearly readable on the oscilloscope. The output value of the system was 0 V when the sensor plate was not in the vicinity of the spindle, and increased when the sensor plate was within 3 mm from the spindle. The voltage went up to 10 V when touching the spindle.

From this it can be concluded that the system can work according to specifications, but
that our first approach didn’t work since we used a too low gain. When correcting for this error, the output is as expected. Further digital signal processing is needed to obtain the differential measurements that we aimed for with two sensors (underneath and above the spindle), however there was no time before the deadline of this report to include these results in this report.
9 Conclusions and recommendations

9.1 Conclusions

The conclusions of this research are twofold. That is because two systems of position detection were researched and implemented. Both systems have their own advantages and disadvantages, which can cause each of them being the optimal solution when developing an AMB system.

When having a big enough budget, or when limited to a very short developing time, it is advisable to use optical sensors. They is a wide range of sensors available off-the-shelf, for all kinds of applications. Their accuracy and range can be perfect for AMB applications. Their main drawback is the fact that they tend to be expensive. Prices exceeding €1.000 amounting even to €4000 are no exception. However, these sensors turned out to be too expensive for the limited budget of this project. An alternative was found for free in the shape of a pair of sensors that were available to be borrowed from the university. The advantage was that a setup could actually be built with these type of sensors. The disadvantage was that these sensors had a wide range, but a bad resolution of up to 100µm, making them less appropriate for the application. However, some preliminary results were booked.

When facing a limited budget in an AMB project, one might be interested in a position sensor setup based on capacitive measurements. The concept proposed in this project basically works as follows: the spindle of the AMB system is charged with a high frequency (100 KHz in this case) sinusoid signal by means of a conducting ring around the spindle. The proximity of that spindle to two sensor plates is then determined by measuring the current flowing to that plate as a result of capacitive coupling between the spindle and said plate. It was proven during this research that the position of the spindle can be determined this way. According to our calculations, a resolution of 100µm can be obtained, and with some optimisations even 10µm is attainable. In practice, these numbers were not met, due to different unsolved errors in our system and a lack of time. Also, some other problems were encountered that must find a solution in further research. These problems mainly are:

- The ring used to charge the spindle introduces a large crosstalk signal if the sensorplates are close to the capacitive ring. In further research, the setup might be adapted to put the ring and sensors further apart, or form some shielding between the ring and the sensor.
- Better filtering might be needed in order to reduce or even eliminate the influence from 50Hz EM-fields.
- Research might be done on the most efficient frequency for this capacitive sensors. Gain-bandwith of operational amplifiers and interference from nearby systems are factors to keep into account in this research.

To answer the question “What is a good yet affordable way of determining position of a spindle in active magnetic bearings?” these results can be summarised as follows: The optical sensors are typically off-the-shelf sensors with performance better then required, although their price
is rather high. The capacitive sensors are very cheap, although the technical specifications required were not met due to a lack of time. Both sensor systems are viable and depending on budget and development time either sensor can be the best solution.

9.2 Recommendations

The sensor designs in this report are still on the development phase. While the concept and basic functionality of both the capacitive sensors and the optical sensors are shown, both need to be improved to get the required specifications for a full AMB setup. Nevertheless both sensor types can be used for simple levitation.

In order to switch to a complete active magnetic bearing setup, the optical sensors need to be improved at the following points:

- **Sampling speed.** A 1KHz sampling rate will only function for rotation frequencies of at most 500 Hz or 3000 RPM due to the nyquist criterium, but preferably more samples are taken per rotation. For higher frequencies this sampling frequency will fail, and should therefore be increased in a full amb setup.

- **Resolution.** The sensors used in this report’s setup have a resolution of 100µm. While this is enough for simple levitation, the position needs to be defined more accurate to keep the spindle in the center in high-precision applications, such as micro milling.

The capacitive sensors need to be worked on in the following ways:

- **Determining resolution and operational frequency.** While the experiments in this thesis report have shown capacitive sensors can be used for measuring position, the resolution is not determined. While theoretically a resolution of 10µm and below should be possible, this is not obtained in these experiments. Also the rectifier network has to be improved to on one hand make the ripple as small as possible, but still be fast enough for high speed measurements.

- **Signal processing** In order to get the output signal usable for the controller, the signal has to be scaled depending on the output of the A/D converter. While the theoretic output of the signal can be determined, it still has to be tested in practice.

- **Shielding** A 100 KHz signal radiates away from all wires, and a strong signal also comes from the charging ring. In order to eliminate that influence on the capacitive sensors or other electronic equipment in the vicinity, shielding from the outside world will have to be applied.
10 Bibliography


Ronde, D. de (2002). Wien-Bridge Oscillator Circuits, Calvin College


A  Spice Files

OPWIEN.CIR - OPAMP WIEN-BRIDGE OSCILLATOR
*
* CURRENT PULSE TO START OSCILLATIONS
IS 0 3 PWL(0US 0MA 10US 0.1MA 40US 0.1MA 50US 0MA 10MS 0MA)
*
* RC TUNING
R2 4 6 1.5k
C2 6 3 1000PF
R1 3 0 1.5k
C1 3 0 1000PF
* NON-INVERTING OPAMP
R10 0 2 1K
R11 2 4 2.2K
XOP 3 2 4 OPAMP1
* AMPLITUDE STABILIZATION
R12 2 8 10K
D1 8 4 D1N4148
D2 4 8 D1N4148
.model D1N4148 D (IS=0.1PA, RS=16 CJO=2PF TT=12N BV=100 IBV=0.1PA)
*
* OPAMP MACRO MODEL, SINGLE-POLE
* connections: non-inverting input
* inverting input
* output
*
.SUBCKT OPAMP1 1 2 6
* INPUT IMPEDANCE
RIN 1 2 10MEG
* DC GAIN (100K) AND POLE 1 (100HZ)
EGAIN 3 0 1 2 100K
RP1 3 4 1K
CP1 4 0 1.5915UF
* OUTPUT BUFFER AND RESISTANCE
EBUFFER 8 0 4 0 1
ROUT 8 6 10
.ENDS
*
* ANALYSIS
.TRAN 0.01MS 10MS
*
* VIEW RESULTS
.PRINT TRAN V(4)
.PLOT TRAN V(4)
.PROBE
.END
B Oscillator Circuits

Figure 29: Armstrong Oscillator

Figure 30: Clapp Oscillator

Figure 31: Colpits Oscillator

Figure 32: Hartley Oscillator
Figure 33: Phase-shift Oscillator

Figure 34: Wien Bridge Oscillator