Investigation of rotational velocity sensors

Examensarbete utfört i Reglerteknik
vid Tekniska Högskolan i Linköping
av

Martin Törnquist

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Tests show that these sensors are capable of speed measurement, but because of noisy angle estimates they need filtering for good speed computation. This filtering introduces a large time delay that is of significance for the quality of the estimate. A Kalman filter has been implemented in an attempt to lower the time delays but since only a very simple model has been used it does not give any improvements over ordinary low pass filtering.

For these sensors the mounting tolerance is of great interest. For best performance the offset between the sensor and magnet centres need to be kept small for both sensors. This is due to a non-linearity effect this causes. The distance between the sensors and the magnet is not critical for linearity issues, but only for the quality of the signal, where it might drop out when the distance is too large. This is where the sensor using GMR technology stands out. Compared to the Hall technology sensor, the GMR sensor can handle distances that are more than 10 times larger.

The conclusion is that these sensors can be a valid replacement of the current measurement system. They will introduce more functionality with the capability of detecting rotational direction and zero velocity. In an application with more than one sensor they can also be used for more purposes, like detecting slip in clutches etc. Depending on the application, the time delays may not be critical, else more work need to be done to improve the estimate, e.g. with a more advanced model for the Kalman filter.

Nyckelord/keywords
Velocity, Sensors, GMR, Hall, Kalman filter, Vehicle, Construction Equipment, Gearbox
Abstract

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Sammanfattning

För att förbättra hastighetsmätning på arbetsmaskiner har olika sensorteknologier undersöktts. Utifrån dessa har sedan två valts ut för vidare studier, magnetiska absolutvinkelgivare som bygger på Hall och GMR teknik, för att avgöra om de är lämpliga för ersättning av det befintliga mätsystemet med en passiv sensor.


För de här sensorerna har monteringstoleranserna stor betydelse. För bästa prestanda och kvalitet bör offsetfelet mellan sensorns och magnetens centrum vara så litet som möjligt, p.g.a. olinjäritets effekter som uppstår. Ur linjäritets synpunkt är inte avståndet mellan sensor och magnet lika viktigt, utan enbart för signalkvaliteten, då signalen försvinner vid för stora avstånd. Här sticker sensorn som bygger på GMR teknologi ut, då den klarar mer än 10 gånger större avstånd till magneten jämfört med sensorn som bygger på Hall teknologi.

Slutsatsen av det här examensarbetet är att den här typen av sensorer kan vara en lämplig ersättning för det nuvarande systemet. De tillför bättre funktionalitet genom möjligheten att mäta rotationsriktning och mätning ner till nollhastighet. Om flera sensorer används kan man även få en utökad funktionalitet, med exempelvis möjlighet att skatta kopplingsslir i växellådan. Beroende på applikationen är det möjligt att tidsfördröjningarna inte är kritiska, annars krävs mer arbete med att förbättra skattningen, exempelvis genom en mer avancerad systemmodell för Kalmanfiltret.
Preface
This master thesis was carried out between January and June 2008 on Volvo Construction Equipment, Component Division in Eskilstuna, Sweden. The thesis was divided in two parts, where my part was focused on finding alternative measurement methods to the current system. The other was more focused on how to extract more information from the current system. This part was carried out by Niklas Willemsen, KTH. He has earned many thanks for the help during this thesis.

First of all I would like to thank my supervisors at Component Division; John Bertling, Gianantonio Bortolin and Christer Asplund for their support during the work. Johan Sutt is also worth a mentioning, thank you very much for helping me acquiring components. And to all other personnel at Component division, thank you very much for all help, interesting discussions and making my time with you more joyful.

Finally I would like to thank Johan Sjöberg, ISY, and Thomas Schön, ISY, my supervisor and examiner at Linköping University.

I hope this work will be useful for Volvo CE and that it will help them with their future work.

Eskilstuna, June 2008

Martin Törnquist
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1. Introduction
This thesis has been carried out at Volvo CE Component Division in Eskilstuna, Sweden. Volvo CE is one of the leading manufacturers of construction equipment in the world with a total production of more than 60000 machines a year [18]. The function of the Component Division in Eskilstuna is to develop control systems, both hardware and software, mainly for use on the power trains in Volvos wheel-loader, articulated-hauler and grader product lines.

The power trains in the wheel-loaders and the articulated-hauler consists of a diesel engine connected to an automatic power shift gearbox through a torque converter. The gearbox is then connected to the wheel axles. Because of this the gearbox has a direct connection to the wheels, whereas the connection to the engine is dynamic due to the converter. This makes it troublesome to use information about engine speed to compute wheel speed. Construction equipment is also not equipped with ABS and are thus not equipped with wheel angle velocity sensors either. Since the wheels are big and the velocity low in these machines, wheel sensors would not give high enough resolution. The rotational velocity is the highest in the gearbox, which will result in better resolution and because of this, sensors are mounted there instead.

Figure 1: The powertrain on Volvo L60-L90 wheel loaders
1.1. **Background**

The background to this thesis is increasing demands on productivity, driver comfort and lower fuel consumption for construction equipment. To fulfil these demands it is necessary to improve the control systems for the machine. One step towards this goal is to improve the quality of the information gathered for the control system.

With this thesis Volvo CE aims to improve the speed and acceleration measurement of their machines. The method used today has been in use for about 25 years [26] and starts to reach the end of its potential. To further improve the gear changing strategies for Volvos automatic gearboxes a better estimation of the speed and acceleration is necessary.

If the control system can detect a significant change in velocity earlier on, e.g. if the vehicle is reaching an uphill slope, it will be able to change earlier to a lower gear. Because of this, more of the vehicle’s kinetic energy will be preserved, leading to lower fuel consumption and a higher productivity.

1.2. **Purpose**

The purpose of this thesis is to identify alternative methods to measure vehicle speed and acceleration and to investigate the performance of a couple of these methods, i.e. if these methods can fulfil the upcoming demands on such a system.

The main purpose is not to present a final solution, but an alternative measurement method that can be a valid alternative to the present method.

1.3. **Method**

First a literature study was performed, both through interviews with personnel at the component division as well through different reports. From this a good overview of what the performance and capabilities of the present system are and also some of the wanted capabilities in the future was obtained.

After this the different alternatives to the current method was studied. Some of these methods were disqualified due to requirements from Volvo, whereas other looked promising. From these methods, two were chosen for further studies.

The studies were conducted in a test bench consisting of a stepper motor and an optical incremental encoder for reference. With this stepper motor a rotating axle can be simulated.

1.4. **Problem formulation**

New technology, higher environmental demands, higher expectations from customers and smart features added to construction equipment require good estimates of the vehicles speed and acceleration. The system used today has, as mentioned earlier, been in use for about 25 years and do not give good enough speed estimates, especially at low speed. The quality of the speed-estimation directly influences the acceleration-estimation, resulting in a noisy estimate.
The speed and acceleration estimates are e.g. used in the gear shifting algorithm and good estimates are crucial for correct gear-changing strategies. A good strategy result in lower fuel-consumption, faster work-cycles and less disturbance for the driver.

One of the problems mentioned by Volvo is that when a fully loaded wheel-loader approaches a hill, it will slow down. If it were possible to estimate this retardation better and to engage a lower gear earlier, some of the torque would be conserved and both fuel and time would be saved.

Wanted features also include rotational direction and zero velocity measurement which is not possible with the technology used today.

Sensors in automotive applications have high requirements for robustness, like insensitivity to dirt, vibrations and high temperatures. These requirements disqualify some measuring technologies as well as cost disqualifies others.

1.5. Thesis Outline

The current method to measure rotational speed at Volvo is presented in Chapter 2. Here is the current sensor described as well as the input electronics in the TECU and the algorithm used to calculate the speed. At the end of the chapter some of the demands that are set on the system are presented. These are both specified demands from the company as well as wanted features from engineers.

In Chapter 3, the different alternatives to the current sensor are presented. Here the theory behind the methods will be presented as well as positive and negative aspects of the method.

Chapter 4 contain a presentation of which sensors are chosen for further studies. There is also a presentation of the test bench and how the measurements are made. Then the results from the measurements on the two sensors are presented. Investigation on signal noise and mounting tolerances are made and the amount of filtering that is needed for the signals.

Chapter 5 contain the conclusions of the study in previous chapters. The advantages of the different methods are compared. A recommendation of which measuring method that has the best potential will be presented. Some examples of interesting things to study further are also presented.
2. Current measurement system

In the current measurement system an inductive sensor is positioned above a gearwheel inside the gearbox. Since the gearbox has a direct connection to the wheels its rotational velocity will be directly proportional to the wheels and thanks to this the rotational velocity of the wheels can be calculated.

The sensor’s output signal is analogue and has to be filtered to increase the S/N ratio. From this analogue signal a square wave with the same period as the analogue is created. This will give a square wave with a rising edge for every tooth on the gearwheel passing by. The square wave is sent to the TECU that counts the rising edges and the time between them. From this and the information of the number of teeth on the gear, the TECU can compute an estimate of the velocity.

2.1. The inductive sensor

The inductive variable reluctance sensor is an electrical proximity sensor, sensing the presence of metallic object without touching them. The sensor consists of an induction loop used to sense the variation of a magnetic field. The magnetic field itself induces an electrical voltage in the loop, which is creating a field opposite to the present field. This will change the impedance in the circuit and significantly affect the current. When a metallic object enters the magnetic field it will cause a change in the induced voltage and therefore influence the current in the circuit.

The variable reluctance sensor is the first sensor that was introduced to the automotive market for crankshaft positioning purposes and is a variant of an inductive sensor. The sensor consists either of a permanent magnet and a coil wound around it as is shown in Figure 2, or just a coil excited with a direct current. This produces a constant magnetic field that goes through the coil. The theory behind this sensor is built on Faraday’s law of induction and the sensor has a very robust and simple design.

When the magnetic field changes, an electromotive force is induced in the coil which results in an electrical potential over it. Because of the induction theory, the signal amplitude is dependent on the rate of change of the magnetic flux, and so, the sensor will not be able to detect a static magnetic flux.
Ferromagnetic materials attract the magnetic flux, concentrating it to the material. Hence, when a ferromagnetic target is introduced into the magnetic flux it will cause a change in the magnetic circuit reluctance, making the flux change. This change is what is detected by the variable reluctance sensors coil.

In automotive applications the sensor is positioned in front of a toothed wheel, either a standard transmission gear-wheel or a slotted wheel. This makes it possible for the sensor to detect the passing teeth on the wheel when it is being rotated. The changing flux results in a potential over the coil, with the same frequency as the number of teeth passing by. In our case the potential has sinusoidal shape due to the shape of the gear wheel. The amplitude of the signal reaches its maximum value at the top of the tooth, and the minimum in between two teeth.

Because the sensor output is dependent on the rate of change of the magnetic flux, this kind of sensor is not suited to measure low speed rotations, since the S/N ratio will become too small to measure.

Figure 3: Example of change in magnetic reluctance

In the case of the variable reluctance sensor, Faraday’s law states that [1]

\[
\varepsilon = \frac{d\Psi}{dt} = -N \frac{d\phi}{dt}
\]  

(1)

where \( \phi \) is the flux through the coil, \( N \) is the number of windings in the coil and \( \Psi \) is the total flux-linkage. If the flux leakage from the permanent magnet going through the coil is neglected, the flux, \( \phi \), in the permanent magnet core is

\[
\phi = \int_{A} B(\sigma) d\sigma
\]  

(2)

where \( A \) is the cross-section of the core and \( B \) is the magnetic field. If we assume a rectangular core with \( L \) as the length across the wheel and \( R \) as the target-wheel radius we get \( \phi \) as

\[
\phi = L \int_{\theta(t)}^{\theta(t)+\delta} B(\alpha) Rd\alpha
\]  

(3)

Combining (1), (2) and (3) gives
\[ \varepsilon(t) = -NLR \frac{d}{dt} \int_{\theta(t)}^{\theta(t)+\delta} B(\alpha) d\alpha = -NLR \frac{d\theta}{dt} \frac{d}{d\theta} \int_{\theta(t)}^{\theta(t)+\delta} B(\alpha) d\alpha \] (4)

At steady-state the wheel has a rotational velocity \( \omega \), which render

\[ \varepsilon(t) = -NLR \omega \frac{d}{d\theta} \int_{\theta(t)}^{\theta(t)+\delta} B(\alpha) d\alpha = -NLR \omega [B(\theta + \delta) - B(\theta)] \] (5)

The peak to peak value of \( \varepsilon \) gives the maximum attainable signal from the variable reluctance sensor.

\[ V_{pp} = NLR \omega (B_{max} - B_{min}) \] (6)

From (6) it can be seen that the peak to peak value depends on the rotational speed. Therefore the signal will disappear at low velocities. It can also be seen that the peak to peak value does not depend on the shape of \( B(\theta) \) but only its minimum and maximum values, i.e. it is not explicitly dependent on the time derivative of the magnetic flux, but only on the peak values of it [1].

### 2.2. Limiting factors on the sensor

The sensors used in Volvo gearboxes today are of inductive type. As described before, these sensors react to changes in the magnetic field and a current proportional to the rate of change is induced in them. This change is caused by the difference in reluctance when a gear passes the sensor and when the sensor is between two gears. This is shown in Figure 3 and Figure 4. When the gear wheel has a high velocity the change in the magnetic field will be faster than at lower velocities and thus give a stronger signal, since the strength of the output signal is proportional to the rate of change of the magnetic field. This fact limits the sensor at low velocities since the signal will be weakened and a gear passing by might not be detected in the output.

The frequency specification for the sensors used in Volvo transmissions are (gears/s) from 20Hz to 4500Hz which correspond to velocities from 0.4km/h to 50km/h. Because of the weakening of the signal, detecting zero velocity is not possible. Furthermore, we also cannot determine the direction in which the gear is turning due to the fact that the gear wheel is symmetric and the induced signal will look the same either way the gear is turning.
Apart from the rotational velocity, the air gap between the sensor and the gear wheel is also a factor determining the strength of the sensor output. In one of the gearboxes used by Volvo, the ideal distance from sensor to gear wheel is 0.7mm when measuring the speed on the outgoing axle with a tolerance of +0.7mm/-0.4mm. This tolerance is due to tolerance stack-up in the different parts and to the fact that the sensor is just tightened down in the transmission housing without any fine adjustment. The tolerance is of importance since a change of distance between the sensor and the gear wheel from 0.5mm to 1.0mm might lower the sensor output amplitude of more than 50%. [20]

### 2.3. From sensor output to velocity estimation

From the sensor the signal will pass through three blocks before an estimation of the velocity is made, as can be seen in Figure 5 above. The first block, *filtering and signal adaptation*, will filter and convert the signal into a square wave. In the second block, Interrupt routine, the pulses are counted and a time stamp for the last pulse is made. In the last block, ECU, the frequency for the signal is calculated, using the number of pulses and the time difference between the time stamps in this measurement period and the previous. From this frequency the rotational velocity or the vehicles velocity can be calculated using information about the number of teeth on the gear wheel together with the gear-ratio.
2.3.1. Filtering and signal adaptation (the first block)

In the first block the analogue signal will be subjected to some treatment in order to create the digital square wave necessary for the interrupt routine. The treatment is done in five separate steps, illustrated in Figure 6 below.

![Figure 6 Filtering and signal adaptation, a circuit diagram of the five step process](image)

The function of every step from analogue signal to square wave is explained below.

1 - Current amplification
Because of the operation method for the sensor it is only capable to generate a small current. Thus, the purpose of this step is to amplify this current.

2 - High voltage protection
The second block makes sure that the voltage passing through it is not too high to protect the comparator. Each diode allows for a potential drop of 0.7V, so with this circuit the outgoing voltage will be limited to +1.4V/-0.7V. This block also has a low pass filtering effect on the signal, although not intentional, because of the resistor and capacitor.

3 - Voltage increase
After the second step the signals amplitude level is centred around 0V and both positive and negative amplitudes are possible. The function of the third step is to centre the signal around +2.5V in order to only have a positive sign on the signal since this will make the signal processing easier. This also has high pass filter effect on the signal, removing low frequency noise.

4 - Low pass filter
This step has a low pass filtering effect on the signal in order to remove high frequency noise and reduce the risk of false activation of the interrupt routine. The filter is realized with a simple RC-filter circuit giving a first order low pass filter.
5 - Comparator
The function of the last step is to create a square wave from the now filtered and adapted but still analogue sinusoidal sensor output. This is realized by the use of an inverting operational amplifier circuit. This means that a high value on the input will create a “low” level on the square wave and the other way around. In order to allow some fluctuations on the input signal the comparator has a hysteresis that triggers at 2.5V +/- 0.63/0.66mV. This hysteresis will however also introduce a small time delay. After this step the resulting square wave will have an amplitude of 4.89V. The behaviour for this step is illustrated in Figure 7 below.

![Figure 7 Illustration of the hysteresis in the comparator.](image)

In the circuit there are three different RC-filter groups. Two of these are acting as low pass filters and one as a high-pass filter. For an RC-filter the cut off frequency can be calculated as

\[
f_{\text{cut off}} = \frac{1}{2\pi \tau} = \frac{1}{2\pi RC}
\]

where

- \( f_{\text{cut off}} \) is the cut off frequency for the filter [Hz]
- \( \tau \) is the time constant for the filter, given by \( R \) and \( C \)
- \( R \) is the resistance [\( \Omega \)]
- \( C \) is the capacitance [\( \text{F} \)]

Thus for the three RC-filters in the circuit the cut off frequencies will be:
The cut off frequencies for the low pass filters are 3.39kHz (block 2) and 48kHz(block 4) respectively and the high pass filter at 16Hz (block 3). This gives a frequency span from 16Hz to 3382Hz for the sensor signal. Because of phase shift that occurs in the filters, a time delay will be introduced for the sensor signal. The phase shift is changing depending on the frequency of the input signal and consequently also the time delay. To calculate the time delay the following equations are used [2]:

\[
\Delta t = \frac{\phi T}{2\pi} \tag{8}
\]

\[
\phi = \arctan(\omega RC) \tag{9}
\]

\[
\omega = 2\pi f \tag{10}
\]

\[
T = \frac{1}{f} \tag{11}
\]

where

- \(\Delta t\) is the time delay [s]
- \(\phi\) is the phase angle [rad]
- \(T\) is the period of the signal [s]
- \(\omega\) is the angular frequency [rad/s]
- \(R\) is the resistance [Ω]
- \(C\) is the capacitance [F]
- \(f\) is the signal frequency [Hz]

These equations can be combined into

\[
\Delta t = \frac{\arctan(2\pi RC)}{2\pi f} \tag{12}
\]

Using the equation above and the values for the RC-filters in the three blocks give approximate values for the time delays in the filters. For block two the time delay will be in the span of 33-47μs for frequencies of 20-4500Hz whereas block four has a time delay with a magnitude of 3.3μs in the same frequency domain. These time delays are very small and more or less negligible. For block three however, the high pass filter, the time delays are not as small. At 4500Hz this filter will give a time delay of 55μs which also is negligible but at 20Hz this filter will create a time delay of 7.2ms, and at 100Hz the delay will be 2.2ms. With a sampling period of 10ms a time delay of this magnitude will be significant.
2.3.2. The interrupt routine
The interrupt routine is implemented in the TECU and the function is to count every rising edge on the resulting square wave from the previous block. A timestamp is given to every rising edge of the signal, however only one timestamp can be stored, so it will constantly be updated to the latest time stamp caused by every interrupt.

2.3.3. Algorithms used in the TECU
Every 10ms an algorithm to calculate the velocity is started in the TECU. From the interrupt routine it receives the number of teeth that has passed by the sensor and the timestamp for the last tooth. The timestamp for the last tooth in the previous period the algorithm was run is stored in the memory of the TECU and by calculating the time difference between the two timestamps and dividing that with the number of teeth counted, a mean frequency for the period can be calculated. Through information about gear-ratios this frequency can easily be converted into a rotational velocity for the gear axle or a velocity for the vehicle.

Since the algorithm is run every 10ms it will work well for frequencies above 100Hz since this will lead to at least one interrupt every sample period. At frequencies lower than 100Hz, an interrupt will not occur every sample period, forcing the algorithm to make assumptions about the frequency. When the TECU encounter a sample period without any interrupts it will check the frequency in the previous sample period, if that was higher than 100Hz the new frequency will be set to 100Hz, since that is the highest possible frequency. If the previously calculated frequency was lower than 100Hz that frequency is kept. If another period goes by without any interrupts the estimated frequency is set to 50Hz, but only if the previously calculated frequency was higher. For every addition period without interrupts the frequency will be lowered to 33, 25, 20, 16, 14, 12, 11, 10 and finally 0Hz in the same way as earlier.

To exemplify this with a worst case scenario, consider a rotating gear axle, resulting in a sensor signal with a frequency of 12Hz. If this axle then suddenly stops rotating, the algorithm will keep the estimated frequency at 12Hz for the next 8 sample periods, since no input signal has been detected. In the next three sample periods the estimate will drop to 11Hz, 10Hz and finally 0Hz. The result is a total time delay of 100ms to detect the frequency drop just from the calculation algorithm.

The first major drawback with this algorithm is that it will only give you the mean frequency during the 10ms sample period. During this time frame, the velocity of the gear can change substantially, making the difference between the true frequency and the calculated mean frequency very large. However this will also have the positive effect that it will filter out some disturbances in the measurement, which result in a more accurate calculated frequency.

The second major drawback is the time it will take for the algorithm to detect changes at low frequencies, in the worst case scenario it will take 100ms to detect that the vehicle has stopped, from any frequency.
2.4. **Specification of demands**

To obtain an insight into what the demands are on the speed measurement, a series of interviews was held with people working at the Component Division. To get quantified demands on the system was very difficult from everyone that was interviewed; mostly it was more specified as wills. Although there were some demands that was clearly specified.

- The measurement system should be able to detect rotational direction.
- It should be able to detect “nearly” zero velocity.
- The system need to handle EMC demands set up by Volvo.
- The price needs to be kept low, preferably lower than the current system.
- Mounting tolerances should be high to make assembly easier and keep the cost low.
- System robustness needs to be high to ensure long lifetime.
- The amount of advanced calculations should be kept low, since the calculation capacity in the TECU is limited.

There are two possible ways to accomplish these demands, either through signal processing on the analogue signal from the currently used variable reluctance sensor or introducing a new sensor. In this report the focus is put on the later. For information about the former alternative see [25].
3. Alternative sensors

In this section some of the alternative sensor solutions will be introduced and described. For a sensor to be appropriate for automotive use, it needs to be of non-contact type because of high demands on long lifetime and robustness. It also needs to handle high amounts of vibrations, heat, liquids and dirt.

The demands for a sensor in this application are considerably tougher than many other applications. Crank shafts often rotate at high speeds, rarely below 600rpm, making measurements easier with simple algorithms. In addition, the target wheel for the engine has more teeth than the gear in a gearbox which results in a better resolution.

Depending on the gear-ratio the outgoing shaft from the gearbox can rotate a lot slower than the engine. The gearboxes used in wheel-loaders use a torque converter, leading to a nonlinear connection between engine speed and gearbox speed. The correlation for the rotational velocity between the engine and the gearbox is dependent on workload which is hard to estimate, thus the engine sensor cannot be used to measure the gearbox speed.

Furthermore wheel-loaders often operate at very low speed and with heavy workloads. Because of this the possibility to measure lower velocities than what is considered interesting in other applications might be favourable. In addition it is important to detect rapid acceleration changes, for the possibility to choose the most appropriate gear at the given time, in order to improve the efficiency.

3.1. Active Inductive Rotary sensor

The active inductive rotary sensor is a non-contact sensor. It is designed with a rotating metallic blade and a sensor-body consisting of numerous coils. An example of this sensor can be seen in Figure 8. When the disc is rotating above the sensor it will change the inductive coupling between the coils making it possible to detect the position of the blade and calculate the absolute angle of the disc.

![Figure 8: Inductive Rotary sensor with rotating blade](image)

Inductive coupling refer to the transfer of energy from one inductive circuit to another. To sense the coupling between the coils a magnetic field is sent from one of the coils and the amount of energy transferred to the other coils is measured. Coils covered by the metallic blade will have greater coupling than those that is not covered.
This type of sensor is more or less insensitive to external magnetic fields, since it is the coupling that is measured. This will create an automatic calibration for every measurement. However, the EMC radiation from the sensor is quite high [19] and so is the manufacturing cost, making them unsuitable for vehicular applications.

### 3.2. Capacitive Sensors

As the name imply, capacitive sensor, these sensors make use of the electrical properties of capacitance. This is a property existing between any two conductive surfaces close to each other. If the distance between the surfaces changes so do the capacitance. Capacitive sensors make use of this change to indicate changes in the targets position. These sensors can be designed for non-contact measuring which is illustrated in Figure 9. They are also capable of very high resolutions. However, capacitive sensors are not suited for wet or dirty areas, which disqualify the sensor from use inside a transmission. [21]

To illustrate the theory, consider a two-plate capacitor. The charges on the plates are +Q and – Q. V is the potential between the two. The capacitance between the two plates is then given by [28]

\[
C = \frac{Q}{V}
\]  

where

- \(C\) is the capacitance of the capacitor [F]
- \(Q\) is the charge on the plates [C]
- \(V\) is the voltage difference between the plates [V].

For a parallel plate capacitor the capacitance is given by

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

where

- \(\varepsilon_r = 1\)
- \(\varepsilon_0 = 8.854 \times 10^{-12} [F/m]\)
- \(C\) is the capacitance [F]
- \(A\) is the area of each plate [m²]
- \(d\) is the separation between the plates [m]

To measure rotational movement with capacitive technology it would be suitable to use a sensor consisting of one segmented sending electrode, one receiving electrode and a rotor. The capacitance between each of the segments on the segmented sending electrode and the receiving electrode is measured and the position of the rotor can be calculated.
Using this setup the exact angle can be calculated by measuring the capacitance between each segment on the sending electrode and the receiving disc. For the segments covered by the rotor, the capacitance between the two electrodes will be lower than for the fully visible case. The transition between the cases will ideally also be linear.

### 3.3. Hall Sensors

The Hall Effect is the bending of an electric current in a conductor caused by a magnetic field. A magnetic field perpendicular to the current will cause the current to bend in a direction perpendicular to both the current and the magnetic field. This is illustrated in Figure 10. An electrical current consist of electrons flowing though a conductor. When a magnetic field, with an effective component perpendicular to the current, is present the electrons will experience a force, called the Lorentz force. This force will cause the current to bend, creating a higher density of electrons on one side of the conductor and thus a potential difference across the conductor.

The electrical potential given by the Hall effect can, in an ordinary metal, be calculated from [28]

\[
U_H = -\frac{IB}{d \cdot n \cdot e}
\]

(15)

where

- \( U_H \) is the electrical potential created with the Hall effect, [V]
- \( I \) is the current with electrons through the Hall plate, [A]
- \( B \) is the magnetic flux density perpendicular to the current, [T]
- \( d \) is the depth of the plate, [m]
- \( e \) is the electron charge, [coulomb]
- \( n \) is the charge carrier density, []
3.3.1. Gear Actuated Hall Sensors

The principle of gear actuated Hall sensors is similar to the variable reluctance sensor. The sensor consists of a biasing permanent magnet, but instead of the coil used in the Variable Reluctance sensor, a Hall element is used to detect changes in the magnetic field.

The presence of a ferrous gear-tooth will attract the magnetic flux toward the lower reluctance of the tooth, creating an increasing flux, which is illustrated in Figure 11. This make it possible for the movement of the gear to be detected by the Hall-sensor, or possibly even the position of the gear tooth. The position of the tooth will result in a specific voltage, but the distance between the gear and sensor will affect the voltage, making it hard to calculate the position without calibration. The voltage created by the Hall-effect is also very small, which can lead to high sensitivity to electrical disturbances. Because of this, most Hall sensors
available for automotive applications make use of so called latching, where the output will be set high when the measured Hall potential goes above some preset value, and set low when the potential goes below another preset value.

Since these sensors work in the same way as the VR sensor they will not give any improvement in the resolution of the signal compared to the current method if mounted similarly. The resolution of the sensor is defined by the associated gearwheel and to improve the resolution, a gearwheel with finer teeth is needed. This can be accomplished in a few different ways.

- The actual gearwheel could be replaced with a finer teeth gear. However this would change the gear-ratio of the gearbox and probably more parts in the gearbox would need to be changed.
- A slotted disc just for sensing purpose could be added to the gearbox. In this way the resolution can be modified to a desired value. However this solution requires an additional component in the gearbox.
- Instead of adding a slotted disc, these slots could be engraved onto an existing part in the gear box, e.g. the same gear used for sensing today.

The number of teeth possible to engrave on the side of the outgoing gear is depending on the sensor. The specification-sheet [11] state that the recommended tooth and slot width is 2mm. The gear has a total diameter of 157mm and with a tooth-height of 12.5mm, the inner diameter is 132mm. The number of possible slots is then given by

\[
n_t = \frac{\pi d_g}{\delta_t + \delta_s} = \frac{\pi \cdot 0.132}{0.002 + 0.002} = 103.6
\]

where

- \(d_g\) is the diameter of the gear
- \(\delta_t\) is the recommended tooth-width
- \(\delta_s\) is the recommended slot-width

According to this around 100 teeth should be possible to engrave into the existing gear wheel inside the gearbox.

Gear actuated Hall sensors are also available with a quadrature output, meaning that a second output that is 90 degrees out of phase with the first is added. This second output is created by simply adding another Hall element and physically displace them with a small distance from each other. This means that the target wheel and the sensor need to match, to truly have 90 degrees between the two outputs.

The quadrature output gives the possibility to detect the rotational direction by controlling which signal is trailing the other. By using the pulses from both outputs the quadrature signal will also give the possibility to double the resolution. Consider a gearwheel with 100 teeth, if we are also counting the quadrature outputs pulses we will get a total of 200PPR (Pulses Per Revolution) and in this way, 7.1 times higher resolution compared to the current systems 28PPR.

If even higher resolution is desired the falling edge of the pulses can also be used, which increases the resolution two times further.
Because this sensor is measuring the size of the magnetic flux, instead of the change as the variable reluctance sensor does, it might be more sensitive to EMC. However, the sensor is mounted inside the casing of the gearbox, so depending on the material the housing is made of, this might give sufficient shielding. This will be necessary to investigate further.

3.3.2. Rotary Hall Encoder

The Rotary encoder sensor measures the angle of the magnetic field formed from an ordinary permanent magnet rotating above the sensor. The exact implementation differs between the manufacturers, but usually four Hall elements are placed uniformly in a circle. Each Hall element can estimate the size of the magnetic flux in one axis. When the magnetic field is rotating above the sensor, this will create a sinusoidal signal. By adding another element measuring the perpendicular direction of the first, it is possible to calculate a two-dimensional direction of the field, since another sinusoidal signal 90° out of phase with the first is added. The angle of the field can now be calculated from

$$\varphi = \arctan\left(\frac{\sin(\varphi)}{\cos(\varphi)}\right)$$  \hspace{1cm} (17)

To get a stronger signal, higher sensitivity, less disturbance from noise and lower the bias error, a multiple of four sensor elements are used. The positive aspects with this are that the magnetic field is approximately stronger at the edges of the magnet, as well as the possibility to use a differential sensing solution, where the two elements opposite each other are connected, giving twice the signal amplitude and also eliminating stray fields.

The sine signal is given by $$S_1 + S_2 - S_3 - S_4$$
and the cosine signal is given by $$S_1 - S_2 - S_3 + S_4$$ [22].

The sensor only consists of a permanent magnet and a small system-on-chip containing integrated Hall elements together with digital signal processing. Since there are no moving parts together with the fact the sensor is an integrated circuit, the sensor is small, cheap and robust. The precision of the sensor depends on the manufacturer, but models with 8-12 bit resolution are available. Since these sensors are system-on-chip, they are available with different types of output signals like absolute angle given in PWM, serial bit stream, analogue sine wave output and incremental signals. Most sensors are capable of rotational speeds of up to 30000rpm which is well over the rotational speed in the gearbox. Since these sensors all measure absolute angles, they are also able to tell the rotational direction and have zero velocity measurement capability.

According to [23], external disturbing magnetic fields, EMC, which are perpendicular to the sensor are completely compensated. The reason is that the sensor measures the magnetic flux direction parallel to the sensor, so external fields parallel to the sensor can add an error to the calculated angle. The size of the error depends on the magnitude of the sensing magnet field as well as the magnitude of the disturbing external field. According to [12], the vehicle needs to handle DC fields of up to 25mT and AC fields up to 200μT. Sensors using this technology usually require an operating magnetic field of 20-70mT.
which imply that the sensor needs to be shielded to ensure the sensing quality. Since the sensor will be mounted inside the gear casing, this could serve as a shield, depending on the casing material. If the housing will provide sufficient shielding needs to be investigated.

3.4. Resolver

The resolver is a very old sensing solution, used in military applications even earlier than World War II. It is used to measure the absolute angle of a rotating shaft through an analogue signal.

The resolver is a rotary transformer where the amplitude of the signal in the resolver varies sinusoidal as the shaft is rotated. It consists of one primary winding, called the reference winding, which is located in the rotor. Then there are two secondary windings, the sine and cosine winding, both located in the stator. To get the sine and cosine signal, these two windings are physically displaced by 90°.

In general the reference winding is fed by an AC-voltage. The induced voltages in the two secondary windings are equal to half the amplitude of the reference voltage multiplied by the sine or cosine of the input shaft angle. The angle of the shaft can then be calculated by

\[
\frac{\sin(\theta)}{\cos(\theta)} = \tan(\theta) \rightarrow \theta = \arctan \left( \frac{\sin(\theta)}{\cos(\theta)} \right)
\]

where

\[ \theta \] is the angle of the shaft [rad]

Figure 12: Signal format from Resolver
Even though this kind of sensor can achieve great accuracy and resolution its design is complex and expensive. The original design with the primary winding in the rotor either requires brushes that eventually will wear out or a transformer to transfer the reference signal into the rotor. There are however new designs that has incorporated the primary winding into the stator together with a solid rotor, allowing a completely contact less design [14].

![Figure 13: Comparing a traditional resolver (to the left) with a resolver using solid rotor (to the right)](image)

Resolvers usually require a high level of manual labour in the manufacturing, which causes a higher price. The new design with a solid rotor do however reduce the windings needed and because of this also the cost.

### 3.5. Optical Encoder

The optical encoder consists of a light source, a receiver and a rotating disc. The sensor can be designed in two ways; either the disc has several transparent sections and is rotating between the receiver and the light source or the light source and receiver is on the same side and the rotating disc consist of alternating reflexive and non-reflexive areas.

This type of sensor is capable of giving very high resolution, but it has some drawbacks. Since it is working with light, there is a great demand for cleanliness [3], making it necessary to enclose the disc, light-source and receiver. Because of this it is also necessary to use bearings to disclose the sensor from the outer world. This will add contact points that ultimately will wear out, increasing the costs for the customer. In addition, the sensor disc is usually made of glass, making it sensitive to vibrations and is not likely to withstand vibrations of up to 50g that can be produced in a vehicle transmission. The rotor plate can however be made in metal and those could be made to cope with these demands, but sensors with metal discs generally have lower resolution.

![Figure 14: Optical sensor](image)
Using an optical sensor for speed measurement would possibly give the required performance. Most optical sensors use a quadrature output, two output signals where one is 90 degrees out of phase with the other, which gives the ability to detect rotational direction. This type of sensor is probably not an alternative for series production. The cost is too high and it will have a finite lifetime.

### 3.6. Giant Magneto Resistive

The giant magneto resistive sensor is sensitive to magnetic fields. The technology is today mostly used in hard-disc drives for computers, due to their high sensitivity to magnetic fields. Theoretically the GMR sensor will give a higher sensitivity than Hall technology, resulting in a possibly higher resolution and/or accuracy due to a higher S/N ratio.

The theory behind GMR is different from the Hall technology. Instead of a voltage, which is produced by the Hall sensor, the GMR will change its resistivity depending on the size of the magnetic field.

The first GMR structures suitable for device applications were multilayer configurations. Usually they consisted of up to 20 non-ferromagnetic/ferromagnetic bi-layers, which resulted in high GMR values. These structures are suitable for detection of in-plane magnetic field strength, independent of the direction of the field.

GMR spin valve structures were developed in the early 1990 for the use in read-heads in computer hard-drives. The properties of the spin valve structure can be adapted to measure field-strength and/or field-direction. A GMR spin valve system consists of two ferromagnetic layers, separated by a non-magnetic layer. One of the ferromagnetic layers is called the “pinned” layer and the other the “free” layer. The pinned layer has a fixed magnetization direction, whereas the free layers magnetization is supposed to follow the external in-plane magnetic field.

When the GMR is being saturated, i.e., for magnetic fields in the range of 10 mT, the free layer will be aligned with the direction of the external field. The resistance of the GMR will then be a function of the cosine of the angle between the magnetizations of the pinned and free layer. In this way the GMR can be used as a rotary angle sensor [4].

Each GMR-structure gives the cosine function of the magnetic direction compared to its pinned layer. The output from the cosine function is unambiguous only over 180 degrees. So to be able to calculate the angle of the full turn the sine function is also needed, which is made by having another structure with the pinned layer turned 90 degrees from the first.

With magneto resistive sensors it is also common to connect several structures in a so called bridge configuration. The reason is that it will double the resistance change of the GMR structure.

In Figure 15, the design of Infineons GMR sensor is displayed. There are two GMR bridges, measuring sine and cosine components respectively. Both components are needed to be able to get 360 degrees repeatability. The small boxes in Figure 15 represent the GMR structures.
and the arrow in each show the magnetic direction of the pinned layer.

**GMR Bridges**

![GMR Bridges Diagram]

**Figure 15: GMR sensor setup**

### 3.7. Conclusion of alternatives

All these sensors are capable of producing signals to compute vehicle speed but they all have different pros and cons.

- **Active inductive sensors** are insensitive to external magnetic fields, but EMC radiation and manufacturing costs are too high.
- **Capacitive sensors** are capable of high resolution measurements. However, these sensors are very sensitive to dirt and liquids.
- **Sensors using Hall technology** are widespread in the automotive market due to low manufacturing costs and adequate performance. There are different approaches on the technology, resulting in sensors resembling of the VR sensor as well as absolute angle sensors.
- **The Resolver** is an old and proven technology that is capable of high accuracy angle estimates, but compared to other technologies these sensors are too large and the cost for manufacturing is too high.
- **Optical encoders** are probably the kind of sensors resulting in the possibility of highest performance. However the technology require a high degree of cleanliness and the manufacturing cost is also not favourable.
- **Giant Magneto Resistive sensors** are very sensitive to magnetic fields. The rotational velocity is computed from the angle of a rotation magnetic field. The GMR sensors offer great possibilities for high accuracy and resolution. Considering the similar approach as with absolute angle Hall sensors both some of the positive and negative aspects with this kind of measuring are present.
4. Results

In this application for a wheel-loader, where the prime objective is to measure the rotational velocity and acceleration, there is actually no need to be able to measure absolute angles for the gear axles.

However, absolute angle sensors are chosen for studies due to their high resolution and the possibility to measure zero velocity and rotational direction. This could also improve the control strategies during a gear shift, since a better control of the clutch slip is possible to obtain.

Since the output from these sensors is the angle of the axle, the algorithm to calculate speed and acceleration has to be investigated considering noise and vibrations. If the signal is noisy it will have to be filtered, which will introduce time delays to the signal.

All absolute angle sensors are active, compared to the VR sensor that is passive. The word active relate to the sensor having a power supply whereas the passive sensors do not. This allows the sensor to send its output digitally to the TECU. A result of this is no need for analogue filtering and hysteresis on the TECU inputs because no noise caused by the transmission will be present. This will possibly lower the time delays as well as cost for the TECU since less hardware is needed. The sensor itself will probably introduce some kind of time delay, but these will be low compared to the analogue filtering.

Because of demands in non-contact measurement and low cost a decision was made to only study magnetic absolute angle sensors. This kind of sensor can be made both with GMR and Hall technology as described above. Both technologies have their pros and cons and will therefore be evaluated considering mounting tolerances, signal quality, measurement accuracy and cost. For this purpose, a Hall sensor from Austrian Micro Systems and a GMR sensor from Infineon have been acquired.

The sensors are evaluated in a test bench, see Figure 16, containing a step-motor simulating a driven gear-axle and an optical encoder to give a good reference signal. The test bench allows tests to be made in similar working conditions as in a real transmission. The tests are focused on low rotational speed because of two reasons. Firstly, the maximum speed of the step motor is limited. Secondly, since good estimations can already be done at high velocity this is the most interesting working condition to investigate. Unfortunately, this does not automatically mean that these sensors will be good at high speed and it needs to be investigated further. Aspects as mounting tolerances will also be investigated.

All sampling of sensor data are made with a measuring system from IMC called Cronos PL3. Measurement data will be sampled to analyze the sensor signals and speed calculation algorithms.

In the conclusions the gear actuated Hall sensor will be mentioned even though it has not been tested. The reason is that it is a proven technology and lots of information is already available and also since there is an interest on Volvos behalf of this sensor.
In this section the results from the tests with the two sensor types studied in this thesis will be presented. The results will include tests of the mounting tolerances both in axial and radial direction required of the sensor. The noise generated by the sensor and the required filtering to get satisfactorily measurement results is also controlled. The algorithm for how the rotational velocity is calculated is also presented.

### 4.1. Rotary Hall encoder

Absolute angle encoders based on the Hall technology is available from a few different manufacturers. Every manufacturers products have their own features and may give different performance in areas like mounting tolerances etc. The sensor chosen in this report is manufactured by Austrian Micro Systems and the model is AS5043 [15]. This sensor uses four Hall elements to detect the direction of a magnetic field and also contain integrated signal treatment to calculate the angle of the field. This specific model represents the angle of the field with a specific signal amplitude.

#### 4.1.1. Output signal format

This specific model represents each angle of the field with a specific signal amplitude as can be seen in Figure 17. Other models use different ways of presenting the angle, e.g. incremental, PWM and serial transfer.
4.1.2. Calculation of speed

Since the intended use of the sensor is for speed estimation it is necessary to control if the signal quality is good enough to derive the speed. The rotational velocity is simply the time discrete derivative of the angle, which is calculated with the following equation

$$\frac{\alpha_t - \alpha_{t-1}}{T_s}$$  \hspace{1cm} (19)

where

- $\alpha_t$ is the angle of the magnetic field at sample $t$
- $\alpha_{t-1}$ is the angle of the magnetic field at sample $t-1$
- $T_s$ is the sample period

At the signal plunge, when the angle passes 360°, some detection and treatment is necessary to get correct speed estimations. The computed rotational velocity can be seen in Figure 18, where the sensor signal has been differentiated with 10ms resolution. In the figure the signal from the optical reference encoder is also included. As can be seen, the differentiated signal is very noisy and filtering of the signal will be necessary.
Calculating the velocity using a Kalman filter instead of the simple differentiation will be discussed further in Chapter 4.3.

### 4.1.3. Filtering of the signal

When choosing a filter one should consider that a flat behaviour in the pass band is necessary to get correct velocity estimations. A steep transition between the pass and stop band is also preferable as well as low time delays. To achieve low time delays small phase delays are necessary.

Among the standard filters there are a few that has a flat behaviour in the pass band, e.g. the Butterworth and Chebyshev type II filters. Compared to the Butterworth filter the Chebyshev is sharper in the transition between the pass and stop band. The Chebyshev type II do however give some ripple in the stop-band.

To compare the two filter types a bode plot for both filters with a cut off frequency of 20rad/s is presented in Figure 19 below. The Chebyshev filter drops a lot sharper than the Butterworth, which possibly can allow a lower order or higher cut off frequency. The phase shift of the signal is however greater, leading to a greater time delay on the signal. This will be investigated more in detail later.
In Figure 20, the filtered velocity signal from the absolute angle encoder is plotted. In the upper plot, Butterworth filters of the order two and four are plotted together with the optical reference signal. In the lower plot, Chebyshev type II filters of the order two and four are used. As can be seen, it is possible to get quite accurate signals with all these filters. With the Chebyshev filters a higher cutoff frequency is possible to use compared to the Butterworth filter, but it can be seen that some higher frequency noise also has passed through the filter.

In the filtered signals in Figure 20 there is low frequency noise present. This noise will be investigated further in Chapter 4.1.4.
The filters used here have a very low cut off frequency which leads to large time delays as can be seen in Figure 21. In [2] the author state that the maximum frequency drop for the old measurement system is 8000Hz/s. This corresponds to a deceleration rate of 1800 rad/s² or 17000RPM/s on the axle. However, the accuracy of this statement can be discussed, during tests in a wheel-loader the deceleration rates never got higher than 140rad/s² or about 1400RPM/s for the gear axle, at quite hard braking.

The frequency drop shown in Figure 21 is about 1500RPM/s, the exact number is hard to say because the axle is vibrating slightly when it is coming to a halt, resulting in the optical encoder to give a bad reading.

Unfortunately, the time delay caused by the filters at this frequency drop is unacceptably high, from 100ms for the best to more than 250ms for the worst. Raising the cut off frequency would lower the time delay, but instead this would increase the influence of noise on the signal.
Figure 21: Time delays from filters on sudden signal drop

Since the signal from the sensor is not sinusoidal the time delays caused by filtering cannot be directly compared with those for the variable reluctance sensor. At a constant speed the angle from the sensor will behave like a ramp and the interesting frequency components will be in the low frequency area. The time delays caused by the filters are interesting since this time delay will be present in the speed measurement.

The time delays in the filters is calculated with equation (20) [17]

$$T_d = \frac{\varphi}{\omega}$$

(20)

where

- $T_d$ is the time delay at frequency $\omega$, [s]
- $\varphi$ is the phase shift in the filter at frequency $\omega$, [rad]
- $\omega$ is the frequency of the signal, [rad/s]

In Figure 22 the time delay for the filters used in Chapter 4.1.3 is shown against frequency. As can be seen the time delay is very large at low frequencies and something needs to be done
to lower the delays. Remember that the sample period was 10ms, so a time delay of 12 times that is not acceptable. Interesting to note is also that even though the Chebyshev filter has a higher cut off frequency than the Butterworth it has a significantly higher time delay.

![Time delay for Butterworth and Chebyshev type II filter](image)

**Figure 22: Time delay for Butterworth and Chebyshev filters of order 2**

To illustrate the effect of the time delays the filtered signals are plotted together with the optical reference when the speed has sinusoidal variation. This is shown in Figure 23 and, as can be seen, the filtered velocity estimation is noticeably delayed compared to the optical reference signal.
4.1.4. Analysis of low frequency noise

The low frequency oscillations seen in the previous paragraph have a repetitive behaviour and to investigate where they come from we start by calculating the period of the oscillations. From the period the frequency of the oscillation can be calculated using

\[ f = \frac{1}{T} \]  

(21)

where

- \( f \) is the frequency of the signal [Hz]
- \( T \) is the period of the signal [s]

From Figure 24, the period of the oscillations from a true signal can be detected. In Figure 24 the axle is turning with a constant velocity which is necessary to get acceptable results. The period of the signal is in the order of 0.2 seconds (0.2289). Using (21) this will result in a frequency of 4.3687Hz.

Since the noise is periodic there was an assumption that it has some correlation with the rotational velocity of the magnet. To prove this the frequency of the noise is used together with the rotational velocity by equation (22)
\[ n = \frac{f_{RPM}}{60f} \]  

(22)

where

- \( f_{RPM} \) is the rotational velocity given by the optical reference, [RPM]
- \( n \) is the number of periods per each revolution of the magnet
- \( f \) is the frequency of the oscillations, [Hz]

The reason for the division by 60 in equation (22) is that the rotational velocity is given in revolutions per minute and the oscillation frequency in Hz. From (22) \( n=1 \) is obtained. This means that the oscillations have the same period as the turning rate of the magnet. There are a few possible causes for these oscillations, for instance linearity errors due to the magnet offset. Which will be further discussed in Chapter 4.4. Other possible causes could be electrical linearity errors, caused by the sensor DAC or displacement of the Hall elements. These causes are more difficult to investigate and are outside the scope of this thesis.

![Figure 24: Low frequency oscillations in speed signal](image)

4.1.5. Mounting tolerances

For industrial manufacturing the mounting tolerances are important since these define the complexity during manufacturing and assembly. For this type of sensor there are two interesting tolerance measures, in axial and radial direction. Both the axial and radial offset will affect the magnetic field strength reaching the sensor whereas it is only the radial offset that will affect the signal linearity.
Measurements in the test rig show that the sensor is sensitive to the distance between sensor and magnet. At a small axial distance like 1.5mm, the signal from the sensor get disturbed and quickly diminishes. The distance is of course very dependent on the magnet that is used and with a stronger magnet it should be possible to increase the distance further.

As can be seen in Figure 25 the signal becomes distorted and to compute a velocity out of this signal is impossible.

In Figure 26 the signal from the sensor with 1.5mm radial offset is plotted. In the figure there is a line that shows how a linear rise would look like and as can be seen the actual signal is warped. An explanation to this phenomenon can be found in Chapter 4.4. It is interesting that the signal with axial offset is not distorted in the same way as with radial offset. Probably this is because the edge of the magnet is still closer to the sensing area with radial offset compared to axial offset.

Figure 25: Signal from Hall sensor at 1.5mm axial distance
4.2. Giant Magneto Resistive Sensor

In computer hard drives the GMR technology has been used for over a decade, but in sensors for automotive it is a new technology. From what has been found, sensors for absolute angle detection are available on the market today from the manufacturers Infineon and the NVE Corporation. For the tests in this thesis, the TLE5010 sensor manufactured by Infineon was chosen.

4.2.1. Output signal format

The TLE5010 sensor uses a serial communication protocol called SSC, Synchronous Serial Communication. The sensor is representing the magnetic field direction with a sine and cosine signal. The amplitudes of these two signals are stored as two signed 16-bit values. In Figure 27, the ideal signal output from the sensor is shown with the two angular components.

To be able to read the values of the two components from the sensor, the SSC had to be created. The measurement system used for these tests was not able to handle serial communication of this type and therefore the sensor was connected to a microcontroller. The microcontroller converted the signal to a format the measurement system was able to read.
The chosen microcontroller was the AVR from Atmel, which supported both the SSC protocol as well as PWM.

Since a microcontroller was needed, the first intention was to use it to also compute the angle of the magnetic field and then represent the angle with PWM. Unfortunately it was not as easy as anticipated since the available implementations of trigonometric functions for the microcontroller had no support for 16-bit unsigned integers. A software implementation for this was made but did not work as intended. Therefore, the two 16-bit sinusoidal signals were represented by PWM instead and the angle computed in Matlab. In addition, the signal from the sensor is not normalized and compensation for that as well as for the offset error needs to be done, which is a lot easier to do in Matlab than implementing in a microcontroller.

The resulting signals after conversion from PWM can be seen in Figure 28. The signal in Figure 28 is the result of the axle turning at 240rpm and at a distance of 4mm. As can be seen the signals are not normalized and quality of the signal is quite good. In Figure 29 a plot of the signal when the turning axle suddenly stops is shown. As can be seen the amount of noise is low when the axle is not turning.
Figure 28: GMR sensor output with axial distance of 4mm

Figure 29: GMR sensor output with axial distance of 4mm when axle suddenly stops
4.2.2. Calculation of angle and speed

To compute the magnetic field angle, (23) is used. However the tangent function is $\pi$ periodic with the primitive period $[-\frac{\pi}{2}, \frac{\pi}{2}]$ so it is necessary to check the sign of the sine and cosine functions, respectively, to get a full $2\pi$ period.

$$\alpha = \arctan \left( \frac{\sin(\alpha)}{\cos(\alpha)} \right)$$

(23)

where

$\alpha$ is the angle of the magnetic field

Using (23), the resulting plot of the calculated angle for the field can be seen in Figure 30.

![Calculated angle of magnetic field](image)

Figure 30: Resulting angle of the magnetic field

Unfortunately, the computed angle is not perfectly linear even though the test bench motor is held at a constant speed. This will probably make the calculation of the speed noisy.

The calculation of speed is made by a simple differentiation using (24). The resulting plot for the velocity is shown in Figure 31. As can be seen and as was expected the resulting signal is noisy and filtering will be needed to get useful information from it. Other methods to calculate the speed in a more robust way will be discussed in Chapter 4.3.
\[
\frac{\alpha_t - \alpha_{t-1}}{T_s}
\]

where

\( \alpha_t \) is the angle of the magnetic field at sample \( t \)

\( \alpha_{t-1} \) is the angle of the magnetic field at sample \( t-1 \)

\( T_s \) is the sample period

---

**4.2.3. Filtering of the signal**

As mentioned earlier in Chapter 4.1.3, some things need to be considered when choosing a filter. As for the Hall sensor, the GMR needs a flat behaviour in the pass band to get correct velocity estimations. Also low time delays are preferable which requires small phase delays. When filtering the Hall sensor the Butterworth and Chebyshev Type II filters was chosen and those filters will be tested here as well. The filters need a very low cut off frequency to get satisfying estimations of the speed. Unfortunately this introduces large time delays to the signal. The time delays for the filters are demonstrated in Figure 33 and can also be seen in Figure 34.

In Figure 32, the filtered signals is shown using a Butterworth filter with cut off frequency 5Hz and a Chebyshev filter with cut off frequency 12.5Hz at a constant velocity. These signals can still seem noisy, but remember that 230RPM only correspond to a velocity of 2km/h for the vehicle, or 100Hz for the current system. A 5% error at this speed is merely corresponding to 0.1km/h.
Figure 32: Filtered Calculated velocity from GMR sensor

Figure 33: Time delay caused by filtering on sudden velocity drop
Figure 34: Time delays for Butterworth and Chebyshev Type II filters

The time delays introduced by the filters are however large, making the speed estimation slow at sudden changes as can be seen in Figure 35. The Butterworth filter is behaving better than the Chebyshev but not much better. The shape of the signal is kept quite good except at some places where the changing rate of the velocity is too big. This signal is good enough to be used as a velocity signal, but it would not be an improvement compared to the current method, considering the time delays.
4.2.4. Mounting Tolerances

For industrial manufacturing the mounting tolerances are interesting since these define the complexity during manufacturing and assembly. For this type of sensor there are two interesting tolerance measures, in axial and radial direction. Both the axial and radial offset will affect the magnetic field strength reaching the sensor whereas it is only the radial offset that will affect the signal linearity.

The GMR sensor is told to be more sensitive to magnetic fields than the Hall sensor. This is also proven in the test bench. The same magnet is used for both sensors which gives a good comparison between the two sensors. In Chapter 4.1.5 it was mentioned that the Hall sensor was not able to measure the angle of the magnetic field at distances larger than 1.5mm. Tests show that the GMR sensor can handle at least ten times of that. In Figure 36 and Figure 37, plots of the components and the computed angle at an axial distance of 16mm are shown. As can be seen the quality is not noticeably worse than at 4mm.

Concerning radial displacement the GMR sensor can handle a larger distance than the Hall sensor and still get a signal. The signal given at radial offset is however not good and can be considered useless. The reason for this is discussed further in Chapter 4.4.

In Figure 38 and Figure 39, the components and the computed angle from the sensor with a radial offset of 3mm is shown.
Figure 36: Signal components from GMR sensor at 16mm axial offset

Figure 37: Computed magnetic field angle at 16mm axial offset
Figure 38: Signal components from GMR sensor at 3mm radial offset and constant rotational velocity

Figure 39: Computed angle from GMR sensor with 3mm radial offset and constant rotational velocity
4.3. Robust differentiation through Kalman filtering

In the previous chapters the velocity was calculated by simply differentiating the measured angle. The measured angle is noisy for both sensors and differentiation yields inaccurate estimates of the velocity which therefore needed to be filtered to give useful information. Unfortunately, results show that the time delays caused by the filters are unacceptably long.

In an attempt to resolve this problem a Kalman filter is used to estimate the velocity in a more robust way.

To describe the system with a turning axle we introduce three states

\[
\begin{pmatrix}
    x_1 \\
    x_2 \\
    x_3
\end{pmatrix} = \begin{pmatrix}
    \theta \\
    \dot{\theta} \\
    \ddot{\theta}
\end{pmatrix} = \begin{pmatrix}
    \theta \\
    \omega \\
    \alpha
\end{pmatrix}
\] (25)

where
- \( \theta \) is the angle of the axle [rad]
- \( \omega \) is the angular velocity [rad/s]
- \( \alpha \) is the angular acceleration [rad/s²]

The result is the continuous state space equation

\[
\dot{x}(t) = A_c x(t) + G_c w(t) = \begin{pmatrix}
    0 & 1 & 0 \\
    0 & 0 & 1 \\
    0 & 0 & 0
\end{pmatrix} x(t) + \begin{pmatrix}
    0 \\
    0 \\
    1
\end{pmatrix} w(t)
\] (26)

\[
y(t) = C_c x(t) + v(t) = (1 & 0) x(t) + v(t)
\]

where
- subscript \( c \) relate to the matrixes being for the continuous model
- \( w(t) \) is the process noise which we assume to be white noise.
- \( v(t) \) is the measurement noise which we assume to be white noise.

Since we are working with sampled values of the angle, the discretized state space form is wanted. According to [16], we will get a discrete state space form where the states still have their physical interpretation by sampling of (26). Such a discretization can be made with different degrees of accuracy. A simple assumption is to make a differential approximation of the derivative in (26). That is

\[
\dot{x}(t) \approx \frac{1}{T} (x(t + T) - x(t))
\] (27)

where
- \( T \) is the sample period [s]

Inserting (27) into (26) results in
\[ x(t + T) = Ax(t) + Gw(t) \]
\[ y(t) = Cx(t) + v(t) \]  \hspace{1cm} (28)

where the matrices \( A, G \) and \( C \) are given by
\[ A = e^{AT} \equiv I + AT + \frac{A^2T^2}{2!} + \frac{A^3T^3}{3!} + \ldots \]
\[ G = \int_0^T e^{As} C \, ds \]  \hspace{1cm} (29)
\[ C = C_c \]

By combining (28) and (29), our discrete state space model will be
\[
\begin{align*}
    x(t + T) &= \begin{pmatrix} 1 & T & T^2 / 2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{pmatrix} x(t) + \begin{pmatrix} T^3 / 3! \\ T^2 / 2! \\ T \end{pmatrix} w(t) \\
    y(t) &= (1 \quad 0 \quad 0) x(t) + v(t)
\end{align*}
\]  \hspace{1cm} (30)

Now when the system is on state space form the Kalman filter can be calculated. According to [24], the observer that minimizes the estimation error \( x(t) - \hat{x}(t) \) is given by
\[
\hat{x}(t + 1|t) = A\hat{x}(t|t-1) + Bu(t) + K(y(t) - C\hat{x}(t|t-1) - Du(t))
\]  \hspace{1cm} (31)

where \( K \) is calculated by
\[
K = \left( APC^T + NR_{12} \right) \left( CPC^T + R_2 \right)^{-1}
\]  \hspace{1cm} (32)

\( P \) is the symmetrical positive semi-definite solution of the matrix equation
\[
P = APA^T + NR_1 N^T - \left( APC^T + NR_{12} \right) \left( CPC^T + R_2 \right)^{-1} \left( APC^T + NR_{12} \right)^T
\]  \hspace{1cm} (33)

where
\[
\begin{align*}
    R_1 &\text{ is the intensity of } w(t) \\
    R_2 &\text{ is the intensity of } v(t) \\
    R_{12} &\text{ is the cross spectrum between } w(t) \text{ and } v(t)
\end{align*}
\]

The observer (31) using the value of \( K \) given by (32) is called the Kalman filter.

When comparing the Kalman estimated velocity to the differentiated and Butterworth filtered signal, the time delay for the Kalman filter is even greater than for the Butterworth filtered signal. Quicker responses are possible, but at the cost of more noise. Figure 40 and Figure 41 show a comparison between the Kalman filtered signal and the Butterworth filtered differentiated signal.

If the system model in the Kalman filter was extended with inputs like demanded torque and brake pedal position, it is possible that the results for the filter would be better. This would
make it possible for the filter to estimate the change in the signal better compared to just have all change as white noise. An alternative to this would be to use change detection instead.

Figure 40: Comparison between Kalman estimated velocity and butterworth filtered differentiated signal

Figure 41: Comparison between Kalman estimated velocity and butterworth filtered differentiated signal
4.4. Magnetic direction deviation due to magnet misalignment

When mounting the sensor, it is difficult to mount it exactly in line with the magnet. This misalignment will affect the calculated angle, and in turn cause an error in the estimated speed.

To simulate its behaviour the magnet is assumed to be spherical for simplicity, resulting in a dipole magnetic field. The magnetic field matrix is calculated, and the gradient for every point on a full circle around the magnet is defined.

The radius of the magnetic field is given by

\[ r = R \sin^2 \theta \]  \hspace{1cm} (34)

where
- \( \theta \) is the angle from the magnets north-pole
- \( R \) is the maximum distance for the field from the magnet
- \( r \) is the distance for the field at angle \( \theta \).

In Figure 42, a simulation is shown. In the simulation \( r \) is held constant, while \( \theta \) and \( R \) are being varied. The measured angle will not change linearly with the actual angle. If the sensor is only used for angular measurements the linear error might be negligible. But since the intended use is to measure rotational velocities it is the derivative of the signal that is interesting. The behaviour of this signal will result in a velocity signal oscillating around its actual value. This oscillation can be removed from the signal but since it is low frequent compared to other disturbances it will require a low cut off frequency for the filter and the result will be large time delays. Thus the offset of the magnet is of great importance for the resulting system performance.
Figure 42: Simulated angular error caused by magnet offset
5. Conclusions

In this chapter, the conclusions from the study will be presented. First a performance table for each sensor is presented; it will give a good overview of the capabilities for each technology. For every sensor, a brief description about the grades are also given. Even though the gear actuated Hall sensor was not included in the study it will be presented here. The reason is company interest in Hall sensors and the fact that this kind of sensor is already well described, not making it necessary to study it much further in this thesis.

Then the final conclusion will be presented where the opinion on which system that has the most potential is given.

5.1. Performance table

The gradings in this performance table will where it is applicable be 1 (low grade) to 5 (high grade)

<table>
<thead>
<tr>
<th></th>
<th>Inductive (VR)</th>
<th>Gear actuated Hall</th>
<th>360 Hall</th>
<th>360 (Infineon)</th>
<th>GMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tolerance to</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>measurement distance (axially)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tolerance to</td>
<td>N/A</td>
<td>N/A</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>measurement distance (radially)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time delay</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>1-2</td>
<td>1-3</td>
<td>3-4</td>
<td>5</td>
<td>Resolution is depending on the application, but very high</td>
</tr>
<tr>
<td></td>
<td>Depending on target wheel, currently 28PPR</td>
<td>Depending on target wheel</td>
<td>Depending on model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Price</td>
<td>~SEK 70 /sensor</td>
<td>~SEK 100 /sensor</td>
<td>~SEK 35 /chip (encapsulation is needed)</td>
<td>~100 /chip (encapsulation is needed)</td>
<td></td>
</tr>
<tr>
<td>Absolute angle measurement</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Rotational direction</td>
<td>no</td>
<td>yes/no depending on actual sensor</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Implementation cost/difficulty</td>
<td>N/A</td>
<td>1-&gt;5</td>
<td>3</td>
<td>3-&gt;5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depending on the application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Possibility to use sensor in more applications</td>
<td>no</td>
<td>Maybe</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>
5.1.1. **Variable reluctance sensor**

This is the sensor used in the current system. The design of the sensor is simple, robust and cheap. It is possible to raise the resolution with this sensor, using a different gear. To detect rotational direction two sensors of this type are needed. The actual resolution can be increased four times using the signal from this extra sensor as well as the falling edges of the signals without any other changes to the gearbox which would be quite a good improvement.

When using two of these sensors the mounting tolerances do however get tighter since they need to have a phase shift close to 90 degrees between each other. Assume we have a tolerance of 45 to 135 degrees phase shift, for the gear with 28 teeth the mounting tolerances for both sensors together then would be 3.2 degrees.

These sensors are also still not capable of zero velocity measurements, since the amplitude of the signal will become too weak. They are also sensitive to the distance between gear and sensor, requiring small distances when being mounted.

5.1.2. **Gear Actuated Hall sensor**

The gear actuated Hall sensor uses the same principle as the VR sensor, by sensing moving teeth on a gear. Therefore, no substantial changes are needed to use this sensor in the current system. However it also means that the sensor does not give any substantial improvement in resolution compared to the current system unless changes in the gearbox are performed. As described in Chapter 3.3.1, the resolution with this kind of sensor can be improved considerably using a different gear wheel which, however, increases the cost for implementation.

These sensors are available with a quadrature output, giving the capability of detecting rotational direction with only one sensor. Since the sensors are manufactured with a specific design of gear wheel it will need to be adapted to the specification of the sensor, or the other way around for this to work. As was written in Chapter 5.1.1, if the quadrature signal together with detection of the falling edges is used an improvement of the resolution with four times can be obtained.

The signal amplitude is also not sensitive to the rotational velocity as the VR sensor is, making it capable of having a signal even down to zero velocity. These two features are the most obvious improvements compared to the VR sensor.

5.1.3. **Absolute Angle Hall sensor**

This sensor is tested and described thoroughly in the Chapters 3.3.2 and 4.1. These sensors use a different way to measure than both the VR and gear actuated Hall sensor do, since they measure the angle of a magnetic field instead of passing gears. The field is created by a diametrally magnetized permanent magnet rotating above the sensor body. For the application in a gearbox this magnet would be mounted in the end of gear axle and the sensor mounted axially with the axle.

Since the sensor is measuring the angle of the magnetic field its resolution is not determined by any hardware in the gearbox, but only by the sensor itself. This will make it easier if higher or perhaps lower resolution is wanted in the future.
The mounting tolerances for this sensor are quite tight, but they are not tighter than for the VR sensor.

These sensors are widely used and are now available with several output formats, like analogue, PWM, incremental and serial transfer. The sensor tested here has an analogue output where the angle is represented with a voltage. This might not be the perfect format to transfer the information since it is susceptible to disturbances and noise from conversion between digital representation to analogue and vice versa.

For the use as a velocity sensor the incremental output might be the most interesting, unfortunately no opportunity was given to test a sensor with this output.

The tests showed that the differentiated velocity calculated from the angular information was very noisy and the signal needed great amounts of filtering. This resulted in time delays on the signal that were quite large. It is hard to tell if an improvement of the time delays is possible unless the amount of noise is reduced.

5.1.4. Absolute Angle GMR sensor

This sensor is tested and described thoroughly in the Chapters 3.6 and 4.2. In the same way as the absolute angle Hall sensor it is based on a different measuring principle than the VR and gear actuated Hall sensor do, since it measures the angle of a magnetic field. The field is created by a diametrally magnetized permanent magnet that is rotating above the sensor body. For the application in a gearbox this magnet should be mounted at the end of the gear axle and the sensor should be mounted axially to the axle.

Like the Hall version of angle sensors this sensor is also not limited by any hardware inside the gearbox. This make it easier when different resolutions are wanted.

The GMR technology has been in use for over a decade in computer hard drives due to its high sensitivity to magnetic fields. In the application of sensing the angle of a magnetic field it has not been used as long but there are a few manufacturers that supply this sensor.

The largest feature for this sensor, compared with the absolute angle Hall sensor is the increased sensitivity. My tests show that this sensor can handle more than 10 times larger distances between the magnet and sensor compared to the Hall sensor. This will greatly simplify the mounting of the sensor. But the sensor is still very sensitive to radial displacement due to distortion of the signal components.

Just like the absolute angle Hall sensor, the GMR require a great amount of filtering to give useful information. This introduces a significant time delay on the signal.

5.2. Final Conclusions

Considering the various demands and the results from my test, my conclusion is that there are in fact two interesting methods to study further. The first is the absolute angle sensor using GMR technology.

Even though the signal must be heavily filtered, it has many positive aspects. The mounting tolerances for this sensor are unsurpassed by any other technology available today. Also the
possibility to detect the exact angle of the axle might be interesting during gear changes to
detect slip in the clutches.

If a shorter sample time is wanted in the future this sensor will be able to cope with that due to
its high resolution and output format. However, it would yield an increased amount of
measurement noise that need to be removed. The only uncertainty factors that is noticeable for
this sensor is the time delays from filtering and the EMC demands.

The other interesting method is, even though it is simple, the gear actuated Hall sensor. It is a
proven technology which is widely used in the automotive industry. Since the measurement is
made on physical teeth the noise can be kept quite low.

Thanks to a quadrature output the rotational direction of the gear is possible to detect and by
also using the quadrature output together with falling edges on the signals a higher resolution
can be achieved.

This kind of sensor would not require especially large changes in the current hard and
software, reducing the cost for implementation. If a higher resolution is wanted than what is
possible from the current gear, finer teeth can be made, either by adding a separate toothed
disc or by milling teeth into an existing moving part in the gearbox.

5.3. Examples of further studies
The disturbances of the measured angle should be investigated further. A good model of this
behaviour could be used to compensate for these disturbances in the vehicle and also be
calibrated at service in the vehicle to compensate for wear. This compensation would allow
less filtering and so less time delays. The compensation could also be used to lower the
tolerances during assembly of the gearbox or other applications.

The aging of the magnets needed for these sensors is also an important issue. If the magnets
weaken during their lifetime the speed measurement can be affected and also fail.

Because of high demands on EMC immunity from Volvo an investigation on how EMC will
affect these sensors is necessary. Is it even possible to shield the sensors enough to handle the
demands that are set?

Investigation on how the sensors act when mounted in a gearbox. How will the mechanical
tolerances affect the sensors? Will it be necessary to lower the resolution or increase the
filtering of the sensor signal to reduce noise?

Mechanical parts inside the gearbox can in some situations become magnetized, how would
this influence the measurement? Would it be possible to use magnetized moving parts instead
of separate permanent magnets?
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**Acronyms and abbreviations**

- DAC: Digital to Analogue Converter
- ECU: Electronic Control Unit
- TECU: Transmission Electronic Control Unit
- GMR: Giant Magneto Resistive
- PPR: Pulses Per Revolution
- VR: Variable Reluctance
- S/N: Signal to Noise
- SSC: Synchronous Serial Communication
- PWM: Pulse Width Modulation
- EMC: Electromagnetic Compatibility
- RPM: Revolutions Per Minute
- DC: Direct Current
- AC: Alternating Current
- ABS: Anti-lock Braking System
- N/A: Not Applicable
- RC: Resistive and Capacitive

**Glossary**

RC-filter: An analogue filter built up with only Resistive and Capacitive components.

Quadrature: A signal that is 90 degrees out of phase with another signal is its quadrature signal.

AVR: An 8 bit microcontroller family from Atmel.