Development of a Testing Assembly for Powertrain Speed Sensors

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Abstract

Knowledge about the speed and the direction of the different shafts in the gearbox and the engine of trucks is becoming more and more important, especially as the industry moves towards autonomous vehicles. The most common way to measure these parameters today is by using inductive or Hall sensors. Testing and benchmarking these sensors has a large significance for heavy truck manufacturers such as Scania.

In order to test these components, a rig assembly was constructed. In this project a LabVIEW program was developed for controlling the rig and gathering the required data. The aim of the rig was to try and simulate the behaviour of the components that are commonly measured in the gearbox or the engine, as well as use it for testing and benchmarking new rotational speed sensors. In order to achieve this, different processes were studied that cover certain working conditions in a Scania truck. The rig’s ability to follow these processes was then studied. In addition, a test case for inductive and Hall sensors was also presented.

It is shown that the implemented solution for testing the sensors can be used for benchmarking different sensors and can be a useful tool for future sensor development at Scania. However, the rig with its current hardware was unable to closely replicate processes that are of interest. There are a lot of improvements that have to be made in order to properly simulate the behaviour of the powertrain components that are of interest for speed sensor applications.

Keywords: Inductive, Hall, Speed Sensors, Powertrain, Rig, Testing, LabVIEW.
Sammanfattning


Den implementerade lösningen för provning av givare visas kunna användas för att jämföra olika givare och kan vara ett användbart verktyg för framtida givarutveckling på Scania. Däremot kan riggen inte återskapa de processer som är intressanta med den hårdvara som var tillgänglig vid tillfället. Förbättringar av riggens hårdvara måste göras för att kunna simulera de drivlinekomponenterna som är av intresse för utveckling av varvtalsgivare.

Nyckelord: Induktiv, Hall, varvtalsgivare, drivlina, rigg, provning, LabVIEW.
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List of Acronyms

AMT  Automatically-shifted Manual Transmission
BLDC  Brushless Direct Current
CAD  Computer-aided Design
DAQ  Data Acquisition
ECU  Electronic Control Unit
GUI  Graphical User Interface
PWM  Pulse Width Modulation
RPM  Revolutions Per Minute
Chapter 1

Introduction

1.1 Background

In the development cycle of a product, a lot of time is spent testing new hardware. In the truck industry, developing new hardware often requires field testing, which in many cases is both expensive and time consuming. Therefore, a way to minimize that lead time in development is often desired. This is especially important for the powertrain components such as the truck’s engine and the gearbox, where careful optimization can lead to huge economic and environmental benefits.

In order to optimize the functionality of the powertrain components, accurate information about their operation is required. One way to obtain such information is by using different kinds of sensors. Sensors provide feedback to control systems in order to perform complex tasks. In automotive applications, sensors are essential for making the vehicle’s engine and gearbox operate smoothly, both providing comfort to the driver and the passengers, as well as making the those powertrain components more efficient. Furthermore, as vehicles become more and more automated or even autonomous, the need for additional high precision sensors becomes significant. Sensor development has thus become an important area in powertrain applications. The purpose of this project is to find a way to simulate how the gears that the sensors measure in a truck’s engine and gearbox rotate in certain conditions. A dedicated testing assembly or “rig” will be developed for that purpose. Having an assembly that can simulate such behaviour can result in decreased lead times when it comes to testing different sensors in the gearbox or the engine, since the sensors can be tested before being mounted on the truck itself. In addition, the assembly can be used for benchmarking sensors from different suppliers, or in some cases be used as a tool in the development of new experimental hardware.

This project is part of a Master’s thesis for the Department of Automatic Control at KTH - Royal Institute of Technology in Stockholm, Sweden. The project was conducted at Scania CV AB in Södertälje, Sweden, from January 2016 through to June 2016. The main subjects covered by this project include mathematical modelling of data, control theory, software development in LabVIEW and simple hardware implementations.

Scania CV AB is a swedish automotive manufacturer, specializing in heavy trucks and buses, as well as industrial and marine engines [1]. Scania was founded in 1891 in Malmö, Sweden and has since grown to become one of the world’s leading heavy truck manufacturers. Today, Scania employs more than 40,000 employees and operates in more than 100 countries. It has its headquarters and the largest part of its production in Södertälje, Sweden, with additional production plants in Sweden and around the
1.2 Project Description and Objectives

The first goal of the project is to study whether different processes in the powertrain of Scania trucks, mainly in the engine and gearbox can be replicated on the rig. These processes refer to the rotational speed of the powertrain components, and correspond to events or time patterns that occur during the operation of a truck that can be important for sensor development. For example, the speed at which the gears have to be for achieving a smooth gear change, is important. The action of decelerating the gearbox shafts and changing gears is such a process. Identifying these processes however, requires data to be gathered first. For that purpose, field tests were conducted in order to gather the necessary data from a truck with a powertrain that has similar components to a production vehicle today.

After having gathered the necessary data, the second goal is to assess whether the designed rig assembly can replicate those processes. The rig consists of a Brushless Direct Current (BLDC) motor that drives a shaft, on which different gears or target wheels from a truck’s engine or gearbox can be mounted. A high precision rotary position sensor is used to provide angular position as a reference feedback to the software. The main software for controlling the assembly was designed in LabVIEW as part of the project. A LabVIEW program was developed specifically for this purpose and is designed around the available hardware on the rig. Finally, the assembly’s performance is assessed, i.e. how well the rig is able to follow the input signals. In addition, the different uses for the rig assembly are discussed.

The project’s objectives can thus be summarized as follows:

1. Data gathering and process classification.
2. Development of the testing rig’s software and hardware.
3. Performance assessment of the rig.
4. Investigation and discussion about the various uses of the rig, such as prototyping and sensor benchmarking.

1.2.1 Scope Limitations

Since the scope of this project could become too large, a few limitations were considered in the beginning. For example, in the process classification phase of the project, only a specific process was considered to begin with, namely layshaft braking at a gear change. That process, which is described in detail in section 2.2, was chosen since it covers the most extreme case for the performance of the rig. However, the project could be easily extended to allow for the modelling of more processes. In addition, a Graphical User Interface (GUI) was created for the rig assembly. The GUI provides a basic interface for interacting with the assembly such as setting the desired reference values and braking the motor. Extra functionality will be implemented in the GUI in order to make the process of testing the sensor hardware more streamlined and standardised. Finally, any development and testing on the rig was done on the available hardware at that time, namely the hardware that is mentioned in chapter 3.
1.3 Related Work

While there are several articles and papers on inductive sensors and their principle of operation, there is not much information available on testing rigs and benchmarking. Manyala J. et. present in their paper details on the principles and designs behind vehicular speed sensors [3]. While the paper presents a similar testing assembly for their experiments, the details of that assembly are not given. Another example of a testing rig was done by Volvo for cylindrical gears [4]. However this rig uses several other sensors, such as microphones and load sensors, instead of inductive sensors since it is used for noise and vibration testing. Due to the fact that sensors for powertrain applications are a significant part of the vehicular industry, there are bound to be similar in-house project from companies, that have not been made publicly available.

Apart from in-house development, there are alternative solutions for inductive sensor testing available on the market. An example is the PicoScope software by Pico Technology [5]. While such solutions often are more than adequate for the task at hand, they are often expensive or inflexible. The rig designed in this project is able to test multiple sensors at the same time, as well as test sensors that are of different technologies. In addition, the rig has the advantage of being developed in-house which makes it easy for Scania to adjust and improve both the hardware and the software if required.

When it comes to the stepper motor found on the rig, there are a few papers on their operation and their drives. A few examples are [6] and [7]. In addition, there are several papers on controlling DC motors through LabVIEW, as was done in this project. Three examples are designing a PID controller presented in [8], using fuzzy logic as presented in [9], or using open-loop control as shown in [10]. However, since the stepper motor and its drive were purchased as a complete solution, these papers were mostly used for better understanding the concepts behind the stepper motor and for tuning the built-in software.

Finally, the main tool used for the development of the software and the GUI was LabVIEW. An example of the usage of LabVIEW for data acquisition is presented in [11]. While the main application differs, the core principles are the same.

1.4 Requirements

There are several requirements set for both the hardware and the software of this project. This section provides an overview of those requirements. Whether each requirement has been fulfilled or not, as well as the reasons as to why they were not fulfilled are discussed in chapter 5.

1.4.1 Hardware Requirements

- The main shaft of the rig should be able to rotate at the following Revolutions Per Minute (RPM) range: 0-2500 RPM. However lower RPM ranges of approximately 0-100 RPM are of significant importance.

- The electromagnetic brake should be able to provide fast transients for testing the sensors.

- The reference sensor should be able to provide a high precision signal that can be used as a ground truth measure for the sensors that are under test.
1.4.2 Software Requirements

- The LabVIEW program should be able to display the output of each sensor. Each measured output should be saved in a file for later study.

- The program should be able to output arbitrary waveforms for the motor to follow.

- The program should allow for high customizability without the need to dive into the LabVIEW block diagram in order to make a small change, such as adjusting important parameters.

- Processing for the signals measured will be done offline. This includes any filtering or speed estimation algorithms.

1.5 Report Outline

This report is divided into 5 main chapters. Chapter 2 introduces the basic concepts that are used throughout this project, as well as how the different experiments were conducted. This includes the basics behind the sensors that were tested, the components that they measure, the modelling process, as well as the signal processing methods that were used. Chapter 3 provides a description of the rig assembly. This includes both the hardware that is responsible for controlling the rig, and the corresponding software. A description of the actual construction of the rig is given in appendix A, while a more detailed description of the software is given in appendix B. In chapter 4, the main implementation tests are described, as well as a method derived for calibrating the rig’s reference sensor. This chapter also includes the main problems that were faced during measurements. Finally, chapter 5 provides a summary of the results. This includes the results from the rig’s measurements, an assessment of the rig’s performance and applications, as well as suggestions for possible future work.
Chapter 2

Background Concepts and Methodology

This chapter provides a description of the main concepts that are mentioned in this project. Firstly, a summary of the truck’s powertrain is given. The focus is placed on the powertrain components that the sensors measure, namely the engine and the gearbox, as well as the sensors themselves. The aim is to motivate the importance of the inductive sensors in the powertrain. Secondly, the classification process mentioned in chapter 1 is explained. Since the rig is based on a BLDC motor, the basic principles behind its operation are also presented here. Finally, in order to have a measure for evaluating the performance of the rig, the speed of the main shaft has to be estimated. The main signal processing methods used for that purpose are shortly described.

2.1 The Powertrain

The term powertrain is used to describe the collection of all the components of a vehicle that aid in transferring its power all the way from the power generation (often a combustion engine) to the actual wheels. The following components are often included when one refers to the powertrain of a typical truck:

- Engine
- Gearbox
- Drive shafts and differential
- Wheels

Today these components often require precise control in order to function properly (or for providing economical benefits and comfort to the driver). For that purpose, angular speed sensors are used in order to give speed feedback to the corresponding control system. Before describing these sensors, a short introduction on what these sensors actually measure is given bellow.
2.1 The Powertrain

2.1.1 Engine

Arguably the most important component of a truck is its engine, since it generates the power that is later converted into torque that rotates the wheels. Scania today manufactures both diesel and gas engines, but for the purposes of this project only the diesel engine principles are described. The working principle of a diesel engine is the conversion of the thermal energy generated from the combustion of diesel fuel to rotational power or torque. An example illustration of a Scania combustion engine is shown in figure 2.1.

The combustion occurs typically in four steps (or strokes) for each piston of the engine, as shown in figure 2.2. Firstly, fuel is injected into the combustion chamber. In the second stroke, the fuel is compressed and ignited. The high-pressure gases that are created from the combustion cause the piston to move downwards, thus generating power. In the final step, the exhaust gases are removed from the chamber. The motion generated from the piston is converted to rotational power with the help of the crankshaft. The valves that open and close for the fuel injection and the exhaust siphoning are timed with the camshaft, also shown in figure 2.2. Measuring the actual position of the crankshaft is essential for controlling the timing of the fuel injection, among other things. Inductive speed sensors are used today for that purpose. The sensors are directly connected to the vehicle’s Electronic Control Unit (ECU), which uses this information to correctly time the injection of fuel into the combustion chamber, as well as optimise the amount of fuel that is injected. The information from the sensors is essential for vehicles since the exact control and timing of the injections determines the performance and fuel efficiency.
2.1 The Powertrain

2.1.2 Gearbox

Another main component that can be found today in any commercial vehicle is the gearbox. Its purpose is to convert the incoming torque from the engine, so that lower or higher speeds than the engine’s speed can be transferred to the wheels. This allows the vehicle to move at low speeds but with high torque, or vice versa, depending on the need. While there are several types gearboxes, Scania today mostly uses a so-called Automatically-shifted Manual Transmission (AMT), meaning that the gearbox is constructed in the same way as a traditional manual gearbox, with electrical actuators for selecting gears instead of having a lever that the driver controls directly. The main working principle is also summarized here can be found in [14]. An example is shown in figure 2.3.

In a manual gearbox, different sets of gears cooperate in order to convert the torque from the engine. There are four shafts in a Scania gearbox, namely the input shaft, the output shaft, the main shaft and the layshaft. A simple illustration can be seen in figure

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_2.png}
\caption{The cycle of a piston in a 4-stroke combustion engine. Source: [13]}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2_3.png}
\caption{Illustration of Scania’s GR900 gearbox. Source: Scania AB [12]}
\end{figure}
2.1 The Powertrain

Chapter 2. Background Concepts and Methodology

Figure 2.4: A simple manual transmission illustration. The dog clutches that connect the gears to the output shaft are shown in purple. Source: [15]

(a) Power propagation with the first gear selected. (b) Power propagation with the third gear selected.

Figure 2.5: Power propagation when different sets of gears are selected.

2.4. The power is transmitted from the engine to the input shaft through the clutch. When the clutch is engaged, the engine’s crankshaft and the input shaft rotate at the same speed. The layshaft, that is always connected to the input shaft, has several gears on it that allow the gearbox to convert the torque. The gears on the output shaft are always in mesh with the corresponding gears on the layshaft. However, the output shaft is able to rotate independently of the other shafts. When a gear is selected, a dog clutch (that rotates together with the output shaft) is meshed with the corresponding gear on the output shaft. This results in the output shaft rotating at the same speed as that specific gear. By changing between gears that have different sizes, the ratio at which the input shaft and the output shaft rotate with respect to each other changes. The principle of selecting different sets of gears is shown in figure 2.5 for the first and third gear.

In addition to the sets of gears that are normally found in a commercial vehicle, Scania gearboxes often have additional gears that can help increase the number of the different ratios that the gearbox can output from the input shaft to the output. The first
set of gears is called the Split. The Split is responsible for changing the power transfer ratio between the input shaft and the layshaft. This means that each selected gear on the layshaft can be "split" or converted into two different ratios depending on the need. The second set is called Range. The Range is a simple planetary gear set that sits just before the output shaft. While the split changes the ratio of each gear on the layshaft, the range converts the output of the whole gearbox. It often offers two different ratios, a lower one if the vehicle is moving slowly and a 1:1 ratio for higher speeds.

Since there are a lot of moving parts that can rotate at different speeds, information about the rotation of the components is essential for a lot of different functionalities. Today, two shafts are measured directly with inductive sensors in AMTs, the main shaft and the layshaft. An example when the information about the layshaft’s speed is essential is when the control unit has to change gear. When the clutch is decoupled, the layshaft has to brake in order to synchronize with the gear speed of the output shaft and connect the next set of gears without causing wear to the gears and the dog clutch, or discomfort to the driver. As gearboxes become more complex, the need for sensors measuring the gearbox components will increase, making a tool for testing them essential for future development.

2.1.3 Speed Sensors

The applications for which the speed sensors are used in heavy duty vehicles differ depending on the component. As mentioned, in the engine one is often interested in the actual position and the direction of the crankshaft, while in the gearbox the rotational speed of the shafts are of importance. Nevertheless, the same type of sensor can be used in both cases. Today Scania uses inductive speed sensors in the engine and gearbox. While inductive sensors are robust for most applications, other types of sensors are also considered. An alternative that is actively considered today is Hall effect sensors. The main operating principles for both sensors are introduced in summary below. Some basic principles on their operation for vehicle applications are also presented in [3].

Inductive Sensors

A typical inductive sensor for automotive applications can be seen in figure 2.6. It comprises of a permanent magnet and a soft magnetic rod that sit inside the sensor, surrounded by a coil of wire. When there is a difference in the magnetic flux that passes through the magnet, the magnet induces a current of the wire. Mathematically, this can be described by using Faraday’s law of induction, namely:

\[
\frac{dI}{dt} = N \frac{d\Phi}{dt} \Rightarrow \quad (2.1)
\]

\[
U = N \frac{d\Phi}{dt}, \quad (2.2)
\]

where \(N\) is the number of wire windings around the magnet, \(\Phi\) is the magnetic flux and \(U\) is the induced electromotive force. Due to its principle of operation, the inductive sensors must measure a target that is made of a ferrous material (often iron). In automotive applications, the sensors measure either the gear directly, or an impulse wheel designed specifically to give a certain output signal. As the wheel rotates, the teeth of the impulse wheel passing by the tip of the sensor, result in a voltage on the output [16]. The faster the target medium rotates, the higher is the resulting amplitude of the signal. Since the sensor sits at a fixed distance from the medium (called the air gap) in a truck, there is a
minimum threshold at which the signal can be detected before it becomes equal to the noise. Being able to test these sensors at low RPM below 100, is important for sensor development. An example of the signal’s form can be seen in figure 2.7.

The form of the output signal from the sensor depends on the symmetry of the wheel that is measured. By knowing how many teeth there are on the measured wheel and the angle between each tooth, the frequency of this signal gives an accurate indication of the rotational speed of the wheel. In many cases the impulse wheel measured is asymmetrical. By detecting these asymmetries in the signal, the direction at which the wheel rotates, or the actual position of the wheel can be accurately measured. The inductive sensor is a passive component, meaning that it does not require an external power source to operate. Figure 2.10 shows a possible placement of sensors on a Scania gearbox.

Hall Effect Sensors

Hall effect sensors differ from inductive sensors in the way that they measure change in the magnetic flux directly. Its working principle is shown in figure 2.8. Hall sensors consist of a semi-conductor material with a continuous current passing through. When a magnetic field is present near the sensor, the electrons and the holes in the semi-conductor are deflected to the sides of the material. Having the electrons and the holes in opposite sides creates a potential difference between the material. This potential difference is called the Hall Voltage. This Hall Voltage is the output of the sensor. Unlike the voltage output of the inductive sensor, this voltage is often small (in the mV range) and it is thus often amplified by an internal circuit [17].

Since Hall effect sensors require a constant current to flow through the material and the amplification of the output signal, they are active components, namely they require a power source in order to function. A typical Hall sensor for automotive applications is shown in figure 2.9.
Chapter 2. Background Concepts and Methodology 2.2 Powetrain Processes

Figure 2.7: Example of an inductive speed sensor output signal measuring a Scania flywheel at 100 RPM.

2.2 Powetrain Processes

The main aim of the project is to simulate a truck’s real operating conditions on the rig. Achieving that requires some kind of model that is going to be used as input to the rig’s software. However, it became clear that the hardware that was already available for the rig would not be able to model all of the cases that were planned. Therefore, only the following concepts are presented: the process of gathering data from a Scania truck, as well as the process that was finally used as a benchmark for the rig.

2.2.1 Data Gathering

The following method was used in order to gather the data required for the modelling. For the purpose of testing new features and monitoring the performance of components, Scania uses a logging system on test vehicles. This system is able to log some predefined parameters from the ECUs of the truck. This can include everything from low-level data such as raw sensor data to application level data such as cab indicators or processed signals. Data from Scania’s database was gathered in order to figure out which parameters were relevant for modelling the models. There are several downsides with this system for the scope of this project however. Firstly, the parameters that have to be monitored must be determined beforehand. Since the amount of data is too large, only several parameters are saved depending on the need each time, resulting in scarce data for specific measurements such as the speed of the gearbox’s layshaft. Another limitation is that often this data is monitored when a trigger occurs. The result is data that is discontinuous in time, making it often difficult to model. For the reasons mentioned above, the data that was finally used for the modelling and the process classification was gathered directly from driving a truck on the test track.
2.2.2 Classification

Due to the limitations of the rig’s hardware, only one process was studied closely, namely braking the layshaft during a gear change. There are several reasons as to why this process was chosen. Firstly, it covers most of the fast transients that can be found on the powertrain today that motivate the use of the electromagnetic brake on the rig. Most other transients can be covered by the performance of the BLDC motor. Secondly, the layshaft is one of the components that is measured directly with an inductive sensor in the gearbox.

When the vehicle has to change gear, the clutch is decoupled. The control unit sends the signal to choose the next appropriate gear by meshing the dog clutch of the output shaft on the desired gear. In order to achieve a change with minimal wear and discomfort to the driver, the layshaft has to brake in order to match the speed of the output shaft. In a series of continuous data, the two most obvious indicators for detecting layshaft
braking are therefore the gear selection indicator and the clutch position. The process starts when the software receives the command to change gear and stops when the clutch is coupled again. By monitoring for those two events, the process of braking the layshaft can be identified. Under this process, the output signal of the sensors measuring the layshaft are logged.

2.3 Motor Control

The rig uses a stepper motor in order to rotate the main shaft. Stepper motors differ in some ways from ordinary BLDC motors. In typical BLDC motors, the permanent magnet that sits on the outside of the motor remains stationary during its operation (stator), while the inner coils of wire rotate (rotor). In stepper motors, the permanent magnets sits on the inside of the motor and is able to rotate (making it the rotor), while the coils remain stationary on the outside [19]. Furthermore, the permanent magnet that sits on the motor consists of several small magnet poles that look like gear teeth instead of a large permanent magnet. An example illustration of a stepper motor can be seen in figure 2.11.

The stepper motor is a type of BLDC motor that takes a Pulse Width Modulation (PWM) signal as an input. In order to properly control the motor, some information about the rotor’s rotation is needed. Rotary encoders are often used for that purpose. Rotary encoders are able to convert the rotary displacement of a shaft into a digital signal. More specifically, incremental encoders provide relative information about a shaft’s position. This type of encoder provides a signal only during rotation. However by properly indexing the output of the encoder in the control unit, it is able to provide accurate position information. In addition, the incremental encoder is able to specify the direction on motion by checking which of the two sensor signals is leading.

There are several advantages in using a stepper motor instead of a typical BLDC motor. Stepper motors are able to output their maximum torque from a stop, making them ideal for applications that require slow rotational speeds. In addition, it offers precise positioning since each step of the motor often has a small error. However, there

Figure 2.10: Possible sensor placement in a Scania gearbox. One sensor sits on the input shaft of the gearbox, while the second one measures the layshaft. Source: Scania AB
are some disadvantages. Having all of its torque available at low speeds, the stepper motor loses most of its torque output at high speeds. In addition, stepper motors often require a dedicated control circuit.

2.4 Speed Estimation

An important aspect of evaluating the performance of the rig, is knowing how well it can follow the input commands. Therefore, a way to estimate the speed of the rig’s shaft from the available sensors is needed. Since the reference sensor that is used in this project gives the shaft’s absolute position, the speed of the shaft can be obtained by calculating the derivative of that signal. However, signal derivation is a process that often yields noisy results. In addition to that, in laboratory environments it is often common that a lot of electric noise is produced by the surrounding equipment, as well as the rig’s own equipment. Performing derivation on a noisy signal can yield unreliable results. Therefore, most of the noise present in the signal has to be attenuated before performing derivation. A common method for getting rid of noise at post processing is digital filtering.

For the purposes of this project two types of filtering were used. The first is a digital low-pass Butterworth IIR-filter for attenuating the high frequency noise found on the measurements. The second filter type is a median filter. This filter takes the input signal and calculates the median value depending on the order of the filter. However special care has to be taken when using these filters. The chosen frequency has to attenuate the noise without distorting important properties of the signal. This is especially true here where the rig’s brake generates fast transients.
Chapter 3

Rig Assembly

As mentioned in chapter 1, the main aim with the rig is to test the inductive and/or Hall sensors that are used for measuring the velocity of several powertrain components in the engine and gearbox on Scania trucks. The rig is designed so that one can mount the gears that the sensors usually measure on it directly, such as a flywheel or an impulse wheel. The mechanical construction is outside the scope of this project and is omitted here. However, a short overview is given in appendix A to give the reader an idea of how it looks. The actual testing rig can be seen in figure 3.2.

In order to replicate the behaviour of those components, the main shaft of the rig has to rotate at specific speeds that match the rotational behaviour of the components during real life conditions. The shaft here is rotated by using a BLDC motor. The rig is controlled from LabVIEW in the following way:

1. The LabVIEW interface allows the user to send commands, such as choose the reference speed of the shaft, brake the shaft, as well as measure the outputs of the connected sensors.

2. LabVIEW sends the necessary commands to an Arduino that is mounted on the rig. Its main purpose is to parse the commands that are sent to the motor and the electromagnetic brake.

3. The Arduino then sends the signals to the motor servo drive that powers and controls the motor.

4. The servo drive then takes care of the motor commutation, as well as the feedback from the embedded encoder that is found on the motor.

5. The sensors that are under test and the reference sensor send their data back to LabVIEW for processing and comparison via a Data Acquisition (DAQ) device.

These steps are illustrated in figure 3.1. This chapter describes in detail each of the above steps that are required in order to operate the rig.

3.1 Hardware

In this section, the hardware that is used for controlling and collecting measurements from the rig will be discussed. This includes the motor and its servo drive, the Arduino board, as well as the sensors on the rig.
3.1 Hardware

3.1.1 Arduino Board

The signals to the motor servo, as well as the electromagnetic brake, are handled by an Arduino Leonardo board that is mounted on the rig. The Arduino is a circuit board with a programmable microcontroller that communicates with a PC via USB. The Arduino has been programmed to receive command inputs from the LabVIEW program. These commands can either be to change the speed of the motor, change the direction of motion, or change specific parameters of the motor. These commands are then sent to the stepper motor servo drive through the analog pins found on the Arduino.

The reference speed is set by sending a PWM signal to the servo drive. The Arduino receives a reference value in RPM from LabVIEW which is then converted to the corresponding PWM signal. The Arduino can also receive commands for operating the electromagnetic brake that is found on the rig. The brake allows for fast transients, but is also used as a safety brake. It is automatically applied whenever the rig loses power, when the Arduino is disconnected from the USB port, or when there is an error reported by the motor’s servo drive. Other uses include the ability to control the acceleration of the motor, change the direction of rotation, as well as make sure that the waveform signals that are sent via LabVIEW are correctly timed. This is especially important if higher sampling times are required, since in an non-real time operating system as Windows, the update rate of the LabVIEW process cannot be guaranteed to be timed perfectly for less than 10 ms. Another important advantage with using an Arduino in this case is that it can be programmed to be independent of the software that sends commands to it. This means that even if the LabVIEW program crashes or stops responding, the Arduino will either keep the rig working or stop it if an error is received.

The Arduino board that was used for this project is an Arduino Leonardo with a 16MHz clock and 2,5kB of RAM. There are several limitations that arise from the hardware of the specific board. Firstly, the PWM signal that is required for controlling the motor is constructed by setting its frequency and duty cycle. Since the Arduino Leonardo has a 16-bit processor, its timers always have a resolution of 16 bits, which in turn limits the resolution of the PWM frequency.
3.1.2 Stepper Motor and Servo Drive

The main component of the rig is the motor. The motor that was used on the rig is a Leadshine ES-MH33480 high voltage stepper motor. Its principles of operation were discussed in section 2.3. One of the advantages of the stepper motor is its high torque output at low speeds, which is desirable for testing inductive or Hall sensors.

In order to drive the motor, a servo drive is required. For this purpose, the Leadshine ES-DH2306 servo drive was used [21]. The drive provides a lot of built-in functionality such as taking care of the motor commutation, setting the default parameters of the motor, as well as tuning the built-in PID controllers. The drive includes two PID controllers, one for the inner current loop and one for the outer position loop. The current loop was tuned using the built-in functionality in the Leadshine software that comes with the servo. The chosen parameters for the servo drive are given in table 3.1 below (the parameters that were left to the default values are not given).

3.1.3 Sensors and Data Acquisition

In order to be able to compare the outputs of the sensors that are under test, a high precision rotational position sensor [22] is also mounted on the rig. The sensor is connected to a DAQ device is used to read the output data from the sensor. In addition to the reference sensor, the DAQ device is able to acquire the output from multiple test sensors at the same time. For the purposes of this project, an Agilent U2351A multifunction DAQ was used. It has 19 analog inputs for measuring single referenced signals, or 8 analog inputs for differential measurements. This means that additional sensors can be measured at the same time, increasing the usability of the rig. The test sensors are always measured differentially, while the reference sensor is measured as a single-ended signal. The data that the DAQ acquires is processed in LabVIEW in real time and can be saved for later study and post processing. A dedicated power supply
### 3.2 Software

The software that is used for the rig was developed in LabVIEW. It includes a GUI that offers the user a way to control the motor, show the rig’s measurements in real time, as well as save the measurements for later use. LabVIEW was chosen because of the ease it provides in creating relatively complex GUI interfaces in a small amount of time, as well as provide a fast way of acquiring and saving measurements. The main aim with the software was to develop an interface that is user-friendly and can be used even by people not directly involved in this project. The program is compiled to run on any Windows computer without having LabVIEW installed. The main window of the GUI is shown in figure 3.3.

The program provides two main functionalities. The first one is to be able to directly control the motor by changing the reference speed of the motor. It also allows the user to change the acceleration and the direction of the motor. This enables the user to perform quick tests that do not require a specific waveform output, such as step responses or sudden braking. The output voltage of each sensor as well as the input reference in rpm can be saved for further processing.

The second functionality allows the user to either create a specific waveform, such as a sine wave or a step-like waveform, or load an arbitrary waveform from a file. This allows the testing of specific cases directly and repeatedly, without requiring any additional setup. The program processes the waveform and sends it to the Arduino sample-by-

---

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*Table 3.1: The parameters used for tuning the Leadshine servo.*

...can also be found on the rig can power the sensors that require it.

#### 3.1.4 Electromagnetic Brake

As mentioned in chapter 2, some powertrain components such as the layshaft in the gearbox, have to perform fast transients during their operation. To allow the measurement of fast transients, the rig is fitted with an electromagnetic brake. The brake is controlled via a relay that cuts or allows current through. In addition to providing fast transients for measurements, the brake is also used as a safety feature, braking the shaft when needed. One disadvantage of the brake is that it only has two states, on or off. Thus only a constant braking force can be applied for braking.
Chapter 3. Rig Assembly

3.2 Software

Figure 3.3: Main GUI window of the rig control software made in LabVIEW.

sample. The Arduino then processes the data in order to make the motor follow the input waveform as close as possible. However as mentioned above, the Arduino has limited RAM and bandwidth. This means that the signals have to be downsampled in the LabVIEW program before sending them. The rate at which the Arduino updates the output to the motor was chosen to 500 Hz.
Chapter 4

Implementation and Testing

This chapter focuses on the tests that were conducted on the rig, the performance of the rig, as well as the way in which the rig’s reference sensor was calibrated. This chapter also includes some of the problems encountered during measurements and their significance on the measurements.

4.1 Problems Encountered

As mentioned in the introduction of this report, all testing was conducted using only the hardware that was already available for the rig. For this reason, some of the hardware was not optimized for providing the best performance and some components presented some problems that made measurements and the evaluation of the performance more difficult. Some of these problems are mentioned below.

4.1.1 Measurement Noise and Offsets

One of the things noticed when the rig was tested for the first time, was the large amount of noise and offsets on both the reference sensor and the inductive sensors. Before starting with the rig calibration and the actual measurements, it would be ideal to get rid of as much of the disturbances as possible. After analysis, the main source for the noise seems to come from the motor servo. After careful examination with an oscilloscope, it was concluded that the servo produced a high frequency noise at around 16kHz. This noise propagated through the system from two different paths.

The first one was through the power outlet. The servo induced a noise that affected most equipment connected to the same power outlet, and most importantly the DAQ device responsible for the measurements. For this reason, the servo was connected to a phase separate from the phase of the rest of the power outlets in the lab. While this solution helped in reducing some of the noise, a significant part of it was still present. The second path was through electromagnetic induction. The rig, being made of metal acted as a conductor. This meant that the noise propagated through the rig and was picked up by the inductive sensors which led to the DAQ also picking up the noise. The first solution was to ground the rig to the servo’s ground connector, which resulted in significantly lower noise levels. However, as will be seen later on the actual measurements, some of the noise is still present that must be filtered in post processing.
4.1.2 Reference Sensor Performance

Another significant problem encountered was the performance of the main reference sensor found on the rig. It showed that the sensor was not meant for high speed applications, but rather for low speed, high accuracy servo applications. This fact becomes apparent by examining the output of the sensor at high rpm.

Initial testing showed that the reference sensor does not have fast enough response time to be reliable at high rpm. The problem is shown in figure 4.1. The figure shows the output of the sensor at 500 rpm, sampled at 10kHz. As can be seen, the output has a step-wise form where each step is of equal length independent of the speed at which the shaft rotates. This was later confirmed to be due to the circuit in the sensor that updates the output at a specific interval. From the initial measurements it showed that the sensor updates its output approximately every 37 ms. In addition, the sensor seems to miss some updates of the output at regular intervals, something that is also due to the circuit of the sensor. At low speeds however, this problem is not as significant, as can be seen in figure 4.2. Since the time span for the project did not allow for the search of new sensors, the current sensor was still used and evaluated. As mentioned in the introduction, one of the most important applications for the rig is measurements at low rpm. For this reason, the reference sensor was still used for all tests.

4.2 Reference Sensor Calibration

After trying to counter most of the problems mentioned above and before attempting to gather data, the accuracy of the reference sensor has to be evaluated. For this project, it is important to have a reference measurement that has a well-known accuracy and precision that can be later compared to the output of the sensors that are tested. The aim is to derive a transformation function from the voltage output of the reference sensor to an angle that can be used for sensor comparison and speed estimation.

The following setup was used for calibration. Two inductive sensors were used that
are known to be reliable, both measuring a Scania flywheel. The flywheel that was
used for the measurements has 158 symmetrically placed teeth along its perimeter, as
well as 16 asymmetrically placed holes on the front of the wheel. The output of the two
sensors can be seen in figure 4.3. Test Sensor 1 measures the teeth of the flywheel,
while Test Sensor 2 measures the holes that can be found on the front of the wheel. As
can be seen, the output of the second sensor is asymmetrical which helps in identifying
exactly the direction at which the shaft is rotating, as well as the time at which the
shaft has completed a full rotation. By separating the signal into periods with the help
of the asymmetrical holes, the signal from the teeth of the wheel can be used in order
to get the exact times at which each tooth passes. Assuming that the teeth of the
flywheel have a negligible manufacturing error, the relative angle can be measured. By
combining the above information, an angle evolution table can be built for each period
of the flywheel. This table can then be interpolated and compared to the output of the
actual reference sensor. The resulting line can then be used in the LabVIEW software
or in post processing, in order to convert the voltage level of the reference sensor to
the actual angle. The following algorithm was used in order to derive the actual angle
evolution:

1. Isolate a period of the reference sensor. This period will be used to build the
   actual angle line.
2. Detect the negative zero crossings on the sensor that is measuring the asymmetrical
   holes on the flywheel. A negative zero crossing is the timestamp when the signal
   crosses 0 V going from positive to negative values.
3. Start with the crossing closest to the start of the reference sensor’s period and find
   when the 'hole' sensor has performed a full rotation. Let $t_1$ be the start of the
   period and $t_2$ the end of the period.
4. Detect the negative zero crossings on the sensor that is measuring the teeth of
   the flywheel. Use least-squares to detect the actual timestamps at which the zero
   crossings occur.
5. Count the zero crossings on the sensor measuring the teeth, between the two timestamps \( t_1 \) and \( t_2 \). The timestamps of these zero crossings are saved in a vector. Using this vector, build an angle vector containing the angle evolution in this interval.

6. Interpolate the angle vector in the previous step in order to get a more accurate time vector, using spline interpolation.

In step 2, the zero crossings are detected by finding the local maxima and minima in the signal and then finding the zeros between them. In step 3, least-squares is used in order to properly detect the zero crossing. This is done because it is not certain that the sampled data will have a sample at exactly the point where the signal is zero. By fitting a line on the points around the detected zero, the actual timestamp for the zero is calculated. Finally, step 6 is required for acquiring a vector that has the same size and timestamps as the reference sensor and can be compared with it.

After having calculated the actual angle, it was compared to the output from the reference sensor. The experiment was conducted at a constant speed of 20 rpm. The result is shown in figure 4.4. It can be seen that the resulting line closely follows the output from the reference sensor at low speeds. Figure 4.5 shows the error in degrees between the two signals. The error signal was filtered with a low pass filter with 0.001 normalized cut-off frequency, in order to get rid of the high frequency noise present. As can be seen, the angle deviates at most approximately 2° from the actual value. The derived line can now be used in post processing in order to transform the voltage value of the reference sensor to a more accurate angle value.
Chapter 4. Implementation and Testing  

4.2 Reference Sensor Calibration

Figure 4.4: Reference sensor output (blue) along with the resulting interpolated angle (red).

Figure 4.5: Error in degrees between the reference sensor and the derived angle line. The error is filtered. Sampling rate: 10kHz.
4.3 Rig Performance

One important aspect of the rig is its ability to follow the desired reference RPM. Five different reference speeds were tested, namely 10, 20, 100, 800 and 1000 RPM. For each case, the rig was accelerated to the specific reference at a constant pace and then kept constant. In addition, a test showing the performance of the brake is also presented in this section. The wheel that was mounted in this case was a Scania reverse gear wheel. The specific wheel is used for measuring the speed of the gearbox layshaft today. It was chosen since it represents a moderate load that can be mounted on the rig. While heavier loads can be mounted on the rig, such as a flywheel, most components will not be that heavy.

The speed of the rig’s shaft was estimated by unwrapping the reference sensor signal and taking its derivative. As mentioned in section 2.4, low pass and median filtering was used in order to attenuate the noise found on the reference sensor signal. For most cases below, the following filters were applied:

- Butterworth IIR Low Pass Filter with 0.005 normalized cut-off frequency on the unwrapped reference sensor signal.
- Butterworth IIR Low Pass Filter with 0.01 normalized cut-off frequency on the derivative of the signal.
- Medial filter with 100 values on the final signal.

It may be worth mentioning that all performance tests were conducted with a Scania reverse gear mounted on the rig, since it is considered a load that should represent the weight of most of the gears that can be mounted on the rig. Heavier loads, such as a flywheel will result in worse performance, both when accelerating and braking. The results for the performance tests are given in section 5.1.1.

4.4 Test Cases for Sensor Comparison

An important feature of the rig is being able to benchmark the performance of different sensors, be it sensors of the same type but from different suppliers, or of different types altogether. Therefore, an example on how the rig can be used to perform such tests is included. For that example, two inductive sensors from different suppliers were used. For the purposes of this report however, the suppliers will not be disclosed. Therefore the sensors under test here are named Sensor A and Sensor B. Both sensors were tested at a constant speed of 20 RPM, with varying air gaps between 0.5 mm and 5 mm for each test. The sensors were placed on opposite sides of a Scania reverse gear, that sits on the layshaft of the gearbox. For each air gap, the max and min voltages of each sensor under a certain period were logged. This was done in order to take into consideration possible asymmetries in the gear, which would result in varying signal amplitudes even at constant RPM. The results are presented in section 5.1.2.

4.5 Powertrain Process Implementation

Another purpose for the rig is the ability to replicate the behaviour of the different drivetrain components on a level that is able to give accurate information of the real-life usage of these sensors. However, during the course of the project, it became clear that
this implementation would be difficult with the current hardware on the rig. In order to motivate this argument, the performance of the rig was compared to an actual layshaft measurement from a Scania truck that uses a production gearbox. The comparison process chosen was the braking of the layshaft during a gear shift. In Scania gearboxes today, the layshaft has to brake from its current speed to the desired speed in order to match the new gear ratio. This process is shown in figure 4.6. The results are discussed in section 5.1.3.

![Figure 4.6: Speed of the test truck’s layshaft during an upshift, as well as a fitted 9th order polynomial.](image-url)

*Figure 4.6: Speed of the test truck’s layshaft during an upshift, as well as a fitted 9th order polynomial.*
Chapter 5

Results and Conclusions

This chapter presents the final results of the project, namely the performance of the rig with regards to speed following, as well as the results of the sensor comparison test case, presented in sections 4.3, 4.4 and 4.5 respectively. The results are then discussed and the overall usability of the rig is assessed. Finally, a few suggestions for future improvements to the test equipment are presented.

5.1 Results

5.1.1 Rig Performance

The estimated speed of the rig’s shaft with the reference signal was set to 10, 20 and 100 RPM can be seen in figures 5.1, 5.2 and 5.3 respectively. As can be seen, the rig is able to accelerate and keep the desired speed. The acceleration for these two references was set to 40 RPM/s in order to avoid potential overshoots on the shaft, but as can be seen a smaller acceleration should have been used for the 10 RPM reference speed. This is because the Arduino board updates the position reference for the motor servo drive at a specific interval. When the acceleration is high at low RPM, the motor will have time to accelerate beyond the set reference before the next update and therefore overshoot. While this problem can be avoided by selecting a lower acceleration, it is left here as an example of why the user has to select an appropriate acceleration when testing.

The same test with the reference set to 800 and 1000 RPM can be seen in figures 5.4 and 5.5 respectively. It is worth mentioning here that speed estimation becomes more difficult as the shaft rotates faster. This is mostly due to the reasons mentioned in section 4.1, namely noise and the accuracy of the reference sensor. Here the acceleration of the shaft was set to 100 RPM/s, which is near the maximum pace at which the motor can accelerate with the specific load. It is worth noting that the rig can also decelerate the shaft at the same pace. When this deceleration is not enough, the electromagnetic brake can be used instead.

Figure 5.6 shows the speed of the rig’s shaft when the electromagnetic brake is applied at 1000 RPM. As can be seen, the response time is approximately 0,1 s until the shaft comes to a complete stop. Since the brake only has an on/off functionality right now, it is difficult to achieve any other transient times with it. The importance of this result for the powertrain process implementation part of this project is further discussed in section 5.1.3. The peaks that can be seen at the timestamps 0,14 s and 0,2 s are due to the slow response time of the reference sensor and the algorithm that is used for estimating the actual speed of the shaft.
5.1 Results

Figure 5.1: Estimated shaft speed with reference set to 10 RPM with acceleration 40 RPM/s.

Figure 5.2: Estimated shaft speed with reference set to 20 RPM with acceleration 40 RPM/s.
Chapter 5. Results and Conclusions

5.1 Results

Figure 5.3: Estimated shaft speed with reference set to 100 RPM with acceleration 40 RPM/s.

Figure 5.4: Estimated shaft speed with reference set to 800 RPM with acceleration 100 RPM/s.
5.1 Results

Figure 5.5: Estimated shaft speed with reference set to 1000 RPM with acceleration 100 RPM/s.

Figure 5.6: Braking performance from 1000 to 0 RPM.
 Chapter 5. Results and Conclusions  

### 5.2 Discussion

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*Table 5.1: Max and min voltage values for the two inductive sensors measuring at different air gaps.*

#### 5.1.2 Test Case for Sensor Comparison

Figure 5.7 shows the max and min voltages for the two sensors with varying air gaps. As can be seen, both sensors follow the same curve both for the max and min voltages. However, Sensor B has significantly lower voltage amplitude at the same RPM speeds. This can be of significant importance since the gearbox ECU expects a signal of a certain amplitude in order to trigger. This means that even with a 1 mm air gap, Sensor B would not result in a trigger in the ECU, while Sensor A one would probably function properly.

#### 5.1.3 Powertrain Process Implementation

As mentioned in section 4.5, the process chosen for evaluating whether the rig is able to follow the actual behaviour in a truck is the layshaft. The process was shown in figure 4.6. The time it takes for the layshaft to brake from 1170 to 750 RPM is approximately 0.5 s, while the brake on the rig brings the shaft to a complete stop from 1000 RPM in 0.1 s (as shown in section 5.1.1 above). In addition, the brake only has an on/off functionality with a slow response time, which makes it difficult to reopen the brake in time before braking to 0 RPM. These reasons make it difficult to follow any transients that require the rig to decelerate fast between two different reference points, without making hardware changes or changing the friction materials of the brake.

However, it was shown in section 5.1.1 that the rig can accelerate with 100 RPM/s up to 1000 RPM, or decelerate with the same rate (100 RPM/s) for most gears that can be mounted on the rig. This means that the processes that fall under those conditions (such as the acceleration of the shafts in the gearbox or the acceleration of the motor), can be tested on the rig.

### 5.2 Discussion

This section provides a short discussion regarding the performance of the rig. This includes the strengths and the weaknesses of the rig, based on the hardware that was implemented, as well as the results presented above.
5.2 Discussion

Chapter 5. Results and Conclusions

Figure 5.7: Max and min voltage values for the two inductive sensors measuring at different air gaps.

5.2.1 Rig Requirements and Applications

As mentioned in several of the previous sections, most of the shortcomings of the rig are due to incorrect choices when it comes to its hardware. The first problem comes from the choice of motor. While stepper motors are good for low speed applications, the chosen motor does not have the necessary output power to accelerate a heavy load such as the rig’s shaft with a gear mounted on it. This also results in a maximum speed range of 1000 RPM, which is not ideal since most of the powertrain components, that are of interest, operate in the range of 0-2500 RPM or even 500-2500 RPM. However, as mentioned in the introduction of this report, low RPM ranges are of higher importance when it comes to future sensor development. At those speeds, the rig provides a better alternative than the current solution used.

The second limitation is due to the electromagnetic brake. As seen in the results above, the current solution provides a great braking power with limited control over it. This makes any attempt to model transients on the powertrain difficult. That said, there are still uses for the fast transients that the brake provides. Future gearboxes are planned to have a brake on each shaft. This means that some shafts, such as the main shaft, will brake to speeds that are almost near 0. Since the transient of the electromagnetic brake is faster than the actual transient in the gearbox, the results can still be used to benchmark the sensors at high speed transients. In addition, there are some ways of changing the braking time mechanically. This includes changing the friction material between the rig shaft and the brake, mounting heavier gears on the rig to introduce higher inertia.

Apart from the limitations mentioned above, the rig has several advantages. Section 5.1.2, presented a few examples of how the rig can be used in order to study important parameters such as the difference in performance of two inductive sensors at different air gaps. With the current sensor positioning system (described in short in appendix A), the sensors can be placed with different air gaps or at different angles from the target medium, increasing the testing possibilities. In addition, the rig makes it easier
mount different types of wheels, even for future components, while the software can be easily extended to include new features and control schemes. All of these points were not possible with the currently available rig for speed sensor testing.

5.2.2 Test Accuracy and Reliability

Reference Sensor

One of the most unreliable factors on the rig and the results presented above is the reference sensor that was used. As seen in figure 4.1, the sensor has a slow update rate and therefore the output becomes a step-like signal. This together with the large amount of noise originating from the motor servo driver made it extremely difficult to estimate the speed of the shaft. For the same reasons, it is difficult to trust the reference sensor as a ground truth for the system, especially at high speeds and another alternative should be considered. A simple solution would be to use an inductive sensor that is known to be reliable for speed estimation. However, using an inductive sensor leads back to one of the problems that the rig was trying to solve and that is speed estimation at low rpm. However, this is not a problem if the estimation can be done in post-processing.

Test Sensors

The rig’s accuracy on the sensors that are tested depends only on the DAQ device and the noise that is picked up from the sensors. The rig software is able to measure at least two test sensors at once, with high sampling rate, something that was not possible with the previous solution for sensor testing.

5.3 Future Work

There are several aspects of the project that could be improved, both with regards to the hardware and the software. The first improvement suggestion regards the reference sensor. The one that is found on the rig has a high response time, making it unreliable and difficult to work with at high speeds. If another alternative cannot be found, both the current sensor and an inductive one could be used together for different speed ranges.

Another hardware improvement that would increase the performance of the rig is the change of motor. Right now the motor that is found on the rig is able to achieve speeds of up to approximately 1000 rpm for most powertrain components of interest, which is not ideal for the purposes of the rig. Ideally, the rig should be equipped with a mechanism that allows for changing the ratio between the motor and the shaft, so that different speeds could be achieved. However, this would require a lot of changes in the construction of the rig and is thus not preferable. In addition to the motor, another servo drive should be considered, since the one used in this project generated large amounts of noise.

The final hardware improvement regards the electromagnetic brake. While the current brake provides a fast transient, that transient is faster than most applications today. In addition, a controllable brake with variable braking force would greatly improve the performance of the rig.

From a software perspective, improvements can be done in order to provide the user with additional functionality or ease of use. From a technical point of view, one of the most important additions is regarding signal processing. Speed estimation would be
the most beneficial in terms of motor control. As mentioned, the servo uses its own PID controllers for the current and position loops. An external position PID would be preferable since it allows for better control over the parameters and the response of the motor for the specific applications.
Bibliography


Appendix A

Rig Construction

This chapter aims to provide an overview behind the mechanical construction of the rig assembly. However, details about the sizing and the mathematics behind the assembly are omitted. All the information and figures presented in this section are based on Filip Fonser’s report on the rig [23].

A.1 Main Rig

![Figure A.1: CAD model of the rig assembly from the side.](image)

The main rig without the sensor positioning can be seen in figure A.1. It comprises of a BLDC stepper motor that is connected to the main shaft via a belt (not visible in the figure). The belt converts the torque from the motor to a lower one, allowing the shaft to rotate at even lower speeds that can be of importance for speed sensor measurements. On one end of the main shaft, different kinds of gears can be mounted with the help of a modular connector. The shaft also includes a brake disc that allows the electromagnetic brake that is found on the rig to stop the rig fast, both for measuring fast transients, as well as safety. The brake is automatically applied when the power is lost or the Arduino that is found on the rig is disconnected from its USB port. Finally,
a high precision position sensor is mounted on the end of the shaft that is responsible for providing a high resolution reference angle to the software of the rig. Figure A.2 shows a CAD model of the rig assembly from above. The following components can be seen:

1. Leadshine ES-MH33480 high voltage stepper motor with a sprocket mounted on it.
3. Brake disc for the electromagnetic brake.
4. The gear used for testing the sensor (such as a flywheel which can be seen in the figure).
5. Ringspann DV 020 FEM electromagnetic brake calipers.
6. The main shaft sprocket that connects to the BLDC motor via a belt.
7. Honeywell SPS-R360D-NBMS0101 high precision position sensor.

Figure A.3 shows a CAD model of the main rig shaft. In the figure from left to right one can see the sprocket that connects the shaft to the motor, the brake disc, as well as the connection point for the different gears. The gear connector is modular, meaning that different kinds of gears can be mounted for measurements such as flywheels or impulse wheels.
A.2 Sensor Positioning

In order to provide flexibility in the placement of the test sensors, two positioning stations have been designed. Each station has two strong magnetic feet that can be placed anywhere on the rig floor. The stations have micro-positioning tools that allow for accurate placement, down to a millimeter of precision. On the top of the station, an adapter is placed. The adapters can be designed to fit different types of inductive or hall sensors, making the choice of sensor for testing more flexible. A picture of the rig along with the positioning stations can be seen in figure A.5.
Figure A.5: The complete rig assembly, along with the two placement stations for the test sensors. A camshaft wheel can be seen mounted on the rig.
Appendix B

LabVIEW Software

This chapter provides a more detailed description of the LabVIEW software that was developed for the testing rig.

B.1 Functionality Overview

The main UI of the program can be seen in figure 3.3. It provides the user with two main graphs, one for the outputs measured, and one for the input signal that is sent to the motor. The two main modes of operation are Direct Control and Waveform. In both modes, the rig can either decelerate at the specified pace, or by applying the electromagnetic brake.

Four tabs can be found on the main window, namely Direct Control, Waveform, Errors and Settings. The first tab allows the user to manually control the RPM of the rig’s shaft. It also gives the user the possibility to set motor specific parameters that are relevant during a run, such as the motor’s acceleration or the direction of motion. A switch is also implemented that switches off the motor control. This option was implemented mostly due to the noise produced by the servo when the motor is controlled. Disabling the motor control reduces the amount of noise generated and lets the shaft slowly decelerate. The second tab, Waveform, has the following provides the following functionality. It allows the user to sent a predefined waveform as an input to the motor. An additional waveform generator was also implemented which can create and save simple waveforms such as square waves or step functions. The most used waveforms can be saved in a list and used between runs. The next tab gives the user a list of possible error messages which can be of help when tracking errors through the program. Finally, the last tab provides the user with a selection of tuning parameters for the software. The following parameters can be set:

- COM and USB ports for the DAQ and the Arduino.
- Sampling rates for the DAQ and the Arduino.
- The channels used for measuring the test and reference sensors, as well as choosing between single-ended or differential measurements.
- The update rate at which the graphs are updated.
- An option to automatically save the outputs at motor stop.
- How many seconds to continue measuring after motor stop.
• The motor "steps per revolution" parameter for the Leadshine servo.

The data acquired with the software can be either automatically saved after each run, or when the user requests it. The data is saved in .csv files with a specific structure so that it can be easily imported to Excel or MATLAB with a simple script for further study.

B.2 Block Diagram

The block diagram of the main window can be seen in figure B.1 below. The program is divided into two main loops. The first main loop waits for the user to press Start and handles all communications with the Arduino depending on the selected mode. On Direct Control mode, the loop is further divided into three loops, one for the Arduino communication, one for data acquisition and one for updating the graphs on the interface. The second main loop is an event handler. This allows the program to respond to any button presses while the rigs runs without having to wait on the data acquisition or the communication with the Arduino to finish. This implementation also allows the user in most cases to safely slowly stop or brake the motor independently of the other loop.

Each loop includes several SubVIs that implement different functionality, such as sending specific commands to the Arduino, saving the acquired data to a file, or performing signal processing where required. All these additional SubVIs are omitted in this report.
Figure B.1: Block diagram of the main window.