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Setting suitable requirements for a 1-cylinder research engine control system

Master's thesis in Automotive Engineering

KARL STÅHLBERG

Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2019

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KARL STÅHLBERG

Supervisor: Alf-Hugo Magnusson, Department of Mechanics and Maritime Sciences
Examiner: Sven B. Andersson, Department of Mechanics and Maritime Sciences

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Department of Mechanics and Maritime Sciences
Division of Combustion and Propulsion Systems
Chalmers University of Technology
SE-412 96 Göteborg
Telephone +46 31 772 1000

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KARL STÅHLBERG
Department of Mechanics and Maritime Sciences
Division of Combustion and Propulsion Systems
Chalmers University of Technology

Abstract

The combustion in modern engines are controlled by electronic systems, with the electronic control unit, ECU, as the main component to control and give commands to the system. The ECU is divided into hardware and software. Being independent of complex, licensed and commercial software and hardware is crucial for experimental research in order to eliminate sources of errors and to minimize the number of parameters that influences the accuracy of the tests performed. The ECU interact with several other components and need to be compatible with those.

This study will investigate what parameters that are crucial in order to control a high pressure direct injection system for a one-cylinder test engine at the Division of Combustion and Propulsion Systems at Chalmers University of Technology in Göteborg, Sweden. The study will investigate how the current system works in order to put specifications of the new system including sample rate, current and voltage values, frequency of the signals and threshold values for different commands given by the ECU.

Today, the ECU used at this specific engine has a licensed software that is designed for and restricted to the hardware it is used in. It is made by a manufacturer that does not let the user edit the code or functionality of the software and therefore the hardware gets restricted as well. The study will set up requirement specifications in order to be able to and give recommendations of how to design a new control system for the 1-cylinder research engine.

Keywords: electronic control unit, signal system, sample rate, spike value, hold value, direct injection.

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Karl Ståhlberg, Göteborg 2019

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1
Introduction

This chapter presents the background of the thesis, in other words what scientific problem that led to the inception of this study. The chapter describes the the content of scope and also the limitations of this thesis. It also presents what the thesis should and should not include.

1.1 Background

Being independent of complex, licensed and commercial software and hardware is crucial for experimental research. One example of this is the electronic control units, ECU's, which interact with several other components and have to be compatible with those. It is important since high compatibility between the components and non-complex systems helps eliminate sources of errors and to minimize the number of parameters that influences the accuracy of the tests performed.

One way to avoid this an be to build an in-house system. In order to do so, it is needed to investigate if it is possible for this purpose. That would include the usage of open source software together with standard control modules. In this thesis to control a high pressure direct injection system for a one-cylinder test engine at the Division of Combustion and Propulsion Systems at Chalmers University of Technology in Gothenburg, Sweden. Today, the ECU used at this specific engine has a software that is designed for and restricted to the hardware it is used in. The functionality depends on not only the component itself, but also which components it does interact with, for example the injection components such as the common rail. Today the components from the manufacturer that build the engines are often limited and restricted in such a way that they may only have full capacity when the different components are from the same manufacturer. Which may not be the best solution for a engine in a experimental environment, such as a testing laboratory.

1.2 Purpose and Aim of The Study

The purpose is to find suitable requirements on the system, that are described in the background, in order for it to be designed and ready to be built. The thesis should investigate how accurate the current control system can control the fuel system, and also identify how variations of the controlled variables depend on the different engine load cases.

The aim of the study is to analyze how the ECU from the engine manufacturer control the fuel system today. Furthermore to set the performance and technical specifications for the control system and give a recommendation of what type of system that could be used, in order to control the fuel pump and fuel injector and regulate the pressure and timing.

1.3 Limitations

When investigating what requirements the system must fulfill it is necessary to limit the work. It's important in order to plan how to proceed with the work and what not to investigate further. Excluded in this work that will take place within the period of time of one semester full speed university studies are:

- Making the system compatible with a multiple cylinder engine i.e. two or more cylinders
- Setting up a system that considers optional aspects as intake air pressure, exhaust pressure, swirl and EGR valve

1.4 Problem Formulation and Statement

Is it possible, by performing measurements on the current one-cylinder test engine, to specify the requirements needed to make it possible to build an new in-house control system? And if so, is it better to build it with an open source software or if the new system can be bought?

1.5 Organisation

The thesis work will take place at the Chalmers University of Technology. In the Department of Mechanics and Maritime Sciences where the practical work will be done in the laboratory at the Division of Combustion and Propulsion Systems. The examiner for this thesis will be Professor Sven B. Andersson and the supervisor will be senior research engineer Alf Magnusson. Also including in the staff, as a tutor, will be senior research engineer Robert Buadu.

2
Theory

Modern combustion engine cars contain complex engine systems which include sophisticated control systems. These type of control systems consist of hardware and software [1]. In the following sections it is presented how a control system works, what parameters it is able to control and what hardware it uses in order to control those. It is important to get knowledge of how the software in the ECU influences the parameters and what softwares that are used today. The following section will present the elements that are included in a fuel injection control system.

2.1 Existing Control System

The existing engine in the engine lab at Chalmers University is a 1-cylinder diesel engine. It is rebuilt from a 4-cylinder Volvo diesel engine, see appendix D.4. For this work, the main engine parameter to study is the injection system. The injection system consists of fuel injectors, a common rail and a fuel pump. The system is controlled by ECU, from the company called Denso, see section 2.2.1.4, by electrical actuators. The ECU is programmed in a software called INCA, see section 2.2.1.1, and does receives a number of information from the injection system by sensors, see appendix A.1. With the sensors, the pressure can be measured in the different parts of the system, the results are then presented in a software from AVL. The ECU also receive data from other parts from the engine beside the injection system. It receives data from the camshaft and the flywheel as well, see appendix A.1. It uses this data in order to control the shape and timing of the injection pulses.

In the following figure a structure chart is built for the injection control system, see figure 2.1. It illustrates how the elements interact with each other mechanically and how information travels throughout the system.

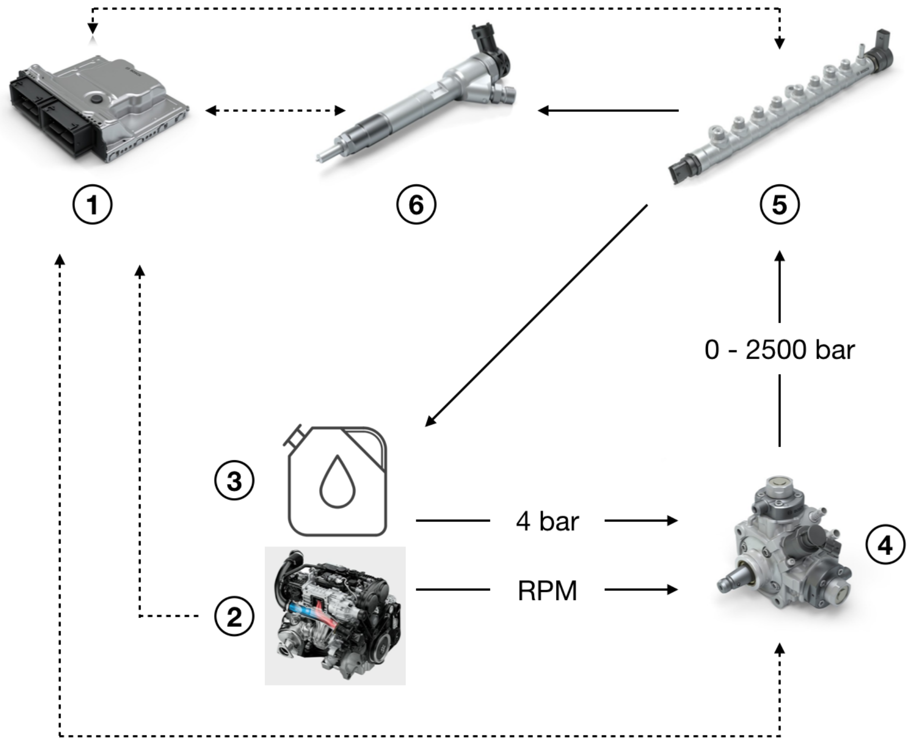


Figure 2.1: Structure chart system of the 1-cylinder test engine, where dotted arrows represent data and fully colored arrows represent mechanical work.

From figure 2.1 we can see how information travels in the engine system. The ECU is referred to as number 1 in the figure. It is the brain of the system and receives information from every part of the injection system and the camshaft and flywheel. The ECU, as mentioned before, also controls parts of the injection system. It controls the fuel pump, number 4, by what fuel pressure it should create and when to create it. The ECU also control the pressure in the common rail, number 5, by when to release the pressure valve in the rail. The last part that the ECU control in the system is the fuel injector, number 6 in the figure. The ECU receives information about, among others, pressure and speed of the engine, see appendix A.1. With this information it can control the timing and pressure of the injection. The timing of the flywheel and camshaft, referred to as as number 2 in the figure, is determined by the engine speed. The fuel tank is referred to as number 3 in the figure. It does not send or receive any information regarding the injection system, however it provides the system with fuel and does also receive fuel from the common rail by the pressure valve when the pressure is to high. The fuel pump, referred to as number 4, also uses the engine speed in order to create pressure. The common rail, referred to as number 5 distributes the fuel from the fuel pump to the fuel injector, referred to as number 6, and does also lower the fuel pressure to the fuel injector when needed by its pressure valve.

2.2 Electronic Control Unit - ECU

The electronic control unit is, as mentioned earlier, the brain of the control system. It distribute and control information between the different elements of the injection control system. In order to receive and give information it uses sensors and actuators [1]. Sensors gives the input signals while actuators actuate the output signals. The input-output relationship is a complex network of the underlying physics. In most cases, a single control input affects several outputs [2].

Control systems are important in order to control emission and performance. While engine performance, dynamic behavior and fuel consumption are important criteria for engine manufacturers, the most important criteria is that all engine system must comply with the emission limits [2]. From a control-engineering point of view, there are three important paths which have to be considered. Those are fuel, air and exhaust gas recirculation, EGR [2]. Notable for a diesel engine is that it produces smoke if the air fuel ratio falls below a certain value due to unburnt fuel. The air fuel ratio is also important in order to reach the best NOx reduction. Due to emission legislation exhaust-gas recirculation is needed to reach the wanted NOx reduction.

The fuel, air and EGR are in the ECU controlled by the main control loops. Main controls are typically air fuel ratio control, ignition control, fuel injection control, knock feedback control, idle and cruise speed control, EGR control, air injection control, canister purge management [2]. The EGR valve position is determined from the difference between reference and measured air massflows. The EGR flow heavily affects the air mass-flow through the states of the intake and outlet receiver.

Additional devices, such as throttles, must be used to maintain a pressure difference over the EGR valve. The ECU are also able to actuate the injection valves multiple times per cam shaft revolution. From this action the system is able to provide the desired amount of fuel per cylinder per cycle [1].

2.2.1 ECU's on the market

ECU softwares have traditionally been written in assembler code, recently it has however been a strong trend towards using standardized high-level programming interfaces. These software are often delivered together with a compatible hardware. Within these programs the software is structured to reflect the primary physical connections of the system to be controlled. [2] The purpose of looking at product that is on the market today is to investigate what kind of and how much information the different companies are willing to write about their product. It is interesting to know if the companies on the market today provides solutions with both hardware and software or just one kind. It is also important to know if the current ECU today are able to edit and program.

This study is however not a product development study and the ECU's on the market will not be analyzed but for future work, it is important to have in mind that the new ECU system should be a non complex and non licensed system. In the following sections, some common commercial control systems are presented.

2.2.1.1 INCA

INCA is one of the leading automotive ECU softwares in the industry today. It is provided by the company ETAS and its main purpose is connected to automotive ECU measurement and control parameter calibration tasks [3]. When using open software interfaces, INCA can be automated and integrated with the test equipment. INCA does in other words not provide any hardware. INCA supports ECU descriptions for measurement and calibration systems, test bench interfaces, measurement data exchange and protocols for communication compliant with the Association for Standardization of Automation and Measuring Systems, ASAM, standards [4]. Those standards gives certain guarantees about the ability to program certain areas such as sensor and actuator devices [5]. It is also the software system used in the test cell today for specifying the wanted set values to the current ECU.

2.2.1.2 Megasquirt

The ECU from Megasquirt provides both software and hardware. It has up to 8 fuel and 8 logic spark outputs offering full sequential fuel and spark for high-end injectors and high-current coils with suitable external ignition module. It means that it is possible to run an full-sequential on a V8 or semi-sequential on a V12 with this equipment. Possible to trim are spark and fuel for each channel and OEM temperature sensors. Initial setup is aided by test modes for the fuel and spark and by built in loggers to help diagnose incoming signals to the system. However it does not reach up to the ASAM standards in terms of programming level.

Injector timing is also possible to map for wanted behaviour. The system has six solenoid outputs for controlling of boost, fan control, shift light, tachometer etc. It is compatible with external MAP sensors and it allows some kind of datalogging with USB-ports and CAN communication ability when used in a more complex environment. The software includes pre-installed features such as two stages of progressive nitrous, water injection and closed loop boost control [6].

2.2.1.3 National Intruments

National instruments provides both hardware and software. Rapidly prototype an engine control unit can be done by the program NI CompactRIO, but there are also more advanced programs. It is possible to implement next- and samecycle control with a resolution of 25 ns. The program are able to control solenoid or piezoelectric direct injectors.

When using the software in combination with National Instruments powertrain control modules, it is possible to set up and control sensor and actuator interfaces within the software LabVIEW. The National Instrument solutions do apply to certain ASAM standards [7].

2.2.1.4 Denso

Denso only provides a hardware solution. It is fully able to control fuelpump, radiator, transmission, camshaft timimng and so on. It is also able to be used within a hybrid powertrain. However the control unit is very complexed and licensed, which means that there are not very much data about the system and it does not comply with the ASAM standards [8]. It is the hardware used today in the test cell with support from the car manufacturer Volvo Cars.

2.2.1.5 Transtron

Transtron only provides a hardware solution. It is able to control the common rail, the fuel injection system, emission gas recirculation, EGR, system and emission gas treatment system. It is fitted with a built-in high-performance 32-bit RISC chip and controls the timing and amount of fuel injected at a rate of 1000 Hz. It uses CAN in order to communicate with other systems and are able to log data [9].

2.3 Fuel Injection System

It is crucial to know what engine parameters there is and to know how the combustion is influenced by those. This chapter will explain what parameters of the fuel injection system that the ECU controls and how they work. In this section parameters controlling the fuel injection system will be explained.

2.3.1 Fuel Injector

The characteristics of the combustion in a diesel engine is depending on the injection process. Control of the injection timing and duration, fuel quantity and rate shape will make it possible to determine the engine performance [10]. There exist at least two types of fuel injectors. Historically the solenoid one has been more common. The solenoid injector works by that an electrical signal is given to energize the coil of the solenoid valve. This energized coil creates a movement of the injector armature, by using spring load and fuel pressure, and causes the valve to open and close. When the electrical signal ends the coil gets non energized and the valve is closed by the return spring. The amount of fuel injected is proportional to the magnitude of the current applied onto the solenoid and the time duration for what type injection that takes place [11].

However, nowadays a piezoelectric type of injector has become more used among modern diesel engines. It has been found by investigations that the characteristics of both solenoid and piezoelectric injectors affect the characteristics of the fuel injection, and thereby the combustion. It was found that the piezoelectric injectors had a shorter injection delay and had a better fuel automation than solenoid [12].

Piezoelectric technique uses a certain type of crystals to open and close the fuel injectors. Due to the characteristics of this crystal it is possible to inject very accurate in time during high fuel pressure and engine speed. Piezoelectric technology can be explained as the result from squeezing or applying pressure onto a certain type of crystal materials or some ceramics that then creates electricity. The process is also possible to execute in the other direction by apply electricity onto the same materials. They will then expand and return to their original size as soon as the electricity is cut off. This expansion is used in the piezoelectric injectors to move the injection needle up and down. Another attribute that the piezoelectric injectors have compared to the solenoid are that they are able to open the injection needle partway. By applying less electricity the piezo crystals expand less and the injectors open less distance. A smaller opening can be used to create a longer injection time with the same amount of fuel. It can be beneficial when injecting a small amount of fuel. The accuracy of the piezoelectric injectors also means that they are able to inject more times per combustion cycle then the solenoid injectors. It can be beneficial when trying to reduce emissions and limit the soot production [10].

2.3.2 Fuel Pump

The test engine in the laboratory uses a high pressure common rail (HPCR) fuel injection system. The selection of pump is determined by the characteristics of the injection system. Hence if a high pressure common rail is used, it's beneficial to use a high pressure fuel pump that fulfills the requirements that such a system demands. The HPCR has a belt arrangement that drives the high pressure rail pump. The common rail injection system requires that the pump are able not only to create a pressure peak but also to constant holding that pressure over a period of time in order to obtain fast opening times [13]. This is a big difference from when the engine uses a cam-controlled injection system, where the fuel pressure reach a maximum injection pressure only for a short period of time [14].

2.3.3 Common rail

Traditionally the distributor pump and common rail are two most used fuel distributors in a car engine. The test engine uses a common rail. The main difference between the two fuel distributor types is that the common rail system has the advantage of being able to adapt the injection pressure independent of the engine speed and fuel quantity. Another advantage of the common rail system is its ability to keep a constant fuel pressure at the nozzle throughout the injection period.

This attribute makes it possible to reduce the hydraulic flow rate at the nozzle without losing any significant power output. While the distributor pump is controlled by a camshaft, the common rail is mechanically independent from other systems and are able to keep constant pressure at the nozzle during the injection time period [14].

2.4 Measurement Instrument

To measure the intended system a measurement system needed to be designed. There are several available softwares at the market, however at Chalmers University a software called Labview was available. That software is suitable since it is simple to integrate with measurement instrument hardware from any vendor. It is a graphical software visualisation program language that is used to visualize among other things hardware configuration and measurement data [15]. The visualization interface is helpful when creating a digital oscilloscope. That was programmed in Labview, see appendix C.2. It was designed in order to be able to extract data from the existing engine system. The acquired data can be saved in several different data types such as a text-file, or .txt file. Text file is a suitable standardized data file type that can be displayed and analyzed many different suitable program, in this case Microsoft Excel and Matlab.

2.5 Sample rate

In order to be able to correctly reproduce the analog signal it is in theory the best method to sample an infinite amount of data points collected along the analog signal. This is however not possible to realize practically and therefore the sample rate must be determined. This is important hence if too few data points is collected, it is not possible to reconstruct the analog signal [16].

One way to solve this is to apply the Nyquist–Shannon sampling theorem. It says that the sampling frequency has to be at least twice as high as the bandwidth of the signal in order to avoid errors in the reconstruction of the analog signal [17]. If the sampling frequency is not as twice as high, the result of the digital reconstruction will have a lower value compared to the measured analog signal. In this specific case, it means that in order to measure the right frequencies we must have at least 2 sample points per injection pulse. From this information the injection pulses duration time had to be investigated in order to reach a suitable sample frequency.

However, even when using the Nyquist theorem there will occur some errors. Figure 2.2 illustrates the estimated error of the signal measured when using the Nyquist theorem. That depends on that there will be data points in between the sample points that are unknown and might create an error.

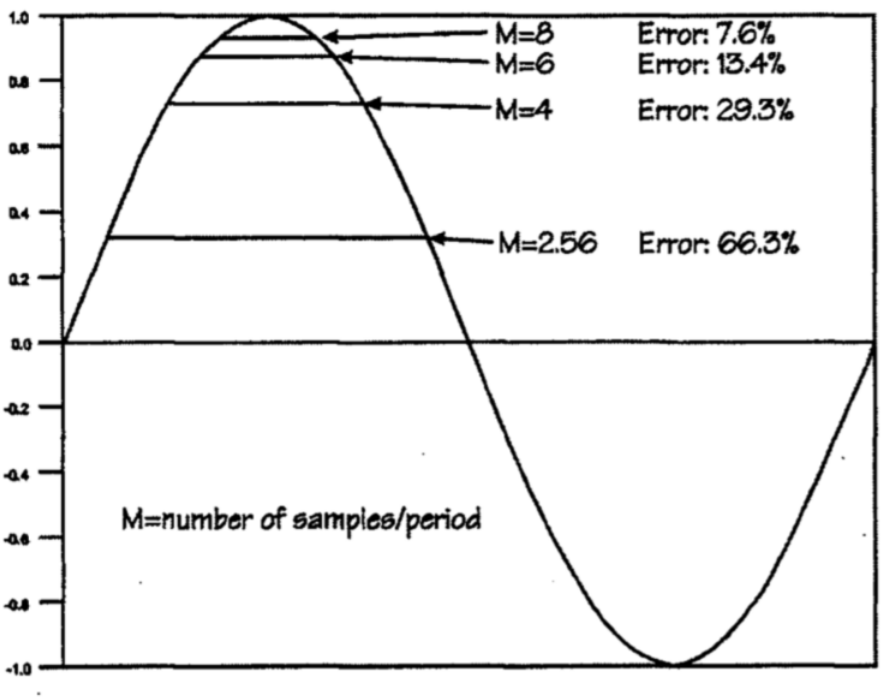


Figure 2.2: Estimated error using a sampling rate based on Nyquist sampling criteria. Where M is equal to the factor of the bandwidth of the signal.

In order to choose the right sample rate one should rather than be concerned with the shape of input shock pulses, use a method of describing the response of the systems to those pulses or impacts [16]. It is in this case not only interesting to control the length of the injection pulse but also the height of the injection pulses. It is possible to see from the measurements in section 4.1.1 that the injection pulses has a peak current when at the start of the injection pulse. It is then interesting to know what bandwidth that pulse has in order to be able to extract that peak value.

2.6 Engine Parameters

As can be seen in figure 2.1 the control system used in this work, and therefore the ECU, does not interact with a lot of engine parameters apart from the including parts of the injection system in the test engine. It is only dependent on the values of the camshaft and the flywheel. The engine parameters does however sometimes need some conversion in order to cooperate and interact properly with the control system. Hence when setting the injection timing, it is in most softwares set in crank angle degrees, CAD, while the injection duration is set in seconds or more specifically milliseconds.

This means that we need to find a correlation between the two units. It is possible to find a general correlation between the two units but it is then crucial to know the speed of the engine or more precisely the engine revolutions per minute, RPM, in order to set the correlation. It can bee seen in equations 2.1, 2.2 and 2.3

$$1[CAD] = \frac{1}{360}[r] \tag{2.1}$$

$$x[rpm] = x * \frac{1}{60}[\frac{r}{s}] = x * \frac{360}{60}[\frac{CAD}{s}] \tag{2.2}$$

$$[CAD] = \frac{1}{\frac{360}{60} * x}[\frac{CAD}{\frac{CAD}{s}}] = \frac{1}{\frac{360}{60} * x}[s] \tag{2.3}$$

Where:
CAD = crank angle degrees
r = 1 revolution of the engine
rpm = revolution per minute
$\frac{r}{s}$ = revolution per second
s = second

3

Methods

The methods chapter will present the workflow and how the work of the report was executed.

3.1 Measurements

To be able to put suitable requirements on the new injection control system, the old had to be evaluated. A prerequisite to measure the existing engine system was to have access to adequate measurement instruments. The new injection control system is going to control and receive signals from both the injection system but also some other parts of the engine, more specifically a high pressure fuel pump, an injector, a camshaft, a flywheel and a common rail, see appendix A.1. The new injection control system is going to control those engine parameters by electrical signals. Those signals was therefore necessary to measure. The electrical signals can be measured by both the current and the voltage.

3.1.1 Measurement instruments

In order to know with what signal frequency and rate the system needed to be able to handle, high resolution digital measurement instruments used. When using analog instruments, such as an oscilloscope, it is difficult to record and make an estimation of how the quality of the signal effects the system. It is also hard to estimate what rate and frequency the system demands or are able to deal with. The digital instrument consist of a data acquisition, DAQ, device from National Instruments to measure the signals from the system. It was connected to an 68-pin screw terminal connector block accessories from National Instruments, see appendix D.1, that was connected onto a computer. The software used was LabView from National Instruments. Before starting the measurements the measurement system had to be validated. It was made by triggering the system with a 5V signal created by a battery, see appendix D.3. The system was accurate programmed as the interfaced showed a sinus curve with the altitude of 5V. The DAQ device had a restriction of $\pm 10V$.

The digital measurement instruments was then connected to the test engine system by clamp meters, or ampere meters clamps, with a resolution accuracy of 1% [18]. They can be seen in appendix D.6 to D.8. The engine was then run on several loads and speeds as an ongoing research project on the specific test engine system. They can be found in appendix B.1.

The main reason to run the engine on different speed and load was however to see how the signal behaved when the parameters changed, this was met by the properties chosen since the engine load and speed between the different engine cases varied. Later in the test cycle, or rather after the sample rate was decided and it was time to measure the shape and size of the current and voltage signals, the project used its own engine load cases adapted for the study, see appendix B.2. They can be read about further down in the engine load cases section.

3.1.2 Sample rate

As mentioned before, the analog signal is digitized by the measure instruments. In order to be able to correctly reproduce the analog signal it is in theory the best method to sample an infinite amount of data points collected along the analog signal. This is however not possible to realize practically and therefore the sample rate must be determined. This is important hence if too few data points is collected, it is not possible to reconstruct the analog signal [16].

From the current ECU software that controls the system today it can be seen that the start of injection timing pulses varies from the different engine running cases, see appendix B.1. The shortest injection pulse was then chosen and the Nyquist theorem was applied onto that specific case. It is then interesting to know what bandwidth that pulse has in order to be able to extract that peak value. This length could not be found in the current ECU software but had to be calculated from the simulation. The calculated sample rate, from when taking the injection pulse length into consideration, then had to be adjusted and the simulations had to be run again.

One note to take into consideration is that the bandwidth of the signal usually is calculated with a Fourier transformation [19]. However, since there is no function but measured data there is no need for a Fourier transform. Even though the frequency has to be calculated manually from the test results.

3.1.3 Engine parameters

The engine parameters that had to be measured was decided by the hardware that interact with the current system. From the structure chart in appendix A.1 we can see what engine parameters that are measured by the current ECU. By connecting the measurement instrument to these sensors it is possible to get electrical signals from all the actual engine parameters that affects the ECU system today. First the current was measured and later so also the voltage.

3.2 Data analysis of sample rate

The data from the measurements in the Labview program was saved as text files and thereafter loaded in Matlab where the timing of the injection pulses as well as the sample rate were investigated. Also the size and the shape of the injection pulses was investigated. All the data was processed and compared to the actual values from the current ECU and the wanted values that was specified to the ECU, see appendix B.1. The Matlab software was considered as a suitable program to use when processing the data and printing out the injection shapes since it easy to operate and compare big data files.

3.3 Voltage Converter

When the data analysis of the sample rate was done, it was time to measure the voltage as well together with the current. This had to be done since every ECU has a limit of what power supply, or voltage it is able to handle. The voltage spikes, also called inrush voltage, are created when load is switched in the power supply system [20]. The value of the voltage spikes are however to high to be possible to measure with the used DAQ device, see appendix D.2. Therefore the voltage signals had to be converted into lower values. It was done with a voltage divider and an isolation amplifier module connected between the solenoid valve and the data logger. The isolation amplifier was needed to protect the DAQ device from any high voltage spikes higher that was expected and to isolate the grounds to prevent noise from being transmitted to the data logger via the ground connections. The voltage divider consisted of a 100k resistor in series with a multi-turn 100k trimmer. The output of the voltage divider was fed into an analog input voltage module with an input range of ± 10V and an output range of ± 5V.

The voltage divider was set to a step down ratio of 20:1 and the isolation amplifier has a step down ratio of 2:1 resulting in a total step down ration of 40:1 from the test object to the data logger. The step down chain was calibrated to give an output voltage of 5V for a maximum input voltage of 200V. There were four such channels in total connected to the data logger to measure control valve signals. This means that all numbers displayed in graphs are 40 times lower then the actual value measured at the sensors by the equipment.

3.4 Engine load cases

After building the measurement instruments, deciding the sample rate and created suitable data analysis programs, it was time to run the engine load cases adapted for the study. There are four load cases that has been chosen in order cover cases with a combination of high and low speed and torque. They are shown in figure 3.1 and can be read about in appendix B.2.

The engine parameters are set to be different for the different load cases. This is done in order to be able to see how they affect the system. The load cases are run on four different engine speed, air pressure, injection timing, injection duration and injection pressure. When running the test engine, load case two was set as the reference case. This meant that it was run as the first and last load case with the other load cases in between. It was done in order to be able to validate that the prerequisites of the simulation was the same for all four load cases and that sources that could influence the combustion did not change over time.

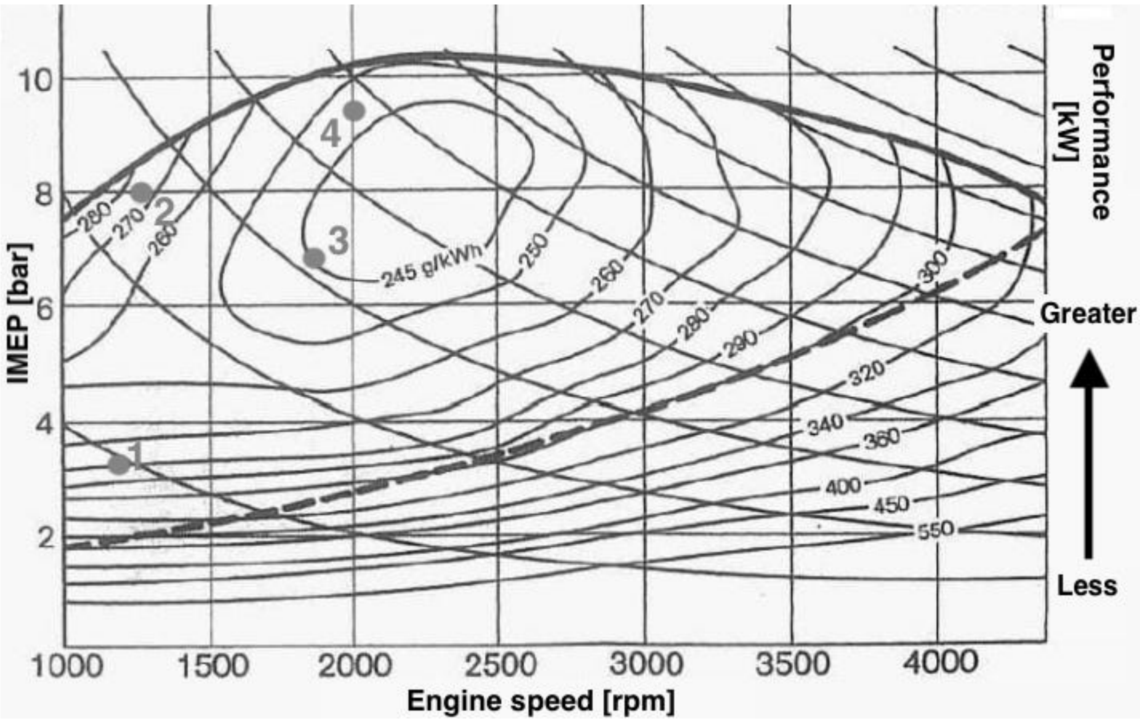


Figure 3.1: Engine load cases when measuring shape and size of current and voltage signals.

Figure 3.1 does not represent the actual load map, since it is not known but it is a representation of how the load cases are distributed. What is important to interpret from the figure is that load case 2 and 3 are performing similar power outcome. However they are doing so in different ways, load case 2 by high load and load case by high engine speed.

4
Analysis

In chapter 3, Methods, it was described how the measurements was done. In this chapter the measurements will be analyzed. The purpose of this chapter is to assemble and compile the measurements so that they can be put in a context later when the result are presented. It will then be easier to interpret the results and understand how they affect each and other.

4.1 Measurements

There were several aspects that were interesting when analyzing the measurements. The first thing that was analyzed was the duration of the injection but also the timing of the start of the injection, in comparison to the top dead centre, TDC. It was also important since by knowing the shape and size of the smallest injection, it is possible to know the size of the shortest sample frequency the ECU needs in order to control the injection system. On the other hand it was also important to know how different parameters affect the combustion. That is important since the new system is supposed to be as simple as possible. In order to make the system non complicated it is important that the ECU does not control parameters that do not affect the combustion or are supposed to be managed by other systems.

4.1.1 Sample rate

The tests was made with different engine speed and load. These tests where made firstly to investigate the behaviour of the injection and to check how and if the sample rate affected the results. The precise data are presented in the results chapter. An example of how the current ECU system and the built Labview system gives different results can however be seen in figure 4.1. It is a representation of the results from the sampled data when running on engine load case 2 from appendix B.1. The actual data from the current ECU system is exported to Matlab files from a program, Indicom. The wanted set values are inserted to the ECU through a program, INCA. The built measuring system is represented in the figure B.1 as Labview. The difference between the results of the built measurement instrument and the current ECU system depends mainly on that they sample with different sample rate.

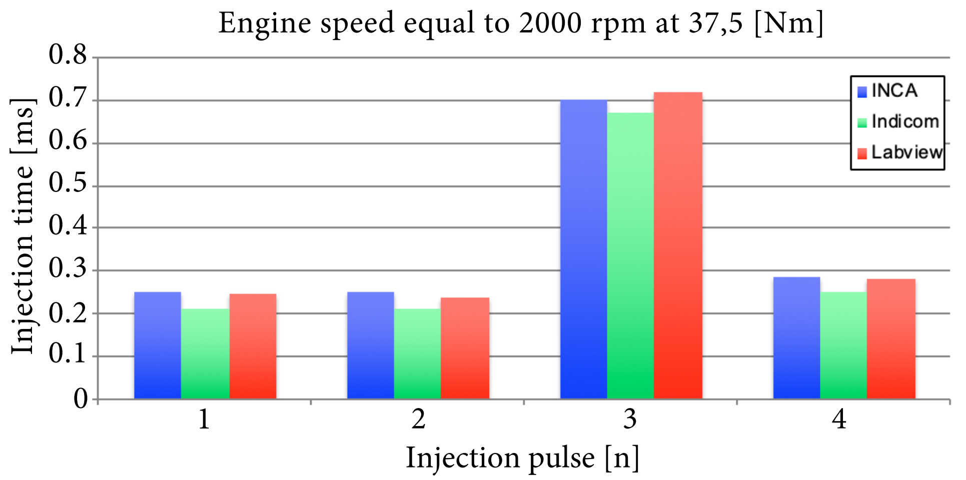


Figure 4.1: A comparison between the current ECU and the built measurement instrument and how they vary compared to the wanted set value.

When running on the current settings the estimated error, between the set value in INCA and the value that the current control system Indicom displays, is around 12% as can be seen in figure B.1. The new built Labview measuring system gives an error of around 1% compared to the wanted set value in INCA. The dimensions of these errors correspond to the error that can be expected when comparing to the theory chapter. Even if the estimated error of the signal, when using the Nyquist theorem, is very small it can be seen in 4.2 that the new measurement system is not able resolve the maximum value of the different current peaks for the injection signal. This can be seen since the 4 peaks does not have the same value. It is however in this case not necessary since the measurement system will give a good estimation of the magnitude of the current and it does not affect the time length error. The time length is more important since the purpose of the system is to control the injection pulse. The start of the injection will happen when it is triggered by the current. It is not of great importance if the size of that current has a small percent error, hence the injection will still initiate.

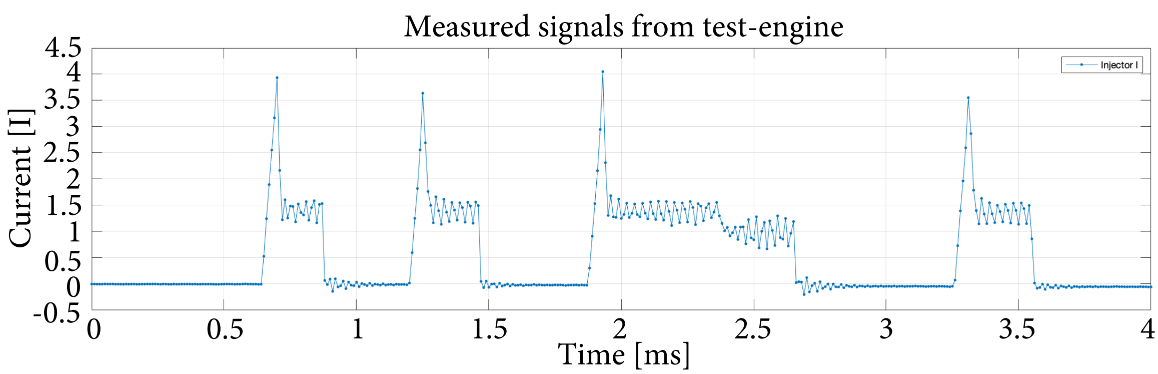
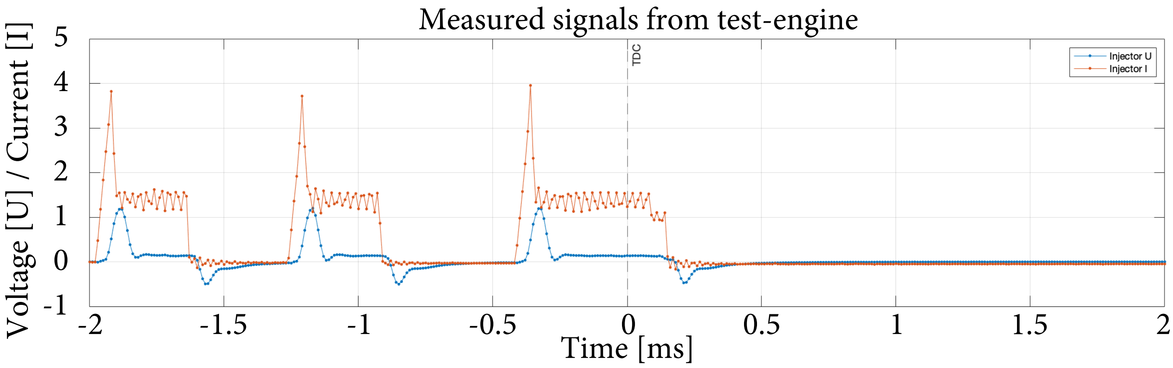


Figure 4.2: Example of injection pulses from engine load case 2, when measuring suitable sample rate.

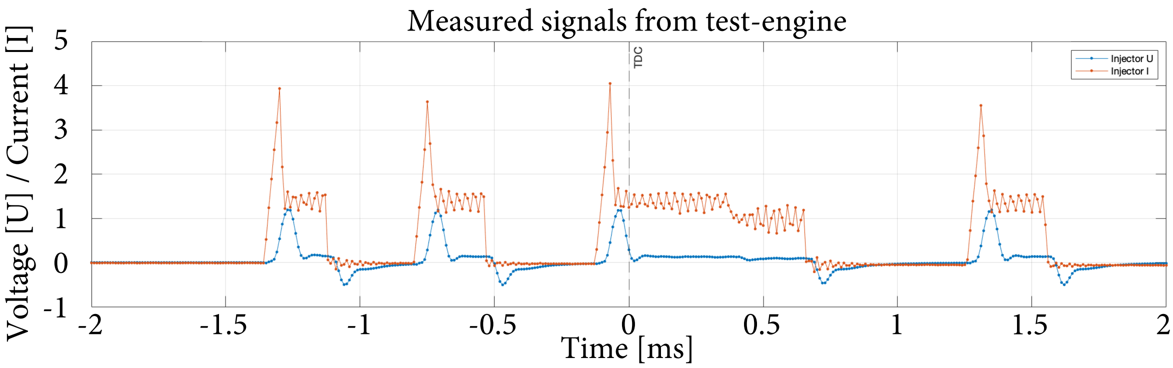
4.1.2 Current and voltage

When the sample rate was decided the voltage and current properties of the current signal could be decided. When measuring these properties, the study changed engine load cases to those in appendix B.2. Both the current and the voltage can be, as mentioned in the theory chapter, divided into inrush value and hold value. When measuring the inrush value, the focus was on measuring the performance of the system but also the value of the voltage spike. When talking about performance, it means how fast the signal can reach its maximum value. It is important since this limits how fast a signal can be triggered and is measured in the corresponding unit over time for both the current and the voltage.

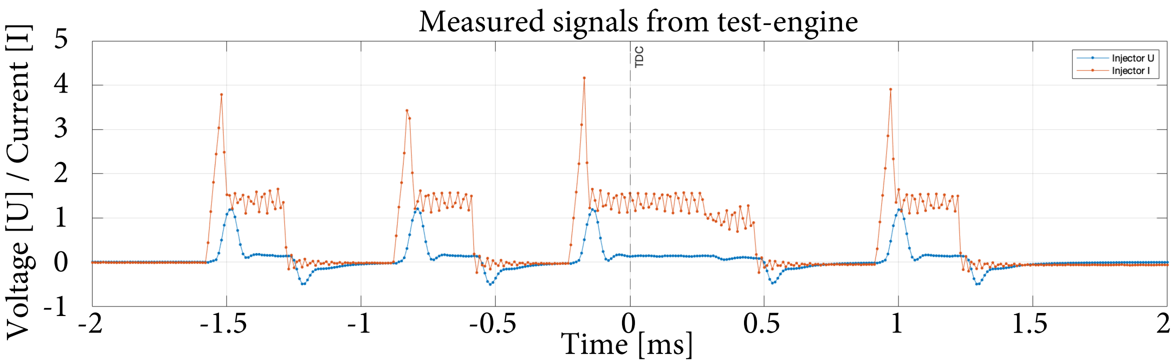
Another value that is important is the maximum peak or spike of the inrush current or voltage and the hold value of them. It is measures in ampere and volt. It is also interesting to see the shape of the signal. It is important to know if these signals change depending on different load cases. when setting requirements on the new system. The result in figure 4.3 show that the signal does not change it properties with the different engine load cases. From this we can assume that the properties of the signal rather depend on the properties of the ECU. We can see that the maximum value of the current and voltage lays around the same for all four engine cases at the inrush signal. The same behaviour can be seen for the hold value of both the current and the voltage. An comparison of what performance the current ECU is able to create is done by analyzing the inrush signal between the different engine load cases.



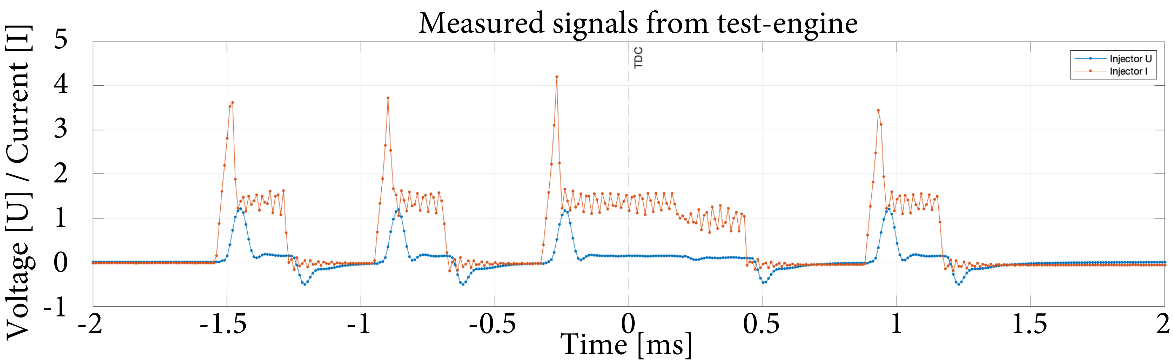
(a) Engine load case 1



(b) Engine load case 2



(c) Engine load case 3



(d) Engine load case 4

Figure 4.3: Measured current and voltage signals from the ECU to the injectors

When analyzing the shape of the signal for the hold value at the third injection pulse, it is possible to see how the decline of the hold value for both the current and voltage. In figure 4.4 we can see that the hold value for the current and voltage starts at one value but then drops for all four engine load cases at the main injection pulse. When looking closer at this phenomenon, it is more clear to look at the voltage signal since there are less fluctuations in the signal, one have to look at the length of the main injection voltage pulse signal for the four different engine load cases. The length of the main injection voltage pulse signal for each engine load case from case one to case four is respectively 0.56, 0.78, 0.69 and 0.76 milliseconds. As can be seen in figure 4.5 the time it takes for the hold value of the voltage to drop is equal for each main injection pulse. This means that the drop will happen at the same time for all engine load cases and be predictable and possible to recreate. It means that the variable length of the hold value signal for the voltage and current will only will take place after the drop. It will start at after a certain time period, calculated to 0.55 milliseconds for the voltage signal and occur until the main injection pulse ends.

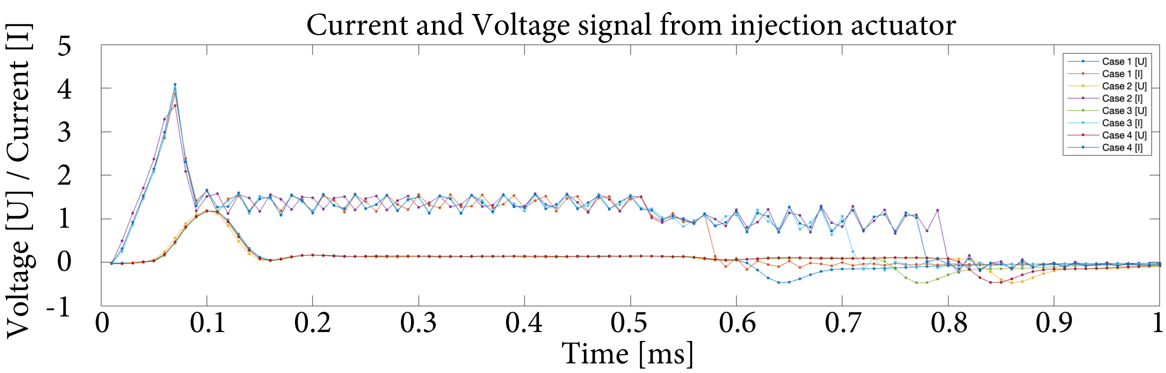


Figure 4.4: A comparison between the current and voltage drop for the third injection pulse for the 4 load cases.

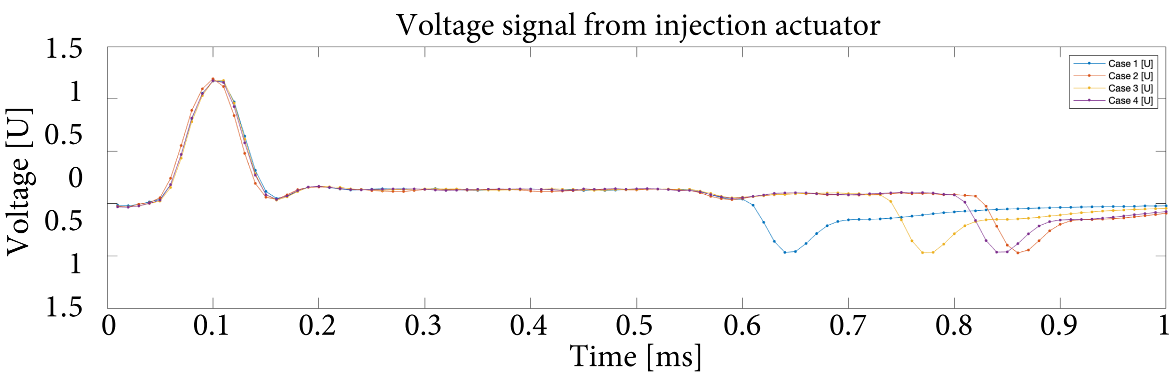


Figure 4.5: A comparison between the voltage drop for the third injection pulse for the 4 load cases.

The drop of the current and voltage might depend on that the ECU is not powerful enough to produce a signal at the current hold value longer then 0.55 milliseconds, however it can also depend on the properties of the injector. In both cases it also means that even if the current ECU or the injector is not able to create a certain current or voltage value, it is still able to create some current or voltage until the longest injection pulse is over, in this case 0.76 milliseconds.

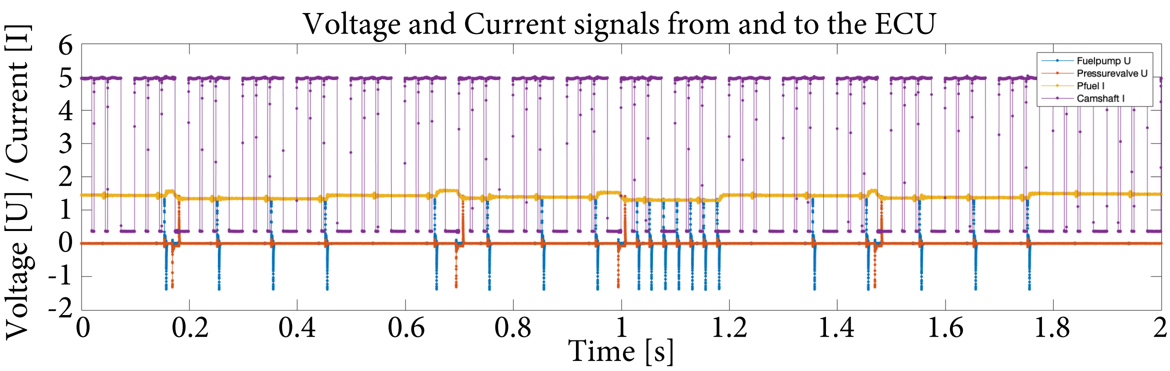
It would be an improvement if the new system are able to create the hold value for the whole injection pulse, however it is critical that it is able to produce a signal strong enough to keep the injection port open. The actual value of how much current that signal needs in order to actuate the injection for the injection pulse time is unknown but from the graph, that has a factor of 40, we can see that the ECU produces a current of 40 ampere and is still able to actuate the injection pulse.

4.1.3 Fuel pressure

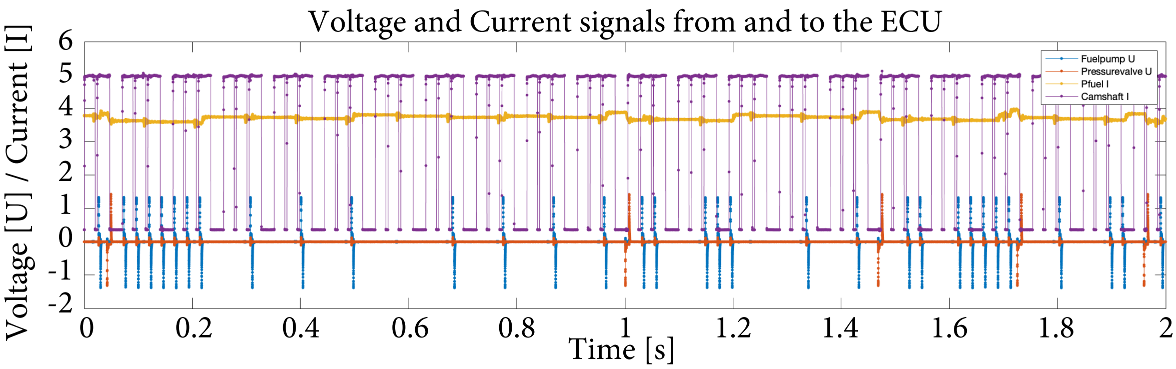
The fuel pressure is, as said in the theory chapter, operated by the fuel pump and the release valve in the common rail. The main task of the release valve in the common rail is to rapidly lower the fuel pressure when it is higher then the set fuel pressure value. At the same time the task of the fuel pump is to increase the fuel pressure when it is lower then the set fuel pressure value. As said in the theory chapter, this is controlled by the ECU. There are sensors measuring the fuel pressure and send this information to the ECU, the ECU then actuates different commands depending on this information. The code and performance in the current ECU in the test engine are unknown. Therefore the signals that affects the pressure value must be measured, in order to be able to reproduce the signals from the ECU. As seen in the figure 4.3 in previous chapter the voltage of the signal is rising before the current of the signal. This is the opposite from when measuring the injection signal but depends on that the the pressure valve in the common rail and the fuel pump has a solenoid actuator instead of a piezoelectric one, as for the fuel injector.

When studying figure 4.6 the current and voltage signal from the actuator to the fuel pump and the pressure valve in the common rail has been plotted in the same graph together with the current signal from the camshaft and fuel pressure. From the figure one can see that the ECU uses the fuel pump and pressure release valve to control the fuel pressure. It does so by sending electrical signals to the pump or release valve in order to initiate an action and lower or increase the fuel pressure. The ECU gets information from the fuel pressure sensor and are then able to send out a signal two times per revolution, or four times per injection cycle.

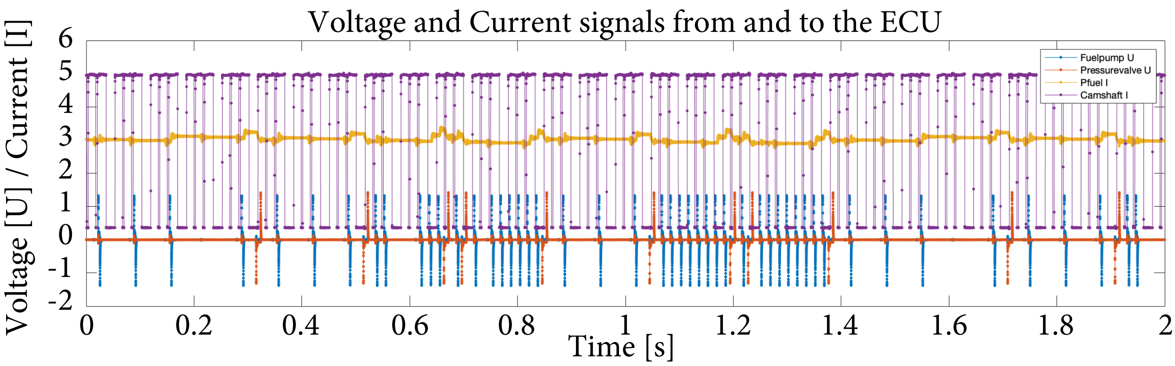
The actuate signals are periodical and are sent out by the ECU depending on the pressure. The ECU are able to send out the fuel pump actuating signal at around 70 CAD, 250 CAD, 430 CAD and 610 CAD after top dead centre fo this engine set-up, or TDC. The ECU are also able to send out the fuel pressure release valve actuating signal at around 10 CAD, 190 CAD, 370 CAD and 550 CAD after TDC for this engine set-up. The ECU does however not send both actuating signals at the same time but combine them over a period of 720 CAD.



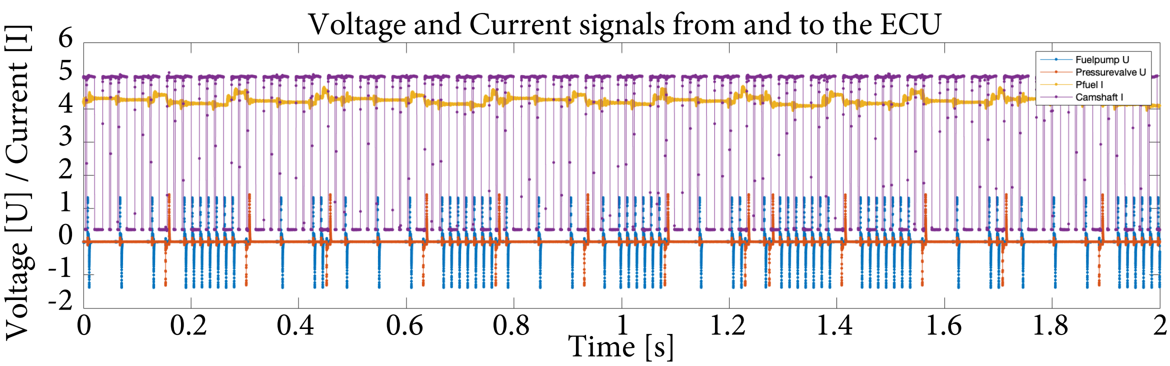
(a) Engine load case 1



(b) Engine load case 2



(c) Engine load case 3



(d) Engine load case 4

Figure 4.6: Measured current and voltage signals from fuel pump and release valve in common rail together with current signal from CAM and fuel pressure.

By combining the different actuating signals the ECU are able to create different commands. There exist four different cases of commands that the ECU gives in order to keep the fuel pressure close to the required value. They are:

1. The first case appears when the pressure is within around 98 % below and 103 % above the mode value that can be assumed to be a value close to the entered wanted set value in the engine cases. Then the ECU will send a command to the fuel pump to build up enough pressure to be able to continue to keep the fuel pressure within that margin. The signal is periodic and will appear once at 70 CAD after TDC when the fuel pressure is within the presented margin.

2. The second case appears when the fuel pressure is around 98 % below the mode value that can be assumed to be a value close to the entered wanted set value in the engine cases. Then the ECU will send a command to the fuel pump to build up enough pressure to be able to raise the fuel pressure until it is within the wanted margin. That signal is also periodic and will appear as long as the fuel pressure is below the presented margin at any cycle of 180 CAD from starting point at 70 CAD after TDC.

3. The third case appears when the fuel pressure is around 103 % above the mode value that can be assumed to be a value close to the entered wanted set value in the engine cases. Then the ECU will send a command to the fuel pump not build up any pressure in order to be able to lower the fuel pressure until it is within the wanted margin. The ECU will at the same time send a command to the release vale within the common rail to open so that the pressure can be lowered. That signal is also periodic and will appear at any cycle of 180 CAD from starting point 10 CAD after TDC. The opening of the release valve will be open enough time to lower the fuel pressure more then needed which will result in that the pressure will always be lowered enough to not having to send an actuator signal to the release valve in two consecutive 180 CAD cycles.

4. The forth case appears in engine load case 1 to 3 when the fuel pressure is around 103 % above the mode value that can be assumed to be a value close to the entered wanted set value. Then the ECU will send a command to the fuel pump not build up any pressure in order to be able to lower the fuel pressure until it is within the wanted margin. The ECU however not send any command to the release vale within the common rail in order to do so.

The current ECU are able to control the fuel pressure with these four commands. It means that future ECU must also be able to do so. As mention before the maximum amount of commands that are actuated by the current ECU are 4 per injection cycle. When considering the engine load cases, that has a maximum value of 2000 rpm per minute, it means that the ECU must be able to receive information from the sensors and send out a signal to the actuators at least every 7,5 milliseconds.

From the test results it is possible to see a tendency of how the ECU is controlling the different commands. The numbers differs some from the different cases and are only about values but with help from the histogram figures, see 4.7, it is possible to interpret a behaviour.

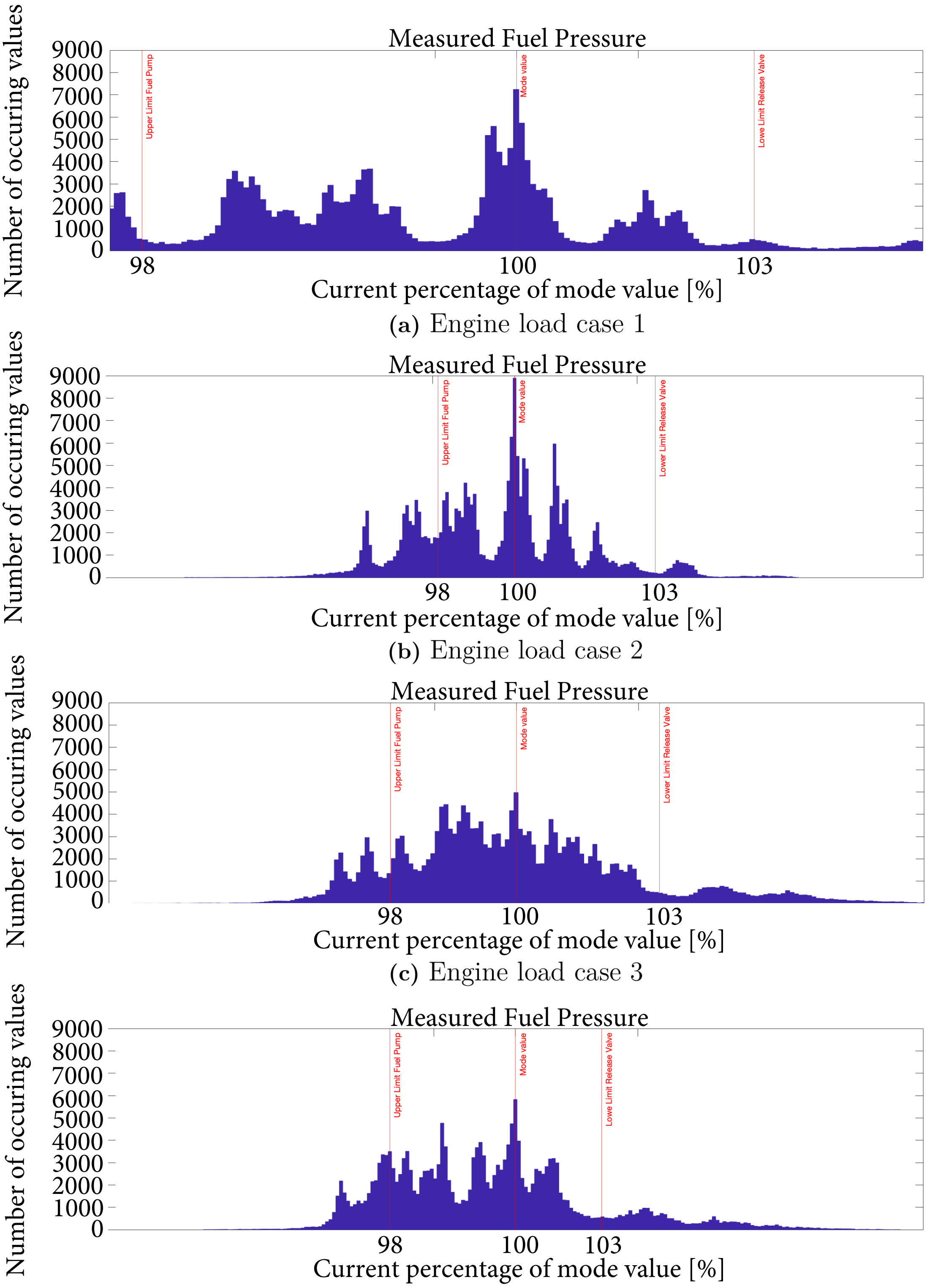


Figure 4.7: Distribution of the measured current signal from fuel pressure sensor.

Even if there is possible to interpret a behaviour from the histogram figure, the absolute numbers are different depending on load case. Especially engine load case one, as seen in the figure. This might depend on that the fuel pressure fluctuates more at low engine speeds. This might depend on several reasons. However, since the engine speed is lower, there are longer time between the ECU actuator signals. This is since the actuator signals are executed in synchronization with the camshaft angle. Another reason may be that the engine and its parts is dimensioned to run on four cylinders and at load cases much higher than those run in the study.

5
Results

Previous chapters have given a lot of useful results from the simulation and test cases. The purpose of this chapter is to present the results so that they can be understood and used to specify the requirements on the new system.

5.1 Sample rate

In the analysis chapter it was found that the current ECU system used by the research engine gave results with an estimated error of 12% compared to the wanted value given by the engine load specifications. If one raise the sample rate from the current value of 24 000 Hz to 100 000 Hz one will instead receive an estimated error of around 1%. That means that the new ECU system must be able to read and send signals with an sample rate of at least 24 000 Hz in order to perform as well as the current ECU system. However if it could perform with a sample rate of 100 000 Hz it would give a more accurate system with higher reliability. The results from the measurements when deciding the sample reate can be found in tabe 5.1 to 5.3. The reason that engine load case 1 from appendix B.1 was not run was due to engine failure. The test was not ran again since the other three engine load cases gave sufficient data enough to validate the test result.

Test data - LabView - Injection duration - Deciding sample rate				
	Injection 1 [ms]	Injection 2 [ms]	Injection 3 [ms]	Injection 4 [ms]
Case 1	-	-	-	-
Case 2	0.31	0.34	0.55	0.32
Case 3	0.26	0.28	0.67	0.28
Case 4	0.25	0.24	0.72	0.28

Table 5.1: Results from Labview when deciding sample rate

Test data - Indicom - Injection duration - Deciding sample rate				
	Injection 1 [ms]	Injection 2 [ms]	Injection 3 [ms]	Injection 4 [ms]
Case 1	-	-	-	-
Case 2	0.27	0.28	0.50	0.26
Case 3	0.29	0.28	0.68	0.30
Case 4	0.26	0.25	0.75	0.27

Table 5.2: Results from Indicom, the current ECU system, when deciding sample rate

Test data - INCA - Injection duration - Deciding sample rate				
	Injection 1 [ms]	Injection 2 [ms]	Injection 3 [ms]	Injection 4 [ms]
Case 1	0.25	0.25	0.75	0.29
Case 2	0.32	0.34	0.56	0.32
Case 3	0.28	0.28	0.68	0.29
Case 4	0.25	0.25	0.70	0.285

Table 5.3: Wanted set values set inserted in INCA when deciding sample rate

When the sample rate was decided it was validated by running the engine load cases as in the actual study and in appendix B.2. These results can be found in table 5.4 and 5.5. As can be read from the tables there is a maximum difference of 0.01 ms between the measured values in Labview and the wanted set values in Inca. This can be seen as a validation of that the picked sample rate is a suitable choice in order to be able to measure the signals in the system.

Test data - LabView - Injection duration				
	Injection 1 [ms]	Injection 2 [ms]	Injection 3 [ms]	Injection 4 [ms]
Case 1	0.33	0.33	0.55	-
Case 2	0.22	0.25	0.77	0.28
Case 3	0.29	0.28	0.68	0.30
Case 4	0.26	0.25	0.75	0.27

Table 5.4: Results from Labview when running the tests engine load cases

Test data - INCA - Injection duration				
	Injection 1 [ms]	Injection 2 [ms]	Injection 3 [ms]	Injection 4 [ms]
Case 1	0.33	0.33	0.55	-
Case 2	0.22	0.25	0.77	0.28
Case 3	0.29	0.28	0.68	0.30
Case 4	0.26	0.25	0.75	0.27

Table 5.5: Wanted set values inserted in INCA when running the tests engine load cases

5.2 Current and voltage

By measuring the current and voltage given by the measurements one can find that there is a hold and spike value for both current and voltage that the new ECU system must be able to handle. These can be found in 5.6 and are around 54 ampere for the hold value and around 177 ampere for the spike value for the current. While the amount of voltage the system needs to be able to handle is around 5.45 volt for the hold value and around 49.4 volt for the spike value.

Current and voltage measurements				
	U max [V]	U hold [V]	I max [A]	I hold [A]
Case 1	49.4	5.45	177	55.0
Case 2	49.3	5.38	177	54.1
Case 3	49.3	5.47	176	54.1
Case 4	49.4	5.48	177	53.8

Table 5.6: Measured average current and voltage values for all load cases

It would be preferably if the new ECU system is able to create a signal with the hold value as long as the longest injection pulse, as mentioned in the analyze chapter. The lowest requirement on the new ECU system is however to be able to create a spike value in order to initiate the injection pulse and then hold the current on a level of minimum 20 ampere, as the current system does.

5.3 Fuel pressure

As described in the analysis chapter, there are a common behaviour for all load cases. The regulation of the fuel pressure is determined by the ECU system through actuator signals to the fuel pump and pressure release valve in the common rail. The new ECU system must be able to receive information about the fuel pressure and send actuator signals at least four times per injection cycle. However there are a fluctuation between the engine load cases when looking at the value of the results in table 5.7. The values in the table is measured ampere and given from the fuel pressure sensors.

In order to be able to see what the result really means for our study, the values has been translated to the pressure unit bar and a percent deviation. This is done in table 5.8 This means that the new ECU system must be able to control the fuel pressure with different threshold values for the different actuator signal commands at different engine speed. The accepted fuel pressure variance should be higher for a engine load case with low engine speed where the variance is high. While the ECU must be able to have a smaller interval of accepted fuel pressure variance when running on engine load cases with higher engine speeds, or less pressure variance during combustion.

Fuel pressure intervals for each ECU command - Ampere					
Command to fuel pump	Mode Value [A]	Extra Pump [A]	Regular Pump [A]	No Pump [A]	Release Valve [A]
Case 1	2.78	- 2.62	2.66 - 2.86	2.86 - 2.96	3.06 -
Case 2	7.46	- 7.52	7.52 - 7.60	7.54 - 7.56	7.22 -
Case 3	6.00	- 5.94	5.88 - 6.24	6.18 - 6.18	6.28 -
Case 4	8.56	- 8.28	8.28 - 8.78	-	8.74 -

Table 5.7: Fuel pressure intervals with results in ampere from sensors.

Fuel pressure intervals for each ECU command - Bar and Percent					
Command to fuel pump	Mode Value [bar]	Extra Pump [bar]	Regular Pump [bar]	No Pump [bar]	Release Valve [bar]
Case 1	350	329.4	335 - 360.5	361.2 - 373.5	384 -
	100%	94.10%	95.7% - 103%	103.2% - 106.7%	109.7% -
		–20.6 -	–15 - +10.5	+11.2 - +23.5	+34 -
Case 2	800	784.8	785.6 - 814.4	808.8 - 809.6	827.2 -
	100%	98.10%	98.2% - 101.8%	101.1% - 101.2%	103.4% -
		–15.2	–14.4 - +14.4	+8.8 - +9.6	+27.2 -
Case 3	670	664	655.3 - 696.8	690.8	700.2 -
	100%	99,10%	97.8% - 104%	103.1% - 103.1%	104.5% -
		–6 -	–14.7 - +26.8	+20.8	+30.2 -
Case 4	910	890.9	880.9 - 933.7	-	928.2
	100%	97.90%	96.8% - 102.6%	-	102%-
		–9.1 -	–19.1 - +23.7	-	+18.2 -

Table 5.8: Fuel pressure intervals in bar and percent deviation.

In addition to be able to put different set values for different commands for the actuator signals the ECU must also be able to read the fuel pressure signal with very high resolution in order to be able to control this. This requirement will be fulfilled if the new ECU system comply with the sample rate requirement put on the system.

6 Conclusion

From the results it is possible to decide with what sample rate or frequency the new ECU system should comply to be a qualitative system. It is also possible to decide with what accuracy the new system are able to be performing with from that data. It is possible to say with what values one want the ECU to control in the different engine load cases depending on the wanted behaviour.

The new ECU system must be able to control the same parameter values as the current ECU in order for the system to work. It must also be able to handle the spike and hold current and voltage values and be able to reproduce those signals with the right value, frequency and timing specified in the results section. Since an ECU system may be divided into a software system and a hardware system, it is not known what kind of new ECU system that should be chosen. However, from the current ECU system, one can tell that it is much easier to edit and control an open source software system and if it should be used. Which means that the hardware must also be compatible with that kind of system. That means that a lot of licensed hardware and software systems from well known companies are not suitable, such as the current hardware and software system used in the test engine today.

The purpose of the work to investigate if its possible to specify and in the end to make it possible to build an in-house control system has therefore been met with the acquired data and the analysis of that. It has been possible to require enough amount of data with the the equipment that was available. The future work is to specify how the new ECU system should be put together in order to meet the requirements set from the results in this study. Future work can also investigate if the engine in the test cell may be changed in any way. Such as use a fuel pump designed for a smaller engine or add one more common rail to the system.

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A

Appendix sensor charts

Sensors from engine system to the ECU.

	SENSORER		Längd på sladden	Kontakt
CAMIN	Camshaft sensor +	A8	1,6 m	Std VED
CAMIN-	camshaft sensor ground	A23		
CAMIN5V	5V for camshaft sensor	A38		
FWS+	Flywheel sensor +	A6	2,2 m	Std VED
FWS-	Flywheel sensor ground	A21		
FWS5V	5V for flywheel sensor	A36		
HPFP+	Fuel high pressure pump high	A93	1,6 m	Std VED
HPFP-	Fuel high pressure pump low	A92		
RPV-	Rail pressure relief valve	A87	1,6 m	Std VED
RPV+	Rail pressure relief valve high	A88		
SWCPS5V	5V for swirl valve	A39	1,6 m	Std VED
SWC-	Swirl control -	A71		
SWC+	Swirl control +	A70		
SWCPS	Swirl feedback	A13		
SWCPS	Swirl sensor ground	A62		
	MATNING			
	Battery	B39		Banan röd
	Ground	B97, B99		Banan svart
	Power +	B77, B100, B101		Banan blå

Figure A.1: System chart of the sensors included in the 1-cylinder test engine control system

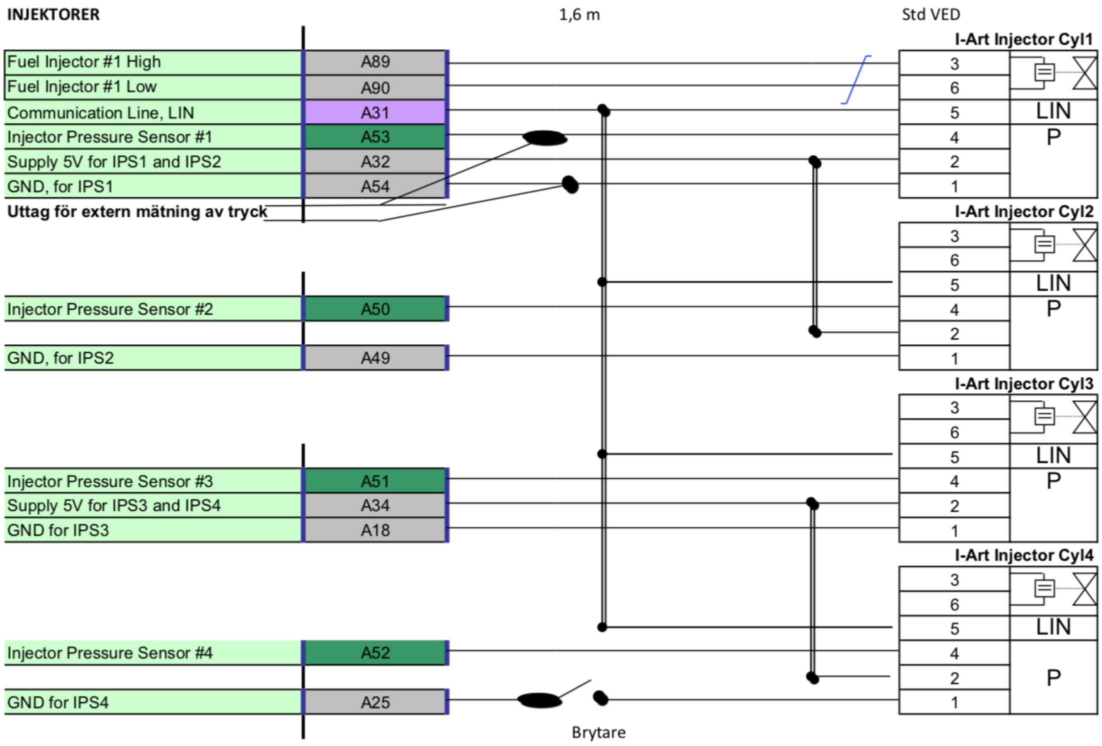


Figure A.2: System chart system of the actuators of the 1-cylinder test engine

B

Appendix engine load cases

Engine load cases for deciding sample rate.

AVL_INDEP_TIME			**1**	**2**	**3**	**4**
NEng	Speed	1/min	1280	1376	1810	2000
single torque	Torque	Nm	32,5	14,3	26,8	37,5
SingleFuel	fuel mass flow rate	kg/h	1,00	0,48	1,10	1,70
PInaAirIm_Abs	intake air pressure	kPa	135	109	158	219
PTubHpBe	Backpressure	kPa	53	26	83	145
TInaAirIm	intake air temperature	°C	52,6	69,5	64,4	63,1
Pilot3Duration	Pilot3Duration	ms	0,25	0,32	0,28	0,25
PreDuration	PreDuration	ms	0,25	0,34	0,28	0,25
MainDuration	MainDuration	ms	0,75	0,56	0,68	0,70
AfterDuration	AfterDuration	ms	0,29	0,32	0,29	0,285
StartOfPilot3	StartOfPilot4	BTDC	7,2	14,6	14,1	13,0
StartOfPre	StartOfPre	BTDC	2,8	9,5	8,8	6,8
StartOfMain	StartOfMain	BTDC	-2,2	2,2	2,5	2,0
StartOfAfter	StartOfAfter	BTDC	-10,2	-5,6	-7,1	-12,0
EEIModule.M01.Scm_FuelHiPres	injection pressure	MPa	88,1	46,56	80,8	105,4
EGR	EGR	%	19,0	41,2	27,0	22,1

Figure B.1: Set engine parameters values into the current ECU during sample rate testing

Engine load cases when running tests.

Engine load cases for test																	
						Start of injection [CAD]				Injection duration [ms]							
Case number	Speed [RPM]	Torque [Nm]	Fuelmass flowrate [g/99s]	Intake air pressure [bar]	Back Pressure [bar]	Pilot	Pre	Main	After	Pilot	Pre	Main	After	Injection Pressure [Bar]	IMEP [Bar]	CAD 50% [CAD]
1	1200	2,3	7	1,05	1,21	14	9	3	-	0,34	0,34	0,56	-	350	2,8	8
2	1280	27,2	27,6	1,35	1,53	10	6	1	-9,5	0,23	0,26	0,78	0,29	800	9,5	12
3	1810	19,2	28,9	1,83	1,83	16,5	9,5	2,5	-10	0,29	0,29	0,69	0,31	670	7,5	12
4	2000	33	46,9	2,45	2,45	18	12	4	-10,5	0,26	0,26	0,76	0,28	910	12	12

Figure B.2: Set engine parameters values into the current ECU during the main testing

C

Appendix oscilloscope in Labview

Oscilloscope structure in the program Labview

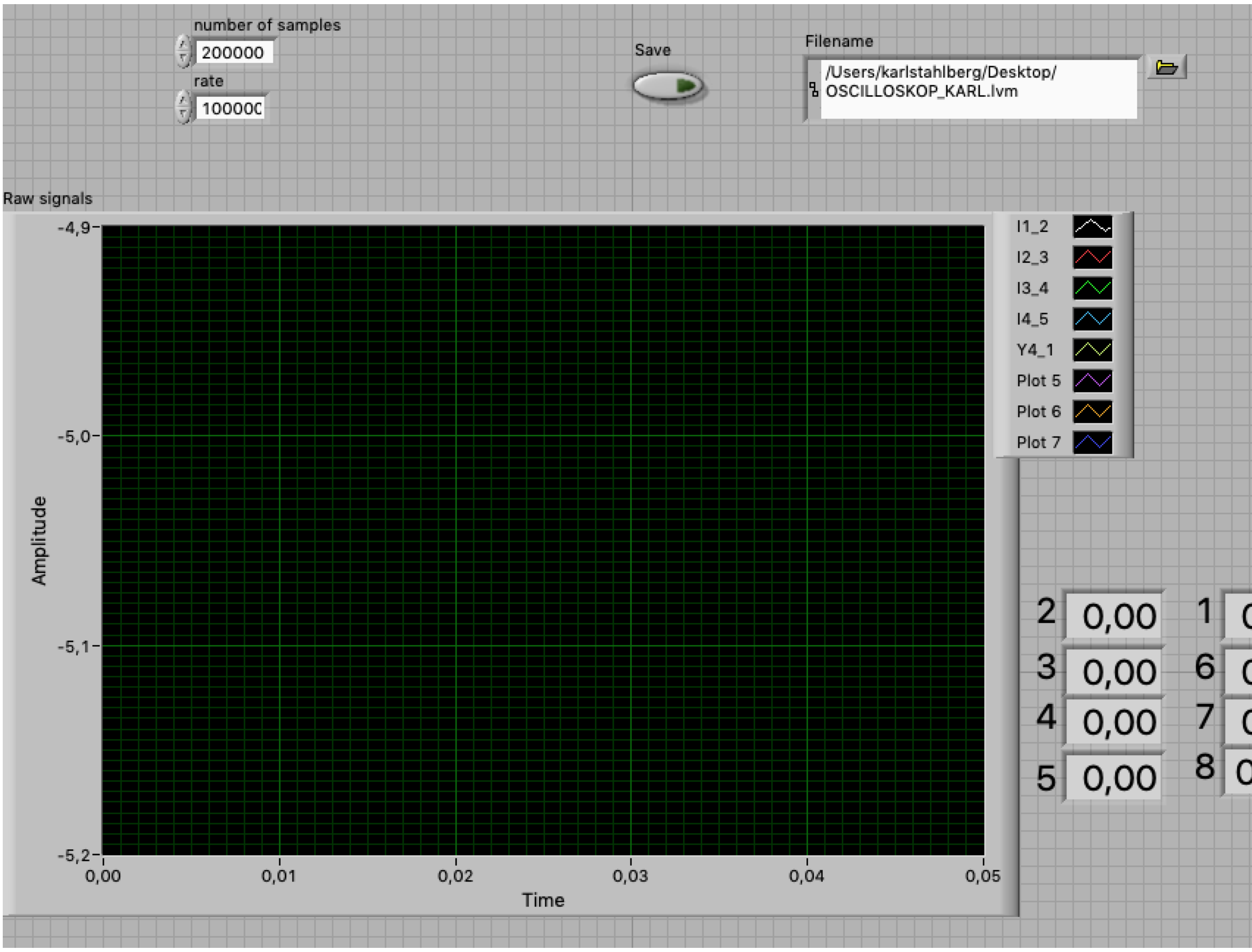


Figure C.1: Interface of oscilloscope when measuring signals

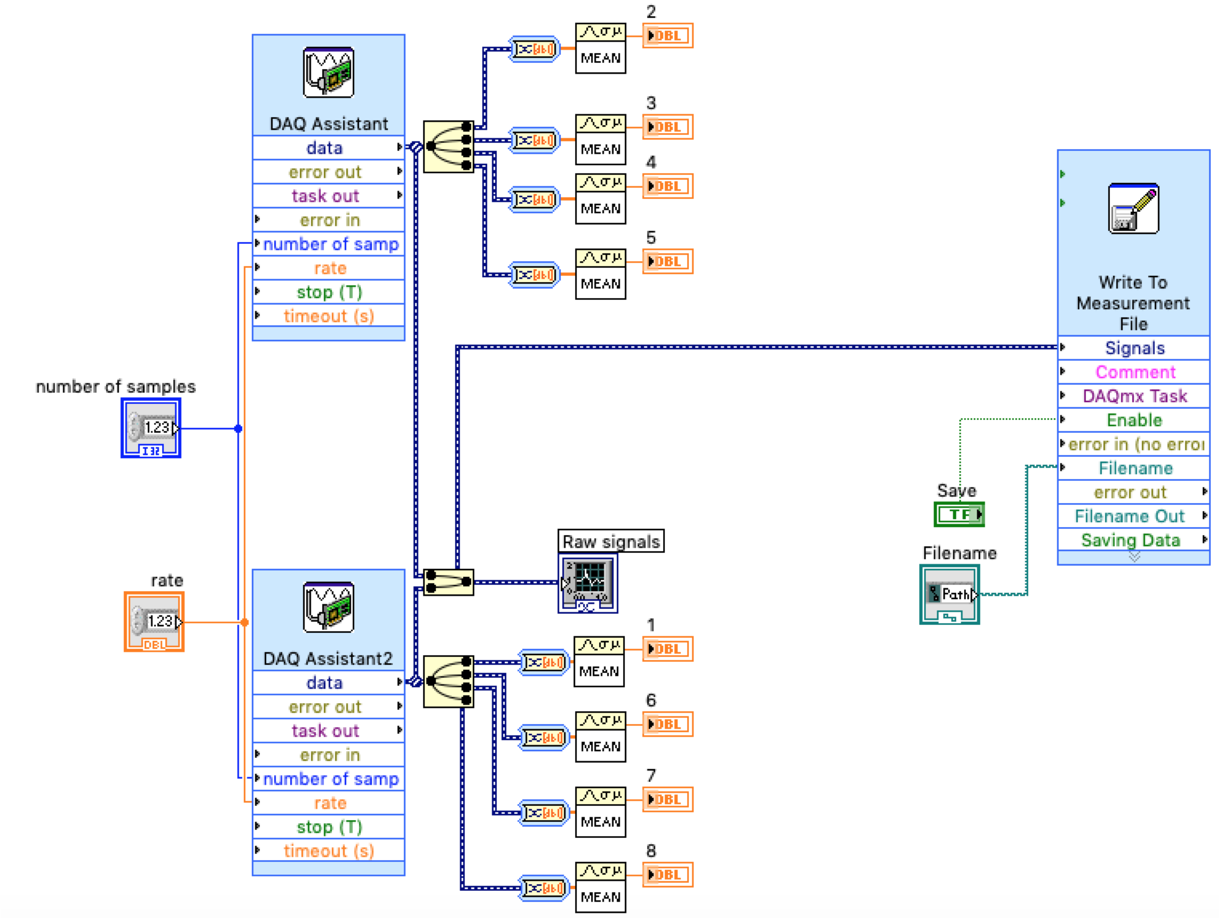


Figure C.2: Structure of oscilloscope inside the Labview program

D

Appendix test equipment

68-pin screw terminal connectorblock accessories from National Instruments connected to computer.

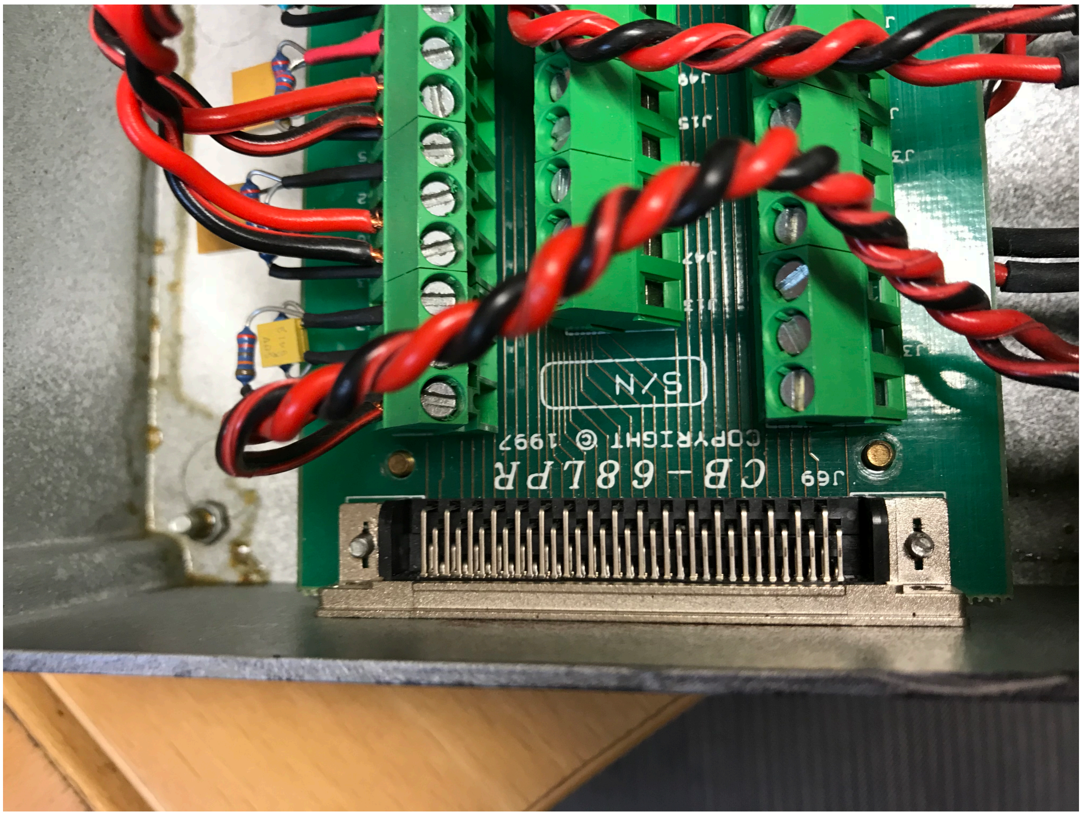
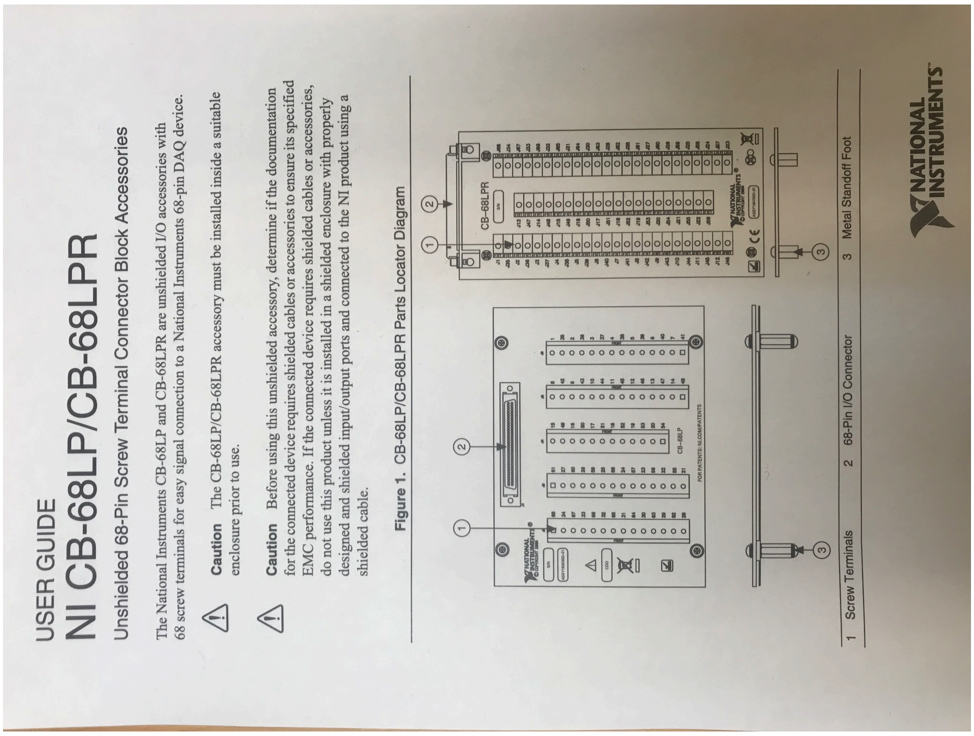


Figure D.1: How the 68-pin screw terminal connectorblock accessories from National Instruments is connected to computer



USER GUIDE

NI CB-68LP/CB-68LPR

Unshielded 68-Pin Screw Terminal Connector Block Accessories

The National Instruments CB-68LP and CB-68LPR are unshielded I/O accessories with 68 screw terminals for easy signal connection to a National Instruments 68-pin DAQ device.

Caution The CB-68LP/CB-68LPR accessory must be installed inside a suitable enclosure prior to use.

Caution Before using this unshielded accessory, determine if the documentation for the connected device requires shielded cables or accessories to ensure its specified EMC performance. If the connected device requires shielded cables or accessories, do not use this product unless it is installed in a shielded enclosure with properly designed and shielded input/output ports and connected to the NI product using a shielded cable.

Figure 1. CB-68LP/CB-68LPR Parts Locator Diagram

1 Screw Terminals 2 68-Pin I/O Connector 3 Metal Standoff Foot

NATIONAL INSTRUMENTS

Figure D.2: Datasheet of the 68-pin screw terminal connectorblock accessories from National Instruments

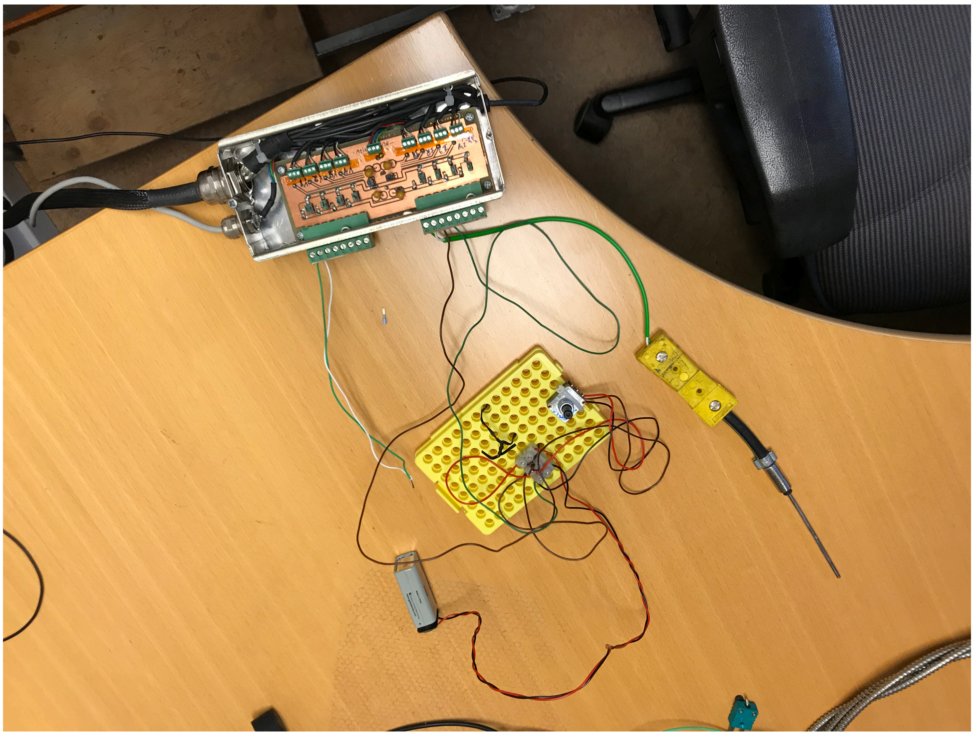


Figure D.3: How a 5V battery was attached to the the computer and LabView program in order to test the accuracy of the system

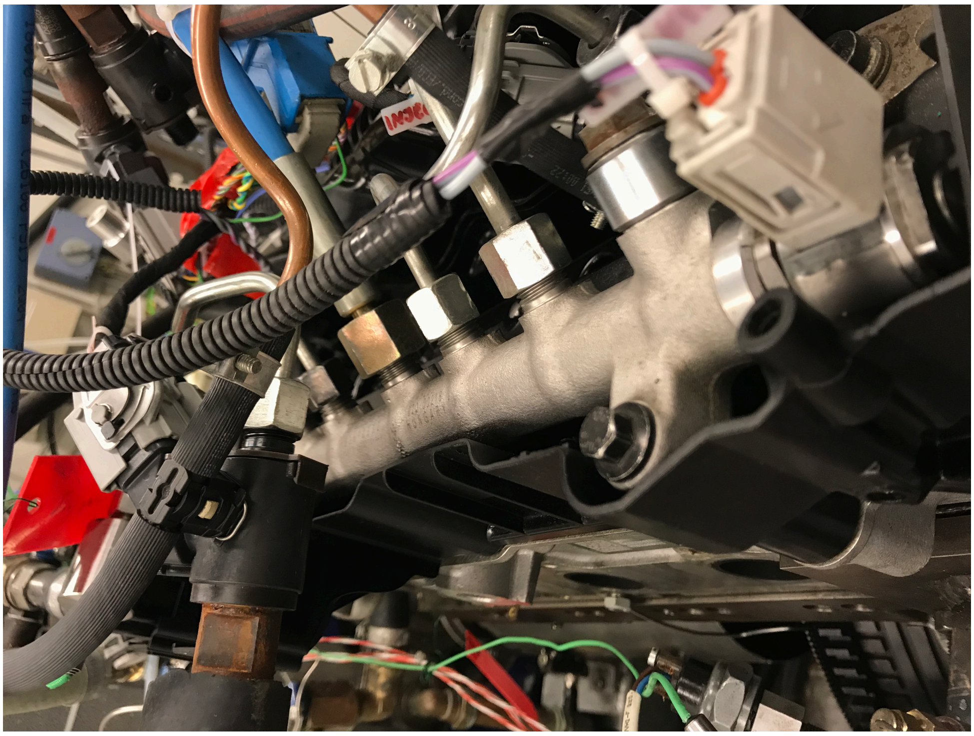


Figure D.4: The 1-cylinder test engine in the lab cell

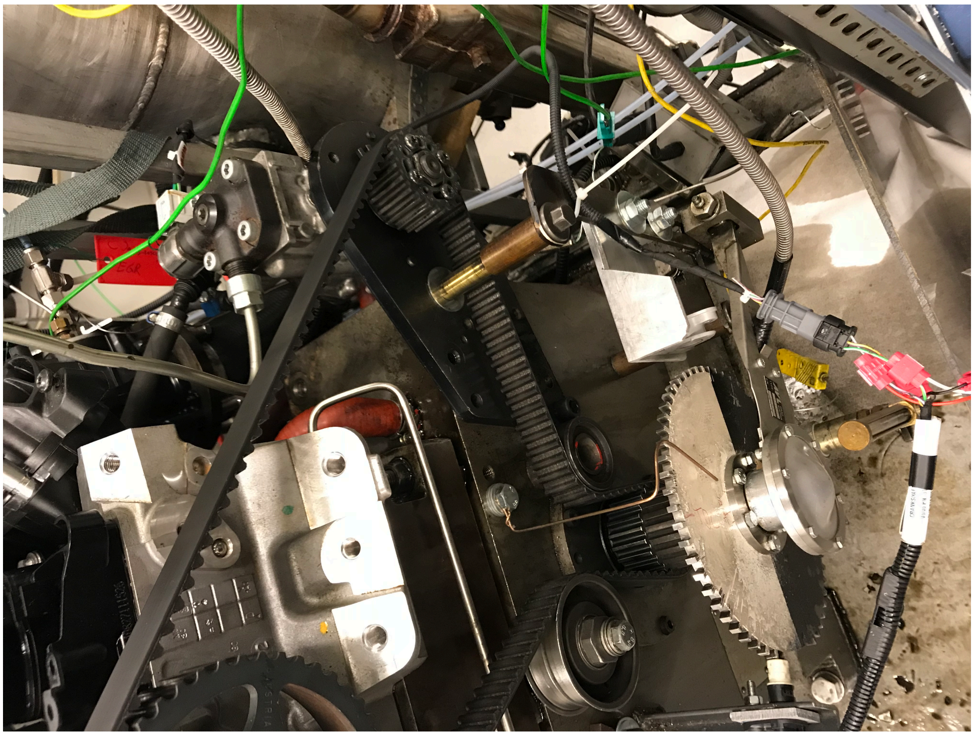


Figure D.5: The fuel pump connected to the camshaft of the test engine

Figure D.6: Clamp meters used to connect DAQ to the test engine

Figure D.7: Clamp meters used to connect DAQ to the test engine

Figure D.8: Clamp meters used to connect DAQ to the test engine