Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Investigation of Correlations Between COV of Ion Integral and COV of IMEP in a Port-Injected Natural-Gas Engine

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan i Linköping
av

Johan Molin

LITH-ISY-EX--08/4110--SE

Linköping 2008

Linköpings universitet
TEKNISKA HÖGSKOLAN

Department of Electrical Engineering
Linköpings universitet
SE-581 83 Linköping, Sweden

Linköpings tekniska högskola
Linköpings universitet
581 83 Linköping

Investigation of Correlations Between COV of Ion Integral and COV of IMEP in a Port-Injected Natural-Gas Engine

Master thesis performed at
Vehicular Systems at **Linköping University**
by

Johan Molin

LITH-ISY-EX--08/4110--SE

Supervisor: **Johan Wahlström**
ISY, Linköping University
Tomas Carlsson
Hoerbiger Control Systems AB

Examiner: **Lars Eriksson**
ISY, Linköping University

Linköping, 12 December, 2008

Avdelning, Institution
Division, Department

Vehicular Systems at **Linköping University**
Department of Electrical Engineering
Linköpings universitet
SE-581 83 Linköping, Sweden

Datum
Date

2008-12-12

Språk
Language

☐ Svenska/Swedish
☒ Engelska/English
☐ ________________

Rapporttyp
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport
☐ ________________

URL för elektronisk version

http://www.control.isy.liu.se
http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-15949

ISBN
—

ISRN
LITH-ISY-EX--08/4110--SE

Serietitel och serienummer
Title of series, numbering

ISSN
—

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Författare
Author: Johan Molin

Sammanfattning
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Nyckelord
Keywords: COV, IMEP, Ion current, EGR

Abstract

Correlations between the coefficient of variations (COV) of ion current integrals and COV of indicated mean effective pressure (IMEP) are investigated. The investigations are made to see if there is a possibility to use ion sense technique for closed loop combustion control to maximize Exhaust Gas Recirculation (EGR) level with remaining combustion stability. The engine studied in this thesis is a stoichiometric natural gas engine with a three way catalyst working with different EGR levels. One way to increase the efficiency in a stoichiometric natural gas engine is to maximize the EGR level [3]. With a higher EGR level it is possible to open the throttle even further with a result of lower pumping losses. Also temperature losses to chamber walls will be smaller with high EGR levels. A closed loop system controlling the EGR valve against COV of IMEP around 5 % is used for this engine. For COV of flame peak integral in range from 0 to 15-20% of COV of IMEP a linear correlation was found for lambda less than 1.3. For COV of two peaks integral a linear correlation was found for the entire measured range. This correlation may not be used for a robust EGR control system due to a small increase of COV of ion integral and due to a high variance in COV of ion integral. Correlations are discussed for different ion integrals with different air/fuels ratios and EGR levels. A control strategy is also presented.

Preface

This master thesis has been performed at Hoerbiger Control Systems AB in Åmål within Department of Vehicular Systems at Linköping University during fall 2007 and 2008. Engine measurements have been made at Lund University.

Thesis outline

Chapter 1: In this chapter an introduction about the objectives of the thesis is described. The basic principle of a combustion engine is explained. Also how ion current, cylinder pressure and natural gas works in a combustion engine are explained.

Chapter 2: In this chapter engine data, measurement acquisition equipment and how ion current interface works are described. How the analyzing and data processing are made and which measurements that have been done in this thesis are presented.

Chapter 3: In this chapter results from the correlation analysis that have been done are presented and explained. Also a control strategy is presented.

Chapter 4: In this chapter conclusions from the thesis results and future work that could put the thesis result further are discussed.

Acknowledgment

I would like to thank Tomas Carlsson at Hoerbiger Control Systems AB for supporting me with the installation of the ion current interface and good support during the data processing. Also I would like to thank Jakob Ängeby and Anders Göras at Hoerbiger for interesting discussions that put the thesis further and made this thesis possible. Thanks to all the nice and helpful people at Hoerbiger Control Systems AB in Åmål that made my time there enjoyable. For all the help with measurements and to made it possible to collect data I would like to thank Mehrzad Kaiadi at Lund University. At last but not least I would like to thank my examiner at Linköping University Lars Eriksson for all help and good feedback and my supervisor Johan Wahlström for good feedback on the thesis report.

Contents

Chapter 1

Introduction

1.1 Background

Recently, the influence on the environment and use of energy resources by combustion engines has become a more discussed and important topic. To decrease these influences alternative fuels are studied and used as a complement for the more common fossils fuels. One good alternative is natural gas with its good burning characteristics and its big resource capacity. One way to get a natural gas engine to work more efficient and with a better fuel economy is to use turbo charging and high EGR levels [1] according to [3]. To have the same power output with EGR than without, the throttle plate has to be opened further with a result of lower pumping losses. The heat losses to the combustion chamber surfaces is reduced with a result of more energy left for the expansion stroke and therefore more power as output. Also the knock tendency is reduced with high EGR levels. To use a three- way catalyst in a stoichiometric natural gas engine the emissions is also radically reduced [2]. Due to differences in the design of intake manifold and the different tolerance due to production and wear between injectors and intake valves AFR and EGR rates are not the same in all cylinders. To be able to control the EGR level to its maximum, information like the cycle to cycle variations is needed from each cylinder individual. Information from the individual cylinders can be taken from cylinder pressure and ion sense signals. This information can be used to change EGR valve opening, fuel injection and ignition time for individual cylinders. In this thesis *ion sense technique* is used with the cylinder pressure signal as reference to investigate the possibility to use *ion sense technique* for closed loop EGR control.

1.1.1 Objectives of the thesis

According to [3] it is possible to use cylinder pressure for closed combustion control for a port-injected natural gas engine. Further, COV of IMEP is a good way to measure combustion stability. Hoerbiger Control Systems AB is interested of using ion sense technique for closed combustion control in a stoichiometric natural gas engine operating with EGR. The goal is to investigate if there is a correlation between COV of ion integral and COV of IMEP because if this correlation exists ion sense can be used for combustion control instead of cylinder pressure. Coefficient of variations (COV) is a measurement of variation between combustions. The control strategy for this thesis is to control EGR rate to obtain a limit of 5% COV of IMEP to accomplish stable combustions. To be able to collect data from the engine by ion sense, an installation of ion measurement equipment must be done. A literature review in this subject should also be done.

1.2 Spark Ignited (SI) engine

A mixture of air and fuel that compresses and ignites with a spark in a combustion engine is working by the Otto principle. A spark ignited (SI) engine with Otto principle is divided into four strokes or two strokes. Nearly every modern production engine is working by the principle of four strokes. These four strokes consist of intake, compression, expansion and exhaust (see figure 1.1). Intake stroke take place when the piston moving down, valves for intake opens and the cylinder fills up with an air/fuel mixture. When the piston reaches the bottom dead centre (BDC) the inlet valve is closing and the piston starts to move up and start to compress the air/fuel mixture. This is the compression stroke and just before piston reaches the top dead centre (TDC) the air/fuel mixture is ignited by a spark from the spark plug. Temperature and pressure in the cylinder increases and the piston gets pressed down due to the gas expansion. This is the expansion stroke. Around BDC the exhaust valves opens and the piston moves up and starts to press out the exhaust gas called exhaust stroke. When piston reaches TDC a new cycle begins. In a four stroke engine there is only the expansion stroke that produces a positive work and there need to be two engine revolutions per cylinder for one cycle. One engine revolution is often divided into 360 crank angle degrees (CAD).

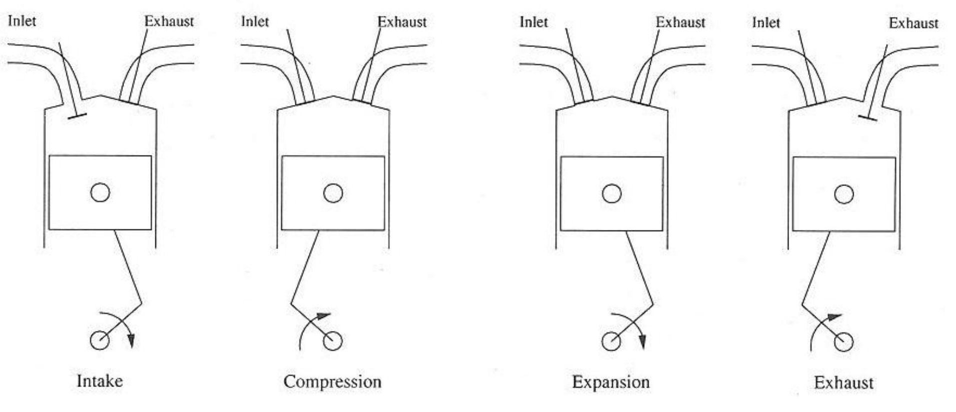

Figure 1.1. Four stroke engine with intake, compression, expansion and exhaust stroke

1.3 Exhaust Gas Recirculation, EGR

One way to increase efficiency and to decrease fuel consumption in a natural gas engine with turbocharging and with a three way catalyst is to cool exhaust gas and lead it back into the intake manifold and mix it with the unburned air/fuel mixture [1], [3]. This method is called Exhaust Gas Recirculation (EGR). EGR contains of already burned gas and decrease the percent of oxygen that can react with the fuel in the combustion chamber. To have the same power output with EGR than without, the throttle plate has to be opened further. When opening the throttle further the losses from the throttle plate decreases with a result of lower pumping losses and an increased inlet manifold pressure. Nitro oxygen with different formations called NO_x has a detrimental effect on the environment. As the combustion temperature increases the production of NO_x increases. This is important to control especially in an engine without a catalyst that can not take care of the NO_x emissions. With EGR the peak combustion temperature is decreased due to the oxygen concentration reduction and the presence of the inert exhaust gases H_2O and CO_2 that provides more heat capacity [4]. By decreasing the combustion temperature the knock tendency is also decreased. EGR reduces losses of thermal energy to combustion chamber surfaces and leave more energy available for conversion to mechanical work during expansion stroke. There can be external and internal EGR in a combustion chamber. The system explained above, with a return system to the intake, is an external EGR system. Internal EGR is accomplished by leading exhaust gas back into the combustion chamber through the exhaust valves. If variable valve timing is applied to an engine the EGR rate can be controlled by the exhaust valves opening time during intake stroke. Increasing EGR makes the combustion speed slower and the cycle to cycle variations will increase with a result of more instable combustions. This is important to control to get stable combustions without any poor combustions or misfires that decrease the efficiency and that can destroy the catalyst. If unburned gas due to misfire are transported out into the exhaust, a combustion can occur in the catalyst due to the high temperature. This can destroy the material in the catalyst and that will increase emissions.

1.4 Natural gas as fuel in a SI combustion engine

On the market natural gas has a varied of different mixtures and it depends on where it is produced. For a combustion engine there are several advantages with gas fuels, like natural gas, than with liquid fuels, like gasoline, discussed in [6] according to [5]. In general natural gas has a higher octane number than gasoline and therefore it has less knock tendency than gasoline and allows more compression that give higher cylinder pressure and then more power as output. Compared to liquid fuel, gas mix easier with air to a homogeneous mixture. A homogeneous mixture gives an almost complete combustion which gives a better fuel efficiency and it reduces coatings and this spares the engine. When the engine is cold it starts easier and when load changes are applied, no surplus of fuel appears due to exclusion of vaporization. With gas it is easier and it gets faster to control the air/fuel ratio. This gives better emissions and the fuel consumption is reduced with gas compared to gasoline. A negative aspect with gas as fuel to mobile engines are the handling with gas that is more difficult then with liquid fuels.

1.5 Cylinder pressure

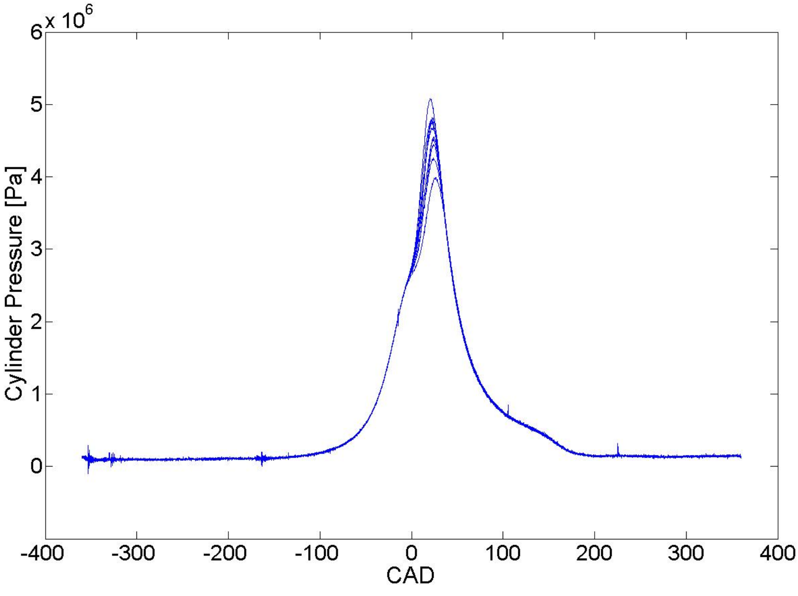

Figure 1.2. Cylinder pressure signals for 10 cycles.

A common way to get information from the combustions is to analyze the in-cylinder pressure. From the pressure signal efficiency and power output can be calculated. To achieve maximum efficiency the maximum brake torque (MBT) is needed to be obtained. MBT is held if maximum pressure occurs at about 16 degrees after Top Dead Centre (TDC) according to [1].This makes it important to know at what CAD the maximum peak pressure position (PPP) occurs. This position is depending on ignition time and flame propagation. To adjust these parameters maximum efficiency can be obtained in every driving condition. The work that is produced by the combustion is the integral over pressure per volume unit, see equation (1.1).

$$W_i = \oint p dV \tag{1.1}$$

One common way to compare engine cycles is to calculate indicated mean effective pressure (IMEP). IMEP is the indicated work per cycle normalized with the displaced volume, see equation (1.2).

$$IMEP_{gross} = \frac{\int_{-180}^{180} pdV}{V_D} \tag{1.2}$$

IMEP can be calculated over compression and expansion stroke, called IMEP$_{gross}$, or over the whole cycle, including pumping losses, called IMEP$_{net}$, see equation (1.3).

$$IMEP_{net} = \frac{\int_{-360}^{360} pdV}{V_D} \tag{1.3}$$

1.6 Ion currents

In SI engines combustion occur when the air/fuel mixture is compressed and ignited by a spark. To be able to discharge a spark, high voltage is applied over two electrodes in the spark plug. When the mixture is ignited a flame travels through the combustion chamber and a chemical reaction occurs in the flame front. The temperature is rising and free charge particles are produced. By applying a low bias (comparing to ignition bias) over the electrode gap of the spark plug when not using it for ignition, a current that appears by the free charged particles in the combustion chamber can be measured. This is called *ion sense*. To analyze this ion current different parameters can be decided. Knock, misfire and cam phasing are used in some of the production gasoline cars today and other parameters have been studied like AFR Control [7] and Spark Advance Control [8]. A large benefit of ion sense is that the existing spark plug is used as a sensor. No extra sensor is needed and that reduces the cost. When using ion sensing technique, in most cases with spark plugs, the result are a local measurement around the electrodes. The measurement does not always represent the rest of the combustion chamber which has to be considered when analyzing measured data.

1.6.1 Shape of ion current signal

The ion current has a characteristic shape with two peaks and three different phases, Ignition phase, Flame Front phase and Post Flame phase. Ignition phase is normally not studied as this phase do not give any combustion information.

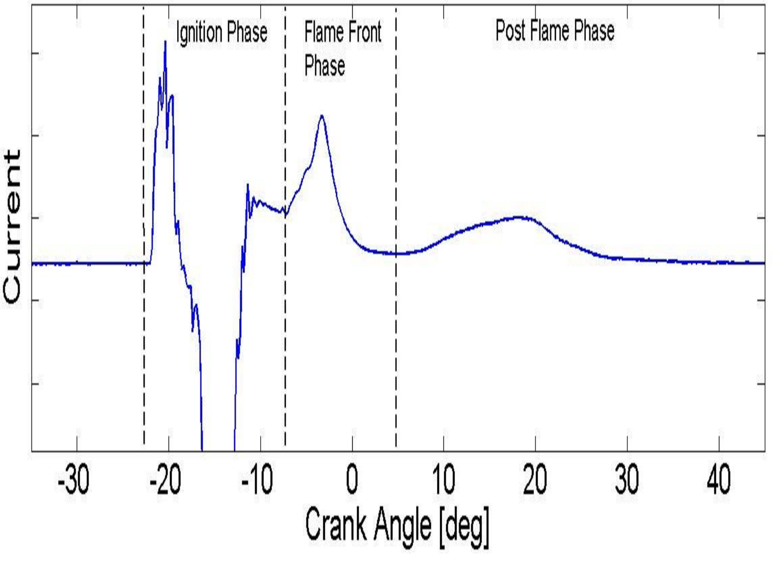

Figure 1.3. Ionization current with three phases, ignition, flame front and post flame.

Ignition phase

The Ignition phase is starting with a charging of the coil and ends with coil ringing. The time when the primary of the coil is charging is called dwell time. When the charging ends duration will occur and a spark will be produced. Due to high biases, charging and duration in the ion current signal will be limited by the ion interface. There are different types of ignition systems on the market like inductive- and capacitive discharging systems with different duration times and this affect the ion current shape.

In the end of the discharging phase, coil ringing phenomenon occurs as a result of a quick discharging and with a too low bias over the electrodes at the spark plug to retain a current (spark). This can be seen in the signal like an oscillating shape in the end of ignition phase. The coil ringing phenomenon is depending on the type of ignition system and operating point. Large discharging energy can be preferred in many cases but it will increase the ringing and that has to be considered. The ringing is overlapped with the flame front phase and under this time no combustion information can be given and this makes it important to limit this period.

Flame front phase

When the spark has ignited the air/fuel mixture a flame starts to travel from the spark plug over the combustion chamber to the chamber walls. Second phase starts when the flame-front is close to the spark gap according to Yoshiyama-Tomita (2000) discussed in [10]. When the flame is travelling through the combustion chamber it consumes the air/fuel mixture and by different chemical reactions in the flame front ions and electrons are generated. Some ions are recombinated into stable molecules fast while other ions remain. This differs from cycle to cycle and leads to that the flame peak looks different from cycle to cycle. In the flame front thermal ionization is negligible.

Post flame phase

The most stable ions remain to the post flame phase. In the burned gases after the flame front when the temperature increases new ions will be produced when thermal ionization temperature has been reached. High EGR rates decreases the combustion temperature and if the temperature is decreased too much the ionization threshold will not be reached and no new ions will be produced. The post flame peak has a strong correlation in position to the cylinder pressure discussed in [10].

1.6.2 Different parameters influence on ion current

The shape of the ion current are influenced by different parameters like lambda, EGR ratio, engine load, engine speed, fuel additives, ignition timing and spark plug conditions. In this thesis the impact of EGR ratio and AFR ratio on the ion current has been especially studied and it has been shown that EGR and AFR ratio in a natural gas engine has a major impact. Flame peak position is increasing with increasing lambda greater than one and increasing EGR ratio as a result of a decreasing flame propagation speed. With increasing EGR ratio the temperature in the cylinder will be decreased. A result of the decreasing temperature is that the integral of post flame peak, also called thermal peak, of ion current is radically decreased. Seen in this thesis the thermal peak integral is almost disappeared for EGR ratio over approximately 10% (See figure 1.4).

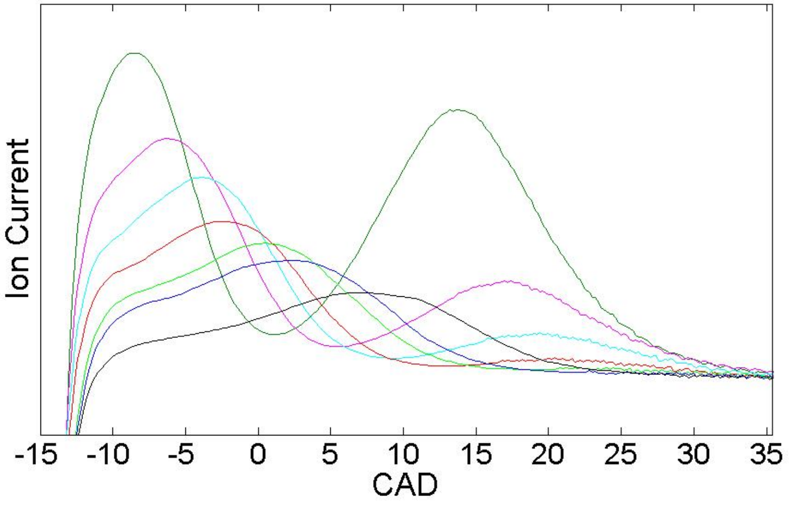

Figure 1.4. Ion current signals with mean value of 400 cycles for EGR sweep with lambda 0.98. The EGR ratios are from largest amplitude in flame peak to the smallest; 5, 10, 15, 16, 17, 19, 21 %. The ion current signals are plotted with the same start of ignition angle and not at the right CAD position.

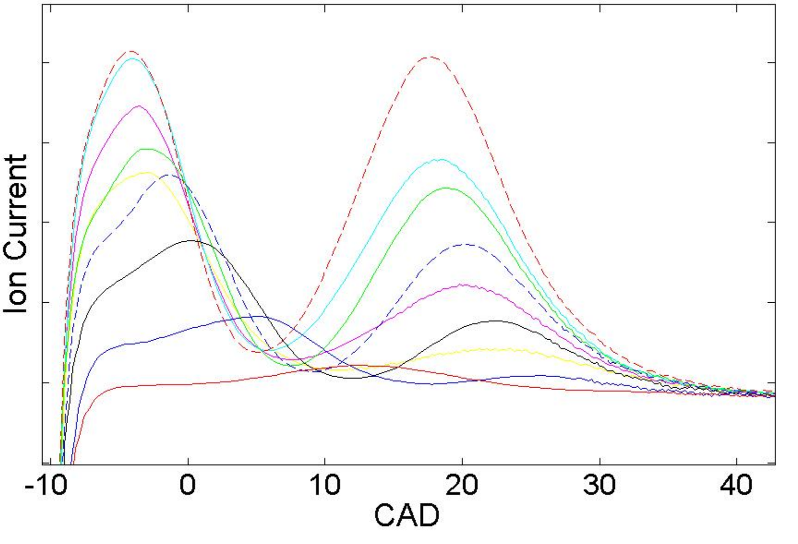

Figure 1.5. Ion current signals with mean value of 400 cycles for lambda sweep with 0% EGR. Lambda is from largest amplitude in flame peak to the smallest; 1.05, 1.00, 0.95, 1.10, 0.90, 1.15, 1.20, 1.30, 1.40. The ion current signals are plotted with the same start of ignition angle and not at the right CAD position.

Chapter 2

Experimental setup

In this chapter engine data, ion current interface and measurement acquisition equipment that have been used in this thesis are described. How data analyzing and data processing are made are explained and measurements that have been done in this thesis are presented in this chapter.

2.1 Experimental engine

Experiments in this thesis were performed with an experimental engine at Lund University. The kernel of the engine is a six cylinder Volvo diesel engine with a total volume of 9.4 l with compression ratio of 10,5:1 and it is turbocharged with a wastegate. The engine is converted to a SI engine and using Natural gas as fuel. To be able to supply the cylinders with enough natural gas the injection system is equipped with two port injectors per cylinder instead of original one diesel injector. A spark plug is assembled in top of the cylinder where the old diesel injector was placed. The engine is also equipped with an external short route cooled EGR system.

Number of cylinders	6
Displacement	9,4 liter
Compression ratio	10,5:1
Cylinder bore	120mm
Stroke	138mm

Table 2.1. Engine data

Composition	Percent [%]
Methane	89.84
Ethane	5.82
Propane	2.33
I-Butane	0.38
N-Butane	0.52
I-Pentane	0.11
N-Pentane	0.07
Hexane	0.05
Nitrogen	0.27
CO2	0.60

Table 2.2. Gas data

2.2 Ignition system

To get the information about the combustion by ion current, which is studied in this thesis, a new ignition system was needed. Coils with ability to return ion current and an ion interface were installed, see figure 2.1. The ignition application for this experiment consists of three Cylinder Control Units (CCU), three Ion Interfaces, six Coils and Data Acquisition (DAQ) Equipment. The CCU get fuel and ignition data from the Engine Control Unit (ECU) and receives a crank signal from a crank- bus on a CAN link. The CCU decides when to activate fuel injection and spark delivery based on the crank signal. One CCU can control two cylinders. The Ion interface receives a current, ion current, from the secondary of the coil and strengthens the signal and then sends it to the DAQ equipment.

2.3 Data acquisition system

Data acquisition card that was used was a Microstar card with 8 input channels with input range of 0-10V. A PC based on GNU/Linux operating system was used as a control system and was communicated with the three cylinder-controls-units (CCU). The pressure signal was measured by a piezo electric pressure transducer, Kistler 7061B. The output of the ion current signal from the ion interface is a current between 4 and 20mA with a zero output of 12mA. Due to the differences in input of bias and output of current the signals from ion interface was short circuit with a resistance of 500 ohm. With a total of 12 input signals, six cylinder pressure signals and six ion current signals and only eight input channels, only ion current from two cylinders were used for measurements and analysis.

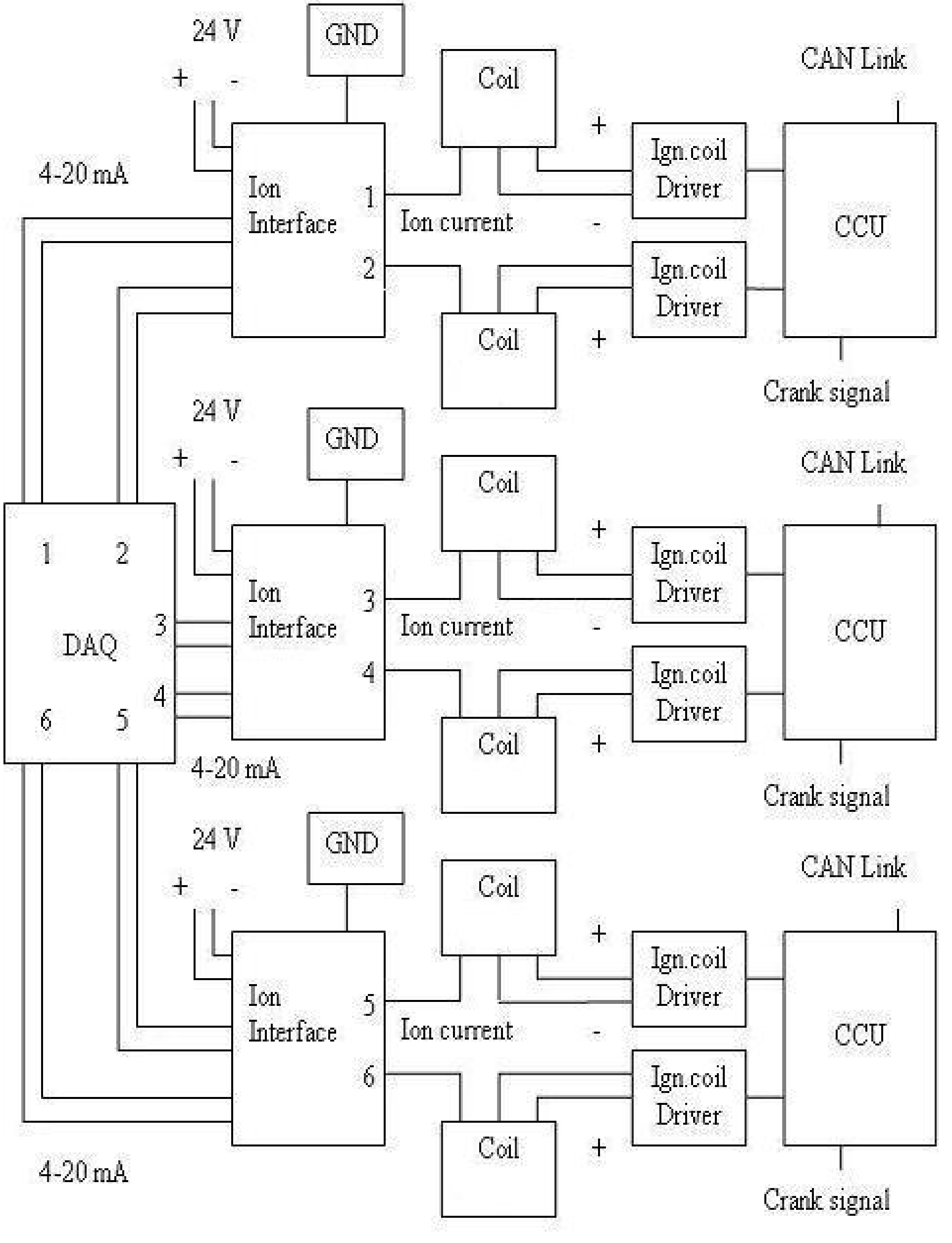

Figure 2.1. Scheme over the new ion interface that was installed.

2.4 Measurements

The measurements were done in steady state conditions with a constant engine speed of 1300 rpm. Data were collected at different EGR levels and with different lambda values. Injection timing was held constant while ignition timing was adjusted to get maximum brake torque (MBT). Due to the differences in amount of air and EGR that fills the cylinders and without individual injection control the work output and lambda is very different between the six combustion chambers. Cylinder three and four seems to get more air and EGR and cylinder one seems to get less air and EGR than the rest of the cylinders and therefore were cylinder one and three used for measurements and analysis. All lambda values and EGR values that are presented in this thesis is a mean value from all six cylinders. The lambda value is measured by a lambdasond in the exhaust and the EGR ratio is the quotient between measured CO_2 from intake and exhaust. This makes it impossible to know the exactly ratio of lambda and EGR in each individual cylinder.

2.5 Analyzing and Data processing

A Matlab script was created to calculate the integral from the ion current signal. Due to the cycle to cycle variations in the ion current signal and that it has rarely the perfect shape of two clear peaks shown in section 1.6.1 limits for the integral were difficult to decide. Because of these difficulties there can be errors in the calculation of the integral. The possibility for an error increases with higher lambda and EGR ratios. The increase of dilution of lambda and EGR make a more unstable combustion with a result of a more random ion current signal with a decreasing shape of two clear peaks. As the first peak, flame peak in the ion current signal is correlated to lambda and EGR (see figures 1.5 and 1.4) this part was interesting to study. To extend the investigation and to decrease calculation errors, the integral over both peaks in the ion current signal was also studied. The second peak, thermal peak, was not studied due to a large possibility of calculation errors discussed above because of an almost vanished peak in most of the measuring points. The integral limits for the integral over flame peak were set in the following way. The start limit was set to the first value over zero plus a constant to avoid the coil ringing and the stop limit was set to the minimum point between first peak, flame peak and second peak, thermal peak. The start limit for the integral over the two peaks was set in the same way as the start limit for the flame peak and the stop limit was set to 140 degrees after TDC. From the measured cylinder pressure, IMEP was calculated by equation (1.2). From the ion integral and pressure IMEP the Coefficient of variations (COV) was calculated, see equation (2.1). In equation (2.1) n is the number of samples, x_i is the sample and $\bar{x}$ is mean value of all samples.

$$COV = \frac{\sqrt{\frac{1}{n}\sum\left(x_i - \bar{x}\right)^2}}{\bar{x}} \times 100 \tag{2.1}$$

Standard deviation is the square root of an unbiased estimator of the variance of the samples and COV is the standard deviation divided to mean value of all samples. 400 cycles were measured for each working point. In the COV calculation the standard deviation and mean value was calculated for 100, 200 and 400 number of cycles. The Matlab command *std* was used for the standard deviation calculation and Matlab command *mean* for the mean calculations. To calculate COV of 100 cycles in a working point with 400 cycles the first 100 cycles was used. Next COV value was calculated from cycle 2 to cycle 101 and so on. Making this for 100, 200 and 400 cycles 300, 200 respectively 1 COV values were given.

EngineSpeed	λ	EGR%	Ignition angle
1300	0.98	5	19
1300	0.98	10	21
1300	0.98	15	23
1300	0.98	16	24
1300	0.98	17	28
1300	0.98	19	30
1300	0.98	21	35
1300	0.90	0	15
1300	0.95	0	17
1300	1.00	0	19
1300	1.05	0	21
1300	1.10	0	25
1300	1.15	0	27
1300	1.20	0	28
1300	1.30	0	31
1300	1.40	0	37
1300	0.90	6	19.5
1300	0.90	10	21
1300	0.90	15	23
1300	0.90	19	33
1300	0.95	5	20
1300	0.95	10	23
1300	0.95	15	25
1300	0.95	20	31
1300	1.00	6	21
1300	1.00	10	23
1300	1.00	15	25
1300	1.00	20	35
1300	1.05	5	21
1300	1.05	10	23.5
1300	1.05	15	25
1300	1.05	21	33
1300	1.10	7	23
1300	1.10	10	25
1300	1.10	15	27.3
1300	1.10	21	35
1300	1.15	5	22.5
1300	1.15	10	24
1300	1.15	15	29
1300	1.15	21	37
1300	1.20	5	23
1300	1.20	10	27
1300	1.20	15	30
1300	1.20	20	38
1300	1.30	5	25
1300	1.30	7.5	27.5
1300	1.30	10	30
1300	1.30	16	34

Table 2.3. Measurements

Chapter 3

Results

Results from this thesis are presented in this chapter. How the results are reached is explained and presented.

3.1 Analysis of IMEP

To understand how IMEP behaves for different dilutions of lambda and EGR rates, standard deviation and mean value of 400 cycles were plotted for the different measured points for cylinder one and three. Discussed in section 2.4 cylinder one get a lower rate and cylinder three a higher rate of dilution of air/EGR compared to the measured mean value. This can be seen in figure 3.1 for lambda 0.90 where IMEP is smaller for cylinder one, with a mixture that probably is much richer than optimal (around lambda one), than for cylinder three with a mixture that probably is around lambda one. When lambda is increasing IMEP for cylinder one gets larger than IMEP for cylinder three with a mixture that is getting from around lambda one to a mixture much leaner than lambda one. It can be seen that work produced in the combustion is decreased with increasing ratio of EGR and lambda. With an IMEP value around zero no work has been produced by the combustion and a misfire have occurred. In figure 3.1 misfires can be observed for cylinder one with lambda 0.90 and EGR ratio 19% and for cylinder three with lambda 1.05, 1.10, 1.15, 1.20, 1.30 respectively EGR ratio 21%, 21%, 21%, 21% and 16%. This is a result of a mixture with a too large dilution of EGR and air to have ability to proceed a complete combustion. Misfires decrease the efficiency and (discussed in section 1.3) misfires can increase emissions by destroying the catalyst. For combustions with misfires no ions will be produced and therefore no peaks in the ion current signal will occur and this can be seen in figure 3.2. The control system will control COV of IMEP to 5% and interesting working points for further investigation will be cylinder three for lambda 1.05 to 1.30 that has more IMEP variations than cylinder one. Further analysis will therefore be concentrated towards cylinder three.

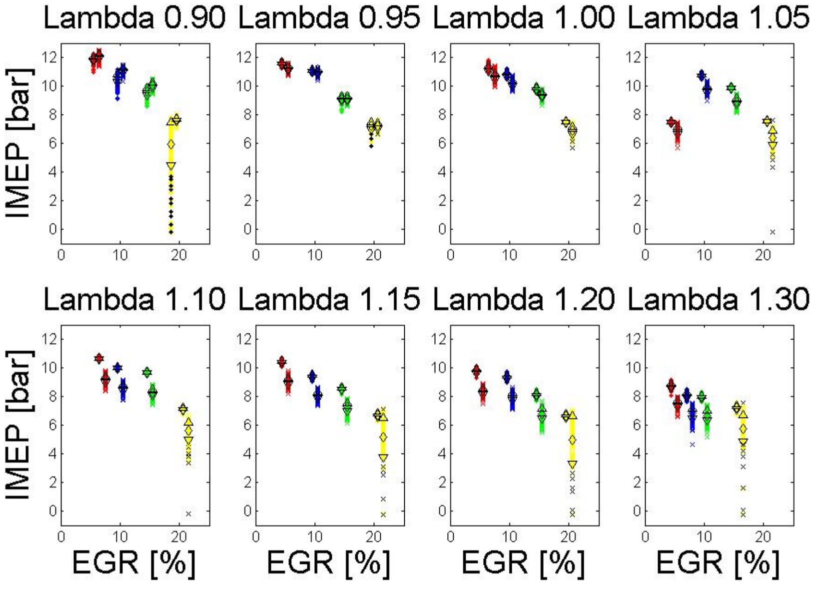

Figure 3.1. Standard deviations and mean values for IMEP(gross) for cylinder one and three. In figure there are four EGR rates per lambda and for every EGR rate there are data for cylinder one plotted to the left and cylinder three to the right. In each working point standard deviation is marked by a triangle around the mean value marked by a diamond. There are probably measurement errors for IMEP for lambda 1.05 and EGR rate of 5% in both cylinders while these values are not correlated to the rest of the measured values.

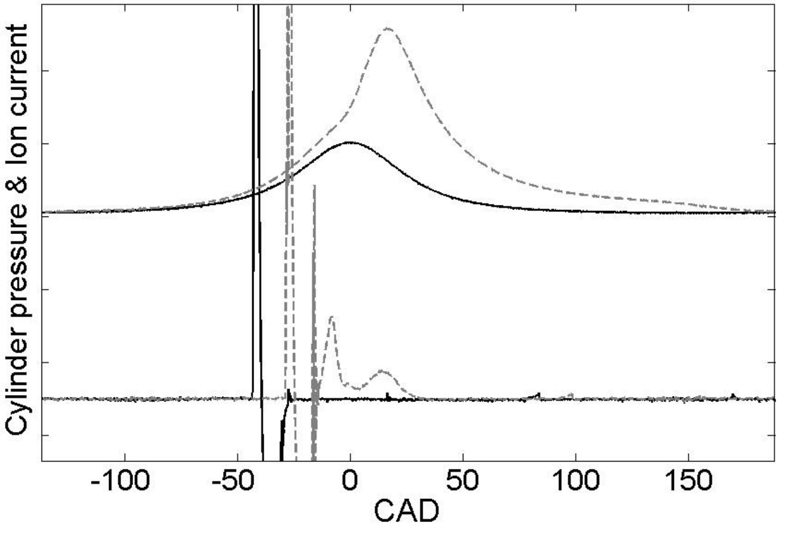

Figure 3.2. Pressure and ion current signals for one combustion with misfire (solid) and one normal combustion (dashed).

3.2 Analysis of ion integral

A first step in ion integral analysing is to decide which part of the ion current signal to integrate. To be able to decide this part the ion integral was also plotted with mean values and standard deviations for the measured data series of 400 cycles. Only integrals for the flame peak and integrals over two peaks were investigated. Post flame peak integrals were not analysed because of difficulties with calculation of a too small peak discussed in section 2.5. It is difficult to see by the figure 3.3 if COV is increasing with increased EGR and air. COV should decrease with decreasing standard deviations and increase with decreasing mean values according to the definition seen in equation (2.1).

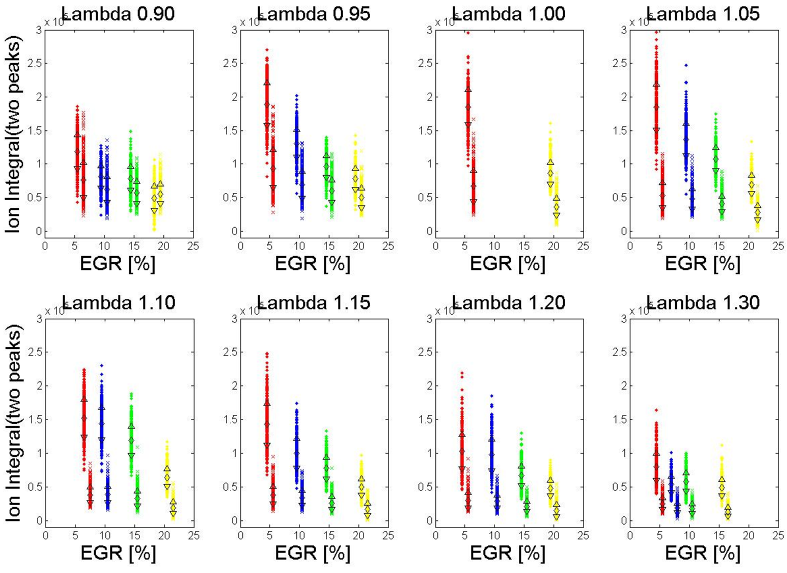

Figure 3.3. Standard deviations and mean values for ion current integral over two peaks for cylinder one and three. In figure there are four EGR rates per lambda and for every EGR rate there are data for cylinder one plotted to the left and cylinder three to the right. In each working point standard deviation is marked by a triangle around the mean value marked by a diamond.

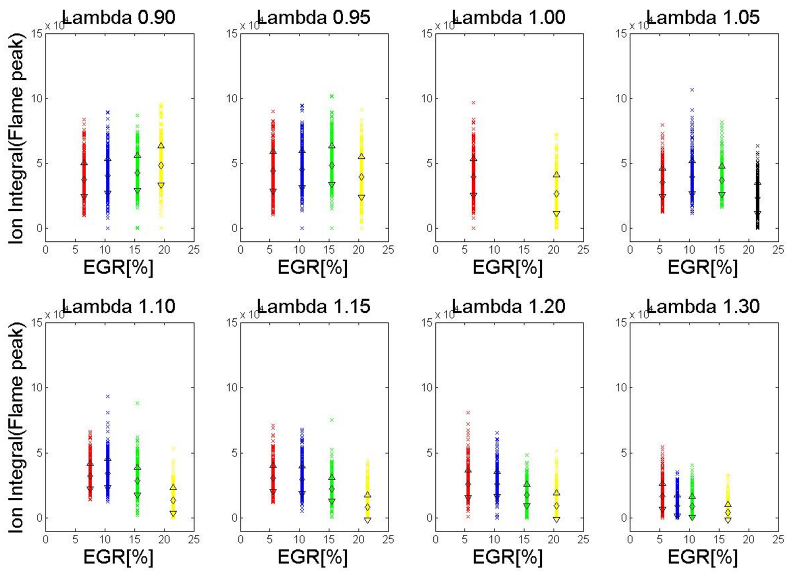

Figure 3.4. Standard deviations and mean values for ion current integral over flame peak for cylinder three. In each working point standard deviation is marked by a triangle around the mean value marked by a diamond.

3.3 Correlation analysis with ion integral over flame peak

A correlation plot between COV of ion integral over flame peak and COV of IMEP was plotted for cylinder three. The working points were lambda sweep from 0.90 to 1.30 and EGR sweep from 5% to 21% seen in table 2.3 calculated for 100 cycles seen in figure 3.5. A correlation plot with working points with lambda sweep from 0.90 to 1.20 and EGR sweep from 5% to 21% seen in table 2.3 calculated for 100 cycles were also plotted seen in figure 3.7. If comparing these two plots it can be seen that for the leanest mixture when the mean value of lambda is 1.3 the COV for ion flame peak integral is increasing rapidly compare to COV of IMEP (see the extra COV values in figure 3.5 compare to figure 3.7). Conditions with lambda 1.3 or greater are working points far from the stoichiometric working point that this engine is designed for. If these working points with lambda 1.3 is ignored in the analysis a correlation can be seen in figure 3.7 in range from 0 to 15-20% COV of IMEP. When COV of IMEP is increasing from around 20%, COV of ion integral has already reaches the maximum value and no correlation occurs here. This operating region is far away from the operating point of the controller which control the EGR rate to obtain 5% COV of IMEP and therefore a correlation is not necessary above 20%.A correlation plot with working points with lambda sweep from 0.90 to 1.20 and EGR sweep from 5% to 21% but with COV calculation over 200 cycles instead can be seen in figure 3.8.

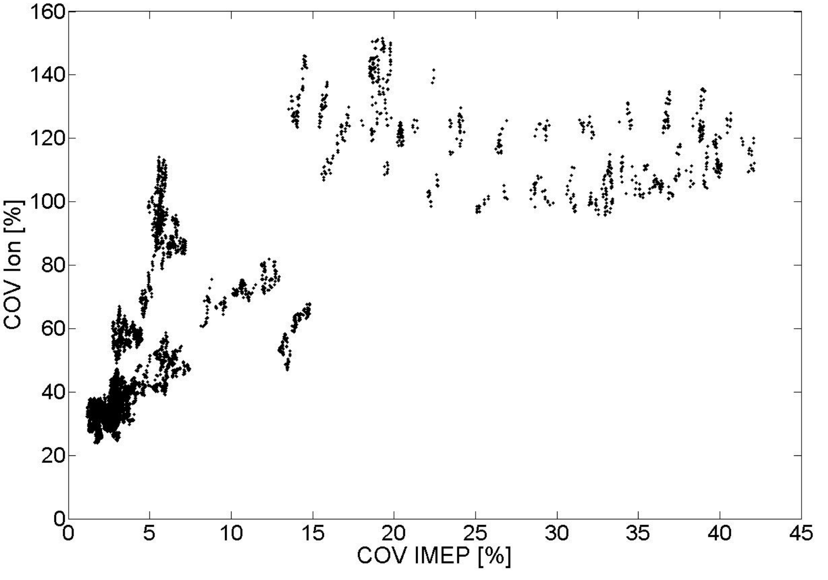

Figure 3.5. Correlation plot between COV of integral over ion flame peak and cylinder pressure IMEP for 100 cycles in cylinder three. Lambda sweep from 0.90 to 1.30 and EGR sweep from 5% to 21%.

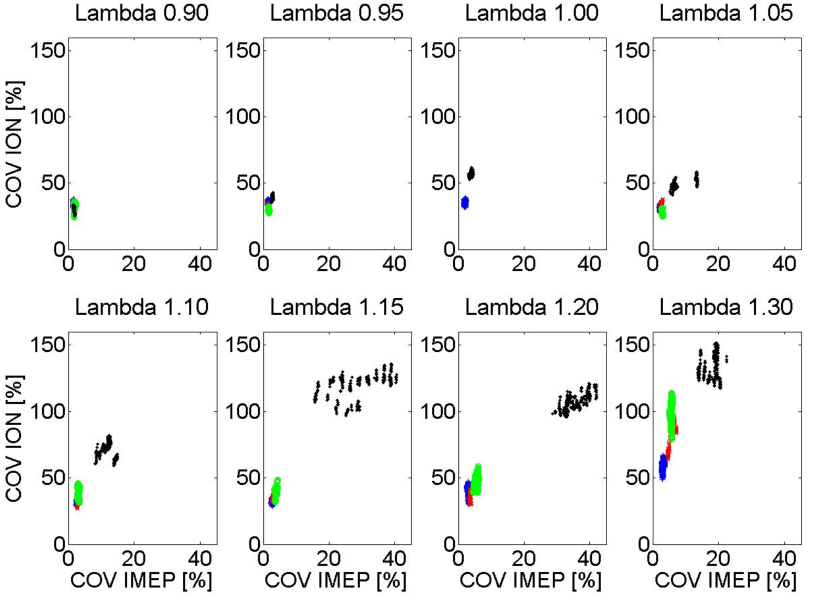

Figure 3.6. Correlation plot between COV of integral over ion flame peak and cylinder pressure IMEP for 100 cycles in cylinder three seen in different subplots. Lambda sweep from 0.90 to 1.30 and EGR sweep from 5% to 21%.

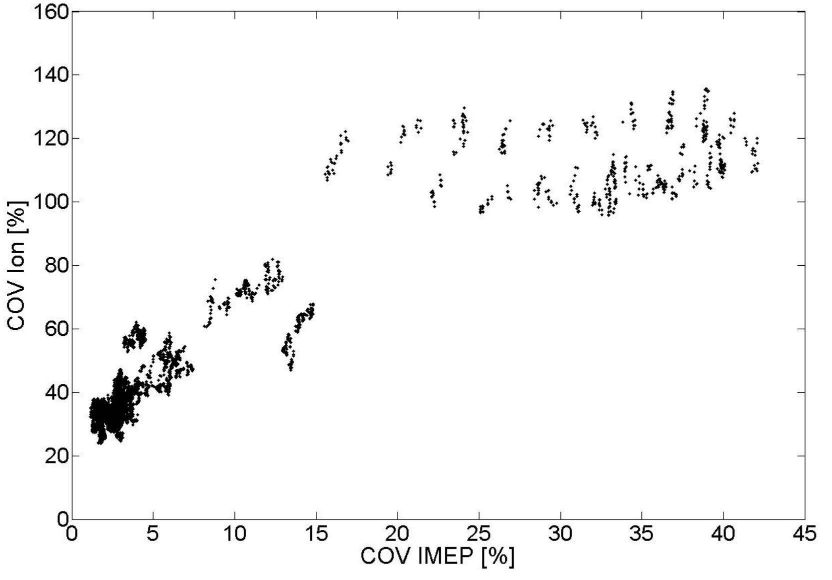

Figure 3.7. Correlation plot between COV of integral over ion flame peak and cylinder pressure IMEP for 100 cycles in cylinder three. Lambda sweep from 0.90 to 1.20 and EGR sweep from 5% to 21%.

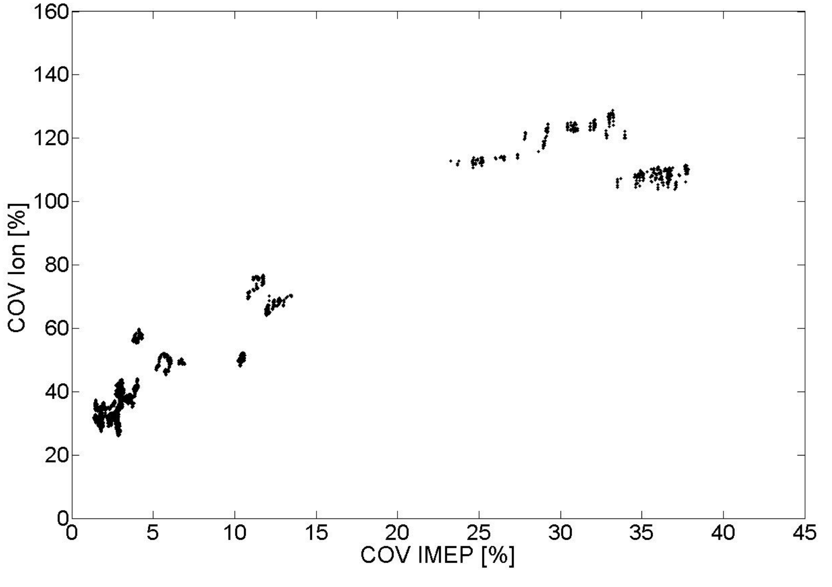

Figure 3.8. Correlation plot between COV of integral over ion flame peak and cylinder pressure IMEP for 200 cycles in cylinder three. Lambda sweep from 0.90 to 1.20 and EGR sweep from 5% to 21%.

3.4 Correlation analysis with ion integral over two peaks

Also a correlation plot between COV of ion integral over two peaks and COV of IMEP was plotted for cylinder three, see figures 3.9 and 3.10. There is no clearly differences between correlation of lambda sweep from 0.90 to 1.30 and lambda sweep from 0.90 to 1.20 like the phenomenon with flame peak integral discussed in previous section. COV of two peaks integral is not increasing with the same rate as it does for the integral over flame peak. Together with this and the large variance in COV of ion integral it gets much more difficult to know with certainty when COV of IMEP is larger than 5% compared to the COV of flame peak integral investigated further in section 3.5. A benefit is that there is a more linear correlation over the whole range of COV than for the COV of flame peak integral.

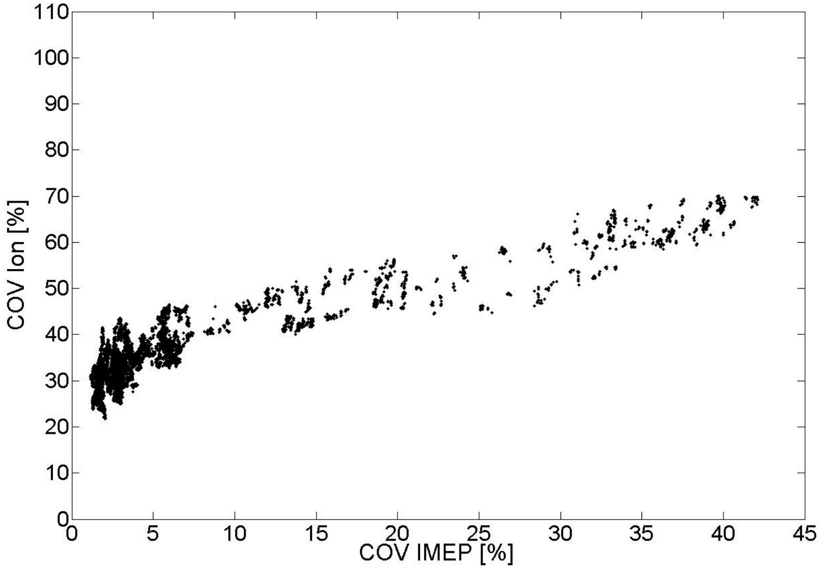

Figure 3.9. Correlation plot between COV of integral over both peaks in ion current signal and IMEP for 100 cycles in cylinder three. Lambda sweep from 0.90 to 1.30 and EGR sweep from 5% to 21%.

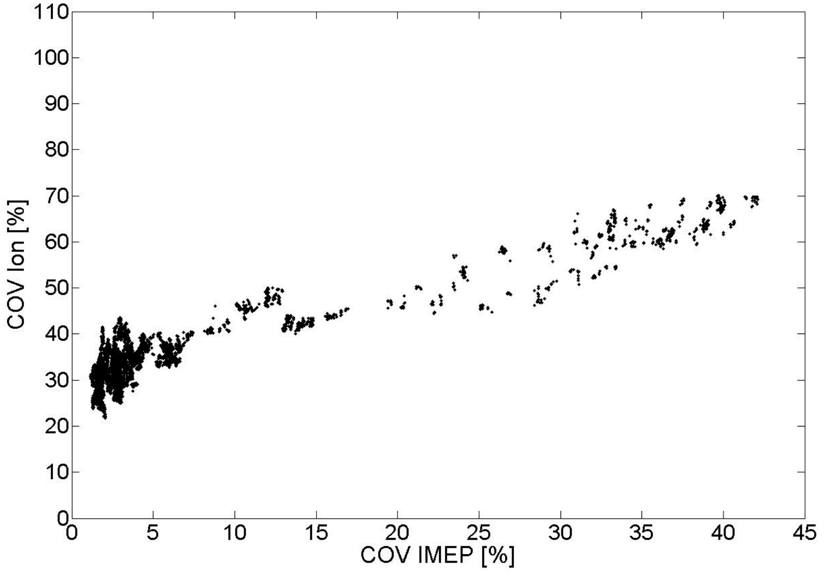

Figure 3.10. Correlation plot between COV of integral over both peaks in ion current signal and IMEP for 100 cycles in cylinder three. Lambda sweep from 0.90 to 1.20 and EGR sweep from 5% to 21%.

3.5 Rate of detection and false detection

To be able to control against 5% of COV of IMEP with information from ion current a threshold for the COV of ion integral is needed. From figures like 3.12 and 3.13 thresholds for COV of ion can be chosen for different requirements depending on ability of detection and ability of false detection. Figures 3.12 and 3.13 have been made by changing thresholds for COV of ion integral from 20 to 160%. On the y-axis in figures 3.12 and 3.13 there are the rate of detected COV values in percent of total COV values correlated to COV of IMEP over 5% that should be detected. COV values from C divided in B plus C in figure 3.11 is the detected rate. On x-axis there is percent of detected COV of ion values that are false detected and should not be detected for COV of IMEP. COV values from D divided in D plus A in figure 3.11 is the false detection rate. COV of ion values are between 20 and 160% and are analysed for cylinder three. In figure 3.12 COV of ion integral over flame peak (dashed) is better in all points compare to COV of ion integral over two peaks (solid) where the percent of detection is greater for the same rate of false detection. For a false detection of zero percent flame peak has a detection rate of 70% compare to two peaks integral with a detection rate of 50%. For full detection rate flame peak has a false detection rate of 17% compare to two peaks integral with a false detection rate of 37%. Figure 3.13 shows detection and false detection rate for COV of ion flame integral for EGR sweep from 5% to 21% and lambda sweep from 0.90 to 1.30 (dashed) and lambda sweep without lambda rate of 1.30 (solid). Discussed in 3.3 a rapid increasing of COV of ion integral for the leanest dilution of lambda 1.30 could be a problem for control strategy. This is for some rates shown by figure 3.13 that with lambda 1.30 a better correlation in aspect of rate of detection and false detection is given. It also gives premonition of a COV increasing which makes the robustness better discussed in 3.6.

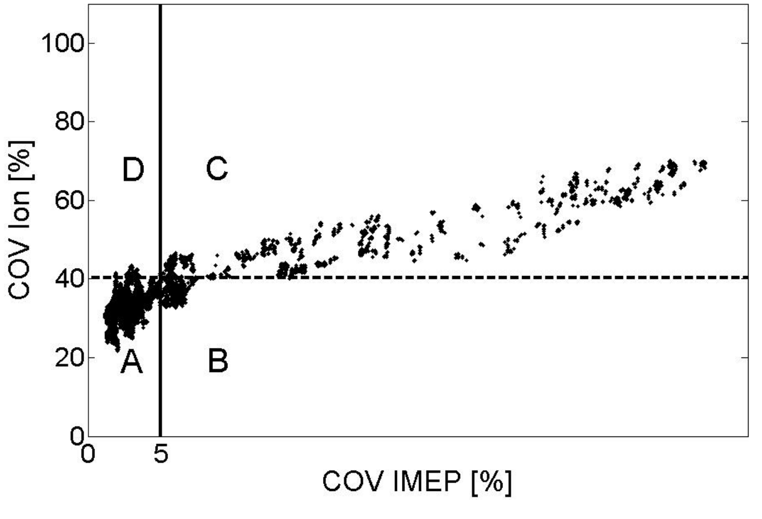

Figure 3.11. Rate calculation of detection and false detection for different thresholds is illustrated by this figure. Dashed line is ion COV threshold and solid line is IMEP COV limit 5%.

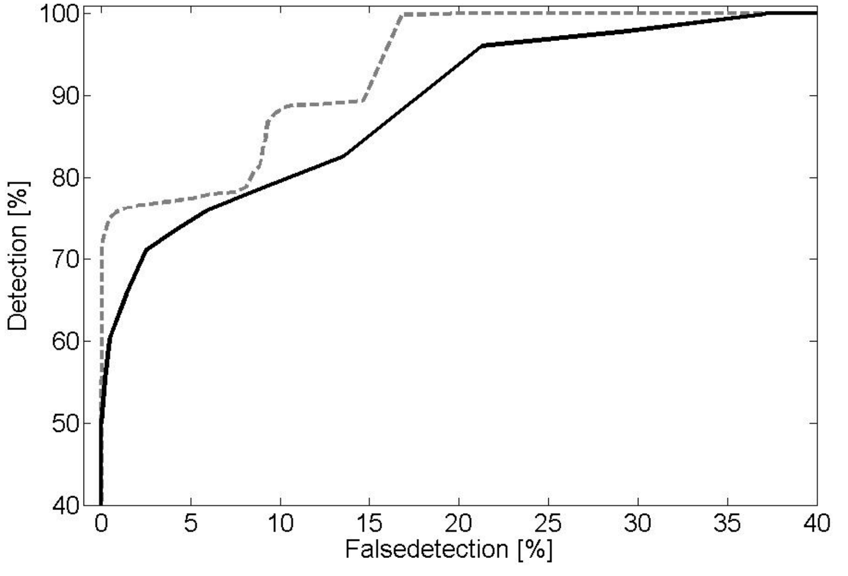

Figure 3.12. Percent of detection and false detection for different thresholds between 20 to 160 of COV of ion integral over flame peak (dashed) and ion integral over two peaks (solid).

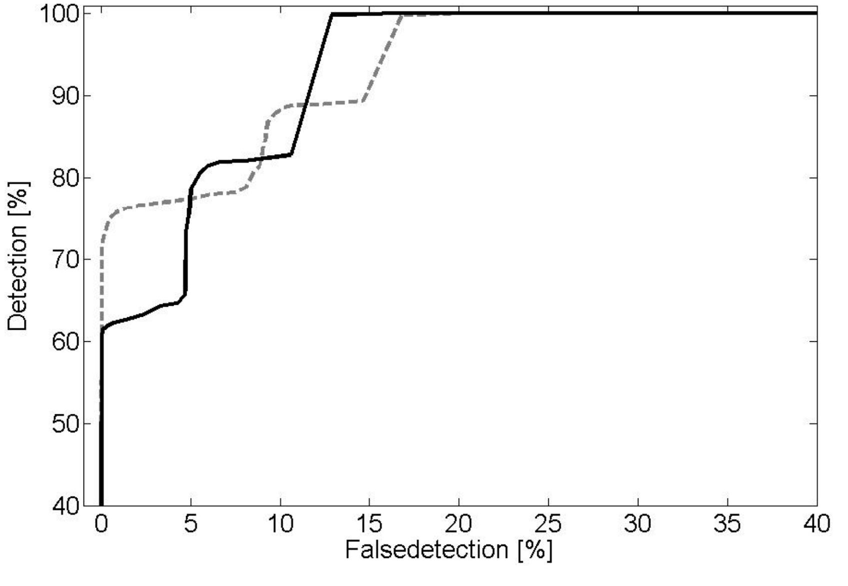

Figure 3.13. Percent of detection and false detection for different thresholds between 20 to 160 of COV of ion integral over flame peak with lambda 1.3 (dashed) and without lambda 1.3 (solid).

3.6 Correlation analysis

Data from the first measurement series with EGR sweep from 5% to 21% and lambda of 0.98 seen in table 2.3 were studied. COV of ion flame peak integral and COV of IMEP for different EGR rates were plotted in figures 3.14 and 3.15. COV of ion integral is rapidly increasing at an EGR rate of 17%, compared to COV of IMEP that has this increasing at an EGR rate of 21%. This earlier COV rising for ion integral makes it possible to control to an ion COV value correlated to COV of IMEP of 5% earlier than a control strategy with COV of IMEP. This makes it possible to make a more robust control system. When COV of ion is increasing and reaches a threshold action can be taken before COV of IMEP increases above 5%. It makes it easier to prevent bad combustions and misfires in critical driving conditions. Further investigations could be done with higher EGR rates or different lambda values to see phenomenon discussed earlier in section 3.3 where COV of ion are flat out after the rapidly increasing. Also it is interesting to see if COV of IMEP increases rapidly when it is reaches over COV of 5%.

3.7 Auto-correlation

Auto-correlation is a measure of the degree of the linear relationship between different values within the same dataset. More precisely, it is the cross-correlation of a signal with itself. With auto-correlation analysis it can be seen if a repeating pattern in the measured series exists. An investigation to see if ion flame integral and ion two peaks integral has a correlation between each cycles were made. One interesting thing to see is if one poor combustion follows by a good combustion and if this can be seen in the ion current signal. To do this analyze the matlab commando *xcorr* was used. The commando gives 1 for an existing positive linear relationship, 0 for no linear relationship and -1 for an existing negative linear relationship. No repeating patterns in the measured series were found. Existing linear cross-correlation were found for ion two peaks integral over the measured lambda sweep and EGR sweep and it can be seen in figure A.1 in Appendix. For ion flame peak integral linear cross-correlation were rapidly decreasing for high lambda and high EGR rates and this is a result of a larger integral variance due to higher dilution rates.

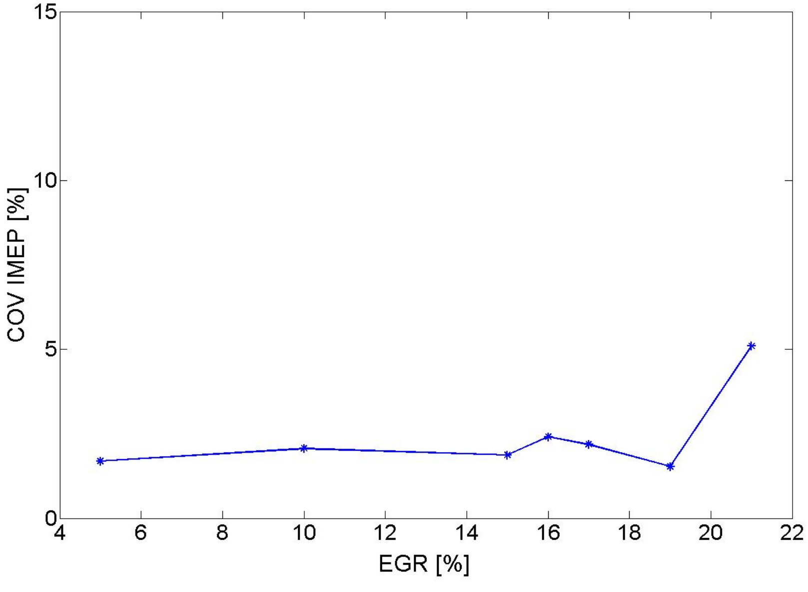

Figure 3.14. COV of IMEP for EGR sweep between 5% and 21% and lambda 0.98

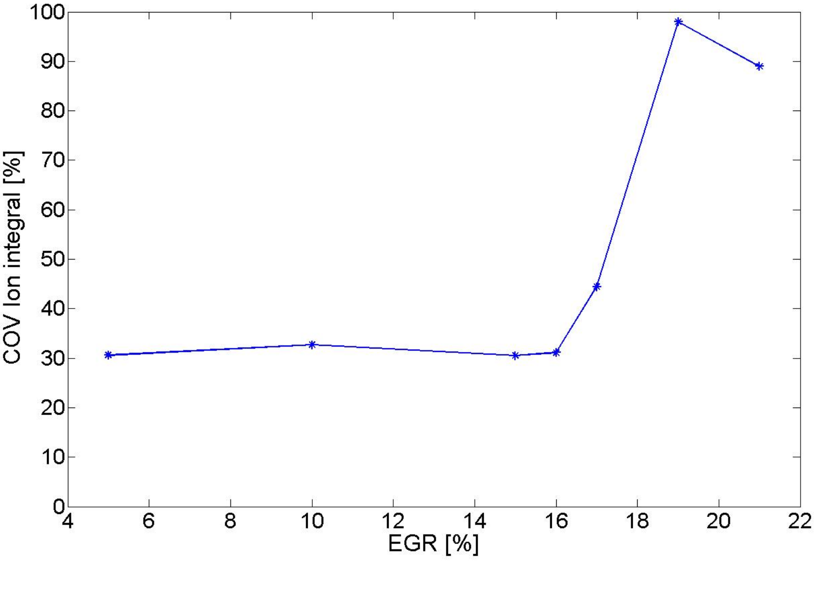

Figure 3.15. COV of ion integral over flame peak for EGR sweep between 5% and 21% and lambda 0.98

3.8 Control strategy

One control strategy can be to adjust fuel and ignition individually to be able to decrease COV for each cylinder and to increase engine efficiency. A first step is to turn off the lambda control and close the EGR valve since no EGR shall be used under the adjustments. If one cylinder is over the threshold of COV of ion correlated to COV of IMEP of 5% (discussed in section 3.5) fuel quantity and ignition timing is adjusted in this individual cylinder. The adjustments shall decrease COV of ion to the dotted line in figure 3.16. All cylinders should be adjusted, when one cylinder increases the fuel quantity, the fuel quantity should be decreased in the others cylinders and vice versa to maintain lambda one. The fuel quantity change is depending on the individual cylinder lambda which is illustrated in figure 3.16. Shown in this thesis COV of ion increases with increasing lambda. Therefore, cylinders with high COV will increase and cylinders with low COV will decrease the fuel quantity. In figure 3.17 COV for cylinder one and cylinder three is compared for a lambda sweep showing that cylinder three has always larger COV values than cylinder one and therefore fuel quantity will be increased in cylinder three and decreased in cylinder one that will result in more stable combustions. Next step in the control strategy is to turn lambda control on again to control engine lambda to one. When lambda one is reached the EGR valve can be opened again to increase EGR rate. The EGR can be increased until the EGR rate limit of COV of ion is reached. Ignition timing is needed to be adjusted to maintain efficiency when flame propagation changes with increasing EGR rates. A control strategy with cylinder individual fuel and ignition adjustment makes the engine more efficient compared to a strategy where the worst cylinder decides the EGR limit. In the engine studied in this thesis cylinder one and three have very different air/fuel and EGR ratios discussed in section 2.4. With a control strategy where the COV threshold is reached in one cylinder the EGR rate will be decreased which makes that the EGR limit is limited by the worst cylinder. By controlling the cylinders individually using control strategy explained above the result will be an engine with higher EGR rates, more efficient and an engine with better fuel economy.

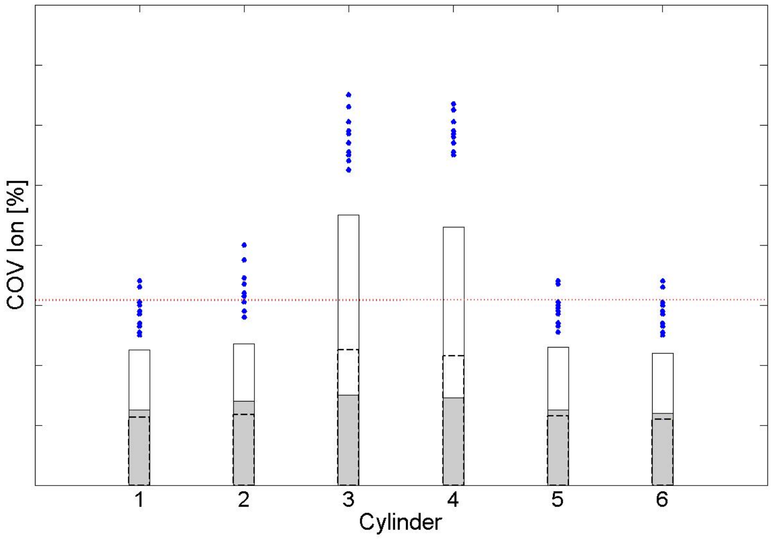

Figure 3.16. An example figure for the control strategy explained above. White bars illustrate air and grey bars illustrate fuel. Dashed bars illustrate the desired fuel quantity. Dots are ion COV for individual cylinders and the horizontal dotted line is the desired ion COV value.

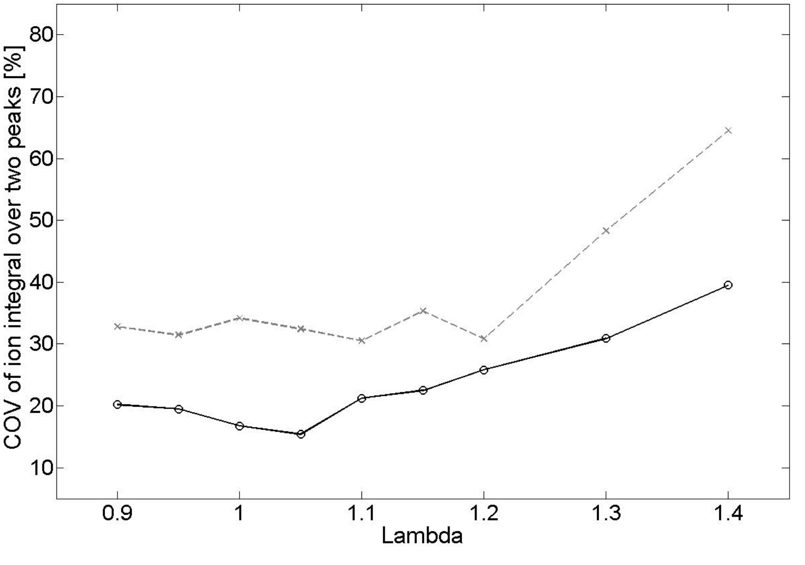

Figure 3.17. COV of ion integral over two peaks for cylinder one(solid) and cylinder three(dashed) for lambda sweep from 0.90 to 1.40.

Chapter 4

Conclusions and future work

4.1 Conclusions

In this thesis correlations between COV of ion peak integrals and COV of cylinder pressure IMEP were investigated. The control strategy for this thesis is to control EGR rate to a limit of 5% COV of IMEP. For COV of flame peak integral in the range from 0 to 15-20% of COV of IMEP a linear correlation was found for lambda less than 1.3. For lambda 1.3 COV of ion has a higher COV value than for lambda less than 1.3 for the same EGR rates and COV of IMEP. For COV of two peaks integral a linear correlation was found for all the measured range. This correlation may not be used for a robust EGR control system due to a small increase of COV of ion integral and that the COV of ion integral has high variance. No investigation of correlation between COV of thermal peak integral and COV of IMEP were done since the thermal peak almost vanishes when using EGR. In chapter 3 section 3.6 it can be seen that the COV of ion integral over flame peak is increasing before COV of IMEP does. This phenomenon gives an earlier hint when EGR limit and COV of IMEP of 5% are reached. The rate of detected ion COV correlated to COV of IMEP over 5% and false detected ion COV for different ion COV thresholds were also presented in this thesis. In this aspect it was shown that ion flame peak integral is better than ion two peaks integral for every threshold. Auto-correlation were investigated to see if any repeating pattern of the ion integral over flame peak and two peaks exist for the cycle to cycle variations. No special patterns were found for neither of the integrals. A control strategy using ion sensing technique for increasing engine efficiency is explained in section 3.8.

4.2 Future work

A control strategy with cylinder individual fuel and ignition adjustments discussed in section 3.8 should be tested with fuel consumption and power output comparison to see how the fuel efficiency changes. Ion current measurements in all six cylinders should then be done to make it possible to control the EGR valve with ion COV signals. In this thesis only steady state condition for one engine speed was used for the correlation analysis. Further investigations of COV correlations for several working points should be done over different loads and engine speeds.

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Appendix A

Auto-correlation

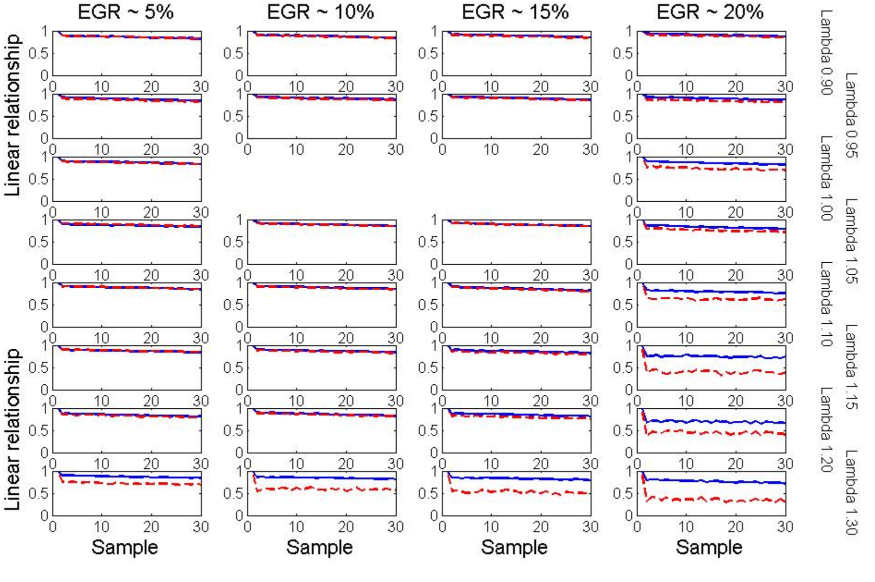

Figure A.1. Auto-correlation plot for ion flame peak integral(dashed) and ion two peaks integral(solid) for lambda from top to bottom; 0.90, 0.95, 1.00, 1.05, 1.10, 1.15, 1.20, 1.30 and with four different EGR rates for every lambda value seen in table 2.3. For lambda 1.00 with EGR rates of 10 and 15% data are missing and no auto-correlations were plotted.