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The Study of the Dynamics of Diesel Engine Fuel Injectors with Alternative Fuels for Diagnosis

# The Study of the Dynamics of Diesel Engine Fuel Injectors with Alternative Fuels for Diagnosis

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# Contents

# Abstract

With the oncoming energy crisis in fossil fuels, the study of alternative fuels has become a topic of much concern for industry in recent years. Among the alternative fuels, biodiesel shows huge potential for solving the crisis as it can be used in traditional diesel engine systems with minimal modifications.

The injector has the highest failure rate in diesel engines, which has more potential for using biodiesels that have higher viscosity and bulk modulus. However, the influence of biodiesel on the injector's dynamics and diagnostics has rarely been reported. In practice, the injector operation is influenced by many factors and it is hard to extract its dynamic characteristics for the purpose of detection and analysis by using the traditional techniques like the vibration and the airborne sound (AS), which are highly affected by other processes in the engine systems, such as combustion.

As a non-intrusive condition monitoring (CM) technique, acoustic emissions (AE) can detect a very high frequency event, which means it has good localized performance and is less likely to be interfered by noises from other engine process such as combustion. Thereafter, as a promising nonintrusive technique, AE measurement is employed in this project to study the injector dynamics for the purpose of diagnosis. At the same time, to verify this method, conventional intrusive monitoring methods, such as cylinder pressure and injector pressure are also investigated.

A series of analytic studies and experiments are carried out based on a four-stroke diesel engine system by changing the running of the engine with different loads, speeds and fuel types. The signals are converted to the angular domain to help understand the behavior of the injection process. From the results analysis, it has been found that the injection parameters, such as starting angle, closing angle and impact strength, have high correlation with AE signals. Moreover, current study results show that the envelope of the AE signal has good performance in estimating the injection open angle for all fuel types. Therefore, AE can be employed as a non-intrusive method for monitoring the injection behaviour of different fuels.

In addition, AE amplitudes of injecting pure biodiesels show little increase although the injection pressures are clearly higher in comparison with normal diesel fuel. This may be accounted by the softening effect of high viscosity.

## Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of the University of Huddersfield or any other university or other institute of learning.

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# Abbreviations

| | |
|---|---|
| AE | Acoustic Emission |
| CI | Compression Ignition |
| CMFD | Condition Monitoring and Fault Diagnosis |
| CM | Condition Monitoring |
| IAS | Instantaneous Angular Speed |
| FFT | Fast Fourier Transform |
| AS | Airborne Sound |
| SNR | Signal-to-Noise Ratio |
| TSA | Time Synchronous Average |
| AR | Autoregressive |
| ARMA | Autoregressive Moving Average |
| STFT | Short Time Fourier Transforms |
| TDC | Top Dead Center |
| RMS | Root Mean Square |
| PC | Personal Computer |
| CP | Computer Program |
| BTDC | Before Top Dead Center |
| ABDC | After Bottom Dead Center |
| BBDC | Before Bottom Dead Center |
| ATDC | After Top Dead Center |
| AC | Alternating Current |
| DAQ | Dynamic Data Acquisition |

# Chapter 1 Introduction

## 1.1 Introduction

As all human beings' lives and existence rely on energy, especially the productive activities for modern people, energy consumption has a major influence on the quality of life. The maintenance and improvement of industry and technology are also based on energy and increase of energy efficiency. The efficiency of energy use influences the economic advance of a country, technological popularization of a society, output and yield of manufacture, and even an individual's social activities.

However the trend, market and type of energy are always dependent on the following conventional factors [1]: (1) availability of the resource, (2) convenience of energy utilization, (3) energy efficiency, (4) technological standard, (5) convenience and safety of transportation, (6) sustainability, (7) renewability, (8) cost, (9) safety and health effects, and (10) environmental acceptance and impact. However, fossil fuel resources are non-renewable and finite and are approaching depletion in the near future. Hence finding an appropriate solution is an important and attractive aim in current research studies. Furthermore, people have a growing demand not only for an alternative energy source, but also one that is convenient with excellent performance and high efficiency. Therefore, alternative fuel needs to be developed much more and the commercial exploitation of this is needed synchronously. It has become a realistic issue for the present, not a consideration for future.

Since diesel engines were designed to obtain the mechanical energy from diesel oil or chemical fuel by Rudolf Diesel [2], it has been a main power source of many machines for its highly mechanical power, thermal efficiency, stability, reliability and economy performance, such as cars, buses, trucks, motorcycles, trains, boats, aircrafts, military equipment, agricultural equipment, power take-off and so on. The compression ignition (CI) diesel engine is a kind of mechanical equipment, which inhales air and compresses it to a very high level for achieving the ignition point of fuel. This process can obtain the thermal source by burning the fuel without spark-ignition, which as a feature leads to the injection process becoming the major determinant of combustion performance [3].

The modern fuel injector is an accurate, high performance mechanical assembly constituted by several components in the diesel engine, which can accurately release the precise fuel amount into an internal combustion engine every single time. Achieving the injection by injector atomizing the fuel has been the primary fuel delivery process instead of using carburetors since the 1980s, because of its better performance in power output, fuel efficiency, emission exhausting, reliability, cost, diagnostic capability and so on. With increased quality demands, the engine performance, economic requirements and pollutant emission regulations also increasing in parallel with one another, this has led to the improvements needed through research and development of injector engines. The use of alternative fuels in particular is such a promising solution to the issue of fossil fuels depletion and the curbing of pollutant emissions, that injector research correlated to alternative fuels has become a research area of much importance.

Alternative fuels are any resources that can be used as fuels in engines and are so-called non-conventional fuels, other than the conventional fuels, which include: petroleum, coal, gas and congeneric fossil fuels. Some well-known alternative fuels include biodiesel, hydrogen, bio-alcohol (methanol, ethanol, butane), vegetable oil, other biomass sources, and so on [4].

As industrial and human survival heavily relies on energy, which comes from the finite resource of fossil fuel, it is expected that it will expend in the near future. Concurrently, the requirement of convenient and high-performance energy source keeps growing. Therefore, additional and alternative sources for fuels and petrochemical feedstock not only need to be developed further but are also needed for immediate commercial exploitation. Although the design of diesel engines is suitable for most alternative fuels be used directly, the change of fuel also brings up some other issues and potential risks. Thus, the study of the dynamics diagnosis of diesel engine fuel injectors with alternative fuels is needed. Even though much research has been carried out, it is still not satisfactory for the immediate issue and requirement in hand [1].

In fuel injector faults, the phenomenon may be caused by unexpected vibrations damaging the engine components. It not only results in low engine efficiency but also high and sometimes even unacceptable level of unburned hydrocarbons. Therefore, the condition monitoring and fault diagnosis (CMFD) has been widely employed to analyze and diagnose the engine performance [5]. Because it's based on the engine's transient dynamic performance, the analysis and diagnosis based development is very reliable and helpful. In the last few years, the application of CMFD for optimized engine operations has experienced major developments, especially for detecting potential faults and keeping engine performance in healthy condition. It can detect the injector faults at an early stage and diagnose the cause of failure, thus an effective solution can be deployed in time to prevent failure occurrence and maintain engine performance [6].

There are extensive techniques in CMFD as it has been widely used now for a long time, and the vibration analysis technique is one of the most commonly used techniques in the industry because of its installation convenience and good accuracy [5]. But the information obtained from the vibrational signal is limited, especially when there are strong noise disturbances and contaminations. As there are many influences from other conditions, it is difficult to use the vibration signal for obtaining the non-stationary characteristics. Acoustic emission (AE) is a measurement from elastic waveform signals with excellent signal results, convenience and accuracy, and is a relatively new, efficient attempt in this area that can provide additional information by determining the defects of the vibrational signal of the engine's condition [7].

## 1.2 Engine Diagnostics

The diagnosis based on conditional monitoring in terms of CMFD is an integrated series of facilities and techniques designed to monitor, analyze and predict the operation of the object. Conditional monitoring (CM), as defined by James in 1992 [8], is a maintenance philosophy that refers to a relatively involved prediction and statement of the mechanical condition of a machine by using periodic measurement of the mechanical and process parameters in related order. Meanwhile, Penman and McEwan put it this way [8]: CM of an item of a plant means the continuous assessment of the health of the plant throughout its working lifetime by the collection and examination of signals that typify the performance of the plant whilst it is in operation. Condition monitoring and fault diagnosis (CMFD) assesses the analysis of the operation of the engine collected by monitoring sensors, in order to diagnose the failure efficiently [5]. Vibration monitoring, pressure monitoring, temperature monitoring, acoustic monitoring, lubrication monitoring and many other monitoring techniques have been developed for using in CM. They were combined with some analytical procedures for approaching the CMFD to solve the fault in mechanical systems as the following characteristics were achieved [8] and [9]:

1) be able to present process condition information and not just mere data.
2) be able to generate the transient dynamic operation for monitoring and diagnosis.
3) be able to predict and detect the failure.
4) be able to accurately measure the engine's state during the operation.
5) be able to optimize the mechanical system and maintenance process.

The conventional operation is using preventative maintenance periodically to reduce the potential risk and cost for engine failures. As the CM results can immediately identify the failure and potential failure and generate a hazardous warning at an early stage to avoid further fault, the CM approach has become the most popular monitoring method in recent years, instead of the more tradition methods, due to its safer, more convenient and reliable ability. It has been used by many manufacturers to ensure product quality and inspire customers to take their "service-based" product, which can assure product availability [9]. CM techniques also help the design testing, development process and product testing of engine development, as it can optimize the component and system and, thus, avoid premature damage and potential failure.

As a dynamic facility, the diesel engine has highly non-linear characteristics because of the complex assembly of components in its mechanical system. The working performance of an engine is a variational process and the ambient conditions are also variational factors. This requires a diagnostic technique that is able to provide dynamic features with an acceptable accuracy. It is difficult to arrive at an overall fault diagnosis using analytical models. Many developments for a variety of CMFD methods or systems have been researched to try to find a solution with more efficiency, reliability, robustness and economical operation for adapting to the increased requirements of the public and environmental legislation. So new techniques and methods of CMFD are still emerging.

Some new designs have been attempted to provide the interface between the engine and the CMFD. The typically on-board CMFD systems monitor has achieved a great success by adopting built-in sensors to get the transient operation state information of a running engine. Some legislation even requires the vehicles to install the on-board device for emission and related components faults detection to insure vehicle safety, its continued environmental efficiency and other advanced purposes. But there are many challenges in adopting on-board CMFD, such as cost limitations and performance ability to for such complex diagnostic algorithms and expensive, delicate components. For instance, the on-board system preferably should measure the rotational speed, but it is difficult to detect the misfire that can more easily be determined by vibration signal methods. The requirements of these techniques are significant and therefore impacts on the objectives for further AE employed techniques in development as AE signals have characteristics of either vibration signal or rotational signal [5].

Today, the vibration signal analysis method is still one of the most commonly used CM techniques in industry as its excellent properties in various data format acquisition and the stability and convenience of facility setting and signal acquisition, especially in real-time operation. Many pre-set alarms are automatically triggered by the vibration signal adopted in CMFD techniques. But the information acquired from vibration signal is limited, which conventionally leads to many additional accelerometers and different measurement positions being applied for CMFD to get effective information. And the noise contamination also brings another challenge for data processing and tends to lead to difficulties in acquiring accurate information. Therefore, an advanced technique for CMFD is required. Even though AE is not novel a in CMFD and there are many advantages to AE characteristics, the adoption in CMFD analysis and practical operation is still awaiting research development.

## 1.3 Alternative Fuels

The research and exploration for discovering an alternative fuel to conform to the stricter environmental standards and solve increasing fossil fuel depletion has not stopped and became more of an issue several decades ago. In 1973, an oil embargo was imposed due to a sudden shortage of petroleum supply, which led the public to start to worry about energy depletion [1].

The combustion of fossil fuel has become a commonly accepted reason for increased global warming and other emission issues. The oxidation reaction in combustion inevitably produce carbon dioxide, SOx, NOx, COx, VOCs, particulate matters, mercury, selenium, and so on [1].

Thus, with the encouragement of governments and environmentalists, a series of correlative measures are being implemented, such as tax incentives, fuel price increases, stricter standards concerning emission gases, increasing requirements of environmental regulations, and so on. All these effects have led to the unprecedented development in alternative fuels.

The new developments in alternative fuels and energy have focused more on non-fossil sources or on mitigation and fixation of carbon dioxide in fossil fuel utilization [1]. The current trend for energy development is focusing on consumption mitigation, fuel utilization efficiency, carbon dioxide reduction, non-fossil source and so on. So consequently much attention is being paid to the renewable energy sources as they are long-term, sustainable and eco-friendly. Biofuel, biomass, hydropower, tidal, solar source, wind energy, geothermal energies and so on have been utilized instead of fossil fuel energy. Compared with the others, biofuel can be more readily used in diesel engines. Vegetable oil and food waste-based biodiesel has been used as alternative fuels for internal combustion engines with good performance and emissions[10]. Hence the increased usage of biofuels for vehicles can be expected.

Biofuels including bioethanol, bio-hydrogen, and biodiesel, can all be directly used in diesel engines and therefore is the alternative fuel we are focusing on in this research. Even though the attempts made to replace fossil fuels has had some successful results, associated damages and failures have also been experienced as well. Biodiesel is the residue of separating the fatty acid distillation obtained from the hydrolysis of a mixture of tallow, animal fat, rapeseed oil, palm oil, vegetable oil, glycerol and free fatty acids. Thus there are some unexpected residues and properties that appear in biodiesel, which is a major problem in using it [10]. However, in economic terms, it's a big challenge for industrial processes to separate a good quality biodiesel from the complex content bio-resource. With the demand of further development, it's necessary to research and improve the biodiesel characteristics for application otherwise engine damage and environmental issues will not be avoided.

A massive amount of research articles, books, monographs, patents, textbooks, reports, and brochures have been widely published, but lack in scientific consistency and technological comprehensiveness. Furthermore, most of the published articles focus on the justification and potential availability of alternative fuel sources rather than the environmental and technical readiness of the fuel's capacity as a principal energy source for the future post-petroleum era [1].

## 1.4 Project Aim and Objectives

The aim of this project is to develop a nonintrusive method based on AE to diagnose the fuel injection characteristics for an internal combustion engine running with alternative fuels. In order to fulfill this aim, the project has proceeded with the following key objectives in order.

1) To conduct a comprehensive review of engine diagnosis techniques;
2) To gain understanding of the common problems of using the most popular alternative fuels;
3) To analyse AE sources according to fuel injection dynamics;
4) To conduct tests to collect AE signals from fuel injections system;
5) To analyse AE signals with appropriate signal processing techniques;
6) To define effective features for online diagnosis ;
7) To analyse the differences of AE responses between diesels and biodiesel blends.

## 1.5 Thesis Outline

Chapter 1 introduces the demand of studying the influence of alternative fuel on the injector dynamics and proposes the aim and objectives in this study.

Chapter 2 presents the current CM techniques and their applicability in monitoring the injector dynamics.

Chapter 3 investigates the fuel injection system and the influence of alternative fuel on the injection systems. In addition, the possible AE sources from the injection process are studied as well.

In Chapter 4, a data acquisition system is setup to monitor the injection process of a four-stroke diesel engine system. A group of experiments are performed by changing the engine running loads, speeds and fuel types.

In Chapter 5, the characteristics of AE signals by using diesel fuel are studied in contrast with the conventional intrusive monitoring methods, such as cylinder pressure and injector pressure.

Based on the analysis in Chapter 5, the characteristics of AE signals for using blended biodiesel fuels (B40 and B100) are studied in Chapter 6.

Finally, conclusions and possible future work were drawn in Chapter 7.

# Chapter 2 Literature Review

## 2.1 Introduction

A diesel engine is a comprehensive assembly consisting of many components working under high dynamic loads. This leads to dynamic performance analyses that are never easy even using the CMFD. Many methods can be considered depending on different monitoring objectives, various measurement parameters, device settings, signal acquisitions, and data analysis processes. What follows is a literature review summary laying out current understanding in this area.

## 2.2 Condition Monitoring Information Sources

### 2.2.1 Cylinder Pressure

There are many pressure conditions that can be considered within engines, such as cylinder pressure, intake and exhaust pressures, fuel system pressure and so on. Cylinder pressure is always the primary factor to be considered in CMFD, because it shows the variety of combustion and the pressure situation, which can be directly used to analyze the combustion operation, thermal process, thermal efficiency of fuels and emissions.

The cylinder pressure is convenient to be obtained either directly or indirectly by various sensors. Conventionally the pressure transducer sensor is mounted on top of the cylinder to determine the instantaneous cylinder combustion pressure condition and is the most widely used direct measurement method. A variety of pressure transducers are available, and the Kistler piezoelectric pressure transducer is the most widely used. The accuracy of measurement is determined by two main factors, the thermal shock effect and the indicator passage effect. Although they can be eliminated or reduced by proper approaches, but the sensor is installed inside of the engine cylinder, it interferes with the engine operation and therefore is not suited in practical operations [12].

The vibration and crankshaft speed are two efficient methods to obtain the cylinder pressure for indirect measurement. The vibration method measurement is generally used in industry to obtain the cylinder pressure, with the structural signals by transfer function or using a Wiener-Hilbert filter to monitor the vibration signals. The crankshaft speed method measurement is convenient and cheap to obtain the cylinder pressure, therefore it's widely used in CMFD to detect and estimate the cylinder pressure. But these two methods are not suitable approaches in the case of low-speed engines and high engine loads; consequently some approaches have been successfully exploited for cylinder pressures monitoring with non-linear sliding observers [11].

The conventional cylinder pressure analysis technique is known as Fourier analysis, which was widely used for combustion interpretation in terms of the advantages of exhibiting a fairly qualitative correlation between combustion performance and precise cylinder pressure. However, much research has shown that the cylinder pressure signal is insufficient to provide the satisfactory information for modern engines because the information obtained from traditional methods contains overall spectral levels of cylinder pressure and radiated noise. Consequently some new methodologies have been developed as solutions. For instance, Payri proposed deconstructing the cylinder pressure signal into three subsignals, namely pseudo-motored, combustion and resonance excitation. Then depending on the engine speed condition, the signal could be broken down into these three subsignals respectively for further more accurate analysis. Indeed, the complex engine cylinder pressure is impacted by many influences; the overall profile of pressure signal and traditional analysis technique is insufficient to provide enough efficient information [12].

### 2.2.2 Instantaneous Angular Speed

Some previous works have successfully attempted to diagnose the combustion or pressure by the instantaneous angular speed (IAS) as the IAS is highly correlated with the torque acting on the in-cylinder pressure and the crankshaft, and in terms of filtrate much disturbed information in cylinder pressure and avoid the intrusive sensor installing. Normally, the IAS should be in a regularly periodic and uniform state, which means the expressed cylinder pressure, then remains in a stable state. Therefore, the faults come with a different pressure and also a change in IAS waveform [11]. According to the IAS waveform, not only the information in cylinder pressure can be provided, but also the vertically unbalanced inertial forces. It has been analyzed in detail of dynamic models in the work of El Hai and Fengshou Gu et. in 2003, and confirmed in experimental results. This work showed the domain contain related to the peak IAS is from the net torque, which comes from the state when one cylinder is in combustion and another is in compression [13]. Therefore, the IAS could be used to identify the faults affected on cylinder pressure and then developed further. Recent research using the IAS of engines has concentrated on improving the neural network and wavelet analysis for post-processing of the IAS signals.

### 2.2.3 Vibration

Depending on the vibration characteristics, there are two type of vibrations, which are forced vibration, and free vibration, and only the forced vibration is typically related to the issue under discussion as free vibration is just a self-excited phenomenon. Forced vibration is caused by vibratory motion and it has been used to analyze dynamic motion and employed as a main technique for CMFD for many years. The vibration transducer is conducted independently, based on the principle of applicability, and only typical failures could be determined with the detection of obvious symptoms or indications, however the vibration analysis technique can be helpful to improve the analysis and detect inconspicuous or potential failures. Nevertheless the vibration signals that come from an engine assembly with many components, which produces a vibration spectrum in different frequencies, can make diagnosis difficult to extract and to evaluate what is happening. Hence the signal process technique is very important in identifying relevant information from the various components events. The time domain, frequency domain, shock pulse, and sound intensity techniques for vibration data analysis have been developed and are widely used in CMFD and industry today, and many signals processing algorithms can be employed to run operations, such as Fast Fourier Transform (FFT), Neural Network, and Wavelet analyses [15].

### 2.2.4 Acoustics

Acoustics is one of the newest applications employed for CM techniques and has been successfully carried out in a number of industries, and is more likely to be widely used in industry due to its advanced characteristics, in particular because of its non-intrusive operation. Airborne sound (AS) transducer is the most commonly used technique with the utilization of sound pressure waves measurement, and can provide additional information on the vibration and pressure signal for engine dynamic performance as well as the condition of the internal components [7]. However the typical frequency range covered by acoustic AS is from 20Hz to 1MHz, and while the transducer range can be set depending on the conditions, this still can't prevent some noise influence from occurring during signal acquisition.

However as this vibration monitoring system is very popular in industry, multiple accelerometers must be positioned at various locations in the engine to accurately detect and identify any faults. The output can be very noisy and will therefore have to be passed through a signal processing system to get the desired output. Therefore, it's not very effective in sensing and recognizing the defects in diesel engines. Hence, the acoustic method has been developed in recent years to solve the defects in diesel engine diagnosis, because AS acoustic signals provide advantages in eliminating noise, as the signal-to-noise ratio (SNR) of AS signals is much higher than vibration or pressure [14]. The higher SNR of AS is due to the AS frequency being much higher than vibration, which means the influence on stress waves has a lesser effecting the signal than in a longer distance spread. The most unfavorable issue of AS is that background noises are still unavoidable, however the AS technique is still significant in being employed in engine diagnosis. In addition, the convenience and the non-intrusive method of AS measurement has many advantages for use in industrial practice.

### 2.2.5 Acoustic Emission

The acoustic emission (AE) is a kind of elastic wave, which rapidly radiates as an acoustic wave because of the irreversible changes that occur in solid internal structures. Therefore an instantaneous elastic energy will be released on the material surface when a small surface displacement is generated by an elastic wave. Based on this principle, the AE transducer can detect the rigid motion signal without many other influences. According to this phenomenon, when mechanical events produce impacts, cracks and even dynamic flows this will generate AE signals which will spread to the surface to be obtained. The AE technique in diagnosis is based on this phenomenon in order to monitor and identify the malfunction in objective material or structures.

In recent years, many developments have been attempted for AE transducer technique and signal processing methods to optimize the signal obtained and the analysis method. Tremendous progress and benefits were achieved for CMFD in applications, because the AE technique conquered many difficulties and defects for using the conventional techniques in CMFD. For instance, the inaccuracy and limitation of vibration monitoring. Even though the AS can provide additional information, the background noises and other disadvantages are still big imperfections, and it's more especially easily contaminated by the noise from cylinder exhaust events. But the AE signal has very high SNR due to its extremely high frequency. Also due to the higher frequency that can enhance the damping distance of elastic waves, the extremely high frequency of AE compared to other signals can overcome the noise influence from long distances. Hence the development by AE is essential for minimizing the noise disturbing in engine performance analysis and diagnosis [7], [14].

As AE has the great advantage over pressure and vibration techniques in CMFD especially as its SNR is much higher than all the others, the potential of its application in the practical industrial setting is enormous, in particular in non-incursive CMFD conditions and long distance detection. However the rigid guarantee of signal quality needs to be ensured certainly from the object surface to sensor, thus using high vacuum grease as a coupling is necessary to maintain signal conductivity [14].

## 2.3 Data Analysis Techniques

According to numerous signal processing techniques and algorithms that exist for mechanical diagnosis, an appropriate approach is required to suit investigational data demand. Three categories can be summarized for data acquisition - value type, waveform type and multidimensional type. Value type data is a single value collected in a specific time; waveform type data is collected in a time series; and multidimensional type data is multidimensional and collect in a time epoch. In CM the most common waveform data are vibration signals and acoustic emissions, while others are ultrasonic signals, motor current, partial discharge, etc. Three categories are mainly used for waveform data analysis, time-domain analysis, frequency-domain analysis and time–frequency analysis. A summary of these will be outlined next [15].

Before data analysis, a cleaning step is needed first to eliminate or decrease noise disturbance and errors, especially the event data. However, it needs to be manually operated, with the help of graphical tools. Various signal processing techniques have been developed to more easily analyze and interpret the CMFD and, in practice, the raw images captured from raw signals are usually used for feature extraction, but immediate information for fault detection is unavailable. Therefore, image processing combined with waveform processing sometimes can achieve better results and interpretation [15].

### 2.3.1 Time Domain

The time-domain analysis is directly based on the time waveform itself and has been widely used to determine impedance values along a transmission line and evaluate engine faults. The traditional time-domain analysis calculates characteristic features from time waveform signals as descriptive statistics such as mean, peak, peak-to-peak interval, standard deviation, crest factor, high-order statistics: root mean square (RMS), skewness, kurtosis, etc. These features are usually called time-domain features [15].

There are many time-domain analysis techniques to analyze waveform data for machinery fault diagnostics and a popular time-domain approach is time synchronous average (TSA). The TSA uses the ensemble average of the raw signal over a number of evolutions in an attempt to remove or reduce noise and effects from other sources, so as to enhance the signal components of interest. TSA is given by [15]:

$$\bar{\mathrm{s}}(\mathrm{t}) = \frac{1}{\mathrm{N}} \sum_{n=0}^{N-1} s(t + nT), 0 \leq t \leq T \tag{1}$$

where s(t) is the signal, T is the averaging period and N is the number of samples for averaging.

More advanced approaches of time-domain analysis apply time series models to waveform data. The main idea of time series modeling is to fit the waveform data to a parametric time series model and extract features based on this parametric model. The popular models used in literatures are the autoregressive (AR) model and the autoregressive moving average (ARMA) model. An ARMA model of order p,q, denoted by ARMA(p,q), is expressed by [15]:

$$x_t = a_1 x_{t-1} + \cdots + a_p x_{t-p} + \varepsilon_t - b_1 \varepsilon_{t-1} - \cdots - b_q \varepsilon_{t-q} \tag{2}$$

where x is the waveform signal, $\varepsilon$'s are independent normally distributed with mean 0 and constant variance $\sigma^2$ , and $a_i$, $b_i$ are model coefficients. An AR model of order p is a special case of ARMA (p,q) with q = 0. Poyhonen et al. applied AR model to vibration signals collected from an induction motor and used the AR model coefficients as extracted features.

### 2.3.2 Frequency Domain

Frequency-domain analysis is based on the transformed signal in frequency domains. Compared with time-domain analysis, frequency-domain is easier to identify and isolate certain frequency components of interest. The most widely used conventional analysis is the spectrum analysis by means of FFT. The main idea of spectrum analysis is to either look at the whole spectrum or look closely at certain frequency components of interest and thus extract features from the signal. The most commonly used tool in spectrum analysis is power spectrum. It is defined as $E[X(f)X*(f)]$, where $X(f)$ is the Fourier transform of signal $x(t)$, $E$ denotes expectation and "$*$" denotes complex conjugate. Some useful auxiliary tools for spectrum analysis are graphical presentation of spectrum, frequency filters, envelope analysis (also called amplitude demodulation), side band structure analysis, etc. Hilbert transform, which is a useful tool in envelope analysis, has also been used for machine fault detection and diagnostics [15].

Despite the wide acceptance of power spectrum, other useful spectra for signal processing have been shown to have their own advantages over FFT spectrum in certain cases. Cepstrum has the capability to detect harmonics and sideband patterns in power spectrum. Among them, power cepstrum, which is defined as the inverse Fourier transform of the logarithmic power spectrum, is most commonly used. High-order spectrum, i.e., bispectrum or trispectrum, can provide more diagnostic information than power spectrum for non-Gaussian signals. The high-order spectrum is also called high-order statistics due to the fact that bispectrum and trispectrum are actually the Fourier transforms of the third- and fourth-order statistics of the time waveform respectively. Bispectrum analysis has been shown to have wide application in machinery diagnostics for various mechanical systems such as gears, bearings, rotation machines and induction machines [15].

Generally speaking, there are two classes of approaches for power spectrum estimation. The first one is the non-parametric approaches that estimate the autocorrelation sequence of the signal and then apply Fourier transform to the estimated autocorrelation sequence. The second class includes the parametric approaches that build a parametric model for the signal and then estimate power spectrum based on the fitted model. Among them, AR spectrum and ARMA spectrum based on AR model and ARMA model, respectively, are the two most commonly used parametric spectra in machinery fault diagnostics [15].

### 2.3.3 Time and Frequency Domain

One limitation of frequency-domain analysis is its inability to handle non-stationary waveform signals, which are very common when machinery faults occur. Thus, time–frequency analysis, which investigates waveform signals in both time and frequency domain, has been developed for non-stationary waveform signals. Traditional time–frequency analysis uses time–frequency distributions, which represent the energy or power of waveform signals in two-dimensional functions of both time and frequency to better reveal fault patterns for more accurate diagnostics.

Short Time Fourier Transforms (STFT) or spectrogram (the power of STFT) and Wigner–Ville distribution are the most popular time–frequency distributions. L. Cohen reviewed a class of time–frequency distributions which include spectrogram, Wigner–Ville distribution, Choi–Williams and others. The idea of STFT is to divide the whole waveform signal into segments with short-time window and then apply Fourier transform to each segment. Spectrogram has some limitation in time–frequency resolution due to signal segmentation. It can only be applied to non-stationary signals with slow change in their dynamics. Bilinear transforms such as Wigner–Ville distribution are not based on signal segmentation and thus overcome the time–frequency resolution limitation of spectrogram. However, there is one main disadvantage of bilinear transforms due to the interference terms formed by the transformation itself. These interference terms make interpretation of the estimated distribution difficult. Improved transforms such as Choi–Williams distribution have been developed to overcome this disadvantage [15].

Time-frequency analysis of engine data combines both domains for a more complete representation of engine state, describing the evolution of the spectral content of a signal through time. The development of analyzing non-stationary signals of time-frequency technology includes the widely used STFT and the wavelet transform. The

STFT capture the frequency characteristics by a sliding window, as a function. The resulting spectra are in correspondence with the duration of the window. But the limitation between the time and the frequency resolution is an inherent drawback of STFT. The wavelet transform is similar to the STFT, however an improvement is achieved with higher frequency resolution and sharper time resolutions. Wavelet analysis is suggested for constructing a model of normality in both frequency and time. The wavelet transform represents a signal in terms of a family of wavelet basis functions, shifted in time and scaled in frequency. These basis functions are typically irregular in shape, making them suitable for the analysis of non-stationary signals with sharp changes, and compactly supported in time, enabling localization of a signal's features in time [16].

Another transform for time–frequency analysis is the wavelet transform. Unlike a time–frequency distribution, which is a time–frequency representation of a signal, wavelet transform is a time-scale representation of a signal. Wavelet theory has been rapidly developed in the past decade and has wide application. Time-frequency analysis of engine data combines both domains for a more complete representation of engine state, describing the evolution of the spectral content of a signal through time. Wavelet analysis is suggested for constructing a model of normality in both frequency and time. The wavelet transform represents a signal in terms of a family of wavelet basis functions, shifted in time and scaled in frequency. These basis functions are typically irregular in shape, making them suitable for the analysis of non-stationary signals with sharp changes, and compactly supported in time, enabling localization of a signal's features in time [15], [16].

One main advantage of wavelet transform is its ability to produce a high frequency resolution at low frequencies and a high time resolution at high frequencies for signals with long duration low frequencies and short duration high frequencies. Another advantage of wavelet transform is its ability to reduce noise in raw signals. Wavelet transform has been successfully applied to waveform data analysis in fault diagnostics of gears, bearings and other mechanical systems. Recently, more extensive applications of wavelet transform for signal processing in machine condition monitoring and fault diagnostics have been attempted successfully [15].

# Chapter 3 Dynamic Responses (AE) of Fuel Injection Systems and AE Based Diagnostics

## 3.1 Fuel Injection System

Figure 3.1 shows the general process structure diagram of a distributor pump fuel injection system. In the diesel engine, fuel is inhaled from the tank by the distributor rotary pump and goes through the fuel filter firstly to leach the particle and debris in the fuel. Then it goes into the pump to be distributed to each injector pipe at a very high pressure and leads to the nozzle inject where a high-pressure injection is made rapidly in the cylinder. The rest of the fuel left in the injector will go back to the fuel tank through a fuel return pipe. In the figure, yellow colour shows the fuel path line, and the red colour shows the high-pressure operation process in it.

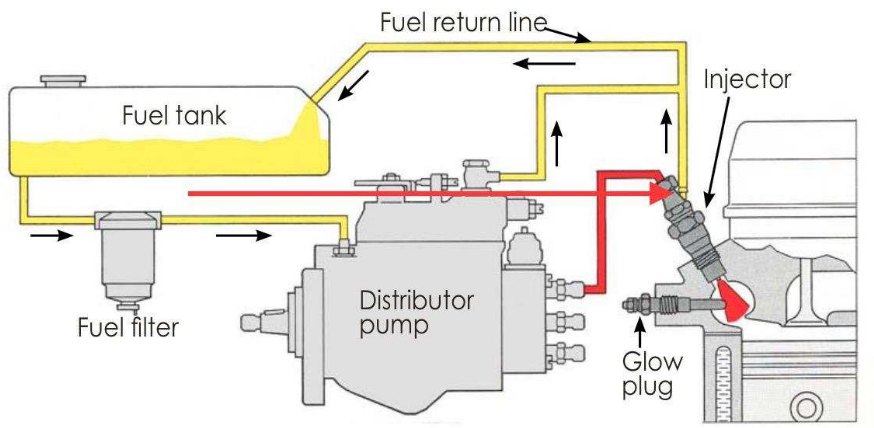


**Figure 3.1 Schematic diagram of a distributor pump fuel injection system [17].**

Figure 3.2 is a schematic of a common rail fuel system layout in diesel engines. The use of a common rail fuel system is a common tendency in modern engine nowadays. The general working principle as the same as the paragraph above, but for a multiform fuel delivery process that delivers from the pump to injector. A common rail system uses an electric or gear pump to provide the fuel that goes through a high-pressure pipe to arrive at a common rail pipe initially, and then goes to a proper injector valve. There are also some differences for the filtration and fuel return process. The fuel is inhaled to a pre-filter in the tank firstly, then it is pumped go through a filter to go to a high pressure pump, after that, conveying the fuel to the common rail. And there are two sources for the rest of the fuel, one is from the injector and the other is from the common rail. The electric supply pump is widely used on many vehicles, and the gear pump is applied on all other applications. In this schematic diagram, the yellow colour express the fuel path line, and the orange colour express the high-pressure pipe part [17].

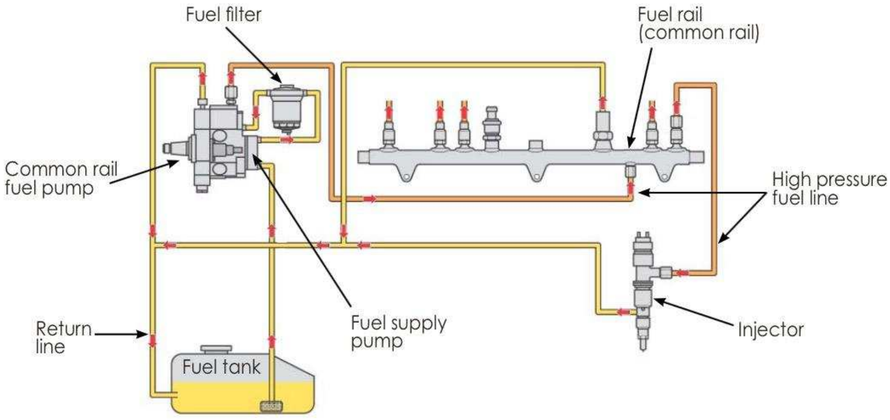


**Figure 3.2 Schematic diagram of a common rail fuel injection system [17].**

In order to ensure the low-pressure fuel circuit is properly operated before starting the engine in a fast engine, the electric fuel supply pump is set in the fuel tank to ensure it is charged while the instantaneous ignition is started. On the other hand, the gear supply pump is located at the back of the high-pressure common rail pump, which is run by the input shaft. The gear supplied pump is composed of the shaft, vane feed pump, gear, cam plate, cam disc, roller, spring, control sleeve, cut-off solenoid, plunger and delivery valve [18]. The structure illustration is shown in Figure 3.3.

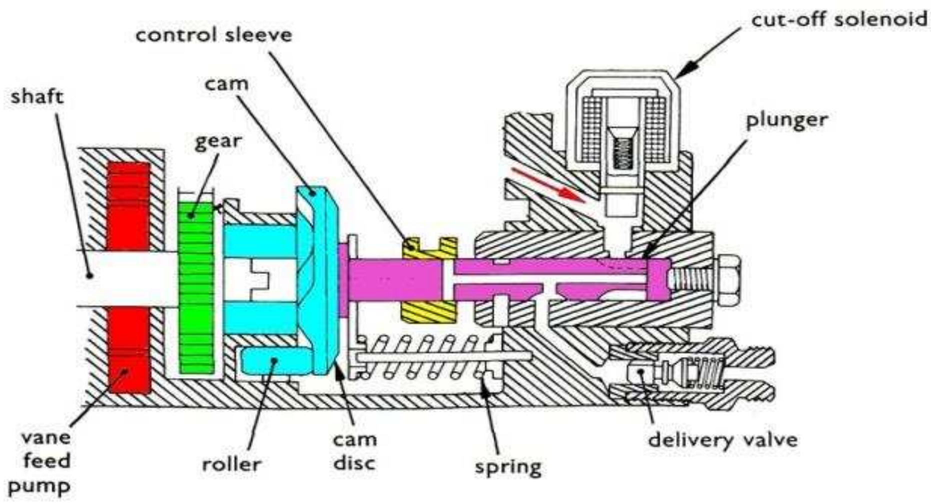


**Figure 3.3 Mechanical of a rotary distributor FIP of diesel engine [18]**

The fuel injector is a mechanical assembly, which can complete the fuel injection into a combustion engine chamber at a high pressure; it contains two main parts generally. A schematic diagram is shown in the Figure 3.4 below. The lower part includes nozzle body and the needle valve assembly, and the upper part includes a valve spring and a preload adjustment assembly, which is composed of a screw adjustment sleeve and capnut or simply a spacing shim more usually. The spring thrust transfers the compressive load from the high-mounted spring to the spindle, which leads to the injector needle valve in a closed state. This is the description of the direct injection, and the only difference in the indirect port injection is the fuel is sprayed into an intake plenum port. Furthermore, there are three basic types of injector nozzle for both injection systems, the pintle type already mentioned, the second is the hole and the third the two-stage, including Pintaux type [17].

The general injector structure is shown in Figure 3.4 [19]

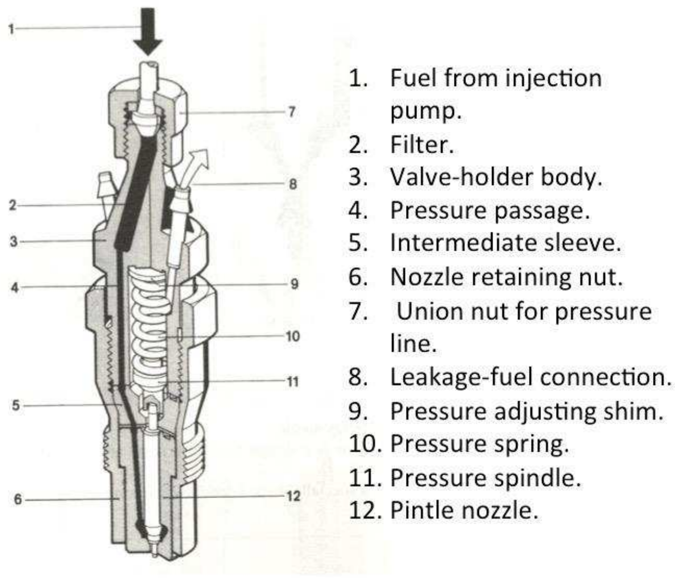


**Figure 3.4 Nozzle holder with pintle nozzle. [19]**

Many injectors have a pre-compressed coil spring because a nozzle spring bears down on the upper end of a needle valve to make sure the pintle seat and the nozzle is sealed [20]. When the leakage fuel goes into the injector chamber, the elasticity of spring and hydraulic force can block the pintle on the seat and the leakage in the chamber. Then, the leakage can go back to the tank or pump via the fuel return pipe.

A common rail injector dynamic working principle is the same as the conventional injector, whereas the injection is controlled by the on-board computer in the engine, which means the injection parameter and feature are accurately determined by the computer.  There are three processes of an injector working operation, which are No Injection, Start of Injection, and End of Injection. Figure 3.5 (a) shows the graph before injection start, and Figure 3.5 (b) shows the point of injection [20]. Generally, the fuel goes inside of the injector chamber at a very high pressure and lifts up the needle to open the nozzle valve to spray the fuel rapidly, which is assured by a pressure form of 50 to 280 bars usually. Furthermore, the initial lift rate is also influenced by the valve seat angle and width. The highest injection pressure is provided with the help of turbocharging and the indirect injection engine provides the lowest pressure injection generally. It can ensure the high pressure for needle dynamic performance and the injection distribution and penetration in proper operation in the direct injection engine, otherwise any dribble or in-proper injection can cause deposits which obviously are not desired. For indirect injection engines, therefore, because of the small diameters of their combustion chambers and very high velocities of swirl, such very high pressures are not only unnecessary but also undesirable. As regards the capacity of the pump to supply the engine with fuel, the important criterion is the mean effective injection pressure.

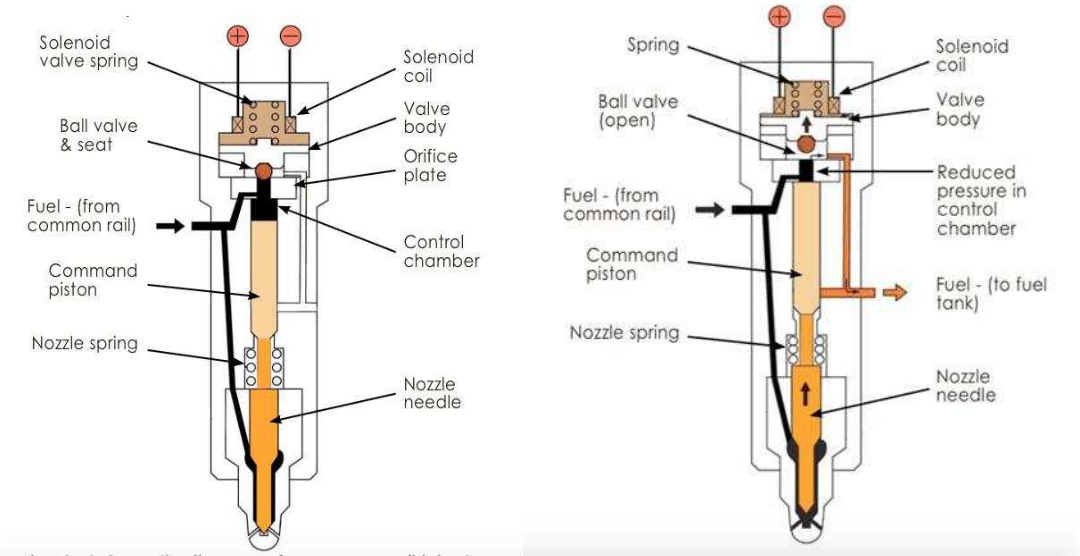


**Figure 3.5 Schematic diagram of a common rail injector showing (a) before injection (b) showing injection happening [17].**

The high velocity of flow through the valve seating area, together with the tendency for evaporation to start, atomises the fuel. However, the rate at which it can be delivered and the pattern of the spray are determined by the effective cross sectional area, length and shape of the short passages past the valve head or through the hole or holes in the tip of the nozzle. In a pintle type nozzle, most of these parameters are to a major extent a function initially of the profile of the pin-like extension of its end, or pintle [20].

The injector is a very important assembly because of its direct performance effect on many parameters. The injection spray in a proper time, fuel amount, spray form, pressure and velocity determine the fuel atomising, air and fuel mix ratio, pressure changing ratio, combustion efficiency, power output, emission situation and so on. Also an accurate injection determines the appropriate combustion process and ending time, which prevents premature and deferred injection as well as cause remains or after-injection, which is a main source of carbon deposit, poor power efficiency and other failures [20].

## 3.2 Fault Modes of Fuel Injection Systems

The diesel engine is a very stable assembly, which can work thousands of hours without any failure in some cases. But the appearance of problems and potential failures still need monitoring and diagnosis to detect and solve in time before it leads to breakdown and causes danger or economic losses. A common checking and turning of the fuel injection valve timing and exhaust or inlet valve clearance is usually used for small engines up to the largest units. But it's not a convenient maintenance solution, as it costs a lot of time and the dismantling of components also leads to potential faults. In some situations, such as marine performances, the technical state of maintained mechanism is worse than the situation before overhaul. Therefore maintenance, prediction and diagnosis can require more advanced and reliable procedures. One of the ways to solve these problems could be using vibro-acoustic diagnostic methods [21].

Figure 3.6 shows the faults ratio according to engine systems and components, and in a report by Exergy Engineering and Afton Chemical marketing [22] recorded the wear rate of modern common-rail diesel injectors to be double compared to past readings with injector fire occurring two or three times in each operation cycle rather than just the once previously. That heavy increased the injector failure opportunity even the production property of injectors has developed a lot. Another report from Afton Chemical’s North American Marketing Manager, David Cleaver, shows the injector failure is highly associated with fuel property, which is the key fact to determine the three major reasons of injector failures, which are excess wear, abrasion, and deposits. Therefore, two aspects determine the diesel injector faults, the soundness of mechanical structure in the injector and the property of the running fuel through the injector.

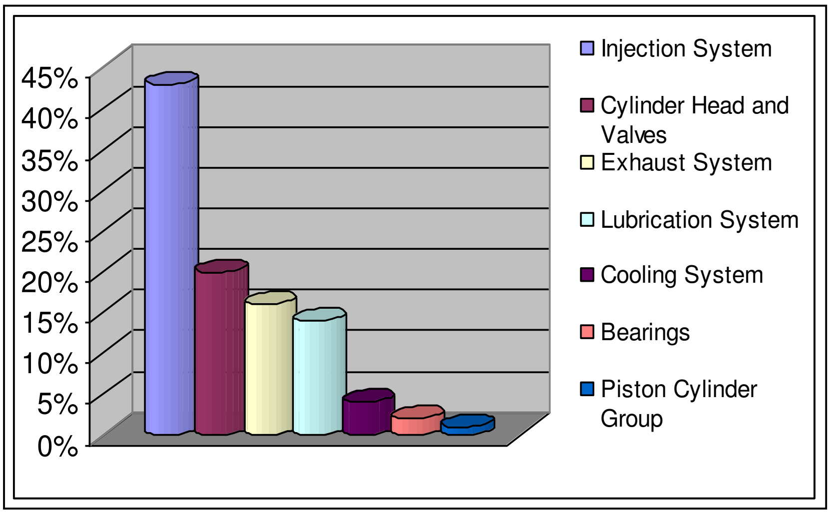


**Figure 3.6 The principal faults arising in diesel engines [9].**

According to the Exergy Engineering's report [22], there are five major reasons of mechanical failures for injectors failing. The internal leakage failure leads to cranking that can't achieve the desired velocity, hence the cranking time can't reach the required level in order to start on time. It also leads to a low-pressure value of injection pressure that leads to the injection and engine ignition being hard to start. The wearing of the injector ball seat, incorrect nozzle clearance, fuel feed pipe leakage, blowing internal high pressure seal, nozzle body cracking or injector body cracking all could be the reason of this failure. So the Exergy Engineering report suggests not to use improperly designed or manufactured injector components from remanufactured or aftermarket production, nor to mix nozzle needles as they are matched to the body and moving one from another can result in excessive clearance or improper needle lift and, consequently any certainty in ensuring the stability of the appropriate mechanical structure; on the other hand, for maintenance aspect, ensuring that the fuel system is clean, keeping fuel filters clean, avoiding the metallic burrs of fuel system replacement parts, using reliable fuel sources, avoiding filling from portable construction fuel tanks, avoiding overly aggressive tuning that increases rail-pressure and injector pulse widths, do not remove pressure-limiting devices from the system.

The no injection failure is one of the major injection failures, it could be caused by debris or a rust plugged nozzle, stuck armature, stuck nozzle needle, incorrect stator rate, cylinder compression lacking or other mechanical problems [22]. As the fuel injection performance is determined by computer analysis, which is decided by the crankshaft rotational speed and the fuel delivery amount, when the computer does not receive an expected crankshaft speed, which is slower or faster than anticipated, the fuel injection will be increased or cut to balance the crankshaft speed. This leads to a poor cylinder contribution and ECU fault. So keeping the fuel systems clean, changing filters, purchasing a reliable fuel source, and avoiding filling from portable construction fuel tanks are very important to refrain from this failure. If a vehicle will be in storage for a long time, prevention should also be considered to avoid internal varnishing and corrosion of internal components.

Excessive injection will lead to the phenomenon of idle smoke, excessive balance rate, banging, over power contribution, improper running and so on, which brings excessive emission temperature and hydraulic conditions to cause detriment to the engine. This failure occurs because of improper injection, typically the poor end of the injection cutting off. Except for the fuel supply system issue, as a precise device the injector components wear and faults become the major failure reason [22]. The wearing and cracking of the injector ball seat, nozzle needle seat, nozzle, and needle all can give rise to over injection, and however the performance requirements for them are very rigid. Even some tiny debris and carbonization deposits will impact on the injection. Hence proper maintenance to keep the injector chamber, fuel system and filter clean and the replacement of worn components are important to avoid this failure.

In the precise injection process, the unstable fuel pressure, incorrect nozzle needle operation and improper components structure (wearing, cracking, missing, unsuitable component) can easily cause injection rate failure [22]. Then an improper combustion, poor cylinder balance, inordinate emission, unsuitable temperature, disorganized vibration may occur engine performance issue or damage. Using reliable fuel sources can effectively decrease the wearing, deposits and damage from happening to the injector nozzle, which can be a commonly faulty part in injection failure. The components used in fuel systems such as metallic burrs and wire-brushed nozzles in cleaning also help avoid faults from occurring.

Incorrect injection timing and duration failure is a high ratio occurrence for engine injectors and is usually caused by the incorrect fuel pressure, injector components wearing (typically nozzle and ball seat), incorrect injector assembly, components missing and incorrect timing of injector needle lift motion. This can be avoided by replacing the worn injectors in time and by using proper injectors from reliable sources.

An appropriate fuel injection advance angle is highly associated with engine performance, which dramatically and directly influences the combustion process and emission conditions. A large injection advance angle will lead to the cylinder temperature being in a low state and the fuel distribution and mixture process in a poor state, which increases the preparation time for combustion and the injection amount, the power output and speed are also determined in an unstable poor condition. Otherwise, a small injection advance angle leads to an incomplete combustion at the top dead center (TDC), which increases the combustion period and decreases the output efficiency. Furthermore, the either incorrect injection or incorrect distribution causes carbon deposits that can, in future, accompany more failures.

Fuel injection advance angle is always sensitively influenced by the injection correlative wearing parts, and leads to serious influence in engine performance. An accurate and convenient measurement for it is desirable in diesel engine diagnosis. In much conventional research, such as Zhiqiang Wang's work [23], he used an oil pressure sensor on the injection pipe nozzle to extract the analysis the injection state and identify the injection advance angle. But a new method, which he presented, achieved the nonintrusive detection for the diagnosis of fuel injection advance angle in diesel engines.

And according to the already mentioned report by Afton Chemical’s North American Marketing Manager, David Cleaver, injector failure is highly associated with the fuel properties [22]. Sulfur is contained in natural lubricant that is refined from crude oil and widely used in fuel systems before. As the sulfur can easily destroy diesel particulate filters, the ultra-low-sulfur diesel has gradually been used instead, and is now mandated in all diesel fuel separation processes. But sulfur division also decreases the lubrication as well, and so less lubrication has been accompanied with larger wear scarring. So additional lubricities additives have been added to maintain the lubrication state, to avoid premature wearing.

However, the wear also comes with the abrasion by fuels, which is determined by inclusions, such as small amounts of impurities and particles. Even in the highest-quality diesel fuels, they are still unavoidable because the size of these particles size are very tiny as in microns which can easily go through all the fuel filters in engine [22]. However while these impurities are very small, the abrasion caused is a still serious impact for the very rigid sensitive injector. Over time, the impact on the fuel spray pattern will be enhanced seriously enough to influence cylinder combustion and even cause obvious influence to engine performance.

Afton Chemical reported the excessive accumulation of deposits has the highest appearance rate of modern injector failure reasons today [22]. The deposits appearing in the internal chamber or external (usually external nozzle) could all cause failures. The external injector deposits are mostly caused by incomplete combustion, so the coking deposits cumulate around the nozzle tip. It directly deranges the spray and combustion process, and related failures can then happen in future. This can be easily observed by the low power output or fuel economy efficiency, because of the lower combustion efficiency. A quick diagnosis and the usage of solubilizers or detergents can solve and prevent the injector failure. Particularly in the last five years, a new kind of internal deposit has appeared typically in newer engines with precision injection systems, but can even form in virtually any type of diesel engine. It's greyish and visually similar to the coking deposit, but is lighter in weight. The deposit buildup has appeared in internal injector components, such as the pilot valve and the needle, which has a fatal impact on the injector.

From another area of research, many studies related to the microstructure of injectors showed that cavitation is a major cause of injector failure in high operating pressure modern diesel engines, as it the primary break up reason of internal injector nozzles. Because of these widely known characteristics, the internal nozzle flow on the spray and its atomization can cause a strong impact, in particular the mass flow collapse of cavitation in the nozzle holes. It enhances the fatigue cracking of the nozzle by the impact and cavitation damage on the internal surface. On the other hand, it also increases the spray cone angle, which is expected to bring a better air-fuel mixing ratio [24], [25].

Cavitation is a result of liquid erosion and occurs due to cavities or bubbles nucleating and growing in a fast liquid flow or vibrating liquid flow, which is caused by local liquid pressure decreasing rapidly. These bubbles collapse and lead to a drastic explosive shock on the surface of material when they come across a high-pressure zone [24]. After this impingement, deformation and pitting will be left on the surface and connect with each pit to produce roughening and material loss of the surface, which leads to a failure eventually. This phenomenon is known as cavitation erosion, and the damage that is caused is known as cavitation damage. It’s similar to the damage caused by particle erosion, but easy to distinguish from the pits' size and shape, which are very localized by the characteristics of round micro-craters with larger and deeper grooves.

Nevertheless, in terms of the extremely small geometry of the nozzle hole, the conventional methods-based experimental and computational studies of the transient dynamic process are still not satisfactory. Even the experimental research results obtained from large-scale nozzle have affirmed the significant influence of injection from cavitation flow. Some computational fluid dynamics (CFD) based investigations have been attempted by creating a numerical model, but the simulation is difficult due to the limited data information, which is provided by the commonly used conventional CM techniques. The attempt of AE in this study showed potential capacity to provide a great deal of additional and accurate information for injector dynamic performance and, therefore, could be a solution that is worthy of further development [25], [26],

## 3.3 Influence of Alternative Fuels to Fuel Injection System

Alcohols, biodiesel and various other sources have been attempted to use as alternative fuels in internal combustion engines; therefore, failures have been correlated with the attempts. Much research has been carried out using alternative fuels and blends in combustion engines and the major failures that have appeared have been indexed into three different aspects: injection, combustion and emission. The attempts of using alcohols, vegetable oils, and biofuels will be discussed below.

Lubrication properties are an advantage of most biofuel but, on the other hand, are particularly poor in alcohols. This is important to remember in helping prevent premature failures, because the lubrication of injector, pump and other injection system components is relied upon through the fuel usage itself. Moreover, the high volatility of the alcohols can also cause vapor lock and cavitation [20].

Volvo, Scania and others have done trials, with the using methanol and ethanol as alternative fuels. Volvo experimentally installed two injectors, one for ethanol and the other for hydrocarbon fuel, in each cylinder of one of their engines. The engine had to be started on diesel fuel because of the low cetane number (poor ignitability) of ethanol. The auto-ignition temperatures of the alcohols, at about 1000deg K, are almost double those of diesel fuels. Ignition improvers can be used, but in proportions as high as 15-16%. For starting, even with the engine at ambient temperatures, high compression ratios and glow plugs would be required. The alternative of blending the two fuels would probably exacerbate cold starting difficulties for alcohol, as alcohol has a low cetane number. Blending it with diesel oil could offset this phenomenon. On the other hand, because of the lower energy content, if the power output demand is same, a larger injection quantity in each cycle is required than the operation with diesel fuels alone. As the load increased, diesel fuel was injected in increasing proportions until, at maximum power output, it amounted to 90% of the total. Under typical running conditions however, about 75-80% of the energy required to propel the truck was obtained from the ethanol [27], [28].

Vegetable oil has a higher viscosity but has 10% lower energy content than crude oil based equivalents, but otherwise their auto-ignition properties are much the same. The general problems in using vegetable oil are the carbon deposits and gummy deposits in the combustion chamber, the lower smoke limits and the filter blockage in cold weather. But a recent discovery by the Scottish Agricultural College found that by adding alcohol to rapeseed oil, glycerol is made to separate out and thus reduce the tendency of gummy deposits to arise in the engine [28], [29].

Also in using vegetable oils, emission of HC and NOx can be higher too. However, these might be overcome by a specific injector design for this fuel or the use of antioxidants, detergents and other additives. Scania found the NOx and particulate output with alcohol to be lower than with diesel fuels. However, aldehydes, the effects of which are not yet fully understood, were more prominent in the exhaust gases. On the other hand, alcohol has the advantage that the $CO_2$ produced during its combustion is taken back from the atmosphere for the production of more alcohol, on a closed cycle basis. Also, the cooler combustion obtained during operation with the ethanol injector reduced both soot and NOx emissions [28], [29].

After a two year test period with five buses operated exclusively over a distance of 1,000,000 miles, Proc et al. reported in 2006, that compared with pure diesel, the B20 alternative blend, which is the percentages of the biodiesel in the fuel are 20%, that was used led to a reduction in fuel economy and maintenance cost per mile. Also the results from the laboratory chassis testing on the CSHVC cycle demonstrated the entire pollutants emission profile reduced with the replacement of B20 blend fuel. A significant decrease of soot level in the lubricant was also found in this experiment. However the maintenance cost was higher for cylinder head and injector replacements due to the sterols content rate being higher in plant source biofuel. Hence the increased fuel filter replacement consumption is required to ensure lowerdeposit accumulation plugs on the injector and cylinder which, if not done, can cause more potential for failure and economic loss [30].

To economize the consumption of products derived from crude oil a 20% blend of alternative fuel with diesel fuel could be practical, even if the energy output is still lower as, on the other hand, the lower pollutant emission and smoke presents welcome benefits. Even when blended with diesel oil, the separation of blend fuel constituents could occur in cold weather and the alcohol-based blend has the disadvantage that they tend to absorb moisture, in which they dissolve and then separate out in the bottom of the tank as sediments. Otherwise, the water and bio-contaminants could cause corrosion and the microbial growth leads to further deposits buildup and contamination. Consequently, unless measures are taken to protect the metal components in the fuel system, trouble can be experienced with corrosion. The air fuel ratio required for their complete combustion is significantly lower than that for the hydrocarbon fuels, so the injection system has to be calibrated appropriately if combustion problems are to be avoided [10], [28].

As mentioned above, the influence of alternative fuel features is an important fact leading to cavitation in fluid dynamic performance. Jonas Galle et al. also summarized in their thesis, cavitation is the only failure in an injector used over a long time, but the viscosity and other characteristics also exacerbate the situation, such as in biofuel. Because the particles in the biofuel increases the micro-cracks that lead to heavy erosion, wear of materials, and then the damage produced is caused by cavitation [10].

Two experimental groups were performed with using wastage source biodiesel in two 8-cylinder engines separately, and more than 30 injectors were replaced during the test with a practical operation period from 50 to 1,500 hours. Premature injector failures were detected and evaluated. It was indexed that a direct consequence of the failures was an unsuitable element contained in the fuel, which was caused by particles and alkalis in major contamination components. Because biofuel raw source comes from animal fat, especially tallow, many agglomerated fatty acids particles in it melted when the fuel was heated. These particles mainly consisted of oxides of different alkaline metals, sulfur, iron and phosphorous. They increase the promotion of oxidation, agglomeration and polymerization such as AlCl and phospholipids, and cause a high tendency of clogging, corrosion and depositing [10].

Indeed, most of the problems no doubt could be overcome with further development. For example, additives might be used to combat deposit and gummy formation and cold weather, as well as the problems already mentioned. Moreover only oils already commercially available for other purposes have been used, so it is not beyond the bounds of possibility that some more suitable vegetable, currently growing unnoticed yet plentifully in the wild, might be discovered [28].

Scania, in the belief that currently no known fuels other than alcohol offer any long term potential as an alternative to diesel oil, ran practical tests with ethanol. They were undertaken in Brazil, where it is relatively easily produced in large quantities from forest and agricultural crops. The conclusion was that even there the cost of ethanol is too high for it to be acceptable for general use. Scania confirmed that, partly because the latent heat of vaporization of both the ethyl and methyl alcohols is so high, alcohols are difficult to ignite. Of the suitable ignition improver additives, nitrates are believed not to be a health hazard, but this has been difficult to prove, so polyethylene glycol might be a preferable alternative [28].

## 3.4 Acoustic Emission Sources of Fuel Injection System

As AE is a kind of elastic wave produced by the irreversible changes in the solid's internal structure and has many advantages in CMFD, consequently many difficulties of instantaneous dynamic processes detection can be monitored with the AE source in the injection system.

According to the fuel supply process, AE waves can be formed mainly by two physical mechanisms: mechanical excitations and fluid impulses. The conventional study is based on noise, which is the vibration source from engine operation. A summary of major factors are as follows [5]:

1) Noise from mutual mechanical impacts between components;
2) Noise caused by the combustion process and vibration phenomena;
3) Noise produced during intake and exhaust procedure.

**Figure 3.7 illustrates a schematic profile of the noise and vibration transmission in the engine to provide better understanding of the signal's source.**

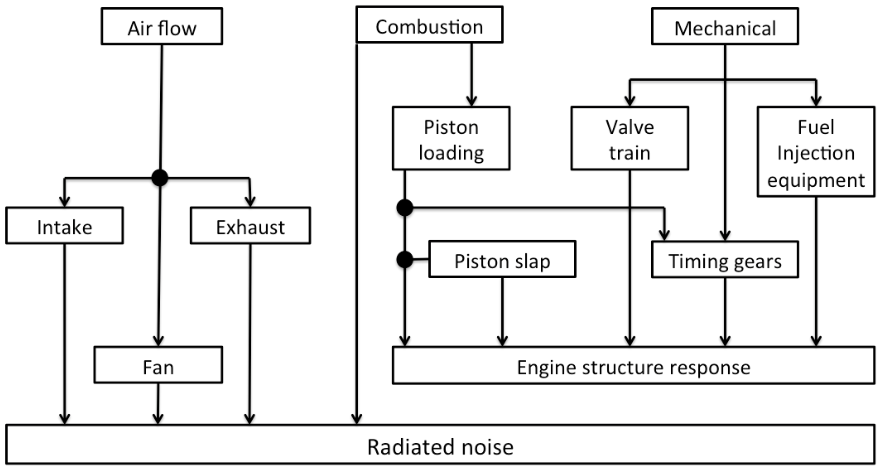


**Figure 3.7 The engine noise generations – a simple model [5].**

Over all, the noise is caused by several mechanical and thermal factors, which sometimes simultaneously affect different phases of the engine cycle. So the relative vibration could be produced by several sources that come from the combination of combustion and inertia forces. The main sources are the combustion process, inertia forces, pistons slaps, high pressure processes in the fuel system, impacts in fuel valves, impacts in the valve gear mechanism, gas flows in engine manifolds, oil flows in hydraulic and lubricating systems and others. As the installation location of the transducer sensor is a major factor in monitoring performance, then the amplitude and frequency setting can be adjusted to connect better with the sensor place condition [21], [31] and [32].

As the pump completes the fuel's delivery by the plunger's rotary and reciprocation in the chamber rotates the cam plate, this leads to fuel being pumped into the injector valve in a short time and at high pressure, which can arrive at a value of several hundred bars usually. Hence the injector nozzle can lift in an acceptable time. But it also sometimes be delayed or deranged by the damping and oscillation of fuels in the injector chamber. Furthermore, the oscillation is kept in a high value all the time, which can lead to a vibrational response occurring to the pump and injector. The delivery of fuel at high pressure and in a short period by pump can also lead to a strong vibration within the engine, which means the frequency and pressure of fuel delivery and fuel quality characteristics are highly correlated to the vibration and AE. Particularly, when using biodiesel, which has high density and viscosity, these are direct factors that can affect operational response. Therefore, the evaluation of internal dynamic impacts in different experimental samples can be analyzed and considered by this related factor [33]–[36],

The major AE signal source from valve motion are distinctly determined as impact source and dynamic source, which come from components colliding and air-fuel flowing [14]. In Jianming Liu's work [37], the accurate valve crash vibratory response signal of the needle valve closing, the usually difficult to measure timing was actually indexed. It was determined by the direct threshold detection and peak detection and was influenced by the double crash phenomenon of the injector needle valve. So an acoustic detection method was introduced and used in this paper to ascertain the start point and end point in acoustic signal that ensured the detection of the crash vibratory response signal and then the description of the needle valve closing timing, which is based on the comparability of the signal in acoustic technology and the vibration signal of cylinder. But the paper also mentioned that the influence of rapid fluctuation and unstable cavitation on needle crash vibration produced a weaker signal.

Tomasz Lus and some other researchers pointed out the main source of the predominant high frequency noise is the mechanical impacts produced by the moving parts in the engine or running cams [21]. During the injection, when fuels go to the high pressure pipe, the impacts of the moving parts in the pumps and fuel valves were produced by the motions in displacement, speeds of displacement and accelerations, which is a high frequency source of vibration and acoustic signals. Therefore, the needle moving, delivery process, fuel quantity, spray situation and so on are very important facts to analyse for injector performance. Signals from diesel engines could be analyzed in time/crank angle domain or in the frequency domain using the FFT. The frequency analysis is useful and the most frequently used for stationary signals. For the non-stationary signals generated by diesel engines the frequency content varies with time and in this case time-frequency or angle-frequency analysis tools could be used.

There are also much research based on high-speed video recording to examine and analyze the fuel's spray in injection systems, such like the research Crua did in 2002.

In Crua's research [32], he reported the direct influence of injector needles in the first injection stage, which was based on a test in the single-hole VCO nozzle. The fuel's spray distribution was influenced and delayed at the beginning, which is also a significant phenomenon for multi-hole nozzle injection performance analysis, especially when considering the first stage process adequately. The slug detachment of fuel was detected at the frequency of 6.8 kHz, and related to the modifications of temperature, pressure, liquid spray distribution, and other different injection conditions. Overall, these detections were due to the vertical oscillation of the needle of the injector [29].

As the most significant airflow is determined by the intake and exhaust flow in diesel engines, the air going through the valve is one of the AE sources. Therefore, the air from cylinder head to the injector is also an important AE source, which could produce a turbulent or cavitation flow in the nozzle and can cause a distinct signal in AE measurement. In terms of the spray performance and its atomization characteristics, these are distinctly determined by the nozzle internal flow character, while typical cavitation influence is also a concern, especially in modern high-pressure injectors [14].

In F.Payri's work in 2012, he investigated the cavitation effects on internal nozzle flow with cavitation modeling approaches and limitations, and pointed out cavitation causes the maximum velocity of liquid core increases. It was understood that the produced cavitation vapor along the nozzle wall reduced the friction, and then the liquid velocity increased. In the meantime, the vapor led to a reduction in the profile of liquid, which also lead to an increase in liquid velocity to complete the quantificational injection quantity. On the other hand, as the cavitation couldn't fill the whole channel, the friction between vapor fuel and liquid fuel occurred depending on the viscosity variety between the two surfaces. But these conclusions need further data based investigation and exploitation to be demonstrated and developed [25].

As mentioned above, Jianming Liu indexed the influence of rapid fluctuation and unstable cavitation on needle crash vibration and noted a weaker signal. But this paper's research is correlated with AE under alternative fuels, where AE is a more specific signal than vibration and the fluid dynamic performance is highly influenced by the type of fuel used. Particularly when the AE sensor is installed near the injector intake valve, the influence of cavitation in fluid dynamic performance will be a significant factor.

## 3.5 Theoretical Basis of Acoustic Emission Based Diagnosis

### 3.5.1 Advantage in Acoustic Emission Based Diagnosis

Usually the diagnosis for an injection system or engine performance is based on the vibration signals, and that can be observed within the crankshaft angle domain. But it is also easily influenced by many disturbances, especially the most widely used way, which is installing a vibration sensor at the cylinder head. Such as in Tomasz's work, he also set the vibration sensor at the cylinder head in his test, and indexed that the vibration signals was disturbed by the strong vibration from the combustion process in other cylinders and mechanisms. So the additional sensors, such as the rocker arms lift sensors, are necessary to indicate the correlation between signals and object motions, which is required to determine the disturbed vibration from other mechanism impacts. Moreover, the signal is limited as only one event in order to analyze in a proper signal selection method when the sampling frequency is high enough in order to make the time/angle axis stable. Hence, in order to synchronize the vibration signals Tomasz used a cylinder pressure signal as a reference signal. But he also explained it's hard to find the failure in the fuel valve when the engine has more than one nozzle in specific cylinder and multi-cylinder engines [21], [38].

In this thesis, the test was required to operate in a four-stork four-cylinder CI diesel engine, which means the conventional vibration based diagnosis is difficult to analyze such a complex situation. Moreover, as the vibration signals is highly influenced by the combustion process and other mechanism events as well as the short period between the injection ending and combustion starting, it is difficult to separate and acquire the determination of the sequence transients injection process in vibration signals. As the usage of AE in injection system has been attempted successfully, the AE based diagnosis will therefore be employed.

### 3.5.2 Previous Works Based on Acoustic Emission Diagnosis

#### 3.5.2.1 Diesel Engine Valve Clearance Detection by Using Acoustic Emission

In Fathi's research [14], a Ford FSD 425, four-cylinder, four-stroke in-line OHV, direct-injection CI diesel engine was used as the source of AE data. Based on previous research, given there were many influences on complex engine operations, in this research two locations were mounted by the AE sensor to collect the signal, which were the front of the cylinder head and the rear side. And vacuum grease was coated on the sensor to obtain effective signal conductivity from the measurement surface. A 0.8 mm (positive) exhaust valve clearance of the cylinder conditions was used as a significant fault condition for comparison.

In the angular domain analysis result, there was no significant difference in comparison to the AE signal result from the sensor (Sensor 1) that was positioned relatively far away from the faulty cylinder However it was clear to see that there was a significant difference in the result of the sensor (Sensor 2) that was positioned more closely, as shown in Figure 3.8 in different loads, which are 0Nm (a), 30Nm (b) and 60Nm (c). Because the AE wave propagation through the engine cylinder head will attenuate a little whilst passing along a transmission path from the AE sources to the position of the sensor, this small increase of attenuation originates from the increase in valve clearance. From the Sensor 2 result, the exhaust valve opening event was also easily identified for both healthy and faulty conditions by the AE signal amplitudes and timing differences. A delayed opening and advanced closing phenomenon of the faulty valve was indicated by experimental testing [14].

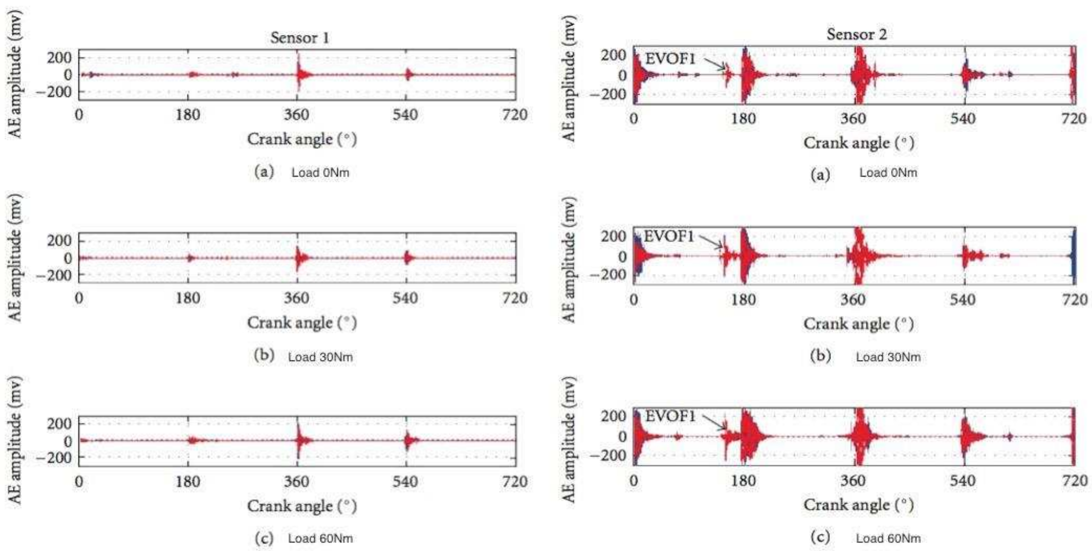


**Figure 3.8 Angular Domain AE Signal at Speed 1000 rpm for Different Loads and Sensor Location [14]**

From the frequency domain analysis, as shown in Figure 3.9 the AE signals were distinctly different between the healthy and faulty conditions and the lower amplitude of the faulty valve condition indicated that the reason for the faulty cylinder was less power output [14].

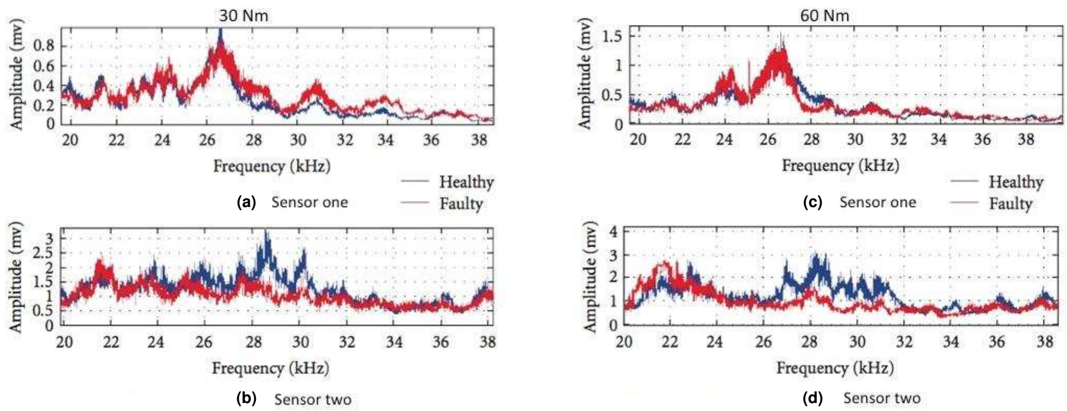


**Figure 3.9 Frequency Domain AE Signal at 2000 rpm for Different Loads and Sensor Location [14]**

The spectrum of measurement in this research confirms that the level of the AE signal is an important indicator of the diesel engine transient operation process, which proved AE could provide an effective solution for CMFD to detect the presence of faults in diesel engines. [14]

#### 3.5.2.2 Investigation of the Relationship Between Internal Fluid Leakage Through a Valve and the Acoustic Emission Generated from the Leakage

The AE technique can be used on valves to detect the qualitative leakage directly related to the AE signals when liquid and gas leak through valves. It has been widely used to estimation the gas and liquid phase in the oil, gas, chemical and petrochemical industries. But the qualitative leakage rate still needs large amounts of experimental results to find out the correlation with the AE signal. In Kaewwaewnoi's work [39], a further analysis and implementation based on theoretical relationship was developed to estimate the valve leakage rate by using AE technique. Based on fluid dynamics theories, he associated the high frequency sound powers (Ps) with the AE signal powers, as shown in Eq. (1):

$$AE_{RMS}^2 = C_0 \cdot \frac{1}{\alpha^5 \rho^3 D^{14}} \left(\frac{Q}{C_V}\right)^8 \left(\frac{P_1 S}{\Delta P}\right)^4. \tag{1}$$

where $AE^2_{RMS}$ is the AE signal powers, $C_0$ was the proportionality constant, Q is the volume flow rate ($m^3/s$), $C_V$ is the valve flow coefficient (dimensionless), ΔP is the pressure drop across valve (kPa) and S is specific gravity ($kg/m^3$). Other parameters $(\alpha, \rho, D, P_1, S)$ are constancy factors of the fluid and valve system. And the Lighthill's equation defines the Ps as:

$$P_s = \frac{\rho v^8 D^2}{\alpha^5}, \tag{2}$$

Therefore, a novel and inexpensive AE instrument was invented for predicting qualitative leakage rate using a microprocessor and derived relationship in his work.

In Kaewwaewnoi's research, a R15 AE sensor with 150kHz natural frequency was employed, and a 60dB pre-amplifier and a 10 MHz maximum sampling rate real-time signal analyzer served to synchronously record the AE waveform in the frequency domain between 0 and 1 MHz. The AE waveform was recorded and converted to AE parameter, $AE_{RMS}$, by a personal computer (PC). The experimental objects were two types of ball and globe valves for valve leakage systems, which are widely employed in industry [39].

From the results, it showed the sound waves for AE source propagated well in the water medium, but the R15 AE sensor obtained a water leakage peak over the 50-200 kHz operating frequency range. The experimental result also confirmed the characteristics influences based on the theoretical analysis, which means the relationship between valve sizes, $AE_{RMS}$, inlet pressure and leakage rate corresponded to the prediction of Eq. (1). In addition, the effect on AE produced by valve type was also determined, which led to the influence on liquid geometrical shapes [39].

### 3.5.3 Theoretical Results by Using AE Diagnosis

According to the dynamic injector performance principle and literature study [40], [41], the AE technique can provide an accurate real-time characteristics monitoring for the transient injection process, which can clearly record events when fuel is pumped in the injector nozzle - the needle arises by increasing fuel pressure, fuel injection is sprayed through the orifice and then the needle goes back to the nozzle seat. In addition, considering the cylinder operation and AE signals feature, the influences of combustion, airflow intake and exhaust-caused valve impacts, other mechanisms events also affect the AE signals. But it’s easier to decrease the disturbance and filtrate the events than using vibration signals, by choosing a higher sampling frequency. The effect of using alternative fuels could be observed clearly by AE diagnosis.

# Chapter 4 Test Facilities and Set Up

To evaluate the influences of alternative fuels to the injector, a group of tests are performed on a four-cylinder diesel engine system at the Automation Laboratory in University of Huddersfield. In this chapter, the engine system, data acquisition system and test procedures are explained.

## 4.1 Overall Test Setup Description

The advanced automotive laboratory engine available in the University of Huddersfield in UK is integrated with state of the art performance and condition measurement facilities. The engine system for experiment is shown in Figure 4.1. The engine under test is a four-cylinder JCB444 74kW diesel engine. The PC control system and data acquisition instrumentation were set up firstly to control the operation conditions and future signal recording. After this preparing stage, the engine was performed in various conditions with several different fuels under the control of computer program (CP) control system. During the test, injector AE signals, engine vibrations, oil pressures and so on were monitored and recorded by the data acquisition instrumentations.

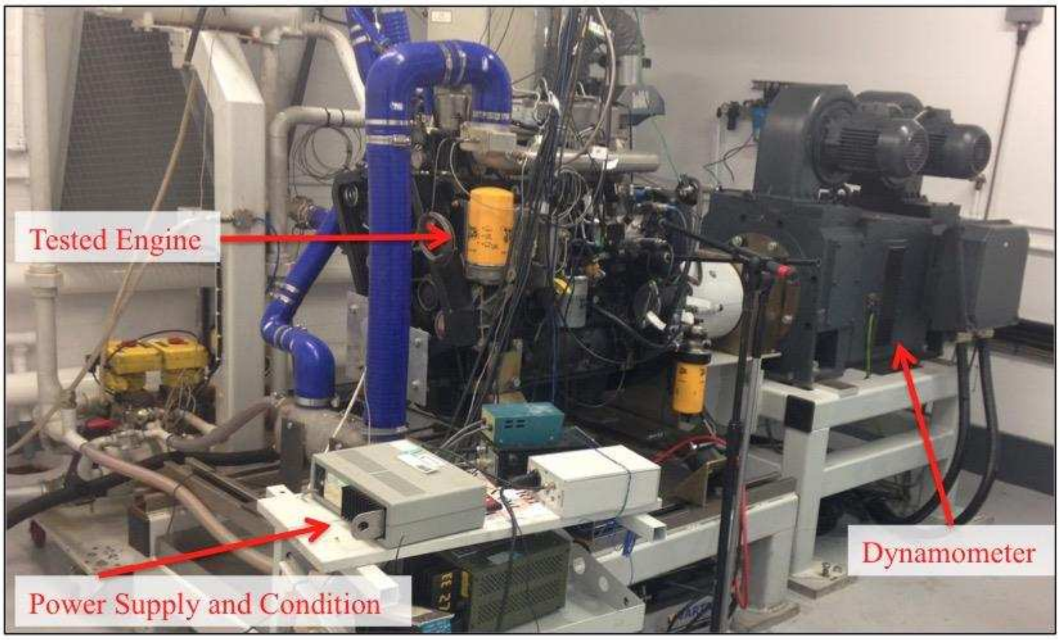


**Figure 4.1 The integrated laboratory engine system**

## 4.2 Engine Test Rig Description

### 4.2.1 Diesel Engine

The engine model under test is JCB444 TCA 74kW Diesel Engine, as shown in Figure 4.2. It is an in-line four-cylinder, four valves per cylinder, four-stroke, turbocharged direct injection and water-cooled engine. Its key specifications are illustrated in Table 4.1.

**Figure 4.2 The JCB444 TCA 74kW diesel engine**

**Table 4.1 Specification of JCB444 74kW Diesel Engine**

| | |
|---|---|
| Technical Code | JCB444 TCA 74kW(100hp) |
| Thermodynamic Cycle | Diesel 4 Stroke |
| Air Intake | TC |
| Arrangement | 4.4L |
| Nominal Bore | 103 mm |
| Stroke | 132 mm |
| Total Displacement | 4399 $cm^3$ |
| Valves Per Cylinder | 4 |
| Injector Firing Order | 1-3-4-2. |
| Cooling | Liquid |
| Compression Ratio | 18.3:1 |
| Maximum Rating*Gross Intermittent | 74.2 kW |
| At Speed | 2200 rpm |
| Maximum Torque | 425 Nm |
| At Speed | 1300 rpm |
| Maximum No Load Governed Speed | 2390 rpm |
| Nominal Idling Speed | 800 rpm |
| Emission Certification | EPA T2, EU St2 |
| Noise At Maximum Rating | 89 dBA 1m |
| Minimum Starting Temperature Without Auxiliaries | -12 $^{o}$c |
| Dry Weight | 477 kg |

The inlet and exhaust valve event information for this engine are presented in Table 4.2. Together with the injector firing order (1-3-4-2) from Table 4.1, the theoretical timings for four cylinders are calculated and illustrated in Figure 4.3, where the red numbers represents the cylinder number under combustion in the corresponding angle, blue number indicate the intake valve timing and the purple number denote the exhaust valve open and close angle.

**Table 4.2 Inlet and exhaust valve event information**

| | |
|---|---|
| **Inlet open angle** | **10° Before Top Dead Center (BTDC)** |
| **Inlet close angle** | **32° After Bottom Dead Center (ABDC)** |
| **Exhaust open angle** | **60° Before Bottom Dead Center (BBDC)** |
| **Exhaust close angle** | **10° After Top Dead Center (ATDC)** |

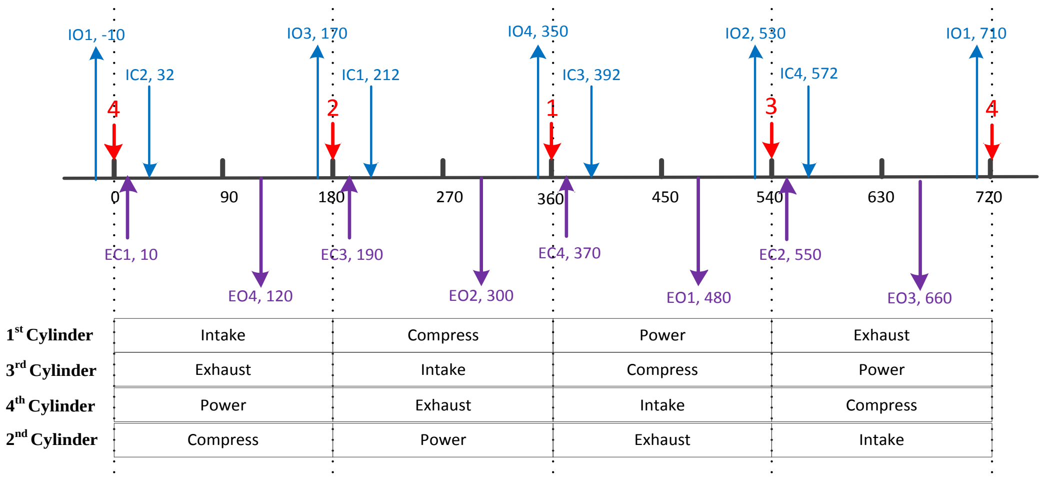


**Figure 4.3 Schematic drawing of combustion process related theoretical timing diagram**

### 4.2.2 Dynamometer

The alternating current (AC) dynamometer is employed to measure the speed, power and mechanical force information. The dynamometer used in the test (Figure 4.4), is a CED1401 200KW AC Dynamometer Quadrant Regenerative Drive with Motoring and Absorbing Capability dynamometer, and contains the speed range from 0rpm to 2200rpm with the resist torque from 0Nm to 400Nm. It integrates with speed measurement optical encoder and in-line torque meter.

The engine drive shaft or transmission is coupled to the dynamometer via suitable couplings and a drive shaft. When the engine is running, the dynamometer exerts a braking force on it.

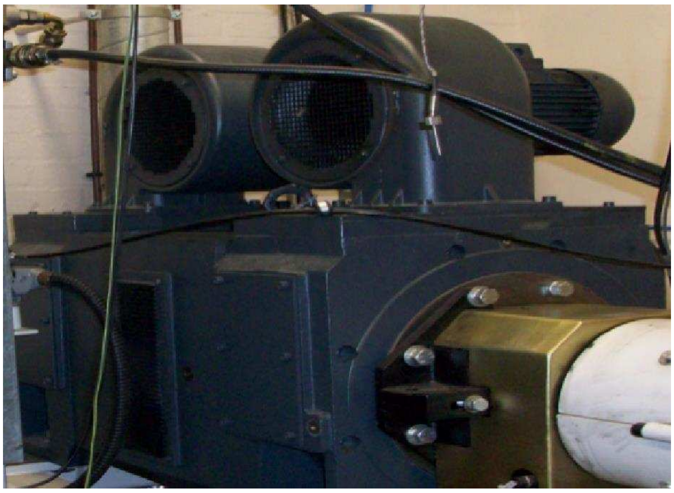

**Figure 4.4 The AC dynamometer using in experiment**

### 4.2.3 Control System

CADET V12 is the data logging system that allows data to be logged at previous defined points in the test or as a result of events of any level of complexity. Complex event logging is provided through user-definable event procedures coded at the Engineering Level in Visual BASIC 6.0. The Operator Level interface also provides for various logging actions on an Event basis [20].

**Figure 4.5 Interface of CP engine control software**

Along with manual entry of data, the CADET V12 allows automatic and continuous entry of data of all the major observable components. With the positive development in IT, storage media has become affordable; thus, all the data can be observed and recorded for a thorough analysis so that questions about reliability or validity of the test can be comprehensively answered [20].

### 4.2.4 Alternative Fuels

The pure diesel (D100) and biodiesel (B100) shown in Figure 4.6 are used to fuel the diesel engine in the experiment. The tests are repeated under all of the operating conditions when the test engine is fuelled by each kind of the fuels. The percentages of the biodiesel in the fuel are 20% (B20), 40% (B40) and 100% (B100) respectively where n% means n percent of biodiesel mixed with (100-n) percent of diesel for the fuel.


**Figure 4.6 The diesel  using in experiment (a) the biodiesel using in experiment(b).**

**Table 4.3 The Fuel Viscosity Measurements**

| Fuel Type | Density(20°) | Viscosity |
|---|---|---|
| **D100** | **0.84 $g/m^3$** | **40.10 cSt** |
| **B20** | **0.846 $g/m^3$** | **40.25 cSt** |
| **B40** | **0.852 $g/m^3$** | **40.367 cSt** |
| **B100** | **0.87 $g/m^3$** | **40.70 cSt** |

## 4.3 Data Acquisition System Description

### 4.3.1 Data Acquisition Systems

Two data acquisitions systems are employed in this experiment, including a two channel SAEU2S Dynamic Data Acquisition (DAQ) for collecting high frequency AE signals and a YE-6232B for collecting ordinary dynamical signals, such as pressure, vibration and acoustics. The one pulse signal from the encoder is connected to both DAQ systems and used as the synchronization signal.

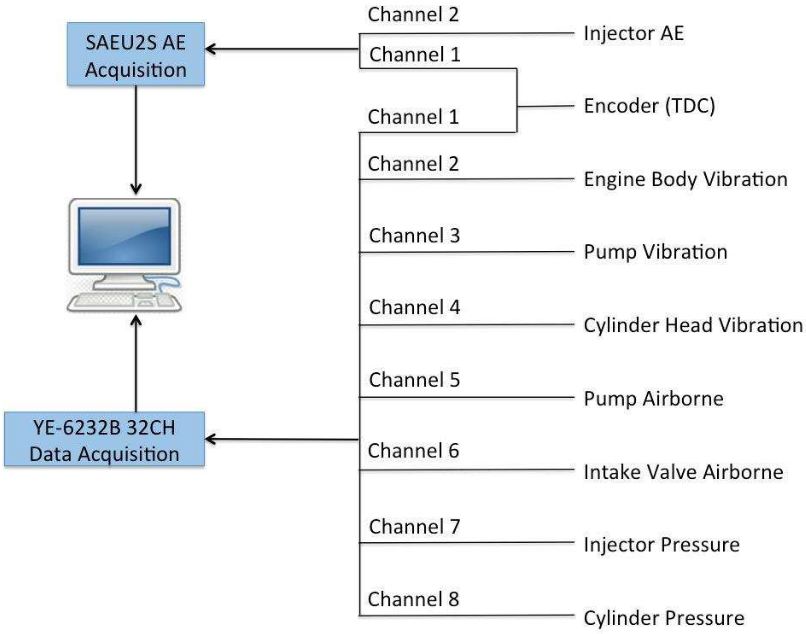


**Figure 4.7 The schematic diagram of data acquisition system**

**Table 4.4 The Characteristics of Acquisition**

| Characteristics | SAEU2S | YE-6232B |
|---|---|---|
| Sampling rate | 2500kHz | 48kHz |
| Sampling date length | 64MB | 15sec |

#### 4.3.1.1 YE6232B-32 Channel DAQ

It is common for data acquisition from internal combustion engines to be timed using the hardware clock in the DAQ system. The Model YE6232B has 32 channels each with 16 bit resolution, synchronized acquisition at 100 kHz per channel. This type of data acquisition is perfectly adequate for monitoring vibration and pressure signals [20]. Figure 4.8 shows the 32 channels YE-6232B data acquisition and the software working interface, and Table 4.5 shows the specification.

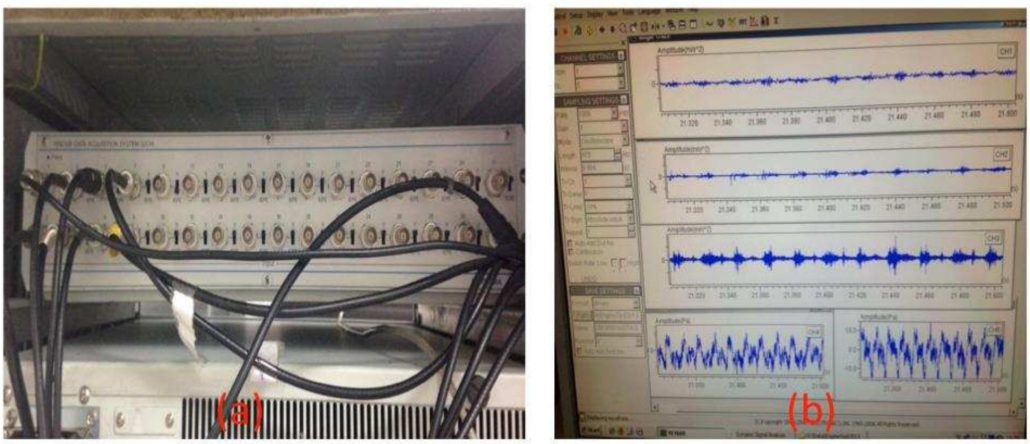


**Figure 4.8 (a) Picture of YE6232B DAQ system and (b) software running interface**

**Table 4.5 Specification of YE6232B Data Acquisition Instrumentation**

| | |
|---|---|
| Model | YE6232B |
| Channels | 32 |
| A/D bits | 24bit(∑-△) |
| Input Mode | V/IEPE |
| IEPE Power Supply | 4mA/+24VDC |
| Signal Input Range | ≤±10VP |
| Signal Frequency Range | DC-30kHZ (-3dB±1dB) |
| Accuracy | ±0.5% |
| Sample Rate (Max.) | 96kHz/CH, Parallel |
| Interface | USB2.0 |

### 4.3.1.2 SAEU2S DAQ

The AE Data Acquisition System consists of four main parts, the AE sensor, the Pre-amplifier, the SAEU2S AE DAQ system, and the PC computer with analysis software installed. The capture card can collect the real-time continuous waveform digital filter and the reconstructed waveform generation filter characteristic parameters on the AE hardware acquisition. Then the hardware capture card acquisition can achieve the FFT analysis of the continuous waveform signal to upload the frequency domain waveforms and power spectral output parameters to computer. The real-time continuous digital waveform signals acquired by AE data acquisition system are shown in Figure 4.9 (b), and the instrumentation is shown in Figure 4.9 (a).

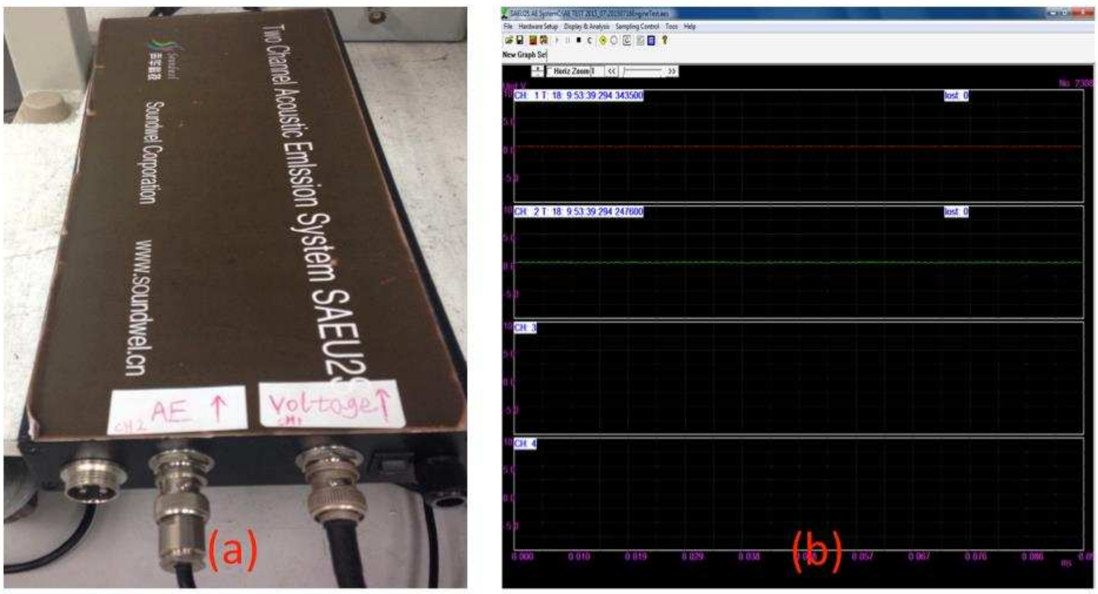


**Figure 4.9 (a) Picture of SAEU2S AE DAQ system and (b) software running working interface**

Table 4.6 Specification of the 2-channel SAEU2S AE Data Acquisition system

| | |
|---|---|
| **Model** | **SAEU2S** |
| **Channels** | **2** |
| **A/D bits** | **16 bit(∑-△)** |
| **Input Mode** | **V/IEPE** |
| **Signal Input Range** | **±10V** |
| **Signal Frequency Range** | **0~3MHz** |
| **Sample Rate (Max.)** | **10M/sec** |
| **Analog filters** | **Supporting various filter settings:**<br>**Low pass（100kHz, 400kHz, 1200kHz）;**<br>**High pass（20kHz, 100kHz, 400kHz）;**<br>**Band pass: any combinations of high pass and low pass;**<br>**No limitation pass.** |
| **Interface** | **USB2.0** |

### 4.3.2 Encoder Signal

An optical encoder (HENGSTLER 0550152) is employed in this test, which is an incremental encoder that measures the angular position within a single turn as illustrated in Figure 4.10. The resolution of this encoder is 500 pulses per revolution and its detailed specifications can be found in Table 4.7 [20].

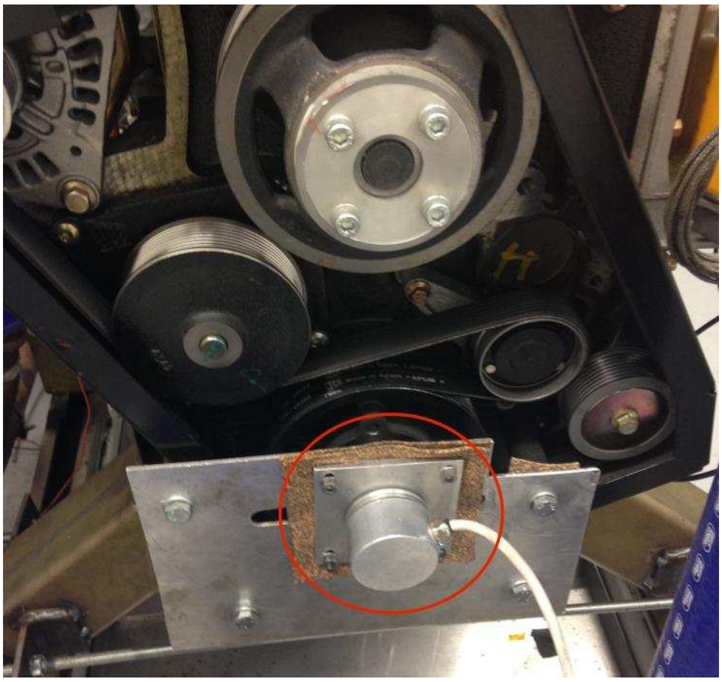

**Figure 4.10 The optical encoder used in experiment**

Table 4.7 Specification of the incremental shaft encoder RI58O

| | |
|---|---|
| **Shaft diameter** | **6 mm/ 6.35 mm/ 7mm** |
| **Absolute max. shaft load** | **∅ 12 mm** |
| **Radial** | **80 N/xial 60N** |
| **Absolute max. speed** | **10000 $min^{-1}$** |
| **Torque** | **≤ 0.5 Ncm, ≤ 1Ncm (IP67)** |
| **Momentof inertia** | **Synchro flange approx. 14 $gcm^2$** |
| **Protection class (EN 60529)** | **Housing IP65, bearings IP64** |
| **Operating temperature** | **RI 58-O: -10…+70°C; RI 58-T: -25…+100°C** |
| **Vibration resistance (IEC 68-2-6)** | **100$m/s^2$ (10…2000 Hz)** |
| **Shock resistance (IEC 68-2-27)** | **1000$m/s^2$ (6 ms)** |
| **Housing** | **Aluminium ∅ 58 mm** |
| **Weight** | **approx. 360 g** |

### 4.3.3 Pressure Signals

The General Electric 4000 Series pressure sensors are illustrated in for the in-cylinder pressure acquisition, shown in Figure 4.11 (a), which offers high accuracy and stability. The core of the 4000 series pressure sensor is a high stability pressure measurement element, manufactured from a single silicon crystal [20]. A CA-YD-124 pressure sensor was installed near the fuel injector intake, as shown in Figure 4.11 (b). The specification of the pressure transducers was declared in Table 4.8.

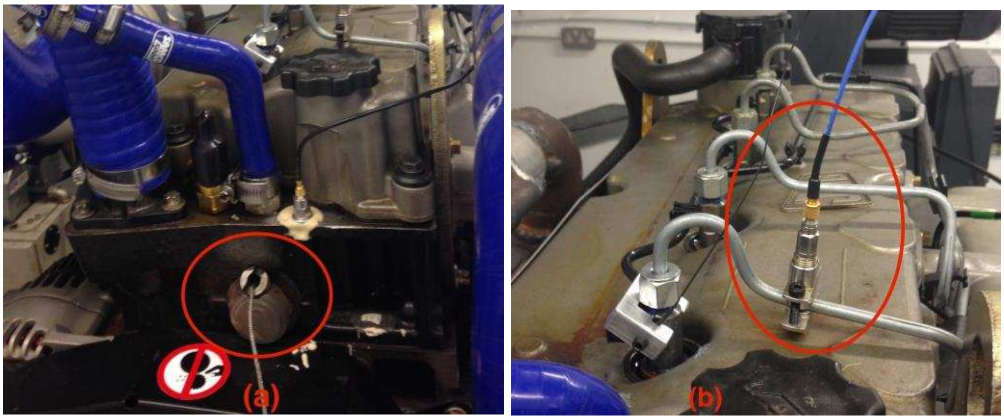


**Figure 4.11 The in-cylinder pressure sensor (a) and injector pressure sensor (b) used in experiment.**

**Table 4.8 Specification of Pressure Sensors**

| Parameter (SI) | Cylinder Pressure | Injector Pressure |
|---|---|---|
| Model Number (Serial number) | (28920) | CA-YD-124 (83764) |
| Sensitivity (-10 to +25%) | 0.160 pC/kPa | 21.7 pC/Mpa |
| Measurement Range | 34475 kPa | 0~200 MPa |
| Resonant Frequency | ≥200 kHz | >100 kHz |
| Temperature Range (Operating) | -240 to +316 °C | - 40~150°C |
| Sensing Element | Quartz | Quartz |
| Capacitance | 18 pF | 4.5 pF |
| Insulation Resistance (at room temp) | $\geq 10^{12}\ \Omega$ | $>10^{3}\ \Omega$ |

### 4.3.4 Vibration Signals

The vibration sensors operated in test are accelerometer sensor, which is a device that measures the acceleration of the object or structure it attached. Inertial force generated by change in motion causes a piezoelectric material contained within the body of the accelerometer to produce an electrical charge that is proportional to the acceleration. One sensor was installed on the top surface near the first cylinder to record the cylinder head vibration signals, as shown in Figure 4.12 (b), the other one was installed on the side surface of cylinder to record the engine body vibration, as shown in Figure 4.12 (a). The specifications are shown in Table 4.9.

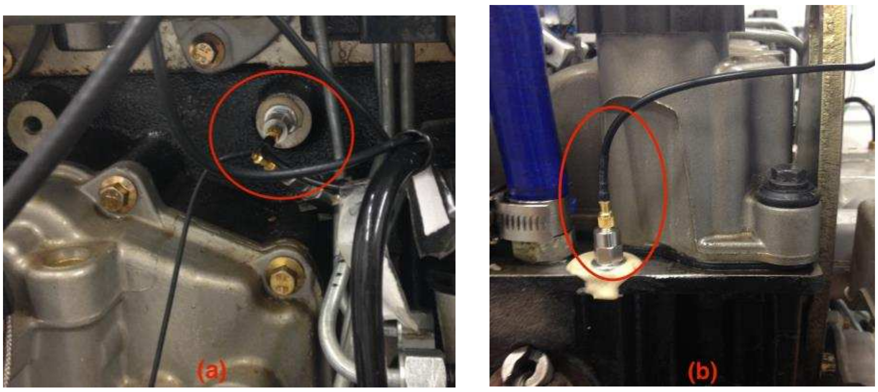


**Figure 4.12 (a) Vibration sensor installation at body and (b) cylinder head**

**Table 4.9 Specification of vibration sensors**

| Parameter | Engine body vibration | Cylinder head vibration |
|---|---|---|
| Sensor type (Serial number) | CA-YD1182 (101156) | CA-YD-182 (72637) |
| Sensitivity | 0.518 mV/ms$^{-2}$ | 2.08 mV/ms$^{-2}$ |
| Frequency Range | 1~15kHz | 1~15kHz |

### 4.3.5 Acoustic Emission Signals

A subminiature MG50 AE sensor from Soundwel Ltd. is employed to acquire the AE signals from the injector on the engine. The resonant frequency of the AE sensor is at 500kHz and its detailed specification is given in Table 4.10. The sensor is clamped on the first injector on the engine as shown in Figure 4.13(a) and its output signal is amplified by 40dB using the preamplifier shown in Figure 4.13(b).

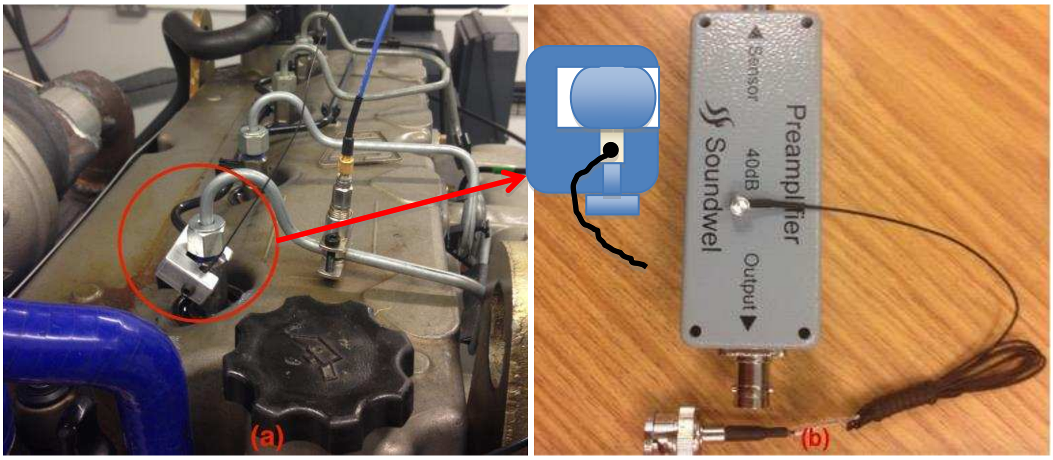


**Figure 4.13 (a) Injector AE sensor and (b) preamplifier installed in test.**

**Table 4.10 Specification of AE sensor**

| | |
|---|---|
| Model Type | MG50 |
| Dimension | ∅ 4.7×4.0mm |
| Operation Temperature | -20~50°C |
| Sensitivity | >70dB |
| Frequency Range | 100~1000kHz |
| Resonant Frequency | 500kHz |

## 4.4 Test Procedure

The test was conducted under various conditions, as shown in Table 4.11, which were in the sequence of increasing speed by 1000rpm, 1300rpm and 1600rpm. In each speed condition, there were four or five states in the sequence of increasing load, which are 0Nm, 105Nm, 210Nm, 315Nm and 420Nm(for speed of 1300rpm only). The alternative fuels were operated in the order of D100, B100, B40 and B20. Signals were recorded when each condition in a stable state, which is 30 seconds after the parameter changed. The various conditions design was determined by the JCB444 74kW engine operation ability, as shown in Figure 4.14.

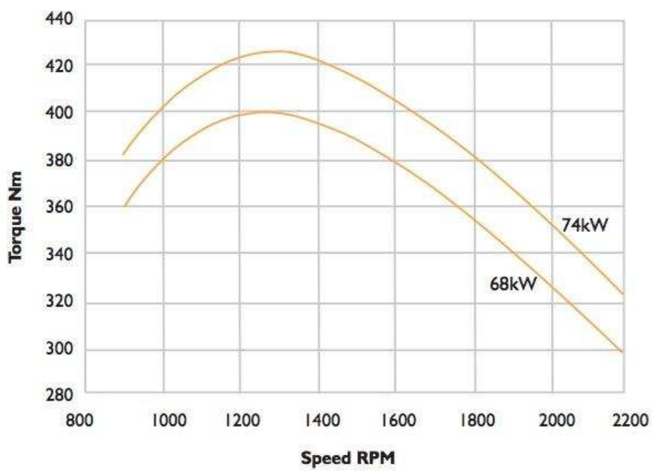


**Figure 4.14 JCB444 TCA 74kW Engine Operation Condition**

**Table 4.11 The Operation State Condition for Each Fuel**

| Speed \ Load | 0 | 105 | 210 | 315 | 420 |
|---|---|---|---|---|---|
| 1000 | ☑ | ☑ | ☑ | ☑ | ☒ |
| 1300 | ☑ | ☑ | ☑ | ☑ | ☑ |
| 1600 | ☑ | ☑ | ☑ | ☑ | ☒ |

# Chapter 5 Acoustic Emission Characteristics of Diesel Injection

In this chapter, the acquired signals for diesel fuel under various speeds and loads are studied. The cylinder pressure and injector pressure are firstly analyzed to help understand the engine stroke stages and the injection process.

## 5.1 Typical Acoustic Emission Signal Characteristics

As two DAQ systems are employed in this study, the signals are firstly extracted out based on crankshaft revolutions according to the one pulse encoder (TDC) signal. Secondly, the signals are converted to the angular domain separately. Thirdly, they are shifted by a specific angle to align it with the TDC point. The shifted angle or TDC angular position are calculated according to the cylinder pressure signal based on the first few cycles of the engine shut down stage, in which case the cylinder pressure changes come purely from piston movements without the interference of combustion. After these computations, the signals from two DAQ systems are in the angular domain, therefore, they can be presented together to examine the signal profiles in association with engine combustion in a full engine cycle.

### 5.1.1 Acoustic Emission Signal Analysis in Contrast with Pressure Signal

A typical presentation of cylinder pressure, injector pressure and AE signal in the angular domain in one revolution is presented in Figure 5.1. The four engine strokes for the first cylinder are roughly illustrated in the figure as the intake, compression, combustion and exhaust stroke happen in sequence.

The cylinder pressure and injector pressure arises and reaches their peaks at around 360°, which is the end of compression stroke and start of combustion stroke. The injector pressure reaches its peak a bit earlier than the cylinder pressure. At this point, it also has the major AE signals, which mainly comes from the injection excitations and combustion actions.

Moreover, several obvious AE events can also be observable in other angular positions. According to AE signal analysis, the AE events are usually localized and should mainly come from the injection and combustion process for this test case. By comparing the signals in Figure 5.1 together with the theoretical inlet and exhaust valve timing diagram in Figure 4.3, the mostly likely events are marked in Figure 5.1. As it shows, both the intake and exhaust valve close events from the first injector can be clearly observed. In the meantime, their open events cannot be noticed. The reason might be that the mechanical impact, especially the flowing of valve close is much stronger than open during which the impact of air flows and rock arms is insignificant.

Another significant obvious amplitude occurs around 540°, may comes from the 3rd cylinder compress process. But according to the conclusion above, a compress process should last longer. Therefore, this signal can only comes from the 2nd cylinder exhaust valve close process. Moreover, there is no compress process signal from the other three cylinders, which obviously shows that the adjacent cylinder compress events would not effect the AE signal collection of the object cylinder, but not the adjacent exhaust valve close event.

A controversial AE signal occur around 650°, which corresponding to 3rd cylinder exhaust valve opening. But as the obtained conclusions above, an exhaust valve open signal should not be obvious, especially this is from 3rd cylinder. A probability is around that period there is no external influence which lead to the acoustic waves transduce achieves the sensor extreme smooth. But the other three cylinder exhaust valve open periods are in the same condition.

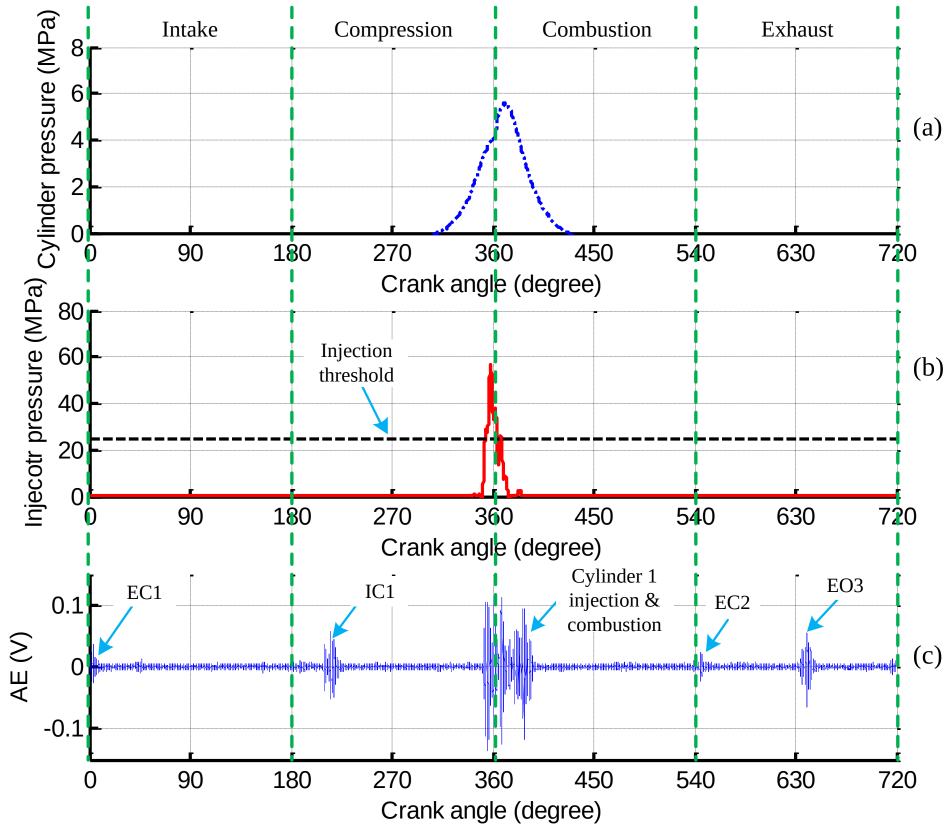


**Figure 5.1 Signal contrast in one revolution at speed of 1300 rpm and torque of 210 Nm (a) cylinder pressure, (b) injector pressure and (c) AE signal**

A magnified view of the injection stage is presented in Figure 5.2 to study the injection process in detail. As shown by the cylinder pressure, the combustion starts with the crank angle at about 363° and the injection process happens a bit earlier than the combustion. From the injector pressure, it can be seen it starts rising at about 351° and reaches the needle raising pressure, 23MPa, at around 353°. In contrast, obvious AE events start happening at this crank angle. These AE events might be due to the mechanical impacts between the needle end and its backstop. After this, the injector pressure fluctuates and reaches its peak at about 357° and drops across the needle raising pressure at about 366°, where obvious AE events can also be observed.

In addition, after the injector closes, some AE events can also be observed from 370° to 400°, which mostly likely come from the wave reflection and reverberation of the high pressure waves inside the high-pressure pipe. The reflected pressure pulses are due to rapid closing of injection and fuel release valves in the high-pressure line. This reflected pulses may cause the needle valve to oscillate and impact the need seat to induce AE waves. Another likely source might be the combustion excitation.

From the above analysis, it can be seen that AE signals measured are highly related to the injection process, especially for the injector open and close events. To confirm this and examine its characteristics, they will be further analyzed to study the characteristics for different engine running conditions.

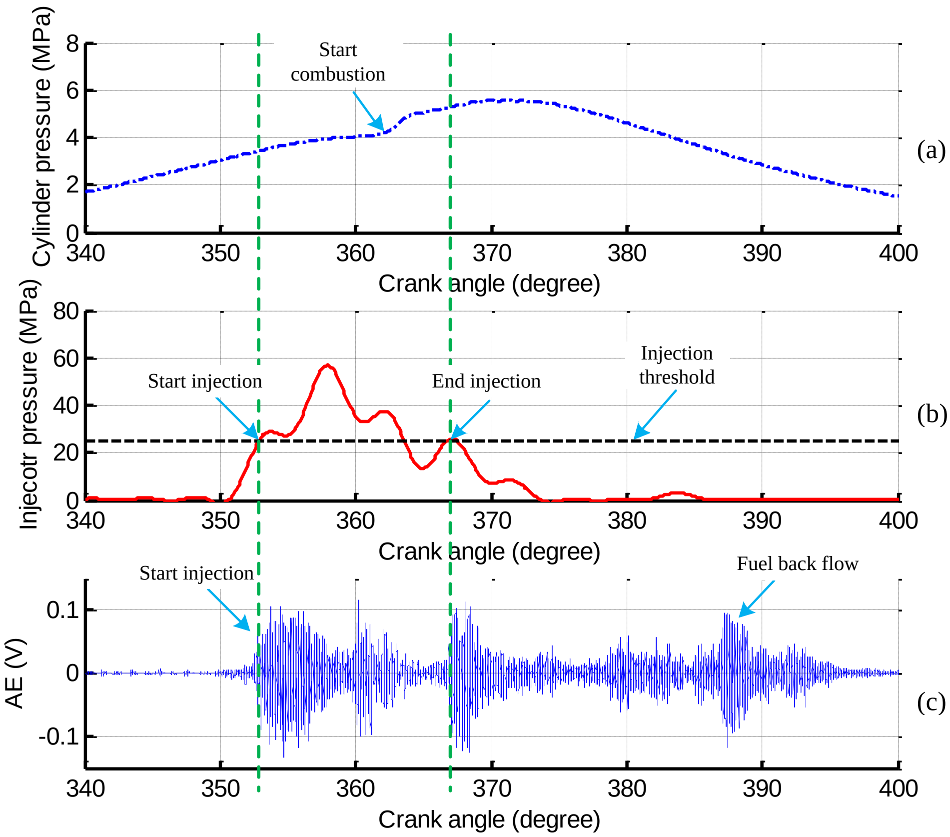


**Figure 5.2 Signal contrast during the injection stage at speed of 1300 rpm and torque of 210 Nm (a) cylinder pressure, (b) injector pressure and (c) AE signal**

### 5.1.2 Time-Frequency Analysis of Acoustic Emission Signal

Time-frequency analysis is a good way to analyze the transient characteristics of a non-stationary signal like the AE signals. Here, the spectrogram of the AE signal during the injection stage is presented in Figure 5.3. It can be seen that the energy of AE signal mainly lies in three frequency bands: lower than 100 kHz, 100-200kHz and 400-600kHz. Recall the employed AE sensor in Section 4.3.5, its resonant frequency is at about 500 kHz, which is in accordance with the strong signals in the band of 400-600kHz.

As the lower frequency bands more likely to contain interferences from the combustion process, a band-pass filter within 400-600kHz is employed to filter out the lower frequency components to reduce the interferences. Then, the envelope of the band-pass filtered signal is calculated and passes through a 10kHz low-pass filter. The comparison of the original AE signal, filtered version and its envelope are presented in Figure 5.4. It can be seen the injector open and close events are preserved in the computed envelope signal, allowing more effective examination of the AE features.

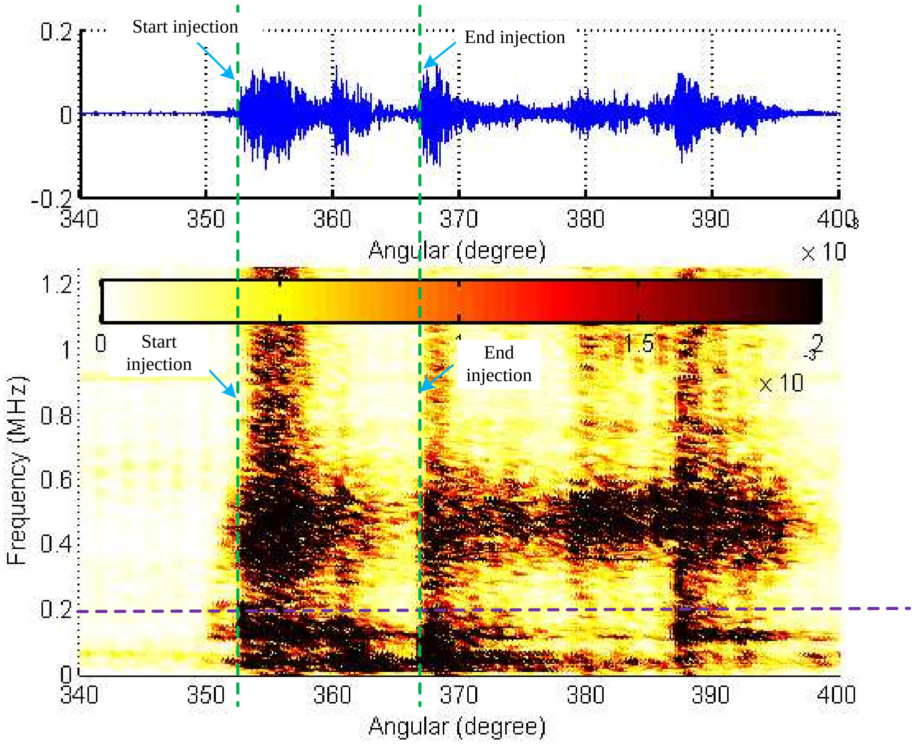


**Figure 5.3 Spectrogram of AE signal during the injection stage**

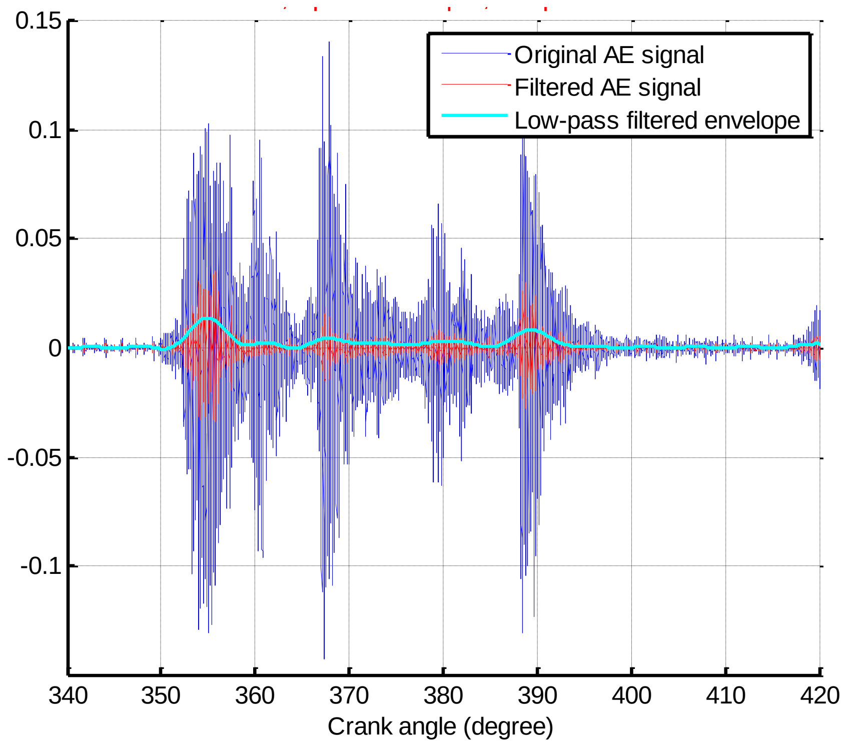


**Figure 5.4 10kHz low-pass filtered envelope of band-pass filtered AE signal**

## 5.2 Acoustic Emission Signal Characteristics for D100

In this section, the cylinder pressure, injector pressure and the envelope of AE signal are compared for various engine running conditions in order to find the AE characteristics with different engine running speeds and loads. In particular, the comparison is made based on that of standard diesel fuel.

### 5.2.1 Acoustic Emission Signal Characteristics at Different Loads

The load variation comparison of cylinder pressure, injector pressure and envelope of AE signal at speed of 1000 rpm, 1300 rpm and 1600 rpm are presented in Figure 5.5, Figure 5.6 and Figure 5.7, respectively. The starting angle of AE event and signal peaks will be used as the main parameters of injection behavior when the analysis is made in following contents

- **Event Starting Angle**

From the injector pressure comparison, it can be clearly seen that the injector open angle is retarded with the load increases for all speed conditions. This can be explained as that with load increases, more force is required from the piston, which results in the cylinder pressure increases and thus a higher injector pressure is required to overcome the increased cylinder pressure. This means the pump needs longer time to let the injector pressure reach the required needle raising threshold.

Accordingly, the injector open angle delay information can be clearly noticed from the first peaks of AE envelope signal for speed at 1300 rpm and 1600 rpm shown in Figure 5.6(c) and Figure 5.7(c). The first peaks of AE envelope signal at 1000rpm, shown in Figure 5.5(c), are rather small and not easy to be based on for estimating the injector open angle, but from their peaks, it can be clearly seen that the injection process has been definitely delayed.

In addition, it can be noticed that the combustion starting time delays for all speed conditions as shown by the in-pressure profiles in Figure 5.5(a), Figure 5.6(a) and Figure 5.7(a). This can be well explained by the delay of injection process resulting in a late combustion.

- **Signal Peaks**

The injector peak pressure and amplitude area increases obviously with loads for all three speed conditions as shown in Figure 5.5(b), Figure 5.6(b) and Figure 5.7(b), respectively. This can be explained as that with load increases, more fuel delivery is required from the fuel pump, and the increase of cylinder pressure during injection process also needs a higher injection pressure. In addition, the area above the injection threshold increases with loads as well, which are in conformity with the fuel injection amount increase.

Cylinder pressures can be viewed as two parts, separated by the starting point of combustion. For the cylinder pressure before combustion starting, peaks from higher loads are larger than those of lower ones. Similarly, it can be found for the cylinder pressure after combustion starting point is also higher for the higher load conditions.

However, the peak AE envelope signals show an opposite trend with the increase in load and speed. As shown in Figure 5.6(c) and Figure 5.7(c), the first peak of AE envelope decreases with load increases. A potential explanation is the increased effect of fuel softening phenomena. According to the analysis in Section 5.1, the first peak of AE envelope corresponds to the injector open, where the mechanical impact between the needle end and backstop contributes quite strong AE events. As the injector pressure increases with load, more leak fuel through the needle valve clearance and lead to higher static pressure in the return line. In another word the pressure difference between the nozzle injection chamber and the return line is smaller. It means that more fuel can be presented between needle and backstop and consequently provides better attenuation to the impact, which in turn results in lower AE events.

For the weak injector open peaks at 1000 rpm in Figure 5.5(c), it can be explained from the point of both lower pressure increase rate and internal fuel leakage. At this low speed, the fuel pressure is lower and the fuel leakage from the injector chamber to the fuel returns path is severer due to longer time duration of fuel supply process at the low speed, which results in a small pressure difference and a small impact force between needle and backstop. Besides, as the fuel flow rate is slower at lower speed, the acceleration of raising needle and needle motion are more tempered, which means the impact force is smaller.

In addition, a small dip in the injector pressure can be viewed in Figure 5.6(b) and Figure 5.7(b) after the first time reaches the threshold. This is due to that when the needle raises rapidly, the fuel flows into the nozzle sac chamber and there is not enough fuel coming from the pump, thus it results in a small pressure drop in conjunction of the effect of the pressure release of fuel delivery valve. It can be noticed that with the load increases, more fuel is available from the pump, this drip trend to be small. For the lower speed in Figure 5.5(b), this phenomenon is not obvious, which might be that the relative lower running speed allows the fuel to fill in time without the drip.

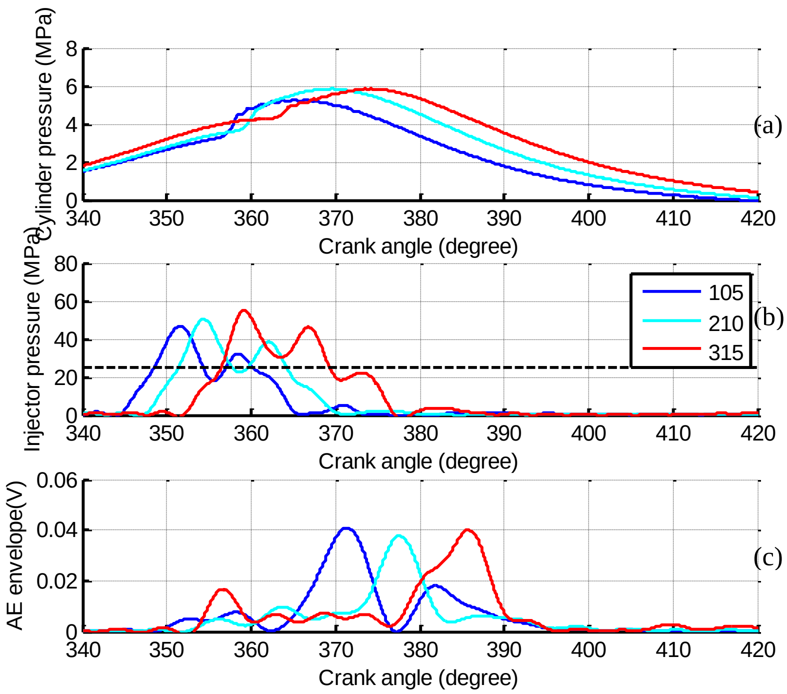


**Figure 5.5 Load variation comparison for 1000 rpm (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

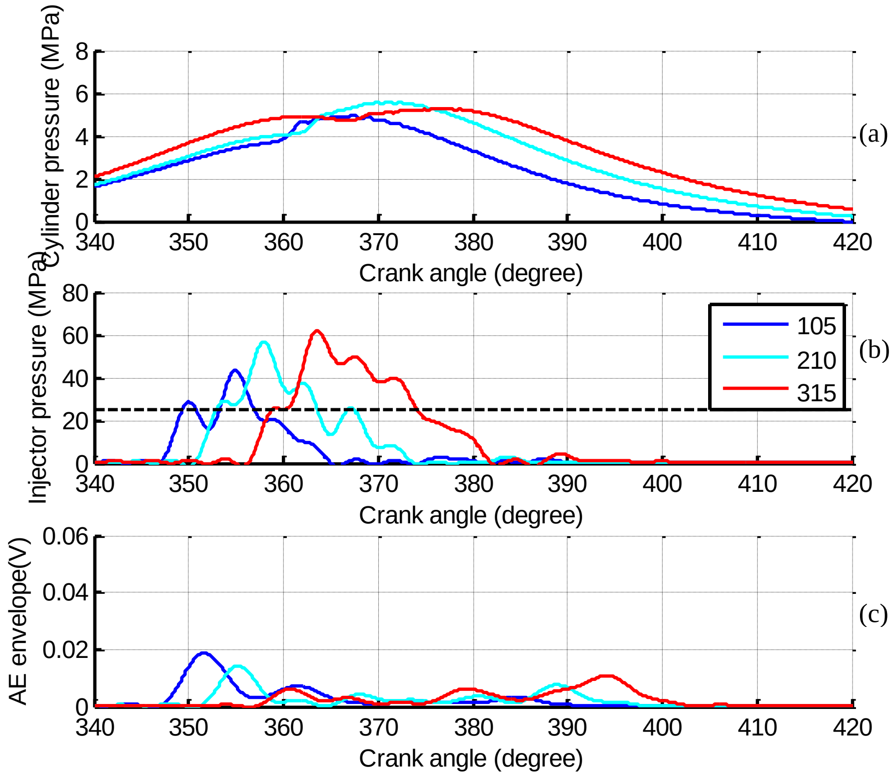


**Figure 5.6 Torque variation comparison for 1300 rpm (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

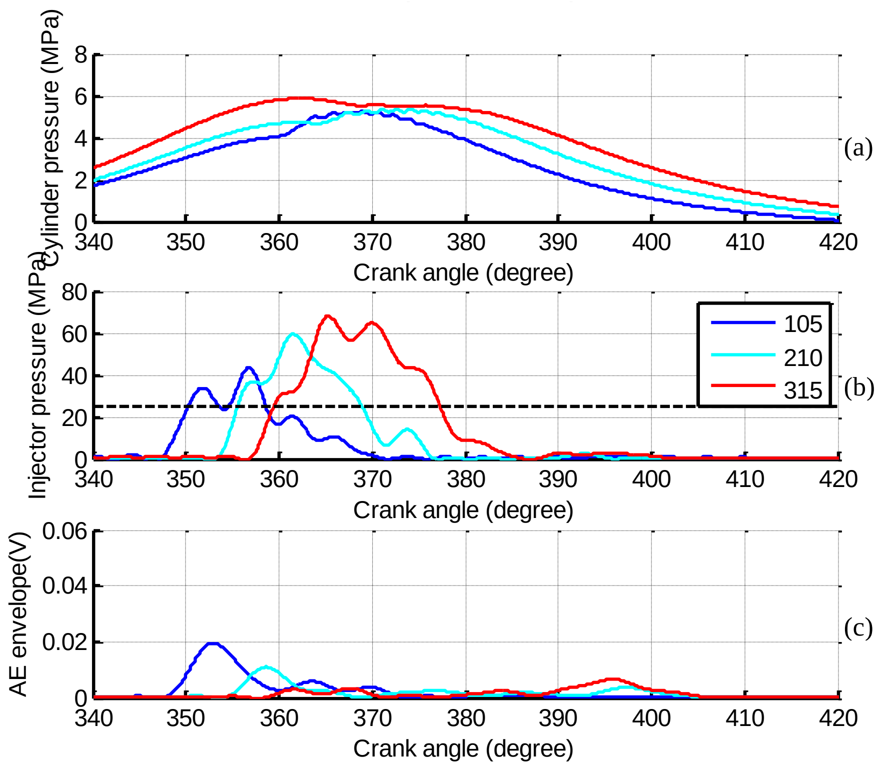


**Figure 5.7 Torque variation comparison for 1600 rpm (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

### 5.2.2 Acoustic Emission Signal Characteristics at Different Speeds

Similar to the load variation analysis, the variation comparison of cylinder pressure, injector pressure and envelope of AE signal at load of 105 Nm, 210 Nm and 315 Nm rpm are presented in Figure 5.8, Figure 5.9 and Figure 5.10, respectively. The event starting angle and signal peaks will be analyzed as well.

- **Event Starting Angle**

From the injector pressure comparison, it can be clearly seen that the injector open angle is delayed with the speed increases for all load conditions. These is mainly because of the engine timing mechanisms and partially because of the higher cylinder pressure in the injection stage needs a higher injector pressure, which results in the pump that needs longer time to let the injector pressure reach the required needle raising threshold.

Accordingly, the injector open angle delay information can be clearly noticed from the first peaks of AE envelope signal for speed increasing from 1300 rpm to 1600 rpm shown in Figure 5.8(c), Figure 5.9(c) and Figure 5.10(c). As AE events for the injector open at 1000 rpm are rather small and are difficult to be based on for estimation, as explained in Section 0. However, for the high load as shown in Figure 5.10(c), the delay information of the injector open can be observed.

Similar to the load variation analysis, the combustion starting time is delayed because of the delay of injection process for all load conditions as shown in Figure 5.8(a), Figure 5.9(a) and Figure 5.10(a).

- **Signal Peaks**

The injector peak pressure increases obviously with speeds for load at 210 Nm and 315 Nm as shown in Figure 5.9(b) and Figure 5.10(b), which can be explained by the increased cylinder pressure during injection stage. For the cylinder pressure before combustion starting, peaks from higher speeds are larger than those from lower ones while the trend for cylinder pressure after combustion starting point varies for different loads.

Similar as the injector open angle delay analysis, the injector open peak for speed 1300 rpm and 1600 rpm is obvious while that for speed 1000 rpm is difficult to estimate. A decreasing trend can be noticed for speed increases from 1300 rpm to 1600 rpm as shown in Figure 5.8(c), Figure 5.9(c) and Figure 5.10(c). Similar as the explanation in Section 0, the increased injector pressure provides better damping performance at high speed.

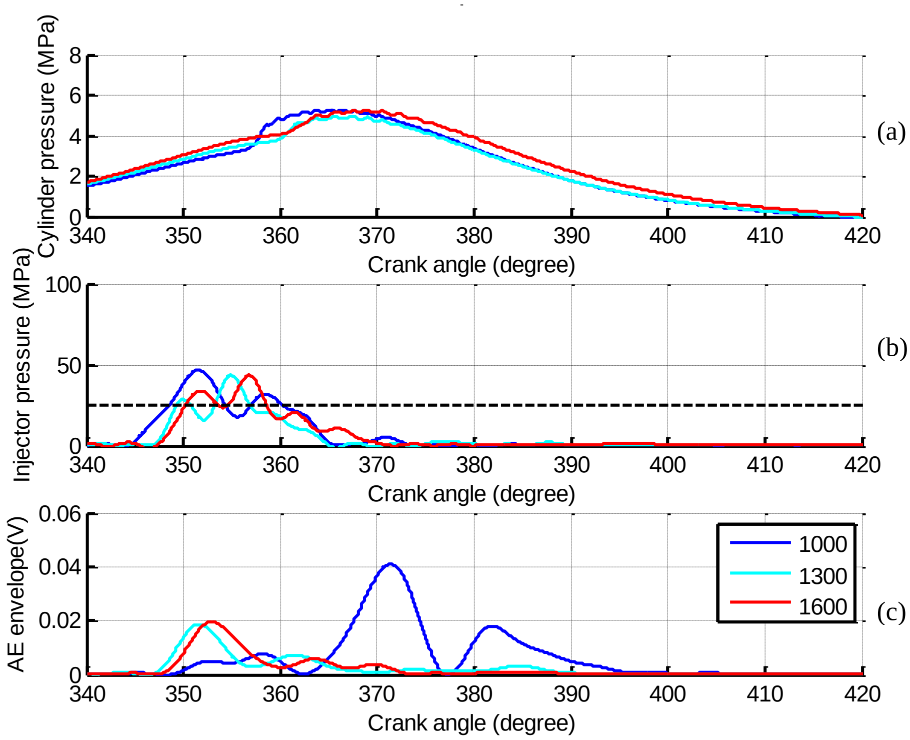


**Figure 5.8 Speed variation comparison for 105 Nm torque (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

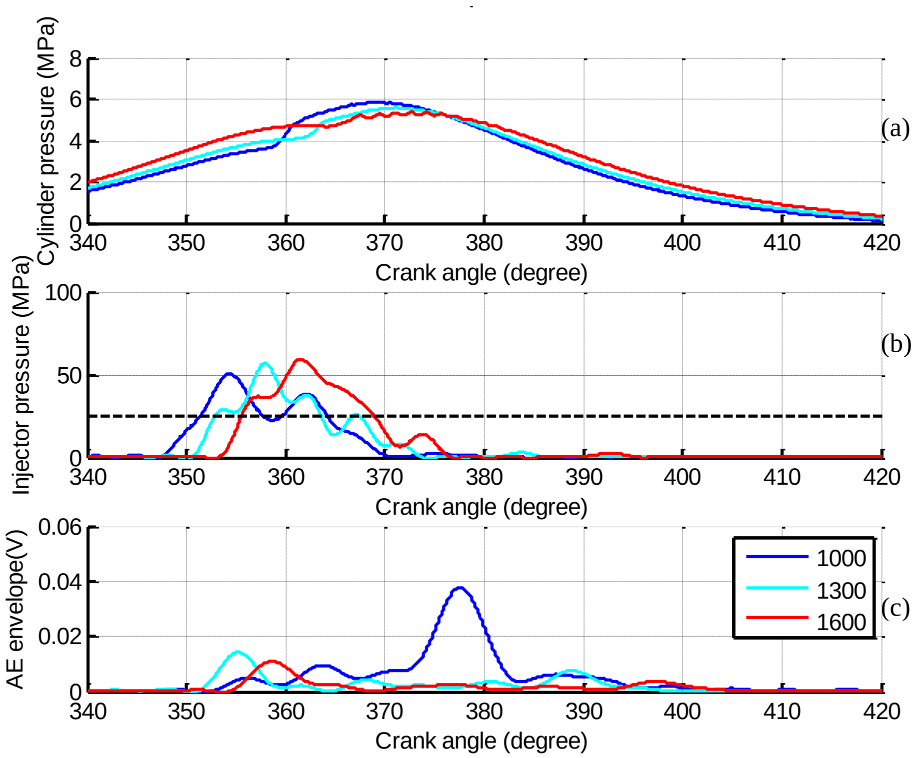


**Figure 5.9 Speed variation comparison for 210 Nm torque (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

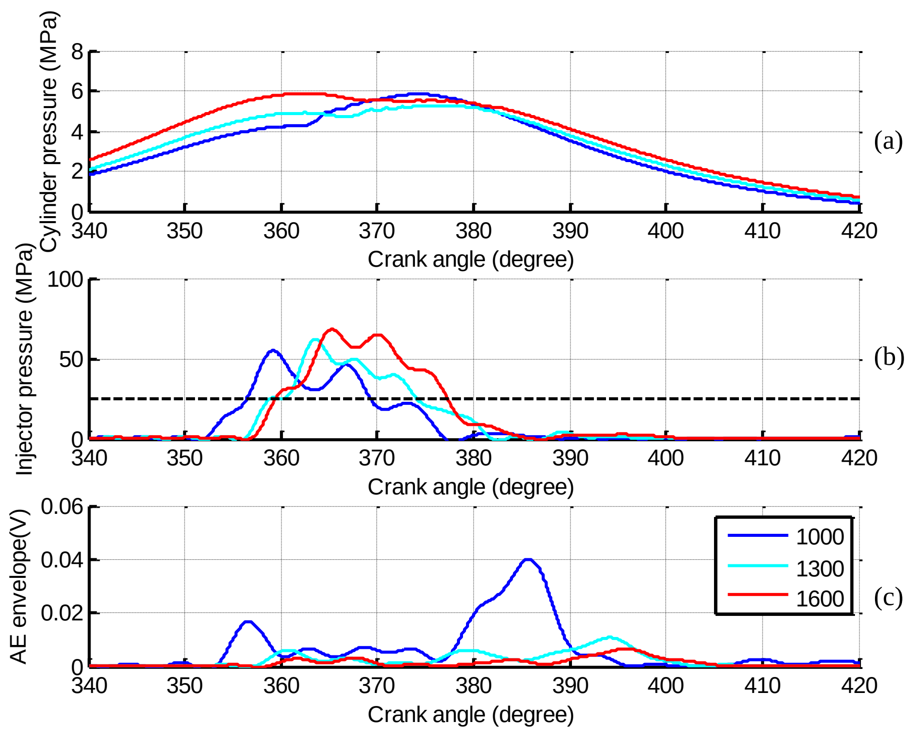


**Figure 5.10 Speed variation comparison for 315 Nm torque (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

## 5.3 Injection Parameter Estimation

Based on the analysis in Section 5.1 and 5.2, it can be seen that AE events are highly related with the injection process and can be based on for the injection estimation at least for most engine running conditions. In this section, the injection parameters are firstly estimated according to the injector pressure as a reference, which is directly with the injection process but is an intrusive measurement method. Secondly, the injection parameters are estimated according to the AE envelope, which can be acquired non-intrusively and suitable for online applications including monitoring and control.

### 5.3.1 Estimation Based on Injector Pressure

**The injector pressure under various speeds and loads are plotted in**

**Figure 5.14, in which the injector open and close timings are marked. From this figure, the corresponding open and close angle information are extracted based on the open pressure and compared in**

Figure 5.12. It can be seen that both the open and close crank angle increases with loads. The open crank angle increases with speed for all loads while the close crank angle increases with speed only for loads at 210 Nm and 315 Nm. Basically, the open

crank angle distributes between 340° and 365° and the close crank angle lies between 350° and 385°.

**Based on the open and close angle information in**

Figure 5.12, the injection duration can be computed as shown in Figure 5.13, where the duration are expressed in angle and time separately. In general, the injection duration angle increases with loads, which is in accordance with the fact that more fuel is required at higher loads.

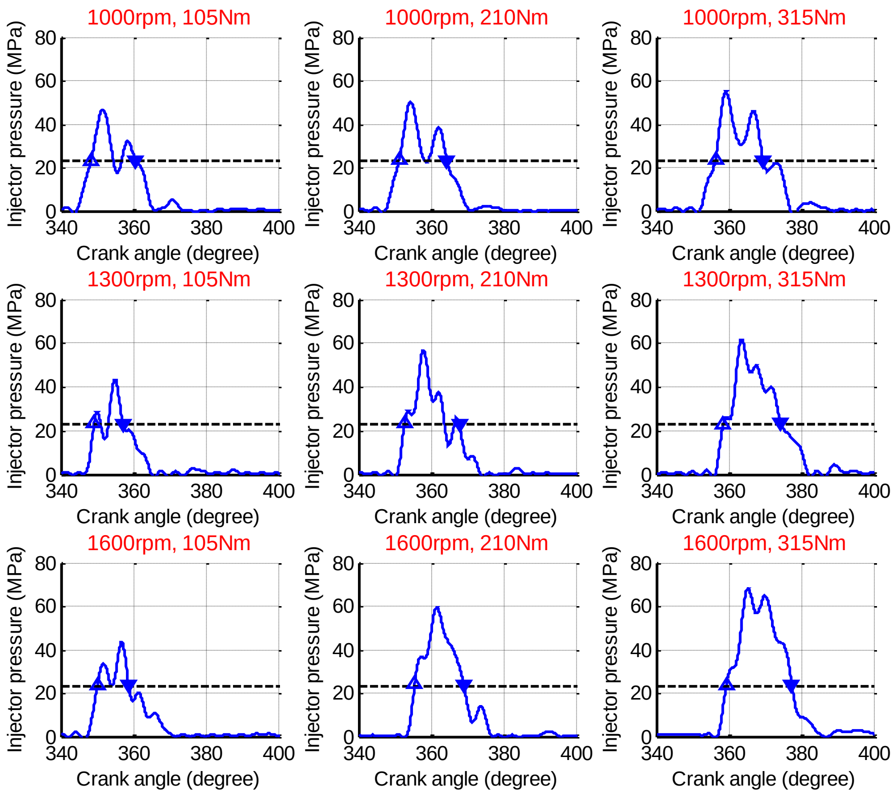


**Figure 5.11 Injector open and close time illustration for various speed and load**

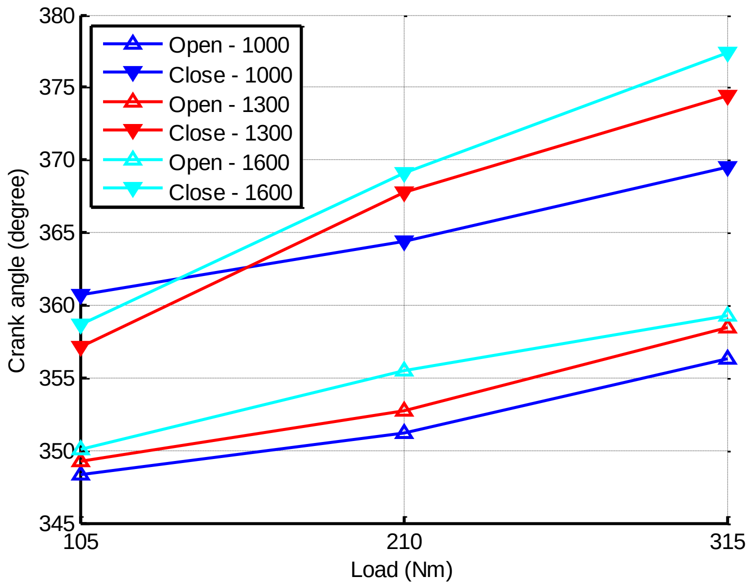


**Figure 5.12 Injector open and close time trend**

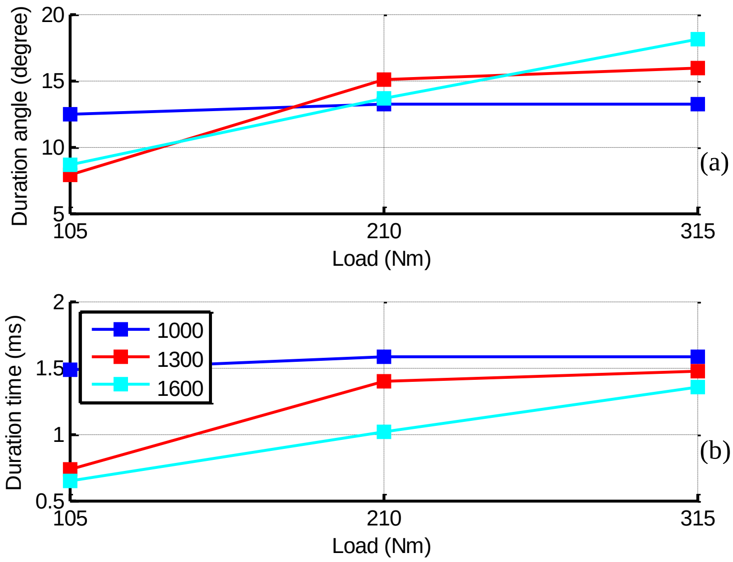


**Figure 5.13 Injection duration (a) measured in angle (b) measured in time**

The injection duration time at high speed is shorter than low speed, that accord with the requirement of high fuel flow rate in high-speed operation. Therefore, the injector valve open angle in high speed and high load is bigger than it in low speed and low load, which means a latter open time to reduce the injection duration, that accord with the requirement of fuel flow rate in injection.

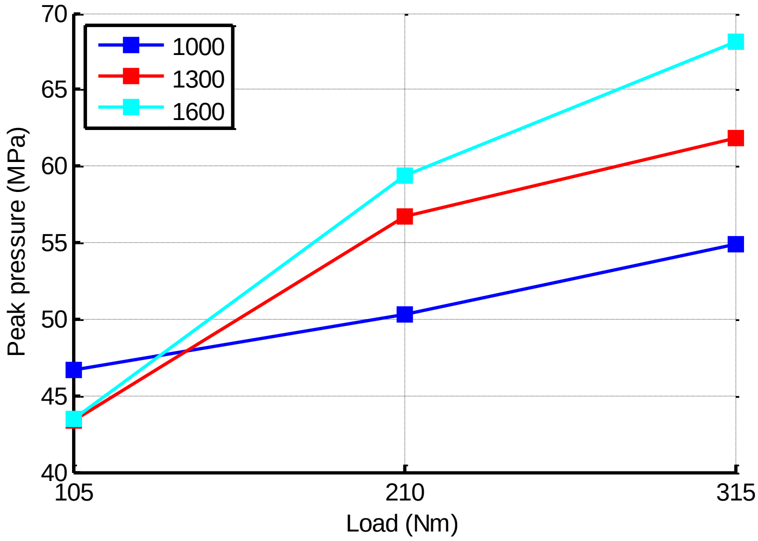


**Figure 5.14 Peak injection pressure**

**From Figure 5.11, the maximum injector pressure can be extracted out and compared in**

Figure 5.14 for different loads and speeds. As it shows, the maximum injector pressure increases with the loads and the increasing ratio of higher speed is greater than that of the lower speed ones. For the load of 210 Nm and 315 Nm, it increases with speeds while it shows different trend at load of 105 Nm.

### 5.3.2 Estimation Based on Acoustic Emission

**The AE envelope signal under various speeds and loads are plotted in**

Figure 5.15. Based on the analysis in the last two sections, the first peak of AE envelope should corresponds to the mechanical impact between needle and the backstop and the injector open angle should be a bit earlier than this point. Moreover, the mechanical impact is proportional to the impact velocity, which reaches to its maximal before its corresponding maximal responses Therefore, the rate of AE envelope signal are based on for the injection event estimation. As shown in Figure 5.16, the first high peak can be considered as the open angle.

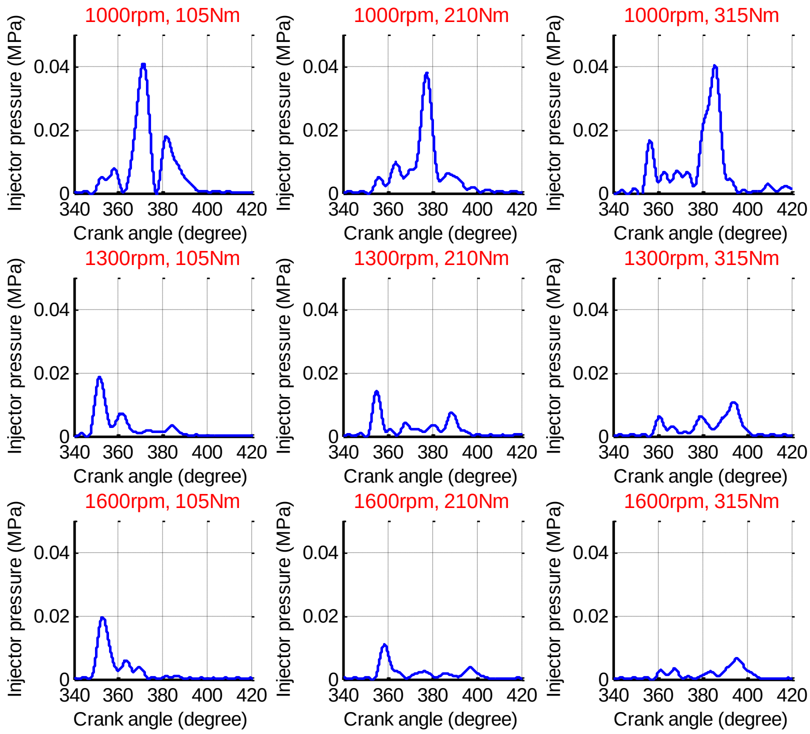


**Figure 5.15 Envelope of AE signal for various speeds and loads**

Based on the estimation according to injection pressure, the open crank angle should be between 340° and 365° and the close crank angle between 350° and 380°. The highest peak between 340° and 365° should be the open angle and the second highest high peak between 350° and 380° should be the close angle. By using this algorithm, the open and close angle are computed and presented in Figure 5.17. As the AE events for injector open are rather small, they are not used for estimation.

**By comparing results obtained from AE signal in Figure 5.17 with those obtained from injector pressure in**

Figure 5.12, it can be found that most estimation are quite similar. Only the close angle for the condition with speed at 1600 rpm and load at 315 Nm, the estimation is not correct. This is because the AE event for the close event for this condition becomes too small due to noise influences.

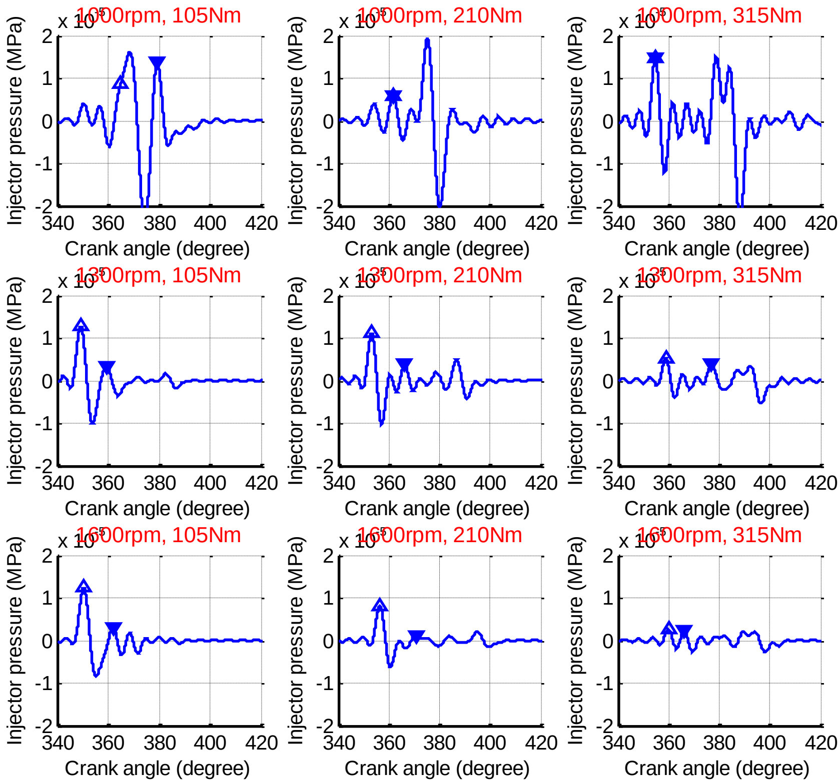


**Figure 5.16 Ratio of AE envelope for various speeds and loads**

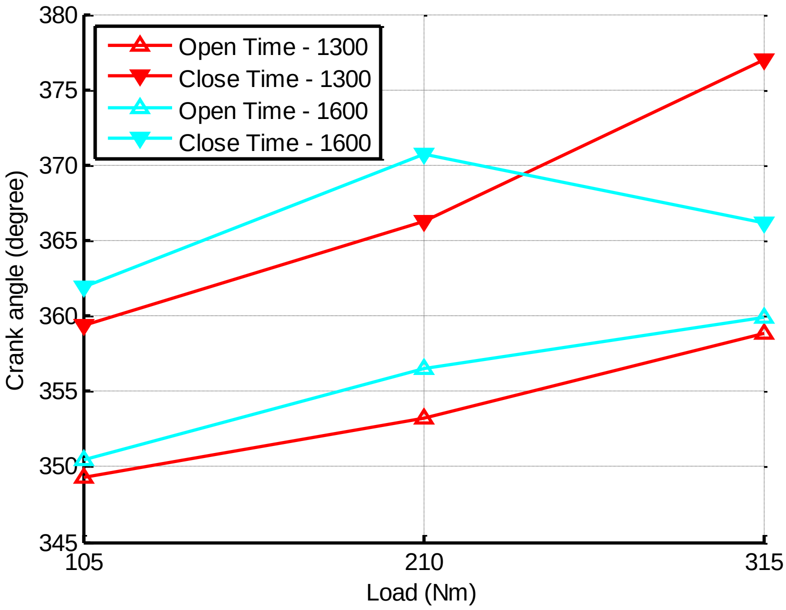


**Figure 5.17 Injector open and close time trend**

Similarly as the estimation from injector pressure, the injection duration in angle and time are extracted from Figure 5.17 and expressed in Figure 5.18.

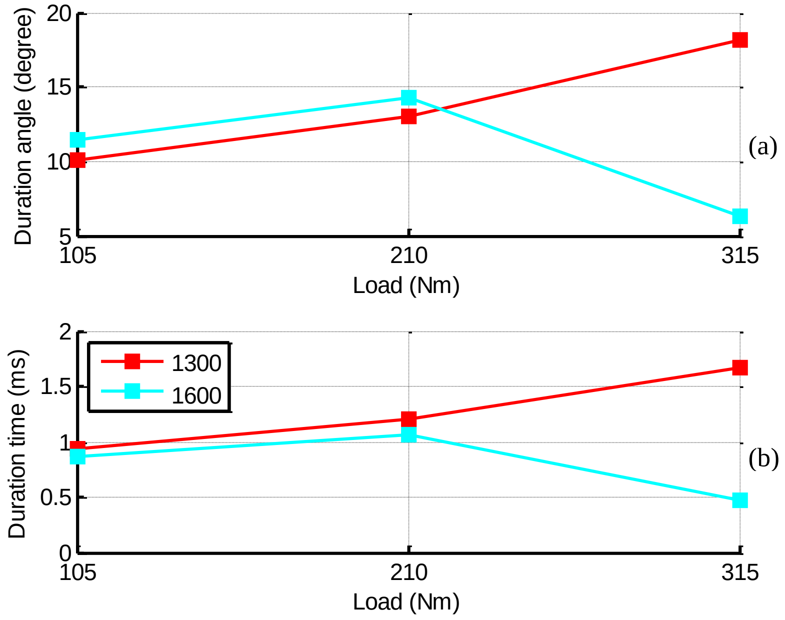


**Figure 5.18 Injection duration (a) measured in angle (b) measured in time**

**From Figure 5.16, the peak ratio of AE envelope at injector open is extracted and shown in Figure 5.19. It shows a clear decreasing trend with the increase of loads and speeds, which is just opposite to the trend of the injector pressure in**

Figure 5.14. This is in accordance with the explanation that the higher injector pressure can provide better damping performance between needle and backstop and thus results in smaller AE events.

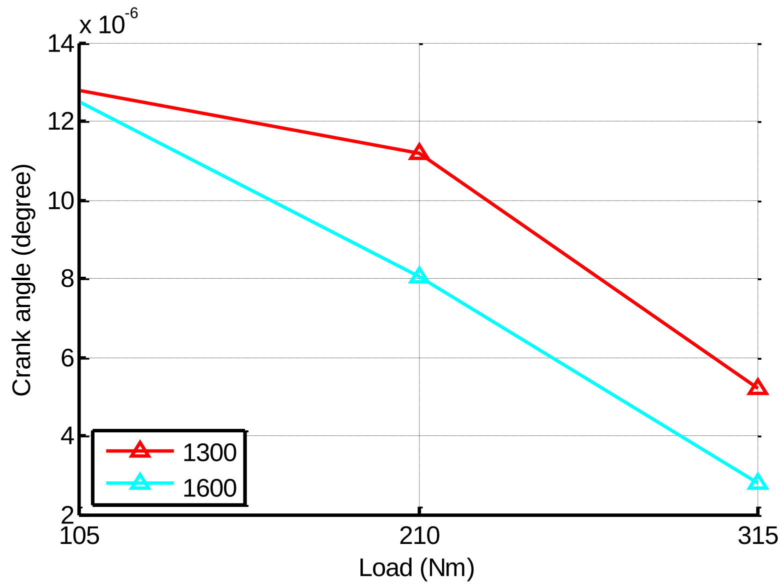


**Figure 5.19 Peak ratio of AE envelope at injector open**

# Chapter 6 Acoustic Emission Characteristics of Biodiesel Injection

The analysis in last chapter shows that AE events have high correlation with diesel injection process and can act as a non-intrusive monitoring method for diesel injection monitoring. In this chapter, the AE signals collected from biodiesel fuel (B40 and B100) are analyzed in together with the cylinder and injector pressure.

## 6.1 Typical Acoustic Emission Signal Characteristics

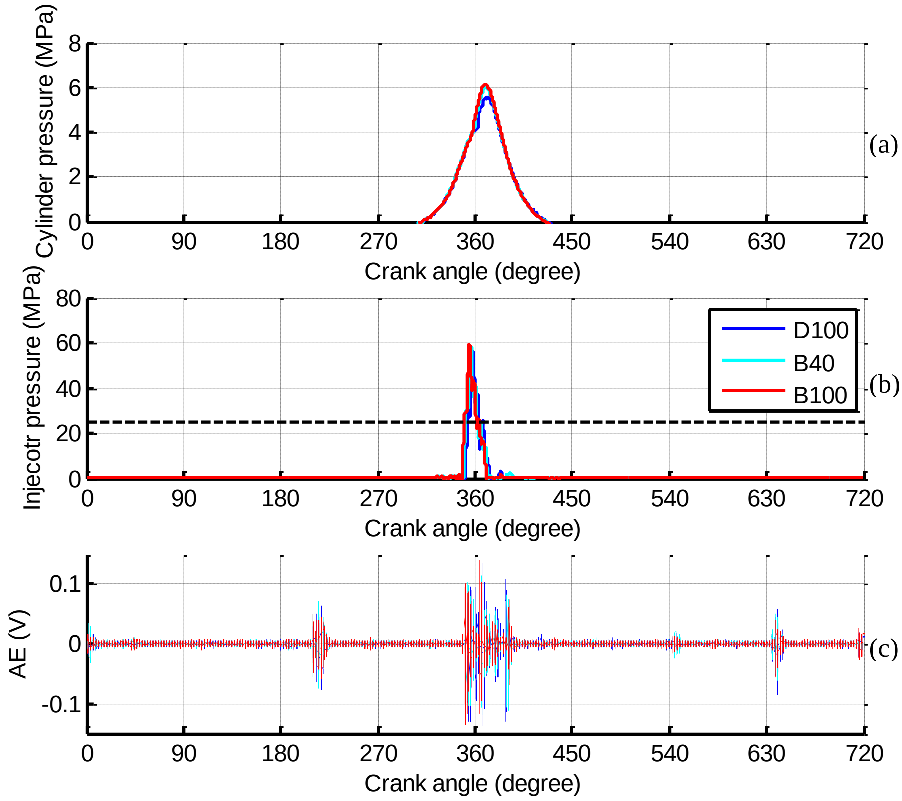


**Figure 6.1 Signal contrast in one revolution at speed of 1300 rpm and torque of 210 Nm using B100 (a) cylinder pressure, (b) injector pressure and (c) AE signal**

The signals for biodiesel fuels (B40 and B100) are converted to angular domain and presented together using the same methods as explained in Section 5.1. Then, the cylinder pressures, injector pressures and AE signals in one revolution under a typical engine running condition (1000 rpm, 210 Nm) are plotted together for comparison, as shown in Figure 6.1. In general, the waveforms of these three signals by using different fuels are rather similar. For cylinder pressure and injector pressure, they start rising at approximately the same angle position and reach their own peaks at similar angle. For AE signals, the events described in Figure 5.1 for diesel fuel can be noticed near similar angle positions for B40 and B100.

In the meantime, small differences can be observed in Figure 6.1 for all these three signals especially in the injection process. Thus, magnified view of the injection stage is presented in Figure 6.2 to study the injection process in detail.

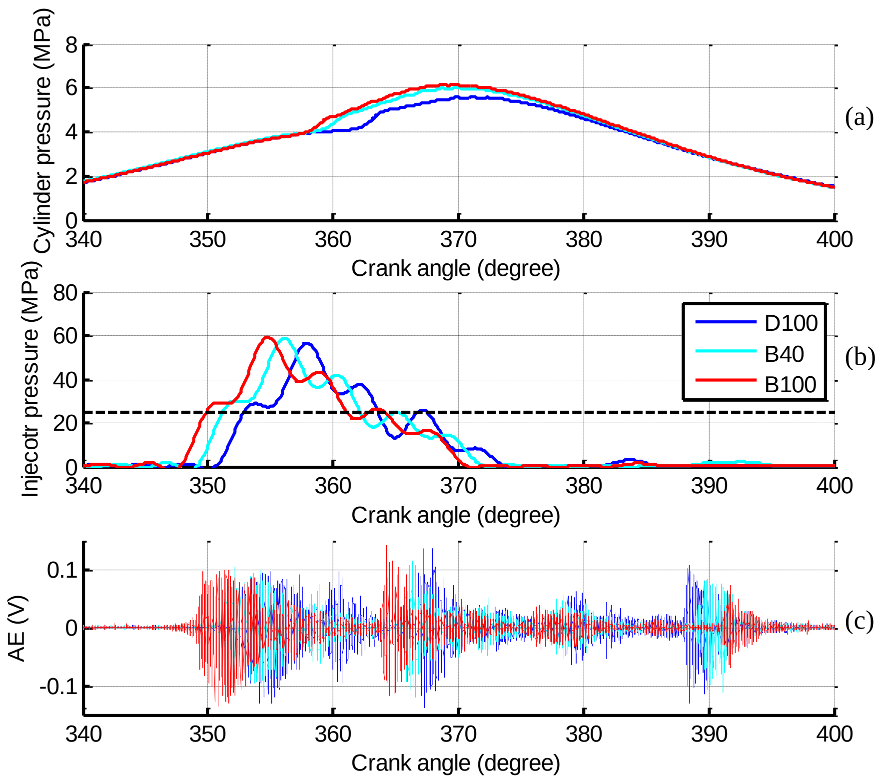


**Figure 6.2 Signal contrast during the injection stage at speed of 1300 rpm and torque of 210 Nm (a) cylinder pressure, (b) injector pressure and (c) AE signal**

From the cylinder pressure in Figure 6.2(a), it can be clearly seen that the starting point of combustion has been brought forward with increase of biodiesel ratio in the fuel. This can be explained by the earlier open of injector as presented in Figure 6.2(b). Besides, it can be noticed from cylinder pressure that the signals are almost the same during the injection process. A potential explanation for the earlier open injector might be that the biodiesel fuels have higher density and viscosity, therefore, the force from the pump can be more efficiently used for raising the needle with less damping loss. In other words, the injector can be open by a smaller static injector pressure for biodiesel fuel.

From the AE signals shown in Figure 6.2(c), significant AE events can be observed at the crank angle corresponding to injector open and close. It can be clearly noticed that the injector open and close angle has been brought forward with the increase biodiesel ratio in the fuel.

For the signal peaks changing, the peak of cylinder pressure increases a bit with the increase of biodiesel ratio while there exists a small increasing trend for the peak of injector pressure and the peak of AE signal during injector open period. The increasing of AE events can be explained by the higher density and viscosity of biodiesel reduces the damping performance, thereafter, there exist a more severe mechanical impact between needle end and backstop for the fuel with higher biodiesel ratio.

From the above analysis, it can be seen that biodiesel fuel has caused similar events on the cylinder pressure, injector pressure and AE signals as the diesel fuel does. In the meantime, the fuel difference has caused observable differences in the injection process on all these three signals. Therefore, they can be employed for monitoring the injection process for different fuels. Especially, it is more meaningful for the AE signals considering their nonintrusive feature.

## 6.2 Acoustic Emission Signal Characteristics for B40 and B100

In this section, the cylinder pressure, injector pressure and envelope of AE signal are compared together for various engine running conditions based on B100 and B40 to check if they have similar changing trend as the diesel fuel. As there are too much figures if all the conditions are compared as those in Section 5.2, here only signals under one typical condition are compared.

### 6.2.1 Acoustic Emission Signal Characteristics under Different Loads

The load variation comparison of cylinder pressure, injector pressure and envelope of AE signal at speed of 1300 rpm for B40 and B100 are presented in Figure 6.3 and Figure 6.4, respectively. In general, the signal trends are rather similar as those in Figure 5.6 for diesel. Similar as the diesel fuel analysis, the event starting angle and signal peaks will be employed in the following analysis.

- **Event Starting Angle**

From the injector pressure comparison, it can be clearly seen that the injector open angle is delayed with the load increases for both B40 and B100, which is similar as the diesel fuel. The explanation also lies in the larger force requirement under higher loads and the pump needs longer time to let the injector pressure reach the required needle raising threshold.

Similarly, the injector open angle delay information can be clearly noticed from the first peaks of AE envelope signal for both B40 and B100 as shown in Figure 6.3(b) and Figure 6.4(b). In addition, it can be noticed that the combustion starting time delays as well for both B40 and B100 as shown in in Figure 6.3(a) and Figure 6.4(a).

- **Signal Peaks**

The injector peak pressure increases obviously with loads for both B40 and B100 as shown in in Figure 6.3(b) and Figure 6.4(b), which is similar as the diesel fuel in Figure 5.6(b). For the cylinder pressure before combustion, the peaks has increased with loads for both B40 and B100 while the cylinder pressure after combustion, the peak at 210 Nm is higher than that of 105Nm and 315 Nm for both B40 and B100.

Similar as diesel fuel in Figure 5.6(c), the peak AE envelope signals of B40 and B100 show a decreasing trend with increase. The fuel softening effect can be used to explain this decreasing trend as well.

From the above analysis, it can be seen that the signal characteristics under different loads for B40 and B100 are rather similar as those for diesel fuel.

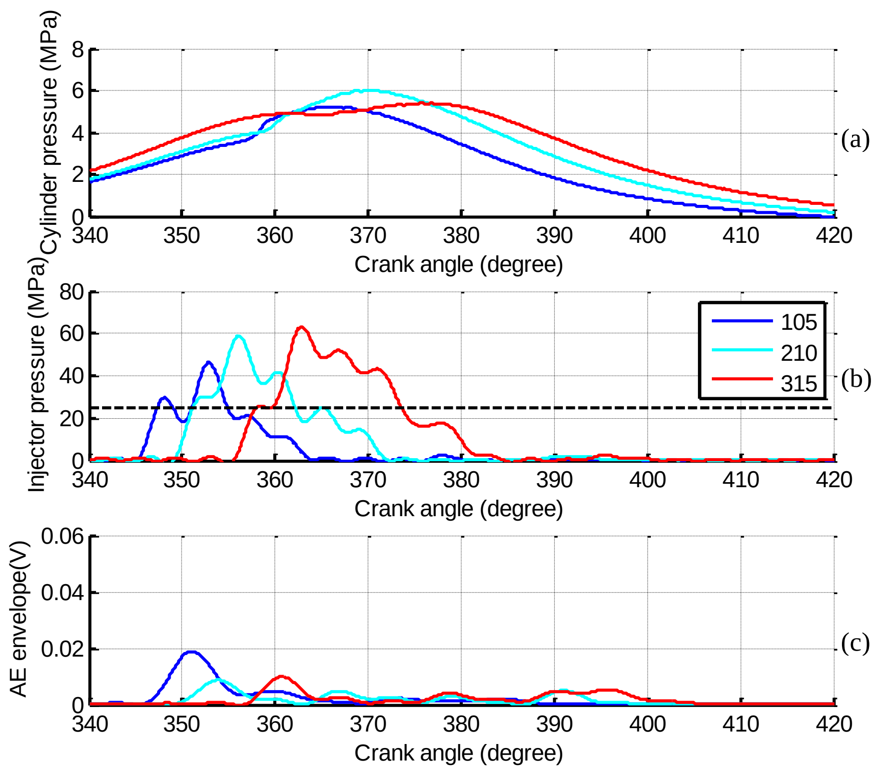


**Figure 6.3 Load variation comparison for 1300 rpm using B40 (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

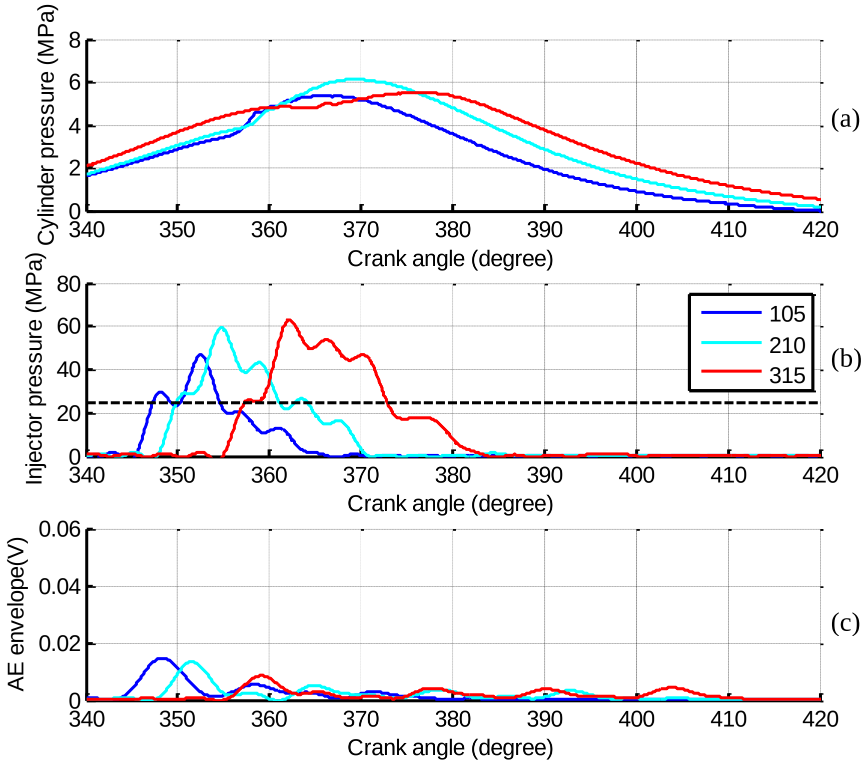


**Figure 6.4 Load variation comparison for 1300 rpm using B100 (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

### 6.2.2 Acoustic Emission Signal Characteristics at Different Speeds

The speed variation comparison of cylinder pressure, injector pressure and envelope of AE signal at load of 210 Nm for B40 and B100 are presented in Figure 6.5 and Figure 6.6, respectively. In general, the cylinder pressure and injector pressure trends are rather similar as those in Figure 5.9 for diesel while the AE signals show a bit different trend. Similarly, the event starting angle and signal peaks will be analyzed.

- **Event Starting Angle**

For the injector pressure comparison in Figure 6.5(b) and Figure 6.6(b), the injector open angle delay information for B40 and B100 is the same as that for diesel in Figure 5.9(c). Similar as that for diesel, the engine timing mechanisms and higher cylinder pressure can explain the delay.

Similar as the injector open estimation from AE envelope in Figure 5.9(c), the delay for speed increasing from 1300 rpm to 1600 rpm can be found for both B40 and B100 in Figure 6.5(c) and Figure 6.6(c). A small difference exists on the B100 where the delay for speed increasing from 1000 rpm to 1300 rpm can be found as well.

Similar to the diesel fuel analysis in Figure 5.9(a), the combustion starting time delay can be found for B40 and B100 in Figure 6.5(a) and Figure 6.6(a).

## ➢ Signal Peaks

The injector peak pressure increases obviously with speeds for both B40 and B100, which is the same as that for diesel. This can also be well explained by the increased cylinder pressure during injection stage as shown in Figure 6.5(a) and Figure 6.6(a). For the cylinder pressure, the waveform for B40 is rather similar as diesel while B100 show a bit different change. But overall, an increasing trend before combustion starting point can be found on all three types of fuels.

Similar as the injector open peak analysis for diesel in Figure 5.9(c), the injector open peak at 1000 rpm is difficult to estimate for B40 while it can be well identified for B100. A decreasing trend can be found in the identified injector open peaks. The better damping performance at high injector pressure can well explain this phenomenon.

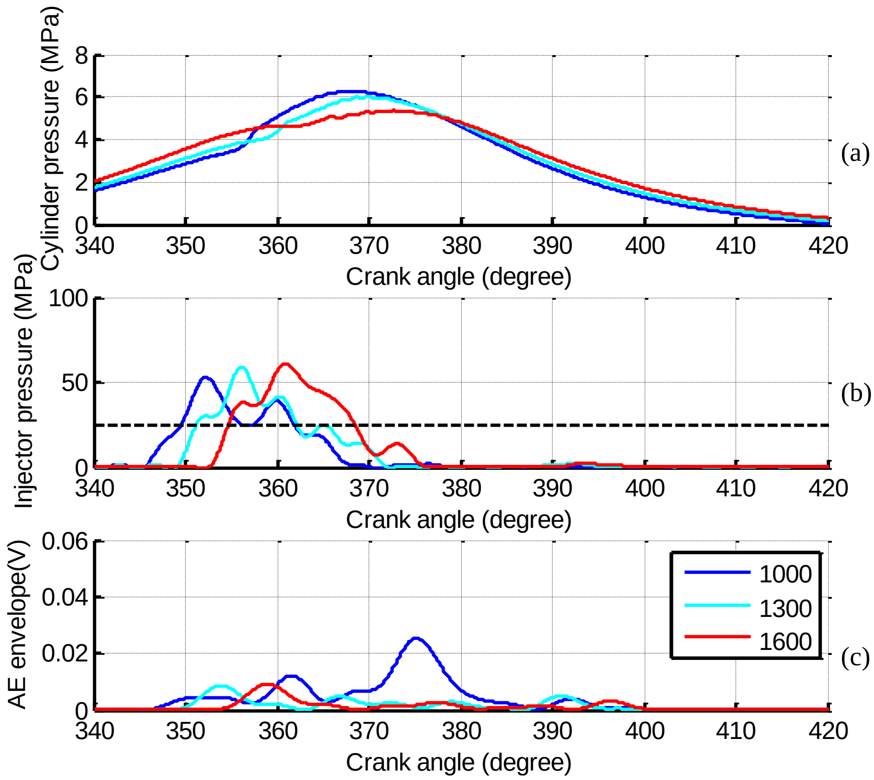


**Figure 6.5 Speed variation comparison for 210 Nm load using B40 (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

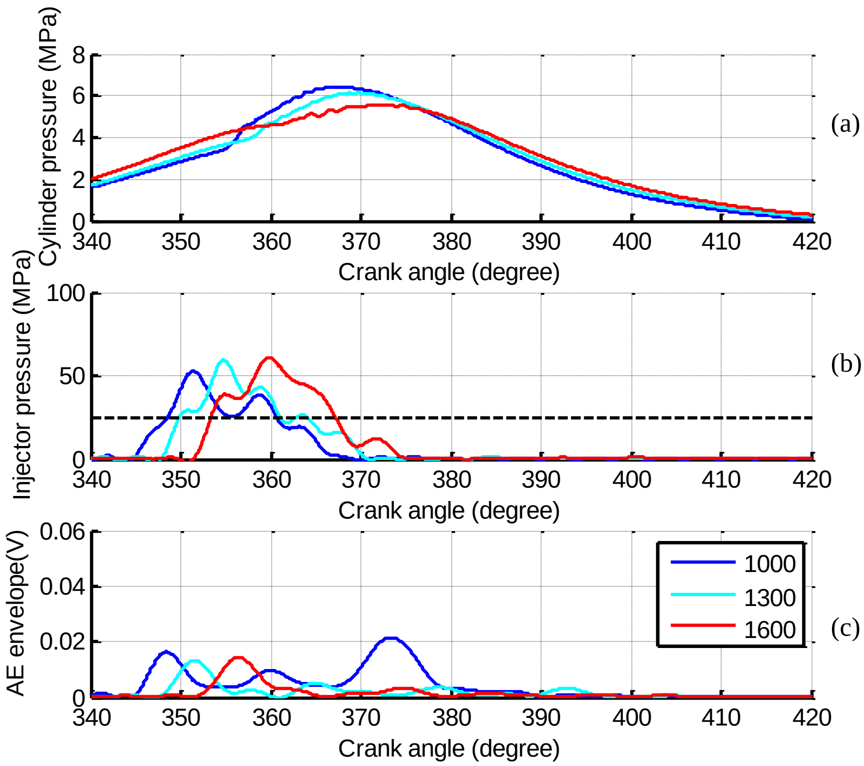


**Figure 6.6 Speed variation comparison for 210 Nm torque using load using B100 (a) cylinder pressure, (b) injector pressure and (c) envelope of AE signal**

## 6.3 Injection Parameter Estimation

Based on the analysis in last two sections, it can be seen that AE events are highly related with the injection process for biodiesel fuel (B40 and B100) as well. In this section, the same estimation method for diesel fuel analysis will be employed for estimating injection parameters from both injector pressure and AE envelope.

### 6.3.1 Estimation Based on Injector Pressure

The injector open and close crank angle information for both B40 and B100 are extracted and plotted in contrast with that for diesel, as shown in Figure 6.7. In general, the increasing trends of open and close angle for all the fuel types are rather similar and the event for the fuel contain higher biodiesel at the same engine running condition is delayed compared to corresponding one for the fuel contain less biodiesel.

It can also be observed that the open crank angle distributes between 340° and 365° and the close crank angle lies between 350° and 385°.

Based on the open and close angle information in Figure 6.7, the injection duration are calculated and presented in Figure 6.8, where the duration are expressed in both angle and time. In general, the injection duration angle for B40 and B100 increases with loads as the similar for diesel.

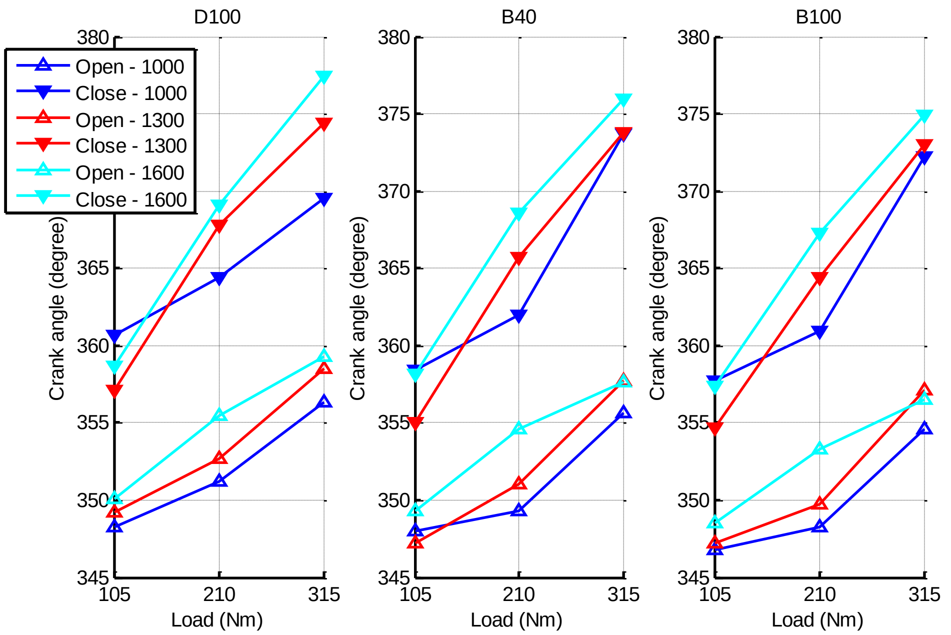


**Figure 6.7 Injector open and close time trend for (a) diesel, (b) B40 and (c) B100**

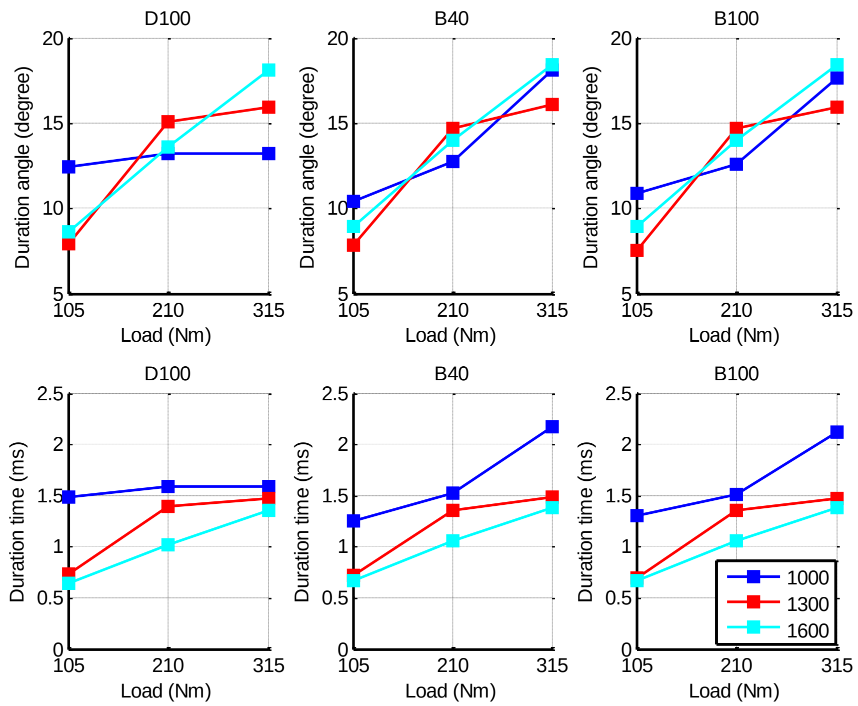


**Figure 6.8 Injection duration**

**Similar as**

Figure 5.14, the maximum injector pressure for B40 and B100 are extracted and compared with that for diesel as shown in Figure 6.9. As it shows, the maximum injector pressure increases with the loads for all fuel types. For the load of 210 Nm and 315 Nm, it also increases with speeds for all fuel types while the trend is different for different fuels at load of 105 Nm. Moreover, the maximum pressure for the fuel contains higher biodiesel at the same engine running condition is relatively larger than the corresponding one for the fuel contains less biodiesel.

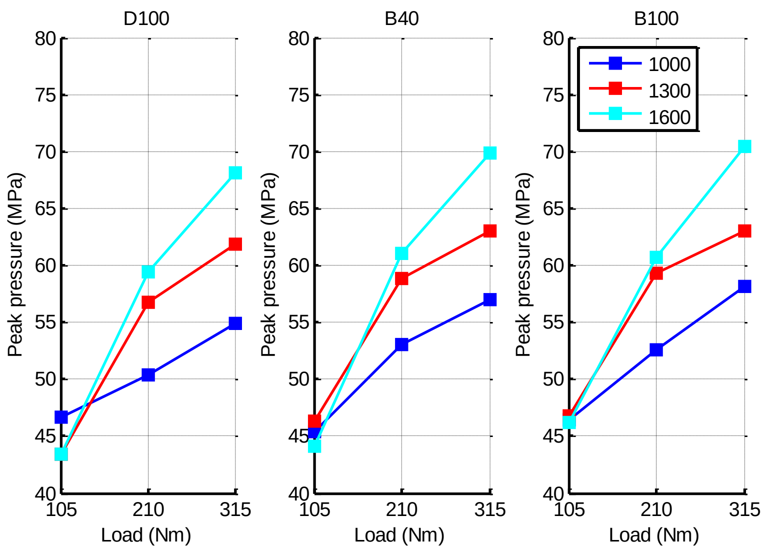


**Figure 6.9 Peak injection pressure (a) diesel, (b) B40 and (c) B100**

### 6.3.2 Estimation Based on Acoustic Emission

By using the same method employed in Section 5.3.2, the injector open and close angle information for B40 and B100 are estimated from their own AE envelope signals and plotted together with those for diesel, as shown in Figure 6.10. It can be observed that the open angle information for all fuels is well estimated and has good conformity with the estimation from injector pressure in Figure 6.7. In the meantime, the estimation for the close angle is not so good.

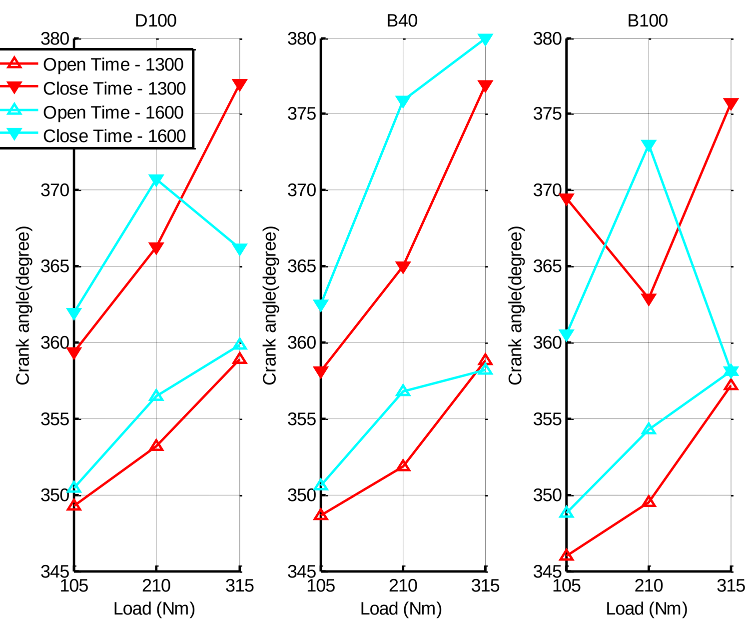

**Figure 6.10 Injector open and close angle trend for (a) diesel, (b) B40 and (c) B100**

Similar as Figure 5.19, the peak ratio changing trends of AE envelope at injector open for B40 and B100 are extracted and compared with those for diesel as shown in Figure 6.11. It can be observed that there exists a similar decreasing trend for three types of fuels at speed of 1600 rpm while trend at speed of 1300 rpm varies for different kinds of fuels.

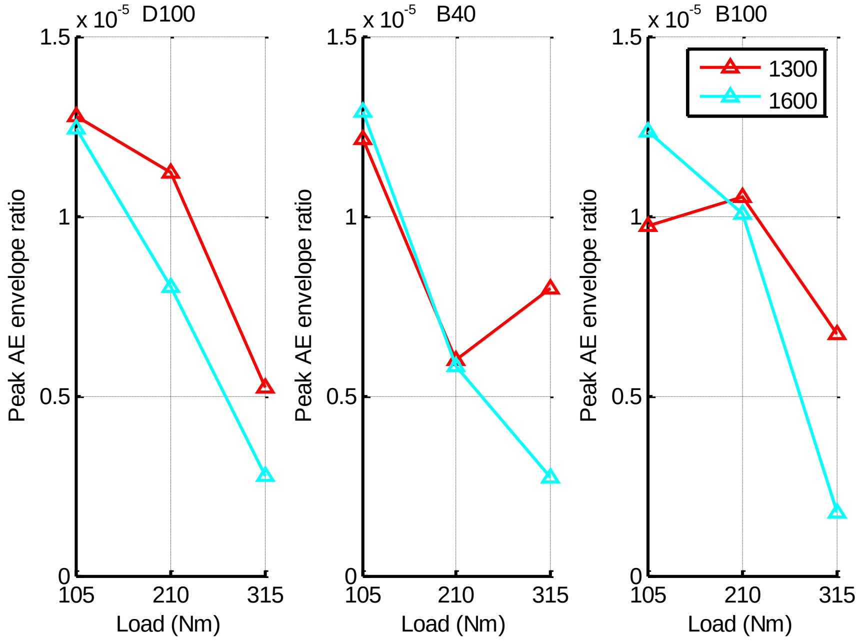


**Figure 6.11 Peak injection pressure (a) diesel, (b) B40 and (c) B100**

# Chapter 7 Conclusions and Future Works

This chapter summarizes the key findings from the research carried out on AE based fuel injection diagnostics and highlights the future work plan.

## 7.1 Conclusions

Based on the studies fulfilled to date, the following main conclusions can be drawn:

1) As a non-intrusive technique, the acoustic emission measured close to injector shows useful information regarding to fuel injection process.
2) The key characteristics of injection process, including open angle, close angle and impact strength, have high correlation with the AE signals. However, this is difficult to be observed when the engine speed is low because of the weak effect of needle impacts.
3) The engine load and speed variation can cause observable differences on the cylinder pressure, injector pressure and AE signals. In general, the increase in load causes obvious delay on the injector opening and closing angle, increase on the injector pressure and decrease on the first AE envelope peak.
4) The increase of injector pressure can soften the needle impacts, which consequently can reduce the strength of AE signal in the opening stage.
5) The higher percentage of biodiesel in the fuel causes earlier injector opening and closing angle and higher peak injector pressure.
6) The envelope of AE signal has good performance in highlighting key AE events and hence allowing the estimation of the injector open angle for all fuel types, whose predicting results have good conformity with those estimated from injector pressure.
7) AE peaks for pure biodiesels show little increase in amplitudes in spite of higher peak pressures compared with normal diesel fuel, showing that biodiesel induce little mechanical impact because of its softening effect of high viscosity.
8) Amongst the possible AE sources in a multiple cylinder engine, the combustion process exhibits the dominated one. It is possible to diagnose combustion based on the characteristics of this AE event.

## 7.2 Contribution to Knowledge

1) AE measurements are confirmed to be effective for the first time in diagnosing fuel injection process.
2) The use of envelope analysis is effective for highlighting AE events relating to injection process.
3) AE signals of injector are mainly from needle impacts due to its rapid opening and closing. Little evidence is found that AE can be induced by the effect of friction between the needle valve and the nozzle body and that of fluid shearing.

4) There is little increase in AE amplitudes by injecting biodiesels, which is novel a finding as most of previous studies believe that higher injection pressure could induce high impacts in comparison with normal diesel fuel.

## 7.3 Future Works

1) Build a mathematic model for the injection process to understand the AE characteristics for different loads, speeds and fuel types.
2) Use more advanced techniques, like adaptive wavelet, to reduce the noise interference on the AE signal and achieve better injection parameter estimations.
3) Further estimation on using alternative fuels, like the experiment result based consequence of forward injection and higher injector internal pressure and so on.
4) Use more techniques to determine the influence level from mechanical impact and fluid flowing to figure out the AE events in each cylinder work cycle.

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