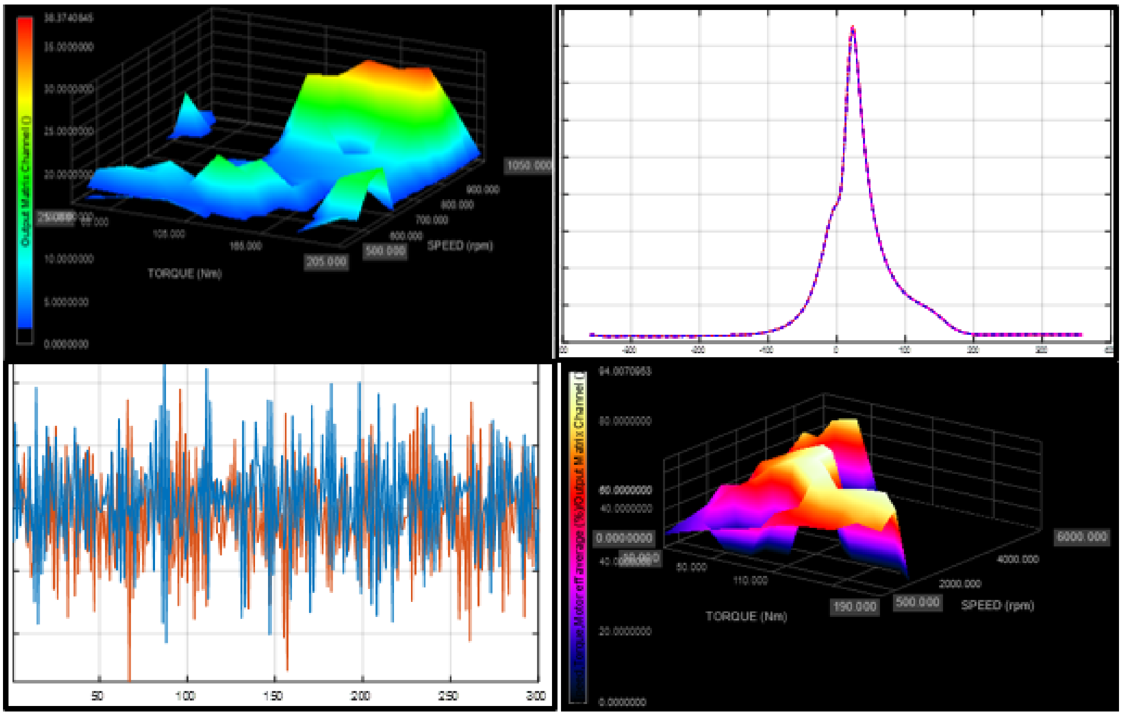
CHALMERS
UNIVERSITY OF TECHNOLOGY



Developing interface using C++ language to visualize efficiency of hybrid power train and comparison between DEWESoft and AVL Data acquisition systems

Master's thesis in Automotive Engineering - MPAUT

AIJAZ AHMED
AJANISH LUTIMATH

DEPARTMENT OF MECHANICS AND MARITIME SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

MASTER'S THESIS 2021

Developing interface using C++ language to visualize efficiency of hybrid power train and comparison between DEWESoft and AVL Data acquisition systems

Master Thesis in Automotive Engineering

AIJAZ AHMED
AJANISH LUTIMATH

Department of Mechanics and Maritime Sciences
Division of Combustion and Propulsion Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

Developing interface using C++ language to visualize efficiency of hybrid power train and comparison between DEWESoft and AVL Data acquisition systems
Aijaz Ahmed
Ajanish Lutimath

Industrial Supervisor: Sergej Abyzov
Support, Application and Calibration Engineer
DEWESoft AB Gothenburg office Importgatan 7, 422 46 Hisings Backa, Sweden

Academic Supervisor : Jayesh Khatri
Division of Combustion and Propulsion Systems,
Mechanics and Maritime sciences, Chalmers University of Technology

Examiner: Petter Dhalander
Assistant Professor,Division of Combustion and Propulsion Systems,
Mechanics and Maritime sciences,Chalmers University of Technology

Master's Thesis 2021
Department of Mechanics and Maritime Sciences
Division of Combustion and Propulsion Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

Developing interface using C++ language to visualize efficiency of hybrid power train and comparison between DEWESoft and AVL Data acquisition systems
Master Thesis in Automotive Engineering
AIJAZ AHMED
AJANISH LUTIMATH
Department of Mechanics and Maritime Sciences
Division of Combustion and Propulsion Systems
Chalmers University of Technology

Abstract

Presently the light-duty vehicle fleet is going through substantial technological changes in the past few years with new power-train design, alternative fuels, and electrification. Due to the overall efficiency, drivability, stability, quality of comfort, and stringent emission laws. In the Automotive industry, major research is carried out to study the overall efficiency of individual power-train. To carry out the research on these vehicles the major equipment required is the data acquisition system. Data acquisition systems are used in every field of engineering to test, measure, and perform research in terms of performance, safety, and reliability.

The main purpose and first objective of this thesis is to develop an interface using C++ language to visualize the efficiency of a hybrid powertrain online and implement it in the DEWESoft software, along with which we will be exploring the measurement techniques, sensors, DAQ hardware, and software used. The models calculate the efficiency in [%] sample-based and also average based for number of samples, time duration, and number of cycles in the case of Internal combustion engine. A 3D surface plot to visualize Speed [rpm], Torque[Nm], and efficiency [%] on X, Y, and Z-axis respectively is a major deliverable. As presently the software lacks visualization. For the study, a thorough collection of experimental data related to the hybrid vehicle will be done at the Chalmers test cell. The significant parameters such as speed[rpm], torque[Nm], fuel flow rate [g/sec], phase,frequency[Hz], three-phase current[A] and voltage[V] are recorded using DEWESoft DAQ systems.

The second objective of this thesis is to compare two different DAQ systems i.e., AVL and DEWESoft under standard test conditions. For the study, a 3cylinder SI engine will be used at the Chalmers test cell to record the In-cylinder pressure as a function of crank angle degree.

As a result of the first objective, the validated C++ models implemented in the DEWESoft software, which determines the efficiency [%] are delivered. In the future, these models can be used in the field of research and development for hybrid and electric vehicles. The major findings for the second objective are different parameters which influence the recording and post processing of in-cylinder pressure data as a function of CAD. A thorough investigation and data analysis of two different DAQ systems, and comparison of measurement accuracy is presented in the report.

Keywords: Data acquisition systems(DAQ), C++, Efficiency, Data analysis.

Contents

Nomenclature

ω	is the rotational speed	rad/sec
$\dot{m}_{fuel}$	mass flow rate of fuel	g/sec
η_f	Fuel conversion efficiency	%
ω	Speed,	rpm
τ	Torque	Nm
A/D	Analog to Digital	–
BDC	Bottom Dead Centre	–
$BSFC$	Brake specific fuel consumption,	$g/kWhr$
CAD	Crank angle degree	–
CI	Compression ignition	–
COV	Co-efficient of variation	–
DAQ	Data Acquisition	–
EM	Electric motor	–
f	Current	Hz
F_{max}	Maximum frequency	Hz
F_s	Sampling frequency	Hz
G_a	Amplifier gain	–
G_s	Transducer gain	–
$HEVs$	Hybrid-electric vehicles	–
I	Current	$Ampere$
i_o	Final drive ratio	–
i_x	Respective gear	–
ICE	Internal combustion engine	–
N	Speed	RPM
N_r	Rotor speed	rpm
N_s	Synchronous speed	rpm
P	Power	kW
P_f	Frictional losses	kW
P_h	Hysteresis losses	kW
$PHEV$	Parallel-hybrid electric vehicle	–
Q_{LHV}	Lower heating value of fuel	–
R_a	Rotor Resistance	Ohm
SI	Spark ignition	–
T_{wheel}	Wheel Torque	Nm
TDC	Top Dead Centre	–
U	Voltage	V
V_{ch}	Voltage output	V

V_{speed}	Vehicle speed	kph
W_{radius}	Wheel radius	m

List of Figures

List of Tables

1
Introduction

1.1 Background

In today's modern world no one would consider building or conducting research on vehicles, equipment used in the medical field, large- and small-scale machinery, etc without involving the Data acquisition systems (DAQ). Any system or device will have many different mechanical and electrical phenomena, and these will be dynamic in nature. These complex phenomena have to be recorded and preserved for later study which is accomplished by DAQ systems [2]. The DAQ systems play an important role in the field of testing and research of different devices in terms of performance, safety, reliability, and durability[dewe]. To name a few physical phenomena pressure, vibration, and temperature can be measured by transducer or sensor. Real-time data acquisition systems help diagnose and solve problems more effectively. This system works by allowing the technician to monitor and analyze the machine's performance without delay. By automating the data capture process, it eliminates the need for humans to enter data into a machine[2]. This procedure is also more secure. Data acquisition procedures help improve processes and procedures, which can lead to faster response times to issues.

Around the world today light-duty vehicle fleet is going through substantial technological changes with new powertrain design, alternative fuels, and electrification. we need vehicles that have higher energy efficiency and lower tailpipe emissions. As we know that the vehicle emissions contribute a major part to the greenhouse gas effect, hence most of the automobile manufacturers are moving towards hybrid and electrification in order to reduce the greenhouse gas effects and achieve a sustainable mode of transportation. Hybrid and electric drivetrains have various features that make them very different from the combustion only systems. For instance, they use regenerative braking. This braking technology generates power back to the battery and is stored for later use. There are various subsystems such as engine, transmission, and charging system among others. These components are often interconnected to form a single onboard computer (MCU)[7]. To achieve these milestones testing of the present technology and researching what modification should be done for technological up-gradation can be achieved with the help of a data acquisition system, as it has become a complex part with all the interconnected systems.

DEWESoft is a company dealing with data acquisition, measurement and analysis for this project DEWESoft data acquisition system and measurement instruments will be used.

Presently there are many different brands of data acquisition systems available in the market, A best DAQ system is one that has the following features such as input measurement channels, sampling rate or scanning speed, switching time, resolution, accuracy, Channel count, and configuration flexibility, System throughput, and Instrument Inputs and Outputs, software, and online visualization. DEWESoft manufactures different DAQ systems for various test systems. for our project we will be using the DEWESoft vehicle testing systems with the combustion and power analyzer software[8].

1.2 Data Acquisition system

Data acquisition is defined as the process by which the data from the real-world physical phenomenon is captured and recorded in digital format. These digital signals can be manipulated by the computer.DAQ systems not only provide real-time data but also can record the data which can be later used for post-processing and analysis. The overview of the basic DAQ system is as shown in the Figure 1.1 [8].

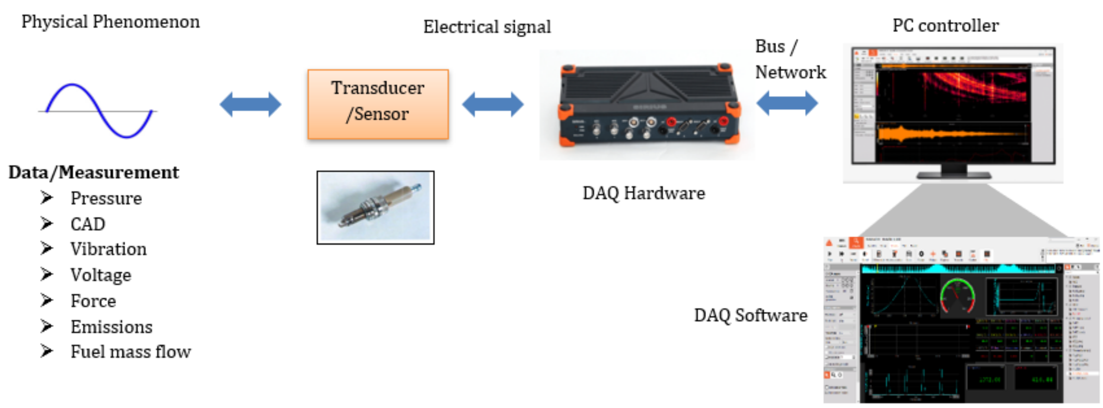


Figure 1.1: *Data Acquisition system overview [1]*

The real-world physical phenomenon such as temperature, pressure, voltage, current, vibration, crank angle degree and force, etc can be measured by the DAQ system.

1.2.1 Sensor and Transducer

The Sensor and Transducer are the physical links for the data acquisition system which converts the physical phenomenon from the real world into readable electrical signals. A sensor is a device that senses the change and provides the reading in the same format. These are used in our everyday life, for example, a mercury thermometer is one of the oldest temperature sensor used. A transducer is a device that converts one form of energy to another form. An example of a common device to measure In-cylinder pressure is a piezoelectric transducer which converts the pressure or strain into an electrical charge which can be further measured [9].

1.2.2 Signal conditioning

The output signals generated by most of the transducers and sensors should not be connected to analog to digital converters. As the generated signal would be very low or high above the measurable range and prone to noise signals and are likely to get corrupted. The Figure 1.2 below illustrates the signal conditioning functions which include amplification, filtering, isolation, and other specific functions. It is integrated into the DAQ device[8].

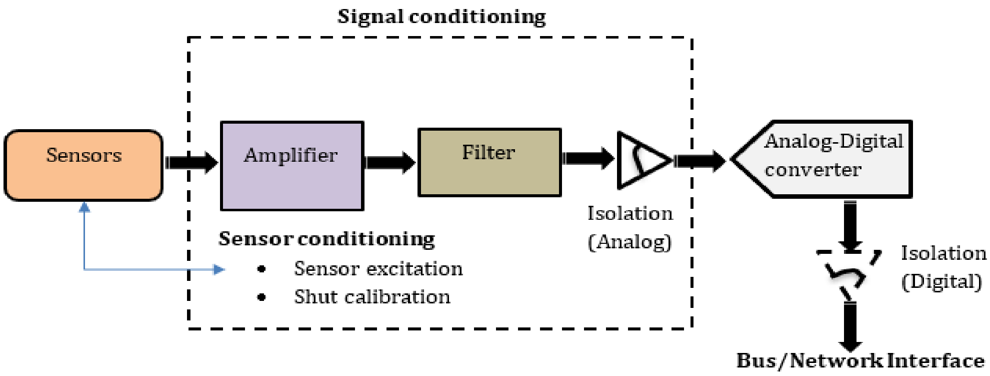


Figure 1.2: *Signal conditioning includes amplification, filtering, and isolation[2]*

.

1.2.3 Hardware and Software

Common DAQ systems will have multi inputs and multi outputs which combines both analog and digital inputs and outputs, and counter timer inputs/outputs. In the latest modular DAQ systems, the individual model is designed for a single function but can be mixed and matched for multi-functions.

Software and visualization are crucial since they improve the readability of data and makes displays even more configurable to satisfy every user's preferences.

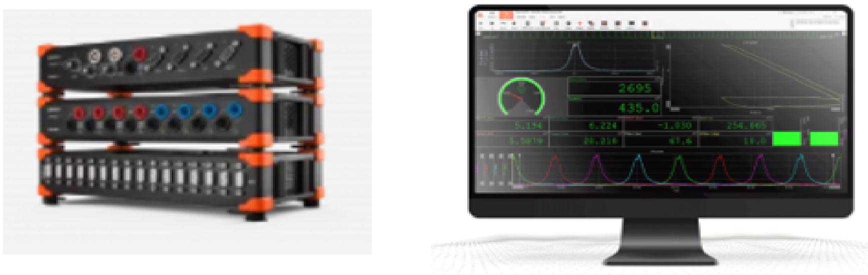


Figure 1.3: *DEWESoft DAQ system hardware and software.*

1.2.4 Features

The important features which are to be considered when selecting a DAQ system are listed below [1][10]:

1. **Accuracy and Resolution**: The major feature of any DAQ system is the conversion of data i.e., analog signals into digital format and vice-versa. which is done by the analog to digital converters, the A/D converter is the interface between the real world and the digital computation[2].

Figure 1.4: *Analog to digital converter [1]*

Accuracy here relates to how close the digital binary code matches to the incoming or the outgoing analog signal and resolution is the spacing between each data point.

2. **Sampling rate**: The sampling rate is the number of data points acquired per second, it is also known as sampling frequency. for example, a sampling rate of 1000 samples means that 1000 discrete data points are acquired every second by the DAQ.

3. **Bandwidth**: It is the maximum frequency (F_{max}) that can be analyzed, and bandwidth is half the sampling frequency. In simple words the Nyquist criterion, which is stated as the repetitive waveform which can be correctly reconstructed if the sampling frequency is two times the highest frequency contained in the signal or else the critical information about the signal is actually lost[10]. **Bandwidth** $= F_{max} = 1/2\ F_s$.

4. **Signal conditioning**: The process of modifying the output signals of a sensor is known as signal conditioning as shown in Figure 1.5. Signal conditioning is essential when dealing with electrical interference or noisy signals. The DAQ systems should consist of physical filters in the hardware and also digital filters which are of four types low pass, high pass, bandpass, and band-reject filters.

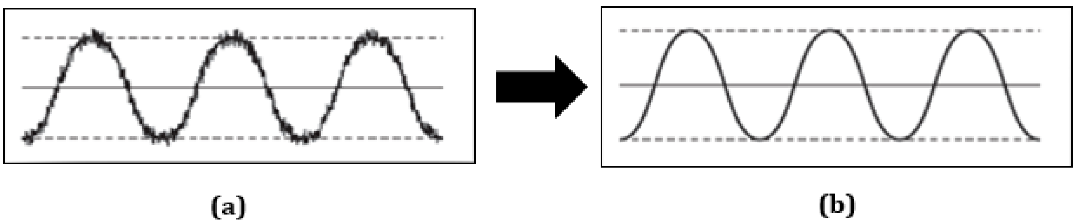


Figure 1.5: *(a) Noisy signal (b) Filtered signal*

5. **Input channels**: Input channels basically means number of channels available on the DAQ systems or number of devices, which can be connected to the DAQ system. In the modern DAQ number of channels range from 2 to 268.The channels can be single ended (SE) or of differential type (DI)[2].
6. **Software**: Software application that allows you to acquire analog data, plot it during acquisition, analyze it, and save it to disk for later analysis.

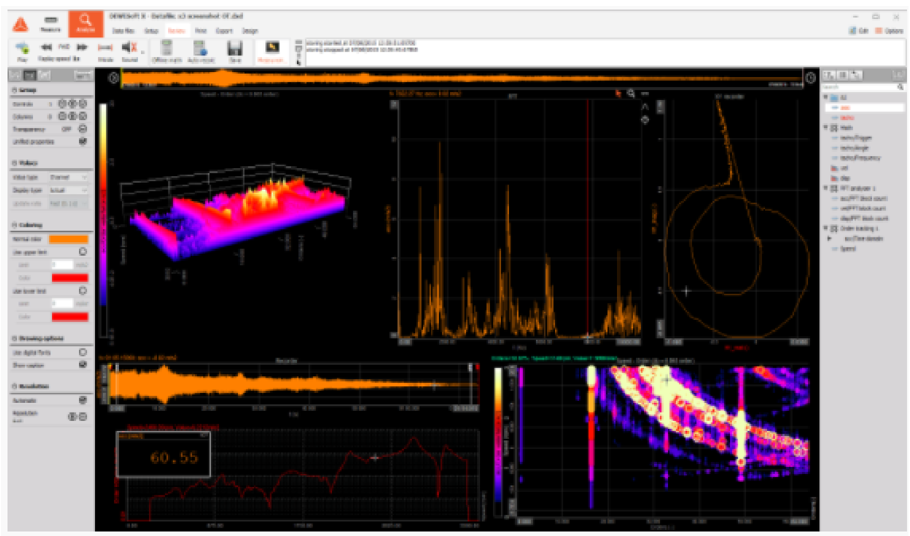


Figure 1.6: *Software application[1]*

1.3 Applications of DAQ systems

The application of DAQ systems is wide spread among the various fields of engineering, few of them are listed below [2]:

1. **Testing and measurement**: DAQ systems are used to test any electro-mechanical devices. In the automotive field, DAQ systems are used to test the vehicles for their performance, safety, and reliability and to measure the vibrations, emissions (conserve the environment), and temperature (for human comfort).

2. **Research and Development**: DAQ systems play a vital role in the field of research and development. They are used for Ozone profiling, Polar ice thickness measurements, Space shuttle launch pads monitoring, radar waveform sampling and processing, and also for increasing the performance of vehicles and reduce emissions.

3. **Large and small scale industries**: Every large and small scale industries have rotating equipment such as Vibro-feeders, induced draft fans, pumps, belt and chain conveyors, pipeline testing etc. DAQ systems are used for condition-based monitoring of the equipment minimizing unexpected break-downs and maintain the maximum production rate also ensuring the safety of equipment and personnel.

4. **Medical field**: DAQ systems are used for Ultrasonic medical imaging systems, Ultrasound imaging, laser scanning for eye diseases, and optical spectroscopy.

1.4 Aim and objectives

This project had the following two different objectives. The first objective of the project was defined by DEWESoft and aims as stated below:

Objective 1: Development of an interface to visualize hybrid power train unit efficiency using C++ programming language and implementing the script in DEWESoft software

In this phase, the required measurement parameters and the type of DAQ hardware required to map the efficiency of the engine and motor will be defined and then the hybrid powertrain will be set up for testing at Chalmers test rig H. The hybrid powertrain is tested for the required data points with the DEWESoft data acquisition system. Thereafter C++ script will be implemented in the DEWESoft software for visualizing the instant overall efficiency of the drive train during the online Test-bed or real field testing. Further, the script will be validated with a test file.

The second objective of the project was defined by Chalmers University of Technology and aims as stated below:

Objective 2: Comparison between DEWESoft and AVL DAQ systems

Under standard test cell conditions for the required measurement points, the data will be recorded by the two different DAQ systems. subsequently, investigation of recorded data will be done for measurement accuracy and repeatability.

1.5 Deliverables

The major deliverables of this thesis project are:

1. Develop the interface using C++ programming language to visualize a 3D surface plot with speed [rpm] on X-axis, torque [Nm] on Y-axis, and efficiency [%] of internal combustion engine and electric motor on Z-axis.
2. The interface should be implemented in the DEWESoft software and should record the data sample and also the average the samples according to the user input.
3. Investigation of measurement accuracy and repeatability of two different data acquisition systems i.e., DEWESoft and AVL.

1.6 Limitations

1. The experimental data that was collected was from the Chalmers test rig.
2. The post-processing of the AVL data was done in MATLAB.
3. The Chalmers test rig did not support higher loads for Electric motor as a result, the test data was limited.
4. Limited availability of test cell, as the test cell was dismantled after the data was collected.
5. The load on the electric motor was controlled by varying the road gradient.
6. All the test data acquired for ICE and EM were from custom-built driving cycles.
7. The Torque[Nm] and Fuel mass flow rate [g/sec] could not be acquired using AVL DAQ system due uncertainty and equipment malfunction.

2

Theory

This section gives a brief introduction about the Data acquisition systems(DAQ), Parallel-Hybrid drive train, and importance of in-cylinder pressure in combustion diagnostics of the engine.

2.1 Hybrid Electric Vehicles

HEVs are the one which utilizes two power sources to propel the vehicle. One power source is an internal combustion engine (ICE) and the other one is electric motor(EM) powered by the battery. The Figure 2.1 below illustrates the concept of the hybrid drive train[3].

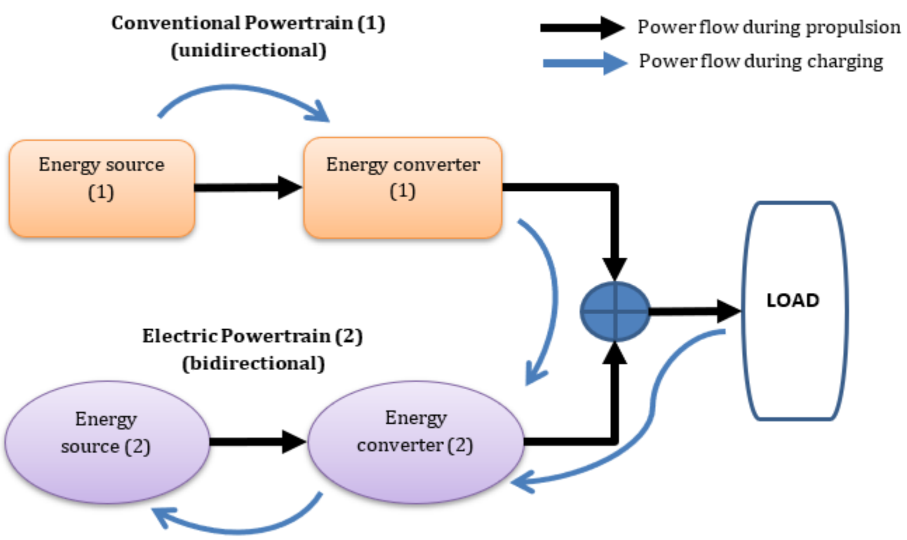


Figure 2.1: *Hybrid Electric Vehicles concept [3]*

The major advantages of HEVs are:

- High peak power and quick response of electric traction drive result in the high vehicle performance
- Downsized ICE and running at an optimal operating point along with recuperation of energy during braking leads to better fuel economy and lower emission rates compared to the conventional drive train.

- High energy density of petroleum fuel and convenient fuelling system offers faster refueling and longer operating range.

As the HEVs consists of two power sources, the configuration of the drive trains can be distinguished into three different types listed below:

1. Series HEV
2. Parallel HEV
3. Series-Parallel HEV

For this project, a PHEV with P 2.5 configuration is used for testing and analysis which is further elaborated:

2.2 Parallel hybrid vehicles

Parallel hybrid vehicles are the ones in which the vehicle can be propelled with an engine and motor when power demand is high, or with a motor and engine alone. There are four different driving scenarios with the PHEV:

1. Vehicle propulsion by only EM-Pure electric.
2. Vehicle propulsion by only ICE-Pure ICE.
3. Electric propulsion, but ICE is charging the battery.
4. All power sources both ICE and EM with battery.

Hybrid vehicles are generally classified as P1, P2, P2.5, P3 and several other configurations, here P represents the position of the motor in the vehicle architecture. The Figure 2.2 below illustrates the parallel hybrid drivetrain with configuration P-2.5, where the motor is integrated into the input drive shaft with dual-clutch transmissions[11].

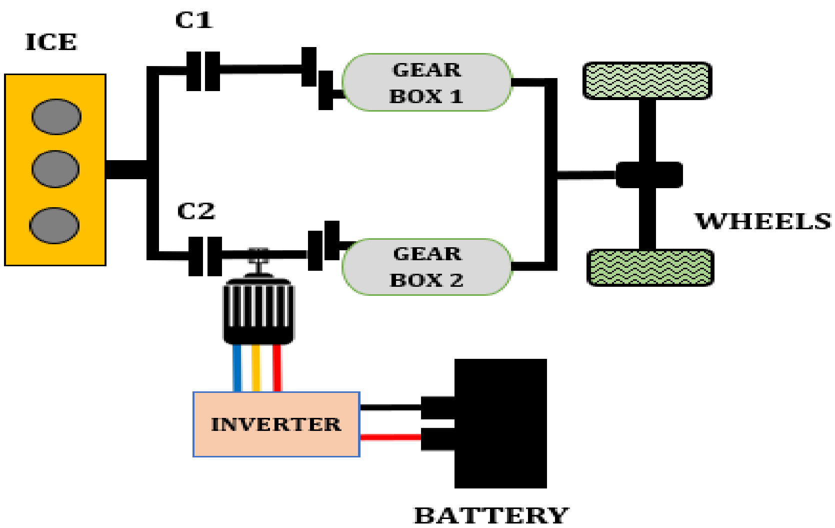


Figure 2.2: *Parallel Hybrid drive train*

2.3 Electric motor

The basic principle of working of an electric motor is described in this section. The motor consists of two main parts the stator and rotor. The stator is basically a three coil winding and three phases AC power input is supplied to the stator. The windings pass through the slots of the stator, which are made by thin highly permeable steel laminations inside the steel or a cast-iron frame. When a three-phase current passes through the windings, it produces a rotating magnetic field, this RMF causes the magnet to turn [12][13].
To understand how a rotating magnetic field is generated, consider a simplified stator winding wherein the coils are connected 120 degrees apart. We know that a wire carrying current carries a magnetic field around it. When a three-phase power is supplied to coils connected by 120 degrees, the magnetic field produced will be as shown in the figure.

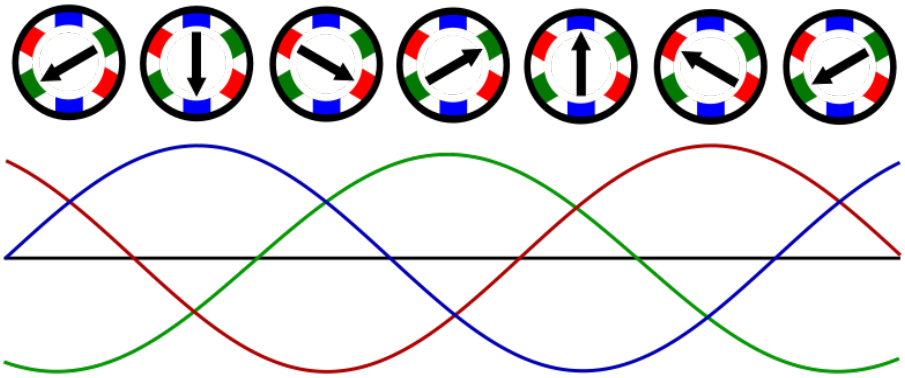


Figure 2.3: Rotating three phase magnetic field indicated by the black arrow

The rotating speed of the magnetic field is known as synchronous speed. With the squirrel cage rotor in place, when the 3 phase AC current passing through the stator produces a rotating magnetic field. This induces a current in the bars of the squirrel cage which is shorted by end rings, causing the rotor to rotate. To aid such electromagnetic induction, insulated iron core lamina are packed inside the rotor. Such small sizes of iron make sure that eddy current losses are minimum. The rotor speed is always less than the synchronous speed. The difference between the rotor speed and synchronous speed is known as slip[14].

2.4 Efficiency of Electric motor

The range of the electric motor usually depends on the efficiency of the motor, efficiency not only affects the range but also the performance of the electric motor. The losses in the electric motor can be both electrical and mechanical. This section deals with the various losses and how they can be modeled[13].

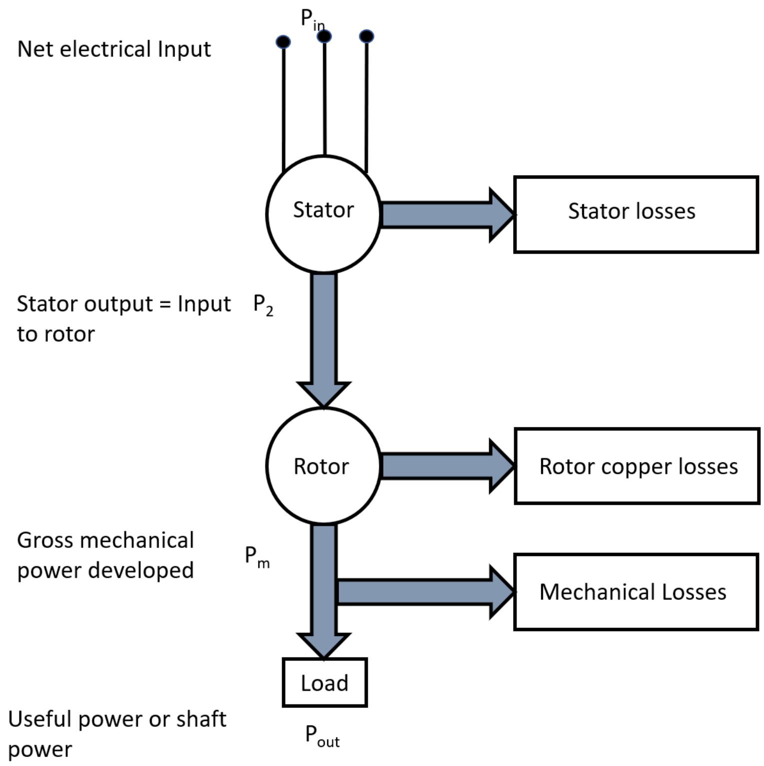


Figure 2.4: Power flow diagram of three phase IM

2.4.1 Copper losses

The input on the rotor is converted into mechanical energy, but the complete conversion is not possible due to copper losses. This type of loss is one of the biggest types of losses in the electric motor. These are also called winding losses or ohmic losses. This type of losses is present due to the resistance offered to the flow of the current in the primary and secondary windings. One way to reduce the copper losses is by increasing the cross-sectional area of the wire. The power of the copper losses in the rotor resistance is given by the following equation[14][13]:

$$P_c = I^2 * R_a \tag{2.1}$$

Where P_c is the power of the losses in the Rotor resistance of R_a and I is the current.

2.4.2 hysteresis losses

These losses are also known as magnetic losses as iron losses depend on the magnetic flux present in the machine. There are two types of iron losses. The first one is the hysteresis losses, as we know hysteresis is a phenomenon in which there is a continuous reversal of magnetization of a core. When the core material rotates in the magnetic field it changes its polarization direction, that is there is aligning and realigning of the magnetic dipoles in the material. As a result of this, there will frictional losses. The hysteresis power loss is given by the following equation[14][13].

$$P_h = k_h * f * B_{max} \tag{2.2}$$

Where P_h is the hystersis power loss, the frequency at which the field direction changes is represented by f. k_h proportionality constant. B_max is the maximum flux density.
Eddy current losses are the second type of losses in the iron losses. When the rotor is rotating in a magnetic field, which is nothing but a conductor is moving in a magnetic field. As a result of this EMF is induced on this, which results in circulation of current in this core. This induced current is known as eddy currents. The heat will be produced in the iron because of this current flowing through the core. This can be reduced by making the core stack of thin electric sheets. Eddy current loses can be given by the following equation[14][13].

$$P_e = K_e * (B_{max} * f * \delta)^2 \tag{2.3}$$

Where P_e is the power losses in the eddy current loss, K_e is the proportionality constant, f is the frequency at which field direction changes.

2.4.3 Friction losses and windage losses

The friction losses in the electric motor are mainly caused by the bearings in the rotor. The power in the friction losses is given by the following equation[14][13].

$$P_f = T_f * \omega \tag{2.4}$$

where P_f is the power losses due to friction, T_f is the constant resistive torque to the rotor, ω is the rotational speed.
Windage losses is the resistance that the rotor experiences when rotating. This losses is speed dependent. This is given by the equation mentioned below[13].

$$P_w = k_w * (\omega)^2 \tag{2.5}$$

P_f is the power losses due to windage, ω is the rotational speed.

2.4.4 Efficiency of EM

When all the losses are calculated, by plotting the speed vs torque curve the optimum operating or the most efficient operating point of the electric motor can be determined [14][13]. We know that the power that the motor delivers can be given by

$$P_out = T * \omega \tag{2.6}$$

where T is the torque, and ω is the rotational speed. The motor efficiency can be calculated by

$$E = (U_1 * I_1 * cos\phi + U_2 * I_2 * cos\phi + U_3 * I_3 * cos\phi) \tag{2.7}$$

where,
E is the Electrical power.
U_1, U_2, U_3 is three phase voltage.
I_1, I_2, I_3 is three phase current.
$cos\phi$ is the phase angle between the voltage and current.

$$M = (2 * \pi * N * T)/60 \tag{2.8}$$

where,
M is the Mechanical power.
N is speed.
T is Torque.

$$\eta = (M/E) * 100 \tag{2.9}$$

where,
η is efficiency of electric power

2.4.5 Slip calculation

Slip can be defined as the difference between the flux speed and rotor speed. The speed of the rotor in a motor is always less than the speed of the synchronous speed. The slip is calculated by the following equations[14].

$$Slip = (N_s - N_r)/N_s \tag{2.10}$$

where,
N_s is the synchronous speed
N_r is the rotor speed
Synchronous speed is calculated by the following equation

$$N_s = 120 * f/P \tag{2.11}$$

where,
f is the frequency of the AC power, Hz
P is the number of poles in the stator

2.5 Internal Combustion Engine

An internal combustion engine is a device that converts the chemical energy contained in the fuel in useful mechanical work by burning the air-fuel mixture inside the engine cylinder, hence the name internal combustion engine. Combustion is a process in which a substance rapidly reacts with oxygen, it is an exothermic process in which the chemical energy of the fuel is released producing high temperature and pressure[4]. The ICE consists of a crank slider mechanism with piston and crankshaft, the pressure release inside the cylinder is exerted on the piston and the mechanism converts the reciprocating motion into rotary motion through the crankshaft.

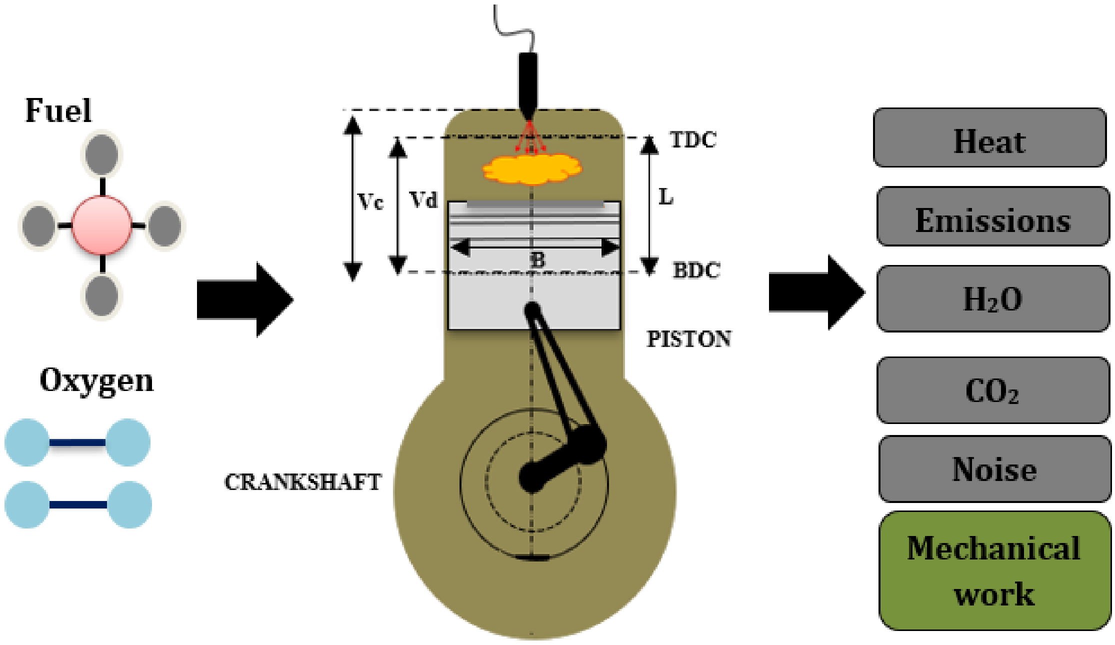


Figure 2.5: Combustion process with inputs and outputs for ICE[4]

Based on the type of combustion the internal combustion engines can be classified in Spark ignition (SI) and compression ignition (CI) type. In SI engines air-fuel mixture is compressed combustion is achieved by igniting a spark via spark plug, SI engine uses petrol and utilizes otto cycle. Whereas in the CI engines air is compressed inside the cylinder and fuel is injected via fuel injector inside the cylinder due to high-temperature fuel self-ignites, CI engine uses diesel fuel and utilizes diesel cycle. Presently, modern vehicles use ICE which operates on four-stroke cycles. Strokes consist of pistons motion from TDC to BDC the crankshaft rotates 180Deg CA. for four-stroke cycle the crankshaft makes two complete rotations i.e.,720Deg CA. A four-stroke cycle consists of intake, compression, expansion, and exhaust stroke. During the intake stroke, the inlet valve opens and the piston moves from TDC to BDC drawing air-fuel mixture in case of SI and only air in case of CI inside the cylinder. In the compression stroke both inlet valves and outlet valves are closed, and the piston moves from BDC to TDC increasing the pressure and temperature of the mixture here work is done by the piston. At the end of the compression stroke spark is ignited (in case of SI) or fuel is injected in the chamber(self-ignites in case of CI), thus expanding the gas and fuel and work is done on the piston. In exhaust stroke, the outlet valve opens and the burned gases are expelled from the engine through the exhaust[5].

2.5.1 Brake specific fuel consumption (BSFC) and efficiency

The fuel consumption is measured as flow rate per unit time. Brake-specific fuel consumption is a parameter which reflects the efficiency of internal combustion engines.BSFC is defined as the ratio of fuel flow rate to the power output which is the product of Torqueτ generated at the crankshaft and speedω of the engine. It is the measure of how efficiently an engine is using the fuel supplied into mechanical work[4].

$$BSFC = \dot{m}_{fuel}/P = \dot{m}_{fuel}/\tau * \omega \tag{2.12}$$

Even though, BSFC relates the engine desired output (cycle to cycle Power) to the input (fuel flow). This parameter cannot be used to evaluate the efficiency of the engine. As the fuel energy supplied to the engine is not fully converted into thermal energy during the combustion process because actual combustion inside the cylinder is incomplete only a fraction of total energy is converted into mechanical

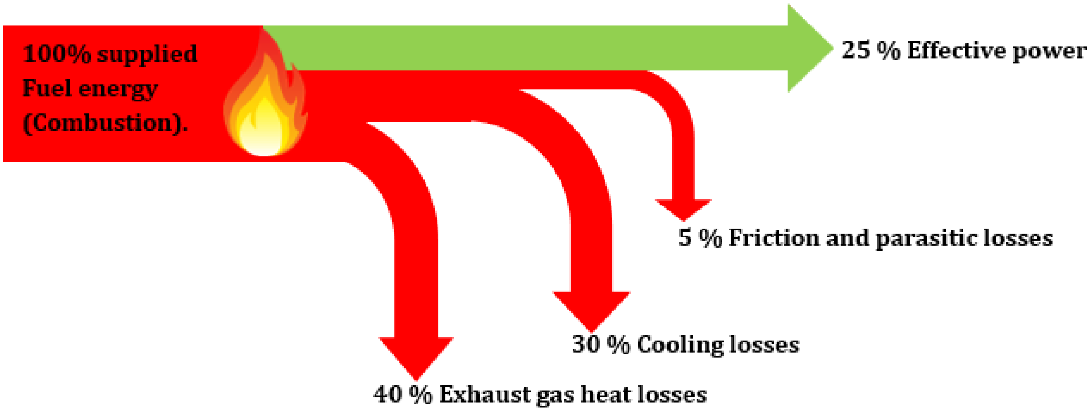


Figure 2.6: Energy losses in ICE

Efficiency of an ICE can be calculated as a function of BSFC and the lower heating value of the fuel (Q_{LHV}) and it defines the energy content of the fuel. This measure is known as fuel conversion(η_f) efficiency and given by the relation [4][15]:

$$\eta_f = 1/BSFC * Q_{LHV} \tag{2.13}$$

Testing of an engine can be carried out in two methods as described below:

1)**Steady-state test:** In this test, the engine is held at a constant speed and appropriate load to attain the desired load point. At that point, the engine speed, torque, and the measured mass flow rate of the fuel data are recorded.

2)**Transient-state test:** : In real driving scenarios, constant engine/vehicle speed are not usual. With the parallel hybrid vehicle architecture and hybrid operating modes, the engine will be subjected to more transient states than a standard vehicle application. Determination of transient state efficiency would be useful during acceleration and deceleration of the vehicle to find the optimized vehicle operating points. Equations related to engine transient-state testing are given below:

$$\omega_{engine} = (V_{speed} * 30 * i_x * i_o)/(\pi * 3.6 * W_{radius}) \tag{2.14}$$

$$\tau_{engine} = (T_{wheel} * 2)/(i_x * i_o) \tag{2.15}$$

In the research and development work of the engine, efficiency analysis plays an important role in evaluating the improvements that occurred by changing the design, combustion mode, fuel, and engine operating conditions [5].To execute this DAQ systems are vital for the measurement, testing, storing, and post-processing of the data as shown in the Figure 2.7.

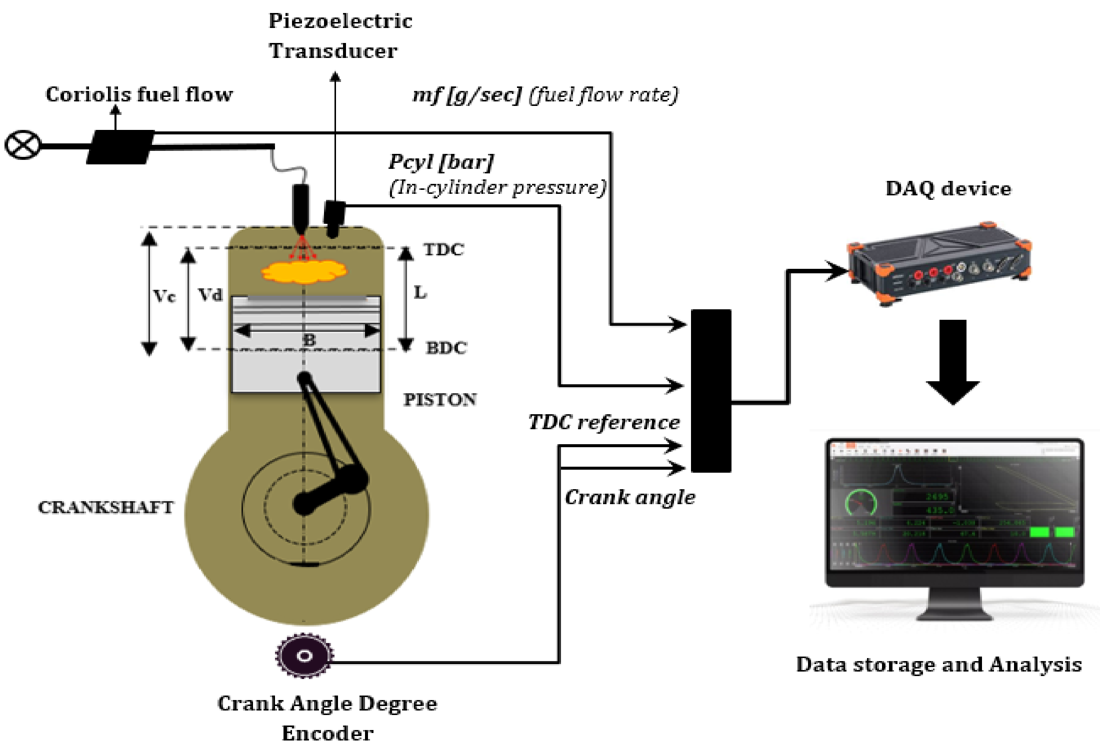


Figure 2.7: *Experimental setup with DAQ device to record In-cylinder pressure*

2.6 Signals for comparison of two different DAQ systems

Combustion diagnostics is always used in engine development. In-cylinder pressure is the best available signal containing most of the information of the combustion process, and presently, it can be measured easily using high-speed data acquisition and modern piezoelectric pressure sensors.

1. In-cylinder Pressure [bar],
2. Speed [rpm],
3. Torque [Nm],
4. Mass flow rate of fuel [gm/sec], and
5. Indicated mean effective pressure ($IMEP_{net}$).

2.6.1 In-cylinder pressure

The In-cylinder pressure of the engine is measured by the means of a piezoelectric transducer, it is a device that measures the phenomenon such as a change in pressure, acceleration, force, strain, etc, and outputs electric charge using the piezoelectric effect. Figure 2.8 illustrates the schematic of a piezoelectric transducer, the change in pressure on the diaphragm is transmitted to the piezoelectric crystal, which generates an electrical charge proportional to the deformation. The output charge from the transducer is weak in terms of pico coulombs per bar(pC/bar). Hence the charge needs to be amplified with a high impedance charge amplifier, The amplifier outputs a voltage proportional to the charge and is given by the equation[5]. Normally, the DAQ systems have an inbuilt charge amplifier.

$$P_{out} - P_{ref} = V_{ch} * G_a / G_s \tag{2.16}$$

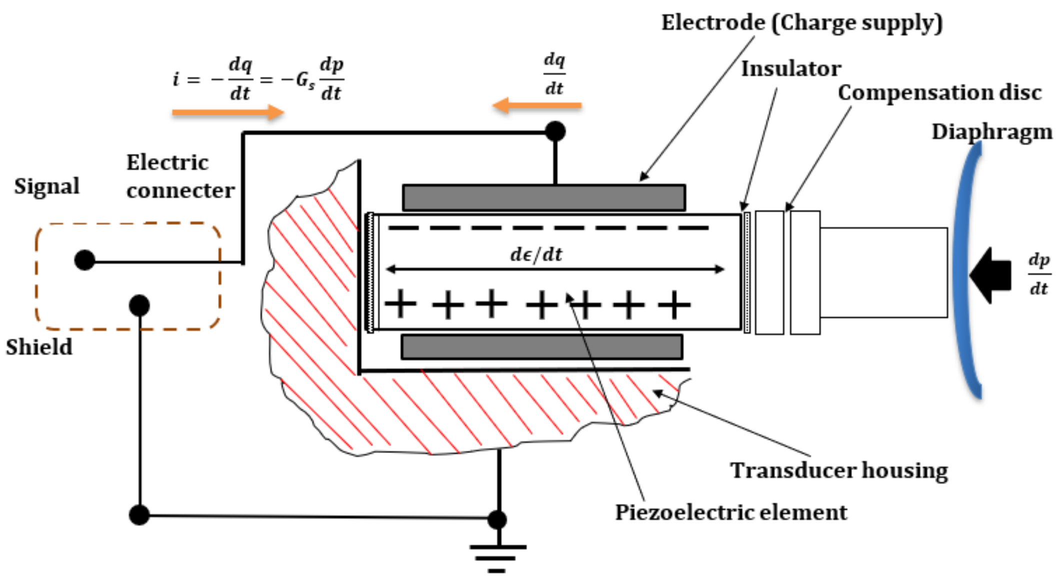


Figure 2.8: *Schematic of piezo-electric transducer[5]*

2.6.2 Fuel flow measurement

The fuel mass flow meter used for this project is the Coriolis effect fuel flow meter, Figure 2.9 below shows the schematic of the Coriolis fuel flow meter. As the name indicates, this device uses the Coriolis effect as the fuel is passed through the vibrating parallel U tubes, which twist as the fluid flows through the tube and the angle of twist is calculated proportionally to the mass flow rate[5].

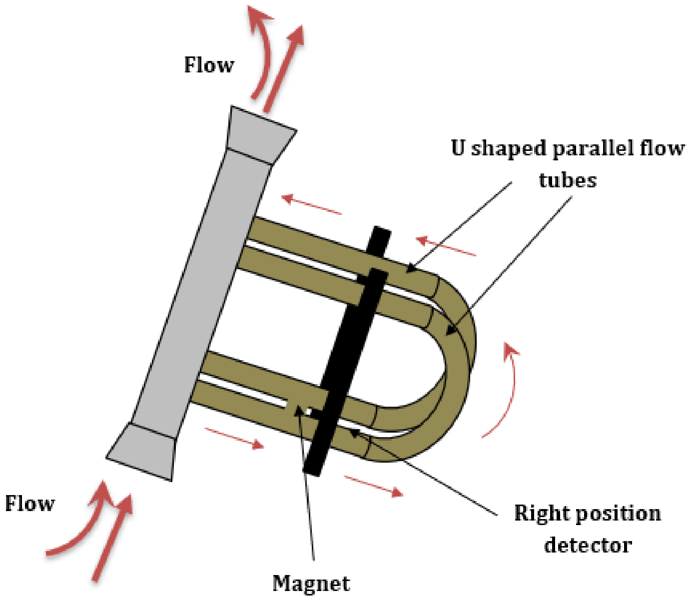


Figure 2.9: *Coriolis effect fuel flow meter [5]*

2.6.3 Indicated mean effective pressure (IMEP)

IMEP was calculated using MATLAB.In a 4 stroke SI engine for inlet and exhaust strokes, the pistons does the work which is considered as the pumping losses or negative work and during compression and power strokes work is done on the piston which is positive work. In the below figure these two regions are indicated in pink and blue color respectively. The area is calculated in MatLab using the below equation[16].

$$IMEP = 1/V_s \oint Pdv \tag{2.17}$$

where,
dv is the variation of volume
P is the pressure
Vs is the piston swept volume at a given time

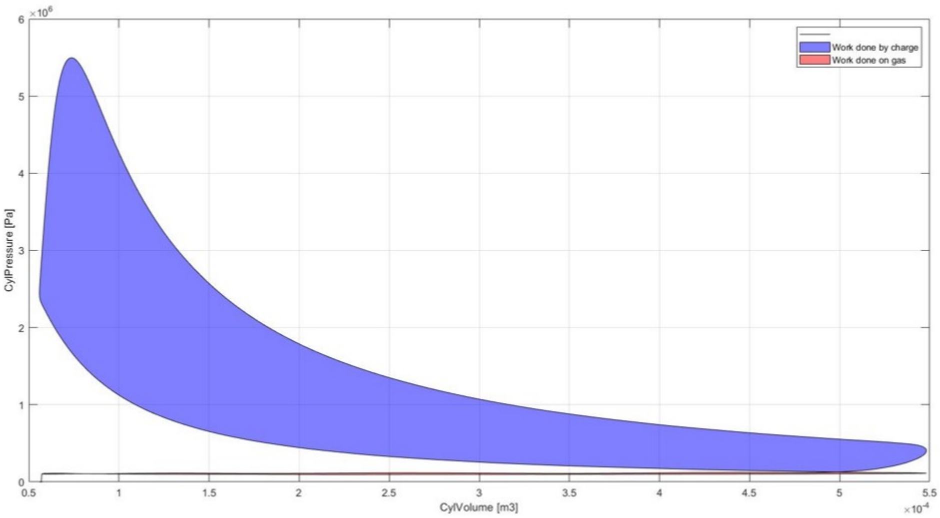


Figure 2.10: *IMEP calculation in MATLAB*

2.6.4 IMEP Calculation in AVL

AVL uses the same equation for measuring the IMEP, but the determination of the exact loop content is possible via AVL method. The TDC sensor delivers a signal from which the firing TDC can be directly[14] calculated. This choice makes determining the TDC accurate down to one-hundredth of a degree, in other words finer than the smallest measurement resolution available. As a result of this, the exact loop content can be determined.

2.6.5 Co-efficient of variation (COV)

The interesting parameters for analyzing the data from the DEWEsoft and AVL were Pressure data, crank angle degrees, Volume of the cylinder with respect to crank angle. The required data from DEWEsoft was exported to .mat format. For AVL the data was exported as ifile first before extracting the data into Matlab. All the analyses and respective calculations were done in Matlab.

Once all the data was available in .mat format then the code was written to process the vast data, as the data was collected for multiple load conditions. In Matlab the code was written to find the peak pressure, minimum pressure, standard deviation, mean, coefficient of variation, and least normalized value. All these parameters were calculated using the following equations[17].

$$\mu = \frac{S}{N} \tag{2.18}$$

where,
μ the population mean
S is the sum of population
N is the number of samples in the populations

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}} \tag{2.19}$$

where,
σ is the population of standard deviation
N is the size of the population
x_i is the each value from the population
μ the population mean

$$COV = \frac{\sigma}{\mu} \tag{2.20}$$

where,
COV is the Coefficient of Variation
σ is the standard deviation.
μ is the mean.

2.6.6 DEWESoft C++ script

C++ script in DEWESoft is a tool which can be utilized to create our own custom math modules the data cycle is as shown in the Figure 2.11. DEWESoft has a different number of modules and functions where the recorded data can be analyzed and also visualized simultaneously. The major advantage of this feature in DEWESoft is that many complex math modules can be included using a single feature and also there is no limitation to the number of input and output channels that can be included. This C++ script can also be exported, which helps in evaluation of the similar type test setups. The way C++ Script works is basically it uses the written C++ code and compiles it into an external library which DEWESoft can automatically load and communicate with. It then continuously fills the data from the input channels and, based on the math formulas inside the C++ Script, outputs the processed data into output channels which can be visualized in the form of pictorial representation (2D and 3D graphs) or as the values in the tabular column [6].

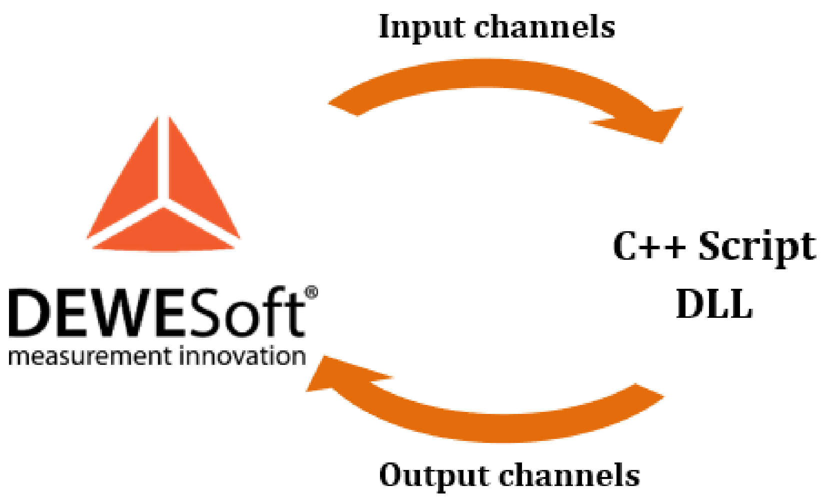


Figure 2.11:
C++ script data cycle in DEWESoft software[6]

3

Test Methodology

This chapter describes the methodology followed during the testing. It starts with two different objectives and how these objectives were executed step by step. Including the type of equipment/apparatus used and experimental approach for testing.

This project is divided into two different objectives the first objective is as stated below:

3.1 Objective 1

Development of an interface to visualize hybrid power train unit efficiency using C++ programming language and implementing the script in DEWESoft software. The flowchart in Figure 3.1 depicts how the first objective was structured and accomplished step by step.

3.1.1 Motivation of parameters to be measured for the script

Firstly, the parameters required to calculate the efficiency of both ICE and EM can be calculated were decided. To determine the brake-specific fuel consumption we need mechanical power delivered and input mass flow rate of the fuel to the engine. After which with the lower heating value of the fuel, we can calculate the fuel conversion efficiency of the engine. The selected parameters which were recorded for the number of operating cycles in the case of ICE and EM are listed below in Table 3.1 :

Table 3.1: *Parameters to be recorded by the DAQ*

Sl.no	Parameter	ICE	EM
1	Torque(τ) [Nm]	✓	✓
2	Speed(ω) [rpm]	✓	✓
3	Fuel mass (m_f) [gm/sec]	✓	X
4	In cylinder pressure [Bar]	✓	X
5	Crank angle degree [CAD]	✓	X
6	Current(I) [Amp]	X	✓
7	Voltage(V) [Volts]	X	✓
8	Phase ψ and Frequency[Hz]	X	✓

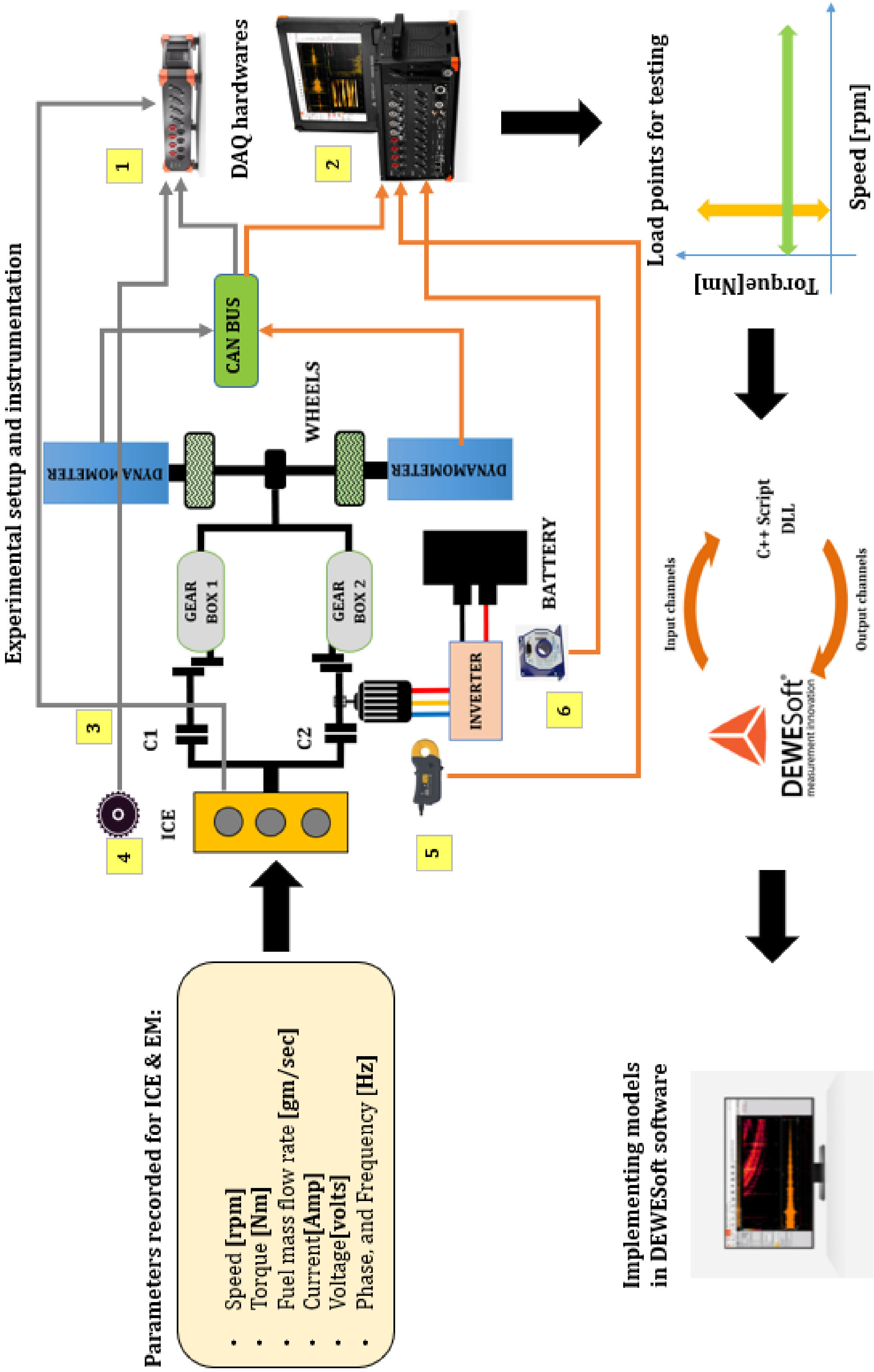


Figure 3.1: *Flowchart depicting overview of project work carried out for accomplishing the first objective[6]*

3.1.2 Selection of Data acquisition hardware.

In this phase, selection of suitable data acquisition hardware and other instruments was done. The list of equipment's and instruments used in the experimental campaign under project are as listed in the Table 3.2:

Table 3.2: *List of equipment used for the objective-1 experimental campaign*

Sl.no	Details	Model	Quantity
1	DAQ Hardware for ICE	SIRIUS I	1No,with accessories
2	DAQ Hardware for EM	R2DB	1No,with accessories
3	Piezo-electric pressure transducer	ZI31	1No
4	Crank angle encoder	-	1No with pulse converter
5	Current clamps	DS clamp 500AC	3No's,HS LV/STG Cable
6	Zero flux DC measuring system	MACC plus	2No's,HS LV/STG

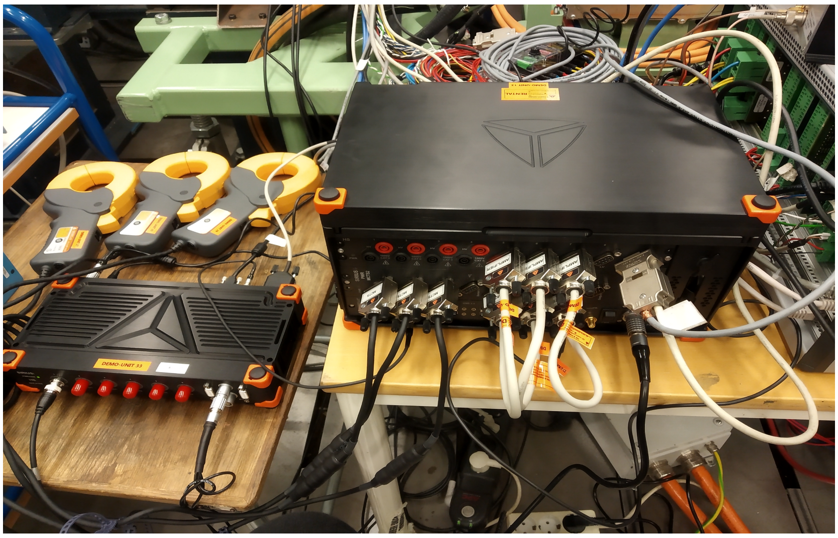


Figure 3.2: *DEWESOft DAQ hardware and instrumentation installed in the test cell*

3.1.3 Experimental setup for ICE Test.

Figure **??** illustrates the experimental setup for engine efficiency mapping. The HEV drive train is mounted on the testbed coupled with the brake dynamometer and the testing is carried out under standard test cell conditions i.e., atmospheric pressure and temperature 25℃. Figure 3.3 depicts the major components which are used for mapping the efficiency of the engine, the major components include dynamometer for measuring torque(τ), speed(ω) and control the engine, piezo-electric transducer for measuring in-cylinder pressure, encoder for crank angle degree(CAD), Coriolis fuel flow meter for measuring the fuel mass flow rate, communication interface (CAN) to ECU, Fuel conditioning system, and emission measurement system.

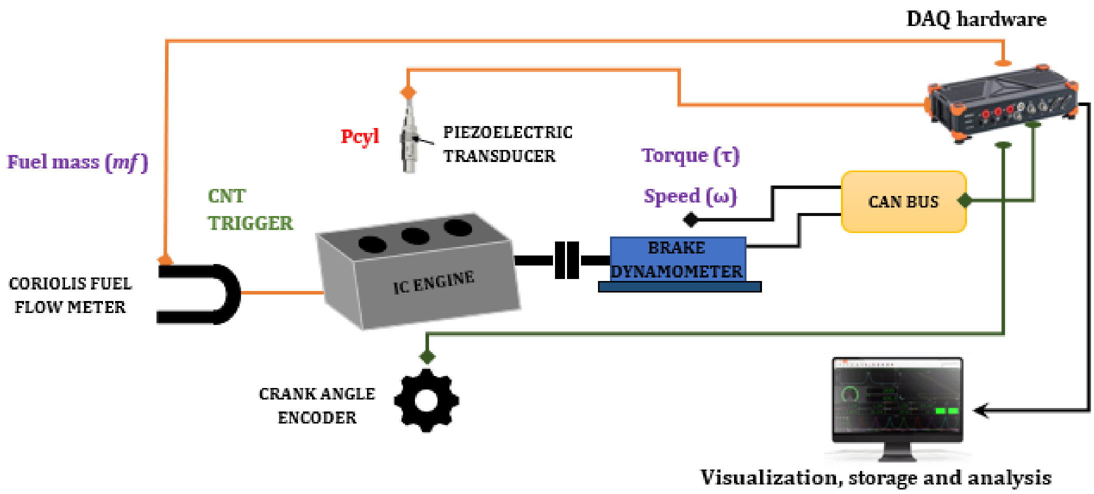


Figure 3.3: *ICE Test bed layout*

3.1.4 Experimental set-up for Electric machine

In order to increase the performance of the electric motor in a hybrid electric vehicle or BEV, it is very important to put the motor to test. When testing the motor it is very important to use the right test equipment's, so that we gather all the data necessary. So for this master thesis a 1.5 L downsized- turbocharged SI engine, this engine is also hybridized. The test was carried in the Chalmers university of technology test rig. All the necessary test equipment's required for the test were supplied by the DEWESoft. The layout of the test set up is shown below.

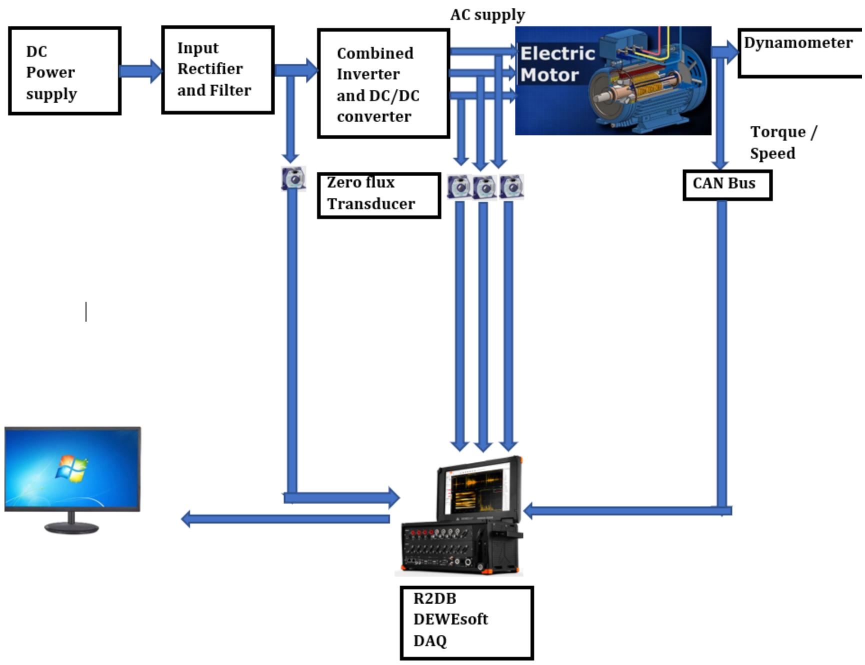


Figure 3.4: Em test bed layout

To measure the DC power supply from the in house power grid in the test cell the current transducer is used.The zero flux current transducer was calibrated at local DEWESoft in Gothenburg. The current transducer is connected to the MCTS unit from DEWESoft, to supply the current transducer. The MCTS unit is in turn connected to the SIRIUS power analyser. The three current measuring clamps used to measure the current from the inverter is also connected to the MCTS unit. The power analyser used for this test is the SIRIUS HS-HV (High speed and high voltage) which is capable of measuring up to 1000 V. Since the voltage measurement for this test does not exceed this range, the high voltage probe were neglected. Since the number of input channels for this power analyser is limited another SIRIUS power analyser is used, which is connected to the Torque sensor. Both the power analysers are synced together using a sync cable. Using the USB channel the power analyser is connected to the computer, where using the DEWESoft software voltage and current are monitored.

3.1.5 Testing of ICE and EM

Engine details:A 3cylinder turbocharged , port fuel injection engine specially designed for hybrid vehicles at Chalmers test rig H with following geometric parameters is used for the project.

Table 3.3: *Engine geometrical parameters*

Parameter	Value
Displacement [mL]	1477
Bore [mm]	82
Stroke [mm]	93.2
Compression ratio	11.5:1
Rated power [kW/rpm]	105/5500
Maximum Torque [Nm/rpm]	215(2500-4000)

The test data points to map the fuel conversion efficiency covered under speed [rpm] and torque [Nm] range, included from 1000 to 5000 [rpm] with increment of 1000 in case of engine speed and engine torque (load) range of 25 to 190 [Nm] with increment of 25 [Nm].The data points for fuel efficiency mapping are as shown in the Figure 3.5. The engine steady-state data was logged with fuel mass flow rate [g/sec] for respective speed [rpm] and load [Nm] point.

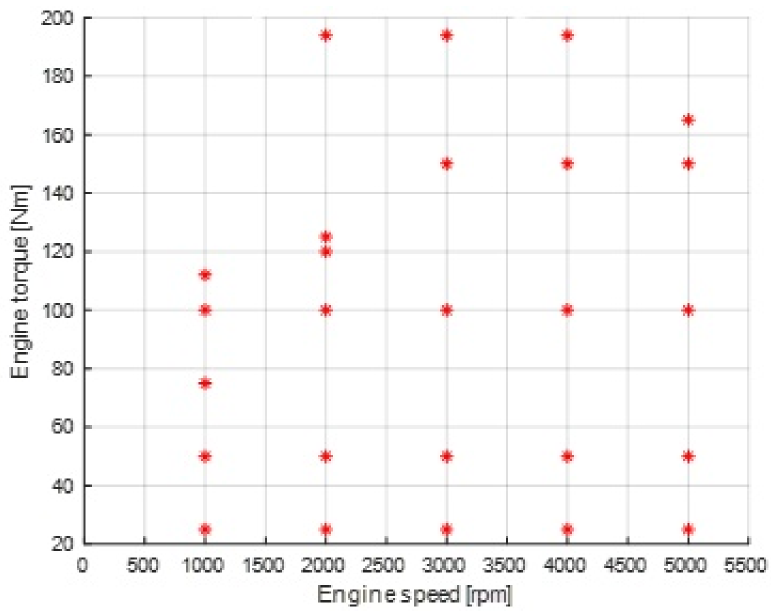


Figure 3.5: *Engine Steady-state testing load points.*

To map the efficiency of the electric motor the ideal way is to run the electric motor in isolation and then with the help of the recorded data efficiency mapping can be done. As the test set up at Chalmers university did not had the provision to run the electric motor in isolation, we had to improvise so as to record data just from electric motor. In order to do this, with help of the test cell engineer the electric motor was isolated so as to run the given drive cycle only on electric motor. Even then the the powertrain of that particular test cell was not designed to run electric motor at higher speeds, which is paramount in testing of electric motor. Since there was no way to regulate voltage supplied to the motor, a custom drive cycle was prepared with help of which by varying the gradient in the drive cycle all the required points for the experiment was achieved. The electric motor was tested for all points as shown in the figure.

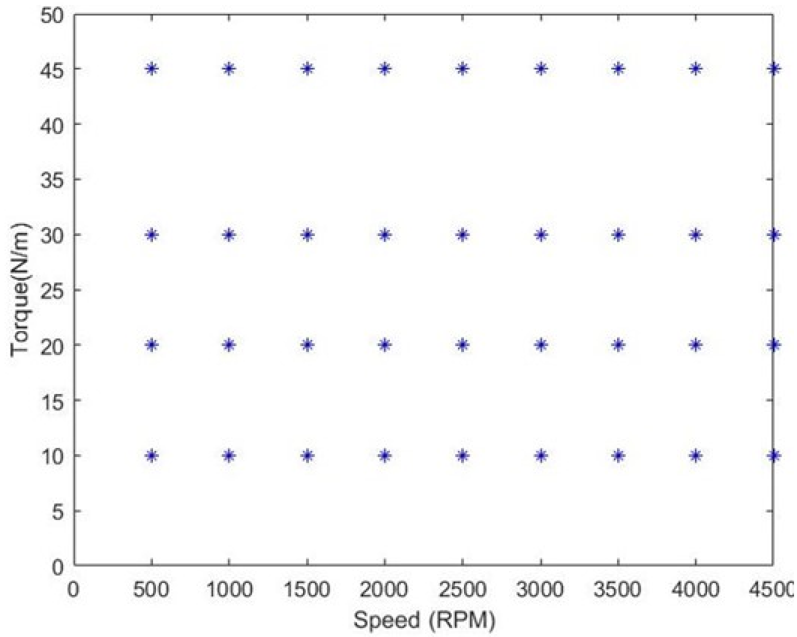


Figure 3.6: Load points for Electric motor

3.2 Developing C++ models and implementing them in DEWESoft software for ICE and EM.

3.2.1 C++ Script for Internal combustion engine.

A math module by writing C++ script is developed in the DEWESoft software, which determines the efficiency of the engine. The input data recorded with the DAQ system such as engine torque (τ), speed (ω), in-cylinder pressure (P), Crank angle degree (CAD), and mass flow rate of fuel for the operating cycles(m_f) are made as input channels. The C++ module calculates and outputs mechanical power(kW),brake-specific fuel consumption (gm/kWh), and Fuel conversion efficiency(%) of the engine. In addition to this a 3D map with speed (ω) on X-axis, engine torque (τ) on Y-axis, and Fuel conversion efficiency (η_f) on Z-axis can be visualized during online measurements as shown in Figure 3.7.

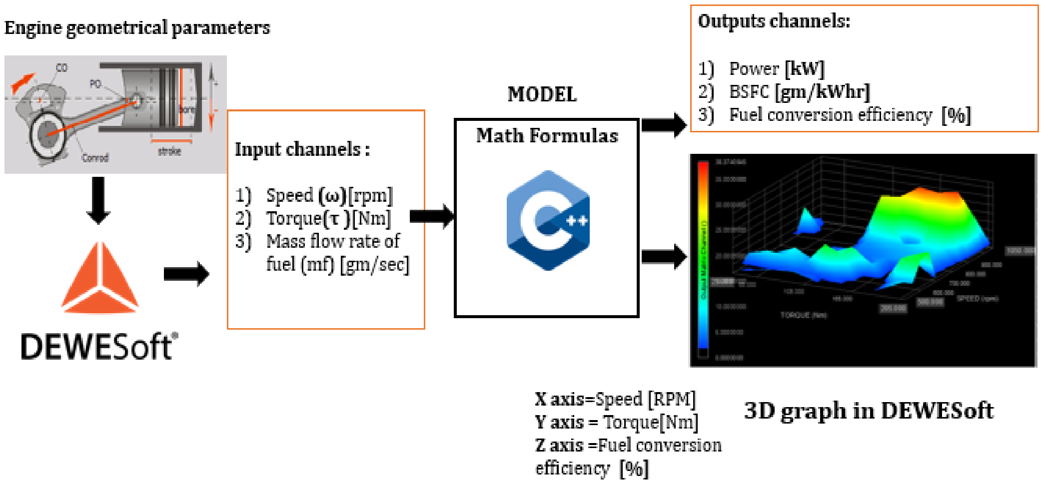


Figure 3.7: *Block Diagram of C++ Script for ICE*

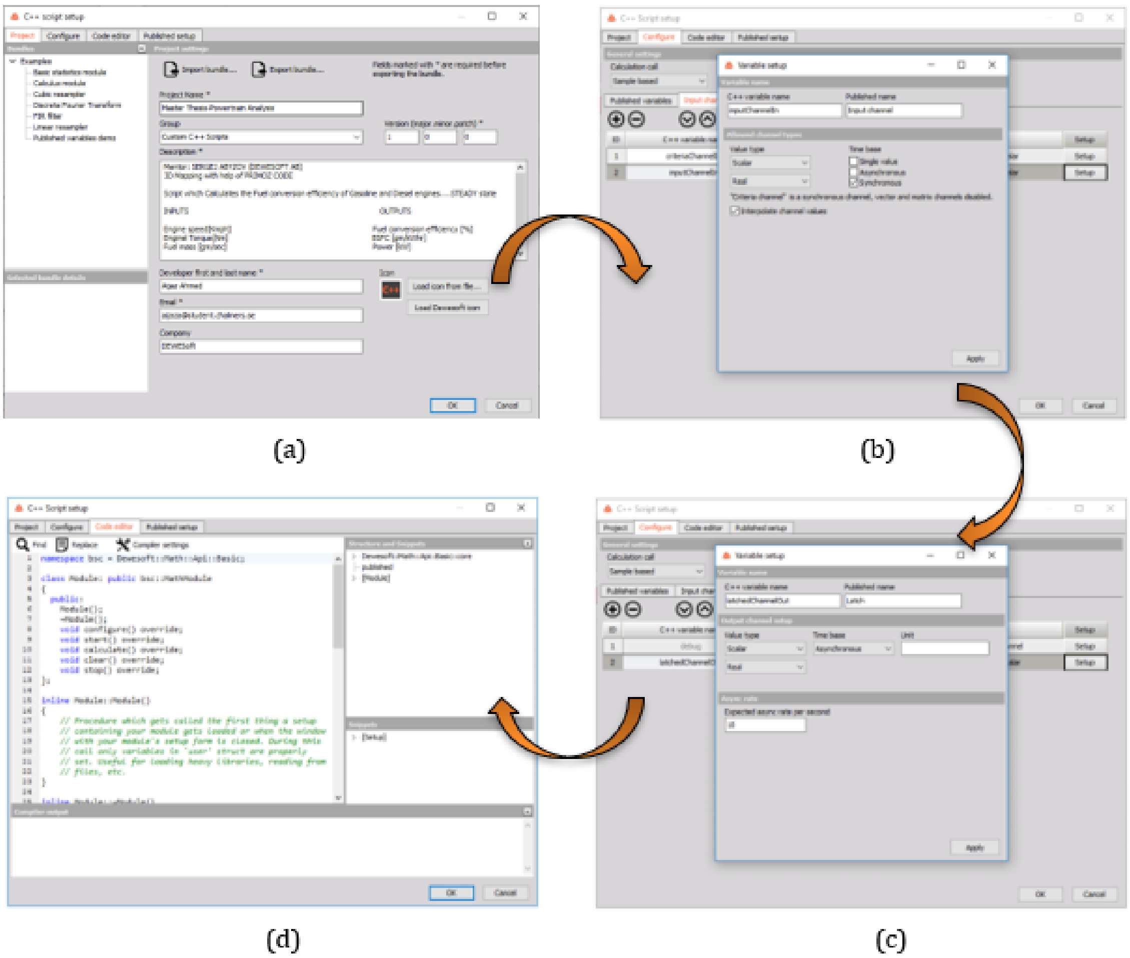


Figure 3.8: *(a) C++ script module in DEWESoft software (b) Creating Input channels (c) Output channels (d) C++ Code editor*

3.2.2 C++ Script for electric motor.

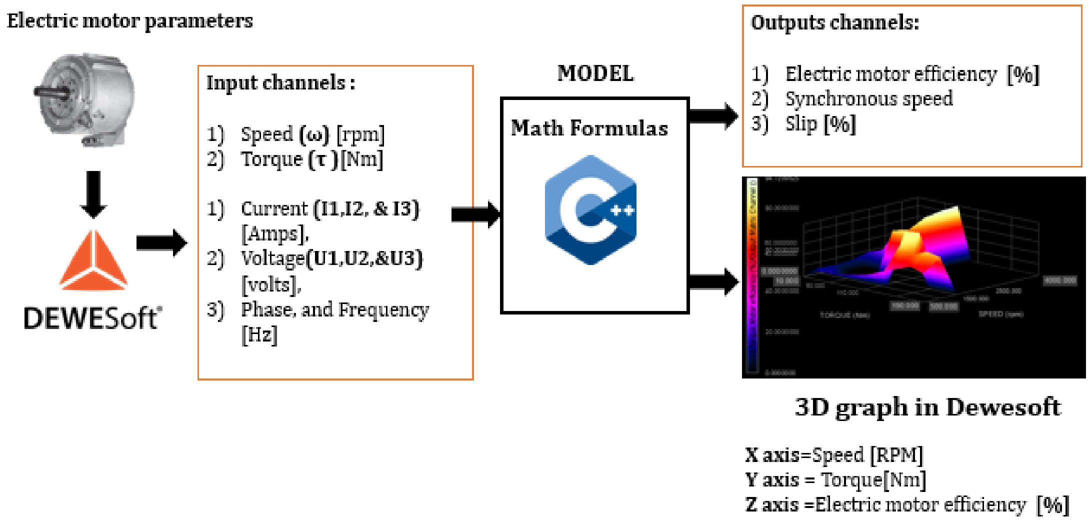


Figure 3.9: *Block Diagram of C++ Script for EM*

To calculate the efficiency of the motor various parameter are required like three phase voltage, current, speed and torque. These parameters are measured and recorded using DEWESoft DAQ in the test cell. The mathematical modules required for the calculation of percentage slip, efficiency and synchronous speed are written in the DEWESoft C++ script tab. For this the various channels that are required for the calculations are selected. These channels are shown on the left hand of the figure under the section input channels. The mathematical module written uses these channels to compute the equation and finally the answer is extracted using the output channels as shown in the figure. With the help of these output channels finally the 3D graph is plotted.The equations used to calculate the slip, synchronous speed and efficiency is mentioned below.

3.2.3 Validation of the Scripts by using the recorded data and recalculating after implementation.

The C++ script is validated by importing it in the recorded data file and by using the analyze option, which is one of the vital feature of using DEWESoft DAQ systems. In the combustion analyzer software the data file is recalculated, after which the output channels mechanical power(kW),brake-specific fuel consumption (gm/kWh), and Fuel conversion efficiency(%) can be visualized during validation. which is same as online measurement for respective engine speed (ω) and torque (τ).

3.3 Objective 2

Comparison of measurement accuracy two different data acquisition systems i.e.,DEWESoft and AVL.

The flowchart in the Figure3.10 below depicts about the work carried out for the accomplishment of second objective.

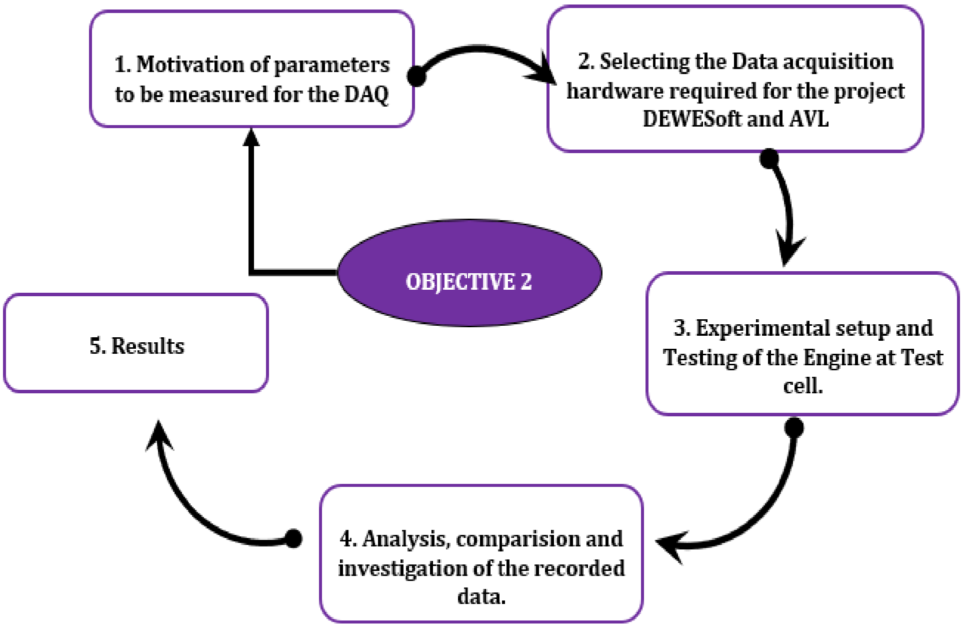


Figure 3.10: *Flowchart depicting the work carried out for accomplishing the second objective*

3.3.1 Parameters which are chosen for the DAQ comparison.

Recording In-cylinder pressure with respect to crank angle degree accurately, plays an important role in combustion diagnostics. As most of the important parameters such as IMEP net/gross, mass fraction burned, heat release rate etc can be determined[5]. Hence it was chosen as an important parameter for comparison of the DAQ systems. Table **??** shows the parameters recorded for comparison of DAQ systems.

Table 3.4: *Parameters which were recorded by the DAQ*

Sl.no	Parameter	DEWESoft	AVL
1	Torque(τ) [Nm]	✓	✓
2	Speed(ω) [rpm]	✓	✓
3	Fuel mass (m_f) [gm/sec]	✓	X
4	In cylinder pressure [Bar]	✓	✓
5	Crank angle degree [CAD]	✓	✓
6	Time [sec]	✓	✓
7	$IMEP_{net}$[bar]	✓	✓

3.3.2 Selecting the Data acquisition hardware required for the project.

The Table 3.5 below gives the equipment details and Table 3.6 gives the measurement accuracy details.

Table 3.5: *List of equipment used for the objective-2*

Sl.no	Details	Model	Quantity
1	Piezo-electric pressure transducers	ZI31	3No's,with accessories
2	DAQ Hardware DEWESoft	SIRIUS STG	1No,with accessories
3	DAQ Hardware AVL	INDIMICRO	1No,with accessories

Table 3.6: *Measurement accuracy of the equipment*

Sl.no	Details	Model	Measurement accuracy
1	Piezo-electric pressure transducers	ZI31	+/- 0.5[bar]
2	DAQ Hardware DEWESoft	SIRIUS STG	+/- 0.53[bar]
3	DAQ Hardware AVL	INDIMICRO	+/- 0.36[bar]

3.3.3 Experimental setup and testing of the ICE at test cell.

Figures 3.12 and 2.10 below illustrates the experimental setup for testing of 3-cylinder gasoline engine. The engine is mounted on the test-bed coupled with the brake dynamometer and the testing is carried out under standard test cell conditions i.e., atmospheric pressure and temperature 25℃. The major components which are used for testing the engine include a dynamometer for measuring torque(τ), speed(ω), piezo-electric transducers for measuring in-cylinder pressure, encoder for crank angle degree(CAD), Coriolis fuel flow meter for measuring the fuel mass flow rate(m_f).Further analysis of the recorded data is done for two different DAQ systems.The experimental setup and configuration setting is as shown in the Table 3.11.

Details/Parameters	DEWESoft(SIRIUS)	AVL (INDIMICRO)
Data acquisition Pressure as a function	Time and CAD	CAD
Engine geometrical parameters	B=82;L=93.5;sL=143.5;CR=10.5; 4S;3Cyl	B=82;L=93.5;sL=143.5;CR=10.5; 4S;3Cyl
Transducer sensitivity	P1,P2,P3=[47.08,46.31,46.2] (pC/bar)	P1,P2,P3=[47.08,46.31,46.2] (pC/bar)
Polytropic coefficient	1.35	1.35
ZLC: Thermodynamic 2 point	Window of ref crank angles Start: **-140** & End: **-90**	Window of ref crank angles Start: **-140** & End: **-90**
Trigger offset	**-175.535 °CA**	**184.1 °CA**
Thermodynamic loss angle	**0.7**	**0.7**
Resolution	**1 deg; 360p/rev**	**1 deg; 360p/rev**

Figure 3.11: *Experimental setup configuration settings and important Parameters.*

In order to compare the DAQ systems in terms of accuracy and repeatability,Given the circumstances and conditions that it was an ongoing research project. We were not allowed to make any modifications or changes in the test set-up. Considering all these facts two different experimental approach/testing procedures were considered which are further elaborated and shown in the below tabular column 3.7.In the first testing procedure three piezoelectric transducers Pcyl1,Pcyl2, and Pcyl3 were connected to the AVL and DEWESoft DAQ systems and 9 trails were recorded for each of the DAQ systems at engine speed 2000 [rpm] and torque [100Nm].

Table 3.7: *Testing of engine procedure-1*

Sl.no	**Cylinder pressure [bar]**	**DAQ system**	**Testing Speed and Torque**	**No of Trails**
1	Pcyl1,Pcyl2,Pcyl3	Data acquired through **AVL**	2000[rpm] and 100 [Nm]	9
2	Pcyl1,Pcyl2,Pcyl3	Data acquired through **DEWESoft**	2000[rpm] and 100 [Nm]	9

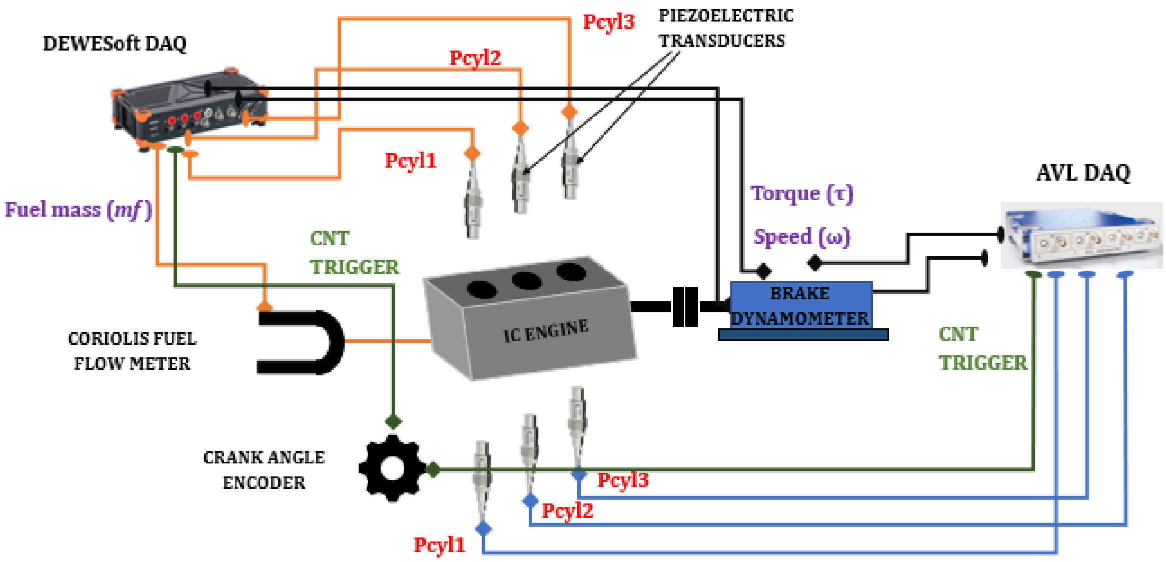


Figure 3.12: *Experimental setup-1 for comparison of two different DAQ systems*

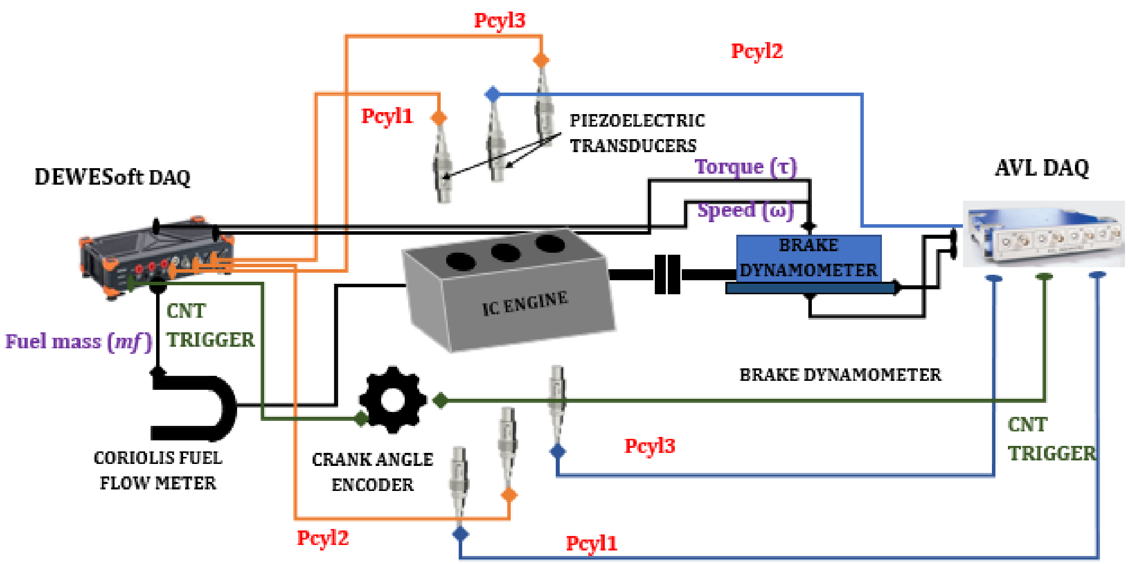


Figure 3.13: *Experimental setup-2 for comparison of two different DAQ systems*

In the second testing procedure, two piezoelectric transducers Pcyl1 and Pcyl3 were connected to the AVL and parallelly Pcyl2 was connected to DEWESoft DAQ systems and vice versa. In order to capture the 18 trails for fair comparison of the DAQ systems at engine speed 2000 [rpm] and torque [100Nm] which is shown in the Table 3.8 .

Table 3.8: *Testing of engine procedure-2*

Sl.no	**Cylinder pressure [bar]**	**DAQ system**	**Testing Speed and Torque**	**No of Trails**
1a	Pcyl1,Pcyl3	Data acquired through **AVL**	2000[rpm] and 100 [Nm]	9
1b	Pcyl2	Parallely Data acquired through **DEWESoft**	2000[rpm] and 100 [Nm]	9
2a	Pcyl1,Pcyl3	Data acquired through **DEWESoft**	3000[rpm] and 100 [Nm]	9
2b	Pcyl2	Parallely Data acquired through **AVL**	3000[rpm] and 100 [Nm]	9

4

Results and Data Analysis

This chapter covers the results of the two different objectives. firstly the interface developed, implemented and validated including the inputs and outputs with 3D visualization.secondly, the data analysis and results related to the comparison of DEWESoft and AVL DAQ systems

4.1 Objective 1

The developed interface by writing C++ script which calculates the fuel conversion efficiency [%] of ICE is presented in the Figure 4.1, on the left we have the necessary input channels engine speed[rpm], torque [Nm], and mass flow rate of fuel [g/sec] and on the right-hand side we have the calculated output channels, which are mechanical power [kW], BSFC [g/kWhr], and fuel conversion efficiency [%]. This model calculates for single sample, and also calculates for the average values given for a particular number of cycles or certain duration of time (time base data acquisition).

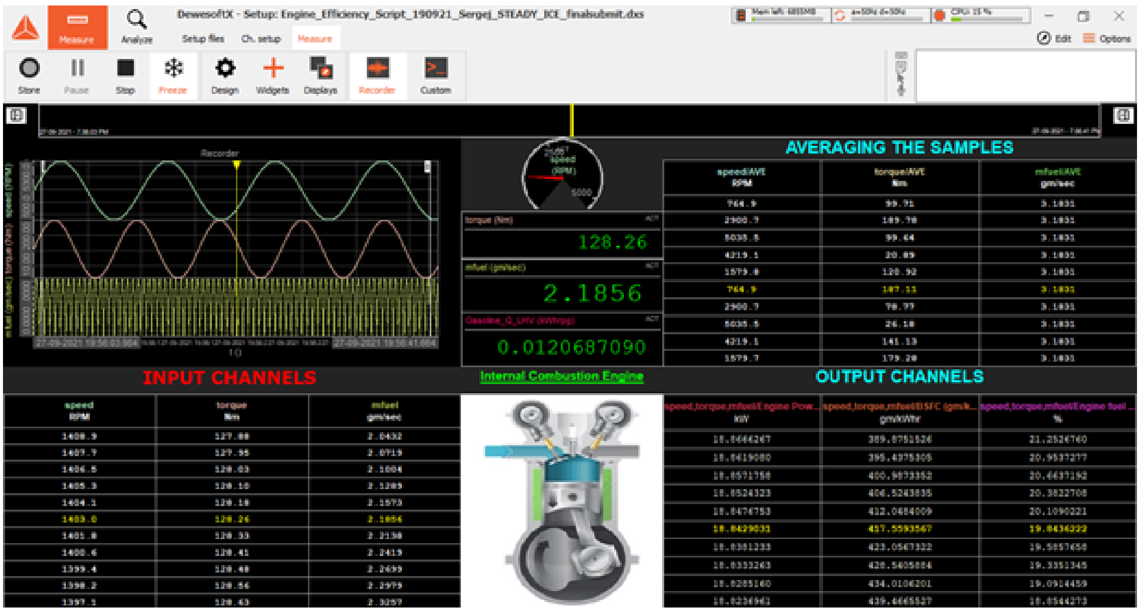


Figure 4.1: *C++ Script implemented in the software for calculating ICE efficiency*

One of the major deliverables of the project was the 3D surface plot, as presently the software lacks the 3D visualization. Surface plots are basically pictorial representation of three- dimensional data, instead of showing the single data point surface plot show the functional relationship between dependent variable on (Z axis) which is fuel conversion efficiency of ICE [%] and two independent variable (X axis) speed [rpm] and (Y axis)torque [Nm]. Surface plot is a companion plot to the contour plot.

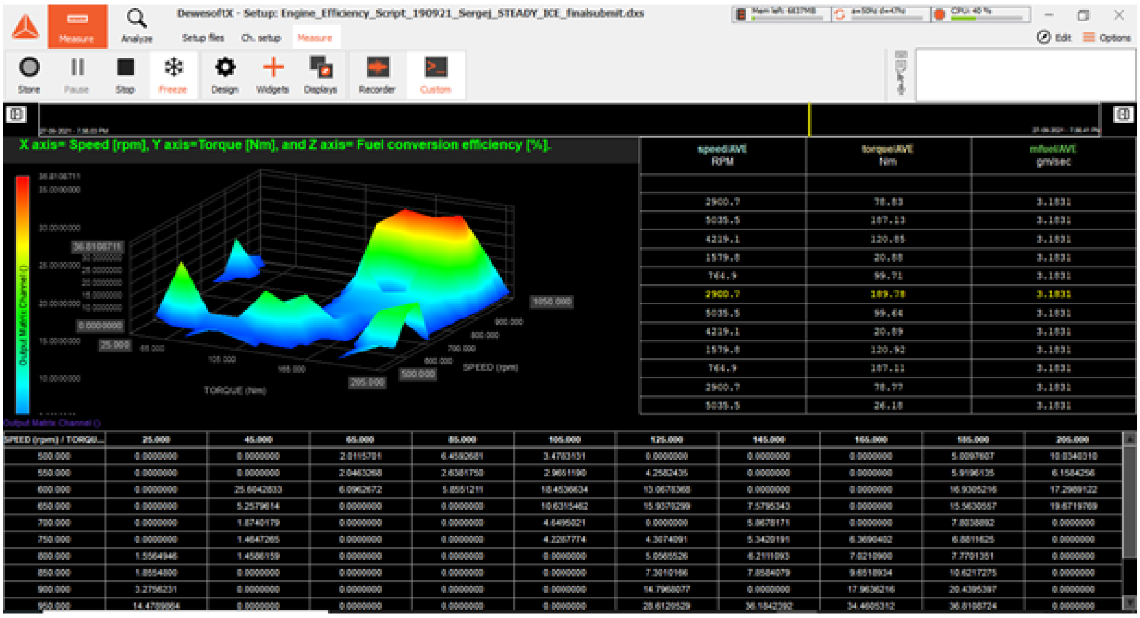


Figure 4.2: *3D surface plot for ICE*

Similarly the developed interface by writing C++ script which calculates the efficiency [%] of EM is presented in the Figure 4.3, on the left we have the necessary input channels, which are electric motor speed[rpm], torque [Nm], three phase current [Amp] and voltage [V], and three phase current [Amp], three phase voltage [V], and power factor and on the right-hand side we have the calculated output channels, which are mechanical power [kW], three phase power [kW], and EM efficiency [%]. This model calculates for single sample, and also calculates for the average values given for a particular number of data set or certain duration of time (time base data acquisition).

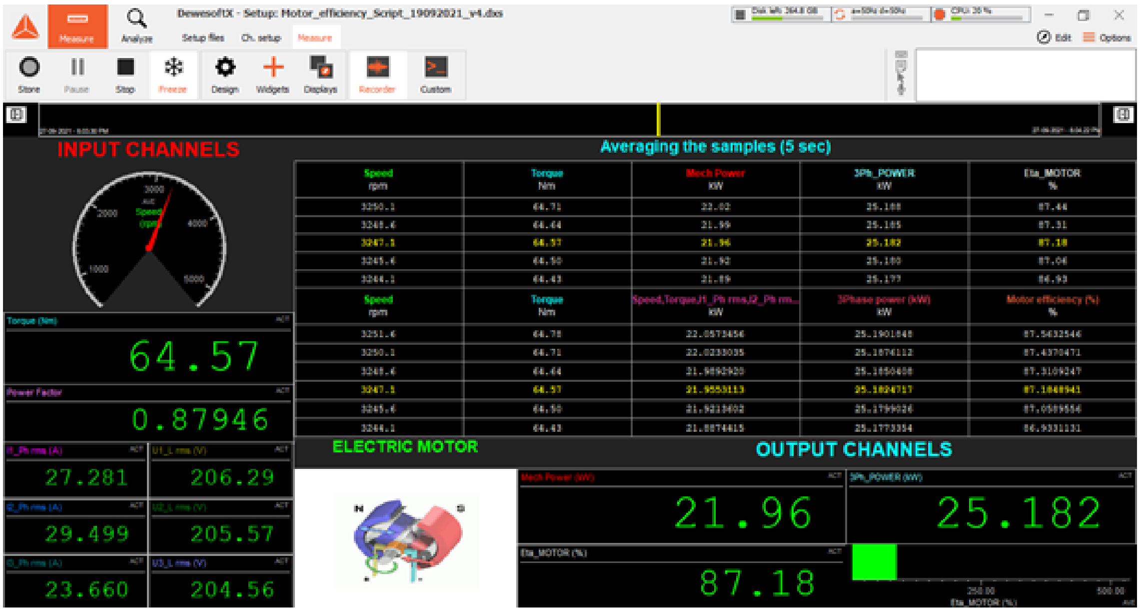


Figure 4.3: *C++ Script implemented in the software for calculating EM efficiency*

Similarly, for the EM Figure 4.4 shows 3D surface plot, which is functional relationship between dependent variable on (Z axis) efficiency of EM [%] and two independent variable (X axis) speed [rpm] and (Y axis) torque [Nm].

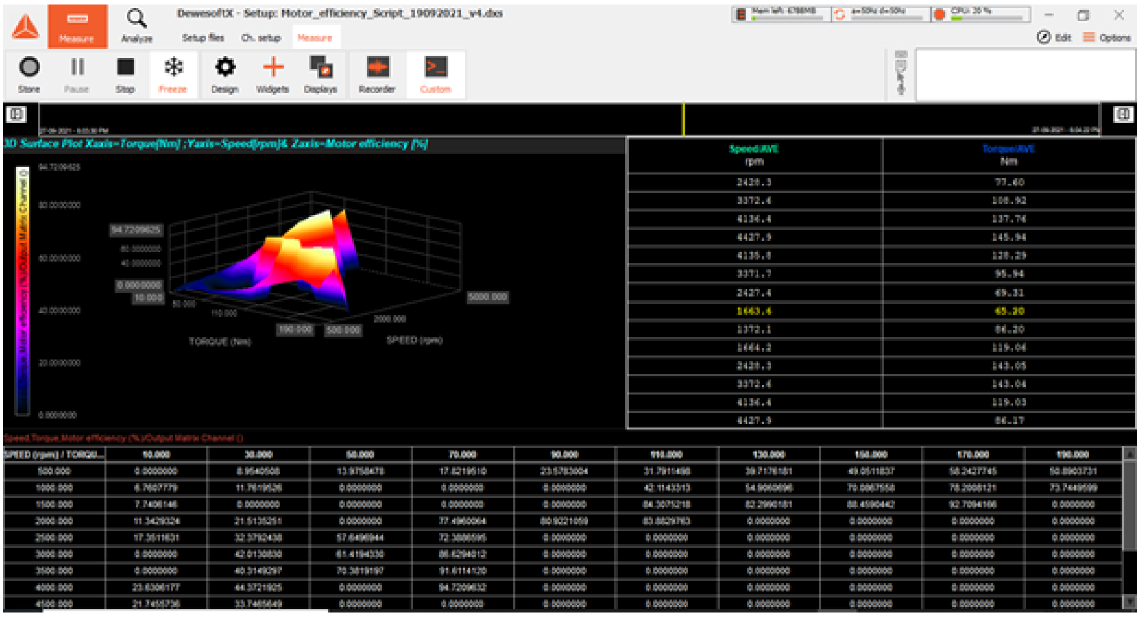


Figure 4.4: *3D surface plot for EM*

4.1.1 Options

The integrated C++ models have various options as shown in the Figure 4.5. If only ICE is tested, then we can select only ICE and only EM for electric motor testing.

And when testing a hybrid drive train, we can select both ICE and EM for data acquisition, visualization, and storage (for post processing).

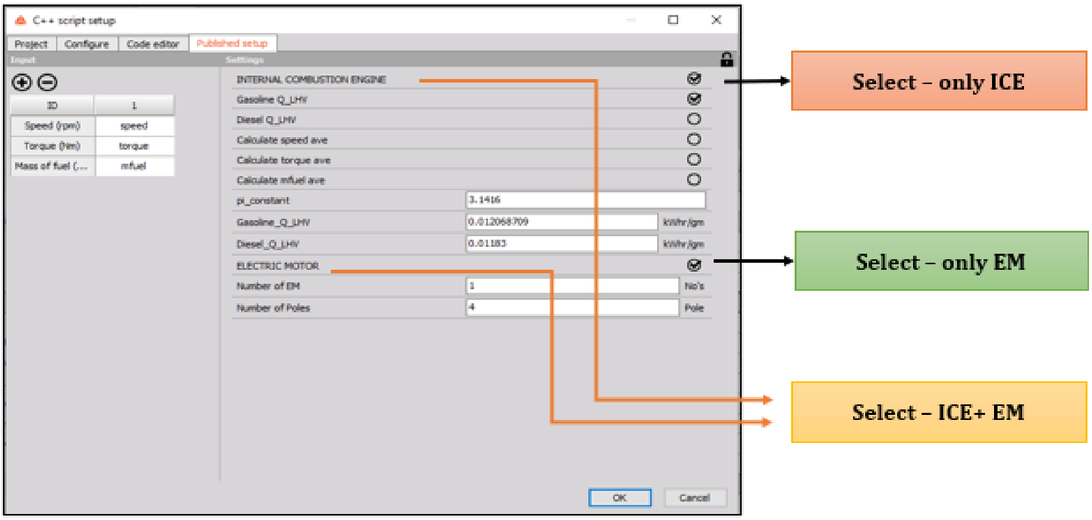


Figure 4.5: *Various options of the integrated C++ model*

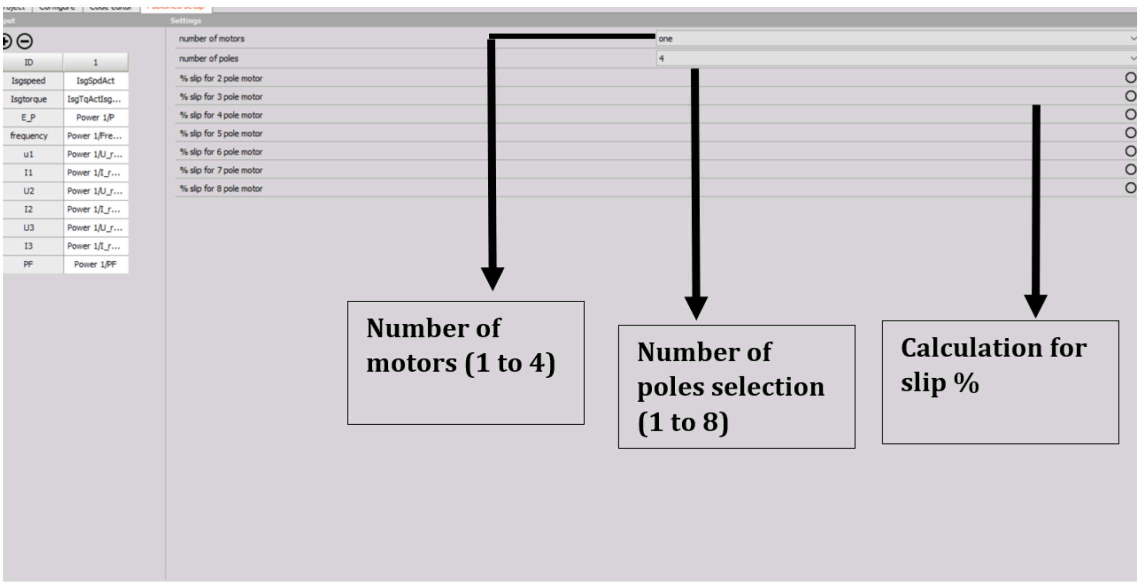


Figure 4.6: *Various options of the integrated C++ model for EM*

In the Electric motor script a provision was made to select the number of motors and the efficiency of selected motor can be plotted in 3D plot. The number of poles for the motor can be selected to calculate the synchronous speed and consequently slip percentage.

4.1.2 Models validation

The model is validated by using the recorded DEWESoft .dxd file as the DEWESoft software has the analyze option. with help of which, the data file can be recalculated with exported model as shown in the Figure 4.7. hence validating the model and 3D surface plot.

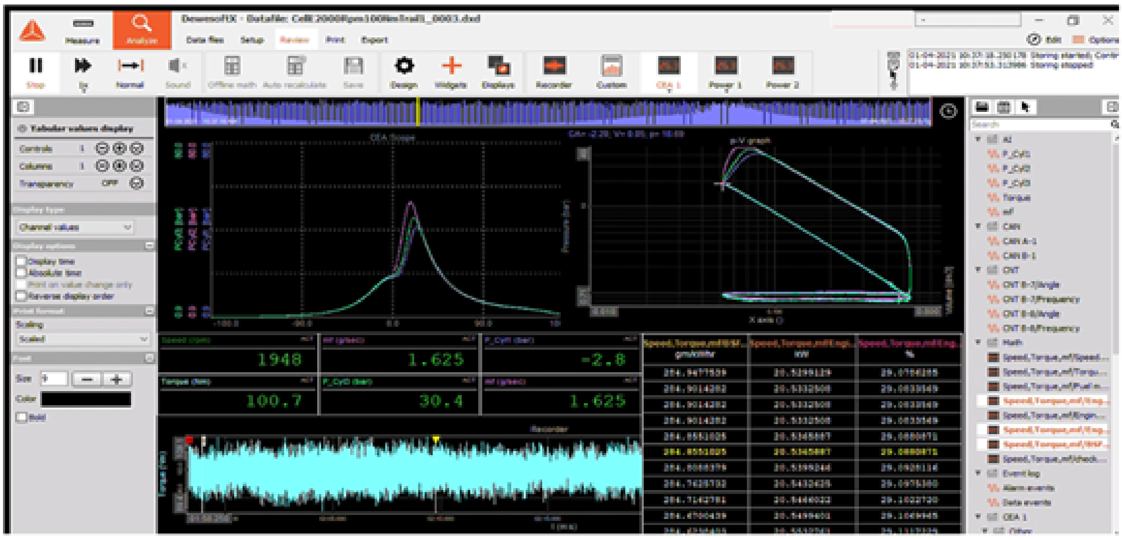


Figure 4.7: *C++ Script validation in DEWESoft for Engine efficiency*

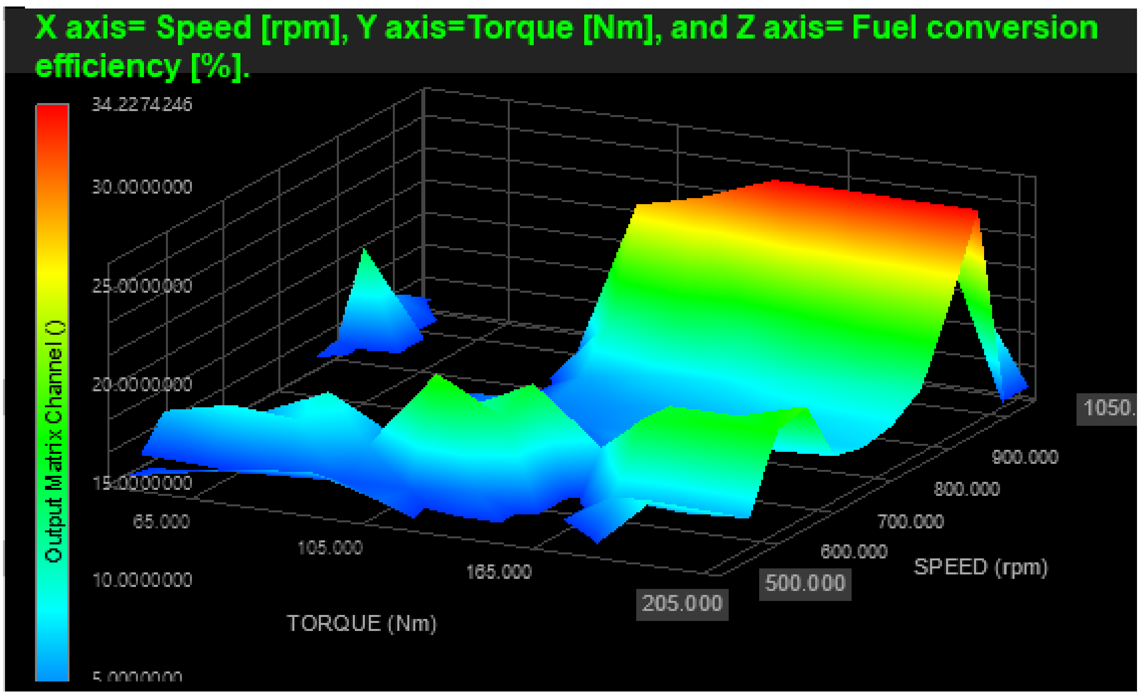


Figure 4.8: *3D surface plot validation in DEWESoft for Engine efficiency*

4.1.3 Significance of the developed C++ models

1. **Time and Money**:When testing an ICE or EM the required data is recorded and stored in the drive. Which is then exported in to the .mat,.xls, or .iso type files and then by using math formulas the parameters such as efficiency [%] is calculated in other software like MATLAB/PYTHON. As the model not only calculates the parameter but also allows the user to visualize the data online. Hence saving time in-turn money.

2. **Online visualization**:Not only allows the user to store the data but, also to visualize the efficiency values online for selected options. Thus, allowing the user to tweak (Ignition timing etc) and different trial and error configurations involving the changes in experiment on the spot.

3. **Modularity**:With necessary changes change in geometrical parameters and poly-tropic co-efficient (gamma). These models can be used for ICE running on Gasoline , diesel, and also works for alternate fuels.

4. **Research and development**:Presently research is carried out on alternate fuels and electric vehicles, these model can be used in efficiency and power analysis.

5. **Easy to use**:The developed models are easy understandable, and can be Imported and exported to different setup files.

4.2 Objective-2

This chapter describes the data analysis performed for execution of second objective. It mainly comprises of the combustion stability,investigation and comparison of in-cylinder pressure data, speed data, and calculated IMEP (indicated mean effective pressure) and COV of IMEP,by two different DAQ systems.

4.2.1 Combustion data stability analysis

In-cylinder pressure of 300 consecutive cycles were captured using AVL and DEWE-Soft DAQ systems to study the measurement accuracy and repeatability of the Data acquisition systems. For this analysis, the absolute In-cylinder pressure data was zero level corrected by thermodynamic 2-point method with reference window of -140 and -90.

To estimate the indicated engine performance, typically indicated mean effective pressure (IMEP) is used. Noise in the cylinder pressure signal and cycle-to-cycle variation in pressure signal result in the significant variation in IMEP value. The coefficient of variation (COV) of IMEP is typically used to characterize engine stability at particular engine operating point. The COV (%) is given by the ratio of the standard deviation of IMEP, σ IMEP (kPa) and its mean value. The COV(%) lower than 3% for 300 cycles is considered as a stable combustion [18].

4.2.2 Co-efficient of variance for IMEP

To evaluate the consistency of data and to check for cyclic variation, COV for gross IMEP was calculated for 300 cycles. The COV was calculated for both AVL and DEWEsoft data, the results to which are shown in table **??** and **??** respectively. The combustion is considered stable when the COV in % is less than 3 % .

Table 4.1: *COV of IMEP in (%) for 300 cycles AVL data*

Testing at speed 2000[rpm] and load 100[Nm]			
Engine cylinder	Cyl-1	Cyl-2	Cyl-3
Trial-1	2.0261	1.8173	1.8152
Trial-2	2.1072	1.7989	1.8801
Trial-3	1.9416	1.7569	1.8790

Table 4.2: *COV of IMEP in (%) for 300 cycles AVL data*

Testing at speed 3000[rpm] and load 100[Nm]			
Engine cylinder	Cyl-1	Cyl-2	Cyl-3
Trial-1	2.1002	1.4602	1.7284
Trial-2	2.2298	1.5269	1.7399
Trial-3	2.1876	1.4466	1.6163

Table 4.3: *COV of IMEP in (%) for 300 cycles DEWESoft data*

Testing at speed 2000[rpm] and load 100[Nm]			
Engine cylinder	Cyl-1	Cyl-2	Cyl-3
Trial-1	1.9341	1.9152	1.9152
Trial-2	1.9813	1.8390	1.8158
Trial-3	2.0865	1.9122	1.6780

Table 4.4: *COV of IMEP in (%) for 300 cycles DEWESoft data*

Testing at speed 3000[rpm] and load 100[Nm]			
Engine cylinder	Cyl-1	Cyl-2	Cyl-3
Trial-1	2.1708	1.6541	1.8713
Trial-2	1.9530	1.5432	1.6007
Trial-3	2.1942	1.6391	1.5522

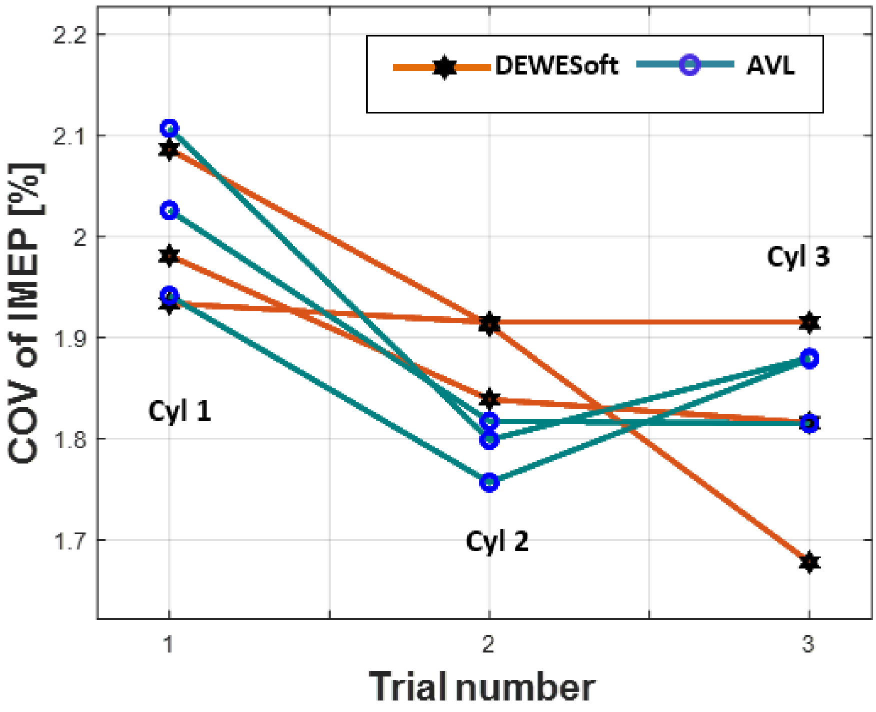


Figure 4.9: *COV of IMEP in [%] for 2000 [rpm] and 100 [Nm] testing.*

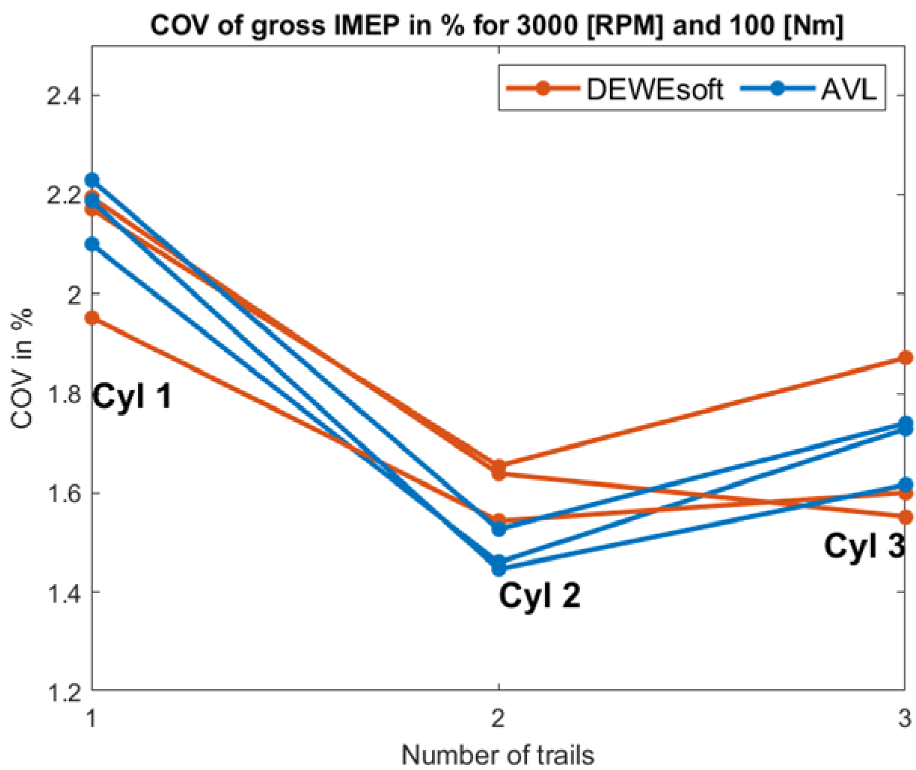


Figure 4.10: *COV of gross IMEP in [%] for 3000 [rpm] and 100 [Nm].*

4.2.3 IMEP calculation in AVL and DEWEsoft

The IMEP calculated in both the software's were also compared the results are tabulated in table **??**. The gross IMEP is the average value for 300 cycles. As seen from the table, the gross IMEP values are very close to each other between the two software's.

Table 4.5: IMEP in [bar] for 300 cycles for Trial-1

DAQ	Testing at 2000 [rpm]			Testing at 3000 [rpm]		
	CYL- 1	CYL- 2	CYL- 3	CYL- 1	CYL- 2	CYL- 3
AVL	9.8134	10.0964	9.9944	10.2506	10.6353	10.5917
DEWEsoft	9.7673	10.0209	10.0371	10.2284	10.5309	10.4993
Integrated in MATLAB	9.8470	10.1326	10.0229	10.2	10.59	10.5949

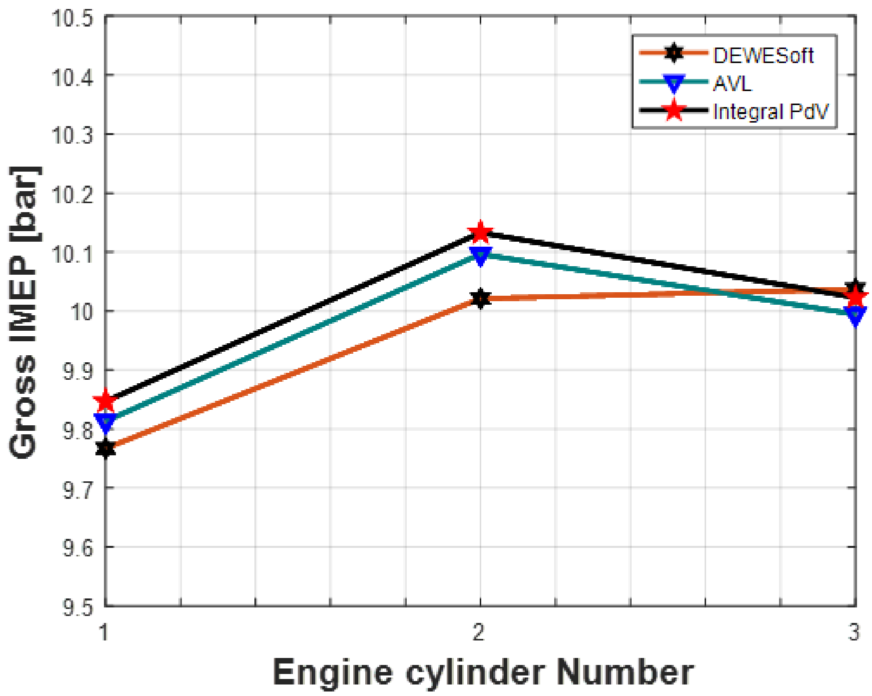


Figure 4.11: *Gross IMEP for 2000 [rpm] and 100 [Nm] Trial-1.*

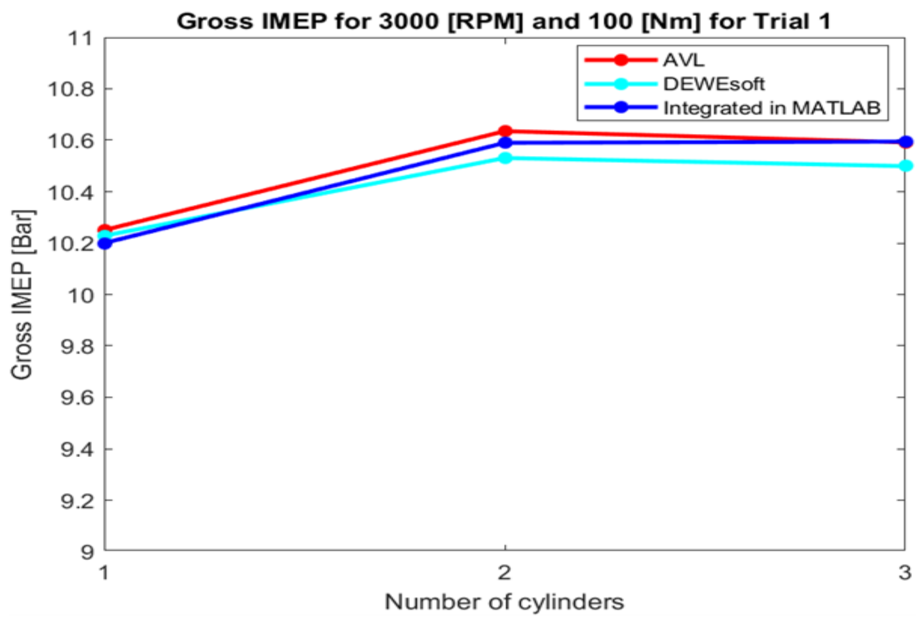


Figure 4.12: *Gross IMEP for 3000 [rpm] and 100 [Nm].*

Table 4.6: IMEP in [bar] for 300 cycles for Trail 2

DAQ	Testing at 2000 [rpm]			Testing at 3000 [rpm]		
	CYL- 1	CYL- 2	CYL- 3	CYL- 1	CYL- 2	CYL- 3
AVL	9.8121	10.0823	9.9846	10.2506	10.6353	10.5917
DEWEsoft	9.7503	10.0177	10.0261	10.2284	10.5309	10.4993
Integrated in MATLAB	9.8458	10.1184	10.0201	10.2	10.59	10.5949

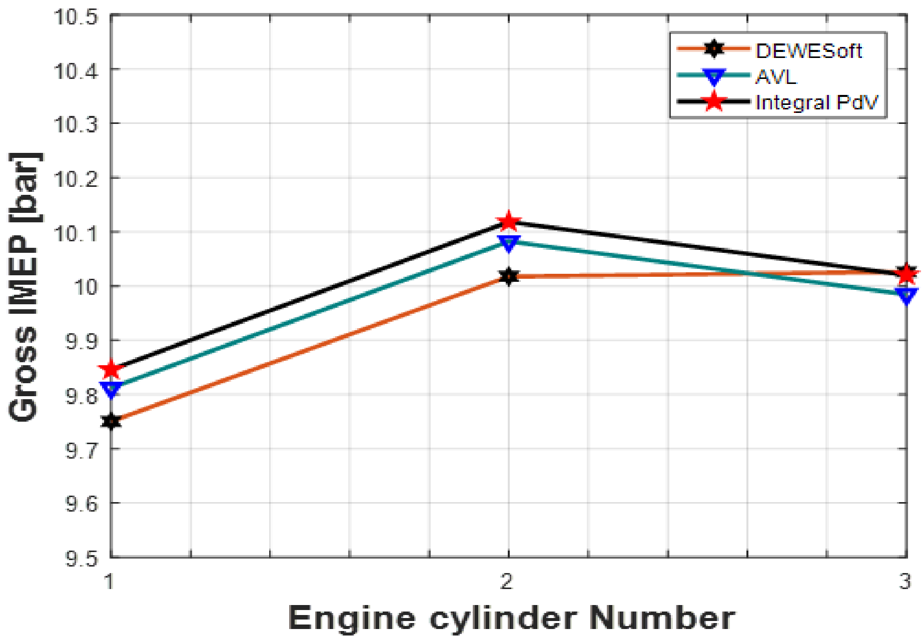


Figure 4.13: *Gross IMEP for 2000 [rpm] and 100 [Nm] Trial-2.*

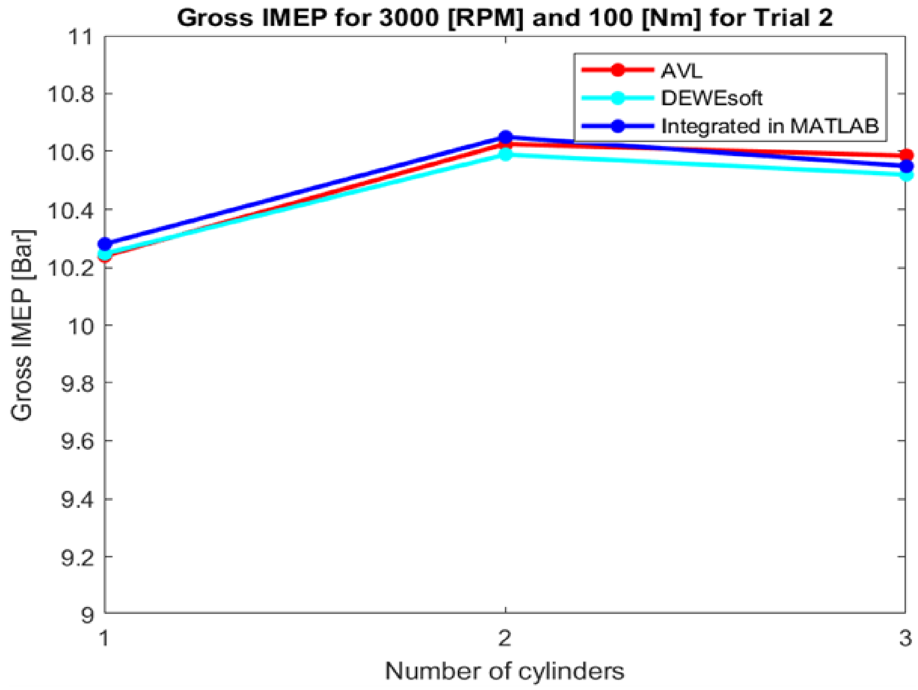


Figure 4.14: *Gross IMEP for 3000 [rpm] and 100 [Nm].*

Table 4.7: IMEP in [bar] for 300 cycles for Trail 3

DAQ	Testing at 2000 [rpm]			Testing at 3000 [rpm]		
	CYL- 1	CYL- 2	CYL- 3	CYL- 1	CYL- 2	CYL- 3
AVL	9.7812	10.0573	9.9683	10.2070	10.6045	10.6139
DEWEsoft	9.7774	10.0231	10.0437	10.3753	10.7263	10.7353
Integrated in MATLAB	9.8147	10.0934	10.0038	10.3745	10.6	10.65

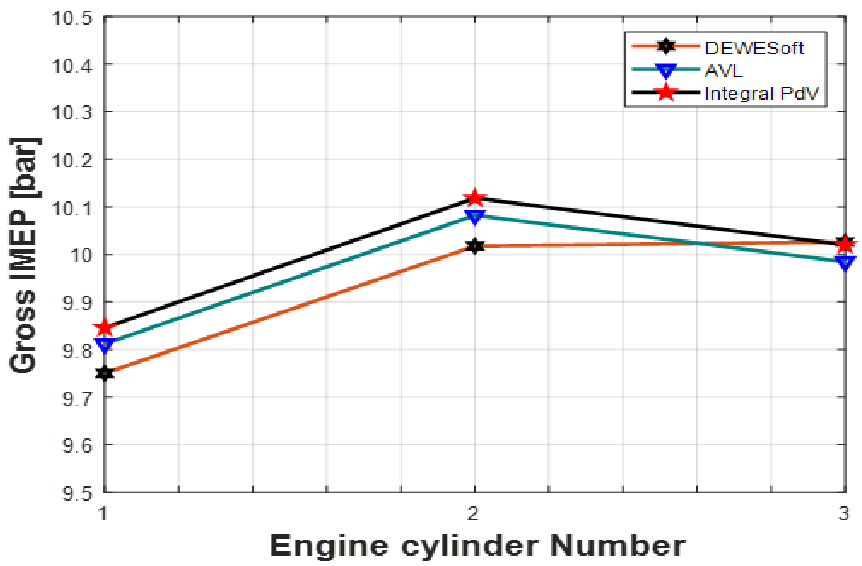


Figure 4.15: *Gross IMEP for 2000 [rpm] and 100 [Nm] Trial-3.*

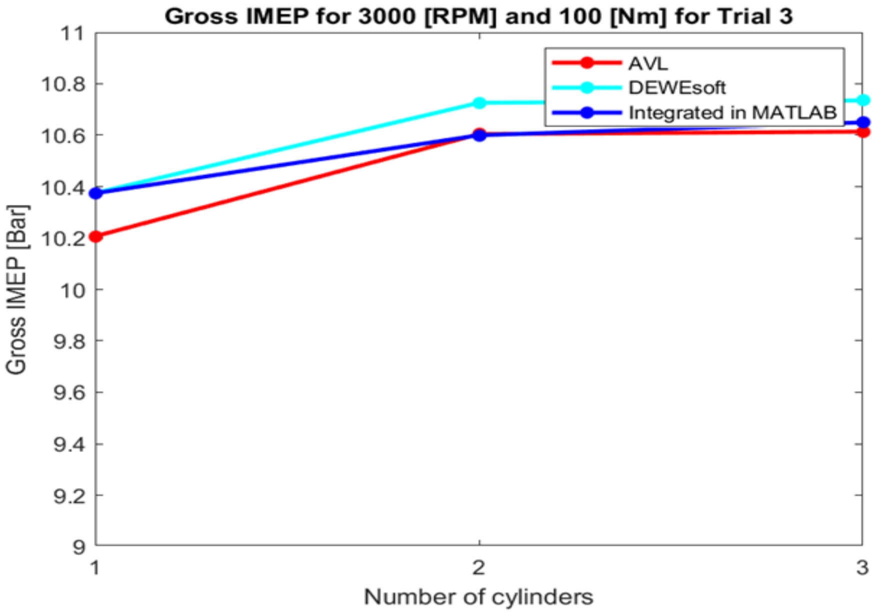


Figure 4.16: *Gross IMEP for 3000 [rpm] and 100 [Nm].*

4.2.4 Effect of CAD resolution on IMEP

In DEWESoft, the data was recorded for 0.1 CAD resolution. The DEWESoft software has the provision to recalculate the data for different CAD resolution. So to check the effect of CAD resolution on IMEP, the DEWESoft data was re-calculated for different CAD resolution for all the cylinders and then the IMEP is tabulated in tables 4.8 and 4.9. As we can see the change in CAD resolution had negligible effect on the IMEP.

Table 4.8: Effect of CAD resolution on IMEP for 2000 [rpm] and 100 [Nm]

Cylinder	CAD Res 0.1	CAD Res 0.2	CAD Res 0.5	CAD Res 0.8	CAD Res 1
1	9.7653	9.7654	9.7655	9.7659	9.7661
2	10.0280	10.0207	10.0211	10.0212	10.0216
3	10.0372	10.0372	10.0373	10.0380	10.0380

Table 4.9: Effect of CAD resolution on IMEP or 3000 [rpm] and 100 [Nm]

Cylinder	CAD Res 0.1	CAD Res 0.2	CAD Res 0.5	CAD Res 0.8	CAD Res 1
1	10.2217	10.2217	10.2217	10.2183	10.2212
2	10.5148	10.5147	10.5147	10.5329	10.5141
3	10.5102	10.5102	10.5102	10.5012	10.5096

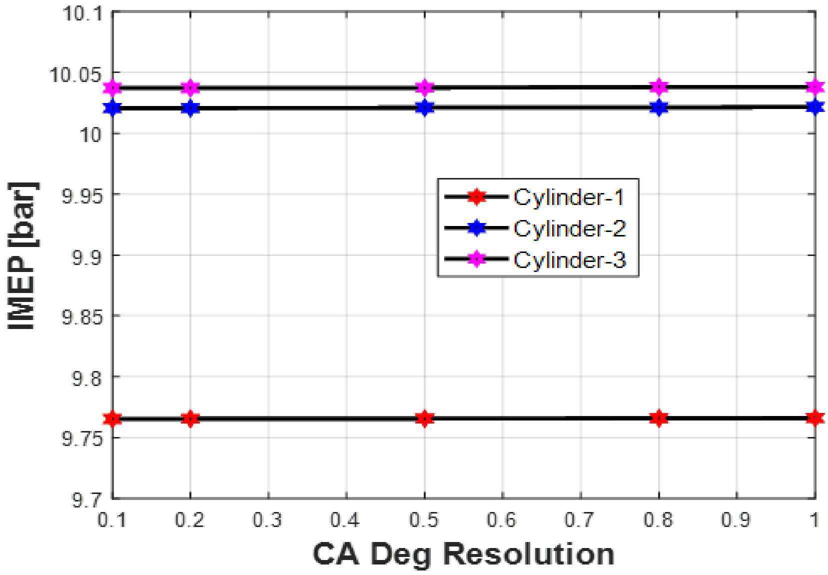


Figure 4.17: *Effect of CAD resolution on IMEP for 2000 [rpm] and 100 [Nm]*

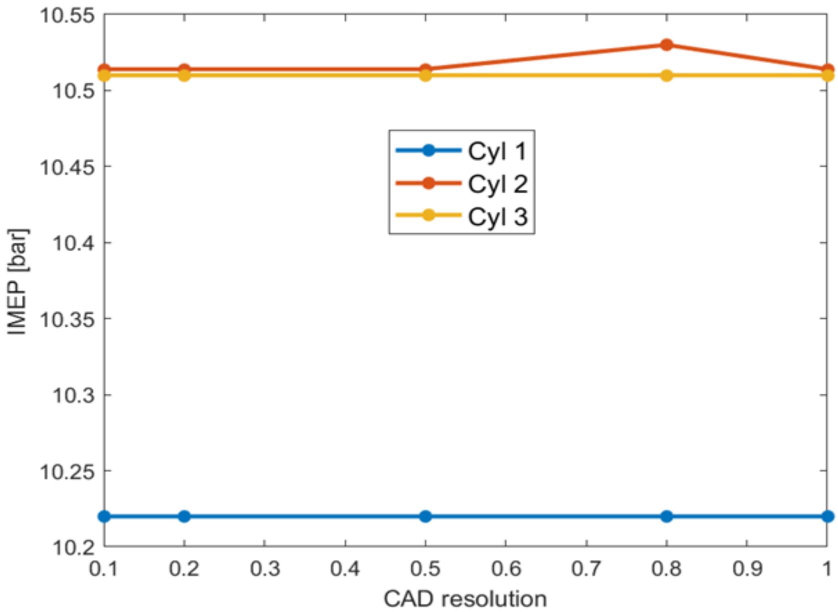


Figure 4.18: *Effect of CAD resolution on IMEP for 3000 [rpm] and 100 [Nm]*

4.2.5 Combustion Phasing

Combustion of air-fuel mixture inside the engine cylinder is the one which controls engine power, emissions, and efficiency[4]. Combustion phasing is the optimum heat-release cylinder volume phasing, at which maximum work output from the engine can be conveniently extracted. If the chemical energy of the fuel released is too early, then the work done by the piston is more resulting in less work output. and if it is too late, then the peak pressure inside the cylinder will be less causing less work output [19]. hence combustion phasing should be optimum.

From the data collected for engine testing at 2000 [rpm] speed and 100 [Nm] torque by the DAQ systems AVL and DEWESoft, graphs are plotted for trial-1 data. Figures 4.19,4.22,4.25 represents CAD angles versus maximum pressure of cylinder-1, 2, and 3 respectively. Figures 4.20,4.21,4.23,4.24,4.26,and 4.27 illustrates the 300 cycles of three cylinders, with the averaged cycle depicting max pressure value with crank angle degree. from the graphs we can see that for steady state testing of engine at 2000 [rpm] and 100 [Nm] torque the peak pressure is at crank angle degree is similar for both the DAQ systems. however there is a slight difference in the peak pressure values, which is further elaborated in section In-cylinder pressure.

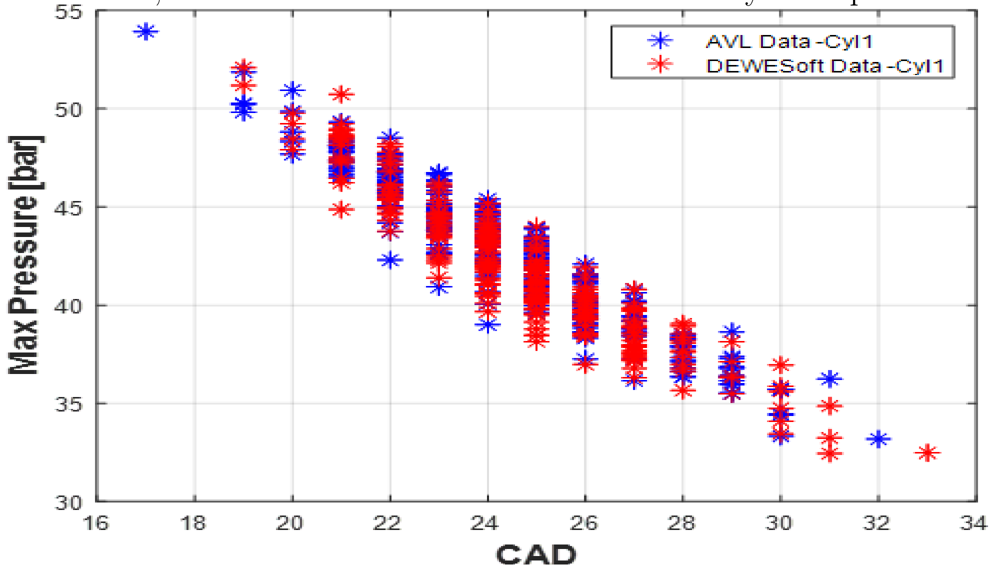


Figure 4.19: *CAD Vs maximum Pressure [bar] for 300 cycles, Cylinder-2 testing at 2000[rpm] and 100[Nm].*

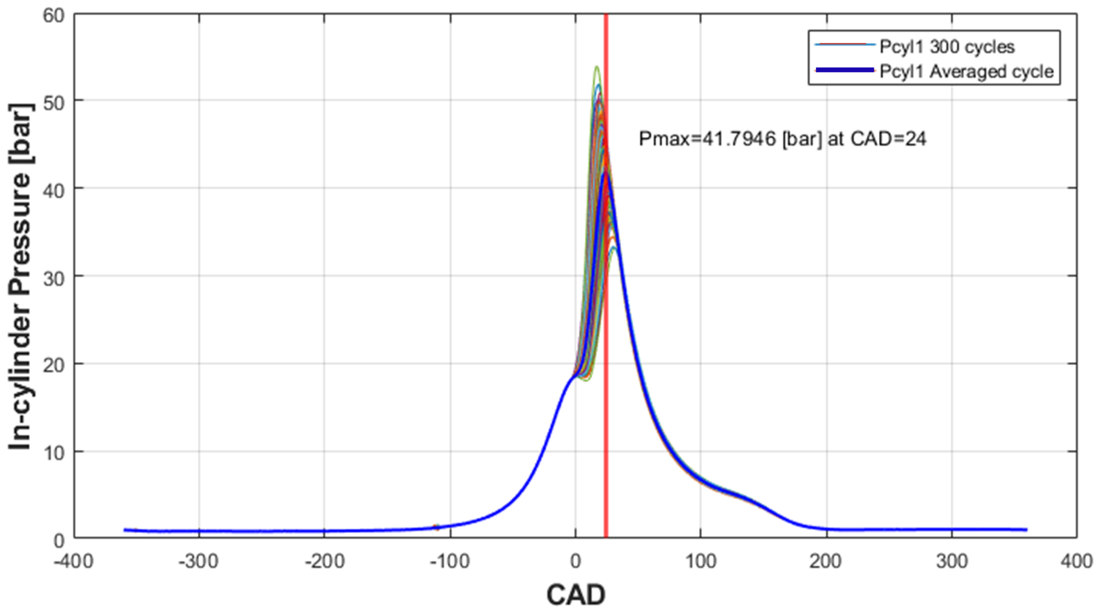


Figure 4.20: *AVL data for Cylinder-2, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

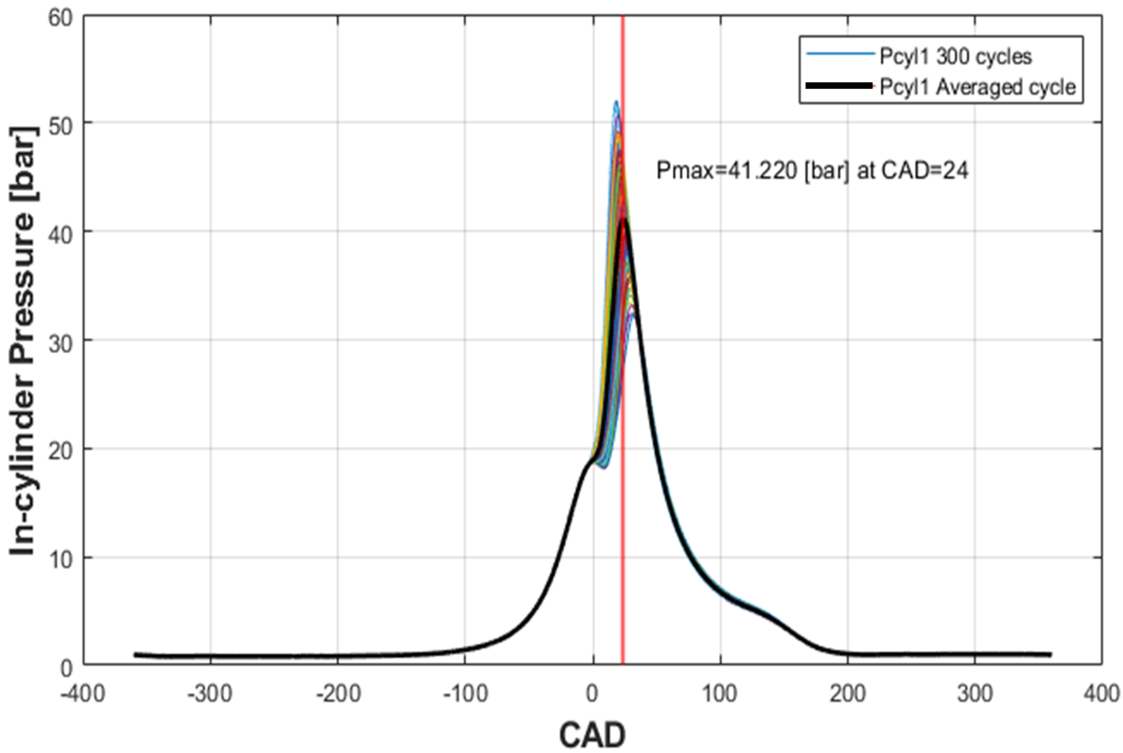


Figure 4.21: *DEWESoft data for Cylinder-2, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

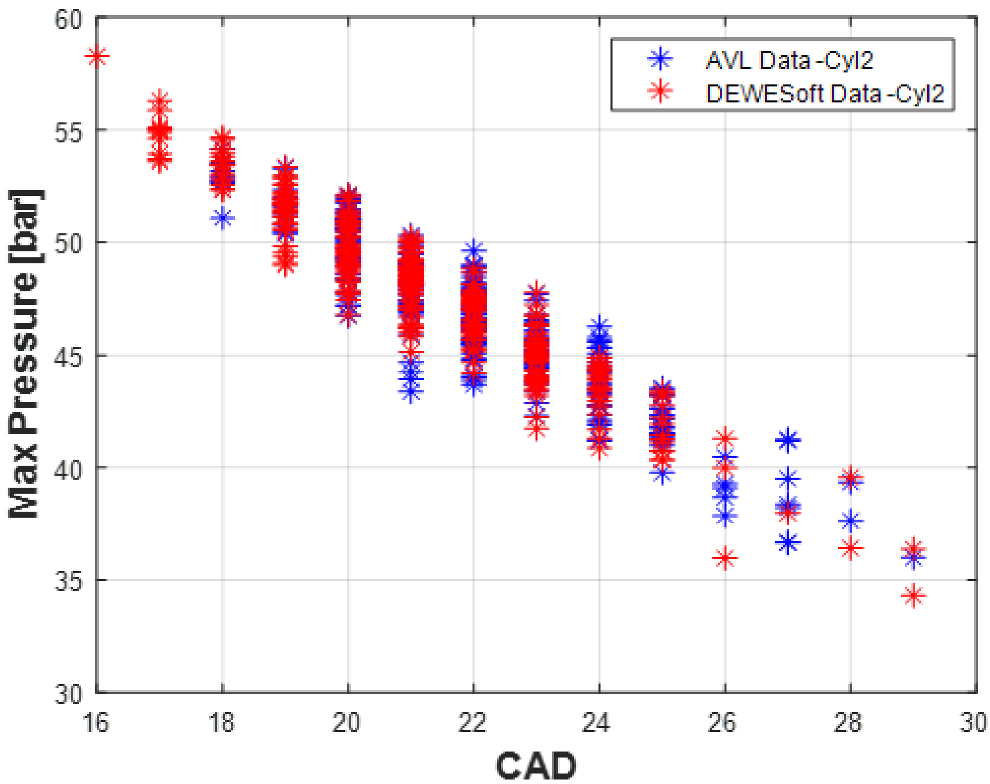


Figure 4.22: *CAD Vs maximum Pressure [bar] for 300 cycles, Cylinder-3 testing at 2000[rpm] and 100[Nm].*

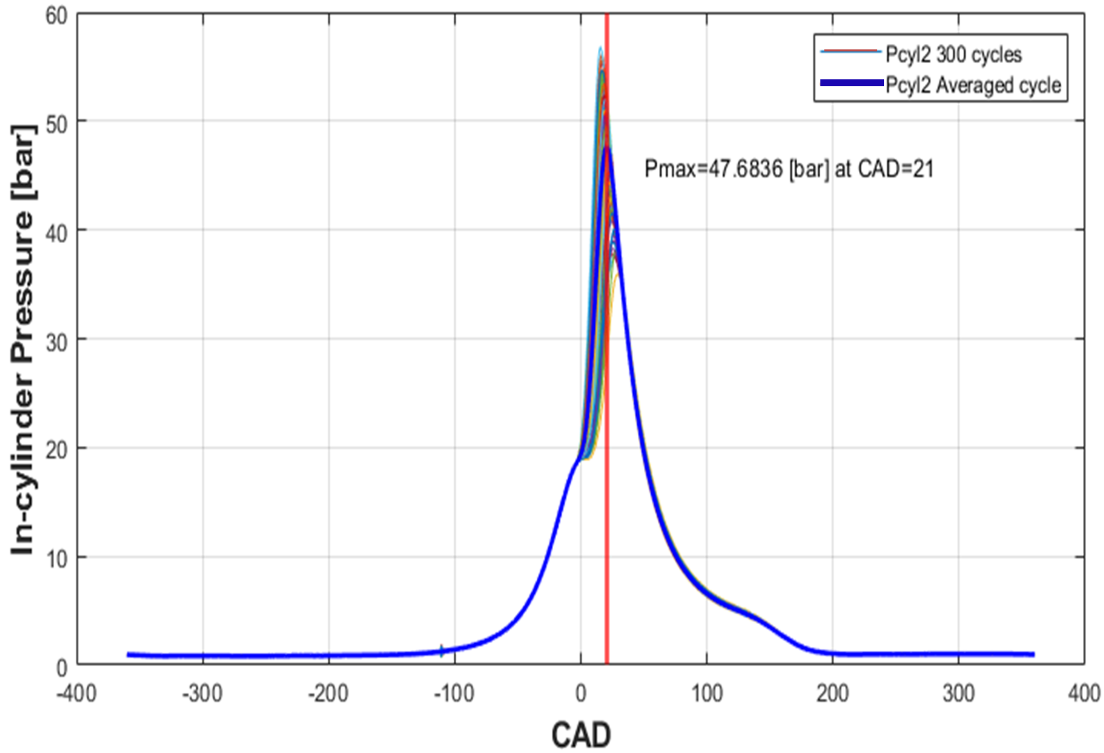


Figure 4.23: *AVL data for Cylinder-2, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

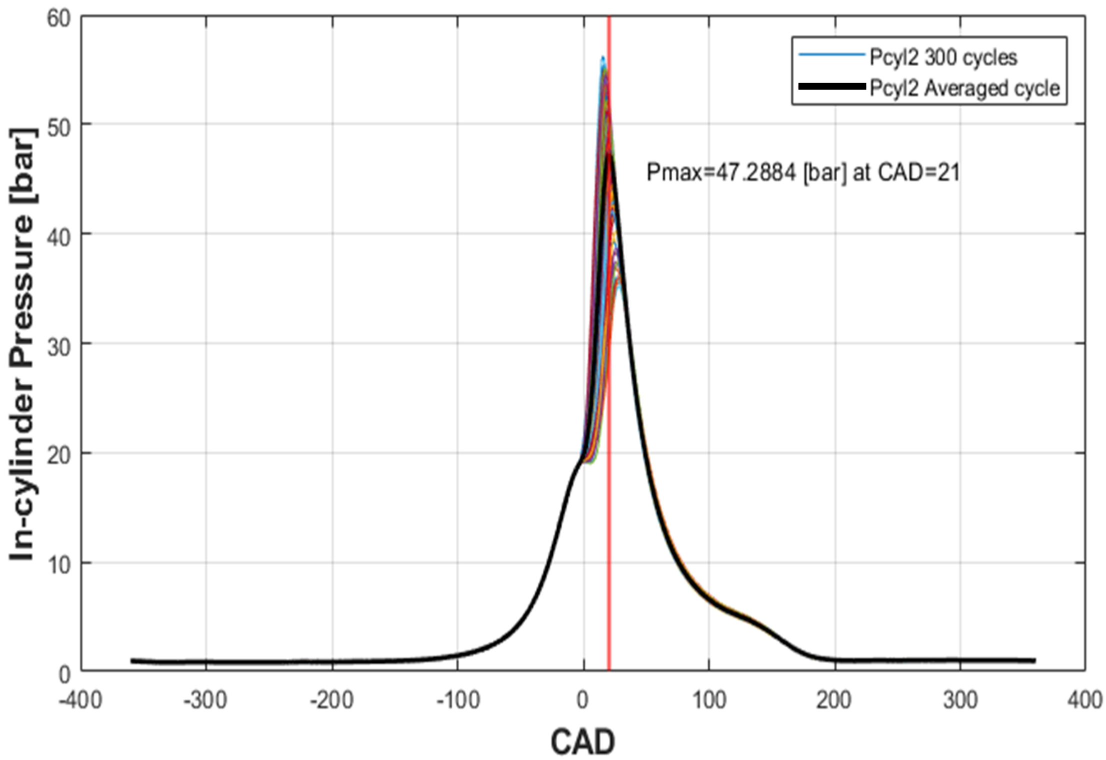


Figure 4.24: *DEWESoft data for Cylinder-2, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

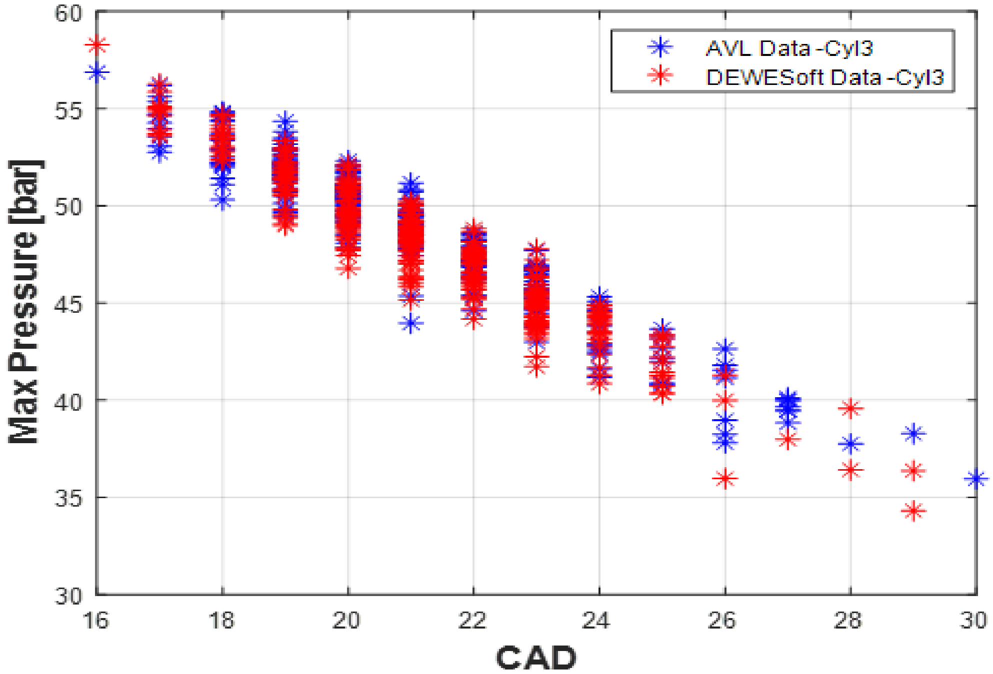


Figure 4.25: *CAD Vs maximum pressure [bar] for 300 cycles, Cylinder-2 testing at 2000[rpm] and 100[Nm].*

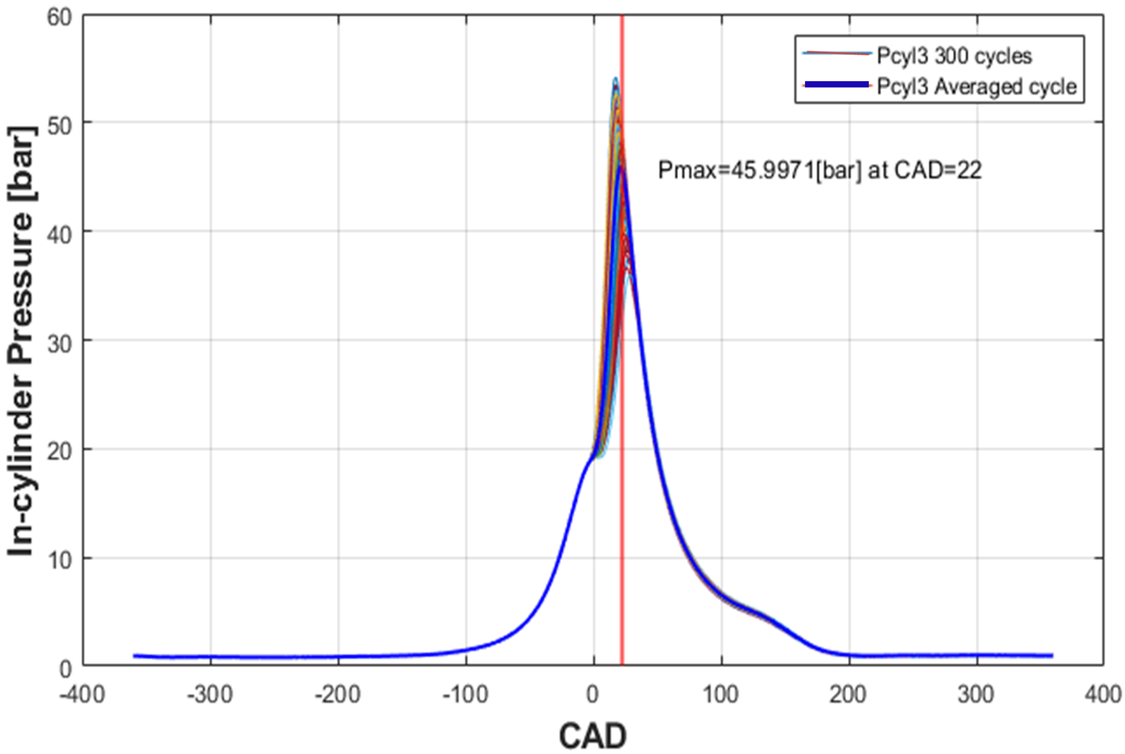


Figure 4.26: *AVL data for Cylinder-3, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

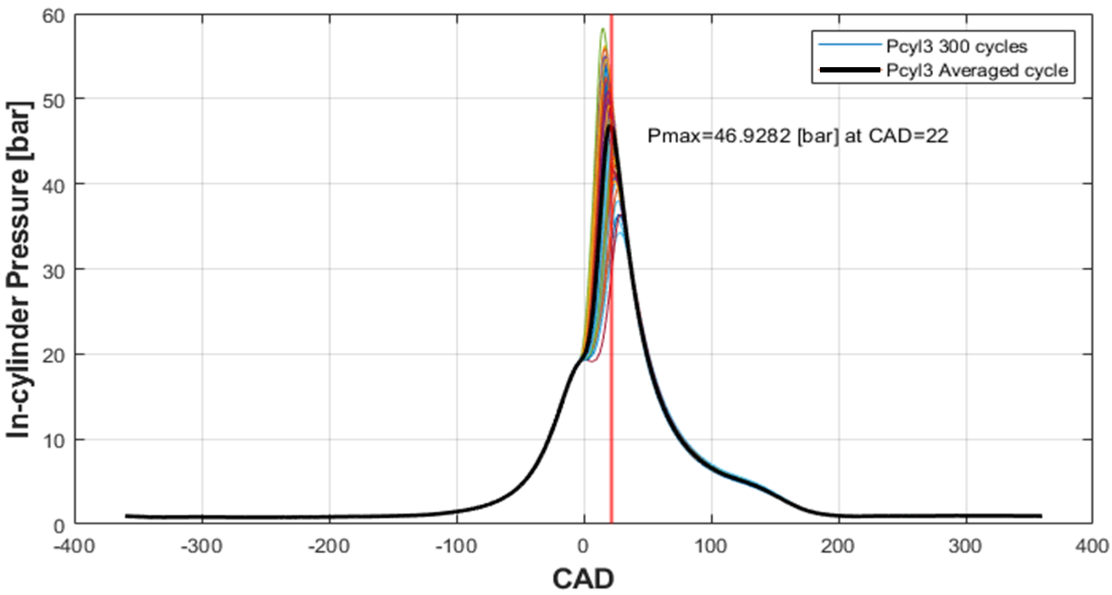


Figure 4.27: *DEWESoft data for Cylinder-3, CAD Vs Pressure [bar] for 300 cycles with averaged cycle for testing at 2000[rpm] and 100[Nm].*

The combustion phasing was also carried out for 3000 [rpm] and 100 [Nm] for all the cylinders and for 300 cycles. The plots for the respective data is plotted below for both DEWEsoft and AVL. The scatter plot represents the crank angle degrees for maximum pressure from 300 cycles. From the spread of the data it can be seen that CAD varies from 18 to 35 degress. The variation in the maximum pressure CAD for different cycles recorded in different DAQ (AVL and DEWEsoft) is similar from the spread of the data. The average pressure curve is also plotted with the respective CAD for maximum pressure for all the cylinder mentioned in the graph. It can be seen that, the corresponding CAD for maximum pressure for the two DAQ's is similar.

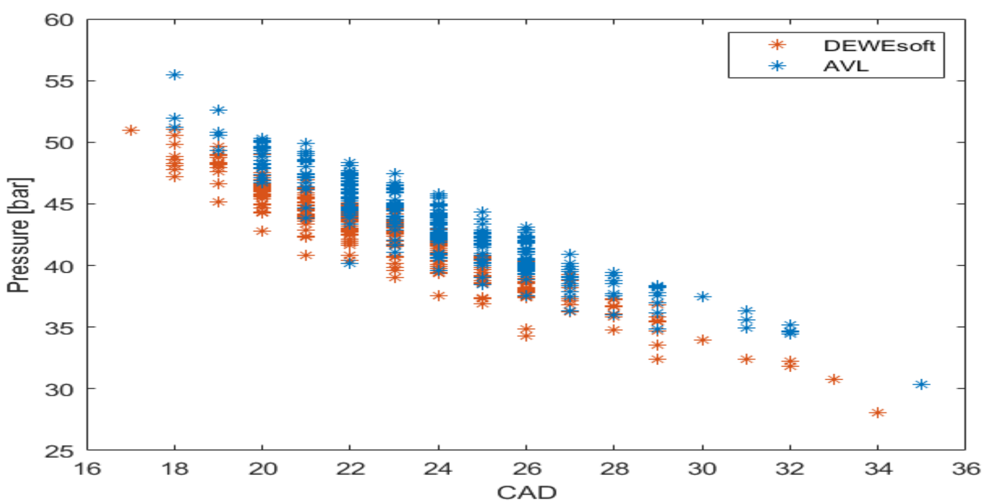


Figure 4.28: *CAD angles for 300 cycles of CYL 1 for maximum pressure.*

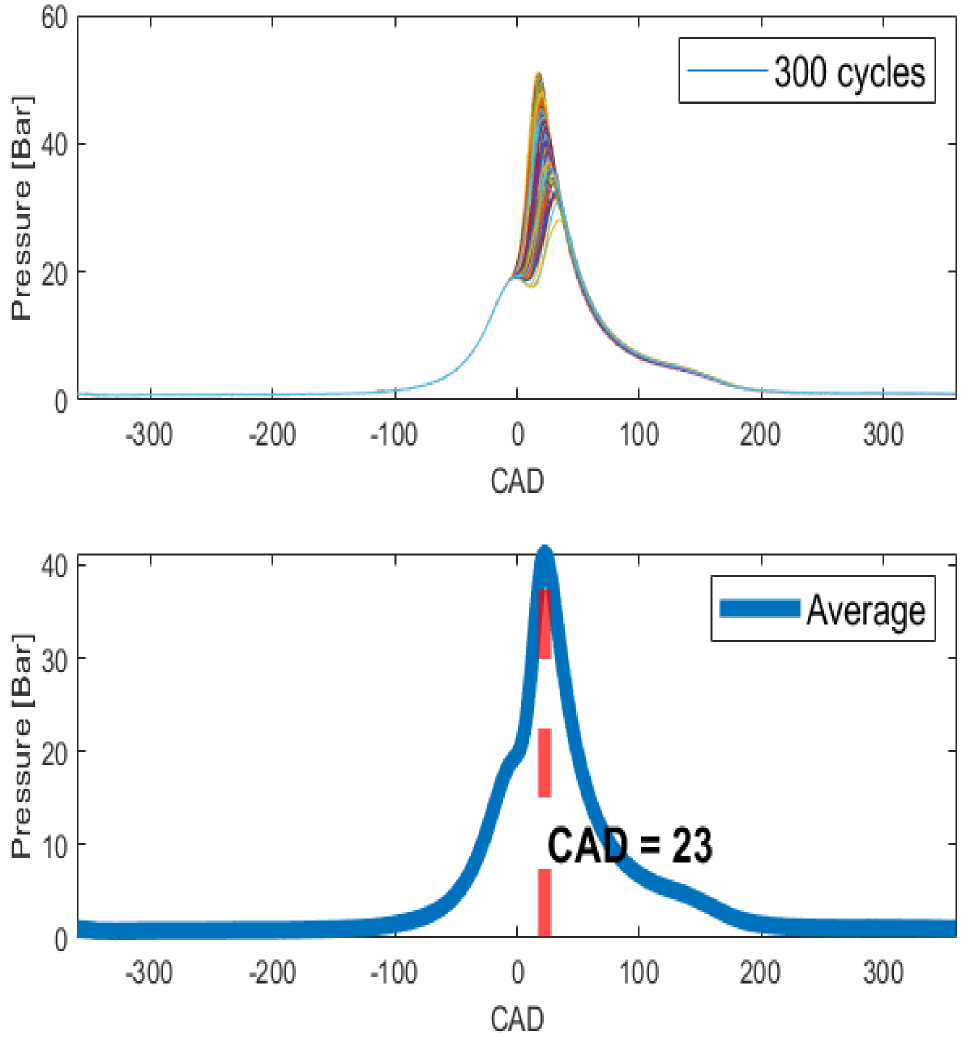


Figure 4.29: *CAD angle of maximum pressure for CYL 1 for DEWEsoft data.*

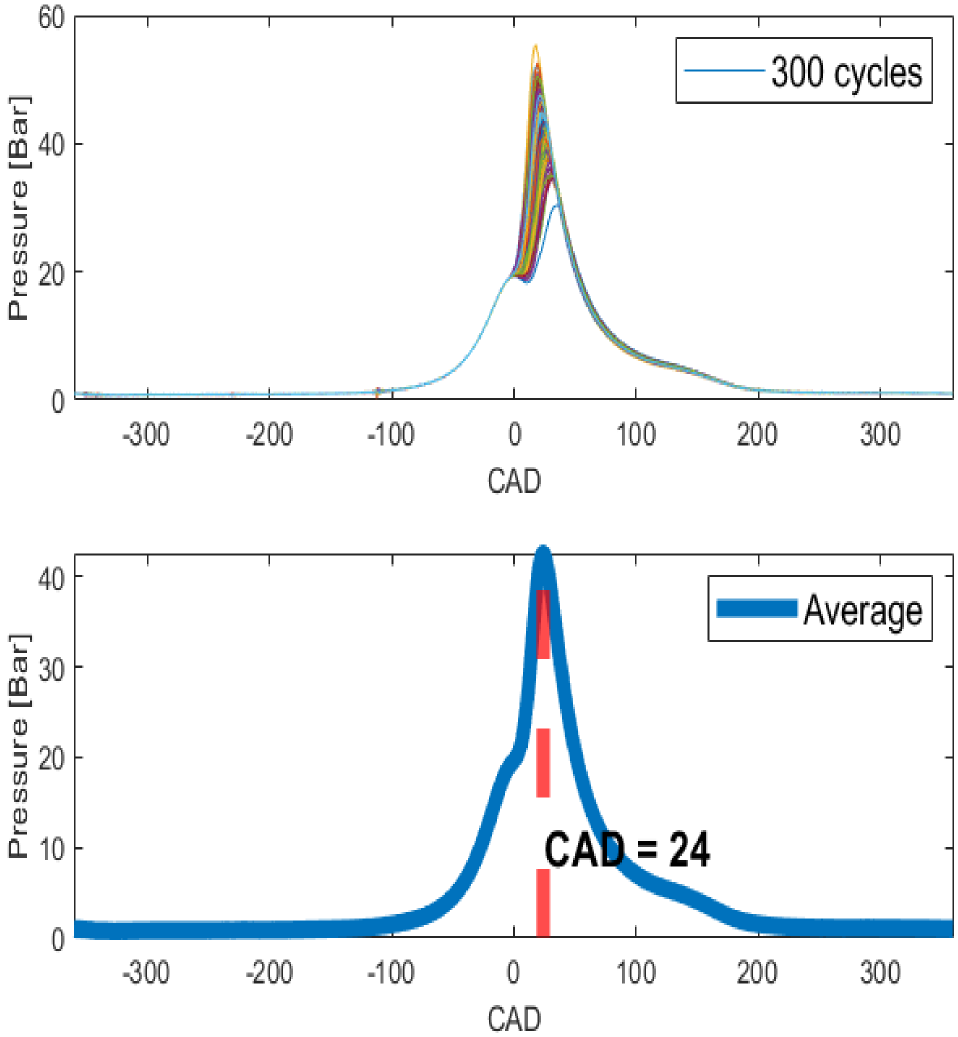


Figure 4.30: *CAD angle of maximum pressure for CYL 1 for AVL data.*

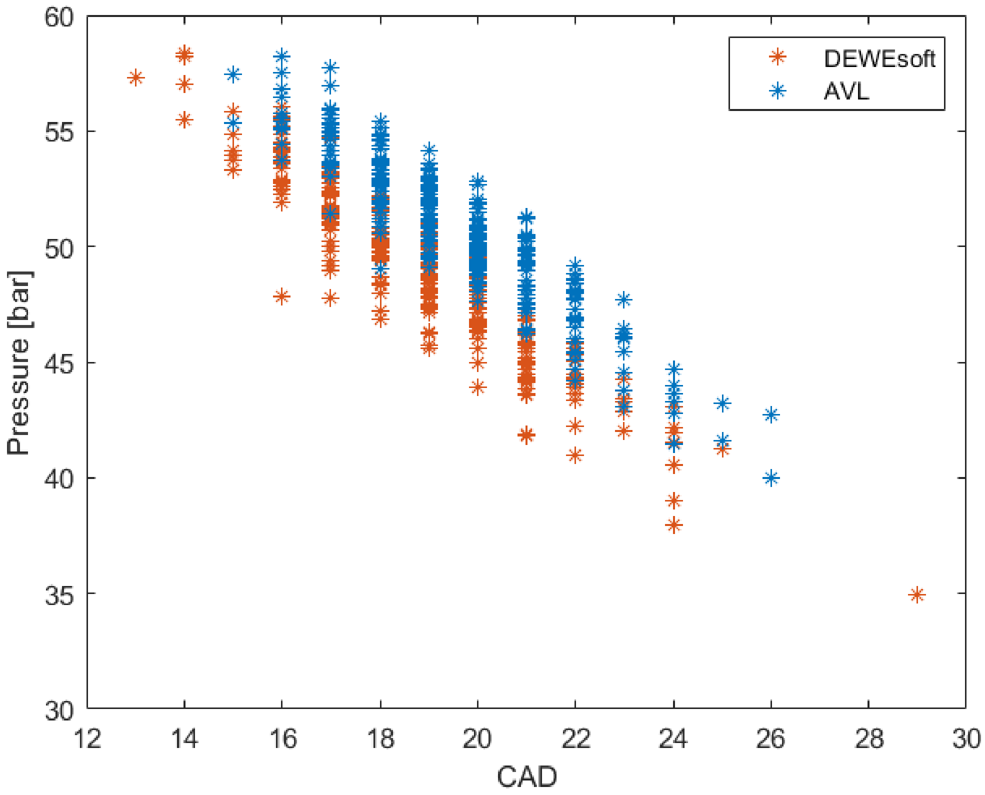


Figure 4.31: *CAD angles for 300 cycles of CYL 2 for maximum pressure.*

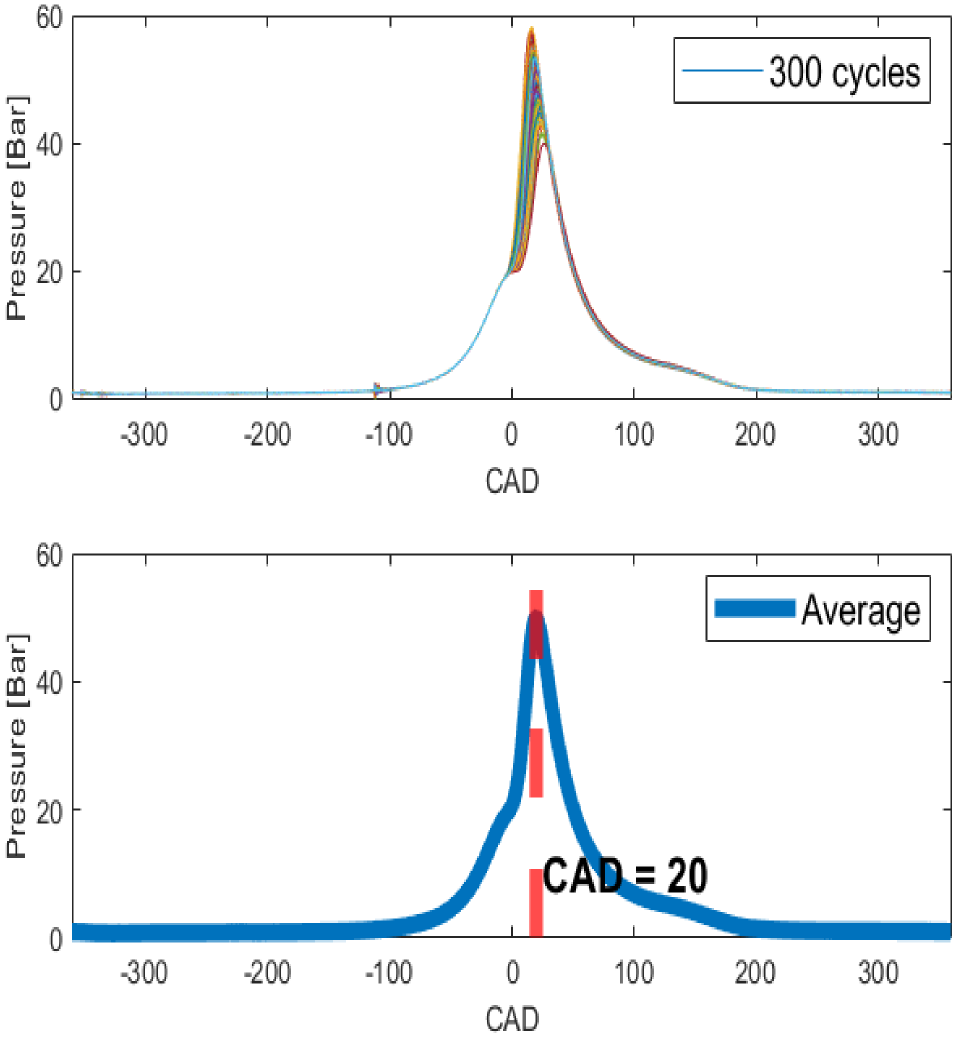


Figure 4.32: *CAD angle of maximum pressure for CYL 2 for AVL data.*

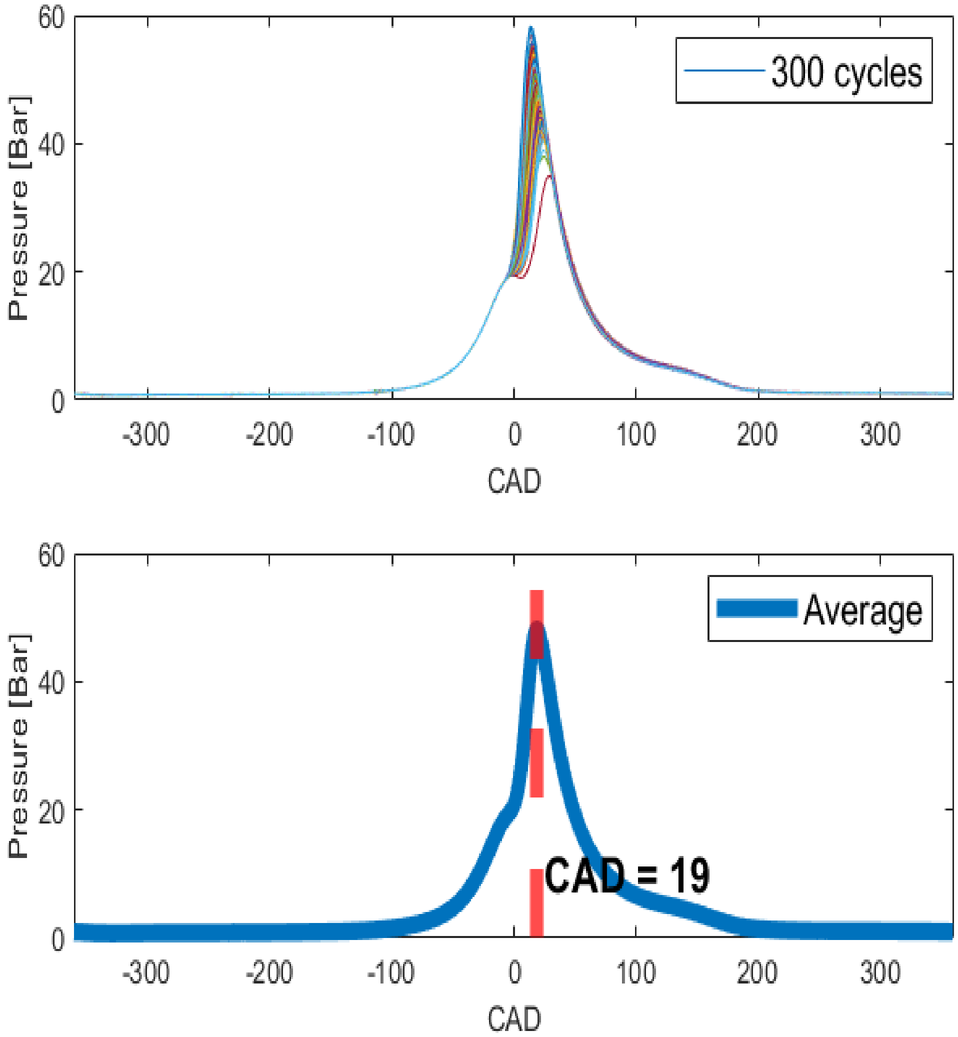


Figure 4.33: *CAD angle of maximum pressure for CYL 2 for DEWEsoft data.*

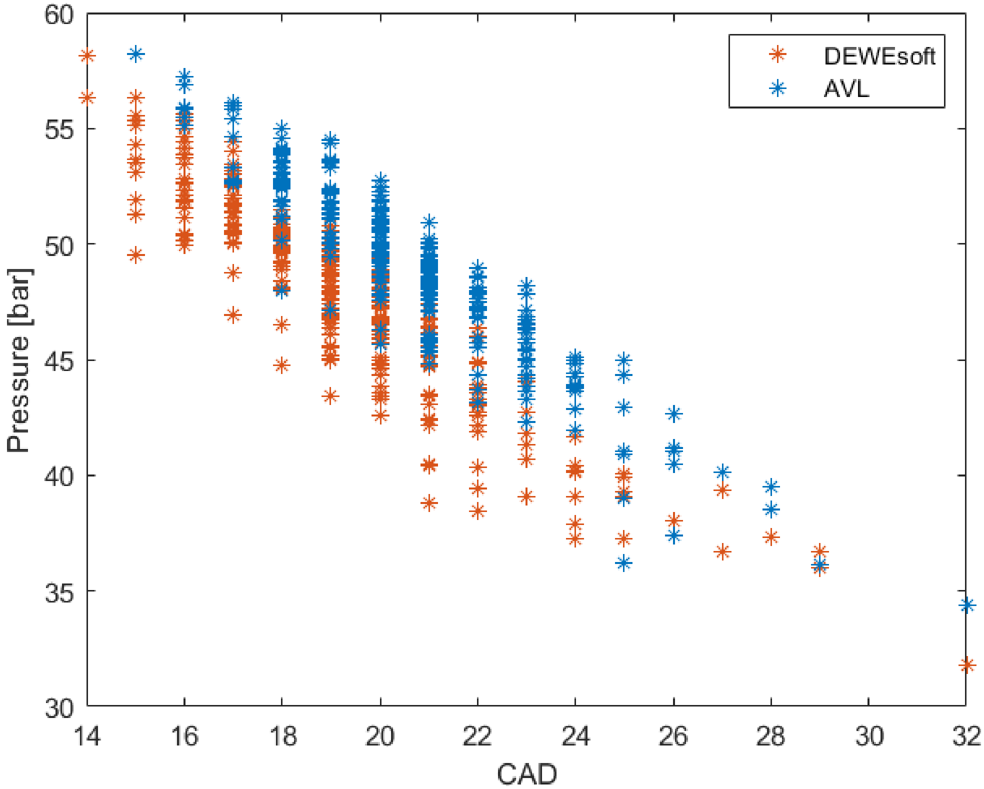


Figure 4.34: *CAD angles for 300 cycles of CYL 3 for maximum pressure.*

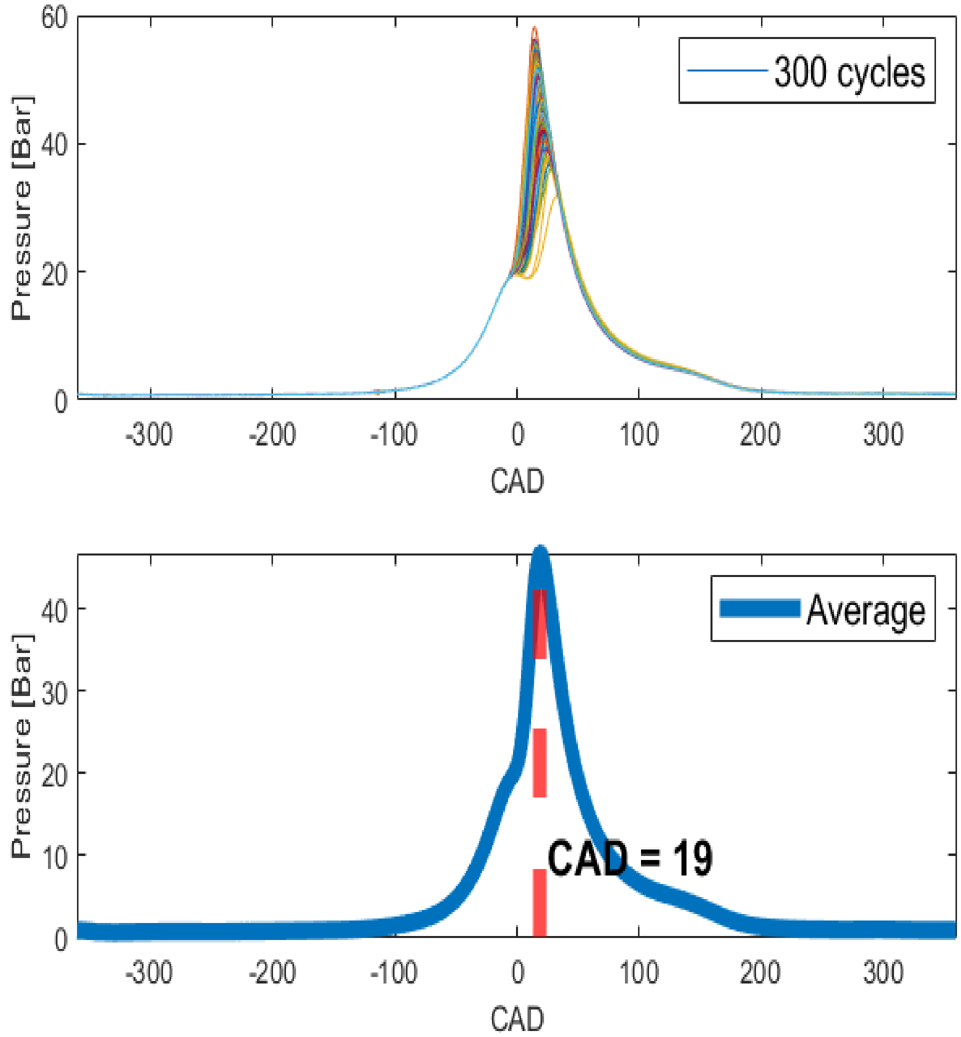


Figure 4.35: *CAD angle of maximum pressure for CYL 3 for DEWEsoft data.*

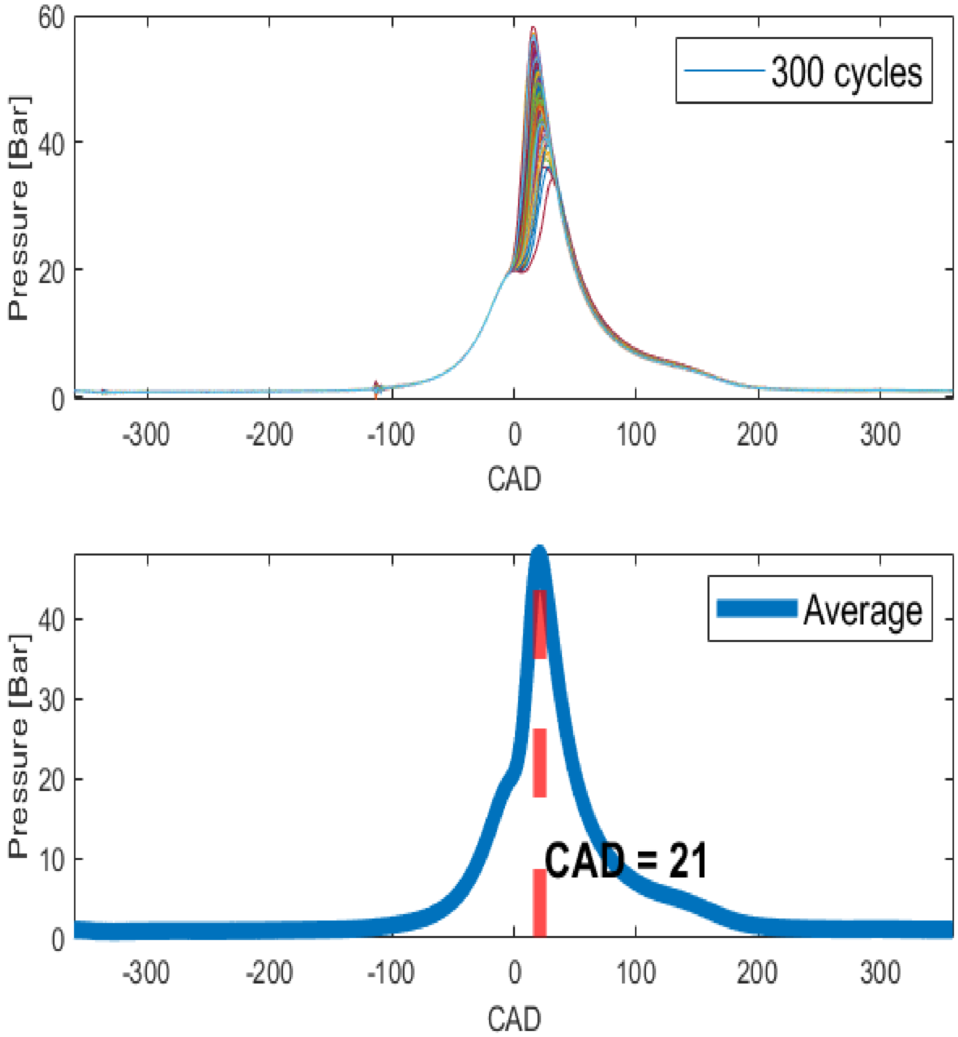


Figure 4.36: *CAD angle of maximum pressure for CYL 3 for AVL data.*

4.2.6 In-cylinder pressure [Bar]

After plotting the averaged cylinder pressure for all the cycles, Figure 4.37 illustrates averaged cycles of Cylinder-2 for trials 1, 2, and 3 acquired via both AVL and DEWESoft DAQ systems. A difference of 0.631 [bar] was observed as shown in Table 4.10 in the case of engine testing at 2000[rpm] and 100 [Nm] torque. And a difference of 0.377 [bar] was observed as shown in the Table 4.39 in case of engine testing at 3000[rpm] and 100 [Nm] torque.

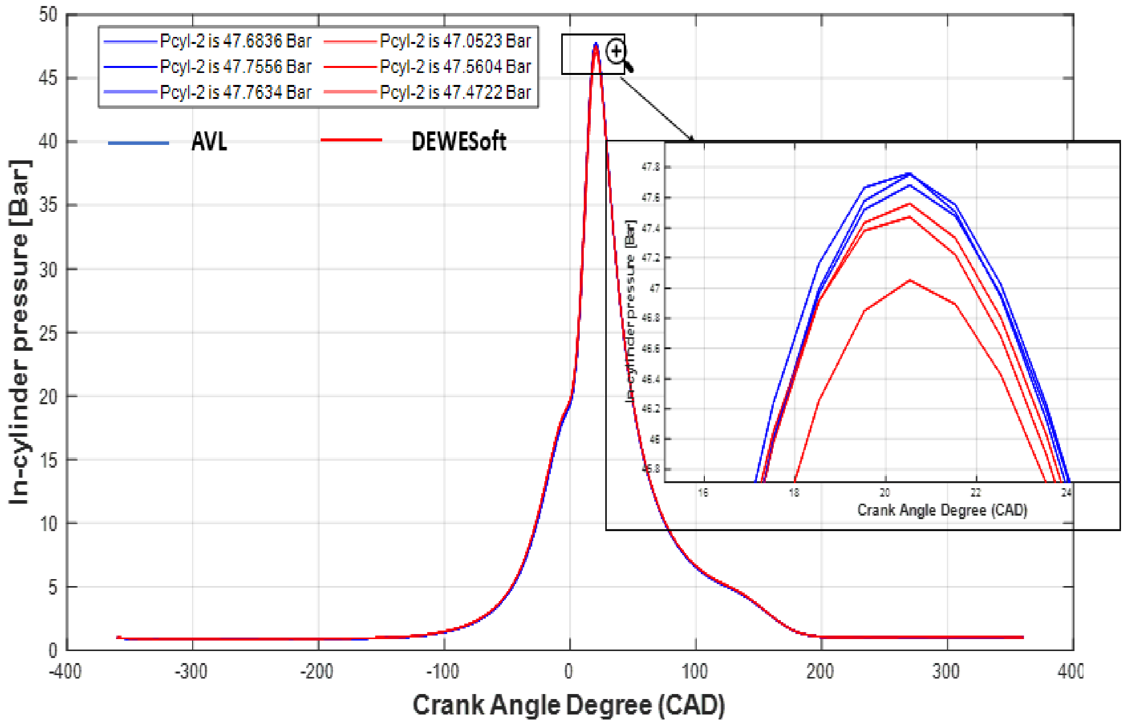


Figure 4.37: *Engine Testing at 2000[rpm] and 100 [Nm], averaged cycles of Cylinder-2 for trial 1, 2, and 3.*

Table 4.10: *Mean peak pressure values in [bar] of Cylinder-2 for 300 cycles DEWESoft and AVL data, 9 different trials*

Trial No	DEWESoft	AVL	Difference
1	47.0523	47.6836	0.6313
2	47.5604	47.7556	0.1952
3	47.4722	47.7634	0.2912
4	47.5263	47.3666	0.1597
5	46.7674	47.6102	0.8428
6	47.2143	48.1807	0.9664
7	47.3012	48.389	1.0878
8	47.4143	48.5653	1.151
9	47.3305	48.5468	1.2163

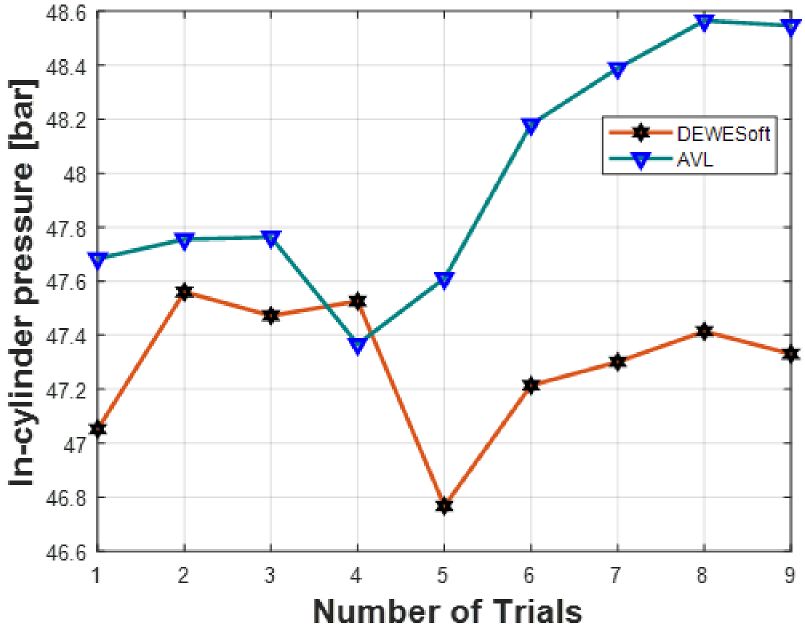


Figure 4.38: *Pressure values for engine Testing at 2000[rpm] and 100 [Nm], 9 No's Trails*

.

Table 4.11: *Mean peak pressure values in [bar] for 300 cycles DEWESoft and AVL data, 9 different trials*

Trial no	DEWEsoft	AVL	Difference
1	42.3859	42.7635	0.3776
2	42.7691	42.9581	0.189
3	42.6647	43.013	0.3483
4	42.4174	42.7566	0.3392
5	42.0353	42.5693	0.534
6	42.4123	42.8577	0.4454
7	42.5480	42.9667	0.4187
8	43.0863	43.4444	0.3581
9	43.4046	43.5730	0.1684

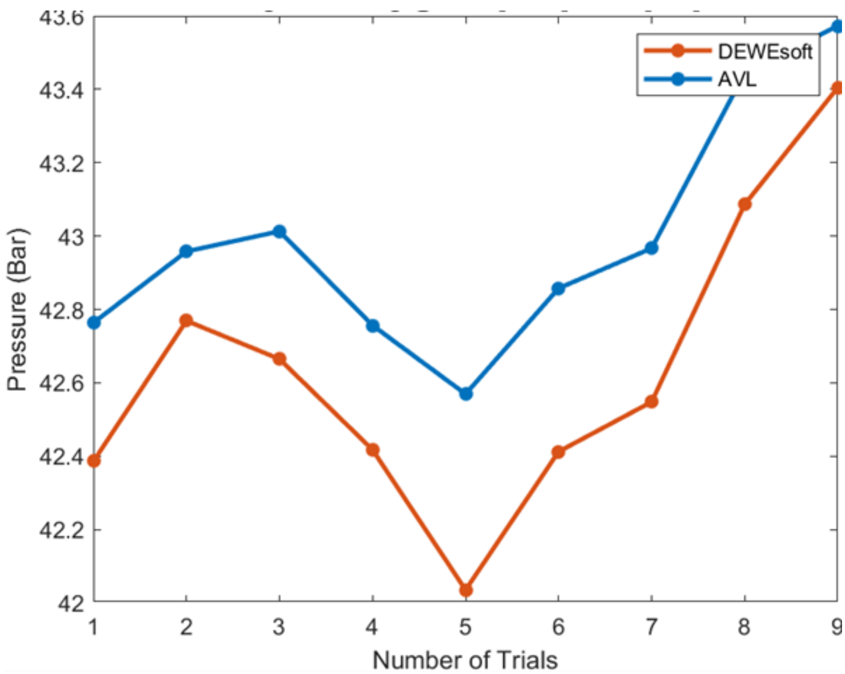


Figure 4.39: *Pressure Curves for 3000[rpm] and 100 [Nm] for 9 trials*

.

The precision of a measurement device is the closeness between the successive measurement which are recorded under unchanged conditions. Accuracy is the closeness of the measured value to the true value. Data may be accurate but not precise, or data may be precise but not accurate. Precision includes repeatability and reproducibility [20] [21].

Precision can be calculated including the range of values. In the above Tables 4.10 and 4.39, 9 trials of mean peak pressure values for engine testing at 2000[rpm] and 100 [Nm] torque, 9 trials for 3000[rpm] and 100 [Nm] torque acquired by both AVL and DEWESoft DAQ systems are presented.

AVL data for 2000 [rpm]: [Max value-Min value]=[48.5653-47.3666]=1.1987.
DEWESoft data for 2000 [rpm] =[47.5604-46.7674]=0.793.

similarly,
AVL data for3000 [rpm]: [43.5730-42.5693]=1.0037.
DEWESoft data for 3000 [rpm] =[43.4046-42.0353]=1.3693.

From the above values it is evident that at 2000[rpm] precision of DEWESoft is good, and at higher speed 3000 [rpm] precision of AVL is good.

4.2.7 Investigation of influencing parameters on In-cylinder pressure

. As we can see that there is a slight difference mean pressure values, investigation of influencing parameters on cylinder pressure is carriedout.In the section test methodology and from Figure 3.11 it is clear that the configuration for both the DAQ systems was same for fair comparison.

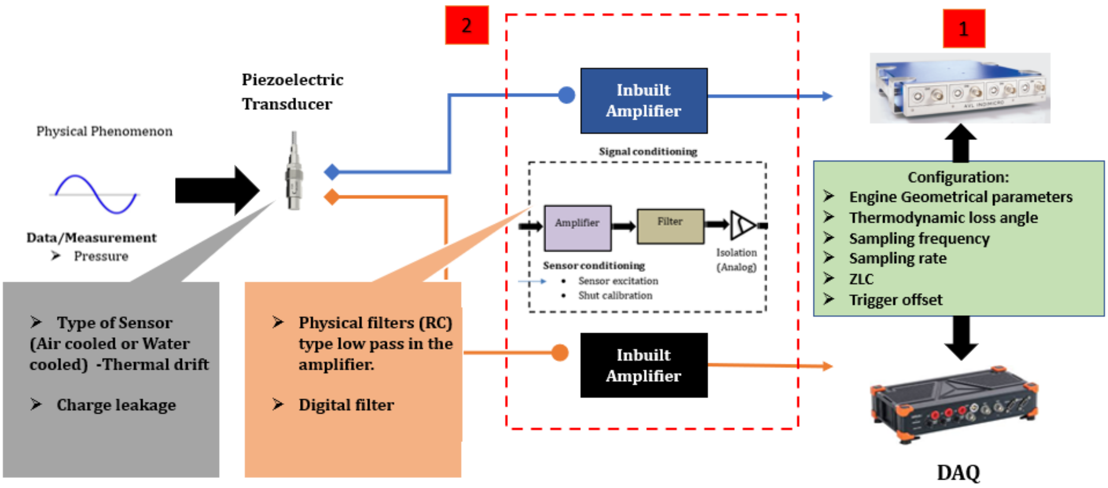


Figure 4.40: *Influencing parameters on in-cylinder pressure signal.*

Firstly, As the data was acquired by the DAQ systems one after the other and the speed and torque of the engine was controlled throug knobs by the operator(human). There is a fair amount of chance that the measurement was not exact same.

Secondly, coming to the Piezo-electric transducer used for the project was an air-cooled type, because of which there is room for error due to thermal drift. Figure 4.41 shows the LogP-logV pressure curves for Trial 1, 2, 3 for AVL and DEWESoft, overlapped on each other .The interpretation from the graph is that the pressure envelops in the inlet and exhaust ports are relatively stable during steady-state engine operation, and from the graph, we can see that the curves overlap on each other without any discrepancies, so the sensor is stable [22].

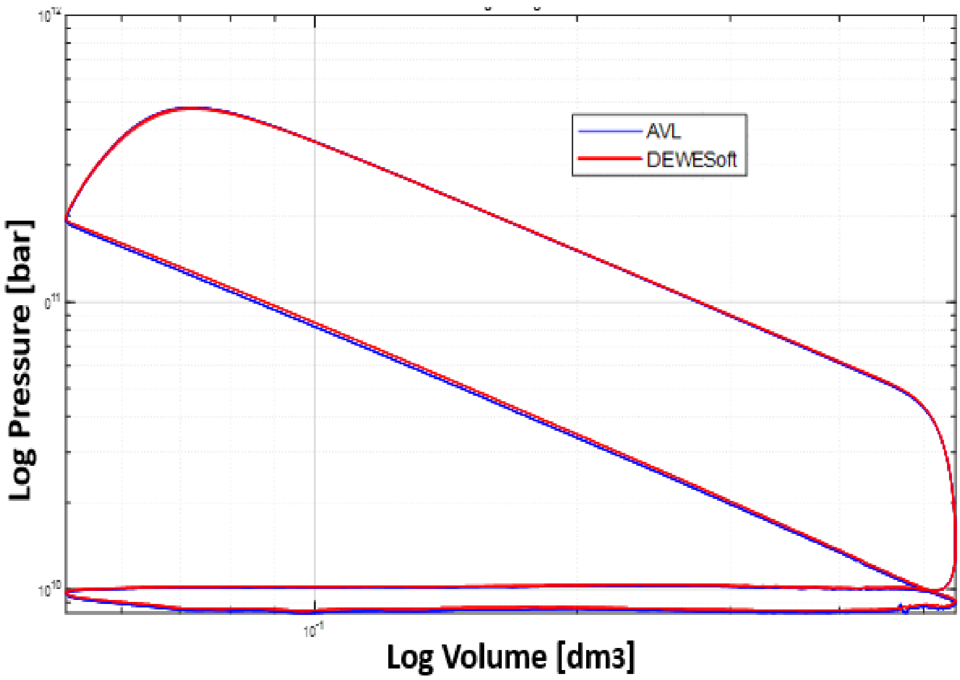


Figure 4.41: *LogP-logV, Trial 1, 2, 3 for AVL and DEWESoft .*

Third, Trigger offset which is used to synchronize the crank angle encoder to the In-cylinder pressure data [5]. It is calculated in the AVL and DEWESoft tools automatically by motoring the engine and trigger offset of 0.05 CAD, do make a difference and affects IMEP, temperature, and rate of heat release.

In addition to these, the major factors causing combustion instabilities are aerodynamics inside the engine cylinder during combustion, amount of air-fuel mixture, recycled exhaust gases in the cylinder,cycle-cycle variations and composition of the local mixture near the spark plug would affect the In-cylinder pressure[4].

4.2.8 Speed [rpm] data comparison

The speed data recorded in DEWESoft and AVL was also plotted for all the cycles. To further evaluate the consistency of the recorded data probability plot was plotted (fig 4.45) so as to analyze how far is the spread of the data with respect to mean. On the probability plot the X axis represent the values of the speed recorded and the Y axis represents the chance of occurrence of the values on the X axis. The lesser the slope of the curve better is data, because it means that the standard deviation of the data is less.

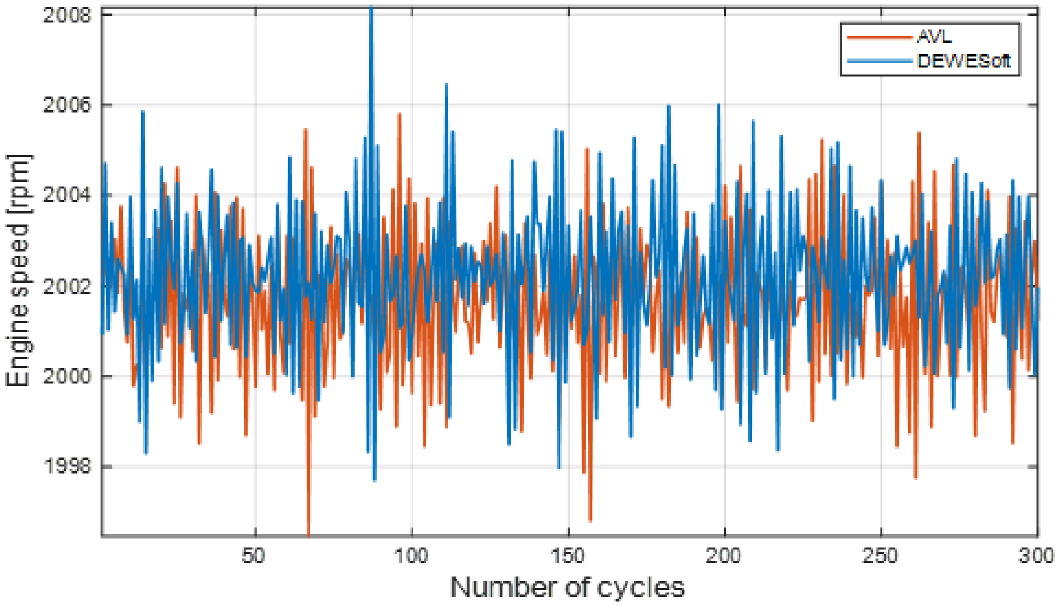


Figure 4.42: *Speed plot for engine speed 2000 [rpm] data recorded by DEWESoft and AVL.*

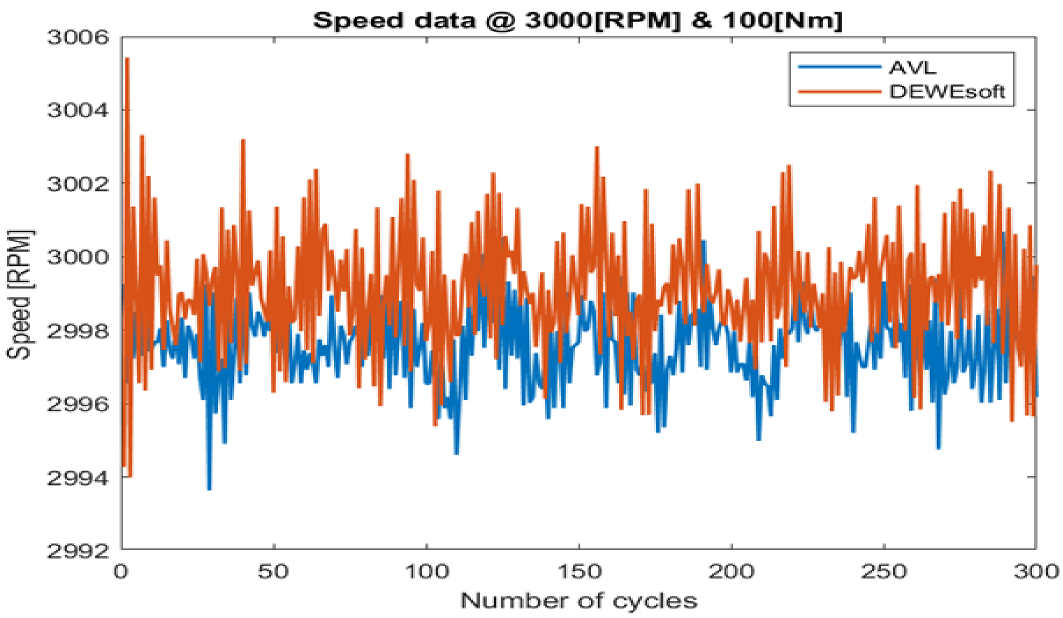


Figure 4.43: *Speed plot for 3000 RPM.*

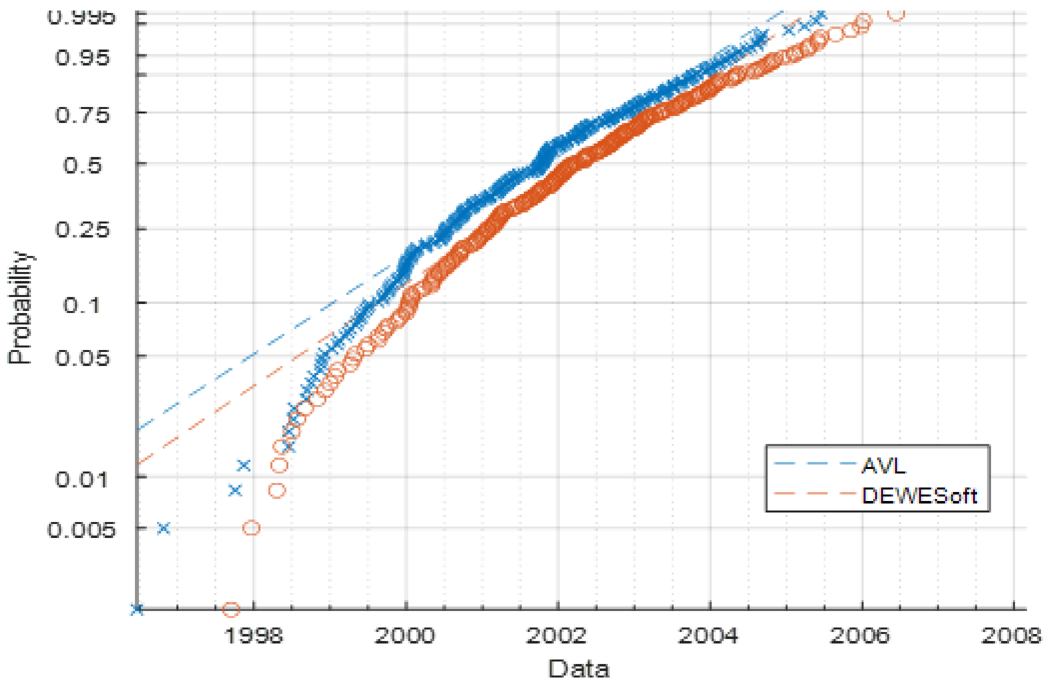


Figure 4.44: *Probability plot for engine speed 2000 [rpm] data recorded by DEWESoft and AVL.*

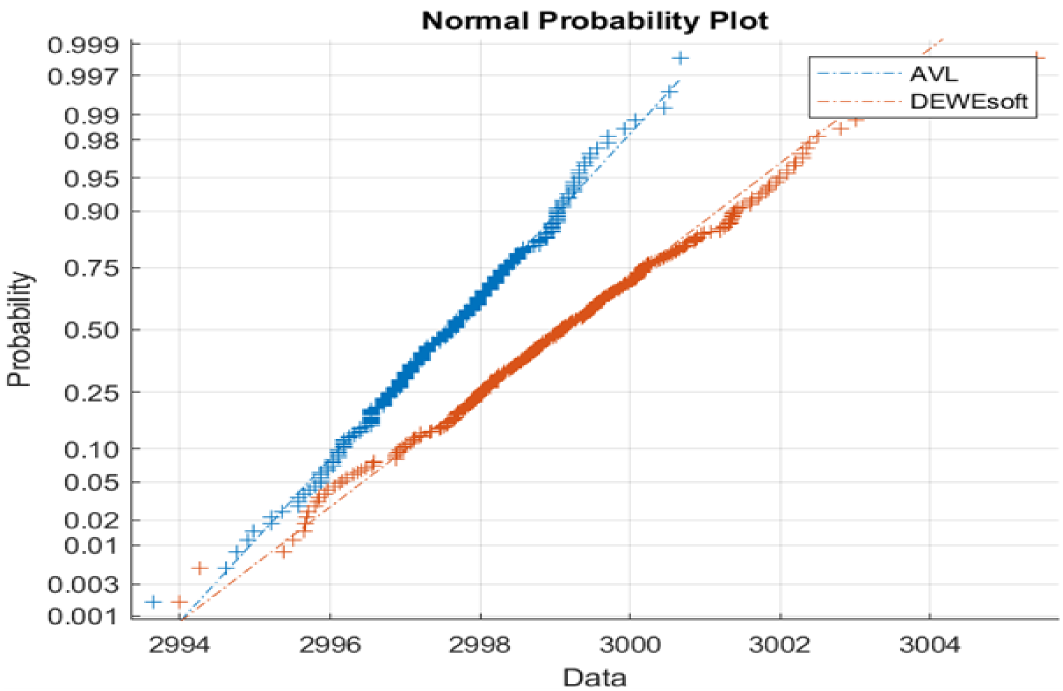


Figure 4.45: *Probability plot for 3000 RPM.*

5
Conclusion

The developed and implemented models in DEWEsoft software for visualizing the efficiency of Internal combustion engine and electric motor. which also calculates the efficiency for constant load as well as transient load. The script provides modular platform to the user, as it can be exported and used on different DEWESoft setups for calculation and visualization of efficiency during online recording or for the prerecorded test file. The script also provides various options such as by changing the geometrical parameters it can be used for different other fuels for ICE, and also calculates the parameters like percentage slip, three phase power in EM etc. The created code also gives the user to choose number of motors that are being tested.In the future, these models can be used in the field of research and development for hybrid and electric vehicles.

The Comparison between two different DAQ systems was the second objective of our thesis, from the COV (Co-efficient of Variance) calculation for IMEP in percentage it can be seen that the combustion is very stable as the values for all the cylinders are within 3 %. Further from the in-cylinder pressure trace, IMEP calculated by the DEWESoft and AVL when compared considering the measurement accuracy error of piezoelectric pressure transducer and DAQ hardware, from the plots it can be seen that the values are close to each other for the recorded trials and for all cylinders.However when the speed data acquired from different DAQ's were compared, it was seen from the probability plot that the data from the two DAQ's was slightly different,this could be because of the different filters used by the two software's.

Bibliography

[1] Grant Maloy Smith. What is data acquisition-the ultimate guide. https://dewesoft.com/daq/what-is-data-acquisition#daq-system-components, 2020. [Online; accessed 21-September-2021].

[2] Nexus Integra. https://nexusintegra.io/10-reasons-why-you-should-include-a-data-acquisition-system-in-your-company/. Accessed: 2021-09-21.

[3] Mehrdad Ehsani, Yimin Gao, and John M. Miller. Hybrid electric vehicles: Architecture and motor drives. *Proceedings of the IEEE*, 95(4):719–728, 2007.

[4] John B Heywood. *Internal combustion engine fundamentals.* McGraw-Hill Education, 2018.

[5] Rakesh Kumar Maurya. *Reciprocating engine combustion diagnostics.* Springer, Switzerland, 2019.

[6] Anonymous. Dewesoft c++ script,v20-1. https://d36j349d8rqm96.cloudfront.net/2/190/Dewesoft-C-Script-Manual-EN.pdf, 2021. [Online; accessed 25-September-2021].

[7] Electric and Hybrid vehicle technology. https://www.electrichybridvehicletechnology.com/features/hybrid-and-electrical-vehicle-powertrain-testing-methods-for-maximum-efficiency.html. Accessed: 2021-09-21.

[8] Halit Eren and David Potter. *Data Acquisition Fundamentals*, pages 330–341. 01 2012.

[9] wikipedia. Piezoelectric sensor. https://en.wikipedia.org/wiki/Piezoelectric_sensor, 2021. [Online; accessed 21-September-2021].

[10] Simens. digital-signal-processing. https://community.sw.siemens.com/s/article/digital-signal-processing-sampling-rates-bandwidth-spectral-lines-and-more, 2020. [Online; accessed 21-September-2021].

[11] Yong Luo, Yongheng Wei, Yingzhe Kan, Lin Ren, Liji Xu, Futao Shen, and Guofang Chen. Control strategy for electric startup of p2.5-phev based on slope memory and driver's startup intention. *IEEE Access*, 9:77044–77057, 2021.

[12] Stephen J Chapman. *Electric machinery fundamentals.* McGraw-hill, 2004.

[13] Yujing Liu, editor. *Electrical Machines – Design and Analysis.* Springer, Sweden, 2019.

[14] John Hindmarsh and Alasdair Renfrew. *Electrical machines and drives.* Elsevier, 1996.

[15] x-engineer.org. Brake specific fuel consumption. https://x-engineer.org/automotive-engineering/internal-combustion-engines/performance/brake-specific-fuel-consumption-bsfc/, 2021. [Online; accessed 25-September-2021].

[16] Wojciech Tutak, Karol Grab-Rogaliński, and Arkadiusz Jamrozik. Combustion and emission characteristics of a biodiesel-hydrogen dual-fuel engine. *Applied Sciences*, 10(3):1082, 2020.

[17] Mehrzad Kaiadi. *Diluted Operation of a Heavy-Duty Natural Gas Engine-Aiming at Improved Effciency, Emission and Maximum Load.* PhD thesis, Lund University, 2011.

[18] da Silva, M.J., de Oliveira, A. Sodré, J.R. Analysis of processing methods for combustion pressure measurement in a diesel engine j braz. soc. mech. sci. eng. 41, 282 (2019). https://doi.org/10.1007/s40430-019-1785-9, 2019.

[19] Fanhua Ma, Yu Wang, Junjun Wang, Shangfen Ding, Yefu Wang, and Shuli Zhao. Effects of combustion phasing, combustion duration, and their cyclic variations on spark-ignition (si) engine efficiency. *Energy Fuels - ENERG FUEL*, 22, 07 2008.

[20] Wikipedia contributors. Accuracy and precision — Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Accuracy_and_precision, 2021. [Online; accessed 04-October-2021].

[21] Wikipedia contributors. repeatability — Wikipedia, the free encyclopedia. https://en.wikipedia.org/wiki/Repeatability, 2021. [Online; accessed 04-October-2021].

[22] Richard Davis and Gary Patterson. Cylinder pressure data quality checks and procedures to maximize data accuracy. 04 2006.

A
Appendix 1

DEPARTMENT OF SOME SUBJECT OR TECHNOLOGY
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY