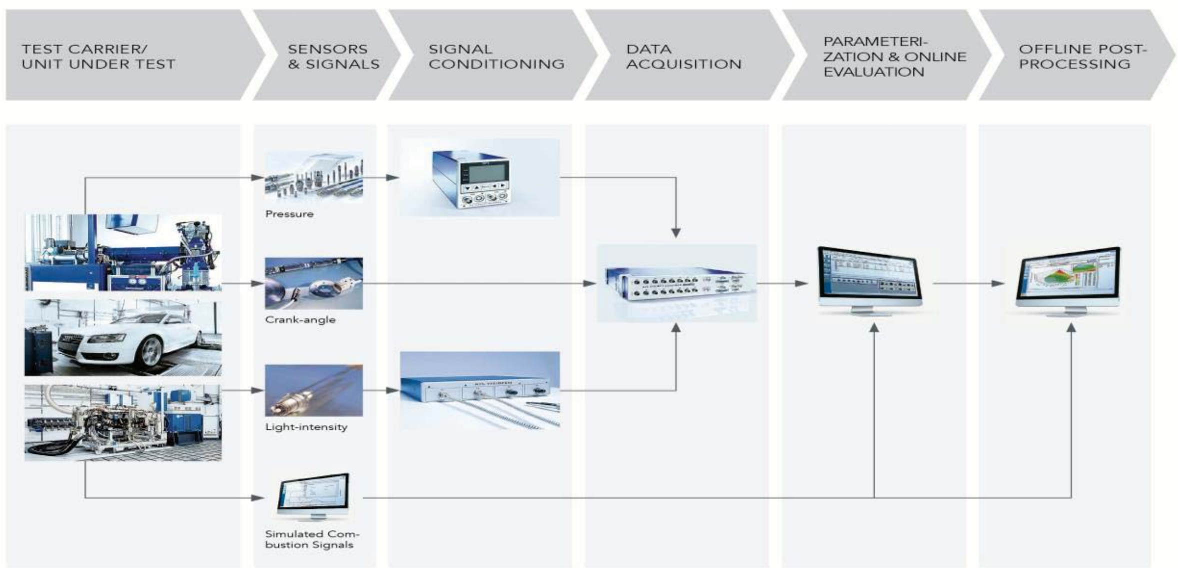
CHALMERS
UNIVERSITY OF TECHNOLOGY

Pressure transducer evaluation in an internal gasoline combustion chamber



Bachelor thesis in Mechatronic Engineering

Anthony Labbé

Department of Signals and Systems
Chalmers University of Technology
Gothenburg, Sweden 2015

ACKNOWLEDGEMENTS

This bachelor thesis has been completed by a student at the bachelor program of Mechatronic engineering at Chalmers University of Technology. The thesis covers 15HP in the department of Signals and Systems whereof the program, mechatronic engineering, comprises a total of 180HP.

Due to the student's interests in both thermodynamics and mechatronics, this assignment for AVL was a suitable choice of project as these subjects are the main part. By completing this project it is a good opportunity for the student to gain more knowledge about thermodynamic analysis in combination with mechatronics.

I would like to thank:
Manne Stenberg at Chalmers University of Technology for being my examiner.

My two supervisors Henrik Ernholm and Fredrik Dunert at AVL List Nordiska AB for the support.

My supervisor Göran Hult at Chalmers University of Technology for the support.

Thorsten Hartleb AVL Germany, Magnus Christiansen AVL List nordiska AB and Erwin Riedler Piezocryst Graz for the support and improvement of my knowledge.

Fredrik Arrhén and Martin Zelan at SP for the shared information regarding pressure transducers and for the possibility to use the SP shock tube.

David Willermark AVL List nordiska AB for supporting me with the thermodynamic information.

ABSTRACT

In-cylinder-pressure measurements in gasoline engines are one of the most important measurement parameters. Engine durability, heat release, efficiency, knock intensity, burn duration and thermodynamic analysis are some of the important parts in the combustion process and they are calculated by using the indicated pressure. By getting a more accurate measurement from the pressure transducer, these factors can be improved, which in turn will improve the development possibilities towards the ideal engine - less fuel consumption and higher power-to-weight ratio. This assignment was done for AVL and the goal with this project was to compare the performance and accuracy of different pressure transducers. Six different pressure sensors were compared to each other by mounting them in the same adapter that in turn was mounted in the cylinder head of a combustion-test engine. They were simultaneously tested in a running single-cylinder combustion engine at AVL/Piezocryst in Graz, Austria and was later proceeded with a ramp calibration to check the different sensitivities. The procedure was followed up by analysis in an indication software. Literature was studied and summarized in order to find out what to compare and what may affect the measurement. During the project, the pressure measurement in the cylinder, the pressure transducers including its necessary components, and the parameters influencing the pressure measurement was the main area to study. In order to get a better foundation of the comparison, the pressure sensors were tested in a pressure shock tube located at SP's laboratory in Borås, Sweden. Test-sensor 1, 2, 3 and 6 were the sensors with highest accuracy and performed the best in the combustion tests whereas test-sensor 4 and 5 lacked in accuracy as they are built to be more robust. The conclusion of the results is that the error sources, such as location of the mounted pressure transducers, affected the measurement more than the accuracy of the sensors themselves when comparing the top-performing test-sensors. Test-sensor 1, 2 and 4 were in the end even tested and compared in a pressure shock-tube to each other and to a reference sensor. Even here, sensor 1 and sensor 2 performed well while sensor 4 lacked in accuracy.

SAMMANFATTNING

Cylindertryckmätning i bensinmotorer är en utav de viktigaste mätparametrarna. Motorhållbarhet, värmeavgivning, verkningsgrad, knackintensitet, förbränningsduration och termodynamiska analyser är några av de viktigaste delarna i en förbränningsprocess och de beräknas genom användning av tryckindikering. Genom att få en noggrannare tryckmätning från trycksensorn kan dessa faktorer förbättras som i sin tur kommer att förbättra utvecklingsmöjligheterna mot idealmotorn – Lägre bränsleförbrukning och högre motoreffekt i förhållande till vikt. Detta uppdrag var utfört för AVL och målet med detta projekt var att jämföra prestandan och noggrannheten hos olika trycksensorer. De sex olika trycksensorerna jämfördes med varandra genom att montera dem i en adapter som i sin tur var monterad i topplocket på en förbränningstestmotor. De var samtidigt testade i en driftsatt, modifierad en-cylindrig förbränningsmotor på AVL/Piezocryst i Graz, Österrike och var senare utsatta för rampkalibrering för att ta reda på de olika känsligheterna. Testerna följdes upp av graf- och kurvanalyser i ett indikeringsprogram. För att veta vad som skulle jämföras och vad som kan påverka mätningen så gjordes litteraturstudier som sedan sammanfattades och under projektets gång var tryckmätningen i cylindern, trycksensorerna inklusive dess erforderliga komponenter och parametrarna som påverkade mätning huvudområdet som studerades. För att få en bättre jämförelsegrund utsattes tryckgivarna även för tryckresponstest i ett tryckstötrör på SP’s laboratorium i Borås, Sverige. Testsensor 1,2,3 och 6 var de sensorer med högst noggrannhet och presterade bäst i förbränningstesterna medan testsensorerna 4 och 5 var mindre noggranna då de är konturerade för att vara mer robusta. Slutsatsen av resultaten är att felkällorna, som monteringsplaceringen på de olika trycksensorerna, påverkade tryckmätningen mer än trycksensorernas noggrannhet påverkade när de toppresterande test-sensorerna jämfördes. Testsensorerna 1, 2 och 4 var i slutet även testade och jämförda med varandra och med en referenssensor i ett tryckstötrör. Likaså här presterade sensor 1 och 2 jämlika medan testsensor 4 presterade mindre noggrant.

TABLE OF CONTENTS

1. Introduction 1
1.1 Background 1
1.2 Purpose 1
1.3 Delimitations 1
1.4 Specification of problem 1
2. Theoretical background 2
2.1 Why is pressure measured? 2
2.2 How does the measurement work and what is each components task? 4
2.2.1 The pressure transducer: 5
2.2.2 The charge amplifier: 9
2.2.3 Indicating system: 9
2.2.4 Indicating Software: 9
2.2.5 Insulated cables: 10
2.2.6 Crank angle encoder: 10
2.2.7 The top dead center: 12
2.3 What are the error sources occurring during cylinder pressure measurement? 15
2.4 Heat release – One of the important calculations in thermodynamic analysis: 17
2.5 Facts about the test engine in AVL – Graz 18
3. Method 20
3.1 Ramp calibration procedure: 20
3.2 Dead weight pressure measurement: 21
3.3 The engine test: 22
3.3.1 Load variation measurement: 22
3.3.2 Speed variation measurement: 22
3.4 The pressure shock-tube tests 23
4. Results & discussion - pressure transducer test 25
5. Conclusion 40

References 41
Appendix 42

DESCRIPTION

- TDC – Top Dead Center
- P_{max} – Pressure max
- dP_{max} – maximum pressure gradient
- RCU – Ramp Calibration Unit
- FSU – Full Scale Output
- RTV - Room Temperature Vulcanization
- STD – Short Therm Drift

1. Introduction
1.1 Background

AVL is a global company that develops powertrain systems including instruments and test systems for vehicle testing. One of the instruments developed at AVL is the pressure transducer and its necessary components for a complete pressure measurement and indication. As fuel efficiency and emission of pollutants becomes more and more important in combustion engines, the engine developers strive to get the most accurate instruments as it leads to better optimization possibilities. A solution to improve the combustion in engines is to know the correct pressure through the whole cycle and the main component for this phenomenon is the cylinder-mounted pressure transducer. AVL has a large amount of different pressure sensors on the market and the right choice of pressure sensor will make the combustion process analysis and development more accurate.

One way to know which pressure sensor is most suitable to use for the assignment above is by comparing different sensor types to each other, competitors as well as internal.

1.2 Purpose

The purpose of this project is to evaluate and determine which pressure sensor is the most accurate and most suitable to use in the spark ignition combustion cylinder. Before the comparison, literature regarding indication will be studied due to find out why pressure measurement is used and due to find out which error sources affecting the measurement and indication. Which components that have to be included in the line-up and what their tasks are to get a complete measurement and indication will be studied and found out as well.

1.3 Delimitations

In order to measure the pressure it is only necessary to study and analyze:

- The pressure measurement in the cylinder
- The pressure transducer
- The measurement components and the signals
- Thermodynamics regarding combustion

1.4 Specification of problem

- Why is pressure measurement used?
- What are the main error sources?
- Which components are included in the measuring chain and what are their tasks?
- Which sensor performs most accurate?

2. Theoretical background

This part describes the theoretical part of the pressure measurement in a combustion chamber. In order to understand what to look for in the practical tests and to understand how the whole measurement chain is structured, the theory of measurement and indication constituted a major part of the project.

2.1 Why is pressure measured?

The points below can be described as the definition of what an ideal combustion engine strives for:

- High power-to-weight ratio
- Low fuel consumption
- Emits few pollutants
- Silent

By measuring the pressure in the cylinder and by doing a cylinder pressure analysis, one can optimize the performance of the engine which refers to the points above since the key to an ideal combustion engine is to know the correct pressure at different stages in the cycle. The pressure measurement is one of the most important measurements in the whole engine as well as it is one of the most important factors in the thermodynamic analysis of the engine. Durability, efficiency, knock intensity, heat release and thermodynamic analysis are all processed and calculated by the indicated pressure values. Down below does the help of pressure measurement determine important points:

P_{max}, dP_{max}: If the maximum pressure and the maximum pressure gradient are determined, the most suitable material of the engine can be selected. In this case the right material means an as light material as possible with sufficient strength.

Indicated Mean Effective Pressure, IMEP, can be compared to the average pressure on the top of the piston during a power stroke of the cycle. This pressure is used when expansion-work is calculated as work is equivalent to the internal energy that makes it possible to calculate the power output and the energy losses in friction. The same goes with the Pumping Mean Effective Pressure. By knowing the PMEP, average pressure of the inlet- and exhaust-valves, the performance and the state of the valve ports can be estimated and calculated. A too high pressure-gradient in the combustion cycle will result in a less noise friendly engine.

When the pressure is known through the combustion cycle, the burn duration can be calculated due to the temperature difference and the pressure difference as the fuel is burning. If the burn duration can be calculated, the efficiency can easier be improved which leads to less fuel consumption. Burn duration is calculated by values of the heat release graph (heat release explained in section 2.4). The amount of crank angle degrees it takes for the curve from ten percent from the start of the energy conversion until ninety percent from the start of the energy conversion is basically used to evaluate the quality of the combustion and burn duration. The optimum scenario is to have an as short burn duration as possible, which is equal to an as short crank angle range as possible.

Heat release, how much fuel is converted to energy: By knowing the heat release emission, noise and efficiency can be improved. Heat release is basically calculated by thermodynamic formulas including the known pressure, the change in volume which can be computed using the area of the piston top and the position of the piston by TDC-determination, and the properties of the air/fuel mixture (internal energy, C_P). Another common process to determine the heat release is by executing a four-stroke cycle without a combustion followed up by a four-stroke cycle including combustion. The difference in pressure is computed as energy that linked to heat. Further explanation is described in section 2.4.

Combustion failure can easily be detected with measured pressure, as the pressure will be much lower through the cycle. If the combustion is not working properly it will affect drivability, the pollutant emission and the efficiency of the engine.

With a known pressure the occurred knocks will be detected in the indication. A too high compression ratio in the engine will promote the risk of knocks. Knock occurs in gasoline engines and signifies that when the fuel is spark-ignited in the cylinder and creates a shock wave, the fuel is self-ignited in another place by the high pressure. Higher pressure results in higher temperature if the volume is constant and the wave from the self-ignited area collides with the spark-ignited wave. The result of the two shock waves colliding is a shock pressure that can reach five bars up to several hundred bars. This phenomenon is one of the worst to both the engine and the pressure transducer due to the drastic pressure rise in the cylinder. [3]

2.2 How does the measurement work and what is each components task?

The whole indicating measurement chain consists of a pressure transducer, a charge amplifier, a data acquisition unit, high-insulated measuring cables, a crank angle encoder and indication software.

This section comprises a more in-depth description of the line-up and the different instruments and objects involved to get a complete pressure measurement indication. There is a variety of every subject in the chain but the basics are the same in each component. Figure (2.1) shows an illustration of the pressure measuring indicating chain, all the way from the in-field sensors to the indicating software.

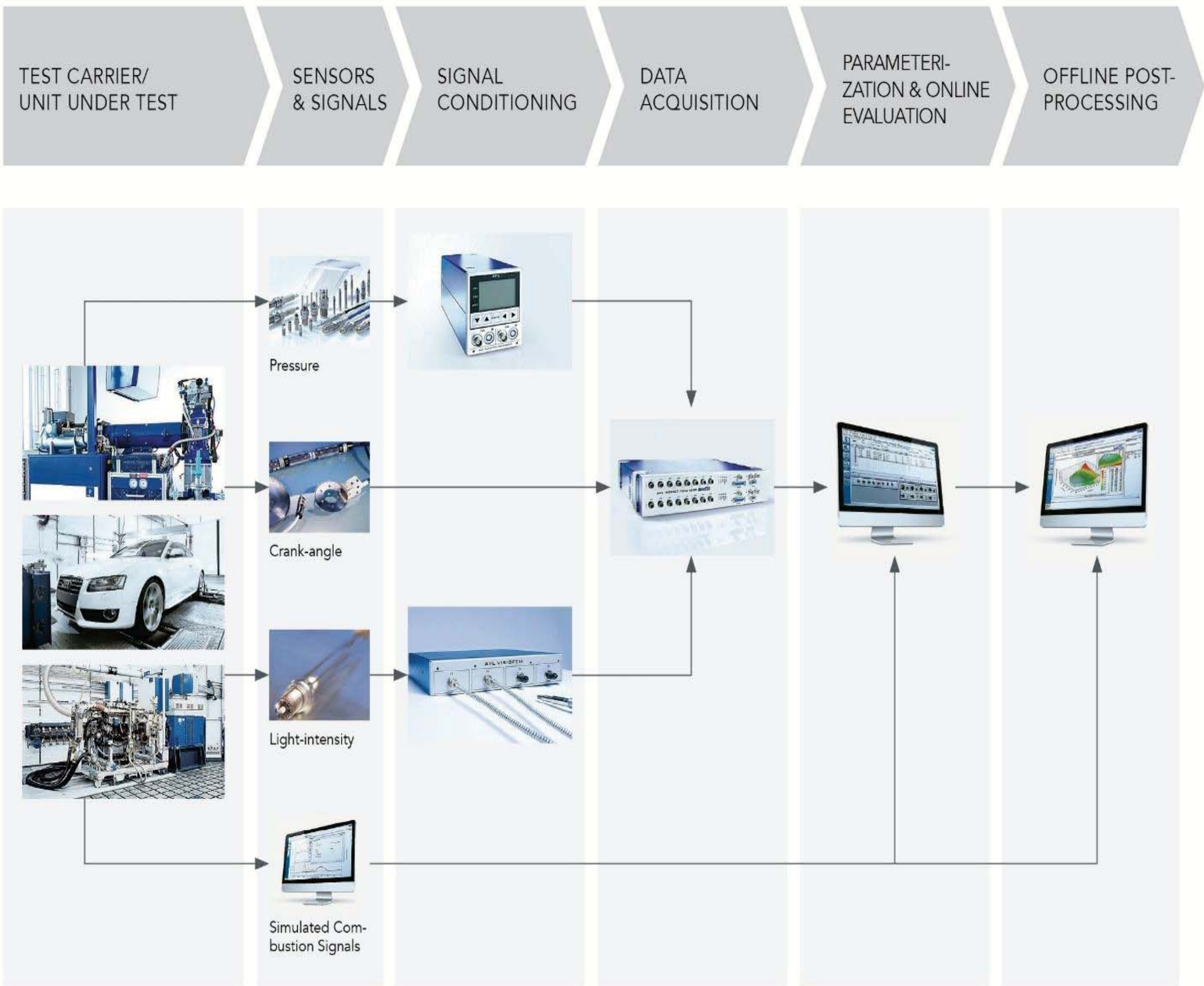


Figure (2.1) - An overview of the processed signals from the exposed pressure into the software. [2]

2.2.1 The pressure transducer:

The pressure transducers from AVL are mainly constructed with a Piezo-crystal. Basically the piezo-crystals have a low cost, good accuracy, can be temperature independent up to 900˚C and have a good linearity and sensitivity[14][15]. The two most common piezoelectric crystal materials are the Quartz-crystal and the Gallium Orthophosphate-crystal, $GaPO_4$. The latter has a good piezoelectric sensitivity and is stable up to 933˚C [10]; it is therefore more suitable for higher temperatures due to its high temperature independency. The Quartz-crystal has half the sensitivity and is temperature stable up to 570˚C. There are four other crystal material that, in few cases, are used instead of the $GaPO_4$ or the Quartz crystal. These materials are Tourmaline, Langasite, Lithium Niobate/Lithium Tantalate and different piezo-ceramics. Due to various disadvantages compared to the Gallium Orthophosphate crystal, for instance worse temperature independency, they are rarely used. If the temperature limit is excessed, the crystal will lose its properties and its linearity due to twin formation[1]. Therefore, the quartz-crystal is regularly run with a cooling media and the Gallium Orthophosphate is not. Nowadays the Quartz-crystal has been permanently replaced by the Gallium Orthophosphate-crystal as the properties of the $GaPO_4$ is better in every way. The advantage with the Quartz is the short time of production. To produce the Gallium Orthophosphate crystal, gallium powder is mixed with phosphate acid at 400˚C at approximately 10 bar. This procedure takes up to one and a half year to complete. On the other hand the quartz-crystal takes only 30 days to produce but requires pressures up to 1000 bar.

[1]Twin formation: When the temperature gets too high, the properties in some areas of the crystal change and the sensitivity decrease. Even at lower temperatures, such as room temperature, twin formation can occur if a mechanical load is high enough (approximately 5000-9000 bar), on the crystal.

The principle of the piezoelectric pressure transducer is that when the piezo-crystal is exposed to a mechanical deformation, by for example pressure, a small charge proportional to the deformation is delivered from the pressure transducer. The disadvantage of this method is that only dynamic loads can be measured. The piezoelectric method cannot be used for absolute pressure measurement and the only thing measured is the differences in the mechanical load that will promote a different charge load in the crystal, either positive or negative. The polarity is inverted due to the fact that the crystal is absorbing the charge when the pressure increases, and an increase of voltage is requested. It is not uncommon to use more than only one crystal as the sensitivity gets better as well as the charge output increases. Smaller angles of the crystal structure in molecular level equal better sensitivity. So when producing the crystal, sharp angles of the structure is aimed for. Generally the piezoelectric pressure transducer measures accurate up to 400˚C. Although the crystal manages higher temperatures the different parts included in the transducer structure is sensitive to higher temperatures, such as the membrane that is one of the most developed objects. The piezoresistive pressure transducer is suitable up to 250˚C.

The principle of the piezo-resistive pressure transducer is different to the piezoelectric as the resistance is constantly measured in the sensor instead of the small charge differences. This method acts as a Wheatstone-bridge. The piezo-resistive pressure sensor is very dependent to the temperature, which is a big disadvantage. A small temperature difference will change the behavior of the measurement. The total size of the pressure transducer is much larger than the piezoelectric making it less suitable in narrow spaces and the piezoresistive method is much slower than the piezoelectric as the natural frequency of the measurement in the piezoelectric sensor goes up to 180 kHz compared to the piezoresistive that goes up to 30 kHz. The advantage, on the other hand, is that the piezo-resistive sensor can measure the absolute pressure unlike the piezoelectric sensor as well as it can be used for both dynamic and static pressure measurement.

The AVL-piezoelectric transducer is constructed so that the pressure must first act on a thin, pliable and sensitive diaphragm at the bottom of the transducer. A pressure plate is on top of the diaphragm to even out the mechanical pressure. The pressure finally reaches the measuring element, the crystals, which in turn deliver a small charge through well-insulated cables. Due to the lower temperature range of functionality, the Quartz-sensor is usually cooled with distilled water to prevent the sensor from going beyond its temperature limit and to prevent thermal drift, see the structure of a cooled pressure transducer in figure (2.5). The water is flowing next to the sensor (0.5 l/min) and the average temperature of the sensor is ~20˚C above the cooling waters temperature. The temperature of the coolant water is usually set at a temperature where the sensitivity of the sensor is known, for example room temperature.

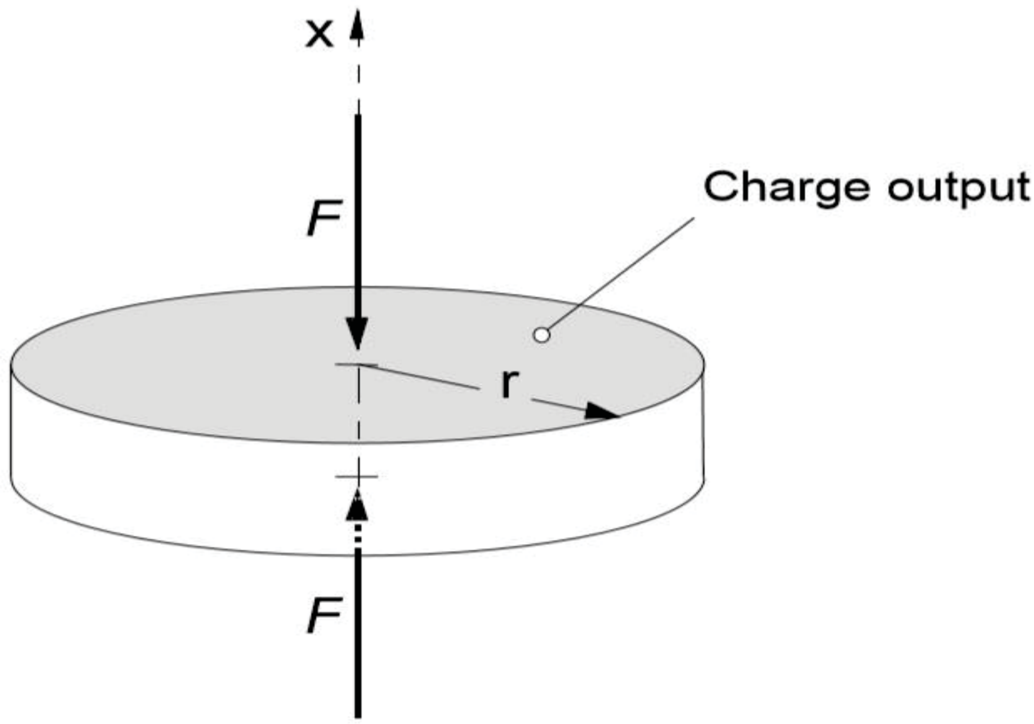


Figure (2.2) - Measuring element – Longitudinal effect. [2]

The disadvantages of using sensor cooling is

- Heat flux and thermoshock – Larger temperature difference between the diaphragm and the gas is achieved if using sensor cooling which leads to thermoshock.
- Bubble formation in the cooling jacket, which will cause a failure in cooling.
- Requires much more space than uncooled. The crystal-elements two most used effects is the longitudinal effect, figure (2.2), and the transversal effect, figure (2.4). The longitudinal effect consists of disc-shaped crystal elements and the effect is signified by the charge delivered from the same surface as the force applies at. As seen in figure (2.3), four or five discs are connected to each other in a row whereas the force is applied at the external discs. Benefits of using the longitudinal effect are that connection errors are neglected as the discs are compressed against each other. Also

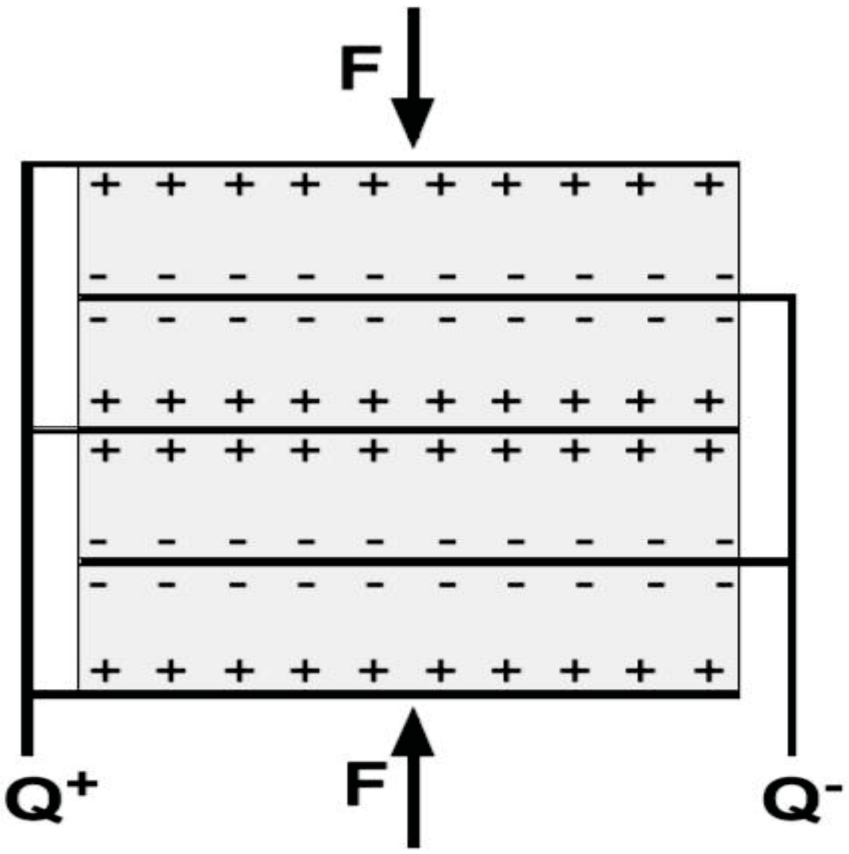


Figure (2.3) - Illustration of four discs in a row, parallel connected to each other. [2]

the design is space saving.

The transversal effect on the other hand consists of bar-shaped elements and opposite to the longitudinal effect; the charge output is delivered perpendicular to the applied force. In this case, when bridge-connection is requested, four or five elements are stacked in columns. Figure (2.4) shows an illustration of the transversal effect.
[1] [2]

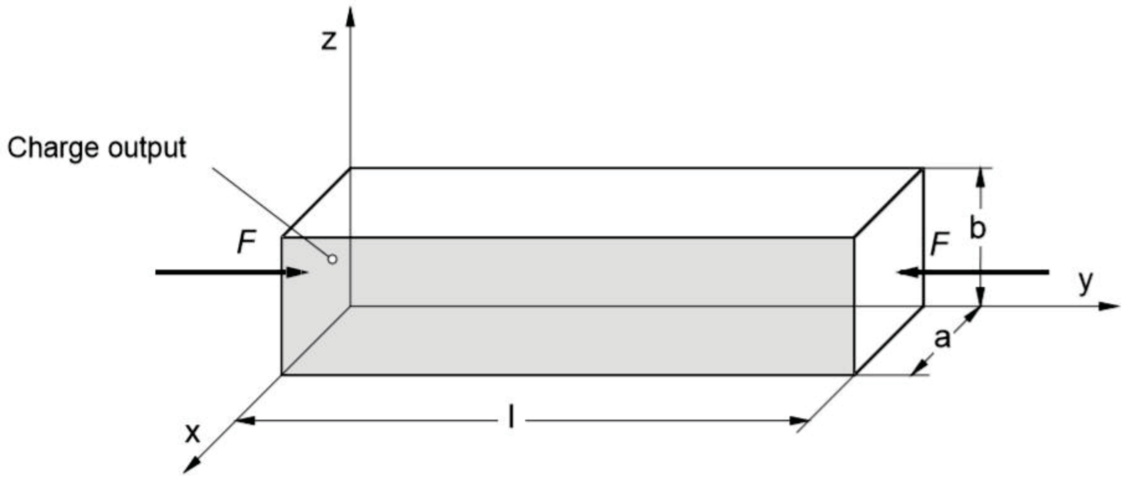


Figure (2.4) - Measuring element – Transversal effect. [2]

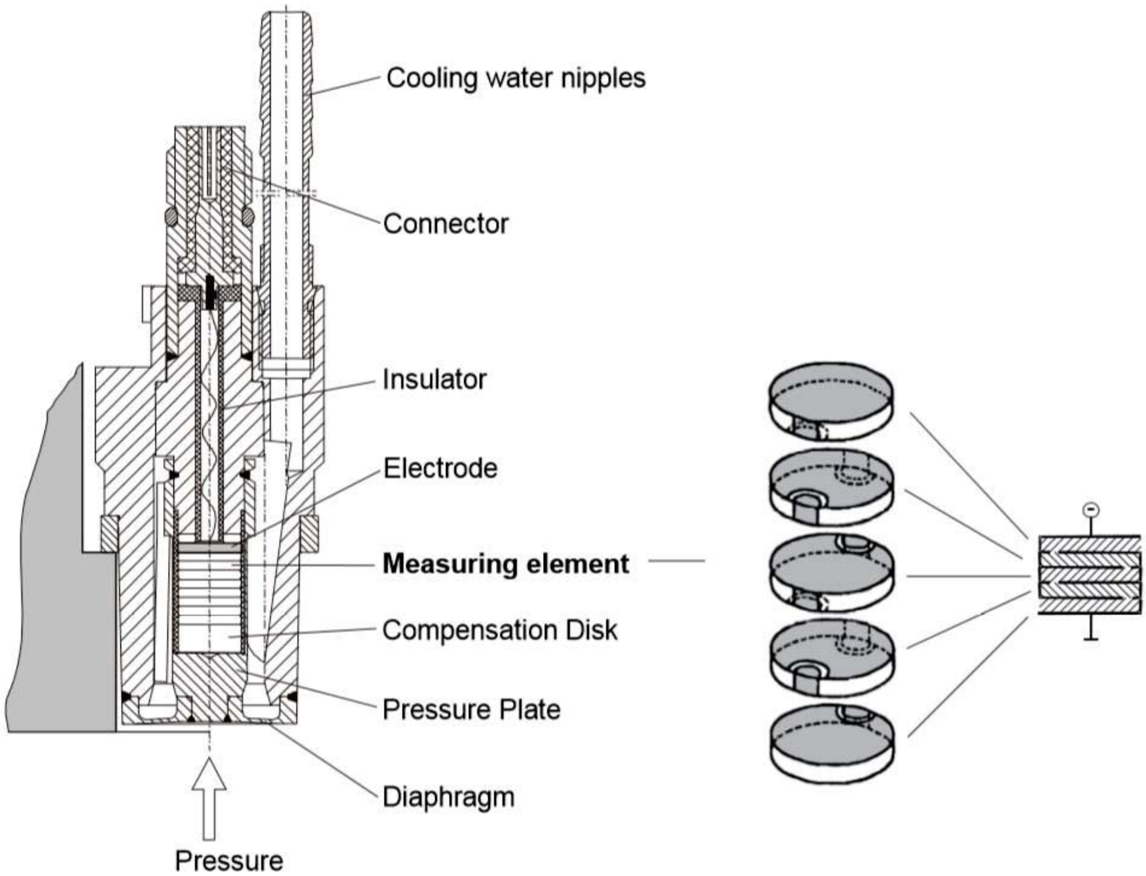


Figure (2.5) - A typical design of a cooled pressure transducer using the longitudinal effect. [2] [11]

2.2.2 The charge amplifier:

The charge amplifiers main task is to convert and amplify the charge delivered from the pressure transducer to a voltage signal. The signal is inverted due to the fact that the crystal in the sensor is absorbing the charge, which results in a negative output. By inverting the poles the charge delivered will be positive. The charge in the pressure transducer is amplified by a factor of 100.000 in the amplifier.

High pass filters and low pass filters can be added in the charge amplifier. The high pass filter is used to out-filter the low frequency signals and promote the high frequency signals. An example of when to use high pass filter is when analyzing knock. Although, most of the time the high pass filters are used in the post process in the software. The low pass filter is used to turn out the signals of high frequency. This can be used to remove the interference signals such as noise and vibration frequencies. One should be careful with filter application due to its impact in reducing too much information. Some information reduced can be important when calculating different parameters. Therefore it is recommended to use the software filters so the raw data signals reaches the data acquisition if further analysis has to be done including the interference signals. Some intelligent charge amplifier has built-in drift compensation and automated sensor identification. The automated sensor identification simplifies the tests and the drift compensation makes the measurement more accurate as it can, by mathematical calculations, compensate for the measurement fails occurred during drifts.
[1][2]

2.2.3 Indicating system:

The indication system is a data acquisition unit with a variety of functions. Integrated in the system is an A/D-converter, which converts the analogue signal transmitted from the amplifier, and digitize it. This unit records the input signal, calculates and processes the signals and finally stores the information, which all happens in a crank-angle based computation, not time-based. The indication system supports real-time parameter calculations such as heat release, peak pressure and knock values. The system communicates with a PC including indicating software to present the real-time process and stored results.
[13] [1] [2]

2.2.4 Indicating Software:

Two common indicating software used when analyzing pressure and combustion are IndiCom and Concerto. IndiCom is used for parameterization as well as it controls the data acquisition. Included in the presented graphs from the measurement, data evaluation can be found. Concerto shows the graphical content of the combustion cycles as well as it is a data post-processing tool aimed towards analysis, validation, correlation and reporting for the data sent from the data acquisition. For example heat release analysis and factors as TDC-angle can be changed.

2.2.5 Insulated cables:

The cables linked between the instrument, amplifier and the transducer require a high insulated resistance due to the small charges delivered. The Insulation resistance is usually over 10^{13} Ω at room temperature.
[1] [2]

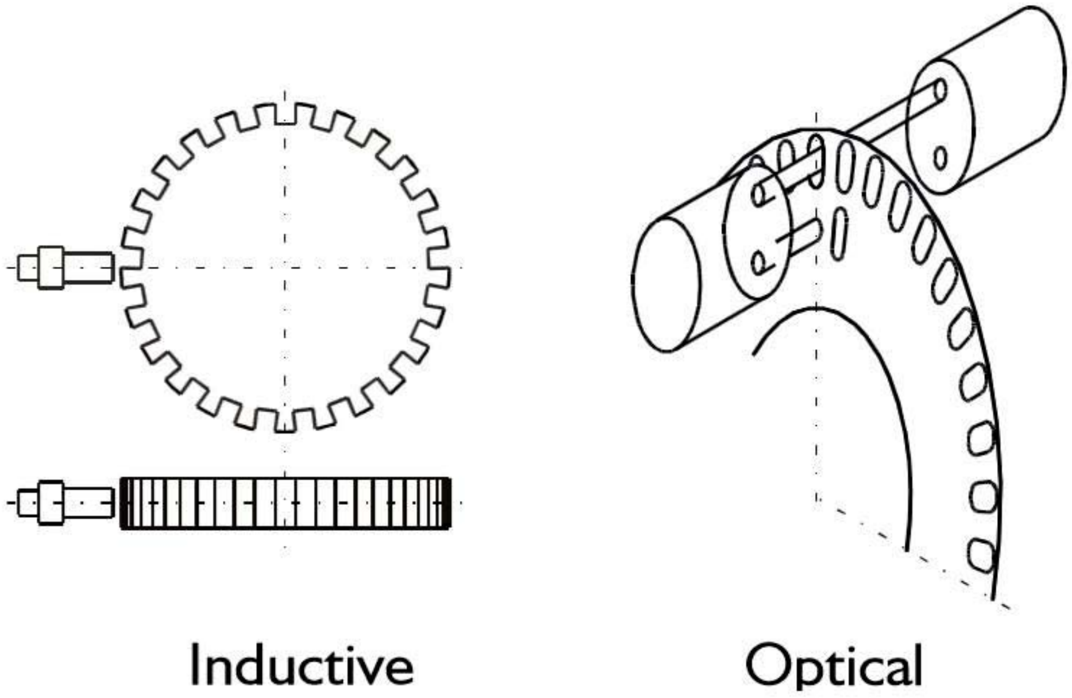


Figure (2.6) - An illustration of the inductive- and an optical crank angle encoder. [2]

2.2.6 Crank angle encoder:

Due to a crank angle based acquisition the crank angle encoder is an important part as well. The most common and accurate principle is the optical sensors although inductive sensors, hall sensors and capacitive sensor are used in some context such as monitoring and speed measurement. In the figure (2.6) below, an image of the sensor-principle is shown. The disadvantage of using the inductive sensor is the time delay occurred during measurement. The higher the speed, the higher the time delay. Therefore, it can only be used for lower speeds since the resolution has to be greatly reduced if higher speed is required. Hall sensors are only suitable where high accuracy is not required. A too high resolution in higher speed will promote information loss due missed signals. The optical sensor can be used by two methods. The first method is a steel-disk with small holes along the edge. An optical sensor is mounted so that there is a transmitter and a receiver on each side of the disk. When the disk spins the receiver gets a signal every time the light is passing the hole and then the speed can be calculated by knowing how often an impulse is occurred. The other method uses a glass-disk and the reflection of the glass. When a hole comes along, the reflection disappears and a signal is not promoted. By knowing how often the wholes come along, the same calculation of speed can be done here. The disadvantage of using a steel-disk is that metal is temperature dependent which can change the distance between the holes if the disk expands and deforms. The optical encoder can be used to revs up to 20000 rpm. The angle resolution is usually 0.5˚ or better, which means that there are 720 holes or more on each disk (360˚). [1] [2]

2.2.7 The top dead center:

The top dead center, also known as the TDC, is equivalent to the position where the piston is at its top in the cylinder. Four different methods can be used to set the top dead center although some methods are more accurate than others, one static and three dynamic TDC determinations.

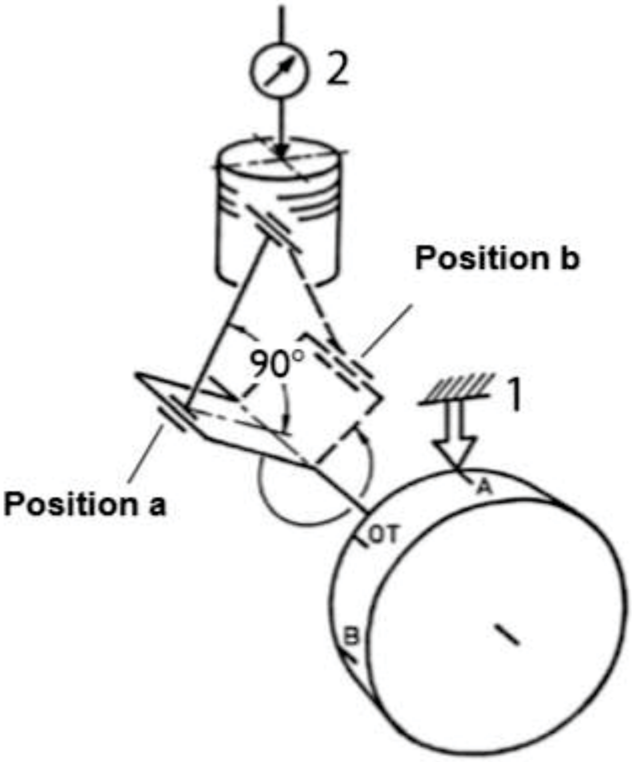


Figure (2.7) – Illustration of static TDC determination. [2]

Using the crank angle encoder information sets the static top dead center determination method. When the crank throw and the conrod is perpendicular, a mark is set on the encoder disc (1), right at the flagging mark. The height of the piston in the cylinder is then measured by using a micrometer screw gauge inserted through the plug bore down to the piston-surface. The crankshaft is then cranked so the piston goes down and up again until the same value as previous is measured at the micrometer screw gauge. The crank throw should now have been turned to the other side. When a new mark is set on this disc (2) at the flagging mark, the TDC is determined by marking a point in the middle of the two marks of the disc and turn this point to the flagging mark. The disadvantage with this method is if the crank angle encoder misses some points of the encoding, the TDC will be offset, In other words, the top dead center is dependent to the crank angle encoder. Figure (2.7) shows an illustration of how this procedure is done correctly. Due to lack of stiffness in some parts of the engine, this method is not the most accurate.

Another method of setting the TDC is by using the measured pressure profile and involves mathematical calculations in a running, motored engine. Although, it is more complicated than looking at the pressure graph and point out the measured pressure peak since the thermodynamic loss angle must be regarded. The thermodynamic loss angle occurs due to the heat losses and heat leakages, which increases due to lower speed whereas the heat has more loss-time. After calculating the loss angle, the motored pressure curve is shifted until the loss angle is nulled. The P_{max} is now equivalent to the TDC. [16]

The third method is the mathematical top dead center determination that is done by doing mathematical calculations of the pressure curve with a different load, and motored, and comparing this curve with the actual measured pressure curve in a specific crank angle. The measured pressure curve will be shifted until the area between the curves is minimized. [17]

The fourth method to determine the top dead center is by using a capacitive sensor that can be mounted in the spark plug, the injection nozzle or in a pressure sensor mounting. The piston position is known by measuring the capacitance between the piston and the cylinder head. Figure (2.8) shows an example of a capacitive sensor mounted into the combustion cylinder. This method is one of the most accurate although it is the most expensive one. The sensor is mounted in the sparkplug or where the pressure transducer is attached. In a running combustion cylinder, the TDC can be studied with different algorithms. The phase where the ignition occurs, not where the intake/exhaust cycle, is of most interests since this will be the phase affecting the material properties the most and reflects the most influencing scenario in the combustion process. With other words, the accuracy should be set regarding the worst terms. Also, the intake and exhaust valves will disturb the measured capacity in the cylinder. When looking at the TDC-sensor graph, the top edge of the curve will flat out for a small range of degrees and exactly where the TDC occurs is hard to tell. Basically, an average value of a definite range of crank angle degrees in the incline part of the curve’s amplitude is calculated as well as the corresponding range’s amplitude in the decline part. These values are summed up and then divided by two, to get exactly where the TDC occurs whereas the bisection points is determined.

[1] [2] [12]

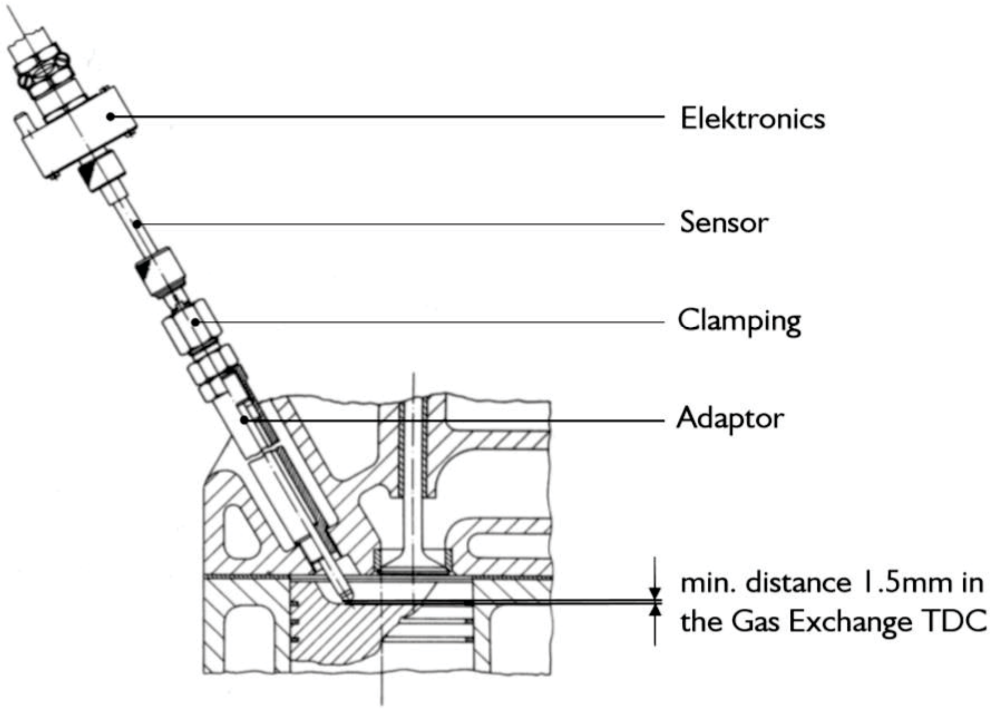


Figure (2.8) - A Capacitive Top dead center-sensor mounted into a cylinder. [2]

2.3 What are the error sources occurring during cylinder pressure measurement?

There are many different error sources influencing the pressure measurement and indication. Further on, a description of the most affecting errors is made. How to solve, prevent or compensate for the problems are included in some points. Many of the parameters are linked to each other such as linearity and calibration, sensitivity and temperature. Factors influencing the pressure measurement and its signal management:

- Placement
- Wrong sensitivity set
- Linearity
- Deviation
- Age of sensor
- Amount of use
- Time since last calibration
- Dirt on the sensor, soot
- Angle of the mounting
- Filter – May out-filter important information
- Recessed sensor – Resonance
- Miscalculations – When the temperature rises, coefficients changes
- Acoustic and electric noise – Resonance, vibrations when valves closes
- Magnetic fields
- Chemicals – Corrosion
- Temperature, thermal shock
- TDC offset
- Drift
- Lack of mechanical strength in engine structure

Overall, the direct-parameter influencing the measurement the most are the temperature differences, linearity and the noise. If the sensor-sensitivity is wrong set during the graph analyze, the measurement will be straight influenced. It is very hard to compensate for the temperature differences, the linearity and the noise and development will always be needed. Down below are descriptions of the different error sources affecting the sensor during combustion tests.

Electrical drift: When there is a false load delivered to the amplifier (leakage) an electrical drift will occur. This incident will result in a false pressure jump in the pressure graph. By obtaining well-insulated cables and a high electrical resistance on the amplifier input, pressure sensor and cables electrical drift is prevented.

Thermal drift: Basically thermal drift defines the pressure changes that occur when the temperature at the pressure sensor is changed. This is a big error source in many measurements. Although now a days some charge amplifiers has been developed great enough and have intercyclic drift compensation. In combustion engines there are two well-known causes of thermal drift
Intracyclic temperature drift that is caused by the fast temperature difference during the combustion of the air and the fuel mixture. The temperature difference influences the tip of the senor for one cycle followed up by a fast recovery. More information about intracyclic

drift can be found in the **short-term drift**-description, as it is equal to the intracyclic drift phenomenon.
Load change drift which is caused by a temperature difference over a longer period of time and cycles making the tip of the sensor becoming warmer in average which influences the measurement and leads to false pressure values.

Short-term drift/Cyclic drift: The diaphragm of the pressure transducer will periodically get heated up by the combustion gases that reaches up to 2000˚C for milliseconds. Due to the high temperature rise, an error will occur in the measurement since the piezoelectric sensor is sensitive to higher temperature. The material of the diaphragm is usually made of stainless steel and due to the high temperature raise the material will expand and have an impact at the measurement. This error will affect the IMEP- and the heat release calculation and the low-pressure part. The short-term drift can be prevented by making tiny passage holes or by covering the front of the sensor with RTV silicone, which will only work for some hours before it falls off. One other way to prevent the STD is to use heat protection plate. Manufacturers are still investing in prevention of intracyclic drift development and the design of the sensor and the housing has a lot of attention.

Some sensors use a flame shield that makes the sensor tip more resistible to the flames occurring during the combustion. The risk of using flame shield is the soot that coats the thin passage holes that will affect the accuracy even more.

Sensor location: One of the most important factors of the pressure measurement in combustion engines is the placement of the sensor. Due to different temperatures in different locations of the cylinder the pressure measurement will be different and as the sensor is sensitive to temperature differences the location is important. It is usual that the engine manufacturers do not prioritize the pressure sensor location in the cylinder head designs; many choices of placement are refused as well as some important measuring factors. These types of sensors are mostly used in the development phase. The ideal is to mount the sensor where it is cold and "calm" – less vibration, avoid injector spray, mechanical strain and heat flux. Near the intake valve is to recommend. The pressure transducer should be mounted perpendicular and flat to the wall or head. A recessed sensor can lead to flow disruptions, resonance and changed measuring parameters as the cylinder volume is changed including compression ratio [6,7]. Resonance can be prevented by installing post-processing filter at the cost of losing knock information. Mounting near the valves will affect the measurement as well. The pressure change during gas exchange will influence the pressure sensor if it is too close positioned. When the valves are closing they are creating an acoustic noise that the sensor is sensitive to. One way to reduce the noise is by using a low-pass filter in the charge amplifier. Although, when using filters in the charge amplifier one should keep in mind to not turn out too much of the frequency span as some important information can be erased. The wall closest to the exhaust valve is always hottest and mounting near the DI should be avoided due to sudden temperature shift and momentum impulse.

Pressure transducer calibration: To make the sensor work more accurately, a regular calibration is needed. When calibrated, the transducer input/output is checked so that the transducer is still linear and does not deviate. The true sensitivity is found due to calibration. It is important to calibrate the charge amplifier regularly as well as this is an important tool in the measurement indication. Although the sensor-accuracy is dependent of the age, it is important to consider that the total amount of use of the sensor is just as important.

Another important matter to get an accurate measurement is to have the sensor cleaned from soot before and after every test or calibration. This will not only give a better accuracy but also a longer life span. Due to the residues from the combustion products in the cylinder the sensor is exposed for corrosion, which is a common error.

Magnetic field is one factor that can disturb the signals delivered between the equipment. Therefore it is important to use well-shielded and insulated cables and observe the cable-position. The inductance from the spark cables produces a magnetic field that can disturb the sensor-signals. Ground loops – If the earth ground potential is different on the both ends of the cables, it will cause a small current flowing in the earth ground cable

If the top dead center is not correctly configured, **TDC offset**, the wrong volume between the piston and the cylinder head will be calculated and this will affect important parameters such as the IMEP-accuracy.

The TDC can be post-regulated in the software, IndiCom, due to integrated mathematic algorithms. Depending on the measurements errors of the TDC, the top dead center is manually shifted couple degrees to the right or to the left whereas parameters such as the IMEP-value will change, as a result of the shift. One more problem occurred during pressure measurement is miscalculation in the data acquisition unit or the indication software. Due to temperature differences, some parameters may get wrong values.
[1] [2] [3]

2.4 Heat release – One of the important calculations in thermodynamic analysis:

As the heat release is used to calculate how much of the total amount of fuel, energy, is converted into useful work, this is an important part of the thermodynamic analysis. The heat release is calculated in different ways. One way is: The pressure difference is known thanks to the pressure transducers, the volume difference is known thanks to the known position of the piston (TDC), and the properties of the mixture is known such as the internal energy and the C_P. By knowing these variables through the whole cycle the energy in the form of heat can be calculated. The most common way of calculating the heat release, is by running some cycles without any combustions and measure the pressure through the cycle. When the values are stored, the cycles are run including a combustion and the pressure values are measured. The differences of the curves, the area between them, are calculated as the energy. Figure (2.9) illustrates two different pressure curves. The lower, solid curve represents a motored curve, without any load. The higher peak, solid curve represents a combustion curve with a known load. The area between these curves is basically the heat release, Q, from the combustion and is calculated with equation (2.1).

$$Q_i = \frac{C}{K-1}[K * P_i * (V_{i+n} - V_{i-n}) + V_i * (P_{i+n} - P_{i-n})]$$ *Equation (2.1)* [5]

$n = interval\ [degrees].$
$K = polytropic\ coefficient$
$P = Cylinder\ pressure$
$V = Volume$
$C = Constant, Set\ to\ 100\ if\ SI\ units\ are\ used$

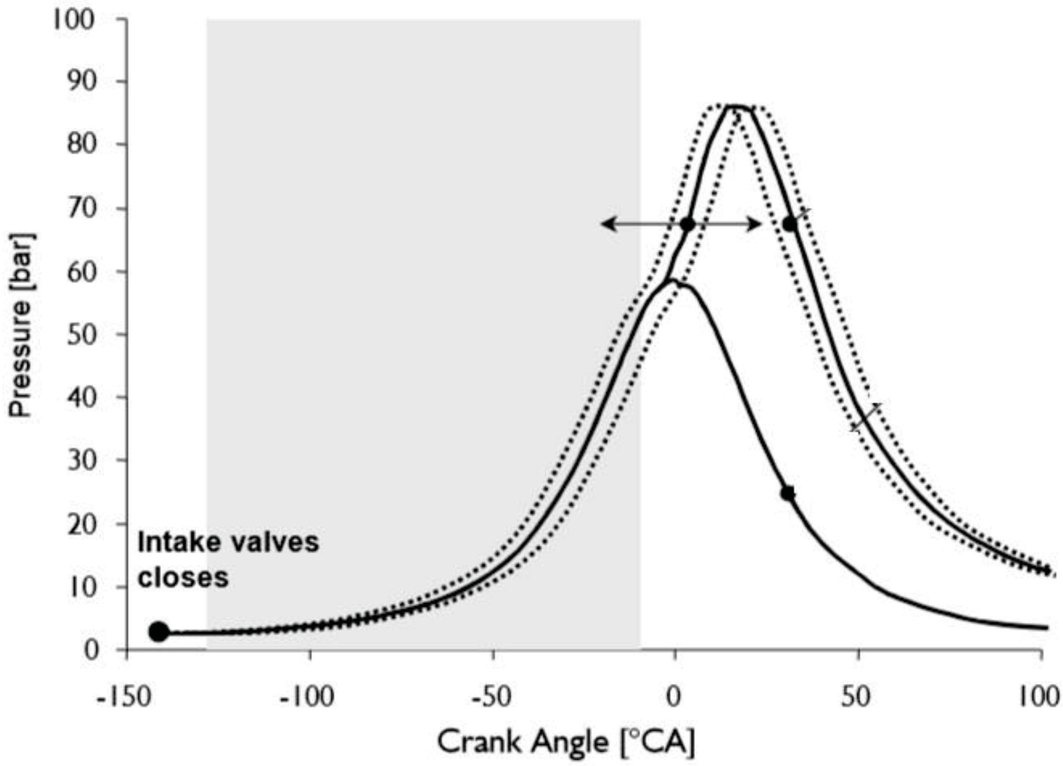


Figure (2.9) - Pressure curves. Motored curve and combustion curve. [2]

The heat release curves are, among many other things, used to see where the combustion starts, where it ends and where the middle of the combustion cycle is.

2.5 Facts about the test engine in AVL – Graz

The test-engine is single-cylinder diesel engine. The P_{max} of the engine cylinder is 180 bar and the $IMEP_{max}$ in the combustion is 18 bar. This diesel test-engine is very adjustable as many parameters can be changed manually at the same time, e.g. the fuel injection timing, the pressure of the air input from the compressor, the dyno speed and the load. The engine also makes it possible to simultaneously measure two up to six different test-sensors in the same cylinder. At the cylinder head there is space for a total amount of four different adapters where two of the adapters are reserved to the reference sensors, one sensor on each adapter. The two other adapters, which contain different amount of thread-connections depending on the thread-size of the pressure transducer, are filled with test-sensors. The bigger the thread-size, the smaller the number of sensor-places. For instance, the M5 threads requires smaller space than the M8, therefore the adapter containing M5 threads has place for totally three sensors whereas the M8-adapter only has place for a total amount of two sensors. The adapters can easily be changed. Figure (2.10) illustrates how the cylinder top looks like. Both reference-sensors are water-cooled sensors, making the use of Quartz-crystals more suitable. Although, only the first reference sensor is coated with silicone rubber to protect the sensor and make it less influenced by the heat. The second reference sensor is used as a check-sensor to the first reference sensor. The measurement value between reference sensor 1 and reference sensor 2 is constantly compared. A certain difference-accuracy is fixed and if the value-difference becomes too large between the two reference sensors, one of the sensors is not measuring accurate enough.

Due to the high sensitivity of the pressure sensors, the outflow of the fuel/air injection valve nozzle is modified so that the outflow is sprayed out between the sensors and then influenced by a stream. If the nozzle were not modified the spray would have affected the measurement with false peaks since the spray would hit the sensors. Also, the modification makes the

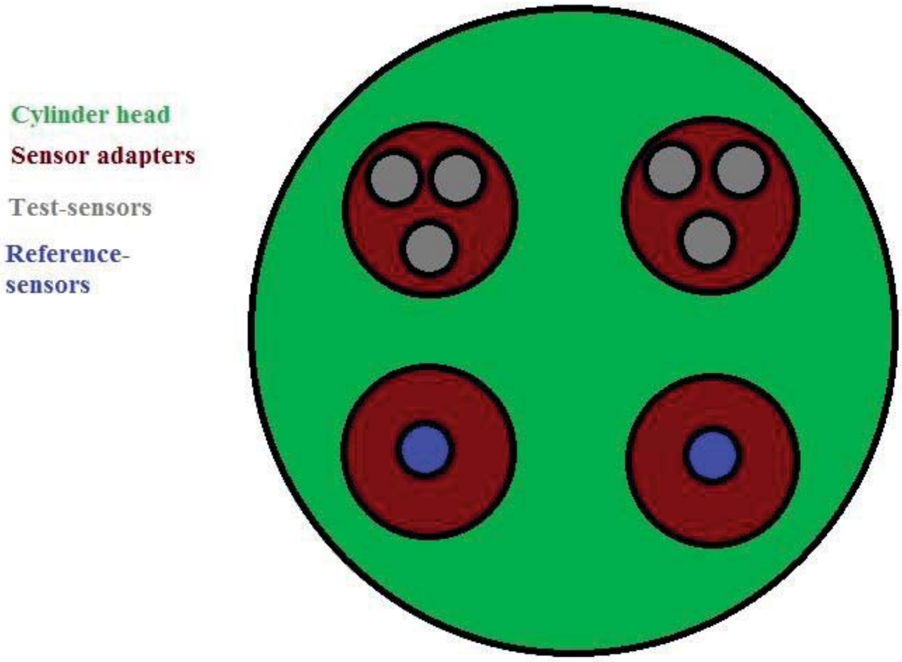


Figure (2.10) - Illustration of the cylinder head, viewed from above.

pressure distribution more even to all the sensors as the stream gets a more consistent flow.

3. Method

There are different methods to determine the accuracy of the pressure transducer, both static and dynamic tests. To fulfill the pressure transducer standard tests correctly, there are three different steps in the execution that has to be done. The ideal execution consists of following points:

1. Ramp calibration before the engine test
2. The actual engine test
3. Ramp calibration after the engine test

Another method that can be used is the dead weight pressure test. The difference between these three methods is:

- The ramp calibration shows the actual sensitivity of the sensor. The sensor is exposed for a mechanical load and the charge that the element is delivering is measured.
- The engine tests show how the different sensors handle the combustion and how accurate they are in different loads and speeds of the engine. Sensitivity to different factors as temperature is shown as well. All of the sensors are compared to the reference sensors.
- The dead weight pressure test shows the sensor's ability to handle fast pressure changes. E.g. the response time of the sensor and is mainly used for sensitivity check.

3.1 Ramp calibration procedure:

All the sensors are mounted into an adapter that is then connected to a pressure calibration unit. An intern and highly accurate pressure reference-sensor measures the actual pressure level with known sensitivity and linearity curve. Depending on the pressure range of the sensor, the pressure is measured from 2 bars up to maximum pressure which usually is 250 bar. When all the sensors have been mounted to the unit, the pressure starts to increase by a pump. The pressure reaches the maximum pressure after approximately twenty seconds and then the pressure decreases due to the direction change of the motor-rotation. The pressure is after further twenty seconds back to atmosphere level and the pump is going idle. The sensitivity curve will then be determined in the system. If the new calibration deviates too much, which value is set manually in a script, compared to the last calibration, this will be shown in terms of a yellow lamp glowing. Different sensor will absorb different amount of charges relatively to the mechanical load and the test will determine the different sensitivities found in different range of the ramp, seven different points of the maximum pressure range and the sensitivity unit is pC/bar. The procedure is than repeated with an applied temperature of 250˚C followed up by the same measurement at room temperature again. The temperature is determined by three thermocouples, which are measuring at three different spots at the adapter to get a consistent temperature measurement. This is a highly automated process making the calibration very effortless. The only disadvantage with this calibration is that the reference sensor regularly has to be calibrated in the dead weight tester. In figure (3.1) is an example of the automated calibration procedure graph. [4]

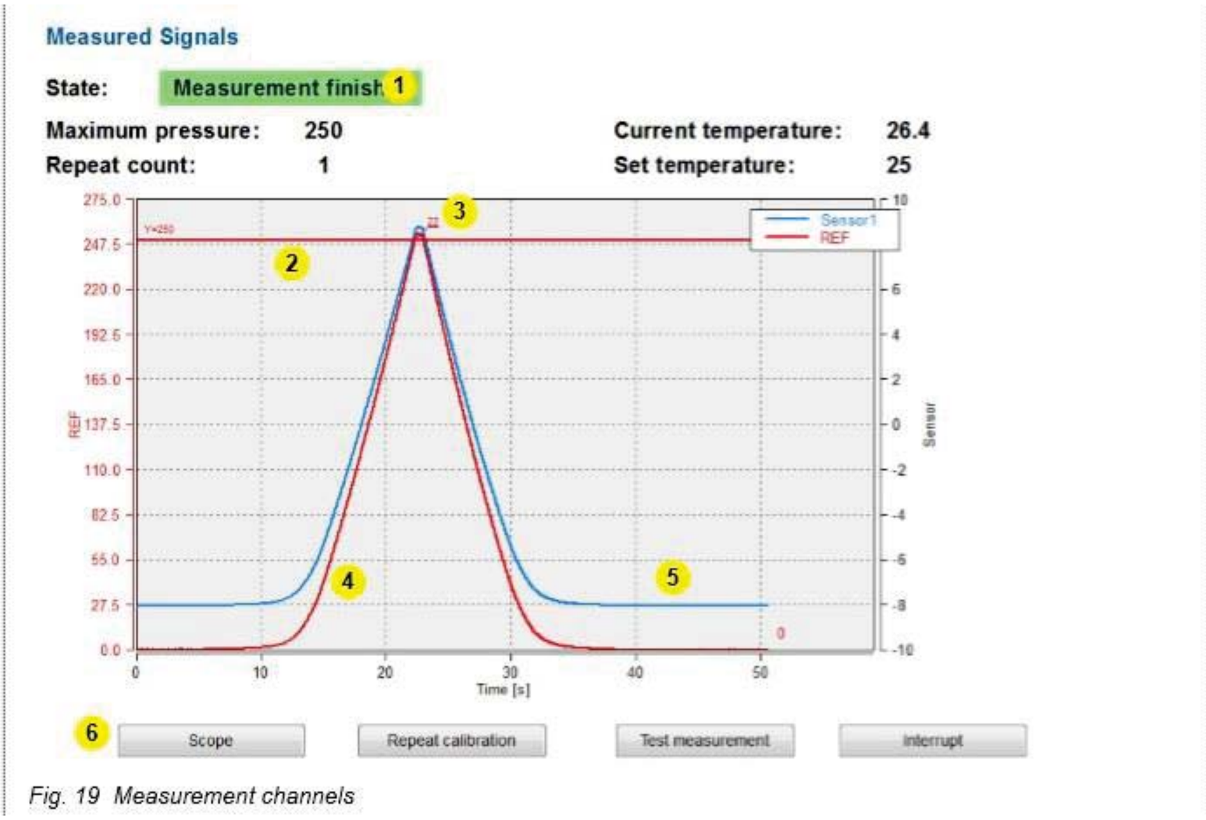


Figure (3.1) - Example of a RCU pressure-time graph during the pressure rise. [4]

3.2 Dead weight pressure measurement:

This type of pressure test tool is used to check the actual sensitivity of the pressure sensor by a fast pressure change, since the pressure transducer only measures the difference and cannot be used for static pressure measurement. This test was more common the automatic calibration unit replaced it since the test is performed manually.

A known weight mass is inserted to the calibration tool in a cylinder hole. The pressure transducer is connected to the same tool but between the transducer and the weight mass is a 3-way switchover valve. At first, the valve is opened between the atmosphere and the pressure sensor, making it possible to pump up the pressure in the lines from the known weight mass and the valve. The pressure is pumped up by a hand-pump until the added weight floats stable. By knowing the total mass of the weight and the area, the pressure can easily be determined when the weight floats by using equation (3.1) and equation (3.2).

$$P = \frac{F}{A}$$ *Equation (3.1)*

$$F = m * g$$ *Equation (3.2)*

When the pressure is pumped up to a certain level where the weight floats, the valve-line is switched so that the pressure reaches the transducer, which occurs in some milliseconds. The valve will then be switched back again so the pressure sensor opens up to the atmosphere, making the pressure drop to atmosphere pressure, once again in some milliseconds.

Dead weight pressure test usually uses oil as a pressure transferor in the lines between the weight load and the valve switch. Gallium is applied in the pressure lines between the pressure transducer and the switch valve. Gallium is used due to its advantaging properties, the melting point is at 29.77˚C making it very suitable to use as liquid in the pressure lines since it is very temperature independent. There are some different, modified types of dead weight pressure testers. Some testers are modified for very high pressures up to several hundreds of bar and some testers that are modified for high temperature tests. The advantage with the dead weigh tester is that no reference sensor is needed when testing but since the procedure is lacking automation the process will require much more time and effort than the RCU.
[2]

3.3 The engine test:

The software measures 256 cycles and calculates a mean value of the pressure through the combustion cycles and the P_{max}. In this case the charge amplifier used was AVL microIFEM and the indicating software AVL IndiCom. Before the testing started the serial number and the sensitivity has to be set and entered. The program measures all the eight (two of them are reference sensors) transducers at the same time and then stores the result in separate file. The test is split up in two parts, load variation and speed variation.

3.3.1 Load variation measurement:

When the load variation test is running, the dyno speed is constant set at 1300 rpm, which is done manually. This means that the dyno is forcing the engine to reach the requested speed with or without any injection of fuel and air. At 1300 rpm the first measurement is at an IMEP-load of 0 bar gauge, thus the engine is motored by the dyno and no combustion occurs. When the measurement on that load is completed, the load is increased to 4 bar, which means that the combustion has now started and running at 1300 rpm. After the measurement, the load is increased to 7 bar, 10 bar, 14 bar and 18 bar until it is decreased straight to 0 bar gauge again. The higher load required, the more injected fuel. When the load is relatively high, the amount of air-supply is getting more and more important as more fuel requires more air. This is done with an air-compressor. The angle of the fuel injection is constantly set to -15˚ during the load measurement as this is appropriate for this type of combustion.

3.3.2 Speed variation measurement:

The speed variation test is, unlike the load variation measurement, set at a constant load of 4 bar. The difference is that the speed varies. The first measurement is completed at 600 rpm and a fuel injection angle of -12˚. Next up is a speed at 1300 rpm and a fuel injection angle of -13˚, 2000 rpm at -17˚, 2600 rpm at -23˚ and finally the speed is decreased to 1300 rpm. The injection angle varies due to get a fair graph that looks similar at all speeds and for not having to change other parameters.

3.4 The pressure shock-tube tests

The pressure shock test is considered to be one of the best tests when checking pressure transducers since the shock waves contains every different frequency due to the rapid rise time of the shock, a few nanoseconds. The SP shock tube is 4 metre long and spliced in the middle. The pressure transducers are mounted into a flange at the end of the tube whereof different flanges are modified for different mounting threads and amount of transducers. The one used had four different spots but the charge amplifier only had space for two slots. In the middle of the tube, where the slice is, the membrane is mounted. The membranes are made of thin cellophane. Between four and eight membranes are mounted into a flange depending on the requested pressure of the shock. More membranes results in a higher burst pressure as the membranes work as a thin wall in the middle of the tube. Air is supplied into the other end of the tube whereas the pressure rises. When the pressure is high enough, the membrane bursts and the build-up pressure will come as a shock wave into the other side of the tube, where the pressure transducers are mounted. The pressure reaching the sensors goes up to approximately seven bars but comes in an incredibly high wave speed. The sensors are connected to a charge amplifier that in turn is connected to a data acquisition unit. The data acquisition unit is connected to the computer where the indicating software act and the system records the incident in 10 mega samples per second, which is a very high sampling rate. The records are saved and stored into a file and can later be viewed. Since there are only two slots in the charge amplifier, two transducers can be compared at the time. Due to the limit of time, only test-sensor 1, 2, 4 and 6 were compared. A 5th sensor with a very high natural frequency was used as a reference sensor in the tests. Three tests were done at almost every setup to get a fair comparison and to and leave out any coincidences affecting the measurements. The setup of the tests:

- Test-sensor 2 – test-sensor 1 3 tests
- Test-sensor 2 – Reference sensor 3 tests
- Tests-sensor 1 – reference sensor 3 tests
- Test-sensor 4 – reference sensor 3 tests
- Test-sensor 4 – test-sensor 2 2 tests
- Test-sensor 4 – test-sensor 1 3 tests

In figure (3.2), an overview picture of the pressure shock-tube setup is shown.

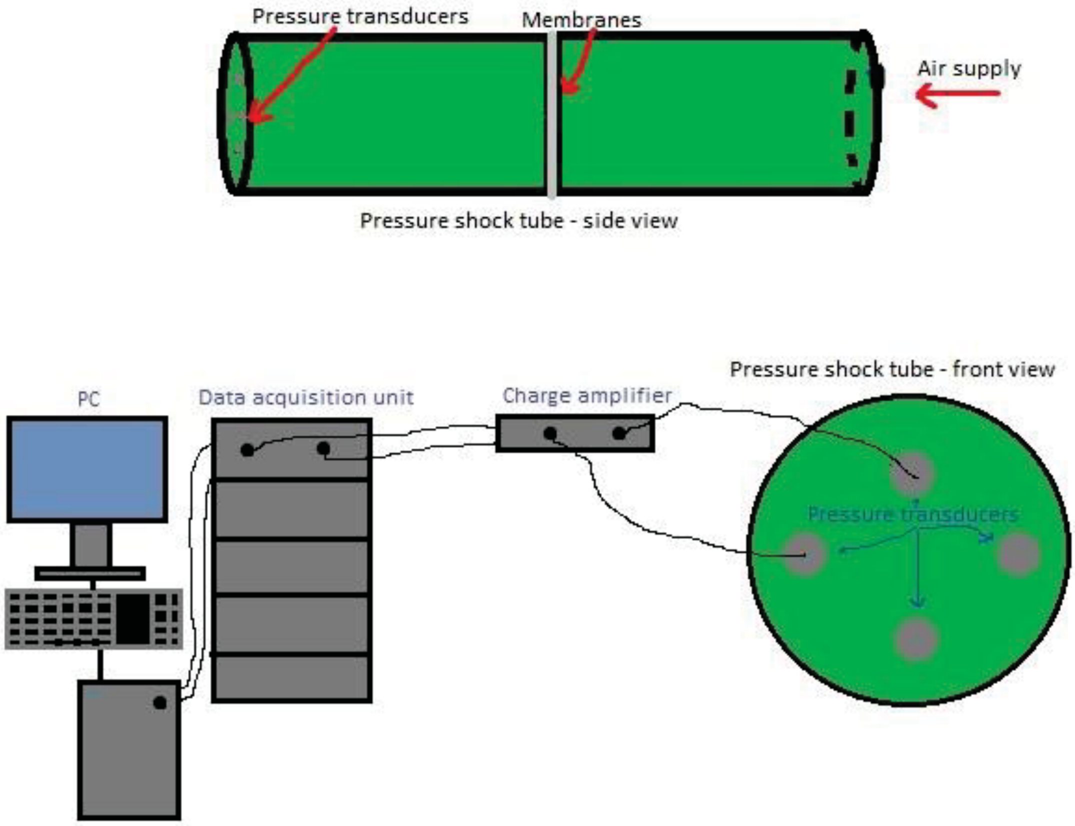


Figure (3.2) – An overview of the pressure shock-tube setup.

4. Results & discussion - pressure transducer test

In this section the current results from all the different tests are presented. As the ramp calibration was done after the engine tests the correct sensitivity of the pressure sensors was found afterwards. The ideal process would have been to do a ramp calibration before and after the engine test to see that the sensitivity was not changed during the test. The found sensitivity value of all sensors can be changed in the indication software afterwards, by using mathematic calculations, which will affect the graph enough to make them correlate with the reality. The different pressure transducer used were two different manufacturers and the different sensors will in these presenting be called test-sensor 1, test-sensor 2, test-sensor 3, test-sensor 4, test-sensor 5 and test-sensor 6. Test-sensor 2 and test-sensor 3 is of the same model as well as test-sensor 4 and test-sensor 5. The performance class is the same for all transducer that makes the test fair and they are of the same type. Test-sensor 2, 3, 4 and 5 was brand new and untested. The test-sensor 1 was 3 years old but had only been tested for approximately 100 pressure shocks at a pressure up to 7 bar. Test-sensor 6 has unknown history.

4.1The calibration results

Figure (4.1) shows the ramp calibration protocol for test-sensor 1. In the appendix section, further calibration protocols from the other sensors are shown, figure (4.22) to figure (4.26). There are seven different measurement points shown in the protocol, one at room temperature and one at 250˚C. The sensitivity of the sensor is found at all fourteen measuring points. The linearity of the sensitivity of the sensor from 0-250, 0-150 and 0-80 bar is determined in the chart under the measuring points including the FSO-accuracy in percentage. The 0-80 bar sensitivity-values are used during tests depending on the pressure range in the tests. For instance, if the maximum pressure of a combustion engine test is 120 bar, then the sensitivity of the range 0-150 bar should be used since it is the most accurate value in that case, also depending on the temperature range, right value should be regarded. As long as the correct sensitivity of each pressure transducer is set before, a transducer with higher sensitivity does not have to be greater in performance than a transducer with a lower sensitivity, which easily can be thought. As seen in the protocols, test-sensor 1 and 6 has by far the highest sensitivity yet the performance is not by far the best. The benefit of higher sensitivity is that the sensor will be less affected to magnetic fields. A sensor should not have a big difference in sensitivity at room temperature compared to sensitivity in higher temperature although this is a bad occurrence.

Table (1) – Calibration used versus calibration found afterwards.

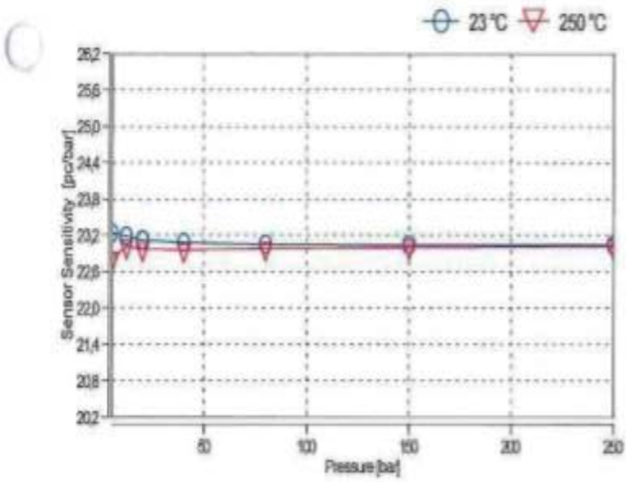
MODEL	SENSITIVITY USED DURING TESTS [PC/BAR]	FOUND SENSITIVITY FROM CALIBRATION [PC/BAR]
TEST-SENSOR 1	22.86	23.07
TEST-SENSOR 2	19.14	19.02
TEST-SENSOR 3	19.00	18.92
TEST-SENSOR 4	18.67	18.69
TEST-SENSOR 5	18.95	18.87
TEST-SENSOR 6	19.42	19.37

In table (1), the sensitivity of the sensors before the engine tests is shown and the calibration protocols shows the found values after the tests. The difference in sensitivity-value is larger in some sensors but none of the values were too deviant. Test-sensor 1 was the sensor standing out the most with approximately 0.2 pC/bar in deviation.

Results Test-sensor 1

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	23,23	22,81
12	23,18	23,01
20	23,12	22,97
40	23,08	22,96
80	23,05	22,98
150	23,03	23,00
250	23,04	23,02

Calibrated Range [bar]	Sensitivity/Linearitiy' at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy ' at 250°C [pC/bar] / [%FSO]
0 - 250	23,04 / ± 0,03	23,01 / ± 0,04
0 - 150	23,05 / ± 0,05	22,99 / ± 0,05
0 - 80	23,07 / ± 0,07	22,96 / ± 0,07



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

' Determined by Tolerance Range Method
(best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment: Indiset Advanced 631	SN:	6310281
Cal.protocol:	PM1196	
Charge Amplifier: MicroIFEM 4FP4	SN: 159 channel 2	
Cal.protocol:	PM1094_04092014	
Measuring Software:	Rampenkalibration_v3.4	

Reference Sensor 0-400 bar:

Typ: WIKA P-30	SN:	2245555
Cal. protocol:	DKD-K-15105-01-00 01729(	

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

Figure (4.1) - RC results for test-sensor 1.

4.2 The results from the engine tests

As seen in the protocols there are two graphs for each pressure transducer. Both X-axis comprises the angle of the crank, [degrees], where zero degrees equals the top dead center of the combustion. The upper graph consists of the total cylinder mean pressure, [bar], at the Y-axis and the lower graph shows the measured pressure differences between the test sensor and the reference sensor. The most important part here is not how the combustion looks like but how the pressure sensors behave compared to each other and to the reference sensor since they are all involved in the same combustions and cycles.

The load variation-protocol of test-sensor 1 is shown in figure (4.2) and the other sensor-protocols are presented in figure (4.28) to (4.32) in the appendix**.** The different curves in each upper graph of the protocols represent the different loads. The curves with highest peak pressure represent the maximum load, 17.87 bar, and the curves with the least peak pressure represents no load. Under the section *IMEP_ref*, in the chart under the graphs, the current load is shown.

The upper graph is just an indication of the different pressure profiles using the crank angle as time base and will not be of importance in this case. The lower graph, on the other hand, is where the interesting results takes part since the test sensor is compared to the accurate reference-sensor and conclusions can easier be made. In this graph the ideal would be to have as straight and flat lines as possible, close to the zero bar. Deviations are to be avoided. By judging only from the lower graphs it is seen that the test-sensor 1, figure (4.2)**,** and both test-sensor 2 and 3, figure (4.3) and (4.4), are the ones deviating the least from the reference sensor when the combustion occurs and shows relatively great results. Test-sensor 6, figure (4.7)**,** is also among the top sensors in accuracy and shows better results than both test-sensor 4 and 5.

Table (2) – Load variation mean value.

LOAD VARIATION

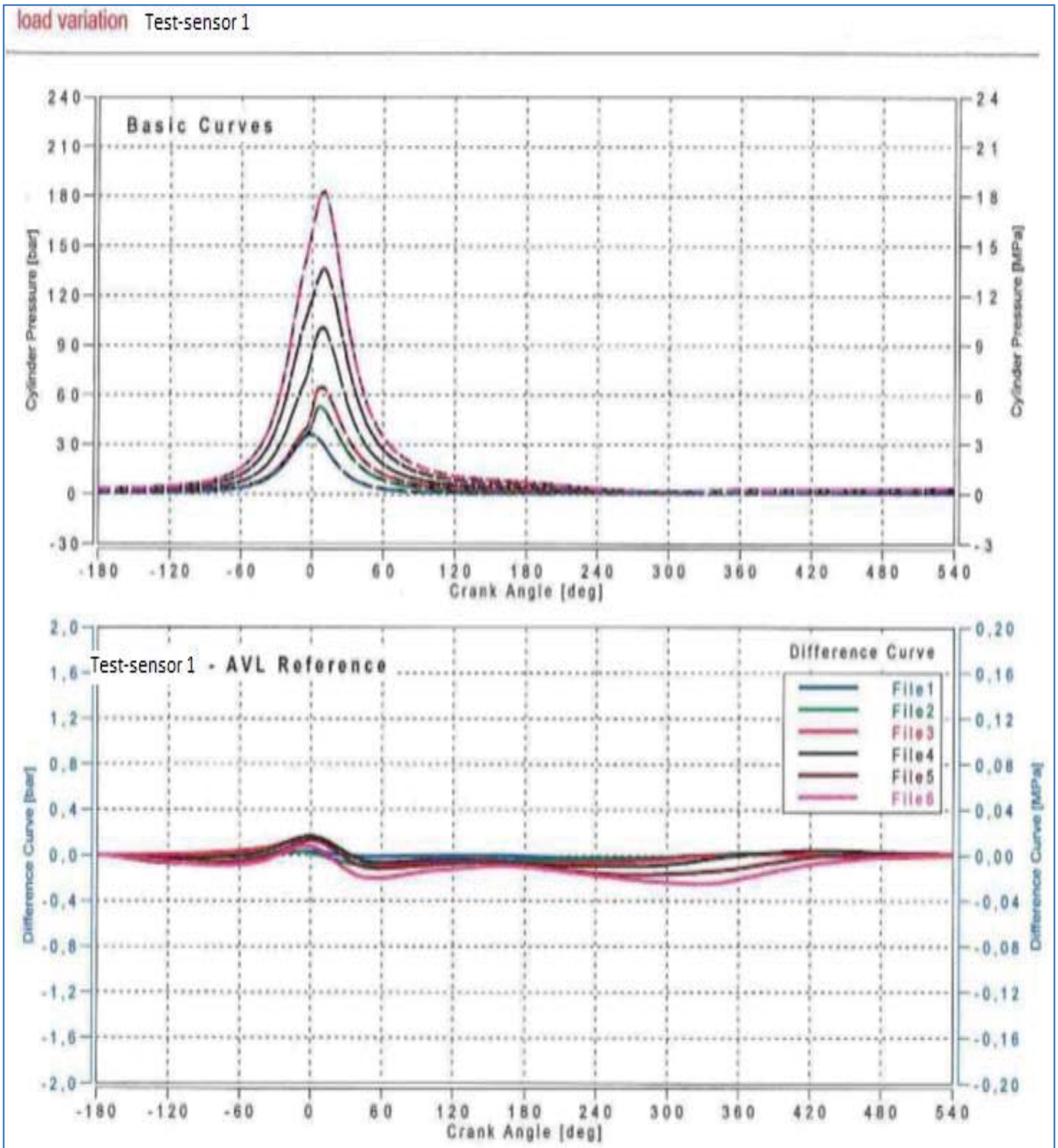
SENSOR	DIFF_IMEP mean value	Diff_Pmax mean value	Max_Deviation mean value
TEST-SENSOR 1	0.060	0.083	0.147
TEST-SENSOR 2	0.100	0.088	0.153
TEST-SENSOR 3	0.120	0.115	0.132
TEST-SENSOR 4	0.133	0.307	0.367
TEST-SENSOR 5	0.102	0.123	0.188
TEST-SENSOR 6	0.122	0.107	0.138

In the measurement table contents, the important values are the ones in the *Diff_pmax-*, the *Maximum Deviation-* and the *DIFF_IMEP-columns*. The closer values to zero, the better the accuracy. In table (2), the mean value of each load diff-columns is calculated. This makes it easier to see which sensor shows the greatest accuracy in average, but it is still not hundred percent fair although some coincidences can affect the different results and peaks, making the whole mean-value worse. In fact, depending on what these sensors will be used for, for instance thermodynamic analysis, knock analysis or endurance testing, different sections are more important than others to look at. If thermodynamic analysis is the main area for these pressure transducers, the *DIFF_IMEP*-column is the main section to look at due to the importance of IMEP accuracy that is deeply involved in the heat release analysis. When performing endurance tests, the *diff_Pmax*-column will be the section prioritized since the maximum pressure is the main area but also the gradient of the pressure rise. The *diff_pmax*-values are, although, important in performance judgement since it is an indication of how accurate the pressure transducers are at higher pressures when the combustion occurs and heat is influencing the sensors which is an important part of the combustion measurement and more or less defines a part of the performance of the pressure transducer.
Table (3) defines the lowest and the highest differences of all test-sensors compared to the reference-sensor in the from the load variation tests

Table (3) – The largest and the smallest differences between the test-sensors and the reference-sensor.

Load variation.

TEST-SENSOR	DIFF_IMEP[BAR] LOW - HIGH	DIFF_PMAX[BAR] LOW - HIGH	MAXIMUM_DEVIATION[BAR] LOW - HIGH
1	0.01 – 0.11	0.01 – 0.15	0.04 – 0.25
2	0.01 – 0.19	0.02 – 0.15	0.06 – 0.21
3	0.00 – 0.28	0.01 – 0.18	0.02 – 0.22
4	0.00 – 0.29	0.14 – 0.47	0.30 – 0.48
5	0.00 – 0.21	0.01 – 0.28	0.11 – 0.28
6	0.00 – 0.25	0.01 – 0.21	0.06 – 0.23



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP[1] [bar]	Diff_pmax [bar]	Maximum Deviation[1] [bar]
File1	1300	-1,11	36,06	0,01	0,04	0,04
File2	1300	4,04	53,05	-0,05	0,01	-0,08
File3	1300	7,07	64,58	-0,05	0,15	0,17
File4	1300	9,99	100,36	0,08	0,15	0,17
File5	1300	14,01	135,78	0,11	0,11	-0,17
File6	1300	17,87	182,63	0,06	0,04	-0,25

Figure (4.2) – Complete sensor protocol, test-sensor 1 – Load variation.

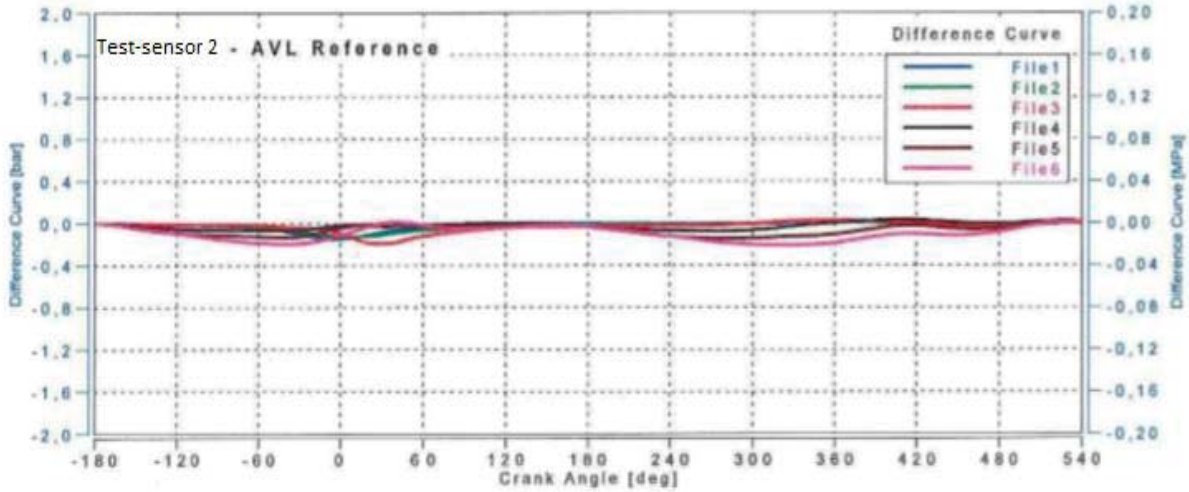


Figure (4.3) – Lower graph, test-sensor 2 – Load variation. Deviations from the reference-sensor.

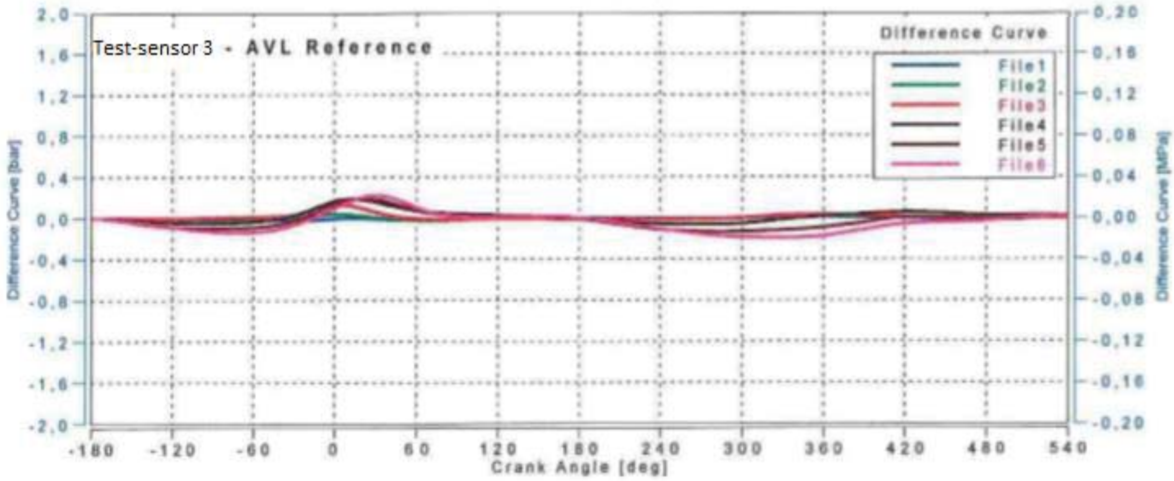


Figure (4.4) – Lower graph, test-sensor 3 – Load variation. Deviations from the reference-sensor.

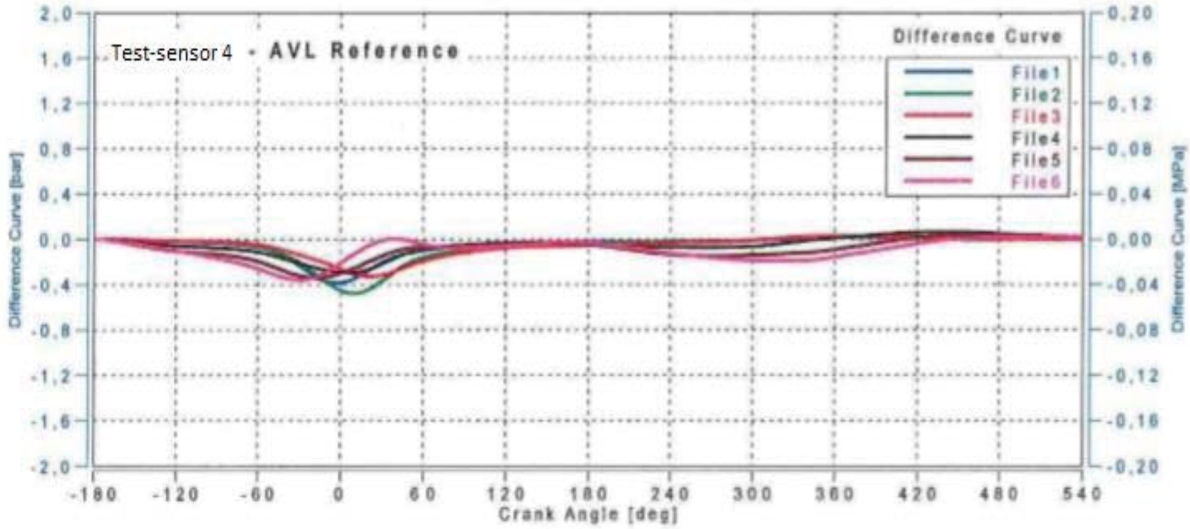


Figure (4.5) – Lower graph, test-sensor 4 – Load variation. Deviations from the reference-sensor.

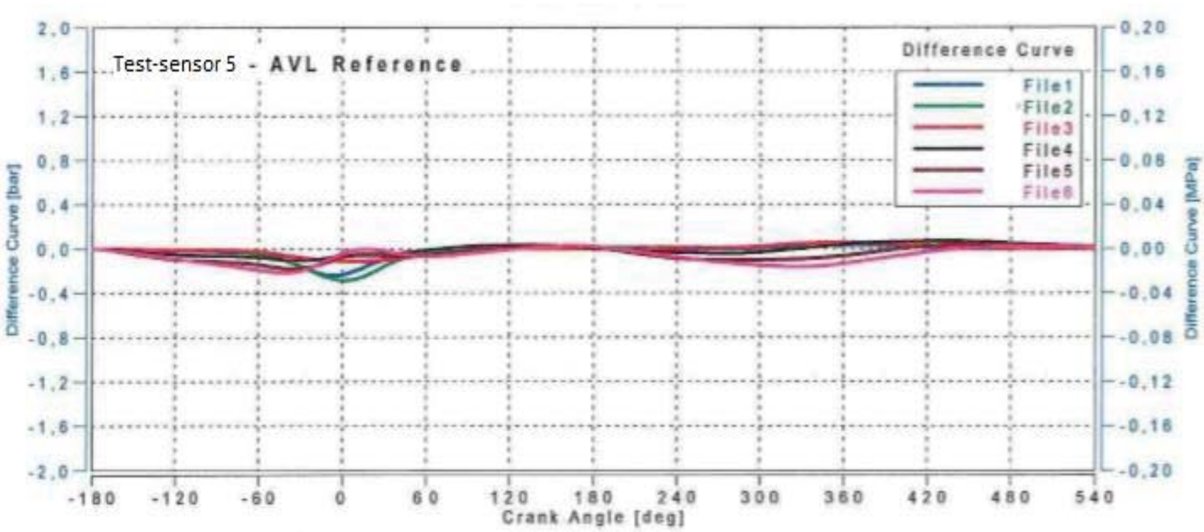


Figure (4.6) – Lower graph, test-sensor 5 – Load variation. Deviations from the reference-sensor

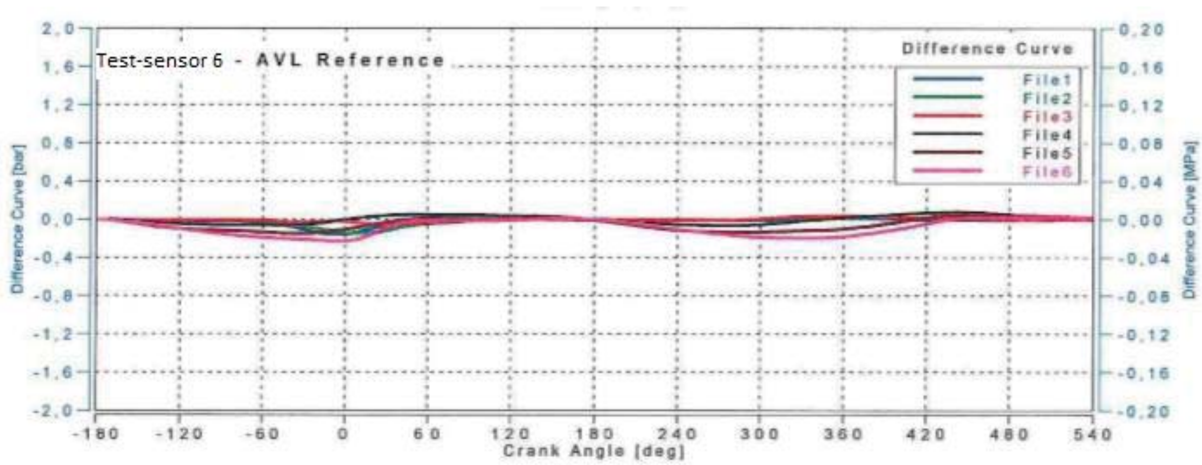


Figure (4.7) – Lower graph, test-sensor 6 – Load variation. Deviations from the reference-sensor.

When comparing the sensors in the speed variation test, there is a similarity in the results. Sensor 6 and 1 are showing well accuracy and the 3rd test-sensor is performing very well in these tests with almost zero deviations. Sensor 2 is as well very accurate since the curves are flat and quite stable and the deviation is small. The test-sensor 4 and 5, as seen in figure (4.11) and (4.12), are still lacking in accuracy but the total percentage of errors are yet very small. By looking at sensor 1-protocol, the lower graph shows that the highest speed test, 2600 rpm, stands out. That is presumably because of the location of the sensor due to the unpredictable fuel ignition area. If the ignition occurs closer to a sensor, the pressure wave will affect the measurement of each transducer in a sufficient matter as well as the temperature, leading to thermal drift. Therefore, straight conclusions cannot be made from only the graphs due to different influences, but assumptions can be made as well as evaluations. In the end of the speed variation protocols is a summed up table, table (4), containing the average values of all the sections with different speeds. Table (5) defines the lowest and the highest differences of all test-sensors compared to the reference-sensor from the speed variation tests.

SPEED VARIATION

SENSOR	DIFF_IMEP mean value	Diff_Pmax mean value	Max_Deviation mean value
TEST-SENSOR 1	0.0375	0.1	0.2
TEST-SENSOR 2	0.065	0.1025	0.13
TEST-SENSOR 3	0.0275	0.05	0.06
TEST-SENSOR 4	0.0925	0.3525	0.3775
TEST-SENSOR 5	0.06	0.2	0.215
TEST-SENSOR 6	0.0375	0.095	0.1225

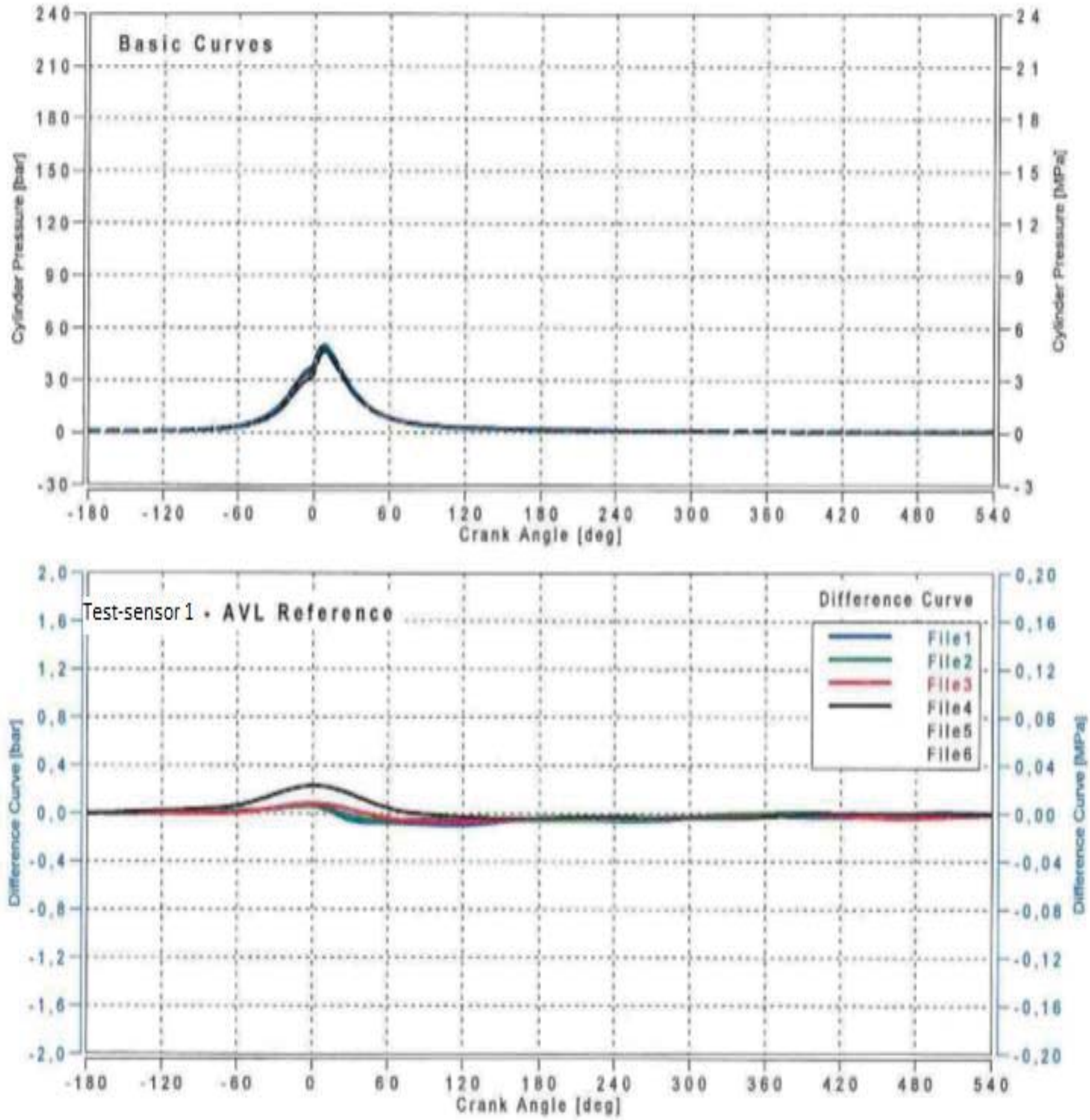
Table (4) – Speed variation mean values, table.

Table (5) – The largest and the smallest differences between the test-sensors and the reference-sensor.

Speed variation.

SENSOR	DIFF_IMEP[BAR] LOW - HIGH	DIFF_PMAX[BAR] LOW - HIGH	MAXIMUM_DEVIATION[BAR] LOW - HIGH
1	0.00 – 0.07	0.05 – 0.22	0.06 – 0.23
2	0.02 – 0.11	0.05 - 016	0.11 – 0.17
3	0.01 – 0.06	0.02 – 0.11	0.03 – 0.11
4	0.04 – 0.13	0.24 – 0.42	0.29 – 0.45
5	0.02 – 0.10	0.14 – 0.24	0.19 – 0.25
6	0.00 – 0.07	0.01 – 0.17	0.08 – 0.19

speed variation Test-sensor 1



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	600	4,02	49,17	-0,07	0,05	-0,10
File2	1300	4,02	50,41	-0,03	0,05	0,07
File3	2000	4,08	46,53	-0,05	0,08	0,08
File4	2600	3,91	47,30	0,00	0,22	0,23
File5						
File6						

Figure (4.8) – Complete sensor protocol, test-sensor 1 – Speed variation.

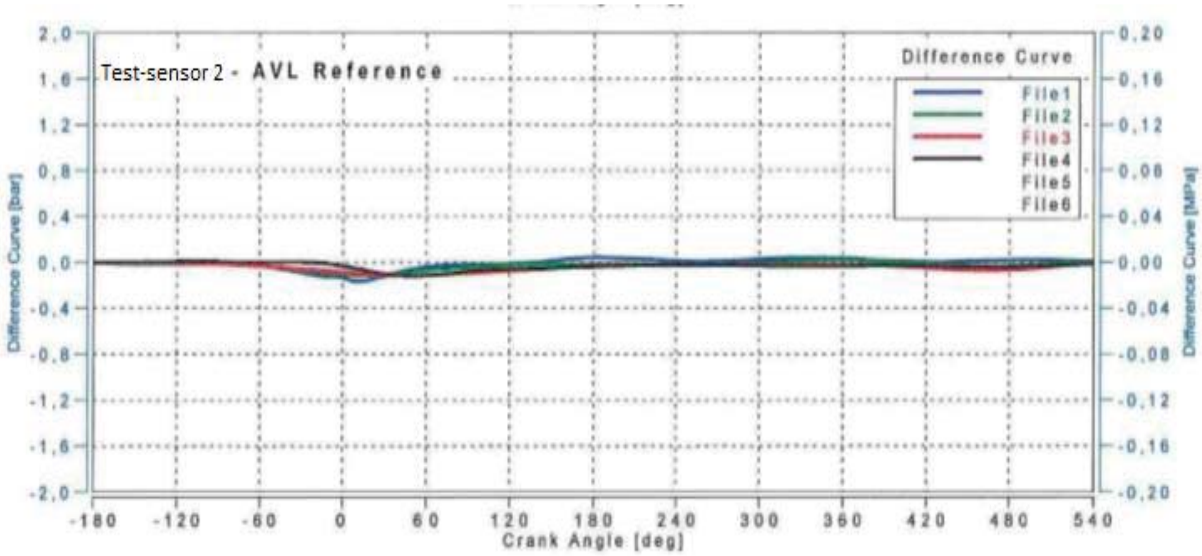


Figure (4.9) – Lower graph, test-sensor 2 – Speed variation. Deviations from the reference-sensor.

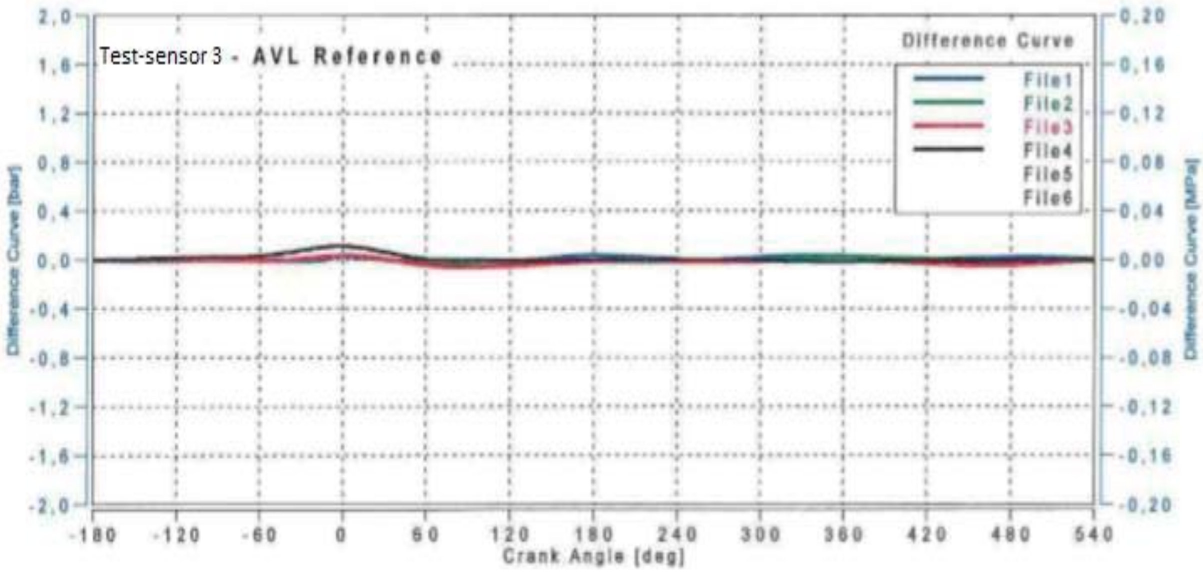


Figure (4.10) – Lower graph, test-sensor 3 – Speed variation. Deviations from the reference-sensor.

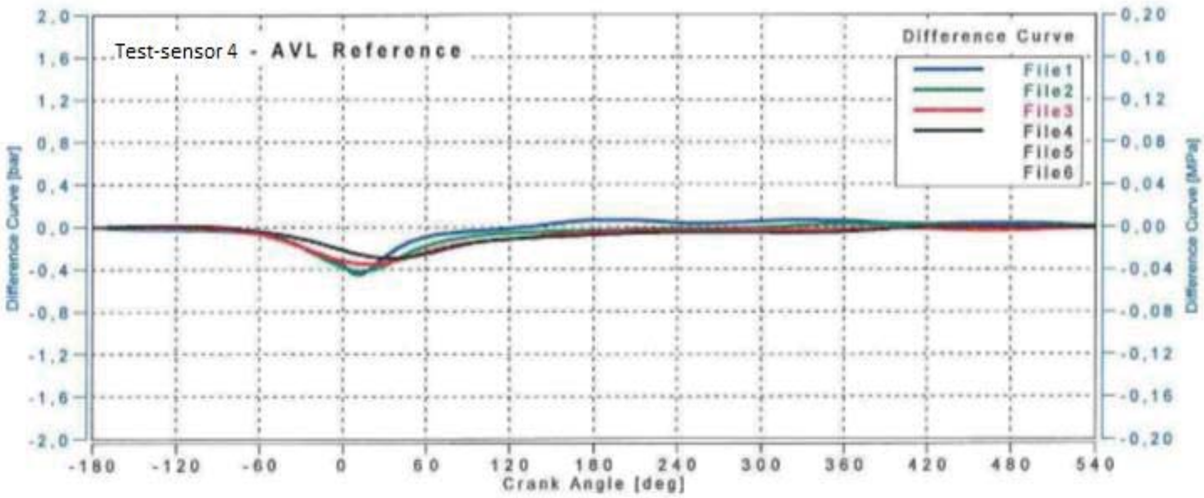


Figure (4.11) – Lower graph, test-sensor 4 – Speed variation. Deviations from the reference-sensor.

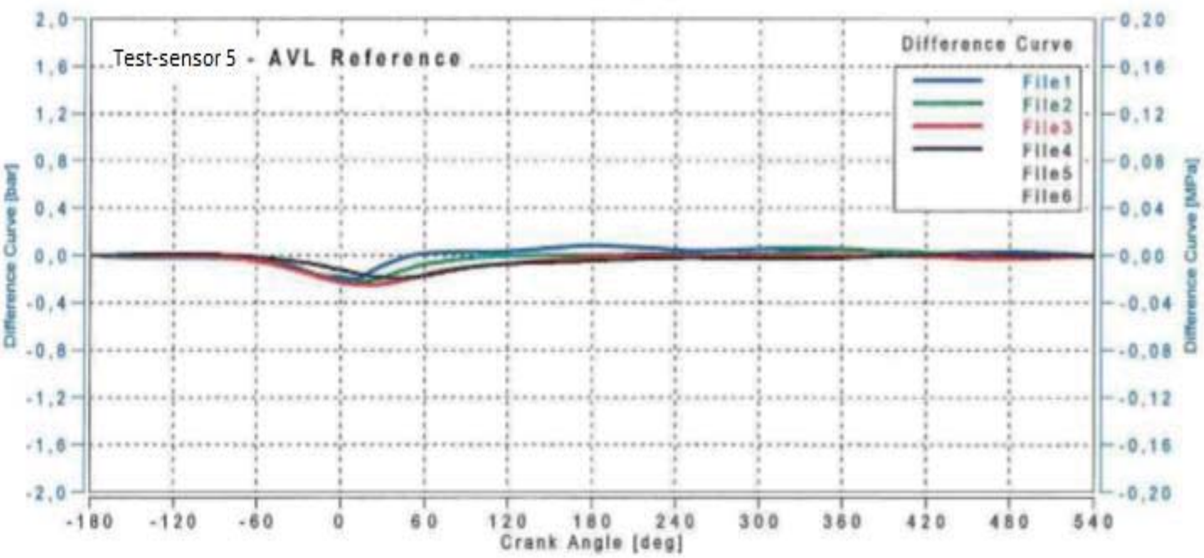


Figure (4.12) – Lower graph, test-sensor 5 – Speed variation. Deviations from the reference-sensor.

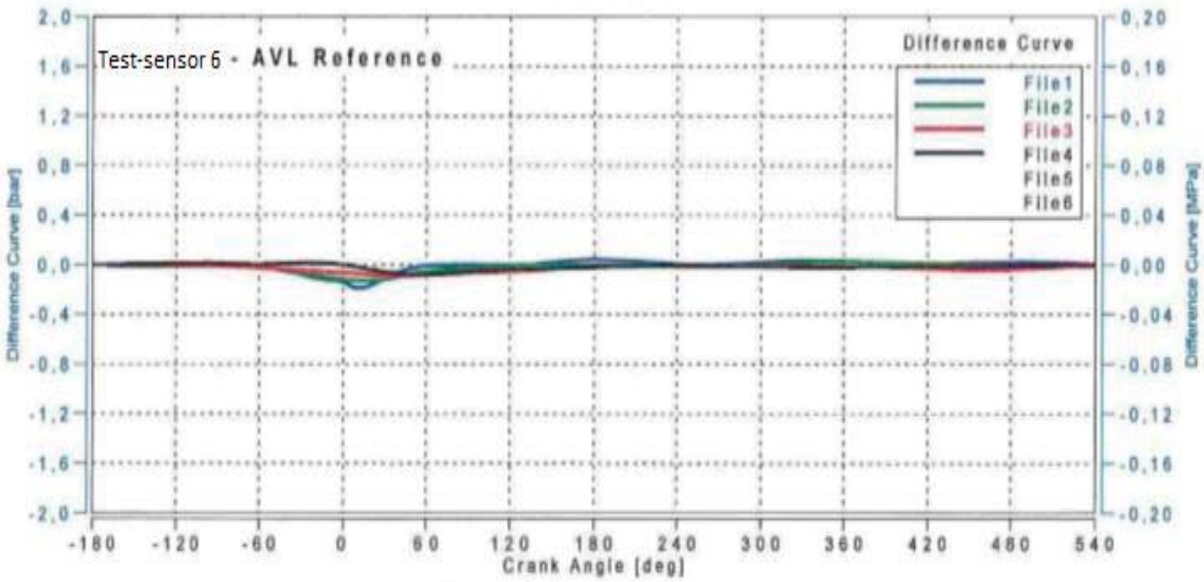


Figure (4.13) – Lower graph, test-sensor 6 – Speed variation. Deviations from the reference-sensor.

In figure (4.14) the heat release graph is presented with test-sensors 2. The Y-axis represents the amount of energy converted to necessary work. Just before the combustion approaches, the curve is stable at zero, as it should. But when the crank angle reaches -40˚ the curve is sinking downwards below the zero point. This happens because the injected liquid fuel vaporizes which requires energy from the environment. The graph is, after its peak, going back to the zero level again as it should. If the curve would never reach the zero level in the end, this would imply that the combustion never ends. Would the curve go below the zero level, it would imply that energy was still absorbed. This is often corrected in the post-processing tool Concerto by shifting the TDC when it is offset. Another factor is if the pressure transducer has been influenced by the heat due to thermoshock, then the pressure measured will be wrong and the difference between the motored pressure curve versus the combusted pressure curve will be wrong as the combusted pressure curve will reach its base pressure later.

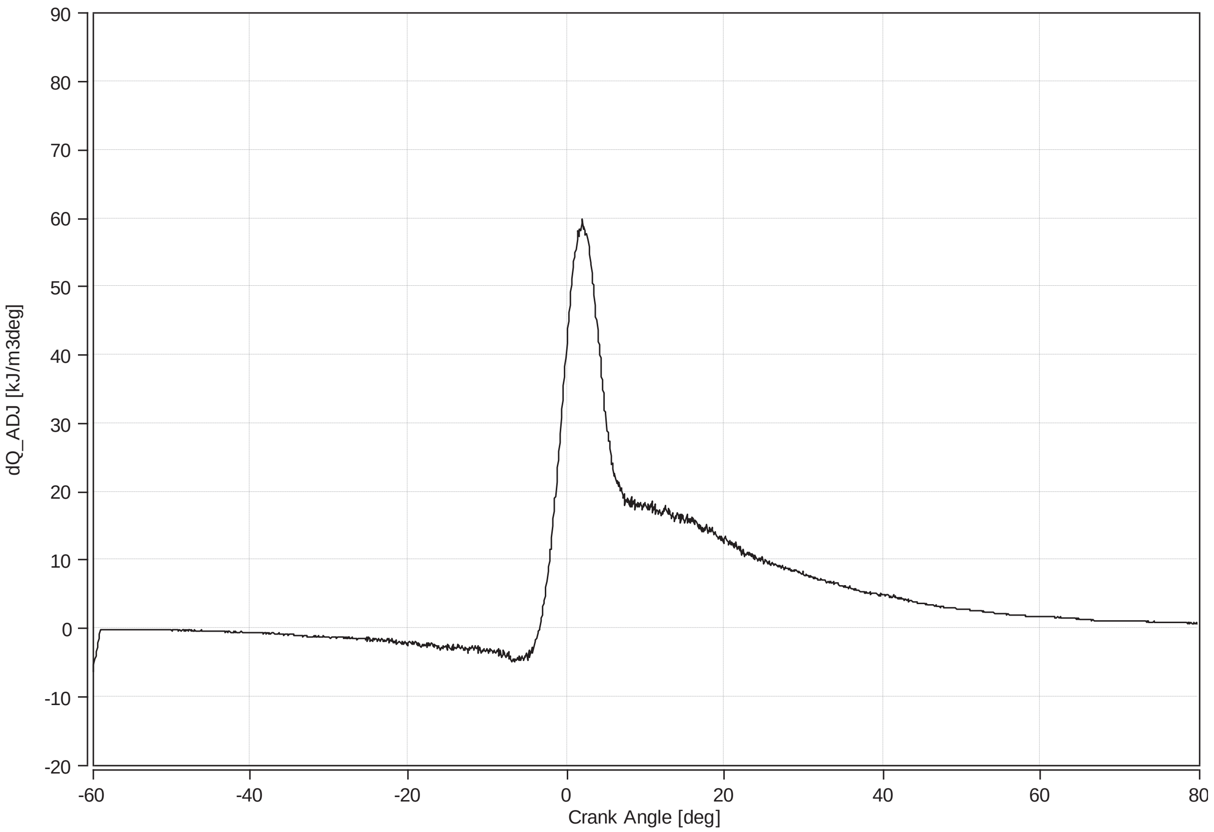


Figure (4.14) - Heat release graph. IMEP 18 bar, speed 1300 rpm.

4.3The results from the pressure shock-tube tests

Now that the sampling rate is as high as it is, 10 mega sample/s, it can be shown well in the graphs if one transducer is mounted deeper into the tube than another. Therefore, where in the X-axis the pressure sensors raises due to the shock is irrelevant as all transducer were not mounted exactly as deep. The most interesting sections of these results are the gradient of the pressure rise and the profile of the curves, such as amplitude. Due to the natural frequency of the sensors, they are fluctuating and as seen in the results, the reference-sensor graph manages to handle the pressure shocks better without fluctuating too much, which is because of its high natural frequency. First overview graphs will be shown of the different results followed up by zoomed in graphs to see the pressure profiles at a shorter time range when the shocks reach the transducers. These results are shown to compare the transducers, thus it is unknown which one is closest to the real pressure. On the Y-axis the pressure is presented, [bar], and on the X-axis is the time scale, [s]. In this case only the amplitude and the profile of the pressure is important to observe and the time scale is relative. As seen in figure (4.21), which is an image of the pressure wave's start in the measurement, the curve is plane in the beginning of the measurement. When the X-axis value reaches -30000 µs, the curve starts to fluctuate around zero bar gauge until it rises up to over six bar. This fluctuating is caused by the pressure wave. Since the sample frequency is so high, the time scale is very high resolved. When the membranes crack, the pressure waves comes and vibrations occurs in the metal. The vibrations in metal goes faster than it goes in the air as metal is a solid material, resulting in the vibrations affecting the measurement before the wave in the air does. Thereof the small fluctuations before the pressure rise. The curves are swaying up and down in the graph after the shock, which occurs due to the bouncing of the pressure waves, back and forth in the tube walls. Four more graphs from the "Test-sensor 2 – Test-sensor 1"-tests are presented in the appendix due to compare these sensors even more, figure (4.45) to (4.48). The comparison tests between the test-sensors and the reference sensors are attached in the appendix, figure (4.39) to figure (4.44).

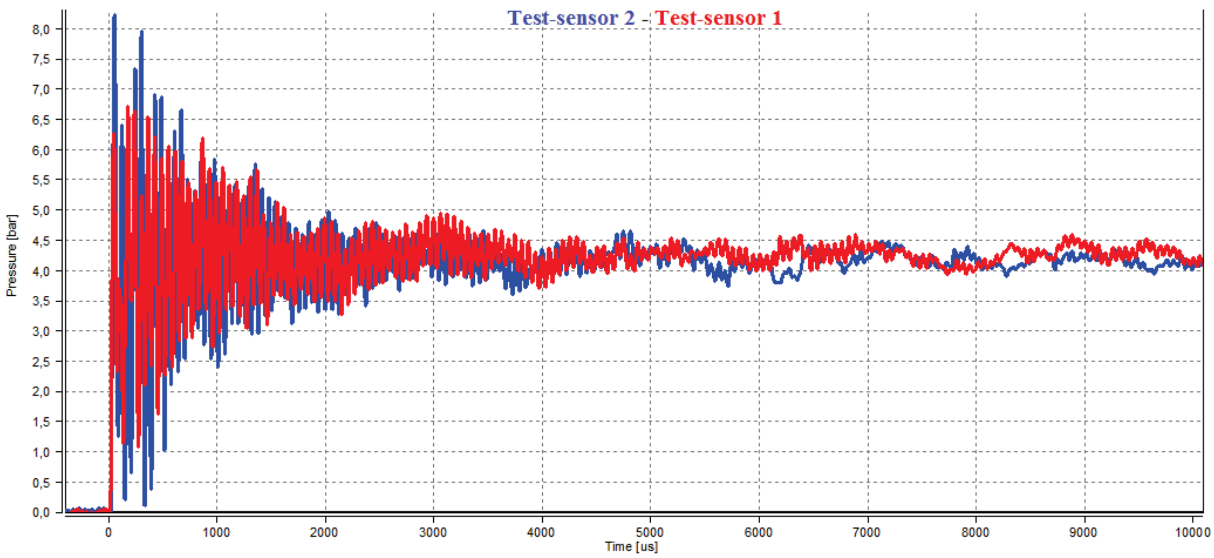


Figure (4.15) – Shock-tube test. Test-sensor 2 – test-sensor 1, overview graph.

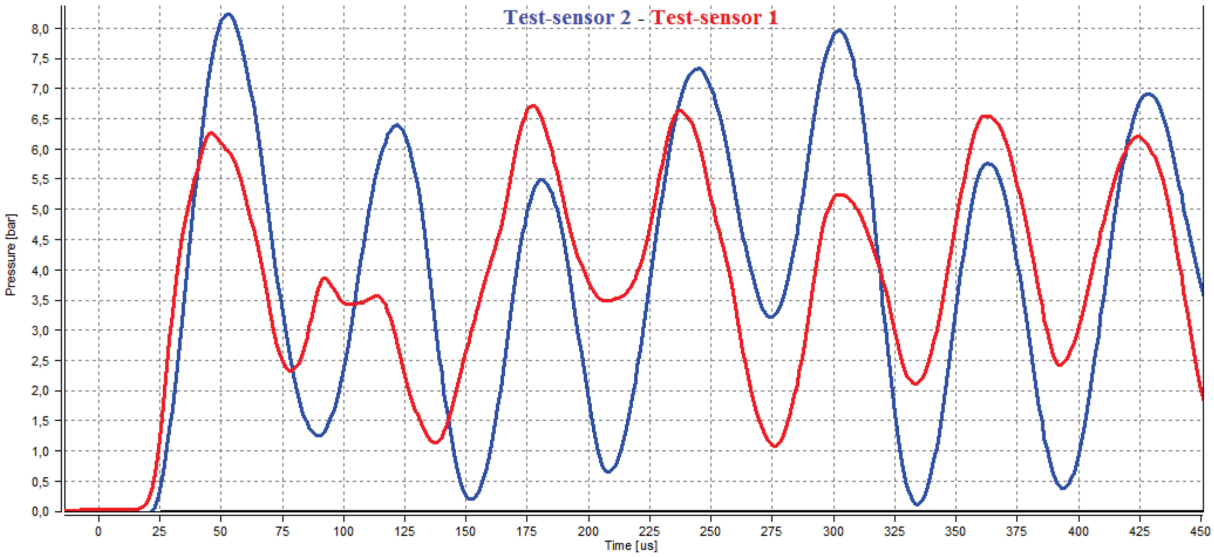


Figure (4.16) – Shock-tube test. Test-sensor 2 – test-sensor 1, zoomed graph.

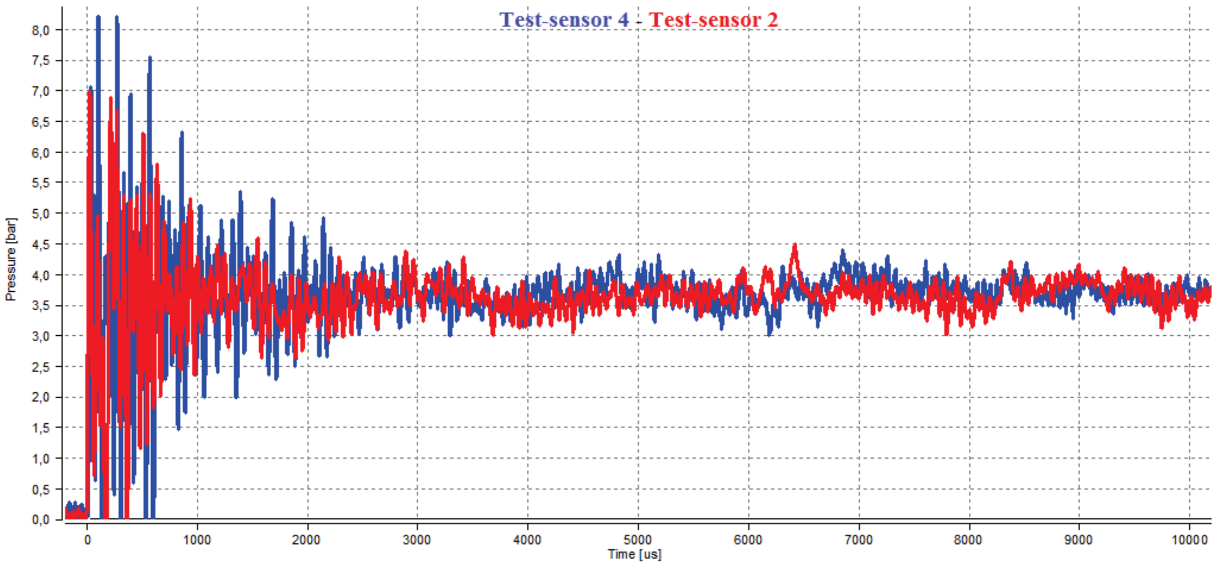


Figure (4.17) – Shock-tube test. Test-sensor 4 – test-sensor 2, overview graph.

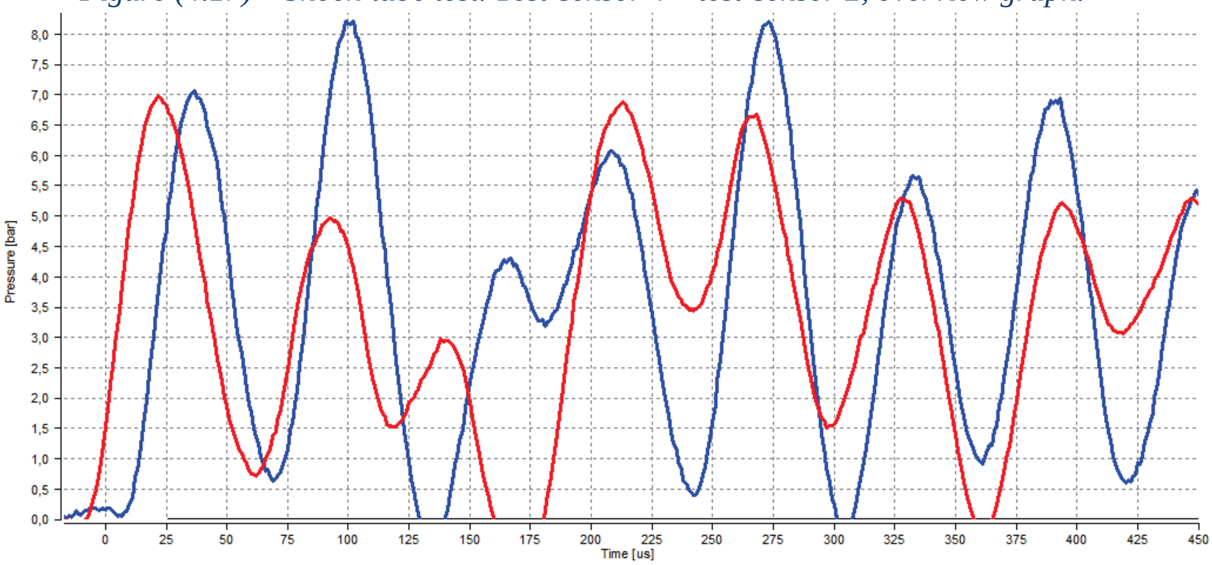


Figure (4.18) – Shock-tube test. Test-sensor 4 – test-sensor 2, zoomed graph.

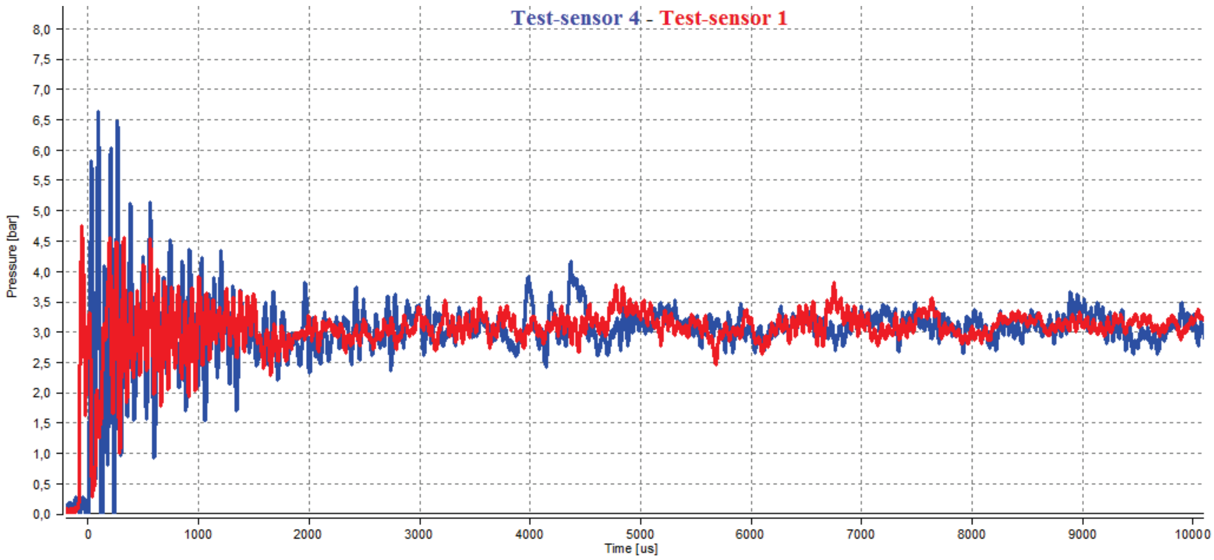


Figure (4.19) – Shock-tube test. Test-sensor 4 – test-sensor 1, overview graph.

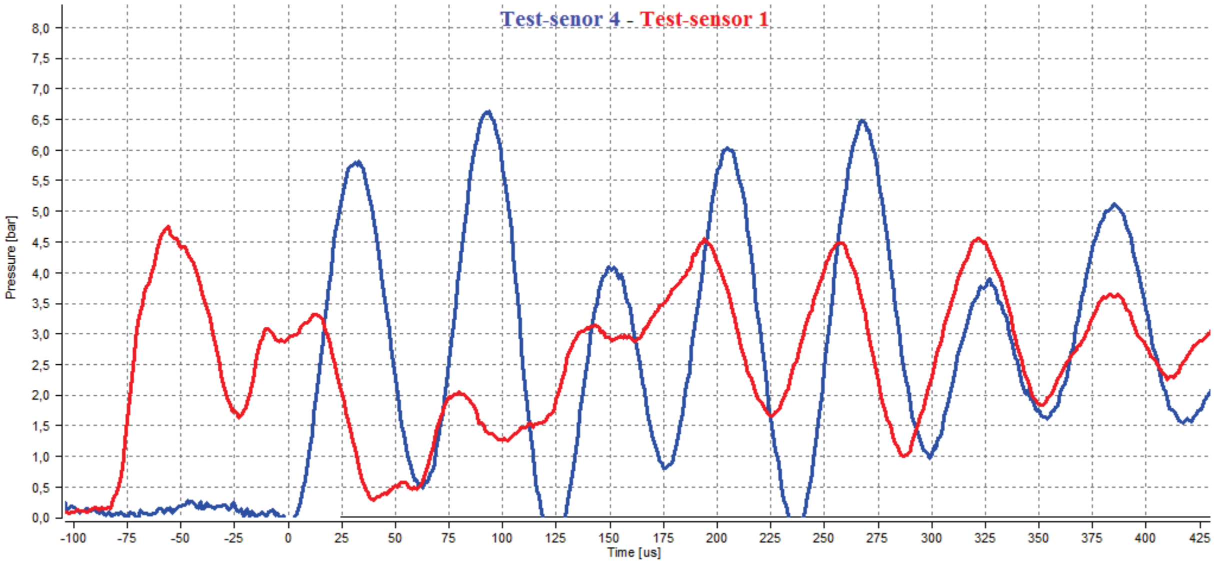


Figure (4.20) – Shock-tube test. Test-sensor 4 – test-sensor 1, zoomed graph.

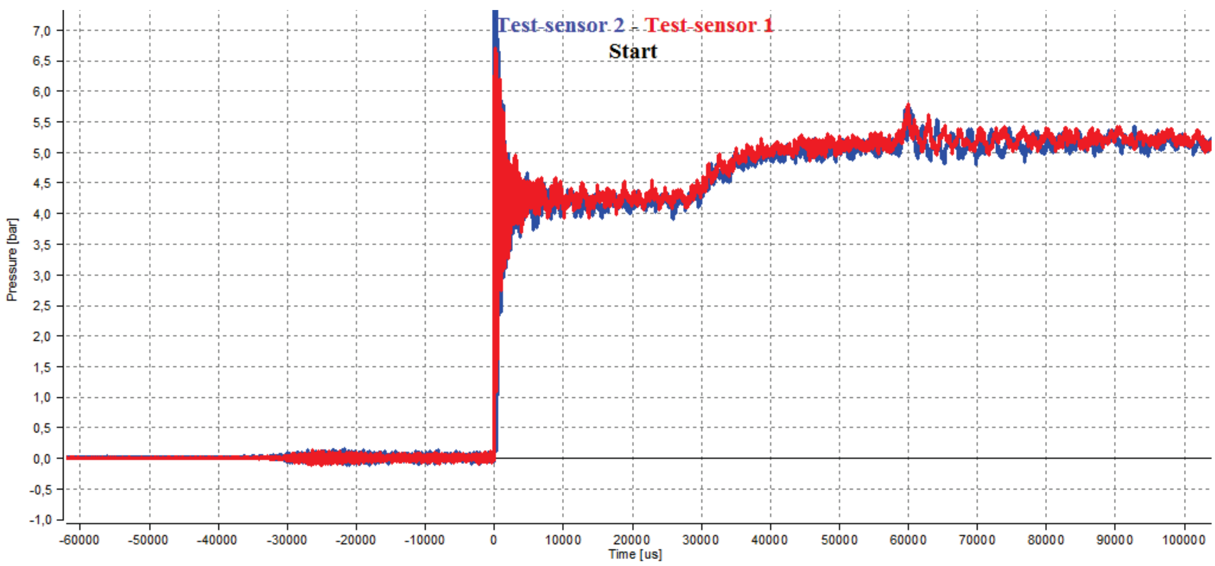


Figure (4.21) – Shock-tube test. Test-sensor 2 – test-sensor 1, wave start graph.

5. Conclusion

Since the aim of the project was to compare different pressure transducers in a gasoline combustion engine, the completed results from the engine test is not fully correct as the tests were made at a diesel combustion engine. Due to the fact that there was no access to such a modified gasoline engine as the diesel engine, it was the only opportunity to get a fair comparison test since the transducers were tested simultaneously. The big difference between a diesel engine- and a gasoline engine-test is that the pressure peaks are higher in the diesel engine as the maximum pressure is around 200 bar in a diesel engine and around 110 bar in a gasoline engine. The maximum temperature is even higher in the diesel engine. However, the temperature gradient in a gasoline engine is higher than in a diesel engine. There are many factors that really can affect the measurement that are almost impossible to get rid of. Some factors are easier to compensate for than others. To get an as fair comparison as possible, as many error sources as possible should be regarded and be taken into account.

Before the mounting, the test sensors were not cleaned which can have affected the pressure measurements. Four of the sensors were brand new and came from an unopened box, among them: test-sensor 2,3,4,5 and the two other sensors were not, test-sensor 1 and 6, making the cleaning procedure even more important. A further factor that may have impacted the comparison is the age of the sensors and amount of use the sensors had been exposed to. The sensor 1 was approximately four years old and had been exposed for 100 shocks whereas sensor 2, 3, 4, 5 were brand new and had not been exposed for any tests at all makes it even harder to conclude what sensor performs most accurate. What one might think is that the brand new sensors should have their top performance the first times they are tested. But the fact is that some sensors have to be exposed for some pressure cycles before it reaches its top performance, although most of the sensor manufacturers already fulfill this act before putting it in the box. When the performance of a sensor starts to deteriorate, the accuracy lacks a lot. With that being said, it is hard to know which one had its top performance period during the tests but due to my assumptions, all the sensor should be in its peak regarding performance. The new sensors should already have been run-in and since the older sensor had only been exposed for a total amount of approximately 100 shocks, regularly for four years, it is not close to be over-used and should still be on its top. Optimal in the cylinder-test would have been to do this test repeatedly, four to six times with the sensors in different positions in the cylinder head every time. This would eliminate the impact of the placement but would still not be hundred percent accurate since every combustion never look the same.

The calibration performed after the engine tests were a ramp calibration, which is the most usual way of calibrating pressure sensors now days. Further calibration tests can be done, such as Dead Weight Tests in different temperatures and different pressure ranges. The advantage of the DWT is the high accuracy due to the exact known weight and pressure. The more calibrations done, the better accurate results, but as usual there is a limit of time. In our case, the sensitivity set in the combustion engine tests were the sensitivities found in their former calibration. These values were later changed in the post process making the measurement and results even more accurate. The calibration should always be done before combustion tests or any kind of tests.

One of the greatest issues of the measurement assumptions though, is the question: Did the reference sensors show the most accurate pressure value through the whole combustion test? Both reference-sensors are water-cooled. But as told earlier in the text, the hardest part of the measurement is when the pressure rises and the combustion occurs. There are two reference sensors for better accuracy but neither of them was cleaned before the test. If there were soot on the sensors this would influence the accuracy negatively enough.

In the comparison of the graphs from the shock-tube results, it is clear that the reference sensor is more stable and the gradient is much higher in the rising phase. With a higher natural frequency comes a faster response time, which would make this sensor very suitable in combustion engines if the response time was the most important in pressure sensor performance or if knock detection was most important. Although, the reference-sensor's work or range of the pressure is lower, as well as the temperature range making it less suitable for combustions seeing that it would not handle higher temperatures as well. When comparing the pressure rise gradient and the amplitude of the test-sensors, test-sensor 4 showed in these results that it lacked in performance compared to the other sensors. Between test-sensor 1 and test-sensor 2, no straight determination can be made since they are too similar in performance in these tests. In the appendix, two more graphs of the "test-sensor 1 – test-sensor 2"-results will be shown as they in average were equally as good.

Further determined conclusions and analysis from the resultant graphs in whole, assuming that the reference sensors measured the pressure most exact, test-sensor 1, test-sensor 2 was most accurate followed up very close by test-sensor 6 during the load variation test due to least deviation. In the speed variation on the other hand, the most accurate sensor was sensor 3 followed up by 6, 1 and then 2. Test-sensor 1, 2, 6 or 3 would in my opinion be most appropriate to use in a gasoline combustion engine due to their performance in the engine tests both in the speed- and the load variation tests. Test-sensor 4 and 5 are not as accurate as the other sensors, although, they are made to be more robust and have an extended pressure range making them more suitable to use for higher temperatures and harsh environments. In total, the deviations from the reference sensor were too small to ignore the fact that error sources are affecting the measurement more than the pressure transducers' accuracy. In thermodynamic analysis, which was the target, sensor 1, 2, 3 and 6 would be most suitable. Between which sensor is performing the best between these four sensors is impossible to tell according to my own opinion. Since their outcome shows very good accuracy and performance, they are almost exactly as accurate. The hardest part from the result that makes it almost impossible to determine which pressure transducer-model is best is that transducer 2 and transducer 3 is of the same model. They are showing different results in the tests. This is because of the nanometer structure differences in the sensors but they both still perform within the accuracy-class range. Since we are talking about so sensitive objects, we can only get a hint, an average estimation, of the performances of the sensors. I believe that if we were to do the same test again, mount them at same position, we would get different results as well. But still the sensors that showed the best results last test would probably show the best results this time too. This has to do with the influencing error sources that are impossible to get rid of and also that the combustions never look exactly the same. Some of the errors can be prevented and compensated for, but due to the high sensitivity and small parts/components involved in the pressure transducer structure, different products of same model does not look exactly the same, when speaking in micrometer structure. Although, if were are up to look at the specific model, it would have been interesting to see more results from the test-sensor 6 since this sensor showed well results as well. Historic information regarding this sensor is unknown and with these conditions, it is not impossible that this sensor could have performed more accurately.

These methods used in the project to determine the accuracy and performance of pressure sensors are the most common methods to characterize sensors. However, better methods have to be used to determine a dynamic pressure sensor's performance.

References

1. *AVL - Combustion Diagnostics – measurement display, evaluation, Rüdiger Teichmann, Andreas Wimmer, Ernst Winkelhofer, Graz. Christian Scwhwarz, München. Graz, 2012.*

2. *AVL - Engine indication user handbook, Rudolf Pischinger, Graz 2002.*

3. *Kistler Instrumente AG- Influencing parameters and error sources during indication on internal combustion engines, Rolf H.Kuratle and Balz Märki, Winterthur 1994.*

4. *AVL – Indical V2.5 for Ramp Calibration System 601/603. Product guide. AVL List GmbH, Graz.*

5. *Equation from Concerto, CalcGraf. Source of equation: Heywood, J.B., Internal Combustion Engine Fundamentals, McGraw-Hill, 1988. Page 515.*

6. *Cylinder-Pressure-Transducer Mounting Techniques to Maximize Data Accuracy. Randolph A.L: SAE paper 900171 (1990).*

7. *Messung Shnell verkänderlicher Drüke am Beispiel der Brennraumdruckindizierung. Pütter R.G., Eisele HP, MTZ 2/1886.*

8. *Vergleihende Untersuchung von piezoelektrischen Druckaufnehmern auf itre Eignung für Verbrenungsmotoren. Müller H., Winter B., Rhode-Brandenburger K.: MTZ 1/1986.*

9. *Verfahren zur genauen Zylinderdruckmessung an Verbrennungsmotoren. Thiemann W., MTZ 2/3/1989.*

10. *AVL Product Information: Gallium Orthophosphat GaPO4, AVL LIST GmbH, 2000.*

11. *AVL Product Information: Druckaufnehmer für die Motormesstechnik (Pressure Transducers for Engine Instrumentation), AVL LIST GmbH, 2001.*

12. *AVL Product Information: OT-Sensor (TDC Sensor), AVL LIST GmbH, 2001.*

13. *AVL Product Information: Indiziertechnik (Indicating Technology), AVL LIST GmbH, 2000*

14. *Analyse und Simulation des arbetisprozesses von verbrennungsmotoren – Modellbildung und meBtechnische Verifizierung, Wimmer A, Graz 2000.*

15. *Druckindizierung an verbrennungsmotoren, Wimmer A., Glaser J., 2002.*

16. *Thermodynamik der verbrennungskraftmaschine, Pischinger R., Sams Th., Klell M., 2002, New York.*

17. *Berechnung des Motorprozesses mit Einpassung wichtiger Paramterer, Feßler H, 1988, Graz*

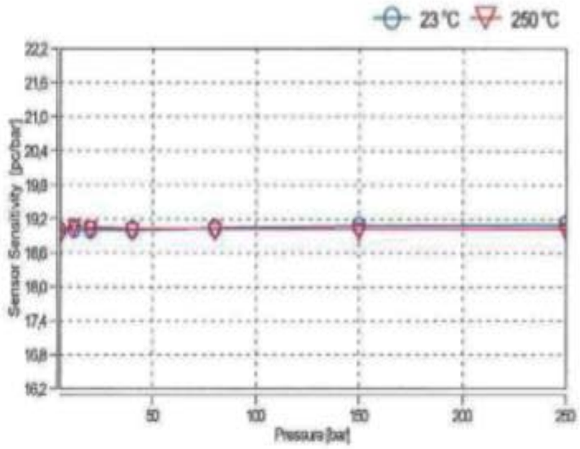
Appendix

In this section, further graphs from the results will be shown if more information from the tests is requested.

Results Test-sensor 2

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	18,99	18,96
12	19,01	19,09
20	19,00	19,05
40	19,00	19,03
80	19,04	19,03
150	19,07	19,02
250	19,10	19,03

Calibrated Range [bar]	Sensitivity/Linearitiy* at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy* at 250°C [pC/bar] / [%FSO]
0 - 250	19,09 / ± 0,09	19,03 / ± 0,02
0 - 150	19,06 / ± 0,09	19,03 / ± 0,03
0 - 80	19,02 / ± 0,07	19,03 / ± 0,05



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

* Determined by Tolerance Range Method
(best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment: Indiset Advanced 631	SN:	6310281
Cal.protocol:	PM1196	
Charge Amplifier: MicroIFEM 4FP4	SN: 373 channel 4	
Cal.protocol:	PM1589_04092014	
Measuring Software:	Rampenkalibration_v3.4	
Reference Sensor 0-400 bar: Typ: WIKA P-30	SN:	2245555
Cal. protocol:	DKD-K-15105-01-00 01729(	

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

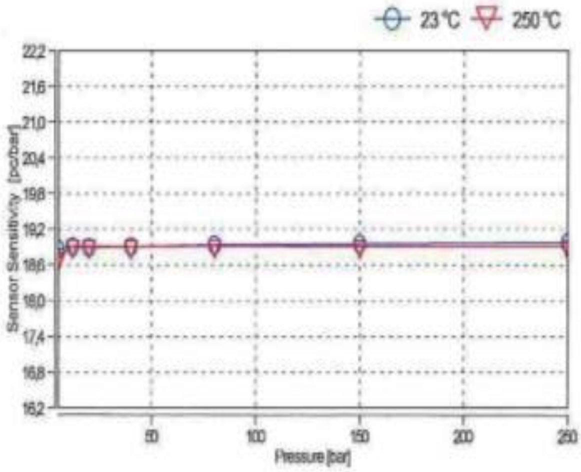
ISO 9001 certified

Figure (4.22) - RC results for test-sensor 2.

Results Test-sensor 3

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	18,86	18,70
12	18,90	18,92
20	18,89	18,91
40	18,90	18,91
80	18,93	18,92
150	18,95	18,91
250	18,97	18,91

Calibrated Range [bar]	Sensitivity/Linearitiy* at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy* at 250°C [pC/bar] / [%FSO]
0 - 250	18,96 / ± 0,05	18,90 / ± 0,02
0 - 150	18,94 / ± 0,06	18,90 / ± 0,05
0 - 80	18,92 / ± 0,07	18,90 / ± 0,10



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

* Determined by Tolerance Range Method (best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment: Indiset Advanced 631	SN:	6310281
Cal.protocol:	PM1196	
Charge Amplifier: MicroIFEM 4FP4	SN: 159 channel 1	
Cal.protocol:	PM1094_04092014	
Measuring Software:	Rampenkalibration_v3.4	

Reference Sensor 0-400 bar:
Typ: WIKA P-30 SN: 2245555
Cal. protocol: DKD-K-15105-01-00 01729(

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

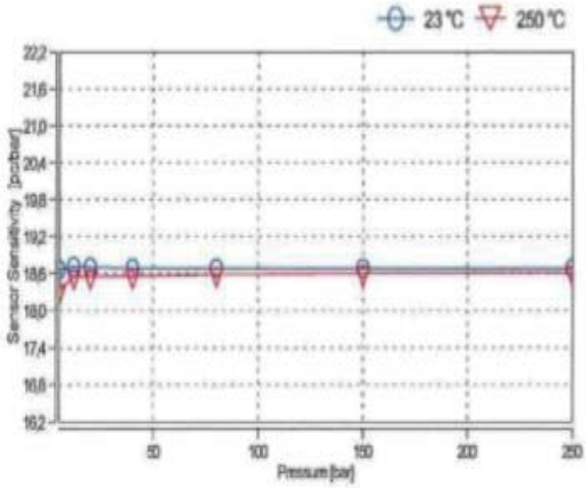
ISO 9001 certified

Figure (4.23) - RC results for test-sensor 3.

Results Test-sensor 4

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	18,66	18,33
12	18,71	18,56
20	18,70	18,56
40	18,69	18,56
80	18,68	18,59
150	18,68	18,61
250	18,68	18,62

Calibrated Range [bar]	Sensitivity/Linearitiy* at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy* at 250°C [pC/bar] / [%FSO]
0 - 250	18,68 / ± 0,01	18,61 / ± 0,04
0 - 150	18,68 / ± 0,01	18,60 / ± 0,06
0 - 80	18,69 / ± 0,02	18,57 / ± 0,11



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

* Determined by Tolerance Range Method (best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment:
Indiset Advanced 631 SN: 6310281
Cal.protocol: PM1196

Charge Amplifier:
MicroIFEM 4FP4 SN: 157 channel 1
Cal.protocol: PM1093_29102014

Measuring Software: Rampenkalibration_v3.4

Reference Sensor 0-400 bar:
Typ: WIKA P-30 SN: 2245555
Cal. protocol: DKD-K-15105-01-00 01729(

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

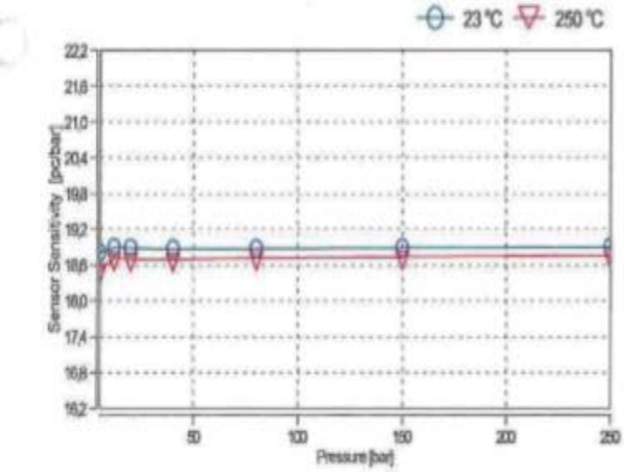
ISO 9001 certified

Figure (4.24) RC - results for test-sensor 4.

Results Test-sensor 5

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	18,81	18,51
12	18,90	18,71
20	18,88	18,70
40	18,87	18,69
80	18,88	18,71
150	18,89	18,74
250	18,91	18,76

Calibrated Range [bar]	Sensitivity/Linearitiy* at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy * at 250°C [pC/bar] / [%FSO]
0 - 250	18,90 / ± 0,04	18,75 / ± 0,06
0 - 150	18,89 / ± 0,04	18,73 / ± 0,06
0 - 80	18,87 / ± 0,04	18,70 / ± 0,09



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

* Determined by Tolerance Range Method
(best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment: Indiset Advanced 631	SN:	6310281
Cal.protocol:	PM1196	
Charge Amplifier: MicroIFEM 4FP4	SN: 157 channel 2	
Cal.protocol:	PM1093_29102014	
Measuring Software:	Rampenkalibration_v3.4	
Reference Sensor 0-400 bar: Typ: WIKA P-30	SN:	2245555
Cal. protocol:	DKD-K-15105-01-00 01729I	

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

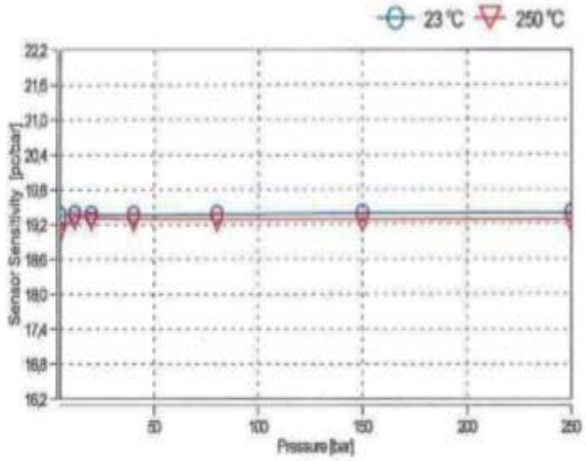
ISO 9001 certified

Figure (4.25) - RC results for test-sensor 5.

Results Test-sensor 6

Measuring Point [bar]	Sensitivity at 23°C [pC/bar]	Sensitivity at 250°C [pC/bar]
5	19,35	19,12
12	19,38	19,33
20	19,36	19,31
40	19,36	19,29
80	19,37	19,29
150	19,39	19,28
250	19,41	19,28

Calibrated Range [bar]	Sensitivity/Linearitiy* at 23°C [pC/bar] / [%FSO]	Sensitivity/Linearitiy* at 250°C [pC/bar] / [%FSO]
0 - 250	19,40 / ± 0,04	19,28 / ± 0,02
0 - 150	19,39 / ± 0,05	19,28 / ± 0,04
0 - 80	19,37 / ± 0,03	19,28 / ± 0,08



Measurement Procedure

Continuous Calibration, Comparison Method

Methods

* Determined by Tolerance Range Method
(best straight line with forced zero) DIN 16086.

Reference Equipment

automatic Calibrationsystem
Typ PZ 350 / SN 001

Measuring Equipment:
Indiset Advanced 631 SN: 6310281
Cal.protocol: PM1196

Charge Amplifier:
MicroIFEM 4FP4 SN: 373 channel 3
Cal.protocol: PM1589_04092014

Measuring Software: Rampenkalibration_v3.4

Reference Sensor 0-400 bar:
Typ: WIKA P-30 SN: 2245555
Cal. protocol: DKD-K-15105-01-00 01729(

In order to ensure traceability to the national standard the reference sensors and the referenceamplifier are examined in regular intervals by an independent calibration service.

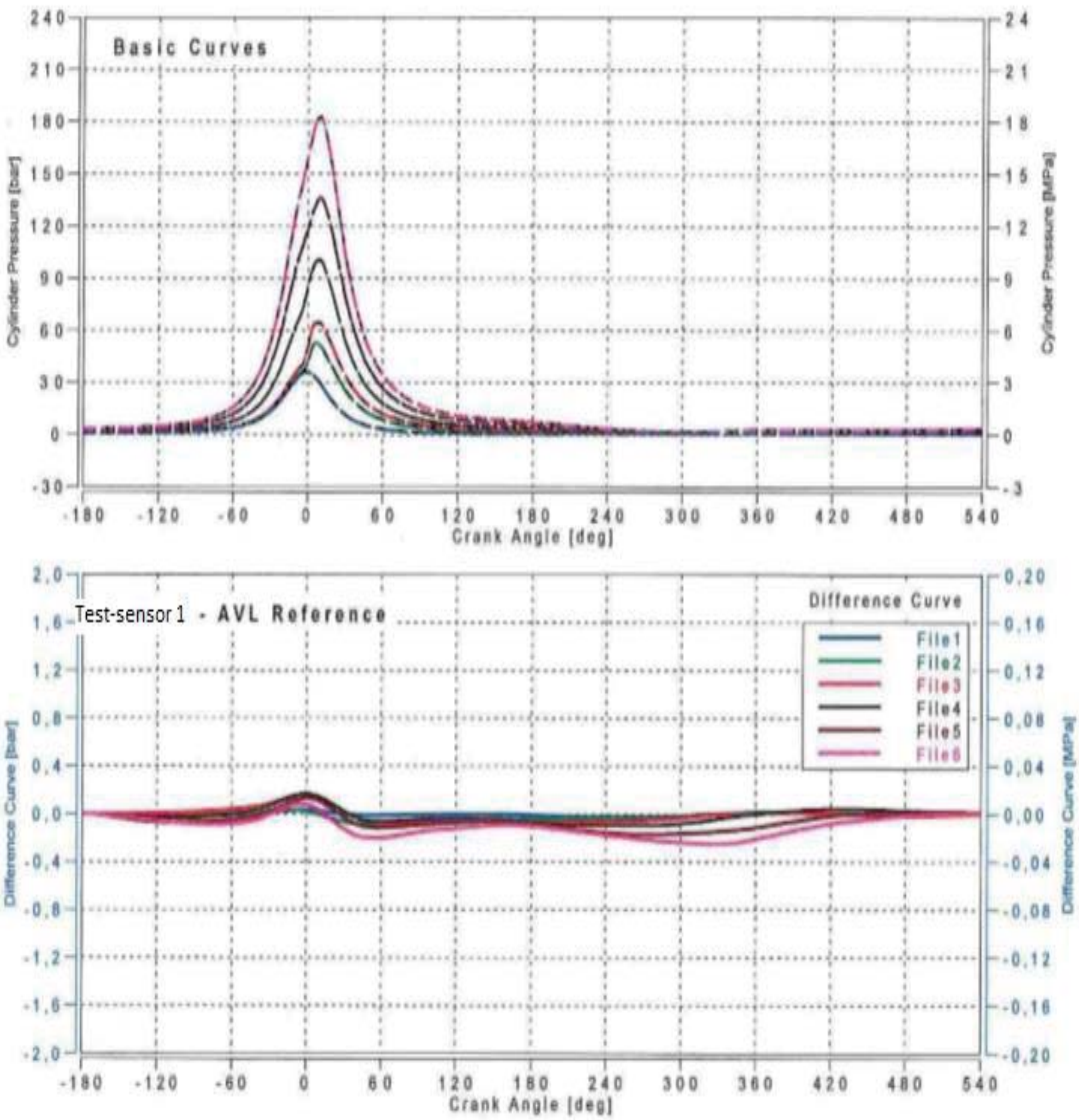
Confirmation

The sensor tested complies with the values specified in the data sheet. We confirm that the device was tested with the equipment and according to the procedures specified. Garanted accuracy of measurement for sensitivity better than 0.2%.

ISO 9001 certified

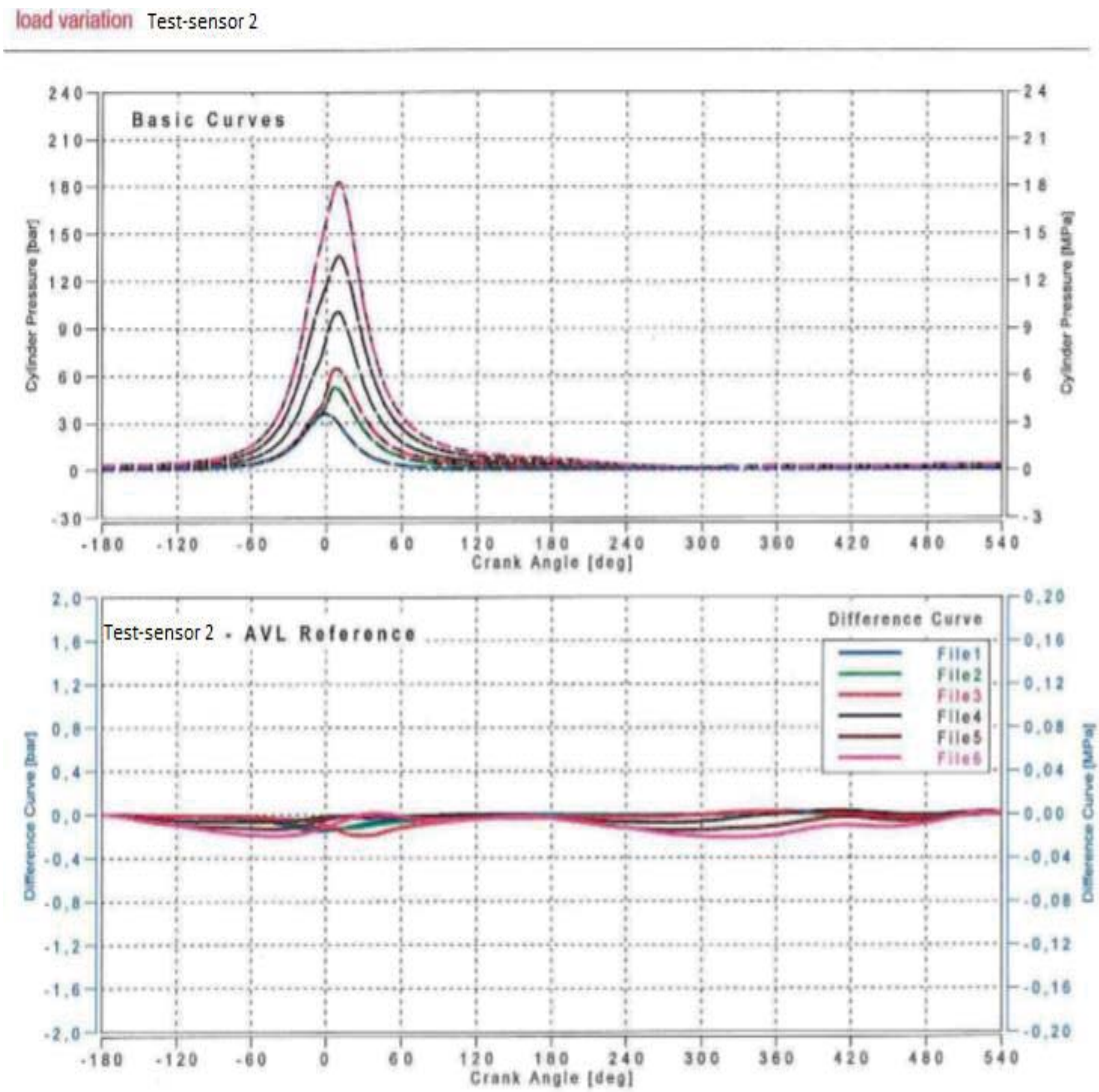
Figure (4.26) - RC results for test-sensor 6.

load variation Test-sensor 1



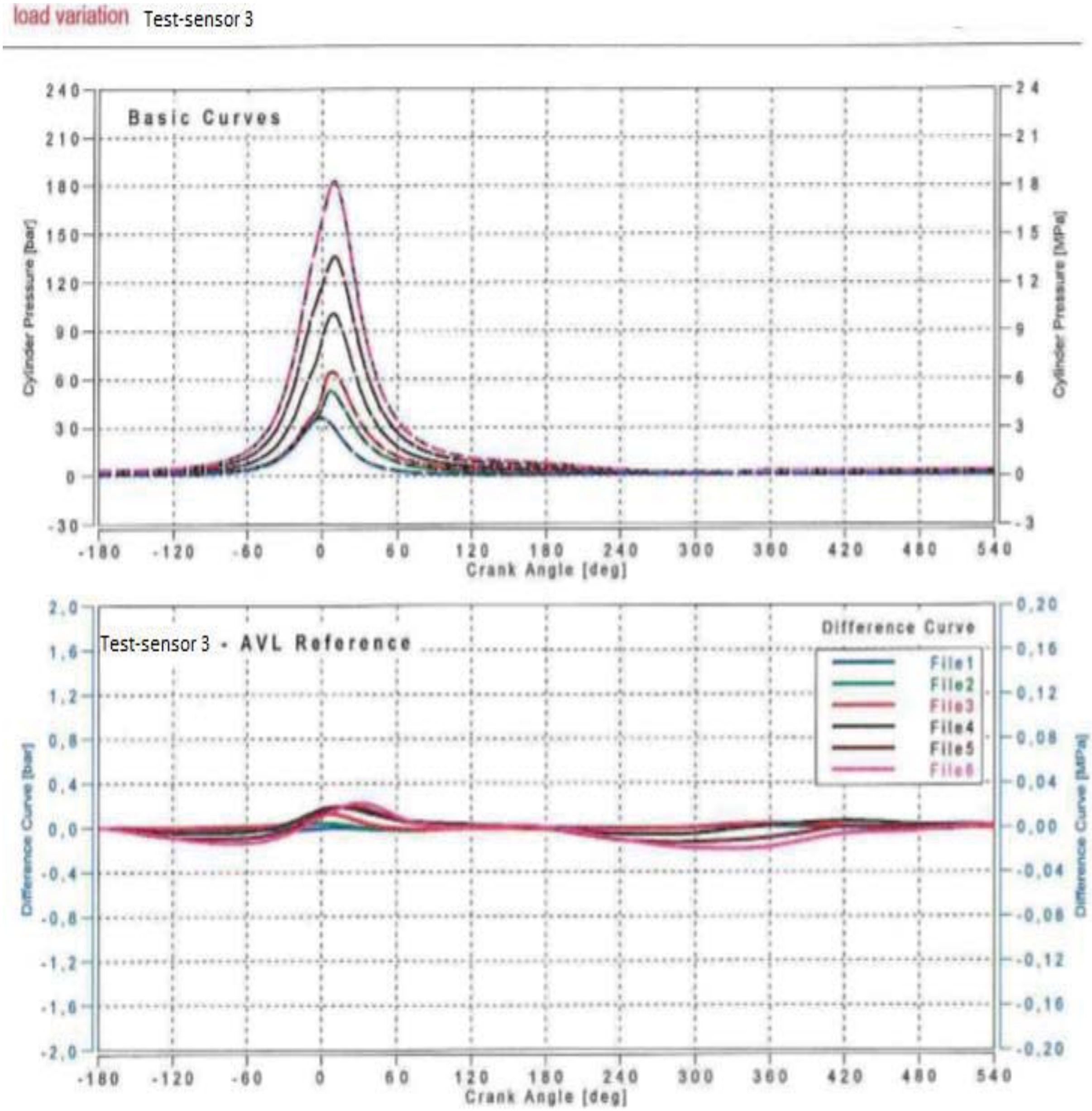
Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP[1] [bar]	Diff_pmax [bar]	Maximum Deviation[1] [bar]
File1	1300	-1,11	36,06	0,01	0,04	0,04
File2	1300	4,04	53,05	-0,05	0,01	-0,08
File3	1300	7,07	64,58	-0,05	0,15	0,17
File4	1300	9,99	100,36	0,08	0,15	0,17
File5	1300	14,01	135,78	0,11	0,11	-0,17
File6	1300	17,87	182,63	0,06	0,04	-0,25

Figure (4.27) - Sensor protocol test-sensor 1 – Load variation.



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	1300	-1,11	36,06	-0,01	-0,15	-0,15
File2	1300	4,04	53,05	-0,03	-0,13	-0,13
File3	1300	7,07	64,58	-0,07	-0,13	-0,20
File4	1300	9,99	100,36	0,12	-0,02	-0,08
File5	1300	14,01	135,78	0,18	-0,02	-0,15
File6	1300	17,87	182,63	0,19	-0,08	-0,21

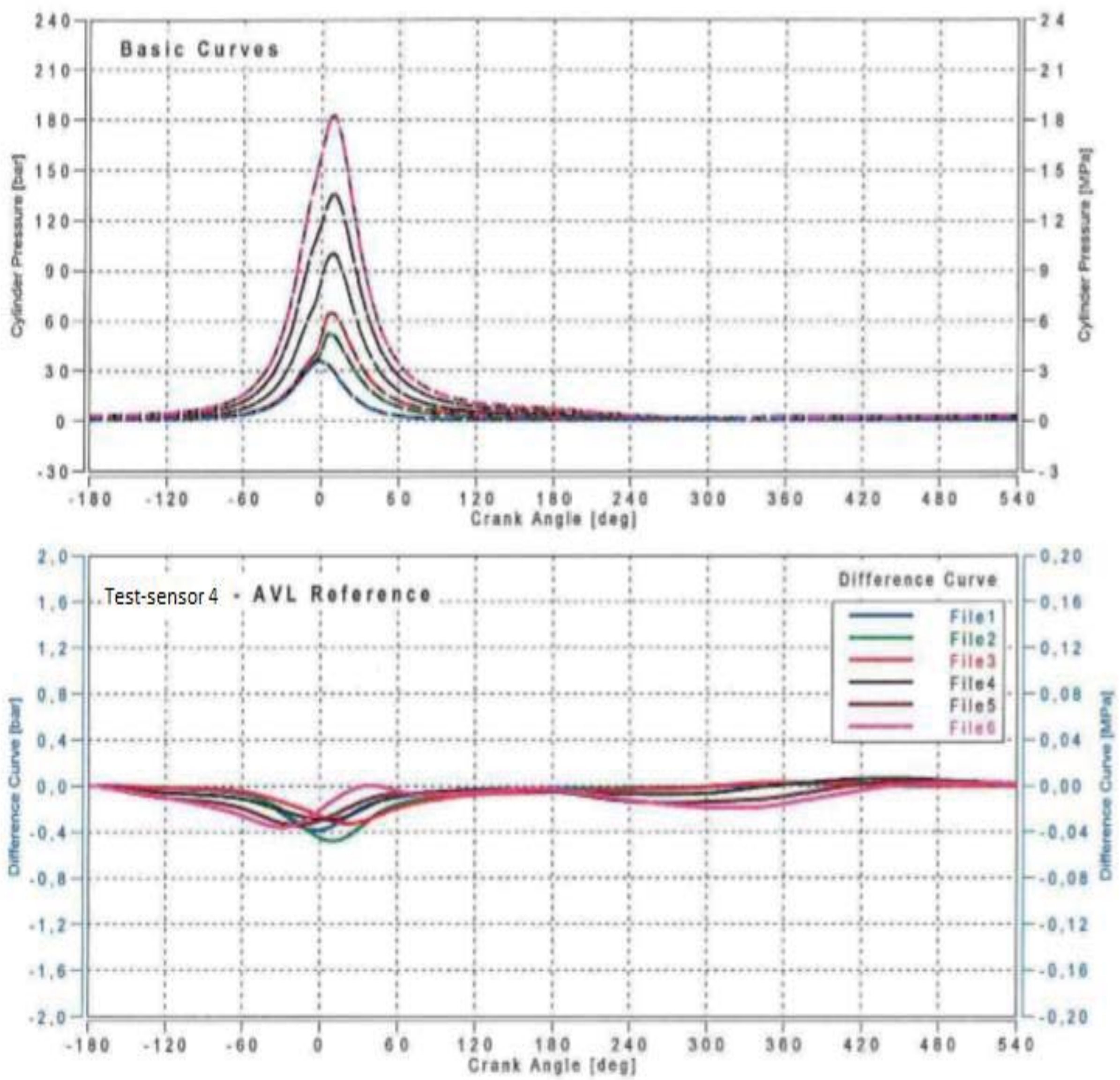
Figure (4.28) - Sensor protocol test-sensor 2 – Load variation.



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	1300	-1,11	36,06	0,00	-0,01	-0,02
File2	1300	4,04	53,05	-0,01	0,04	0,04
File3	1300	7,07	64,58	0,00	0,13	0,13
File4	1300	9,99	100,36	0,18	0,18	0,19
File5	1300	14,01	135,78	0,25	0,18	0,19
File6	1300	17,87	182,63	0,28	0,15	0,22

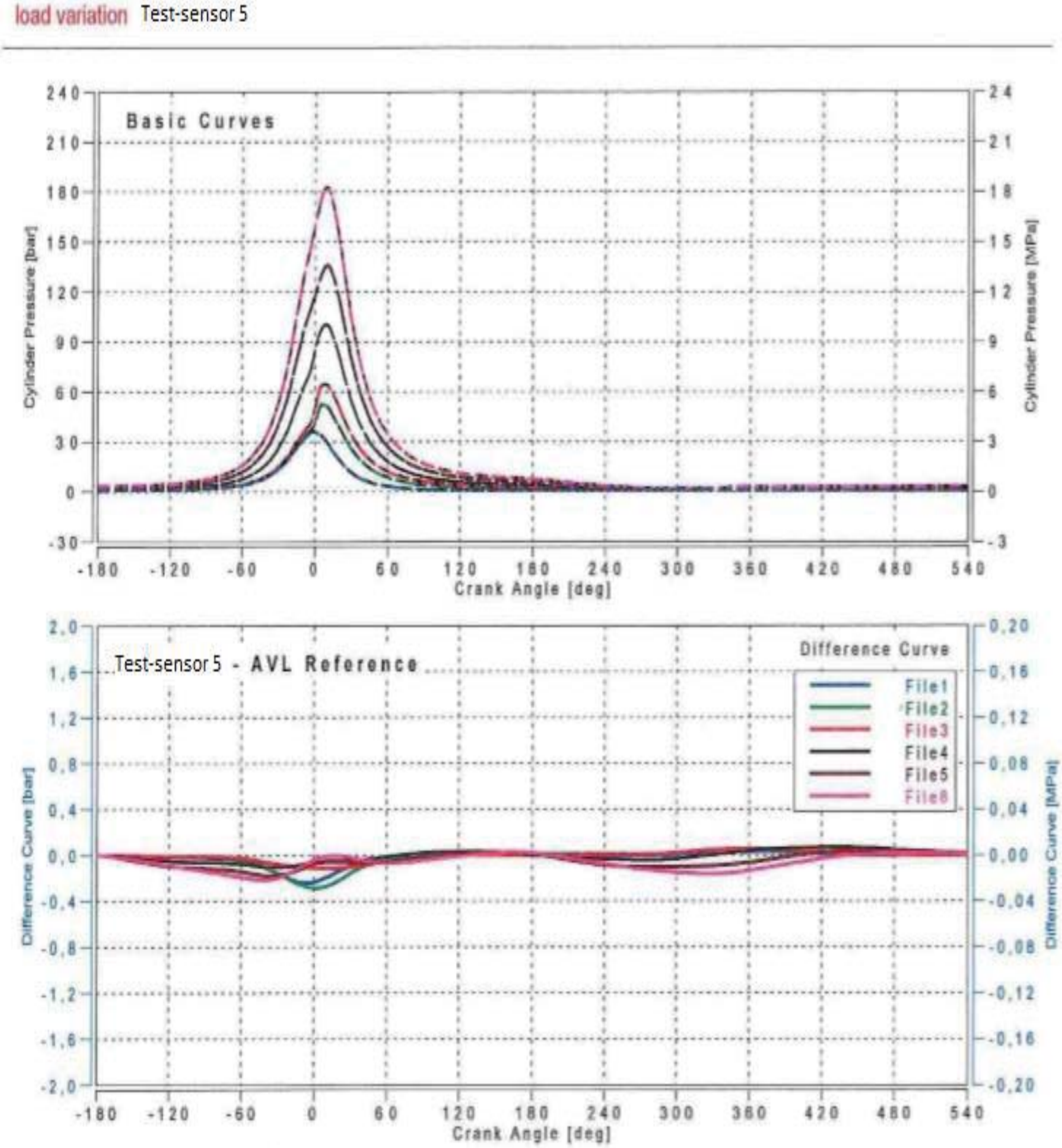
Figure (4.29) - Sensor protocol test-sensor 3 – Load variation.

load variation Test-sensor 4



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP[1] [bar]	Diff_pmax [bar]	Maximum Deviation[1] [bar]
File1	1300	-1,11	36,06	0,00	-0,39	-0,39
File2	1300	4,04	53,05	-0,06	-0,47	-0,48
File3	1300	7,07	64,58	-0,08	-0,30	-0,33
File4	1300	9,99	100,36	0,13	-0,29	-0,30
File5	1300	14,01	135,78	0,24	-0,25	-0,34
File6	1300	17,87	182,63	0,29	-0,14	-0,36

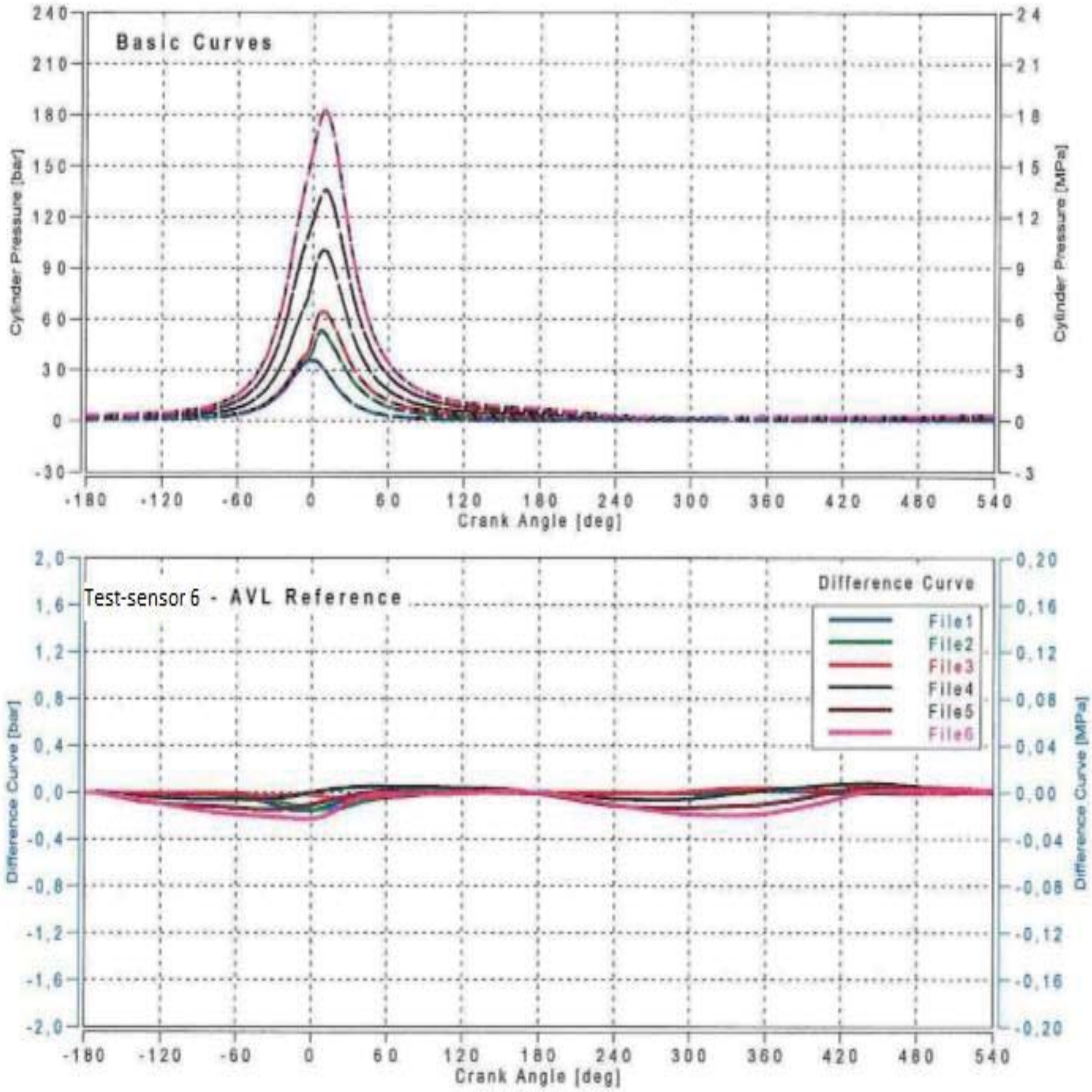
Figure (4.30) - Sensor protocol test-sensor 4 – Load variation.



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar] [1]	Diff_pmax [bar]	Maximum Deviation [bar] [1]
File1	1300	-1,11	36,06	0,02	-0,23	-0,24
File2	1300	4,04	53,05	0,00	-0,28	-0,28
File3	1300	7,07	64,58	-0,01	-0,11	-0,11
File4	1300	9,99	100,36	0,16	-0,06	-0,11
File5	1300	14,01	135,78	0,21	-0,05	-0,18
File6	1300	17,87	182,63	0,21	-0,01	-0,21

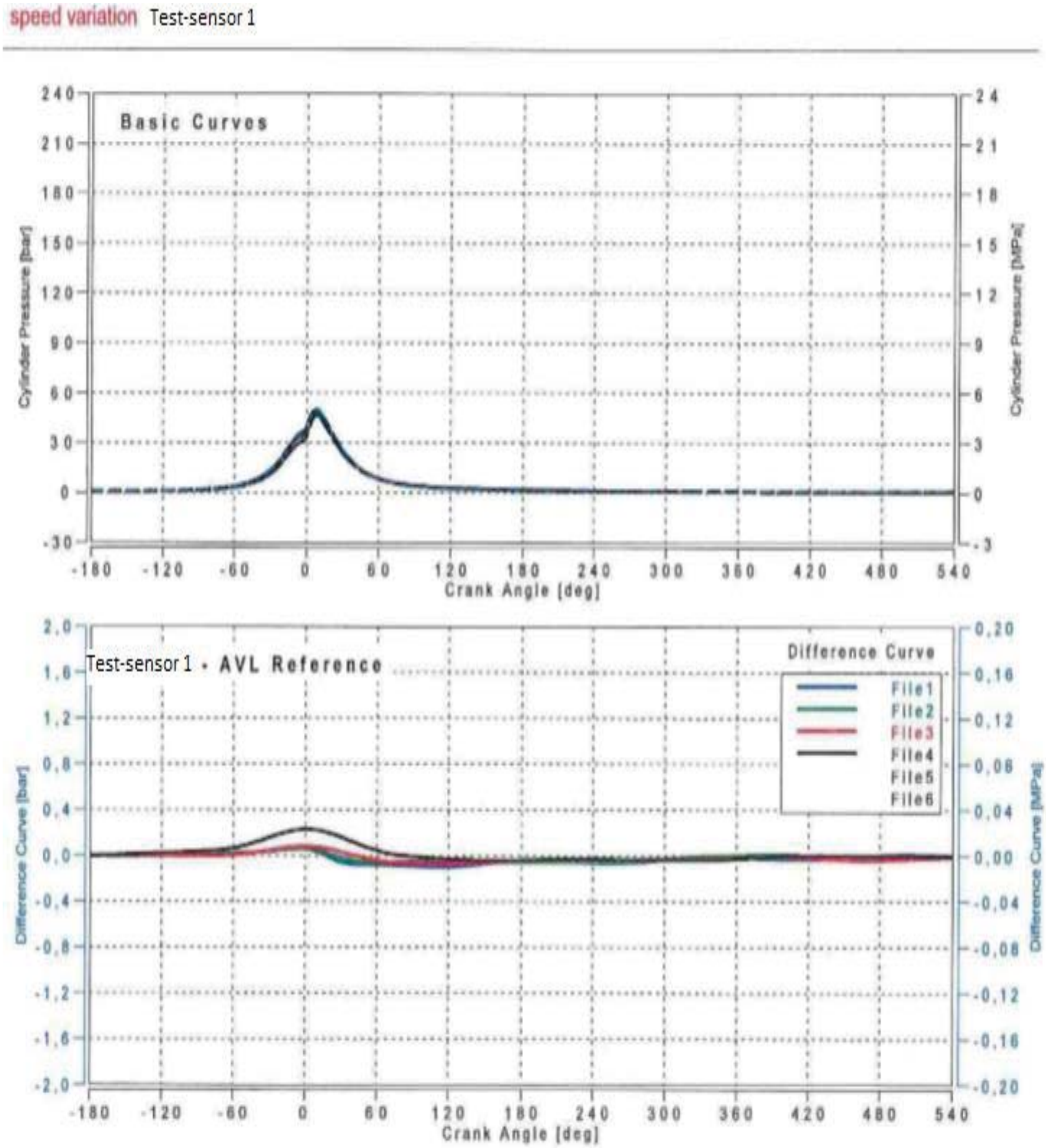
Figure (4.31) - Sensor protocol test-sensor 5 – Load variation.

load variation Test-sensor 6



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	1300	-1,11	36,06	0,02	-0,16	-0,16
File2	1300	4,04	53,05	-0,01	-0,15	-0,15
File3	1300	7,07	64,58	-0,00	-0,03	-0,06
File4	1300	9,99	100,36	0,20	0,01	0,08
File5	1300	14,01	135,78	0,25	-0,08	-0,15
File6	1300	17,87	182,63	0,25	-0,21	-0,23

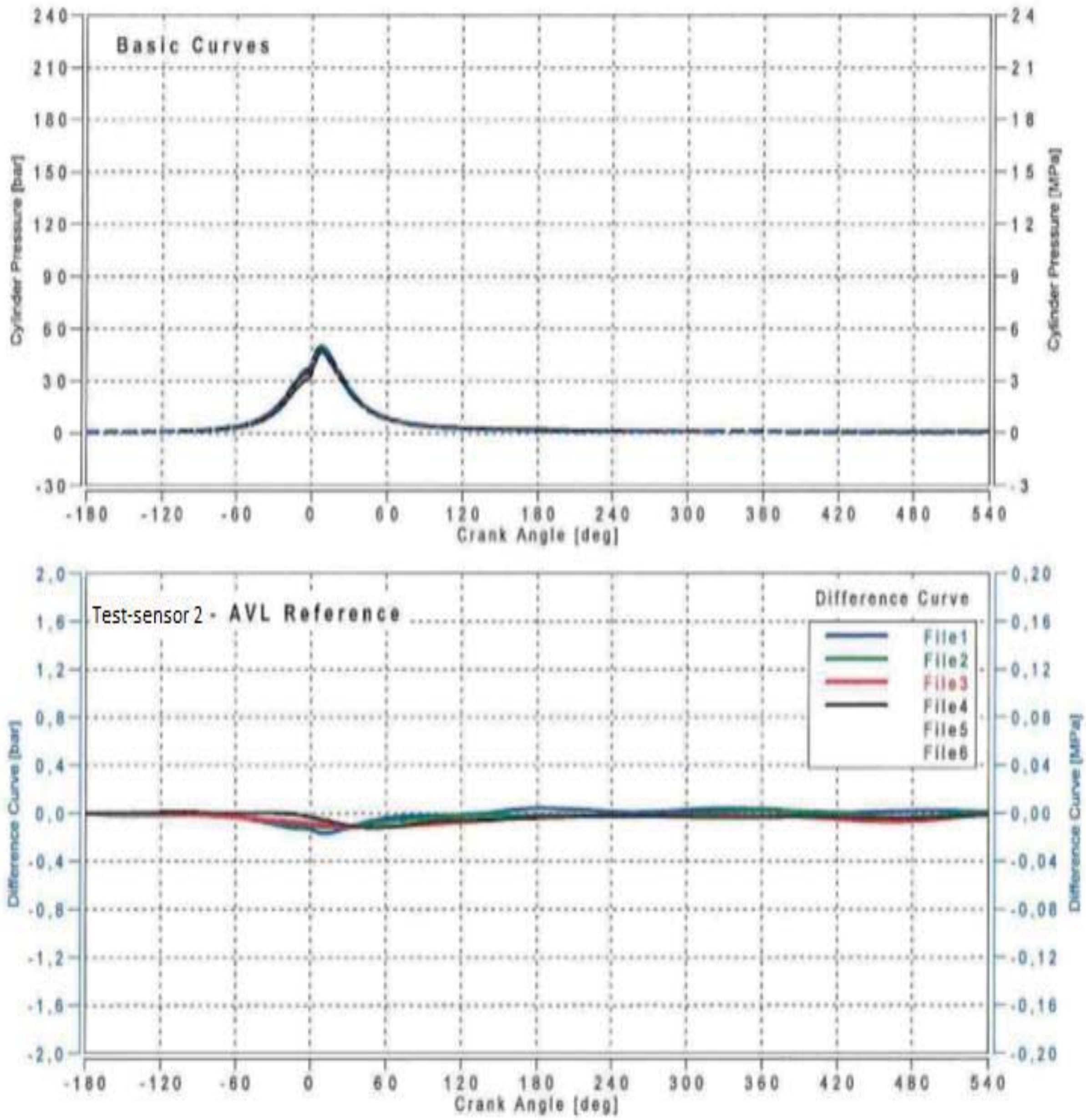
Figure (4.32) - Sensor protocol test-sensor 6 – Load variation.



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP' [bar]	Diff_pmax [bar]	Maximum Deviation' [bar]
File1	600	4,02	49,17	-0,07	0,05	-0,10
File2	1300	4,02	50,41	-0,03	0,05	0,07
File3	2000	4,08	46,53	-0,05	0,08	0,08
File4	2600	3,91	47,30	0,00	0,22	0,23
File5						
File6						

Figure (4.33) Sensor protocol test-sensor 1 – Speed variation.

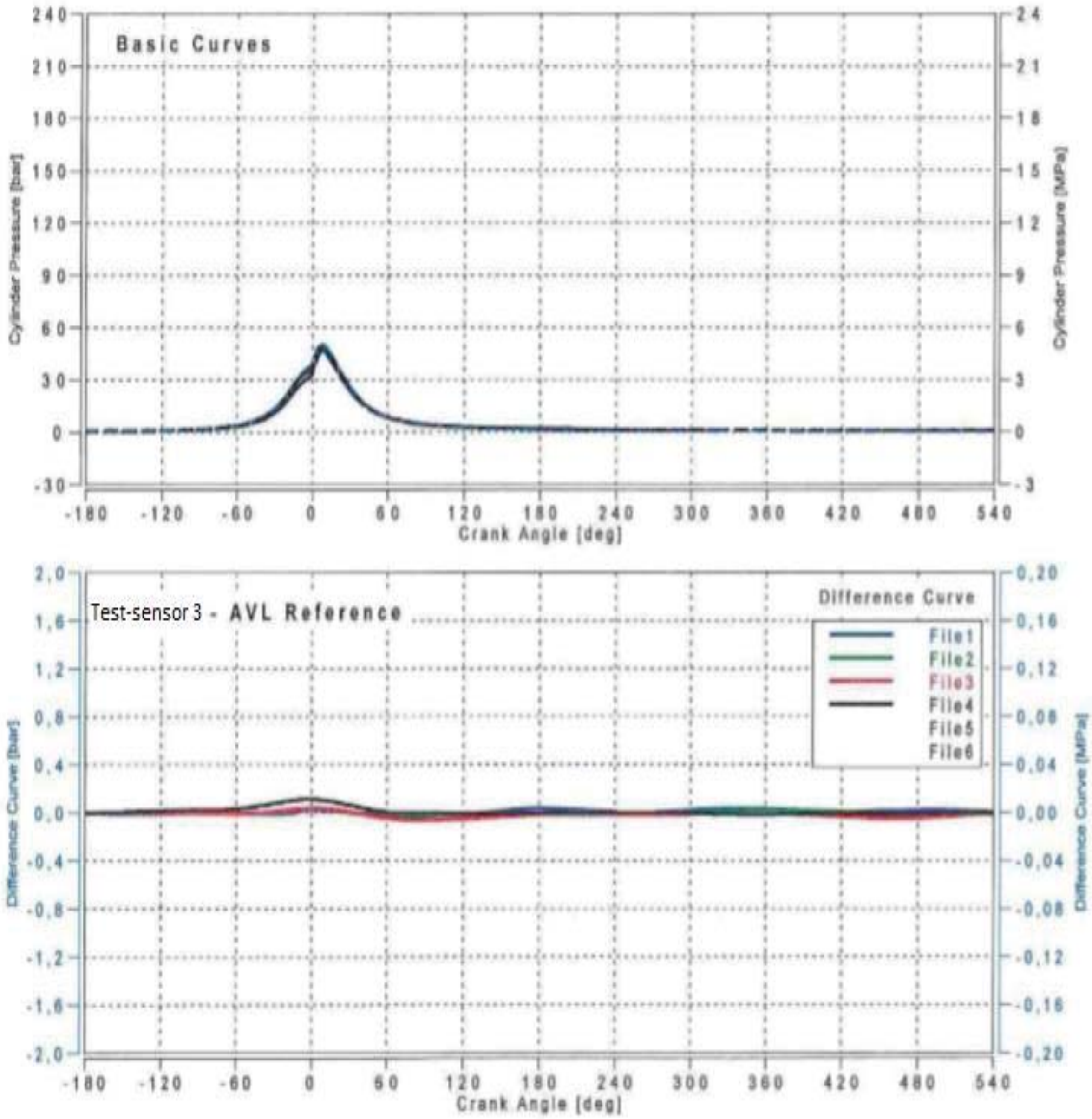
speed variation Test-sensor 2



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	600	4,02	49,17	-0,02	-0,16	-0,17
File2	1300	4,02	50,41	-0,03	-0,11	-0,11
File3	2000	4,08	46,53	-0,10	-0,09	-0,12
File4	2600	3,91	47,30	-0,11	-0,05	-0,12
File5						
File6						

Figure (4.34) Sensor protocol test-sensor 2 – Speed variation.

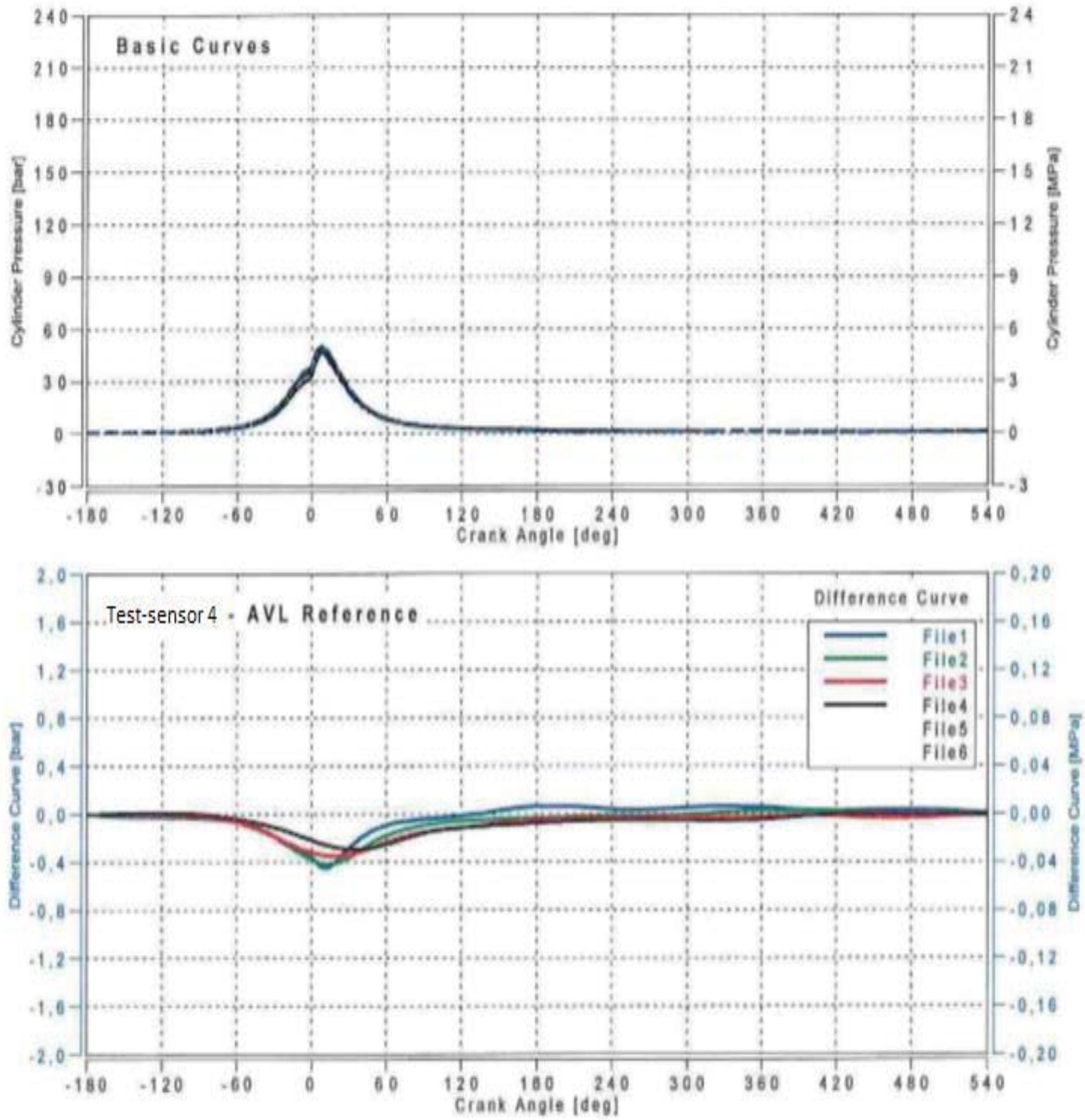
speed variation Test-sensor 3



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	600	4,02	49,17	-0,01	0,02	0,03
File2	1300	4,02	50,41	-0,01	0,04	0,04
File3	2000	4,08	46,53	-0,06	0,03	-0,06
File4	2600	3,91	47,30	-0,03	0,11	0,11
File5						
File6						

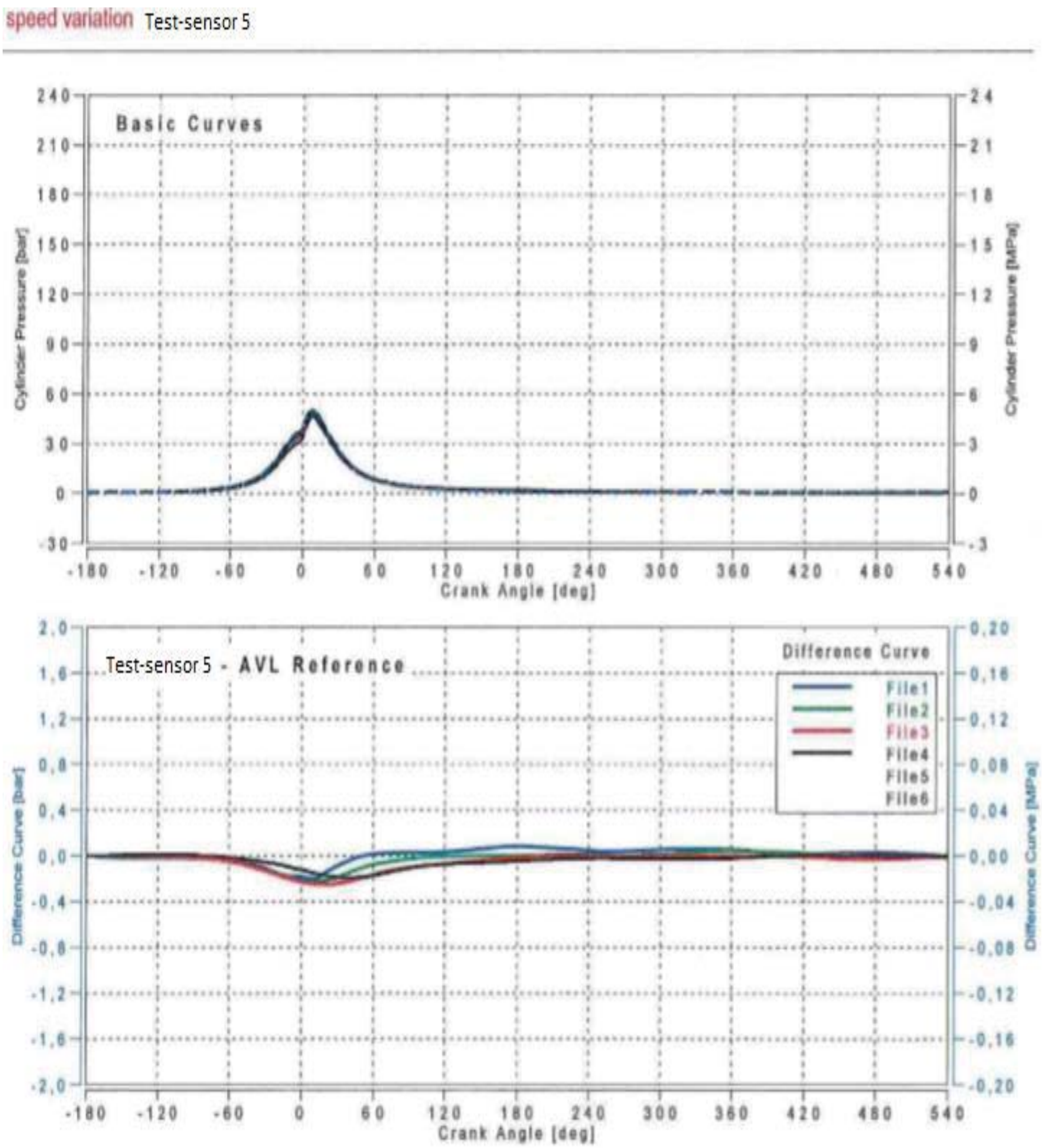
Figure (4.35) Sensor protocol test-sensor 3 – Speed variation.

speed variation Test-sensor 4



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP [bar]	Diff_pmax [bar]	Maximum Deviation [bar]
File1	600	4,02	49,17	-0,04	-0,42	-0,45
File2	1300	4,02	50,41	-0,07	-0,41	-0,42
File3	2000	4,08	46,53	-0,13	-0,34	-0,35
File4	2600	3,91	47,30	-0,13	-0,24	-0,29
File5						
File6						

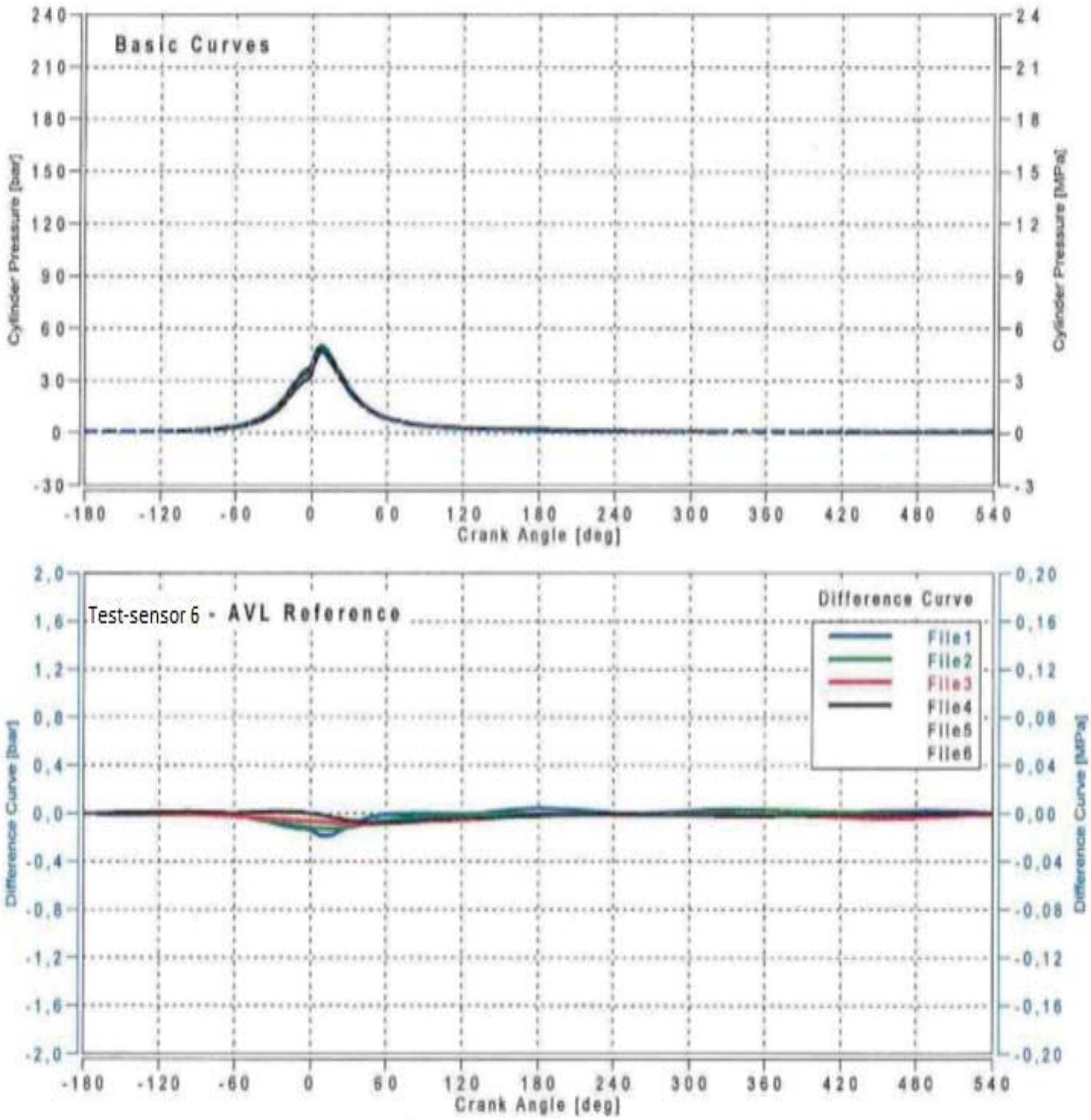
Figure (4.36) Sensor protocol test-sensor 4 – Speed variation.



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP[1] [bar]	Diff_pmax [bar]	Maximum Deviation[1] [bar]
File1	600	4,02	49,17	0,02	-0,20	-0,20
File2	1300	4,02	50,41	-0,02	-0,22	-0,22
File3	2000	4,08	46,53	-0,10	-0,24	-0,25
File4	2600	3,91	47,30	-0,10	-0,14	-0,19
File5						
File6						

Figure (4.37) Sensor protocol test-sensor 5 – Speed variation.

speed variation Test-sensor 6



Results	Speed [rpm]	IMEP_Ref [bar]	pmax_Ref [bar]	Diff_IMEP[1] [bar]	Diff_pmax [bar]	Maximum Deviation[1] [bar]
File1	600	4,02	49,17	-0,00	-0,17	-0,19
File2	1300	4,02	50,41	-0,01	-0,13	-0,13
File3	2000	4,08	46,53	-0,07	-0,07	-0,09
File4	2600	3,91	47,30	-0,07	-0,01	-0,08
File5						
File6						

Figure (4.38) Sensor protocol test-sensor 6 – Speed variation.

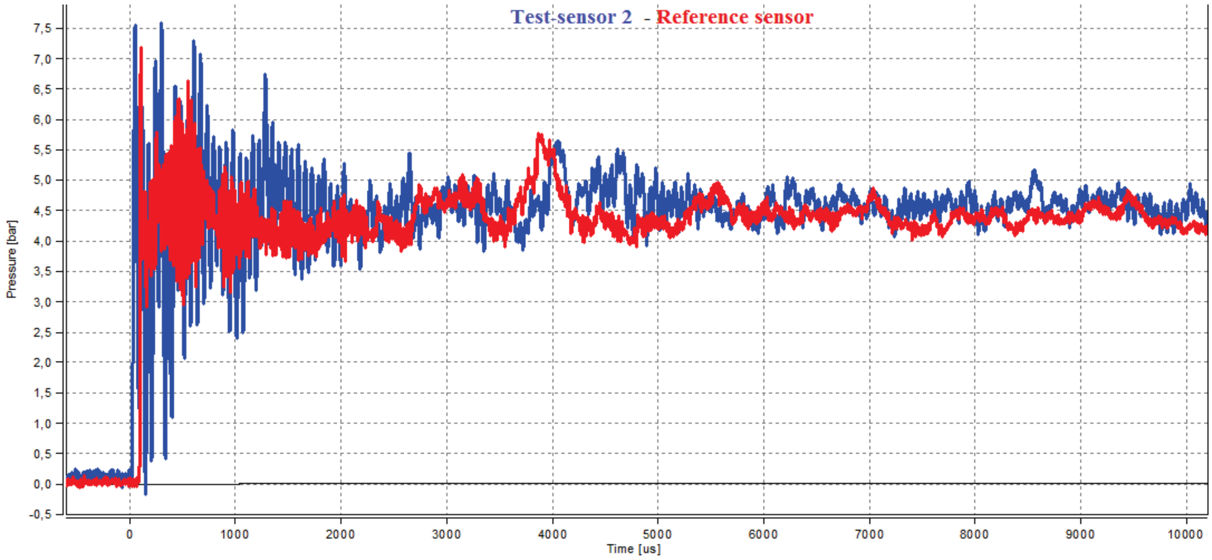


Figure (4.39) – Shock-tube test. Test-sensor 2 – reference sensor, overview graph.

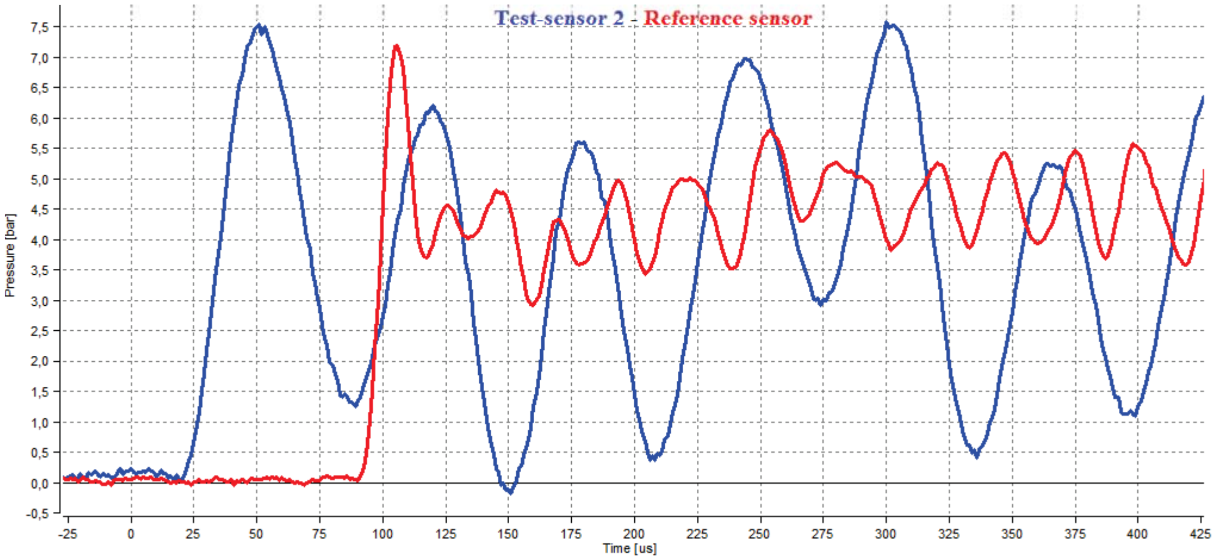


Figure (4.40) – Shock-tube test. Test-sensor 2 – reference sensor, zoomed-in graph.

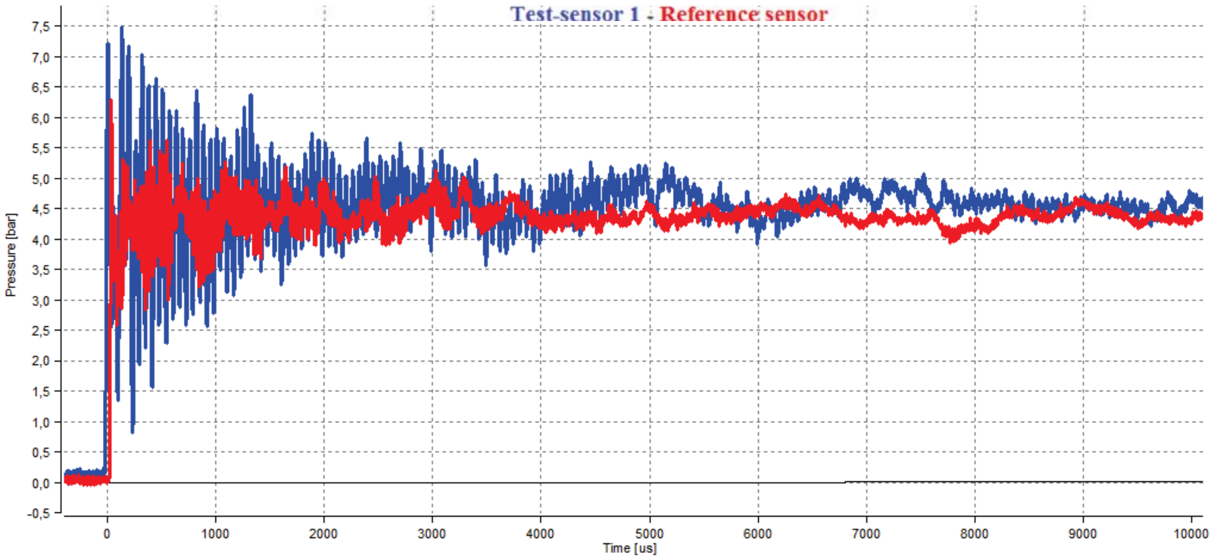


Figure (4.41) – Shock-tube test. Test-sensor 1 – reference sensor, overview graph.

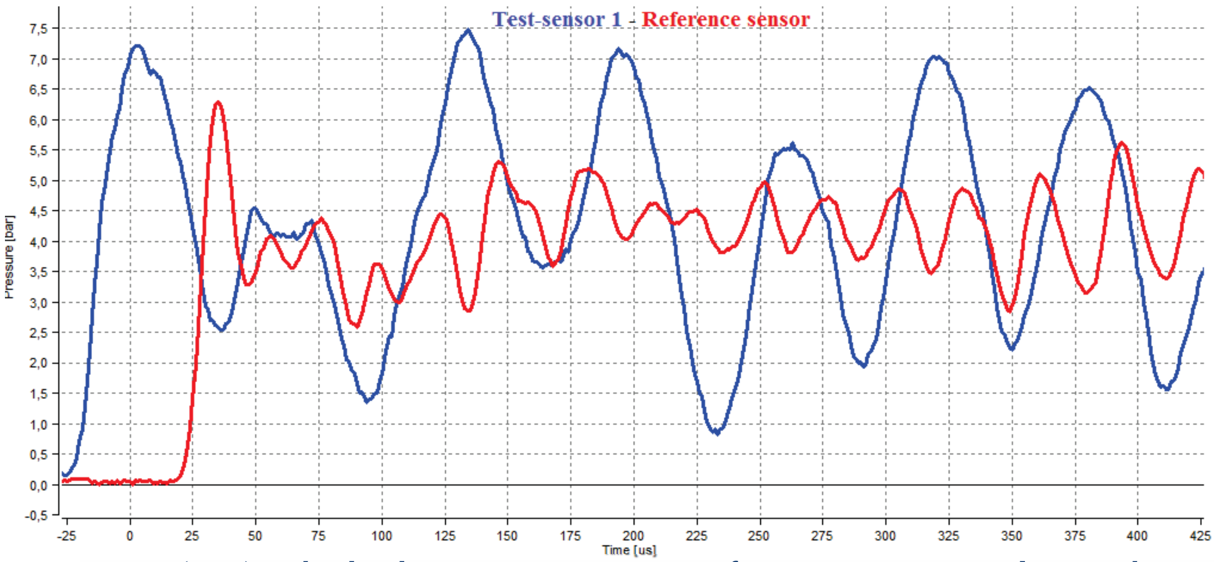


Figure (4.42) – Shock-tube test. Test-sensor 1 – reference sensor, zoomed-in graph.

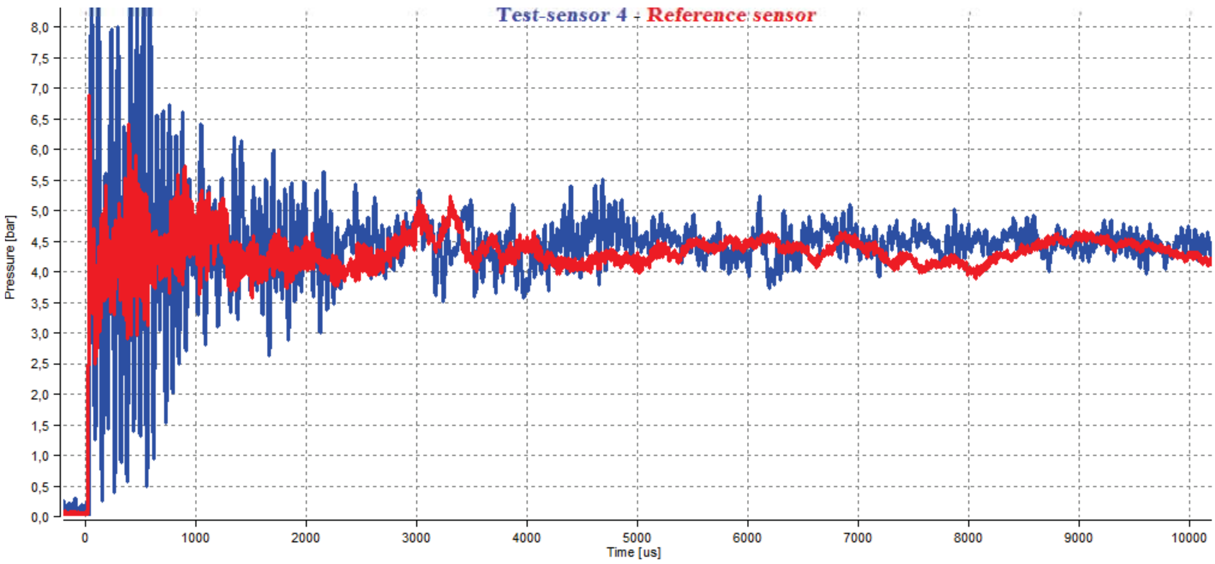


Figure (4.43) – Shock-tube test. Test-sensor 4 – reference sensor, Overview graph.

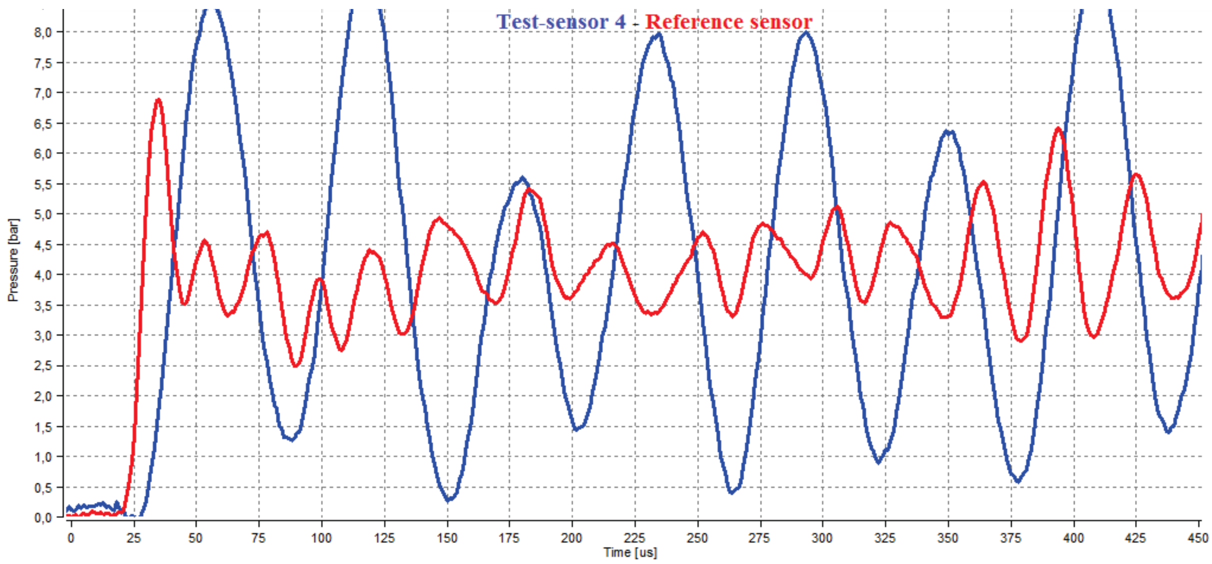


Figure (4.44) – Shock-tube test. Test-sensor 4 – reference sensor, zoomed-in graph.

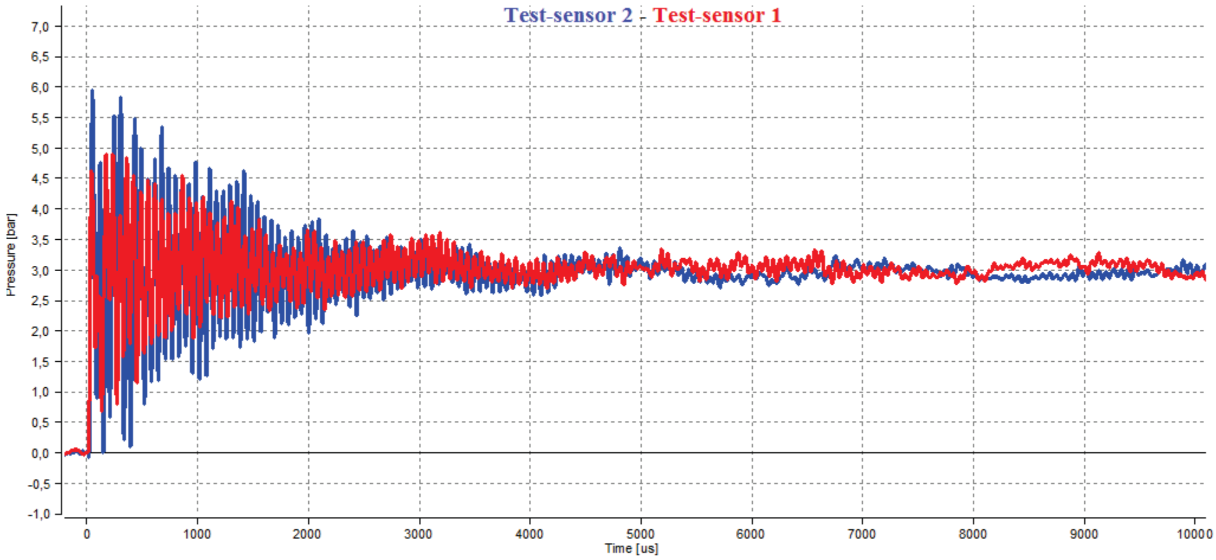


Figure (4.45) – Shock-tube test 2. Test-sensor 2 – test-sensor 1, overview graph 2

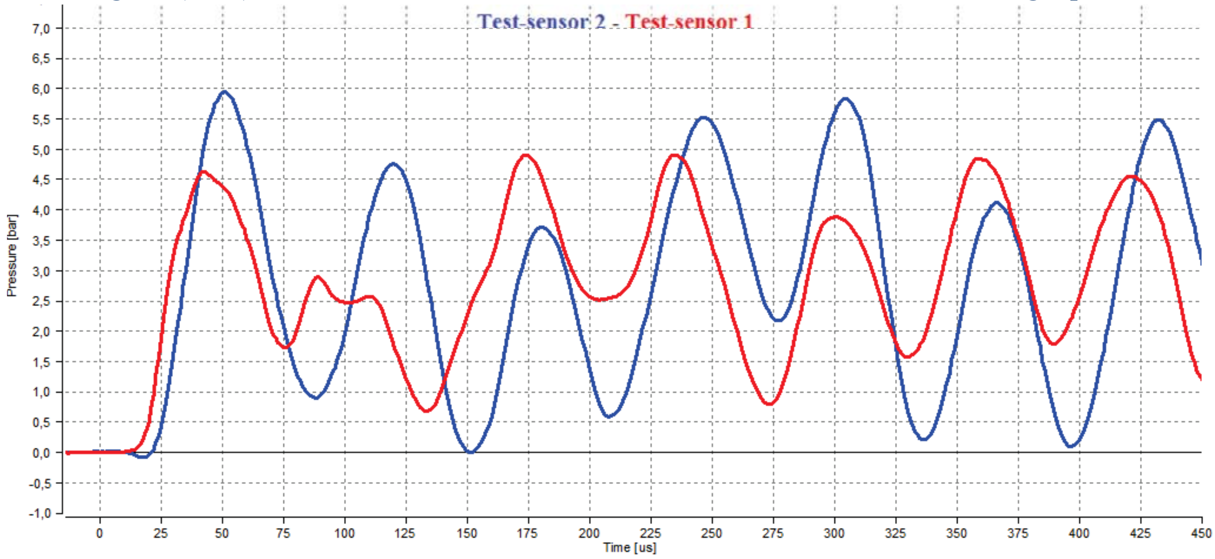


Figure (4.46) – Shock-tube test 2. Test-sensor 2 – test-sensor 1, zoomed graph 2.

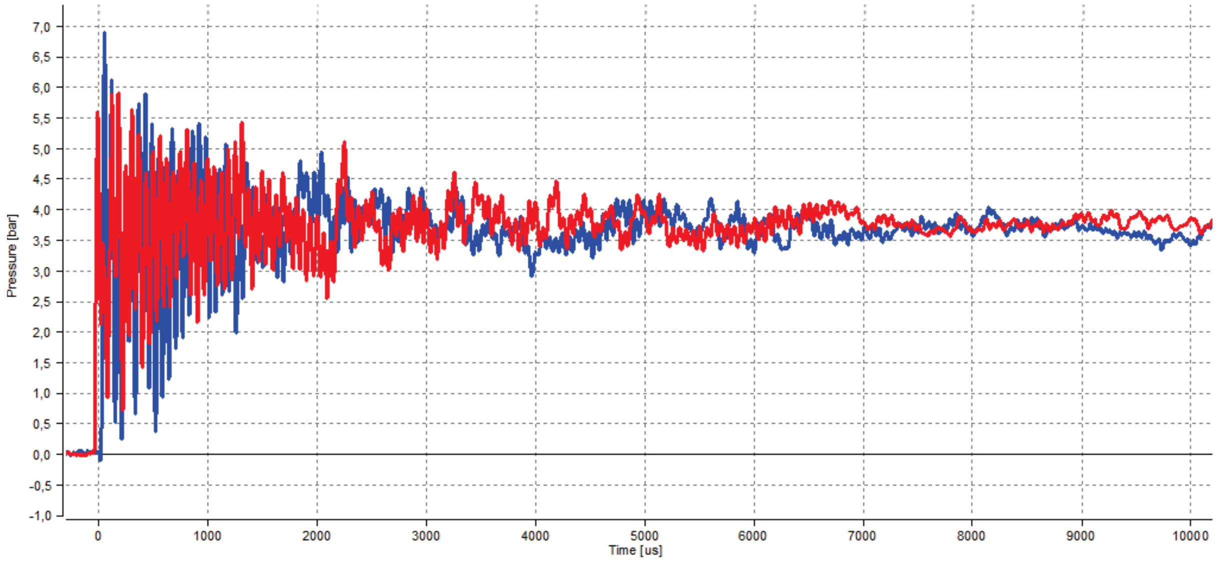


Figure (4.47) – Shock-tube test 3. Test-sensor 2 – test-sensor 1, overview graph 3.

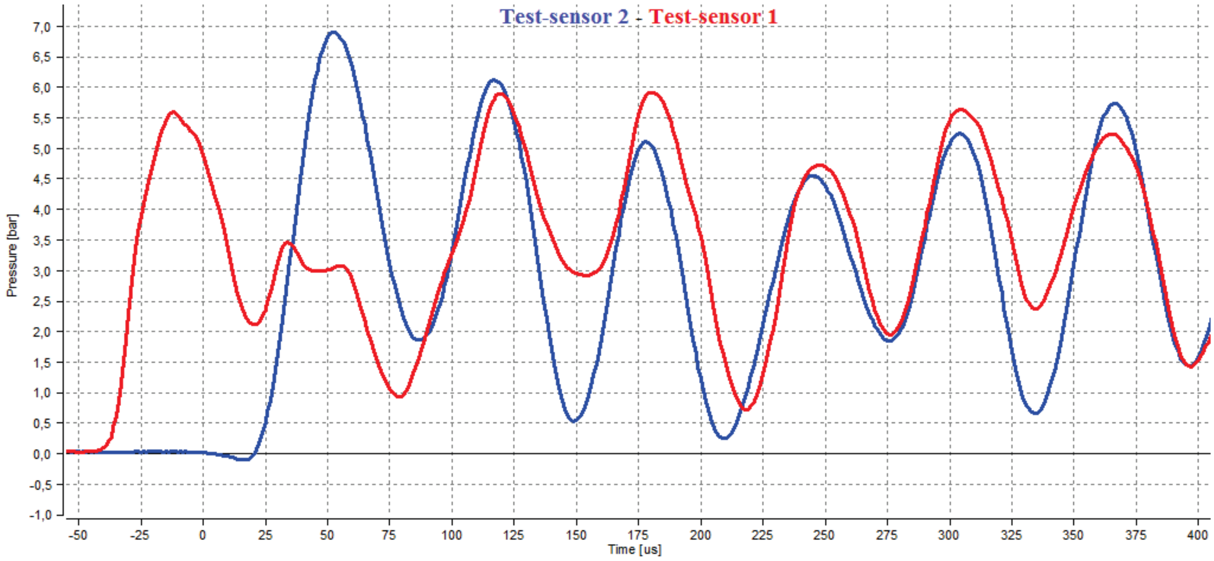


Figure (4.48) – Shock-tube test 3. Test-sensor 2 – test-sensor 1, zoomed graph