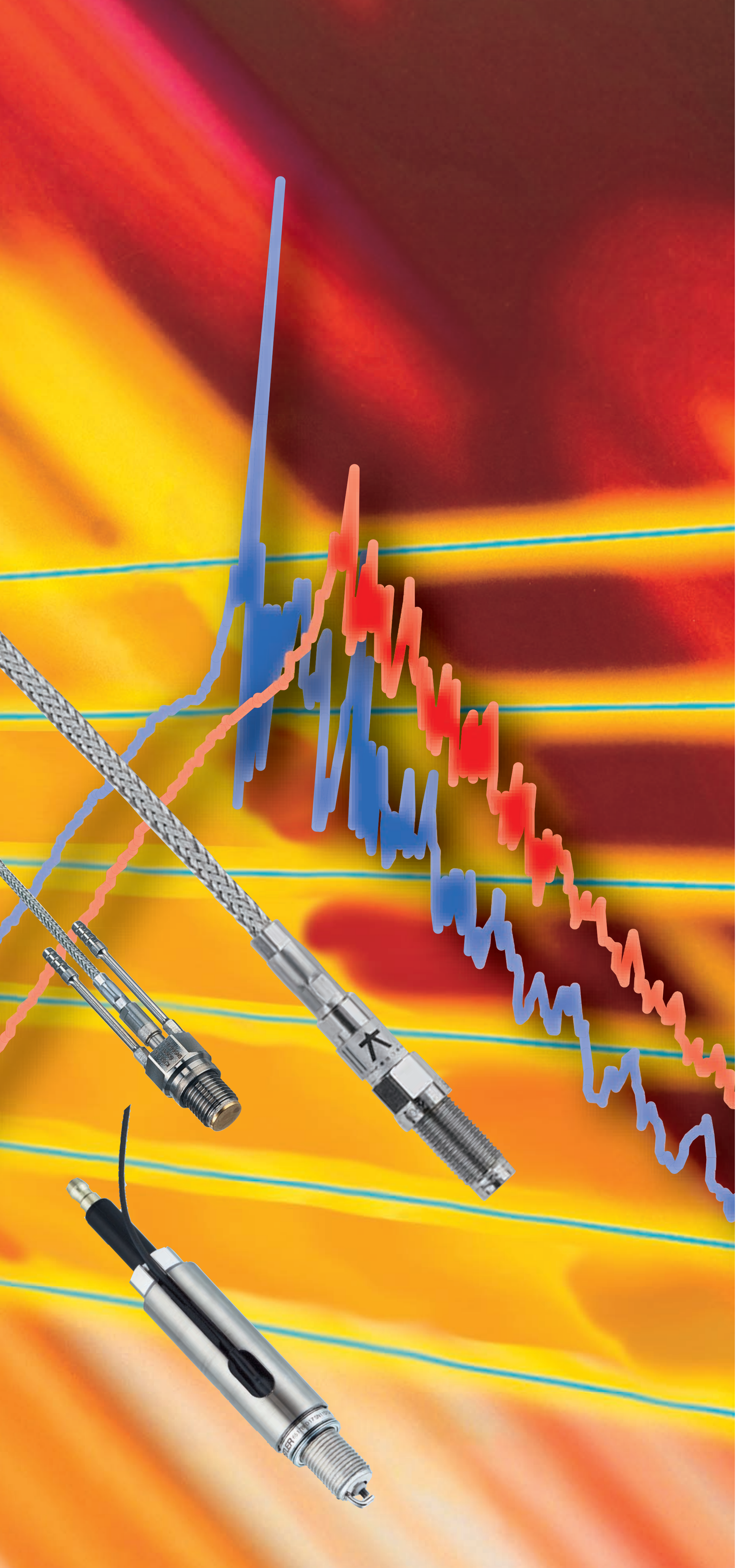

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Pressure Sensors

Pressure Indication During Knocking Conditions

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Content

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1 Abstract

Depending on its frequency and intensity, knocking combustion can cause engine damage due to excessive thermal or mechanical stress on components. During knocking combustion, the cylinder pressure signal is overlaid with high-frequency pressure oscillations. Reliable detection of the knock timing and quantification of the knock intensity based on local measurement of the cylinder pressure demand for particular care, especially when it comes to selecting and adapting the sensor technology and also during the evaluation process using customary knock analysis methods. This publication examines various types of cylinder pressure sensors, how they are installed in the combustion chamber, the effect of sensor positioning and assesses them with regard to accuracy. Finally, on the basis of the test results, recommendations are given for selecting sensors and adapting them within the combustion chamber.

A crucial factor for pressure measurement during knocking combustion is the sensor position within the combustion chamber. The sensor type is of secondary importance; at most, cavities between the combustion chamber and the sensor may influence the measuring signal.

To assess the sensitivity of the knock evaluation algorithms to various mounting positions and sensor types, it is advisable to carry out comparative measurements between different sensor positions and the measuring spark plug.

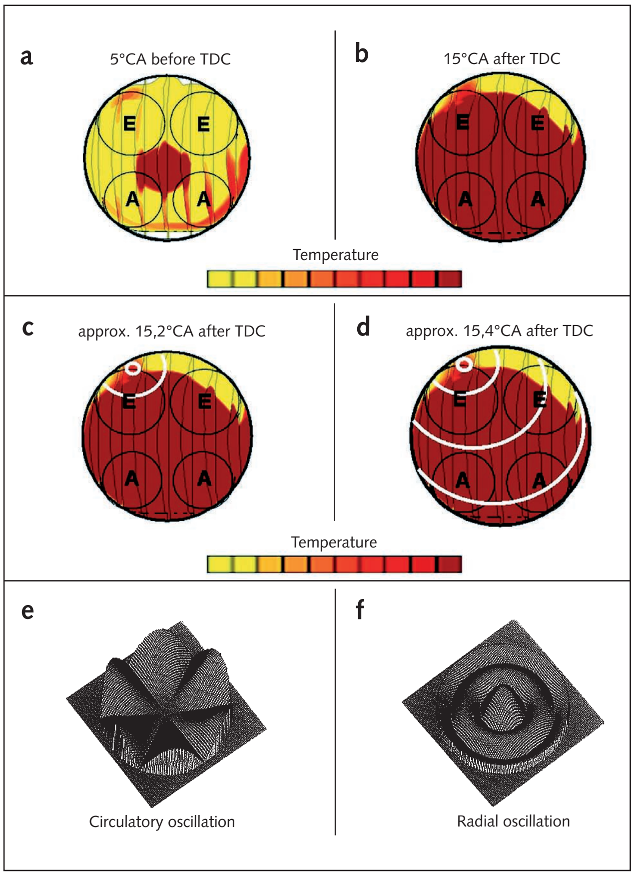


Fig. 1: Flame propagation, end gas zone, exothermal centre, pressure waves and standing waves

2 Introduction

2.1 The Knocking Phenomenon

Spontaneous ignition of unburned fuel mixture in the end gas zone has been identified as the cause of knocking combustion. Figure 1 shows the characteristics of knocking combustion and how these are changing from ignition up to the formation of a standing wave.

Following ignition, the propagation of the primary flame front (Figure 1a and Figure 1b, border line between light and dark cylinder areas) takes place at approx. 25 ms^{-1} ... 70 ms^{-1} starting from the spark plug. Due to a non-central spark plug position and/or the primary flame front being directly influenced by in-cylinder swirl, uneven distribution of spatial combustion of the cylinder charge may occur (Figure 1b). The part of the mixture that remains unburned is called the end gas zone, within which temperature gradients may exist and in which spontaneous ignition is liable to occur (Figure 1c). The existence of exothermal centres is entirely due to inadequate mixture formation, i.e. the inhomogeneous distribution of fuel, air and residual gas.

In the event of spontaneous ignition, if the reaction speed (chemical conversion rate) in the exothermal centre is sufficient, the pressure in the ignition volume may not distribute fast enough over the whole combustion chamber, leading to the formation of a shock wave which propagates at the speed of sound through the surrounding unburnt and already burnt mixture (Figure 1c, Figure 1d). This shock wave is reflected off the walls of the combustion chamber and moves around the combustion chamber again in the opposite direction, similar to an echo.
As a result, complex pressure wave profiles or 'standing waves' in the form of circulatory or radial oscillations may develop (Figure 1e, Figure 1f and Figure 2).

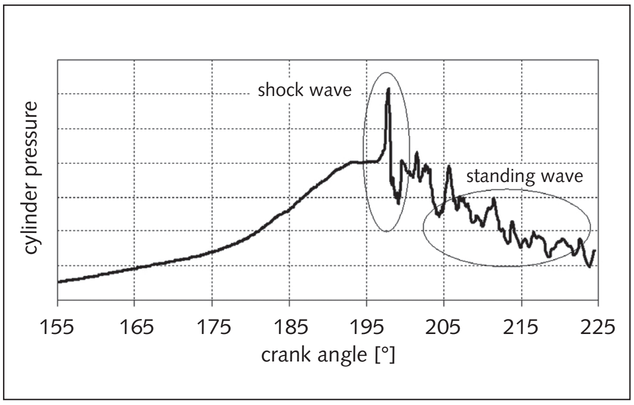


Fig. 2: The standing wave is clearly recognizable from the local pressure peaks (resonance frequency of the first circulatory oscillation = 6,5 kHz)

The areas where these shock waves are reflected are also the regions where the greatest mechanical stresses occur. Typical damage phenomena affect the top land of the piston in particular (as erosion, spalling, etc.). The sensors also experience far greater stress in the reflection area, which can increase the rate of sensor failure.

2.2 Parameters Influencing the Pressure Signal and Effects on the Analytical Methods

Various algorithms are used to determine timing and intensity of knock. Different requirements are made of the signal quality depending on the detection method.
The different methods are essentially based on the following principles [1]:

- Filtering (bandpass filter) of the pressure curve and determination of the maximum amplitude or signal power (variance) in a particular crank angle window
- Derivation (1st or 3rd derivation) of the filtered pressure curve and determination of the maximum value or of the signal power of the derived signal
- Determination of the heating curve, filtering and formation of the 2nd derivation, thereby determining the maximum
- Transformation of the signal into the frequency domain and determination of the amplitudes at characteristic frequencies (e.g. 1st mode of the combustion chamber oscillation) or determination of the signal energy in a defined frequency range

The processes for determining the knock timing rely on a clearly distinguished initial pressure increase. The moment at which the pressure wave reaches the pressure sensor depends on the position of the exothermal centre in relation to the pressure sensor.

The determination of the knock intensity demands representative and accurate measurement of the amplitude of the high-frequency pressure fluctuations, whether one is evaluating the maximum values or the signal power of the pressure signal. The following two factors influence the quality of the high-frequency portion of the pressure signal:

- Position of the pressure sensor in the combustion chamber (representivity):

Accurate measurement of the amplitude of the shock wave and of the subsequent reflected pressure waves largely depends on the position of the pressure sensor in the combustion chamber. The shock wave is detected at the knock centre and in central locations in a representative fashion. In positions close to the wall which lie opposite the exothermal centre, the reflection of the pressure wave causes the pressure to be amplified (due to a 'surging wave'). Positions close to the wall therefore exhibit different shock waves and reflected pressure wave amplitudes depending on the location relative to the exothermal centre.
If standing waves (combustion chamber oscillations) are formed after the wave propagation, the amplitude of the measured oscillation is heavily dependent on the position of the pressure sensor in relation to the corresponding mode (see Figure 1e, Figure 1f).

- Transmission behaviour of the indicating bore (pipe oscillation):

If a pressure sensor cannot be flush-mounted in the combustion chamber, but is set back from the surface of the combustion chamber, pipe oscillation may be generated in the resulting indicating bore. The longer such an indicating bore is, the lower the resonant frequency of the resulting pipe oscillation.
For example, if a front-sealing sensor is installed in a standard indicating bore, the result will be a pipe resonance with a resonant frequency of 30 to 45 kHz. This is overlaid on the knock signal and may lead to misinterpretation of the knock amplitude and signal power.

3 Instrumentation

3.1 Sensors for Combustion Pressure Measurement

With their wide measurement range, minimal thermal drift and high natural frequency, piezoelectric pressure sensors are the standard measurement technology for pressure indication on internal combustion engines. Today many different sensor types are available, and pressure sensors with suitable characteristics can be used depending on the specific measurement task.

Cooled or uncooled pressure sensors and also measuring spark plugs are typically used in spark-ignition engines, as shown in Table 1.

Sensor Type	Advantages	Disadvantages
Cooled pressure sensor, e.g. Type 6061B (shoulder sealing)	- high capacity - high temperature resistance - flush-mounted installation - no indicating bore[1] - no pipe oscillation	- bulky (≥ M8) - cooling system
Uncooled pressure sensor, front-sealing e.g. Type 6052C	- compact (≥ M5) - easy to install - front-sealing: good sensitivity stability with alternating load operation - long service life	- front-sealing sensor: indicating bore[1] - pipe oscillation possible - lower accuracy
Measuring spark plug, e.g. Type 6118A	- no additional bore - no change to geometry - quickly interchangeable - very little pipe oscillation - long service life	- front-sealing measuring element cavity in front of the diaphragm[2] - low sensitivity - lower accuracy - must be adapted to individual engine

[1] A dead volume in front of the sensor diaphragm is referred to as the indicating bore if the sensor is not flush-mounted in the combustion chamber.
[2] If a sensor is shoulder-sealing and flush-mounted in the combustion chamber but the sensor diaphragm is recessed, the resulting dead volume is referred to as a cavity in front of the diaphragm.

Table 1: Advantages and disadvantages of different types of combustion pressure sensors for use in spark-ignition engines

The heat transfer into the combustion chamber walls and into the sensor diaphragms, especially during knocking combustion, requires highly heat-resistant sensors. The integrated cooling (water cooled sensors) enables shoulder-sealing installation, thus allowing the sensor diaphragms to be installed front-flush with the combustion chamber wall (see Figure 3a, Figure 3c).

The use of multi-valve technology means that space is increasingly scarce in the cylinder heads of modern engines, so that often it is no longer possible to install cooled sensors, and uncooled sensors have to be used to a higher degree.

Uncooled sensors offering high accuracy require a front seal (Figure 3b), so that the heat conducted to the sensor via the diaphragm can be given off directly to the cooled combustion chamber wall. However, the front seal design has the disadvantage that an indicating bore exists between the combustion chamber and the diaphragm, which can cause pipe oscillations and corresponding uncertainty of the measuring signal.

A measuring spark plug gives quick and efficient access to the combustion chamber and means that any engine can be set up for indicating measurements in a short time.

There is no need to create a separate access to the combustion chamber, there is no change to the combustion chamber geometry and the measuring spark plug is quickly interchangeable. The disadvantages are lower accuracy and the effort required to match the thermal value and electrode geometry [3].

As illustrated in Figure 4, the pressure sensor is installed very close to the combustion chamber and fixed with a banjo bolt.

By optimizing the cavity and the hole, the acoustic resonance frequency can be made as high as possible (resonance frequency typically >60 kHz) so that it lies outside the frequency range of significance for engine measurements.

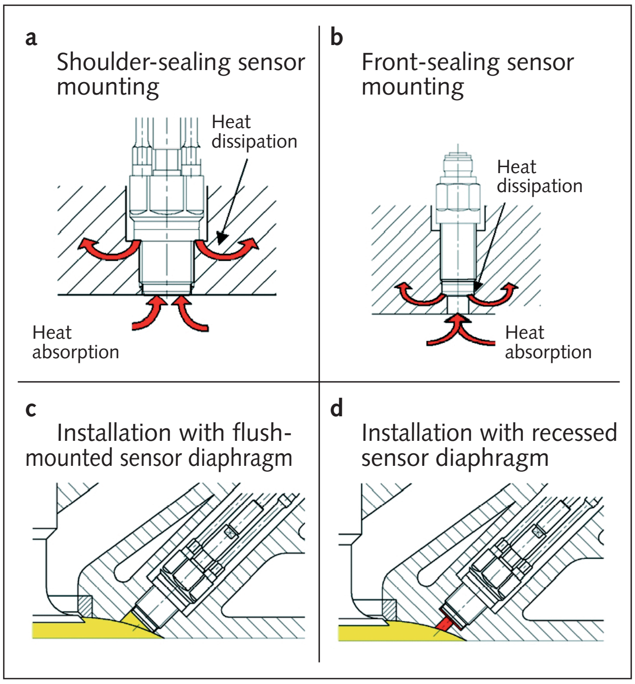


Fig. 3: Mounting methods for cylinder pressure sensors

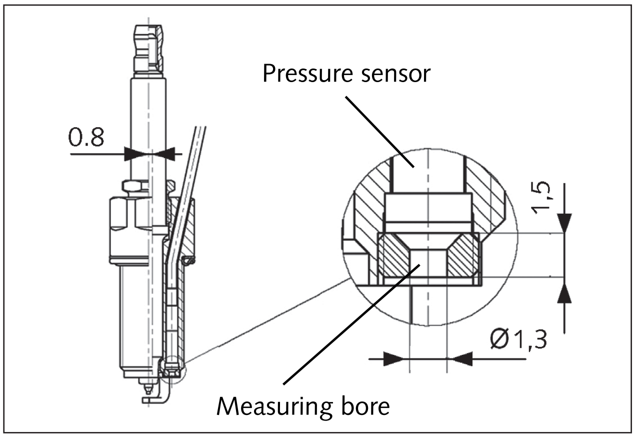


Fig. 4: Design of measuring spark plug, Type 6118A

3.2 Test Set-Up, Sensors and Data Acquisition

The measurements were carried out on a modern, four-cylinder, spark-ignition engine (V_h = 0,5 l, 4 valves per cylinder) with direct injection in homogeneous charge operation. On each cylinder, one intake port is designed as a swirl port, the other as a filling port. At low engine speed the filling port is closed by a valve near the cylinder head; by continuously opening the filling port with rising load, the swirl is reduced in favour of filling.

Figure 5 shows the arrangement of the different access points for the pressure sensors. The cylinder pressure measurement takes place in five positions with the piezoelectric pressure sensors. The characteristics of the access bores for pressure sensors and the sensors used are summarized in Table 2.

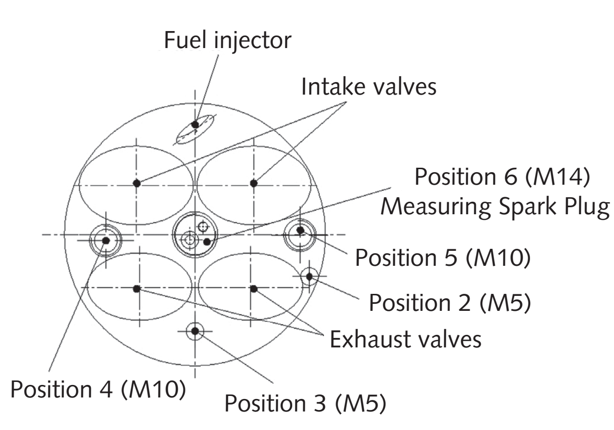


Fig. 5: Arrangement of sensors and associated position numbers in the combustion chamber

The signals from the pressure sensors were processed by Type 5011 charge amplifiers and recorded in the measuring system (Smetec Combi Pro) at 0,1 °CA. No filters or other forms of signal conditioning were used. An acceleration sensor (Kistler Type 8742A10, resonant frequency 100 kHz, with Kistler Type 5134A Piezotron coupler) was mounted at a rigid point on the crankcase.

This signal was used in addition to the cylinder pressure signal to assess the knock behaviour of the individual combustion cycles.

Figure 6 compares the same combustion cycle at different crank angle resolutions. Obviously the greatest possible resolution is needed for accurate detection of knocking combustion cycles in typical spark ignition engines. As soon as the resolution is reduced from 0,1 °CA to 0,2 °CA, the peak pressure signal is out by 15 bar. Where the resolution is reduced to 1 °CA, reliable detection of a knocking combustion cycle is no longer guaranteed, which can have serious implications.

It is important to point out that, in order to compare knocking combustion cycles, all cycles must be measured with the same resolution. In the example shown the engine speed is 5 000 1/min. At lower speeds the comparison is more critical due to the fact that the pressure peaks and the oscillations have the same time scales, but the sampling rate is lower.

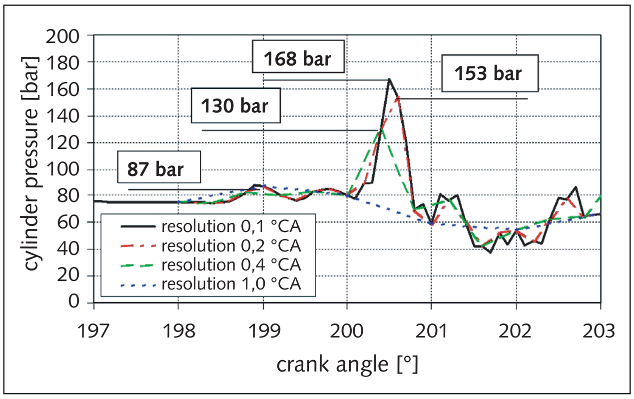


Fig. 6: Effect of different resolutions on measuring signal at 5 000 1/min

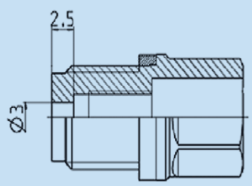
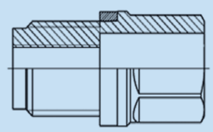
	Pressure Sensors Used and Type of Installation		
Position 2 Position 3	- Type 6053C, front-sealing, indicating bore Ø 3 mmx2,5 mm in cylinder head		
Position 4	- Type 6061B, shoulder-sealing, flush-mounted - Type 6052C, front-sealing in adapter, indicating bore Ø 3 mmx2,5 mm present (Figure on the top right) - Type 6052C, shoulder-sealing in adapter, flush-mounted (Figure on the bottom right)	Adapter for Sensor Type 6052C fs	
Position 5	- Type 6081AU37 shoulder-sealing in adapter, flush-mounted, cavity in front of the sensor diaphragm present (banjo bolt same as in Type 6118A, Figure 4)	Adapter for Sensor Type 6052C ss	
Position 6	- Type 6118A (Figure 4) - Type 6117B		

Table 2: Access points in the combustion chamber and used sensor types

4 Measurement Results and Discussion

Within a research project (FVV Project no. 816 "Extreme knocking" of Forschungsvereinigung Verbrennungskraftmaschinen e.V.), in which the knocking behaviour of a production engine was investigated, the engine was equipped not only with pressure indicating instruments but also with extensive optical measuring equipment. This permitted examination of the primary flame propagation, detection of the respective knock centres and determination of the propagation directions and propagation speeds of the reaction fronts. Two reference points at full load (3 000 1/min and 5 000 1/min) with different knocking behaviours were selected.

At both operating points it was found that the knock centres, during cycles with damage relevant knocking amplitudes greater than 20 bar, were in stable positions in the combustion chamber. The 3D-CFD simulation revealed, at the identified principal knock centres of the reference points, a local temperature increase caused by inhomogeneities of the mixture. The 5 000 1/min full load operating point with extreme knocking behavior exhibits a far larger end gas zone at the moment of knock, which proved to be the primary parameter influencing the knocking behaviour [2].

Based on the finding that knocking is a stochastic process that is subject to strong cyclical fluctuations, a selection of measurements was first made (Table 3) in order to create a representative basis of comparison. From the four different measurements taken at 3 000 cycles, based on the signal from the acceleration sensor, 20 severe knocking events were chosen. In this way it was possible to identify a repeatable pattern in the signal profile and select one representative combustion cycle per measurement, which then forms the basis for the sensor comparison.

Measure-ment	Cycle	Position 4, sensor type	Position 5, sensor type	Position 6, sensor type
M 3.2	230	6061B	6061B	6118A
M 5.1	2533	6081AU37	6061B	(standard spark plug)
M 6.1	2181	6052C ss[1]	6061B	(standard spark plug)
M 7.1	1159	6052C fs[1]	6061B	(standard spark plug)
[1] Installation ss = shoulder-sealing, fs = front-sealing				

Table 3: Selected representative measurements for sensor assessment and related sensor positions

This procedure is preferable to a statistical evaluation, as any processing of the signals such as averaging or smoothing will make the result less meaningful. Figure 7 shows the representative combustion cycles measured in position 5 with watercooled sensor Type 6061B.

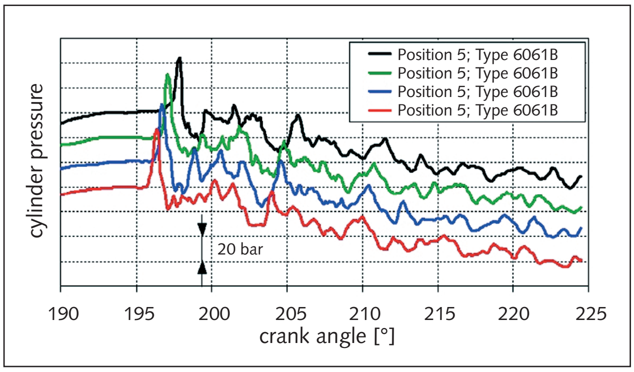


Fig. 7: Comparison of cylinder pressure curve of representative combustion cycles obtained from different measurements. Cylinder pressure measured at position 5 with sensor Type 6061B. The pressure curves are shown with an offset of 20 bar for a better comparison

At 5 000 1/min full load this engine has a positionally stable exothermal centre in the end gas area which causes severe knock events. In the combustion cycles selected for sensor characterization, the knock centre is in the area of the intake valve close to the wall near sensor position 4 (see Figure 1c and Figure 5). According to [2] the amplitude of the first pressure wave is directly proportional to the volume of the exothermal centre, conversely the delay in the pressure rise is determined by the temperature in the exothermal centre. The size of the exothermal volume of the combustion cycles observed in Figure 7 is more or less constant. This is manifested in a similar signal characteristic in terms of amplitude, duration of combustion chamber oscillation and its attenuation behaviour. This satisfies requirements necessary to be able to compare measurements with different sensors at different combustion chamber positions.

4.1 Influence of Sensor Position on the Measured Pressure Signal

The measurements clearly show that the measuring position in the combustion chamber is of primary importance for correct measurement of the physical phenomenon of knocking (timing of the event, amplitude of the pressure wave). Two locations can be compared.

Sensor Position Near the Cylinder Wall

To assess the influence of position, the representative combustion cycle 230 is analysed in measurement 3.2. Figure 8 shows the cylinder pressure curve measured in position 4 and position 5 with sensor Type 6061B, and those with measuring spark plug Type 6118A arranged centrally.

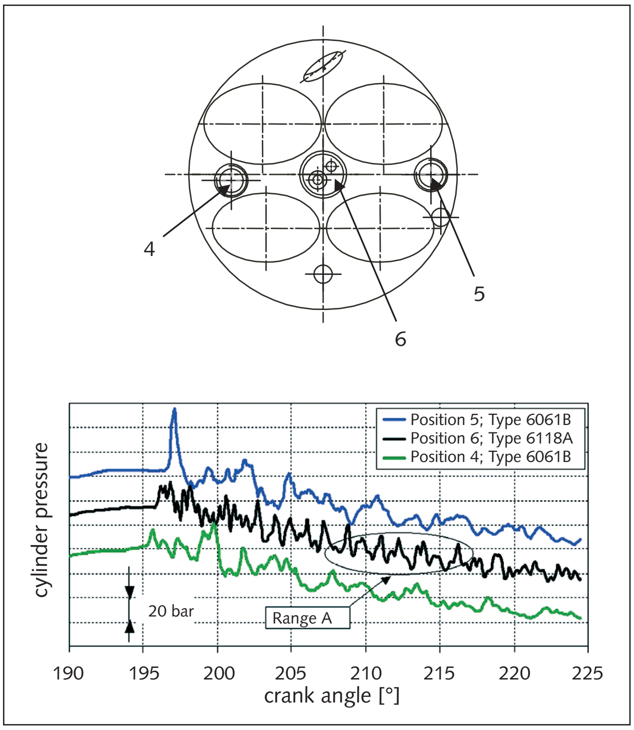


Fig. 8: Comparison of cylinder pressure curve measured at different positions. Position 4 and position 5 sensor Type 6061B; position 6 sensor Type 6118A. Range A discussed in section 4.2

The difference in the case of the first pressure rise is obvious and corresponds to the observations in [6]. Position 4 is near the knock centre, whereas position 5 lies on the opposite side of the combustion chamber. The amplitude of the first pressure wave becomes stronger with increasing proximity to the wall. The first pressure rise of the measuring spark plug Type 6118A in central position 6 is equal to that of the signal measured in position 4.

In order to obtain a good representivity of the first shock wave, the pressure sensor should not be installed near the cylinder wall. The proximity of to the wall causes, due to reflection, increased amplitude of the measured pressure. Moreover, the amplitude of the first shock wave is enhanced by different extents for different knock centres.

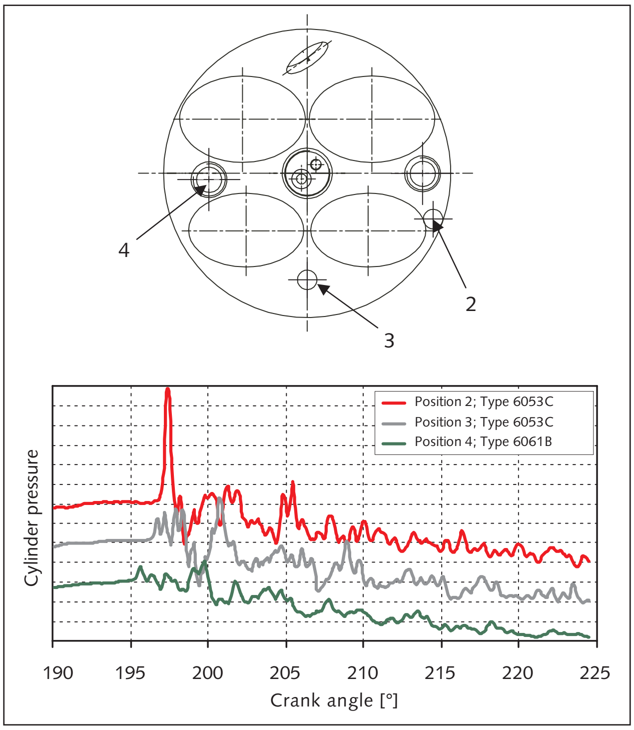


Fig. 9: Comparison of cylinder pressure curve measured at different positions. Position 2 and position 3 sensor Type 6053C (in squish-gap); position 4 sensor Type 6061B

Sensor Position in the Squish-Gap

To investigate the effect of squish-gap, the representative combustion cycle 230 in measurement 3.2 is considered again. In Figure 9 the cylinder pressure is measured with sensor Type 6061B in position 4 and sensor Type 6053C in both positions 2 and 3. The latter positions are situated in the squish-gap area.

The amplitude enhancement of the shock wave depends on the relative sensor position with respect to the position of the knock centre. The pressure signal in position 4 is measured in the combustion chamber without restraints; on the other hand, in position 2 and position 3, the amplitude of the shock wave is increased by the squish-gap geometry and the proximity of the cylinder wall. The squish-gap length and the wall proximity influence the amplitude enhancement, so the measured pressures in position 2 and position 3 are different. In general, the highest pressure amplitudes are expected in the region of the top land of the piston, as the amplification due to reflection at the cylinder wall and the squish-gap geometry are unfavourable.

A central measuring position in the combustion chamber provides a representative measurement for different knock centres and thus offers the greatest safety margin in terms of amplitude enhancement, as knocking always occurs in the area close to the cylinder wall. A centrally located measuring spark plug is therefore ideal for pressure measurement, as it will register hardly any enhancement of amplitude of the first pressure wave, regardless of the knock centre. Moreover, each cylinder can be analyzed from the same position, allowing direct comparison of the measurement results.

4.2 Influence of Sensor Type and Indicating Bore

The sensor type is of secondary importance; at most, cavities between the combustion chamber and the sensor may influence the measuring signal. To investigate the effect of sensor type and indicating bore, using the selected combustion cycles, the differences in pressure characteristics measured at position 4 are now presented.

Figure 10 shows the pressure characteristics of combustion cycles of different measurements. Whereas the signal of the recess mounted sensor was measured with a front-sealing (fs) sensor Type 6052C, the other three pressure curves were recorded with sensors flush-mounted in the combustion chamber (Type 6061B, Type 6052C shoulder-sealing (ss), Type 6081AU37).

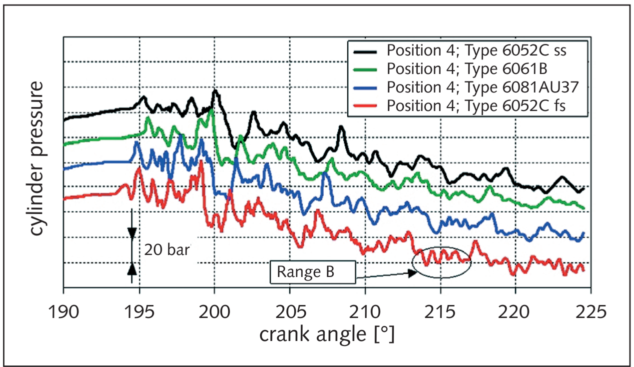


Fig. 10: Comparison of cylinder pressure curve of representative combustion cycles obtained from different measurements. Cylinder pressure measured at position 4, sensor Type 6061B; sensor Type 6081AU37; sensor Type 6052C shoulder-sealing; sensor Type 6052C front-sealing

The amplitude of the first shock wave increases slightly in the case of sensors with an indicating bore or a cavity before the diaphragm. Figure 10 shows a prime example of this situation: both flush-mounted sensors Type 6061B and Type 6052C ss measure a similar pressure characteristic upon the occurrence of a similar shock wave. If, on the other hand, the measuring signal of a flush-mounted sensor is compared with that of a sensor with indicating bore (e.g. comparison of Type 6061B with Type 6052C fs in Figure 10), then only the pressure signal of the flush-mounted sensor shows the Type 6052C pressure actually existing in the combustion chamber at this location correctly. In the case of the sensor with indicating bore, the amplitudes are slightly increased.

The amplitude enhancement depends on the dimensions of the indicating bore [4]. The effect of a cavity before the diaphragm is evident in the comparison of pressure signals of sensors Type 6061B and Type 6081AU37. Here too, there is a slight falsification of the pressure signal due to the cavity in the case of sensor Type 6081AU37.

The error due to the installation situation becomes visible in the spectral power density. Figure 11 compares the spectral power density measured with sensor Type 6061B with the result obtained with sensor Type 6052C in a front-sealing installation.

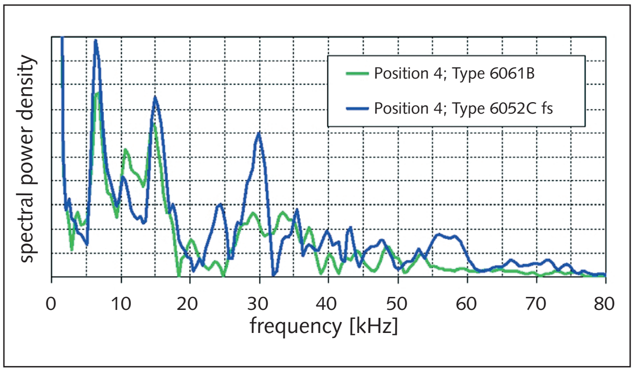


Fig. 11: Spectral analysis of cylinder pressure signal of representative combustion cycles from different measurements. Cylinder pressure measured at position 4. Sensor Type 6061B; sensor Type 6052C front-sealing

The calculated frequencies of the combustion chamber oscillation [2] are 6,5 kHz, 11,1 kHz and 15,5 kHz for circulatory oscillation, which can be detected very well (Figure 11), whereas the resonant modes of the radial combustion chamber oscillation at 13,1 kHz, 19,0 kHz and 23,1 kHz do not appear as additional peaks in the power density.

The indicating bore, needed for the front-sealing mounting of the sensor Type 6052C, causes pipe oscillation. Figure 11 shows a sharp increase in power density at a frequency of 30 kHz as well as in the high frequency range around 57 kHz. These high-frequency components are also seen in the part of Figure 10 marked as range B.

Figure 12 compares the spectral power density of sensors Type 6061B and Type 6118A.

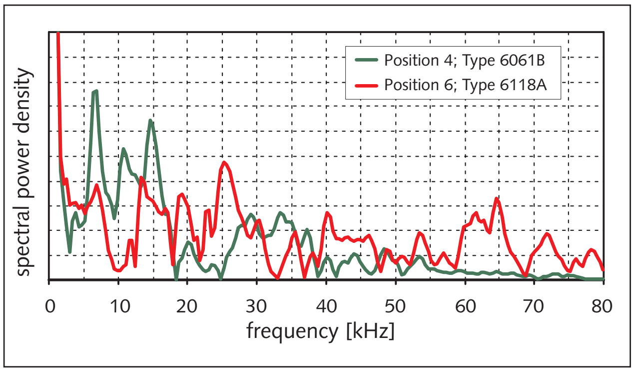


Fig. 12: Spectral analysis of cylinder pressure signals measured at different positions, representative combustion cycle. Position 4 sensor Type 6061B; position 6 sensor Type 6118A

Whereas sensor Type 6061B is flush-mounted in the combustion chamber, measuring spark plug Type 6118A has a cavity before the sensor diaphragm.
In view of the central location of the measuring position, the circulatory oscillations are not detected with the spark plug sensor. However, it is also apparent that the measuring spark plug Type 6118A has a resonance at high frequencies around 65 kHz caused by the cavity before the sensor. High frequencies are also evident in the pressure signal of the measuring spark plug, highlighted as range A in Figure 8. The power density of sensor Type 6061B, arranged in position 4, clearly shows the combustion chamber oscillations mentioned above.

Flush-mounting of the sensor with a high natural frequency is preferable, regardless of how the data is further processed.

4.3 Evaluation of Knock Intensity

The influence of the sensors and their position on the evaluation by means of knock algorithms can be illustrated, for example, by the knock intensity [1], [2] and [5]. From the 20 severest knocking events in relation to the signal of the acceleration sensor, the knock intensity (KI) is calculated and plotted in Figure 13. These are the same combustion cycles measured in different positions within the combustion chamber.

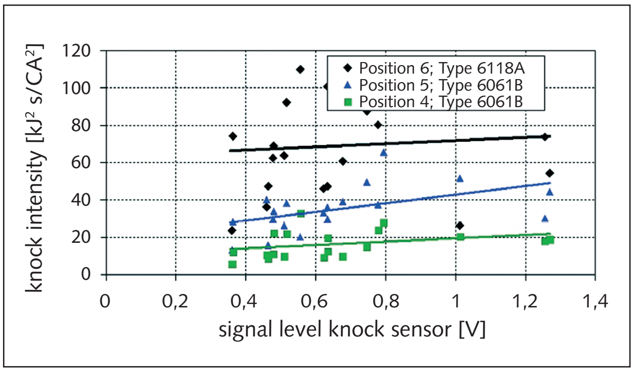


Fig. 13: Comparison of knock intensity of the 20 severest knocking events in relation to the signal of the knock sensor of a measurement. Position 4 and position 5 sensor Type 6061B, position 6 sensor Type 6118A

The different pressure curves at different positions (shown in Figure 8) have a major influence on the calculated knock intensity. Close to the knock centre (position 4), the knock intensity is lower by a factor of 2 than on the opposite side of the combustion chamber (position 5). This evaluation algorithm also takes into account high-frequency oscillations, therefore the centrally located measuring spark plug (position 6) with a natural frequency of 65 kHz records the greatest knock intensity. However it should be noted that, where different knock algorithms are used with the measuring spark plug in a central combustion chamber position, a reduced knock value may be recorded due to the mode of the surrounding combustion chamber oscillation.

Figure 14 shows the calculated knock intensities for the same sensor position, but different sensor types or installation conditions.

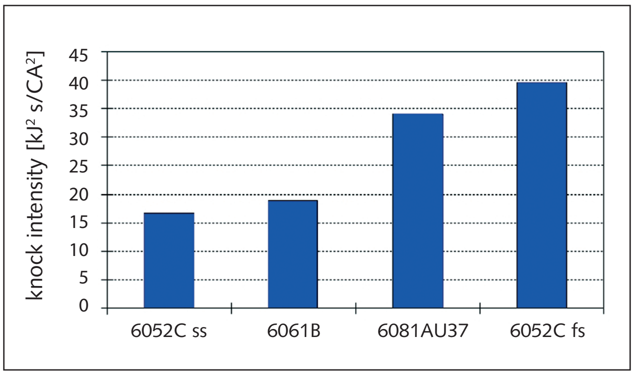


Fig. 14: Comparison of knock intensities of representative combustion cycles. Cylinder pressure measured at position 4. Sensor Type 6052C shoulder-sealing; sensor Type 6061B; sensor Type 6081AU37; sensor Type 6052C front-sealing

Due to the overlaid high frequency oscillations, the signal energy is increased, and this is reflected in the knock intensity. This difference reveals the influence of the indicating bore in the case of sensor Type 6052C front-sealing, and that of the cavity before the diaphragm in the case of sensor Type 6081AU37. By comparison, in the case of a flush-mounted installation there is hardly any difference in knock intensity between the M5 sensor Type 6052C ss and the water-cooled M10 sensor Type 6061B (Figure 14).

The analysis of 3 000 combustion cycles (measurement 3.2) will be discussed next, in order to determine if the detection of knocking combustion is influenced by the sensor position or by the sensor type.

The quotient of the variance of the pressure signals (calculated in a window of 10 °CA) is shown in Figure 15, here the flush mounting installation of sensor Type 6061B in position 4 is compared with the measuring spark plug Type 6118A. The pressure signals are filtered with highpass or bandpass filters prior the variance computation.

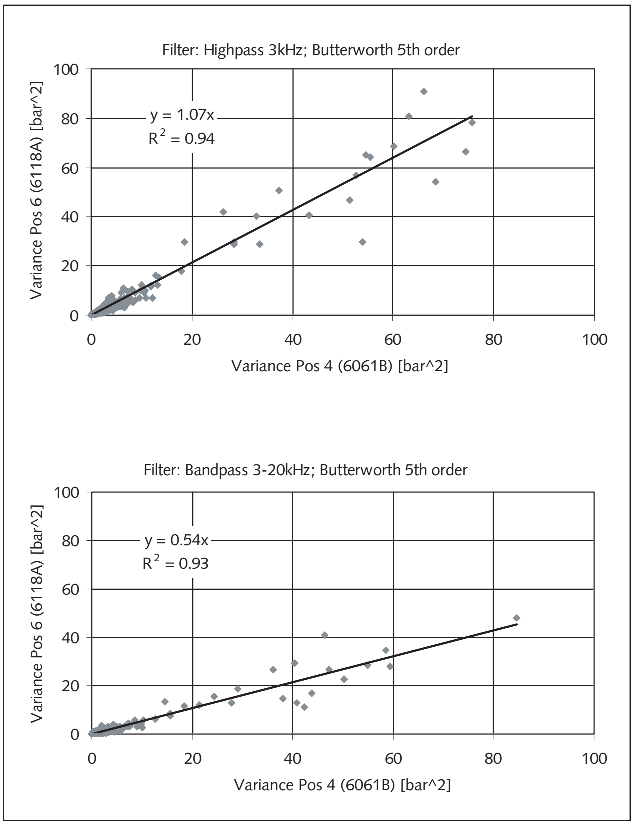


Fig. 15: Correlation of the variance of the filtered pressure signal of 3000 combustion cycles. Position 4 measured with sensor Type 6061B; position 6 sensor Type 6118A

A rather good correlation of the two sensors exists. The quotient of the variance depends upon the choice of the filter used. This can be explained by the fact that the measuring spark plug Type 6118A contains more high-frequency signals (pipe oscillation), which are filtered off by the bandpass filter so reducing the variance.

By comparing the same sensor at different measuring positions it is possible to determine the amplification factor due to position. Figure 16 shows this fact by means of flush mounted sensors Type 6061B in position 4 and position 5.

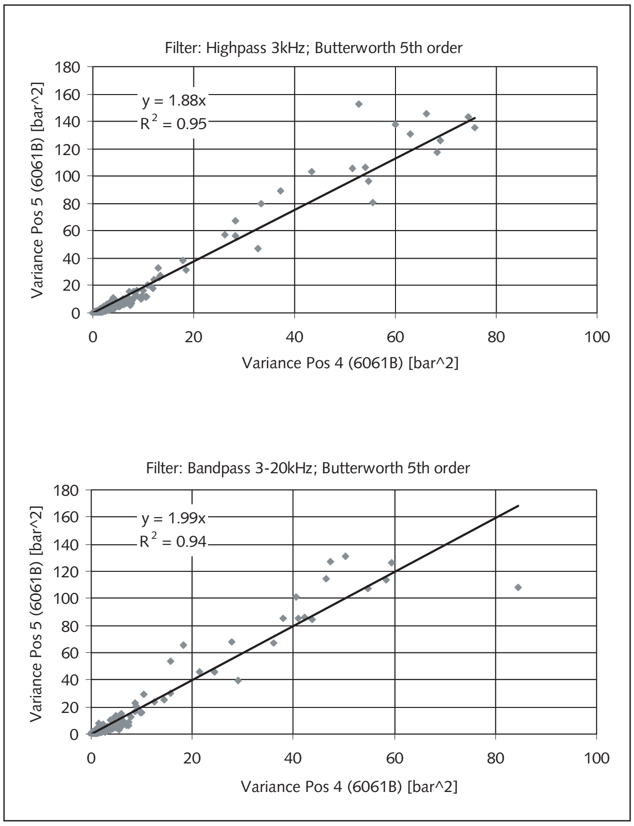


Fig. 16: Correlation of the variance of the filtered pressure signal of 3000 combustion cycles. Position 4 measured with sensor Type 6061B; position 5 sensor Type 6061B

The proximity to the cylinder wall of the sensor in position 5 shows already a quotient of the variance of approx. two, which can not be influenced by the choice of the filter. This result confirms that the sensor position is relevant also for the algorithms.

1 $V = \frac{1}{n-1}\sum_{195°KW}^{205°KW}(p_\alpha - \bar{p})^2$

The effect of the squish-gap is evaluated by comparing sensor Type 6061B in position 4 with sensor Type 6053C in position 3.

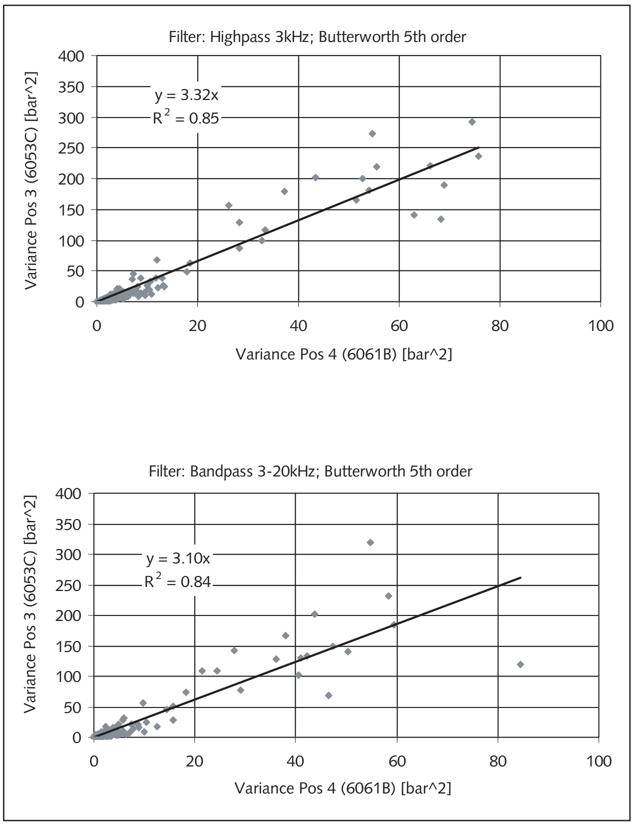


Fig. 17: Correlation of the variance of the filtered pressure signal of 3000 combustion cycles. Position 4 measured with sensor Type 6061B; position 3 sensor Type 6053C

The squish-gap increases the variance by a factor of three, whereas the cavity of the front-sealing sensor Type 6053C shows an influence of ca. 10 %. Interesting is the lower correlation quality as the values obtained with the sensors in the combustion chamber without geometric constraints (R^2 = 0,95 in Figure 16 without geometric constraints, R^2 = 0,85 over the squish-gap in Figure 17). This is due to the fact that different knock locations influence the knock amplitude in the squish-gap and, on the other hand, the signal varies with turbulences in the squish-gap.

Figure 18 shows a comparison of the variance in position 2 with sensor Type 6053C with that of the basis position 4 with sensor Type 6061B .

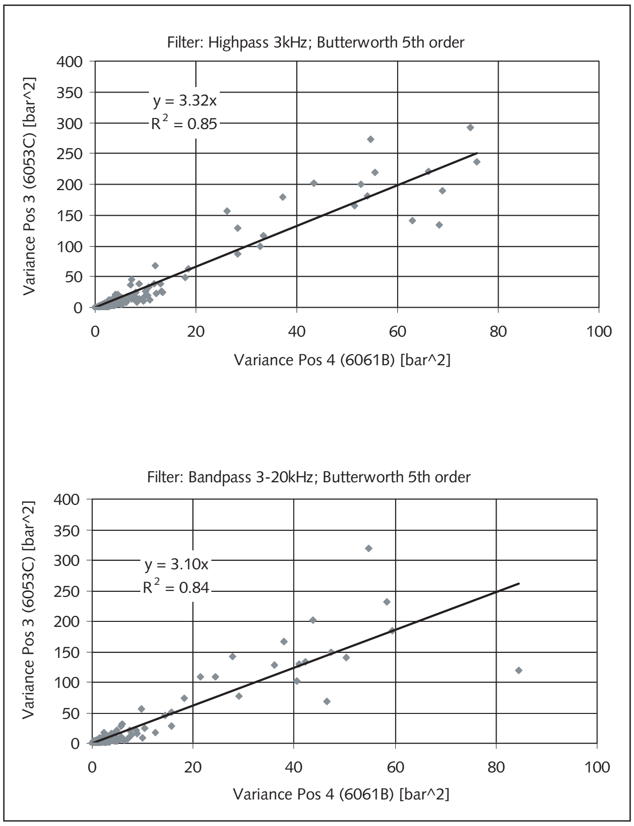
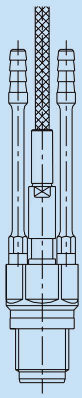
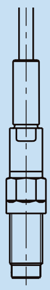
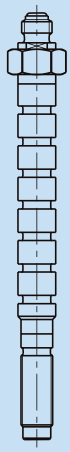
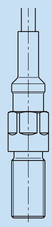
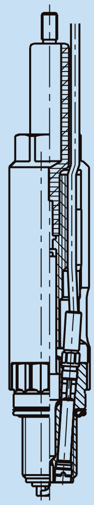
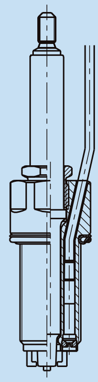


Fig. 18: Correlation of the variance of the filtered pressure signal of 3000 combustion cycles. Position 4 measured with sensor Type 6061B; position 2 sensor Type 6053C

To sum up, it may be concluded that the calculated variances are heavily dependent on the measuring position and mounting situation of the sensor. Therefore the values derived from the pressure measurement may only be compared with one another provided the mounting position, sensor type, signal filtering and sampling rate are considered.

4.4 Sensor Characteristics

The general characteristic of the sensors used in this investigation are shown in Table 4. These sensors are commonly used for thermodynamic analysis, knock investigations and engine mapping thus representing a wide spectrum.

Kistler Sensor Type	6061B	6052C	6053C	6081AU37	6117B	6118A
						
Mounting bore [-]	M10	M5	M5	M5	M14	M14
Typical installation[1] [-]	ss	fs	fs	ss	ss	ss
Sensitivity [pC/bar]	–25	–20	–20	–10	–15	–10
Measuring range [bar]	250	250	250	250	250	250
Thermal shock[2] [bar]	0,2	0,5	0,5	0,8	0,8	0,8
Natural frequency[3] [kHz]	90	130	130	120	130	130
Resonance frequency[4] [kHz]	—	>30	>30	>60	>55	>60
Excentricity of central electrode [mm]	—	—	—	—	2,2	0,8

[1] typical installation ss = shoulder sealing, fs = front sealing
[2] Thermal shock at 1‘500 1/min and 9 bar NREP
[3] Nominal natural frequency of sensor, without installation
[4] First acoustic resonance frequency with typical installation, Type 6061B flush mounted (no pipe oscillation)

Table 4: General characteristic of the sensors used

The usual method of selecting sensors for general pressure indication cannot be used in the case of knocking combustion.
Whereas in the thermodynamic analysis of combustion cycles, properties such as thermal shock and average time drift of the sensors are decisive, in the case of knocking combustion, other characteristics are significant.

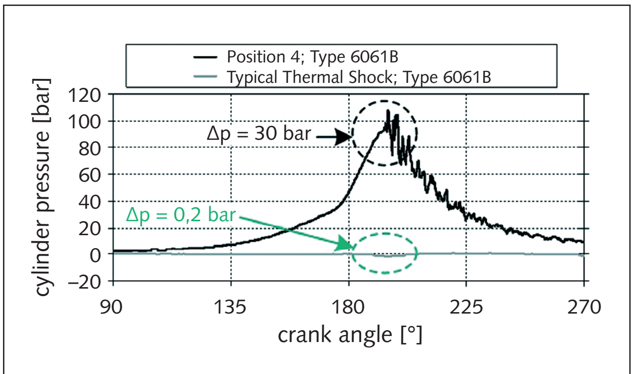


Fig. 19: Comparison of pressure signal during knock and typical thermal shock of a sensor Type 6061B

In Figure 19 the amplitude of the pressure oscillation measured with sensor Type 6061B is around 30 bar, whereas the error due to thermal shock referenced to a sensor Type 7063 can be quantified at approx. 0,2 bar.
The pressure oscillations of knocking combustion are by a factor of 100 greater than the maximum error due to thermal shock. Therefore it is obvious that the traditional variables of thermal shock and middle time drift are not relevant for knock analysis.
To measure knocking combustion cycles on the other hand, the service life of the sensors is crucially important, since the diaphragm and the measuring element are exposed to very high thermal and mechanical loads. Water-cooled sensors or uncooled front sealed mounted sensors are therefore to be preferred. On the other hand, the installation situation is crucial, flush-mounted installation being desirable in order to prevent possible effects caused by the indicating bore or cavity.

5 Conclusions, User Recommendations

A crucial factor for pressure measurement during knocking conditions is the sensor position within the combustion chamber. The sensor type is of secondary importance; at most, cavities between the combustion chamber and the sensor may influence the measuring signal. These findings provide the basis for general recommendations:

Sensor Position:
The position relative to the knock centre and the combustion chamber geometry is of primary importance. The pressure amplitude is highest in the area of the combustion chamber wall on the side opposite the knock centre. If the sensor is positioned close to the wall, it is primarily the reflection of the pressure wave that is measured. Amplitude enhancement also occurs in the area of the quench zone, therefore these measuring positions should be avoided. Pressure amplitude measurements taken in the centre of the combustion chamber are the most representative, regardless of where the knock centres are located. A central sensor location within the combustion chamber is recommended for accurate determination of the knock timing.

Sensor Mounting:
Flush-mounted positioning of the sensor diaphragm within the combustion chamber is ideal. This ensures that no pipe oscillations are generated that could influence subsequent calculations. If flush positioning is not possible, the indicating bore should be short and with the largest possible diameter, therefore allowing high resonant frequencies.

Sensor Type:
A measuring spark plug allows quick and easy indication of all cylinders in exactly the same position, so that signals can be compared. Moreover, by developing a specific measuring spark plug for each application it is possible to match the thermal value, and achieve the correct electrode position and type. In this way the sensor manufacturer can minimise the differences compared with the original spark plug.

With water-cooled sensors, overheating of the sensor caused by the higher thermal stresses during knock is prevented Measuring spark plugs also have a thermal advantage in that they have a good ability to dissipate thermal load thanks to their favourable heat transfer properties.
The advantages of uncooled sensors include compact and robust design and optimal heat dissipation with front-sealing mounting.
The most critical type appears to be the shoulder-sealing sensor without water cooling in view of the risk of overheating, even after a few combustion cycles.

Evaluation in Relation to Knock Intensity:
A general recommendation regarding knock algorithms is not possible, a large variety of methods with regards to filtering methods and filtering frequencies is used. Moreover, the combustion chamber geometry influences the data post processing; the position of the pressure sensor related to the squish-gap and the cylinder wall having a predominant influence.

Nevertheless, representative results are obtained with sensor positions not in the squish-gap and with a high distance to the cylinder wall. A central sensor position in the combustion chamber means that the circulatory pressure oscillations are not measured. This means that the low-frequency signal portion is less evident. But this does not mean that this sensor type is not suitable for the detection of knocking combustion.
On the contrary, because of the optimal central position in the combustion chamber the measuring spark plug measures a highly representative pressure signal without wall or squish-gap influence. This circumstance is confirmed by a good consistency of high correlation quality.

To evaluate the knock intensity of an existing test setup, it is advisable to install a measuring spark plug in a central position as a reference sensor. In this way the measured pressure signal can be compared with that of the measuring spark plug and any discrepancy can be quantified. Existing experience of an analytical routine can thus be transferred to a different combustion chamber position and a different pressure sensor and the sensitivity of the analysis can be established. In the case of a new engine design, where no or very few empirical values are available, it is recommended to conduct a basic evaluation of the engine using a variety of sensor positions. The preferred method is to compare a flush mounted sensor with a centrally mounted measuring spark plug. In this way it is possible to assess the sensitivity of the knock algorithm to the measuring position in that particular engine.

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