

A New Method to Detect Knocking Zones

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ABSTRACT

It is a well known fact that indicated efficiency of a SI engine at WOT is predominantly limited by knock occurrence. Therefore many investigations have been carried out to avoid knocking. Considering the further development of downsized engines knocking will also pose a greater challenge. Not only knocking but also irregular combustion in general will require further investigation in supercharged SI engines. Premature ignition, for instance, hasn't yet been completely understood and therefore limits the low end torque of supercharged SI engines.

The purpose of this paper is to introduce different analysis methods which allow to identify the knock onset and the knocking zones in the combustion chamber. In addition to established methods new techniques have been developed to account for the complex nature of pressure oscillation during knocking combustion.

Experimental data was acquired on a single cylinder research engine to validate the methodology using six pressure transducers.

INTRODUCTION

Downsizing an ICE promises to be an ideal approach in satisfying the customer's demands with regards to dynamic drivability as well as the fuel consumption. Depending on the downsizing factor, a reduction in fuel consumption of upto 30% in a NEDC Cycle can be achieved [11, 13, 14, 15, 16]. To do this the low-end torque has to be increased sufficiently. Irregular combustion e.g. the knocking phenomena, is a limiting

factor which becomes even more relevant when achieving high mean effective pressures at low engine speeds.

As a compromise between knocking combustion avoidance and acceptable thermodynamic efficiency, the engine is operated at WOT near the knocking border line. Ignition advance is usually controlled to limit knocking intensity, which is evaluated measuring the vibration through the engine block or cylinder head with a knock sensor. Turbo-charging a gasoline engine can highly increase the mean effective pressure. But on the other hand it might also lead to severe knocking or at high boosting levels to uncontrollable irregular combustion phenomena, e.g. premature ignition. This results in very high pressure peaks and high frequency pressure amplitudes which can lead to serious engine damages [16, 17, 18]. This phenomenon occurs sporadically and apparently cannot be predicted in previous combustion cycles [16, 18, 23, 24]. The first step when investigating these phenomena is to understand the phenomenon itself and pinpoint it in the combustion chamber.

STATE OF THE ART

Many authors have been investigating the nature of knock to provide us with a suitable method of knock detection and prediction; some of them are mentioned here representatively [1, 3, 5, 6, 7, 8, 9, 19]. They had more or less in common, the formulation of a generally valid approach, which enables the development of a thermodynamic knock model to predict knock onset and its intensity. Basically three different approaches are discussed in the literature:

- Kinetic mechanisms with a detailed chemistry, consisting typically of several hundred components and reactions;
- Reduced kinetic mechanisms using less than hundred components and reactions;
- Empirical formulations based on an Arrhenius function;

The goal of this work is not to develop a completely new knock prediction method, but to focus on the knock analysis itself. The emphasis is on two important attributes, while using multiple pressure sensing:

1. Exact detection of the knock onset
2. Identification of the knock location

Therefore several methods were evaluated to identify the time delay observed between the different pressure transducers.

Table 1: Knock detection methods based on the time domain of a pressure signal.

Time domain pressure signal	KO: Knock Onset	KI: Knock Intensity
Pressure signal	- crank angle at peak pressure	- peak pressure
Band pass filtered (bpf) pressure signal	- crank angle at maximum amplitude	- maximum amplitude
	- crank angle exceeding a threshold value	- integral over a range - energy density over a range
1 st derivative	- crank angle at maximum	- maximum value - integral over a range
3 rd derivative	- crank angle at max. negative amplitude	- maximum negative amplitude
	- crank angle at abrupt rise of heat release	- max. negative value of 2 nd derivative
Heat release	- crank angle at change to high frequent signal components	- pressure rise due to isochoric auto ignition of end gas zone

Table 2: Knock detection methods based on the frequency domain of a pressure signal.

Frequency domain pressure signal	KO: Knock Onset	KI: Knock Intensity
Pressure signal	-	- energy density over a frequency range

State of the art methods based on the indicated pressure for knock onset and intensity detection are reported amongst others in [3, 9, 12, 20]. The established methods are summarized in Table 1 and 2. The methods to detect knock onset were helpful to start with while developing a model to analyse knocking zones in the combustion chamber.

Previous papers have been already published which have shown that the methodology using multiple pressure sensors can be used to determine the knocking zones [2, 4, 10, 22]. All approaches were using a constant acoustic speed, which was either estimated or calculated based on a heat release analysis over the mean pressure trace. Depending on the knock behaviour, engine setup, pressure transducers and the developed methodology, knock locations due to autoignition are determined precisely enough. Liiva et al. [4] report up to 80 % of knocking cycles calculated with a knock location in the combustion chamber within a resolution of 10 mm. Castagné et al. [2] focused their efforts even to determine the self ignition locations with a precision better than 5 mm. With regard to the fact, that autoignition often is not initiated in a single zone [22, 25], the rate of successfully evaluated single knocking locations reported by Castagné et al. is high.

The herein developed methodology for knock location analysis was implemented in Matlab® code whereas the knock analysis tool was embedded in a sophisticated Pressure Trace Analysis (PTA) software [29]. Not only was this designed for analysis but also for 0-D simulation. Thus a comprehensive analysis can be done based on pressure indication.

EXPERIMENTAL SETUP

The technical data of the single cylinder engine used for this analysis is presented in Table 3 and Figure 1. For the analysis of the thermodynamic process, pressure indication was utilized. A gas exchange analysis using manifold pressure indication was employed for residual gas fraction estimation. Conditioned piezo-resistive pressure sensors Kistler 4075 were used for this purpose. For thermodynamic analysis a conditioned (cooled) piezo-electrical pressure sensor Kistler 6061B is utilized. This pressure transducer provides the most

accurate pressure indication among the used pressure sensors and still has a high enough natural frequency of 90 kHz.

Table 3: Single Cylinder GDI-Engine.

Stroke [mm]	85.0
Bore [mm]	82.0
Geom. Compr. Ratio [-]	11.5
Displacement [cm³]	449
Connecting Rod [mm]	145
Fuel	EuroSuper 95 RON
Injection System	Bosch Direct Injection
Injector	Bosch HDEV 1.2; 5.1
Valve-Train	Bosch EHVS v0.7

For knock location diagnosis 4 more Kistler sensors 6053CC60 and a Kistler pressure indication spark plug 6115AFD were applied. The 6053CC60 sensors were chosen because of their high natural frequency of 130 kHz and their smaller bore diameter. The indication spark plug transducer itself has a natural frequency greater than 100 kHz and provides a better insight to the central position of the combustion chamber. All pressure signals are amplified with a Kistler 5011B amplifier. The positions in the combustion chamber are shown in Figure 2, whereas the cylinder head is shown mirror inverted.

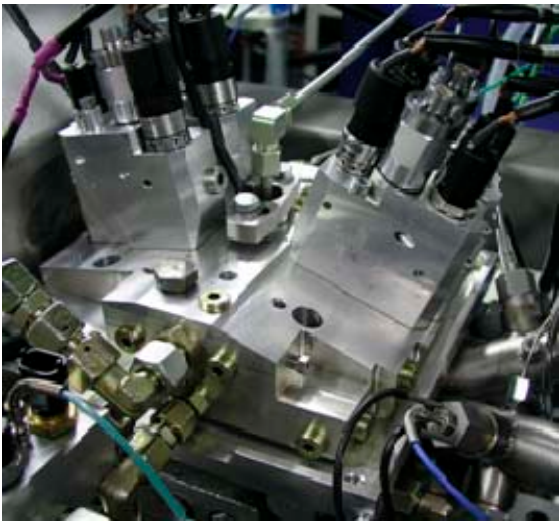


Figure 1: Single cylinder GDI research engine with centrally-mounted injector and fully variable valve-train.

Pressure traces were recorded with a AVL IndiMaster Advanced 671. Basically the data acquisition system could be used to sample the signals with a maximum sampling rate of 800 kHz. The data amount acquired in this case would be quite excessive. With an estimation

of the error calculating the knocking location in dependency of the sampling frequency it was found to be sufficient to indicate with 0.025 crank angle degrees (cad) at 2000 rpm (approximate sampling rate is 480 kHz). The sampling rate equals approximately 2 µs, which is in good accordance with the recommended sampling rate in [2]. To avoid huge data amounts data resolution of 0.025 cad was used in knocking area of -20 to 80 cad after TDC. For this purpose a Heidenhain crank angle encoder with a resolution of 3600 increments per revolution was mounted to the crank shaft. To obtain the high resolution both, equally spaced positive and negative signal slopes, were used (7200). A further equidistant point is added by the software to increase the resolution to 14400 increments per revolution.

To evaluate the developed methodology, data was acquired at different operating points at WOT at 2000 rpm. Spark advance was adjusted to acquire a spectrum of data with slight knocking cycles up to heavy knock conditions. Also cycles with premature ignition were analyzed using this method, but due to their rare occurrence no statistical evaluation is available so far.

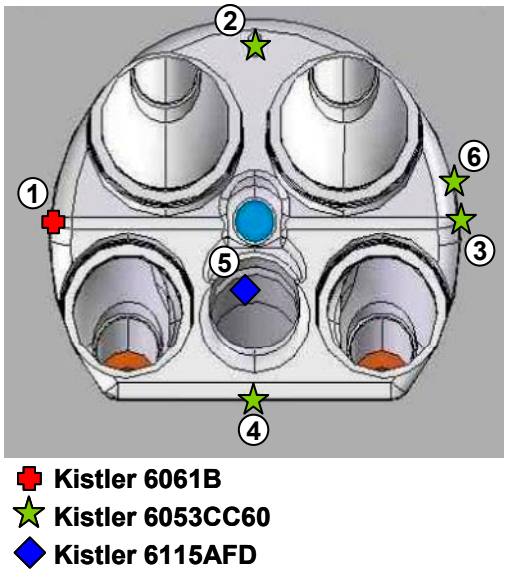


Figure 2: Sensor types and positions in the combustion chamber; Cylinder head is shown mirror inverted.

In conjunction with the results of other authors [3, 9, 21] who had previously shown that pressure indication is sensitive to parameters like sampling rate, sensor position, sensor type, indicating bore and knock location, the focus was put on the problem of utilizing different pressure transducers. Due to the different pressure characteristics of the sensors the analysis becomes even more complex. Details of these challenges are explained in the next chapter.

DEVELOPED METHODOLOGY

PRESSURE TRACE CHARACTERISTICS – The starting point for every analysis is the pressure trace indicated by the pressure transducers. As already mentioned above, there are a lot of parameters which distinguish the recorded signal. Mainly the pressure trace can be characterized by its superimposed noise, gradients, amplitude and frequency. More or less all methods summarized in Table 1 are based on one of these characteristics. Filter characteristics are described in the Appendix.

The knocking signal trace differs strongly from one cycle to the other. Consequently this applies likewise for derived quantities like knock intensity and knock onset. Figure 3 shows three characteristic knocking cycles, chosen to point out some general differences. One can see that cycle 89 has a very clear and smooth pressure rise due to the arriving pressure wave. The first pressure amplitude (compare the hpf pressure trace in Figure 3 on the left) itself is dominant and is not disturbed by relevant noise or any wave interaction. Even the pressure gradient can be clearly observed without smoothing the data. In this case an indication of knock onset would be rather simple to accomplish with any method described in Table 1.

Unfortunately not every knocking cycle shows such a clear characteristic. For instance, the maximum of the band pass filtered signal of cycle 10 (Figure 3 center) reaches 1.8 bar. Since a knocking cycle was defined as a threshold of the bpf pressure trace exceeding 1.5 bar, this cycle definitely can be categorized as a knocking cycle. However it is hard to tell which pressure peak should be chosen as the real knock onset, the first one at 10.6 cad (not exceeding 1.5 bar) or the second more dominant peak at 11.6 cad (marked on hpf pressure plot). For knock onset analysis with a single sensor definitely the first one could be chosen. But with regard to knock localization other sensors might even not notice the first impact and the result would be a wrong triangulation of the knock origin in the combustion chamber. For this cycle a characteristic change of pressure gradient can hardly be recognized.

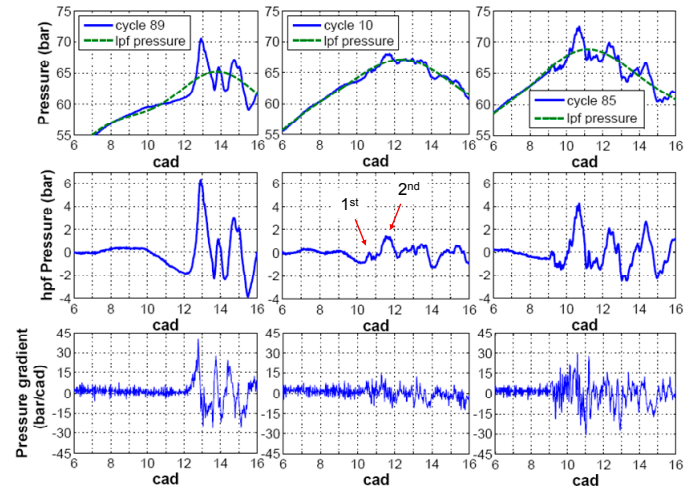


Figure 3: Three different knocking cycles indicated with Sensor 6061B at position 1.

With regard to a dual knock occurrence, cycle 85 on the right side of Figure 3 illustrates a knock behavior similar to cycle 10, where potentially two events could be interpreted as knock onset. The difference in this cycle is a distinctive amplitude of the second event, similar to cycle 89. Nevertheless with regard to the pressure gradient trace it is obvious that the pressure rise isn't smooth like cycle 89. Analyzing the pressure traces of the other 5 sensors for this cycle, we observe two separate knock events. The first one to auto ignite results in a very weak amplitude which can be observed on the traces of the nearby sensors. The sensors on the opposite site of the combustion chamber don't record the first event since the weak developed pressure wave reaches these sensors after the second more intensive autoignition event. Since the separated events can not be indicated on all pressure traces it is hardly possible to differentiate between the two events. Any algorithm determining the knock onset would fail to diagnose the specific knock location in this knocking cycle.

Concerning the pressure traces in dependency of the cycle to cycle variation, indicated on a single sensor, it can be summarized that there is a broad variety in characteristics. With regard to a single pressure trace, as described above, it becomes obvious that any method will fail to detect the right knock onset for a certain number of knocking cycles. Predominant cycles with multiple autoignition zones will not be calculated correctly by an automated evaluation procedure. These cycles are characterized by a high residual which will be explained and discussed in the further sections.

New challenges in analysis of pressure traces arise with utilization of different types of sensors and/or installation of the sensor (flush or shoulder sealed). The example illustrated in Figure 4 shows the single knocking cycle 89 indicated by the 6 pressure transducers. Even though the onset of knock can clearly be observed on all traces, there are still different pressure characteristics one has to deal with and which have to be considered while developing evaluation methods.

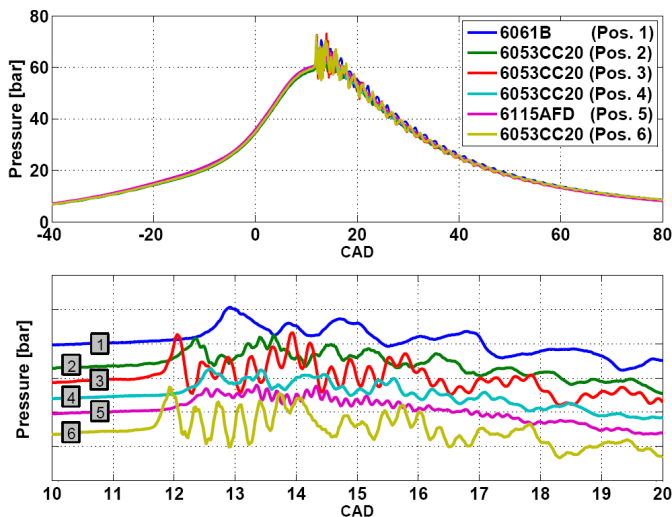


Figure 4: Typical knocking cycle at 10 bar NMEP and 2000 rpm (Cycle 89); for the sake of clarity the pressure traces are shifted by 5 bar from each other in the bottom figure

The abrupt pressure rise due to autoignition is detected unequally among the sensors. Furthermore the same knock event results in different pressure amplitudes. Generally, pressure sensors with an indication bore show higher amplitudes, as well as sensors which are located at the combustion chamber border compared to sensors placed centrally (compare Pos. 5 in Figure 4 with other Positions). For pressure traces with a low signal-to-noise ratio due to any reason (e.g. sensor signal quality, knock intensity recognized, indication position, mounting conditions, influence of additional noise sources) an exact detection of knock onset is a challenging task. Even for the knock event shown in Figure 4, which shows a distinguished knock characteristic on most pressure sensors, an evaluation of pressure trace from sensor 5 still stays challenging. Although Cross Correlation Method proves to be the most promising method to detect the observed time delays between the pressure traces, as reported by other authors [2, 4, 10], one has to deal here with

different frequencies. Since a whole data range is evaluated as against single point evaluation (pressure rise, gradient, amplitude etc.), Cross Correlation tends to perform usually very well. But all said and done this method only results in a good correlation for similar signal characteristics, especially in the frequency domain.

FREQUENCY ANALYSIS - For the frequency analysis a spectrum estimation method is applied. The pressure traces were analysed using a thompson multitaper power spectral density estimate [27] with a time band window (TimeBW) of 4. The spectrum estimate is shown in Figure 5 for all 6 pressure traces averaged over 50 knocking cycles at the same operating point. Also the results of the 3D modal analysis are shown for the first 10 modes.

Generally the eigenfrequencies can be estimated for a geometrical simple hollow cylinder with the assumption of homogeneous gas mixture by applying the acoustic theory. Bessel's equations of the first kind can be used to find a separable solution of the cylindrical wave propagation problem [9]. Using this approach it was found that the calculated eigenfrequencies don't really correspond exactly with the measured signals. Therefore a 3D mode analysis was performed with COMSOL to explain some discrepancies. The results (see Figure 5) show a very good agreement between the calculated and measured eigenfrequencies. The speed of sound in the analysis was set to 950 m/s and the piston position to 30 cad after TDC. All framed eigenfrequencies describe the same mode. The 1st number in the bracket describes the circular and the 2nd number the radial mode.

In an ideal round cylinder the modes are free to rotate around the cylinder axis and establish in dependency of the excitation location. But since the combustion chamber is not an ideal cylinder (see Figure 6) some modes are oriented due to the geometrical restrictions. Therefore some modes are detected twice, where the frequency is nearly the same but the mode itself is oriented in the combustion chamber.

For those modes where the difference in frequency is marginal (e.g. mode (2,1), (3,1), (1,2)), this effect can not be observed on the measured pressure traces. But this behaviour can be clearly observed comparing the frequencies of the first mode (1,1) which are calculated to be 6.5 and 8 kHz.

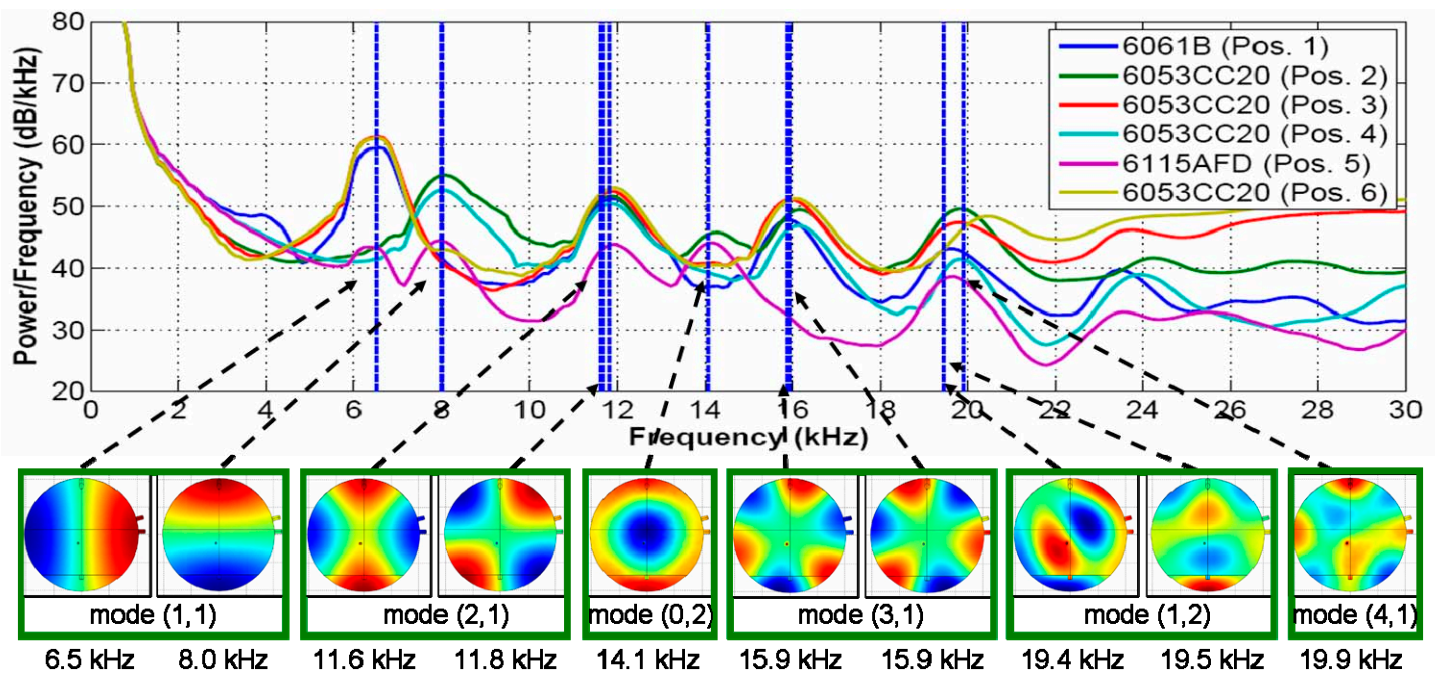


Figure 5: Thompson Multitaper Power Spectral Density Estimate averaged over 50 knocking cycles compared with results of the 3D modal analysis.

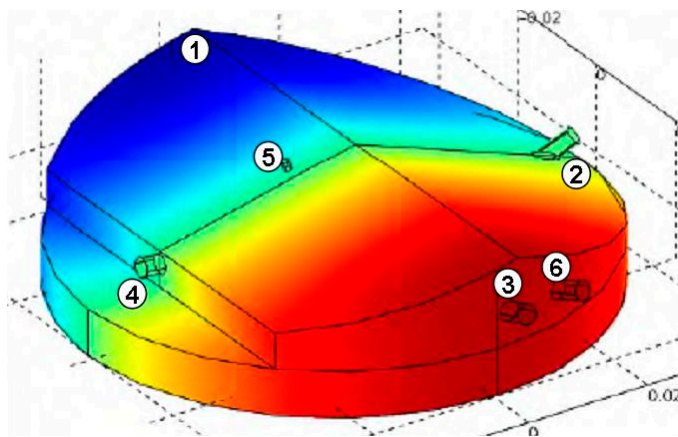


Figure 6: First eigenfrequency mode of the combustion chamber; Sensor indication bores are considered as well for further detonation simulations.

Due to the squish area, the combustion chamber has a reflection zone where the fundamental wavelength is less than in the perpendicular direction. Thus, the frequency for the same mode is slightly higher, which can also be clearly observed in the experimental data. But only sensors which are not placed in the nodal line for this mode can really observe the different frequencies. Sensors at position 1, 3 and 6 are excited at 6.5 kHz at the mode (1,1) and sensors at position 2 and 4 are excited at 8 kHz at the same mode. For this special

mode only the indication spark plug (pos. 5), which is not placed exactly centrally, is able to observe both frequencies but with substantially less power. It is also obvious that the power of the spark plug sensor is less for most of the modes observed in comparison to the sensors placed nearby the combustion chamber border. Only for mode (0,2) where pressure peak amplitude matches best Position 5, the power is considerably high.

As a matter of fact the simple 3D model can be used to determine positions in the combustion chamber which are more reasonable to use for pressure indication. Up to a certain accuracy the influence of the indication bores on the indicated pressure can also be estimated. But to do so, the boundary conditions concerning geometry as well as thermodynamic conditions in the indication bore have to be known accurately.

METHODS FOR TIME DELAY CALCULATION – When starting with the development of the methods itself, from a more general approach, it is reasonable to consider which attributes of the pressure signal might be used to define the onset of knock. The considerations have to be made from a physical as well as from a signal processing point of view. Figure 7 again illustrates cycle 89. Since the triangulation method only works with the time delay between the signals, from a practical point of view, any attribute can be used. Four important attributes were discussed as follows:

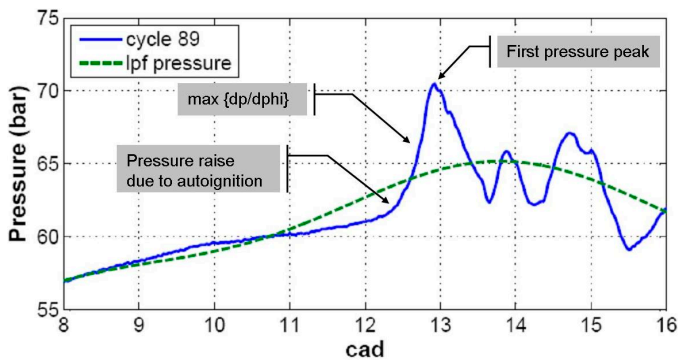


Figure 7: Pressure trace attributes for knock onset detection.

(a) – One possible method for time delay calculation is to define the knock onset as the point where the pressure rises abruptly due to autoignition. The change in pressure from normal flame propagation to knock is observable in a rapid increase of pressure gradients, see Figure 7. As discussed previously, this attribute can be very weakly developed due to the knock occurrence itself or due to sensor dependency, compare Figure 3. The assumption in this case would be that knock onset is equal to the very first impact of the propagating pressure wave. Implemented knock onset identification methods could be based either on the high pass filtered (hpf) pressure, where a threshold value is exceeded or on the pressure gradient where also a threshold value just above the noise level is exceeded.

(b) – Another formulation for knock onset could be defined as the maximum pressure gradient. Hereby it is assumed that the maximum change in pressure caused by the propagating pressure wave indicates knock onset. Methods relying on this assumption would use the 1st or 3rd derivative of the pressure, where the crank angle at maximum or minimum respectively would be treated as knock onset. Since the maximum pressure gradient of the first pressure wave is hardly detectable for weak knocking cycles (compare cycle 10 in Figure 3), no knock onset identification was performed using this attribute.

(c) – Eventually the first pressure peak of the propagating pressure wave itself can also be defined as knock onset. In this case we would assume that the point in time where the propagating wave reaches its maximum impact on the sensor will be treated as knock

onset. Therefore the bpf pressure would be analyzed to find the crank angle of the first maximum peak in pressure. Generally for distinctive knocking cycles the 1st gradient could be used as well, where the crank angle at the point with derivative equalling zero could be determined. Regarding the pressure gradient traces in Figure 3 it becomes obvious that this is very challenging.

(d) – Another distinct approach is the utilization of the Cross Correlation function. Hereby not just a single attribute is related between the different pressure signals but a whole part of the signal is taken into account. Mostly the total first pressure waves of the bpf signal itself are correlated. But it is also possible to correlate only a part of the first pressure wave, for example the positive pressure gradient of the first pressure wave. The reasons for that are explained later.

Knock Event Identification – Before starting with the different methods to detect the exact knock onset, an evaluation window has to be identified with the range of data including the relevant knock information. The window includes the signal history just before knock onset and a part of the following signal trace. The most important result of this operation is the event where knock is clearly observed on the pressure trace for the first time.

In order to find the knock event first of all the signal energy equation is applied. It was found to provide the most accurate results for the event by calculating the signal energy of the differentiated hpf pressure, according to equation (1). The cumulative signal energy can be interpreted as noise, where E_{dp} is increasing linearly for non knocking data and increases strongly in the range of knocking data.

$$E_{dp_{hpf}}(t) = \int_{-\infty}^t \left(\frac{dp_{hpf}}{d\tau}(\tau) \right)^2 d\tau \quad (1)$$

In the next step a first order polynomial is fitted in a least square sense to the basic noise level, which can be observed in the central figure shown in Figure 8. By subtracting the basic noise level, the signal energy related only to knock can be evaluated (see lower plot of Figure 8). Finally the knock event is determined as the point where a certain level of the knock signal energy is exceeded.