

# **4<sup>th</sup> Dessau Gas Engine Conference**

**Hochtemperaturfeste- und intelligente Sensoren auf Dünnschicht-technik incl. Messdatenerfassung und -auswertung zur Druckregelung an Gasmotoren**

**High temperature resistant and intelligent pressure sensors based on thin film technology including modular electronic concept of data acquisition and processing for closed loop control on gas engines**

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## **INTRODUCTION:**

Cylinder pressure is the fundamental variable that determines a combustion engine's operating state. In particular, combustion pressure information can be used in advanced engine control and monitoring systems, if available continuously and in real-time. Based on cylinder-specific pressure information, closed-loop control applications have been proposed for power balancing in gas engines. The most advanced controls each cylinder and each combustion cycle are controlled in what has been termed the Controlled Combustion Engine.

The new concept for high efficiency gas engines obtains best efficiency if every cylinder combustion is individually controlled with utilizing a combustion pressure sensor. Higher output can be reached with less NO<sub>x</sub> is produced, if individual knocking in every cylinder will be detected and evaluated. Also too lean mixture will cause misfiring.

As a result, it is important to operate the engines as close to the limit as possible with an appropriate safety margin. This safety margin is necessary because of unexpected factors such as change in fuel quality, hot spot occurrence on combustion chamber walls and so on.

Each data acquisition module monitors and analyses up to 10 cylinders of an engine. It measures the knock intensity, mis- and wrong firing of each cylinder. The information of knock intensity is used to adjust the cylinder specific pilot fuel timing and gas admission.

Light knocking signal is used to adjust the pilot fuel timing and cylinder specific air fuel ratio. Heavy knocking leads to load reduction or a gas trip.

## Main part:

### Sensor

The objective was to develop a high temperature pressure sensor, which will withstand the extreme hostile environment on the gas- and diesel engine process. These sensors also can be employed on other processes such as measurement of compression pressure, injection pressure or for common rail applications.

In addition to the general required performance characteristics as low hysteresis, high linearity (0,2 %), and low temperature dependency cylinder pressure sensors must fulfil the following requirements:

1. Resistance to extreme variation of media temperature (RT-1700°C).
2. Resistance to combustion residues (sulphur etc.).
3. Extreme high load cycles ( $10^8$  to  $10^9$  full load cycles).
4. Long term stability up to temperature of 250 °C
5. Small temperature shock drift of pressure signal
6. Small dimensions (not larger than a spark plug).

### Calculation of the mechanical properties

Using the Finite Element Method (FEM) the measure cell is designed for extreme full load use (ref. fig.1). The light areas are those with high load-bearings, the darker areas show parts of the measure cell with lower load-bearings. Using the FEM-calculations the measure cell/membrane was designed to the optimum dimensions.

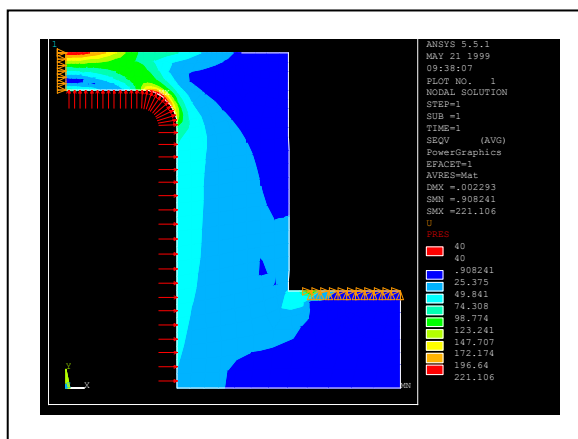


Fig.1: FEM (Finite Elements Method) of the mechanical properties of the des base material

## Thin film technology

In thin film technology the isolation layers and functional layers are applied to the membrane in a sputter process (fig. 2). The advantage of this technology is, that there is no physical separation necessary between the membrane and the measuring element (no moving parts).

Prior to the production process the steel of the sensor tip must be polished on the side where the measuring element will be placed. SiO<sub>2</sub> (Silicon dioxide) is sputtered onto the membrane as an isolation layer in a plasma process. The functional layers TION (titanium-oxy-nitrite) and nickel are precipitated and structured in a cathode - atomising process. Following this process the measure cell will be pre stressed at high temperatures.

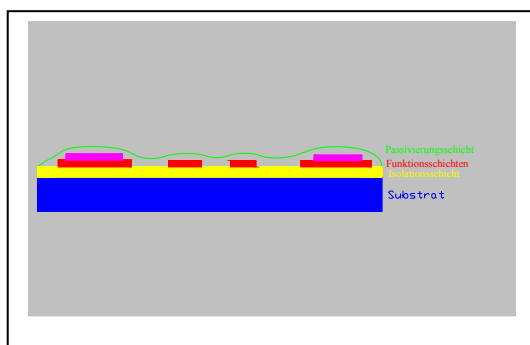


Fig. 2: Thin film structures – side view.

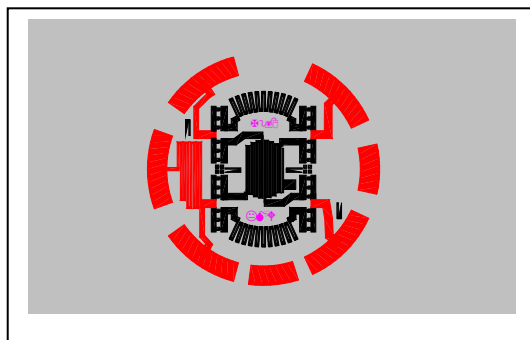


Fig.3: Thin film structures of a strain gage measuring cell.

The strain gage principle uses the change of resistance of the bridge resistors to produce the measure signal (fig. 3). The functional layer responsible for producing the measure signal consists of TION, which has its advantages in the extreme high load cycles life time and high resistance to temperature. Die TION-layer is sputtered onto the membrane in a precise controlled atmosphere of argon/nitrogen/oxygen. The temperature coefficient of the bridge (TCR) is of very high importance for the thermodynamic properties of the thin film strain gage and can be controlled by adjusting the ratio of the argon/nitrogen/oxygen atmosphere during the sputter process.

## Cylinder pressure sensor type HTT

All 3 standard types are designed such, that sensor and signal conditioning unit (SCU) are electrical connected via a signal cable and calibrated over the full range of pressure and temperature prior to delivery. The most commonly used sensor is of type HTT-01 with M14\*1,25 threading. Also a variant with M10\*1 threading and a variant called head-mounted sensor are available (fig. 4- 6).



Fig. 4: HTT-01



Fig.5: HTT-01MTV



Fig.6: HTT-01JEV

## Comparison measurement

Engine: Otto-Gas (4-stroke)

Mean indicated pressure: 14 bar

Sensor type: HTT-01JEV

Reference sensor: water cooled, piezo electrical

## Combustion sequence:

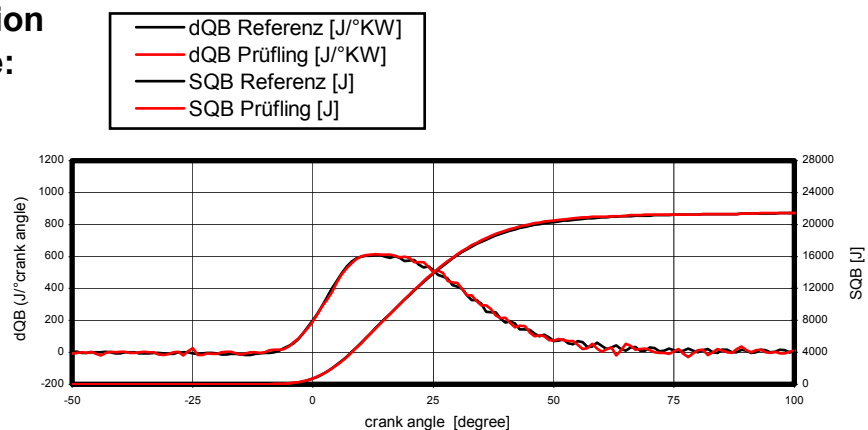


Fig.7: Combustion sequence IMES HTT-01JEV compared to reference sensor

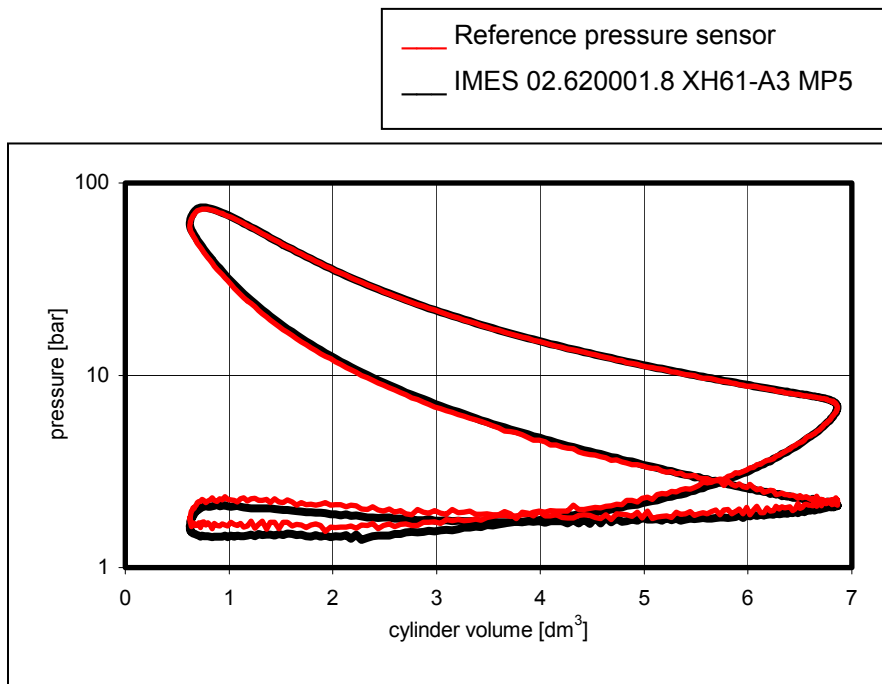


Fig.8: P/V Diagram HTT-01JEV compared to reference sensor

The comparison of the selected sensor HTT-01JEV to the water cooled reference sensor shows good or even very good matching in the high pressure area. In the low pressure area there is some degree of deviation shown.

### Long-term experience

Engine: Otto-Gas (4-stroke)

Revolutions: 750 RPM

Mean indicated pressure: 18-20 bar

Sensor type: HTT-01

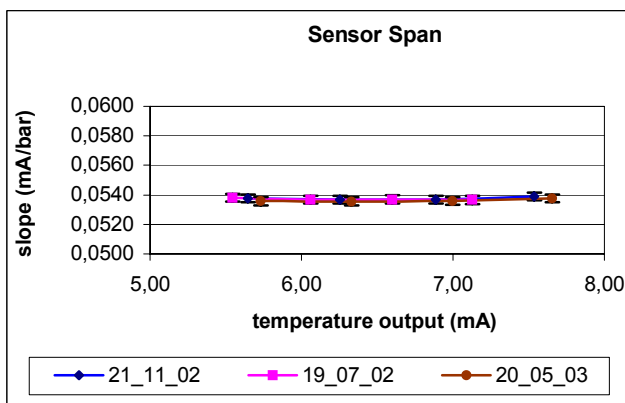


Fig.09: span, long-term performance

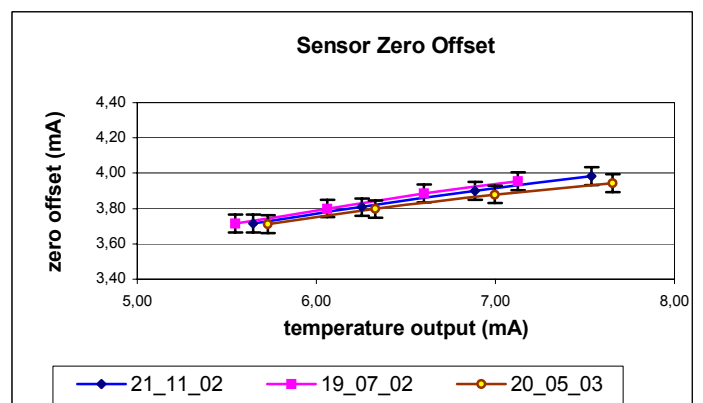
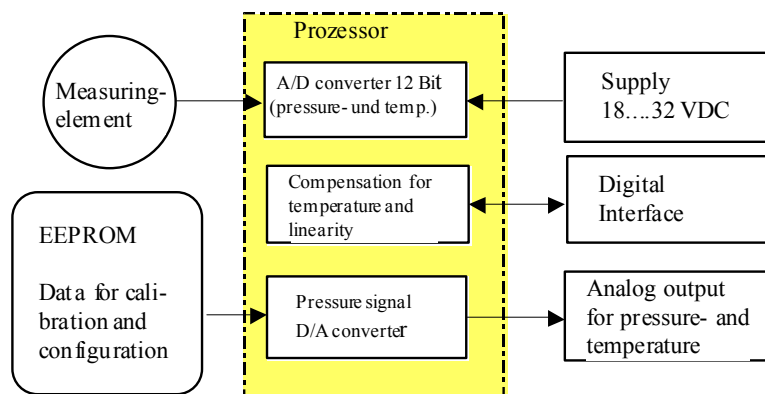


Fig.10: offset, long-term performance

During a long-term test on an Otto-Gas-Engine the sensors were taken off from the engine after 5.000 and after 10.000 running hours and sent back to IMES for checking the calibration. The span and offset of each sensor was measured over the full temperature range. The experienced drifts in span and offset were minor (fig.09 and 10). 1.000 HTT-01 sensors are in operation with more than 10.000 running hours.

## Fast digitaly compensated cylinder pressure sensor HTT-02



The sensor signal is measured with a high precision signal conditioning unit (SCU) which is processor controlled and also allows peak value detection (event storage) and automatic zero offset compensation. The analog signal has a bandwidth of 15 KHZ and is compensated for gain- and offset deviation over the full temperature operating range.

### **Digital compensation**

Non linearities and temperature dependency of the pressure sensor can be eliminated with mathematical modelling. Every pressure transmitter will be adjusted and calibrated over the operating temperature range as part of the production process to minimize the temperature effect on gain and zero offset.

The following formula is used to calculate the temperature compensated pressure reading from the pressure signal and temperature signal:

$$p = \sum_{i=0}^n \left( \sum_{k=0}^m \text{coeff}_{i,k} * \text{temperature}^k \right) * \text{pressure}^i$$

p: calculated pressure reading  
 Temperature: measured temperature at sensor element  
 Pressure: measured pressure signal  
 Coeff: coefficients  
 n,m: order of polynome. range: 1...3

## Digital Interface

In addition to the analog signal output the new generation of digital signal conditioning unit incorporates a serial interface which is used for the following functions:

- Read out of Pmax and Tmax as well as run time and runtime over preset temperature limit
- Recalibration of sensor gain and zero offset at customer site
- Read/Write configuration parameters
- Read/Write sensor serial number, compensated pressure/temperature range

This compensation method will reduce the total error to  $< 1\%$ FS over the full temperature/pressure range. Every pressure sensor is delivered with a calibration protocol which documents at least 7 pressure settings each at 3 different temperatures. The offset compensation mode can be activated either after factory calibration or at customer site.

## Fast data acquisition and evaluation of cylinder pressure signals

The working window (characteristic map, fig.11), with high mean pressure  $> 18$  bar and simultaneously growing request to perform as per environmental rules, is getting continuously smaller. Therefore the engine needs to be protected against knocking and misfiring with the utilization of innovative sensor technology and evaluation electronics and software. At the same time the Pmax values of all cylinders can be calculated and used for cylinder pressure equalization control.

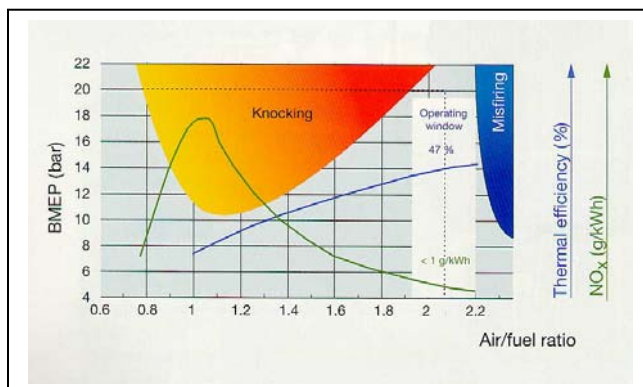


Fig.11: Example characteristic map of a gas engine

When in an online application knock detection algorithms have to be implemented or the analysis of the spectrum of the cylinder pressure signal is to be analysed, digital data processing is absolutely necessary. These digital processors on one hand contain the so called MAC-operation for the calculation of linear equations and on the other hand also have the necessary resources for addressing, which allows the efficient processing of the FFT (fast Fourier transformation).

The consequence of these design decisions ("the processor matters") are explained on the example of digital filtering, which is used for the knock detection functionality:

### Example: Digital filtering

The equation/calculation rules (IFE):

$$y(n) = \sum_{k=0}^{N-1} h(k) * x(n - k)$$

with

$y(n)$  Filter output at scanning point  $n$

$h(k)$  the  $k$ -th filter coefficient

$x(n - k)$  the input value at time  $n-k$

$N$  length of filter

The implementation at a signal processor takes  $N + 14$  cycles (engine), this means with a clock frequency of 50MHz a filtering cycle with filter length of 50 values takes:

$$(50 + 14) * 2ns = 128ns$$

For knock detection if the filtering of e.g. 256 values around TDC is decided, the time for filtering will be:

$$128ns * 256 = 32768ns = 32,768\mu s$$

On a 4-stroke engine with 1000 RPM a working cycle is 60 ms, therefore the before described computing would take 0,05% of the time of the working cycle.

If a general purpose controller as for example the C167 with 40 MHz clock frequency is used, the time needed for a similar filter would be:

$$104 * 50ns = 5200ns = 5,2\mu s \quad \text{for one filter interval (INF) and}$$

$$5,2\mu s * 256 = 1331,2\mu s = 1,3312ms \quad \text{for 256 values}$$

This would in case of the above referenced engine mean 2,2% of the working cycle.

In order to fulfil the before described technical requirements, the IMES data acquisition system (ZAD) was developed, which collects the signal information from the connected pressure sensors which are evaluated with a resolution of 0,5° crank angle. The calculated information than will be available to the automation system and/or visualization system via CAN - Bus (fig.12).

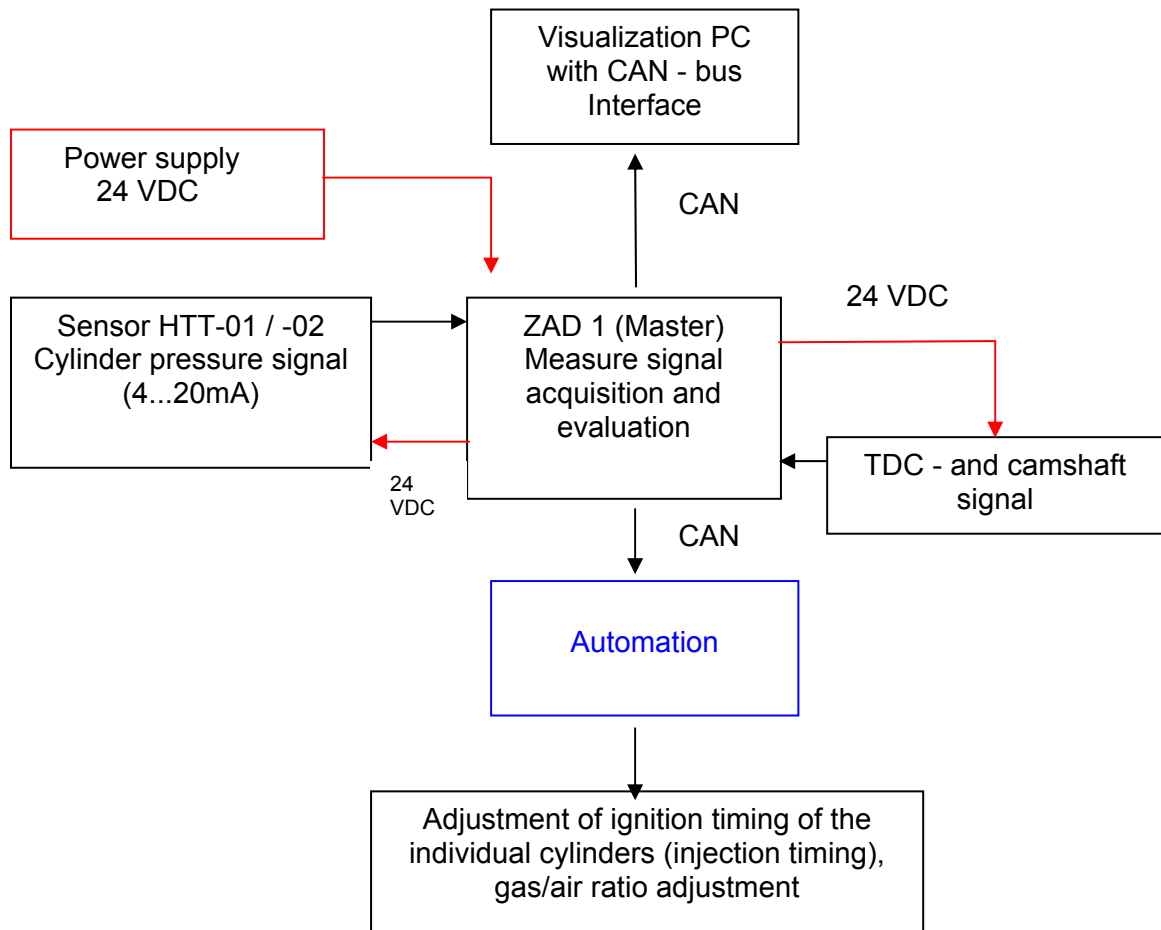


Fig.12: Overview data acquisition and evaluation

The ZAD unit (fig.13) performs the following functions/calculations:

- acquisition and evaluation of the cylinder pressure signals
- Measurement of the TDC - and camshaft pulses as a reference timing for the cylinder pressure signals
- control of the relay outputs
- functional monitoring of the pressure sensors
  
- positioning the pressure signal referenced to the TDC
- knock detection
- detection of miss firing and weak firing
- calculation of Pmax
- statistical calculations



Abb.13: ZAD unit on a 20 cylinder gas engine

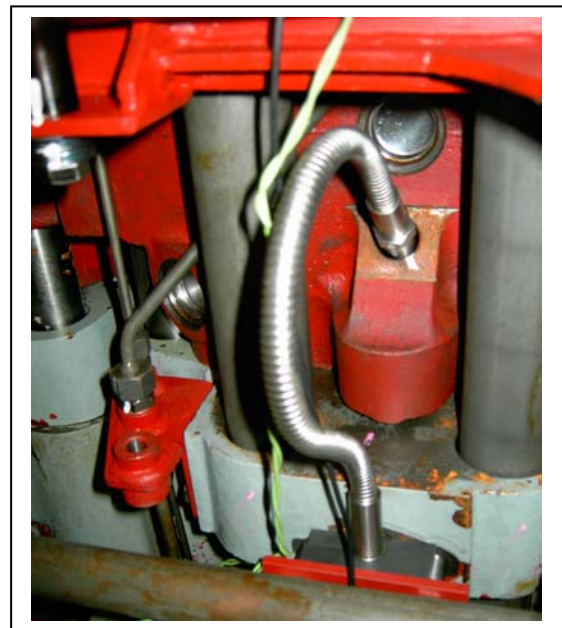
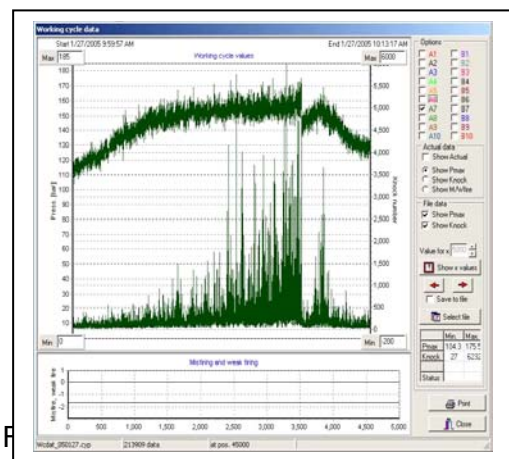
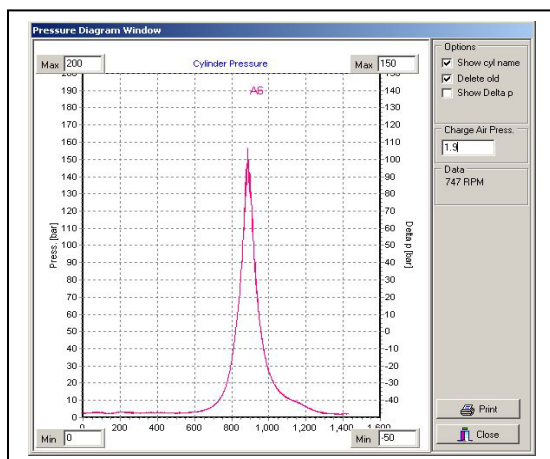


Abb.14: Mounting of the HTT-01 sensor on a gas engine

## Knock- / Misfire Parameter

A knocking combustion (fig.15) will produce changes in the frequency spectrum and the energy level of the cylinder pressure signal. The analysis of the cylinder pressure signal will be conducted during every working cycle by means of digital filtering and evaluation of the signal energy in the remaining frequency spectrum. The calculated value for the signal energy is called knock number (fig.16). The knock number for a cylinder will be transmitted via CAN- Bus, as soon as the working cycle for this cylinder is over.



The detection of misfiring and weak firing is performed with evaluating the differences of the pressure values within a preset window around TDC. This function is conducted in real time during every working cycle. When misfiring is detected, this will be transmitted to the automation system via CAN- Bus as soon as the actual working cycle is finished.

## **SUMMARY AND CONCLUSIONS:**

An extremely durable (long-life) cylinder pressure sensor was developed for continuous operation temperatures up to 250 °C (short time up to 300 °C), which also can be used on other industrial applications. The cylinder pressure sensor is well suited for applications such as engine monitoring and engine control. Up until now, more than 3.000 sensors are installed on gas engines. The first installed sensors (> 1.000 sensors) have logged over 10.000 operating hours with span deviations < 1%. The target is to reach more than 15.000 running hours with installed HTT-01 sensors on different gas engines.

The new concept for example on lean-burn gas engines obtains best efficiency if every cylinder combustion is individually controlled with a combustion sensor. Higher output can be reached with less NOx is produced, if individual knocking in every cylinder will be detected and evaluated. Also too lean mixture will cause misfiring.

The specially developed combustion monitoring system is designed to send combustion specific signals from ZAD module via CAN bus to the engine automation system to meet the challenge in controlling the combustion process in each cylinder. Stable and well-controlled combustion also contributes to less mechanical and thermal load on engine components.