Intelligenter, miniaturisierter und langzeitstabiler Zylinderdrucksensor mit integrierter Klopfanalyse zur Druckregelung an Gasmotoren

Intelligent, miniaturized and longlife cylinder pressure sensors with integrated knock analysis for closed loop control on gas engines

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Summary:

This paper describes the design and performance of an intelligent, miniaturized long-life cylinder pressure sensor that has been specifically developed for monitoring of high speed gas engines (1500 – 1800 RPM) with output >30 kW/cylinder.

In a robust, durable, and low-cost design the IMES pressure sensors utilize the principle of thin film layers. Basis is a thin film cell which forms a metal substrate. Finally, the measuring cells are thermally aged at high temperature. Altogether the miniaturized knock pressure sensor has a dimension with thread M10 and a diameter of 13 mm.

The electronic of the knock pressure sensor includes a new microprocessor type which allows two functions: cylinder pressure measurement and knock detection. The knocking value and the maximum pressure value are transmitted for each cycle via CAN Bus to the automation system.

Operating data (for example motor running hours or maximum pressure value) is stored in the sensor electronic and can be read via CAN-bus.

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 efficency gas engines obtains best efficency if every cylinder combustion is individually controlled with utilizing a combustion pressure 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 which cause misfiring can be eliminated.
As a result, it is important to operate the engines as close to the limit as possible with an appropriated 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.

The knock-pressure sensor provides two main functionalities: cylinder pressure measurement and knock detection. The sensor has an analog output (4…20mA), on which either the cylinder pressure or the knocking value is displayed. In addition, there is a CAN-bus-interface, by which, among other information, the knocking value and the maximum pressure value are transmitted for each cycle.

Operating data (for example motor running hours or maximum pressure value) is stored in the sensor electronic and can be read via CAN-bus.

Main part

Cylinder pressure sensor

The objective was to develop a high temperature pressure sensor, which will withstand the extreme hostile environment on the gas engine process.

In addition to the general required performance characteristics as low hysteresis, high linearity, 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 high vibration during heavy knocking.
3. Extreme high load cycles ($5 * 10^8$ to 10^9 full load cycles).
4. Long term stability up to temp. of 300 °C.
5. Small temperature shock drift of pressure signal.
6. Small dimensions (not larger than a spark plug).

Calculation of the mechanical performance

Using the Finite Element Method (FEM) the measuring cell (fig.1) is designed for extreme full load use (fig.2). 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.

Fig.1: Measuring element

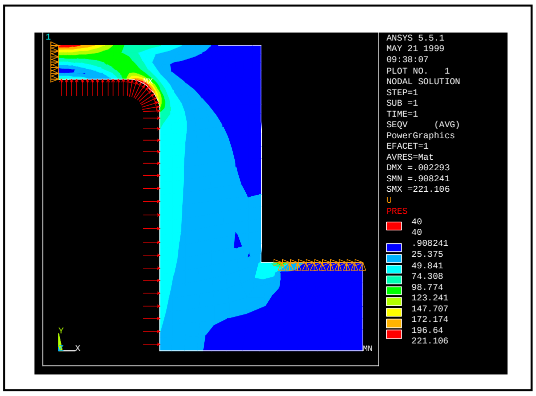

Fig.2: FEM (Finite Element Calculation) of the mechanical properties

Sensor types

The most commenly used sensor type is the HTT sensor (fig.3) with thread M14*1,25. HTT long life cylinder pressure sensor is mounted directly at the cylinder head (fig.4), which is designed for long term, continuous operation at up to 300 bar and 300°C. During long-term tests on different engines the drifts in span and offset were minor.

More than 7000 HTT sensors are produced for application on gas engines.

Fig.3: Sensor head of HTT-sensor

Fig.4: Installation place of HTT-Sensor

The CPS sensor (fig.5) with thread M10*1 is specially designed for high speed gas engines with small installation places at cylinder head. The installation place is head mounted and has a measuring range of 0…300 bar.

The pressure signal is temperature compensated to realize high performance for span- and offset on different temperastures. HTT- and CPS sensor types are designed for minimum 16.000 running hours.

Fig.5: CPS-sensor

Installation place

Speziell at the presure measurement under knocking combustion high heat flow to the combustion wall, requires high temperature performance of the sensor. The indirect cooling erfolgt vis combustion wall.

There are two possibilities for installation: head mounted (fig.6) or back implemented (Fig.7). At back implemented installation there are some possibilities to get pipe vibrations.

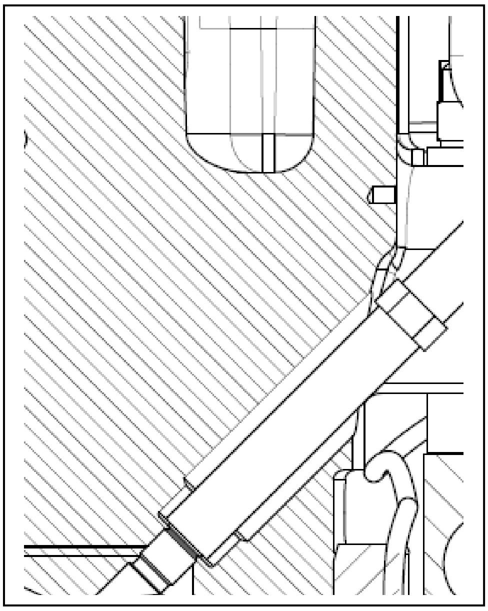

Fig.6: Head mounted installation

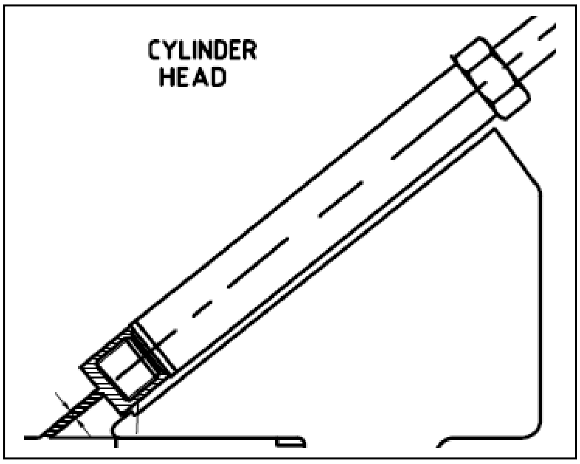

Fig.7: Back implememted installation

Knocking combustion produces changes in the frequency spectrum and the energy level of the cylinder pressure signal. The analysis of the cylinder pressure signal is conducted during every working cycle by means of digital filtering and evaluation of the signal energy in the remaining frequency spectrum.

Long-term operation

During a long-term operation the sensors were taken off from the engine after 8000 h and sent back to IMES for checking the original calibration data. The span and offset of each sensor was measured over the full temperature range. The experienced drifts in span and offset were minor (fig.8 and fig.9).

Engine: 4-stroke high efficiency gas engine
Speed: 720 RPM
Pmi: 18-20 bar
Sensor: HTT-01

Calibration at IMES: 27.05.2002			Calibration at IMES: 25.05.2004		
T_ref	P_CAL	P_HTT	T_ref	P_CAL	P_HTT
PT 100 (°C)	(bar)	(mA)	PT 100 (°C)	(bar)	(mA)
200,83	0,01	4,00	198,90	0,10	3,84
	64,72	7,45	199.10	59,95	7,06
	121,52	10,49	199,20	119,95	10,26
	183,11	13,76	199,60	179,85	13,45
	239,28	16,77	199,80	239,50	16,63
	300,85	20,06	200,20	300,05	19,86
	0,00	4,01	199,80	0,10	3,87

P_HTT	Zero Offset			Span	
span (mA/bar)	corrected (mA)	Dev. (mA)	Dev. (% FS)	Dev. (mA/bar)	Dev. (%)
0,053364	4,006				
0,053359	3,850	-0,16	-0,78	-0,00001	-0,010

Fig.8: Calibration data
Kalibrierdaten

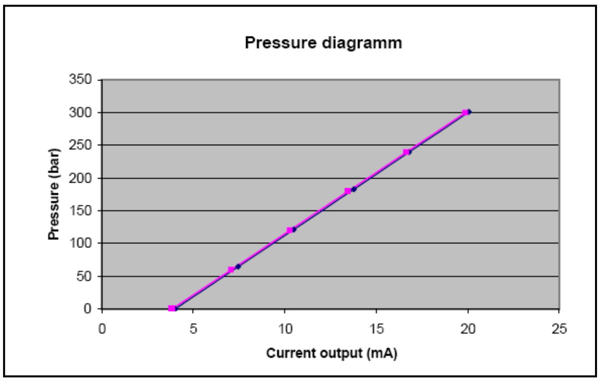

Fig.9: Comparison of calibration data

Comparison to reference sensor

Engine: Dual-fuel (4-stroke)
Speed: 500 RPM
Pmi: 14 bar
Sensor: HTT-04
Referenzsensor: Water cooled piezoelectric

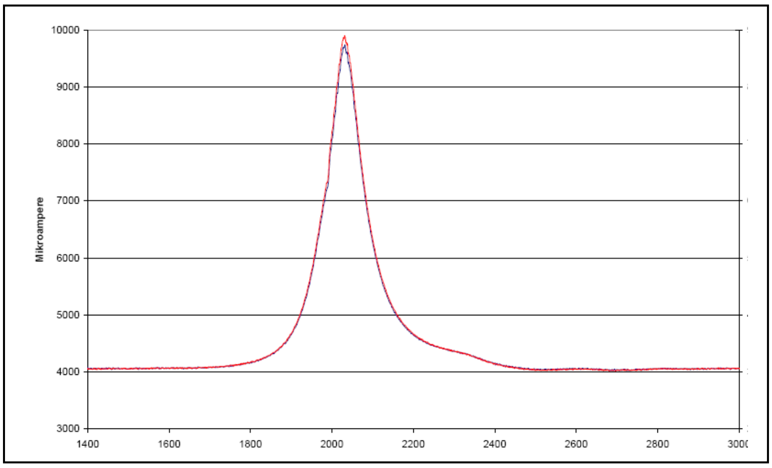

Fig.10: Pressure curve of a selected HTT-04 sensor (blue color) to reference sensor (red color)

The comparison of the selected sensor HTT-sensor to the water cooled piezo-electric reference sensor shows good or even very good matching in the high pressure area (fig.10).

Cylinder pressure sensor with integrated knock signal

The cylinder pressure sensor with integrated knock signal (Knock-Pmax sensor) includes sensor head and signal condition unit. (SCU) (Fig.11). The pressure signal will be evaluated by a micro processor. The two most important measured value: cylinder pressure and knock value will be valuated in real-time and will be send via analog- and digital interace.

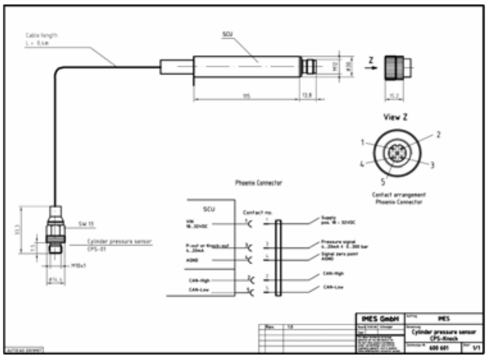

FIg.11: Knock-/Pmax sensor incl. SCU

In addition to the analog signal output the new generation of digital signal conditioning unit of pressure sensor 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
- Activating or deactivating of offset compensation
- Read output signal in mA at 0 bar
- Read/Write sensor serial number, compensated pressure/temperature range

Together with a bridge interface box (BIF-box , fig.12) and a connected PC, the operator has the opportunity to be connected with the serial interface of sensor.


Fig. 12: BIF-box

At the analog interface of knock-Pmax sensor the user can select output of pressure or knock as a 4…20mA signal.

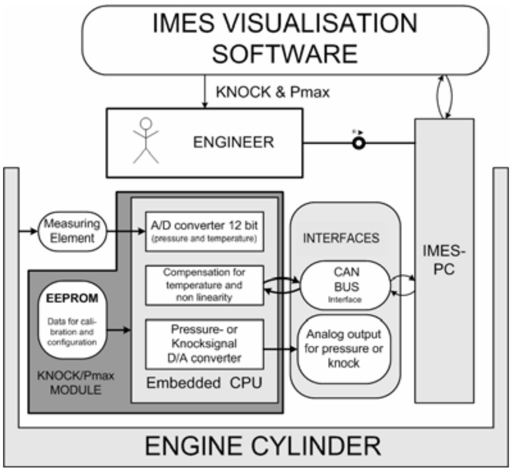

Fig.13: Data acquisition of one cylinder

Function description of knock / Pmax sensor

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.

Temperature 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:

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

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

Knock algorithm

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:

Equation:

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

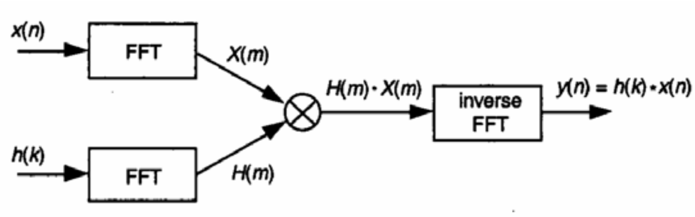

Fig.14: Diagram for equation

Multi channel application for Knock- Pmax sensor

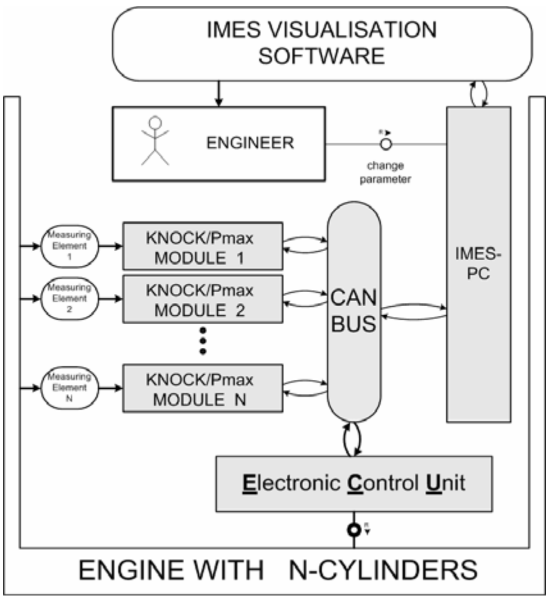

Bild.15: Multichannel application

The visualisation software

The visualisation software is working on a notebook or PC. The values of the CAN-bus messages from Knock/Pmax-sensor can be monitored as Pmax- or Knock data (Pmax in Bild.15) und Klopflinien (Bild 16) dargestellt warden. All data can be stored during measurement.

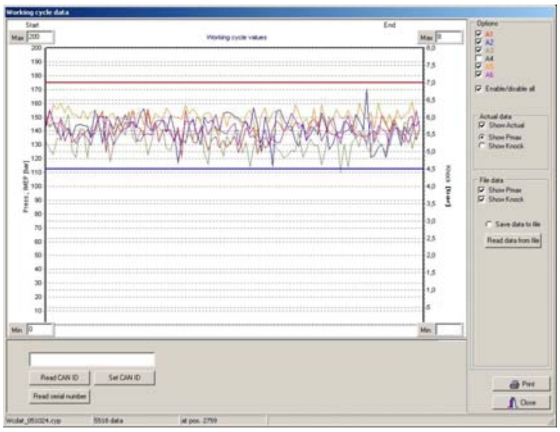

Fig.16: Visualisation of Pmax values

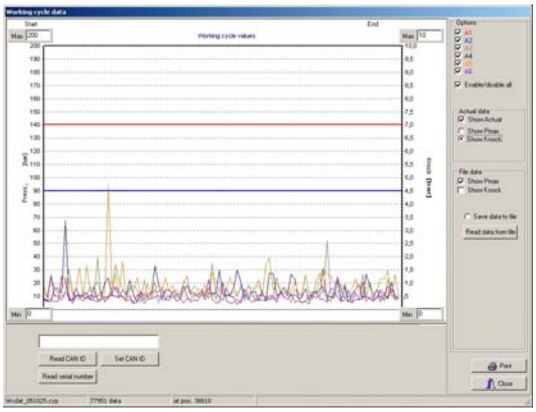

Fig 17: Visualisation of knock values

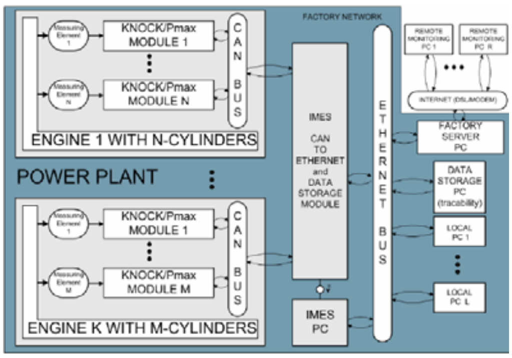

Fig 18: Total overview of Pmax/Knock modules

SUMMARY AND CONCLUSIONS:

The knock-pressure sensor measures continuously the combustion of the cylinder and sends value of Knock and Pmax to the automation system, so that operation is possible under conditions close to the knock limit.

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

The knock-pressure sensor has been designed for the high volume market of small high speed gas engine applications (1500 – 1800 RPM) with output per cylinder > 30kW.