www.MTZonline.de

MTZ

07-08 July-August 2010

ISSN 0024-8525 10814

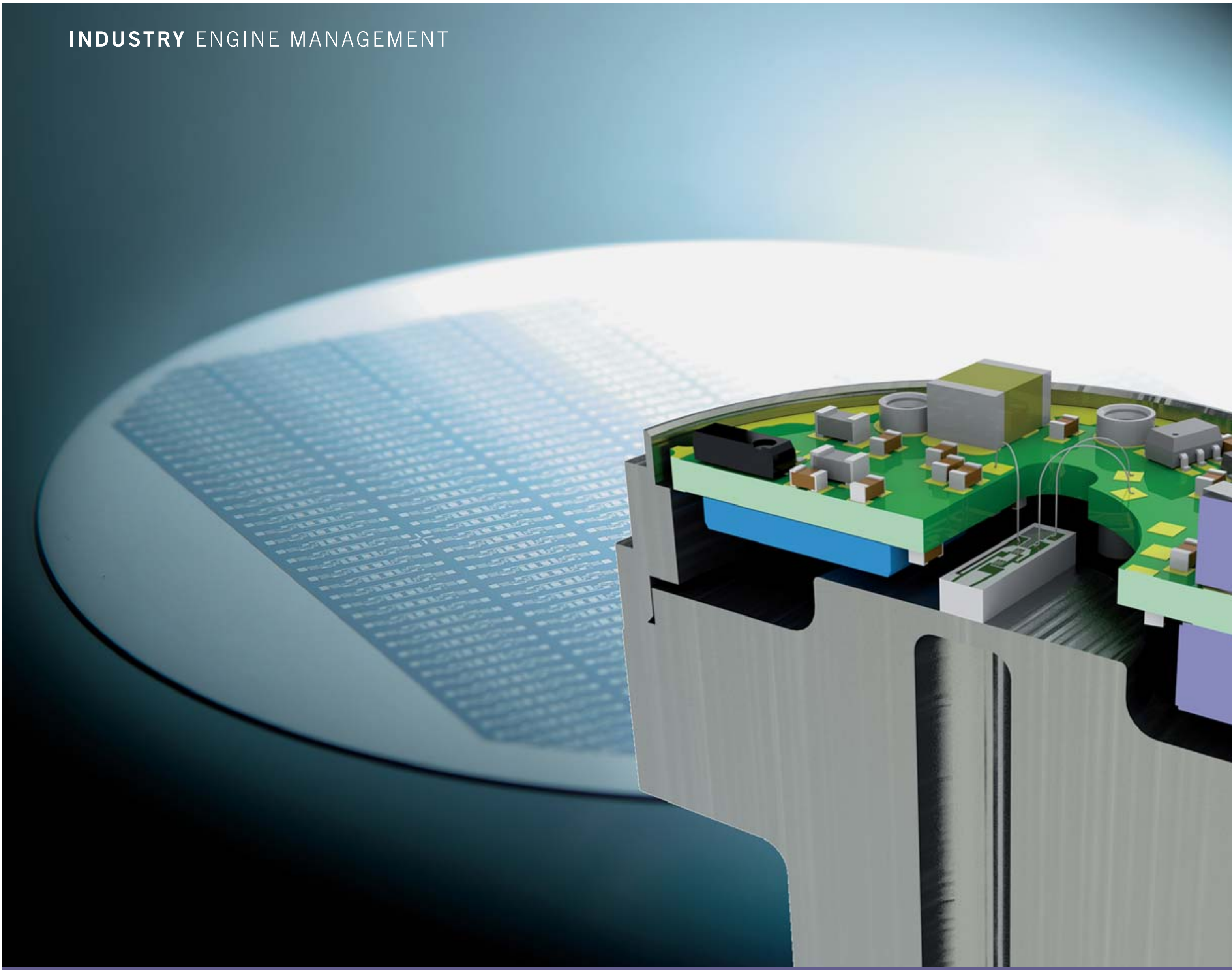
REPRINT from MTZ 08/2010
Springer Automotive Media
GWV Fachverlage, Wiesbaden

MOTOR MANAGEMENT

EPNCR: Precise and Weldfree

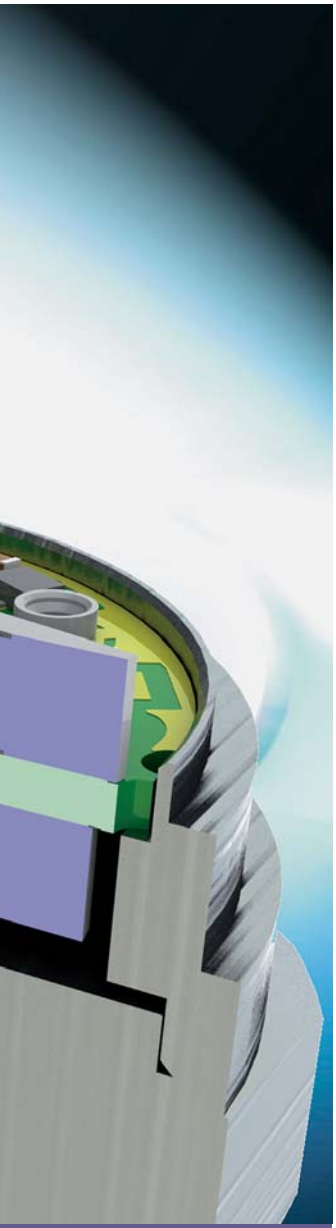
High-pressure Sensor for Large Engines

trafag
sensors + controls



PRECISE AND WELDFREE HIGH-PRESSURE SENSOR FOR LARGE ENGINES

High pressure sensors used with large diesel motors must offer a very high level of robustness and precision. At the same time the cost of the sensor must be such that its series use in large engines is practicable. The new Trafag high-pressure sensor fulfils all three of these critical requirements, as described in the following report.



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MOTIVATION

The elevated media temperatures – up to 150 °C – of the heavy fuel oil (HFO) and the relative variations in injection pressure in excess of 1500 bar call for sophisticated and innovative sensor design. The operational lifetime requirement of 10^{10} full load cycles and ever increasing system pressures of up to 3000 bar encountered in common rail systems must be taken into account, as must the high levels of vibration encountered.

The development and optimization of combustion control processes for large engines, such as fuel injection modulating in common rail systems, demand ever more precise and robust sensory components which are also economically priced. Trafag AG has been manufacturing common rail pressure sensors for measuring peak pressures of up to 3000 bar for ten years. These sensors are also used for monitoring peak pressures in a range of unit pump systems. On large diesel engines an operational lifetime of up to 10^{10} load cycles from 0 to 2000 bar is required, calling for an extremely robust design with outstanding long-term stability.

In essence, there are three main requirements which a high pressure sensor must meet. Firstly, it should be economically priced. Secondly, it must be extremely robust and stable in order to withstand the harsh conditions met in large engine environments. Finally, the sensor must be equipped with high performance electronics capable of processing the measured data quickly and demonstrating a high level of accuracy over a wide range of temperatures.

SENSOR DESIGN

Of the numerous sensor technologies available on the market today, that most frequently used in the high pressure sector is resistive measurement, which boasts the advantage that the pressure signal is referenced to ambient. In addition to the MSG (metal strain gauge) technology reported in MTZ some years ago [1], thin film methods are also available. This process essentially makes use of two coating techniques. Firstly, in order to electrically insulate the active sensor components from the body of the device, a SiO_2 glass layer is laid down using a CVD process (Chemical Vapour Deposition). This provides insulation from the device housing which is capable of withstanding in excess of 500 VAC. The resistors which form the Wheatstone bridge measurement circuit are made of nickel and nickel-chrome alloy, and are sputtered directly onto the SiO_2 surface. In subsequent process steps conventional lithographic techniques are used to create the meander-shaped conductor paths typical of the strain gauge.

In contrast to the widely used silicon-based pressure sensor systems [2], sensors using thin film technologies show much lower temperature errors and an increased long-term stability due to the fact that all the materials used in their construction have similar coefficients of thermal expansion.

The relative zero offset of a Wheatstone bridge circuit can be used as a parameter to measure sensor stability. In order to evaluate long term stability over the sensor lifetime under conditions met in the large engine environment, a number of different sensors were subjected to a temperature of 120 °C over a period of seven years during which time the zero offsets were recorded. ❶ shows the drift values measured, all of which lie well below 0.5 % FS (FS = Full scale measurement range). The zero offset drift of other pressure sensors based on another resistive technology, thick-film on ceramic (previously known as hybrid-technology), which were also investigated, is almost an order of magnitude higher. The NiCr alloy used to fabricate thin-film devices has the additional advantages of having a very high manufacturing reproducibility as well as temperature stability to 200 °C.

NON-WELDED CONSTRUCTION OFFERS HIGH SECURITY

The latest generation of the high-pressure sensor utilizes a non-welded design based on a monolithic body of precipitation-hardened 17-4PH CrNi stainless steel. The sensor diaphragm, which must be of an exactly defined thickness, forms the bottom of a highly accurate deep bore machined into the centre of the device body. The membrane is designed to operate at very high pressures, in excess of 3000 bar. The thin-film structure is not directly located on the diaphragm but is deposited onto a tiny cantilever beam attached to it at the thinnest point. This avoids the need to create the sensor structures on diaphragms individually, which would be laborious and inefficient. In such highly loaded sensors it is essential to maintain low stress levels in relation to the elastic limit in order to maximize the operational lifetime. While 17-4PH steel (material number 1.4542) has a maximal tensile strength of 1300 MPa, more recent studies show that its load cycle endurance in the giga-cycle range can be reduced under some circumstances [3]. In contrast to welded constructions, a monolithic sensor body offers enhanced security under fatigue stress conditions due to the seamless design and a lower internal residual stress level.

FEM CALCULATION INCORPORATING INSTALLATION CONDITIONS

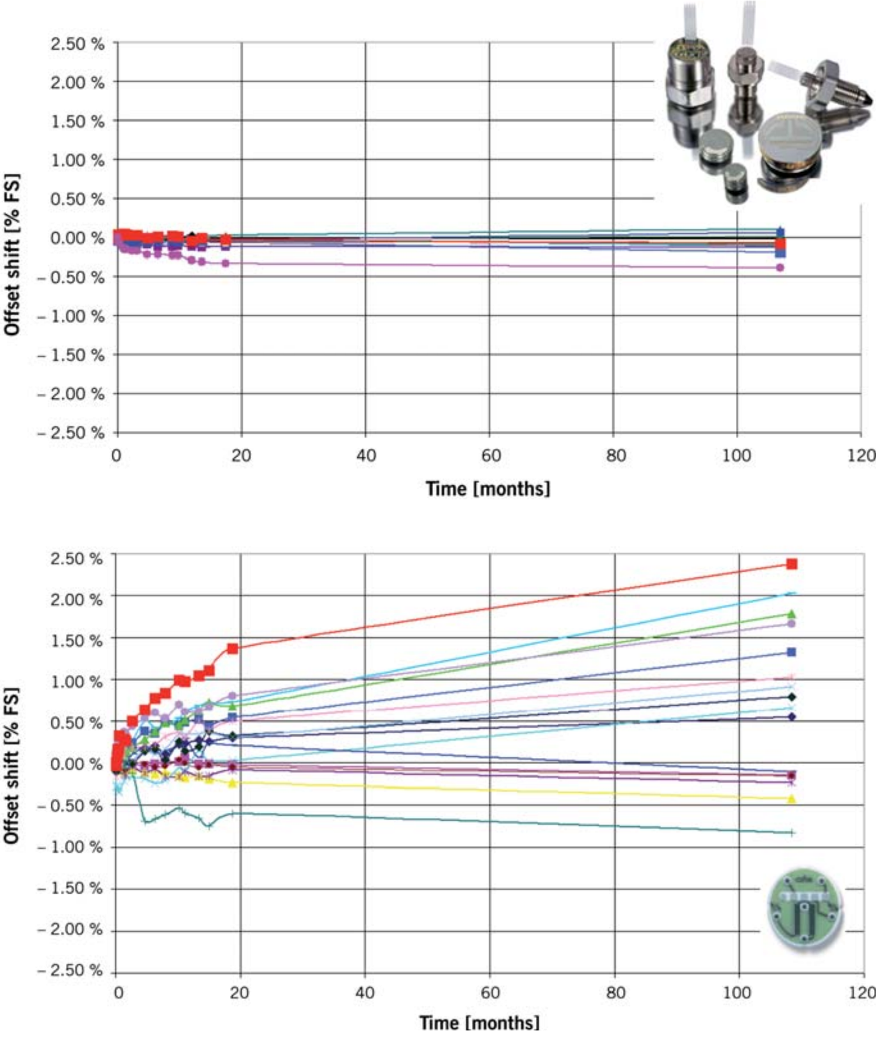
During the finite element analysis of the sensor body two different load situations were investigated. The first case indicates the deformation and stress when the sensor is fitted and tightened with a specified torque. A difference in cone angle of 0.5 to 1° between the sensor body and the mounting seat results initially in a line contact between the two which usually forms a seal on the high-pressure side. The seating force generated by the tightening torque is in the > 10 kN range and this causes the contact areas of the two parts to deform until the stress in the cone surface shell falls below the elastic limit, ❷. At this point the sensor and the seat have mutually adjusted their shapes, allowing continuous sealing to occur. Important in this context is the well-defined lubrication of the sensor screw-thread.

The second loading case modelled is based on the installation conditions as described above, with the addition of operating pressure to evaluate the deformation and stresses in the sensor body and diaphragm when the device is in use. The deformation of the cantilever beam when the nominal pressure of 2500 bar is applied is just a few microns, ❸.

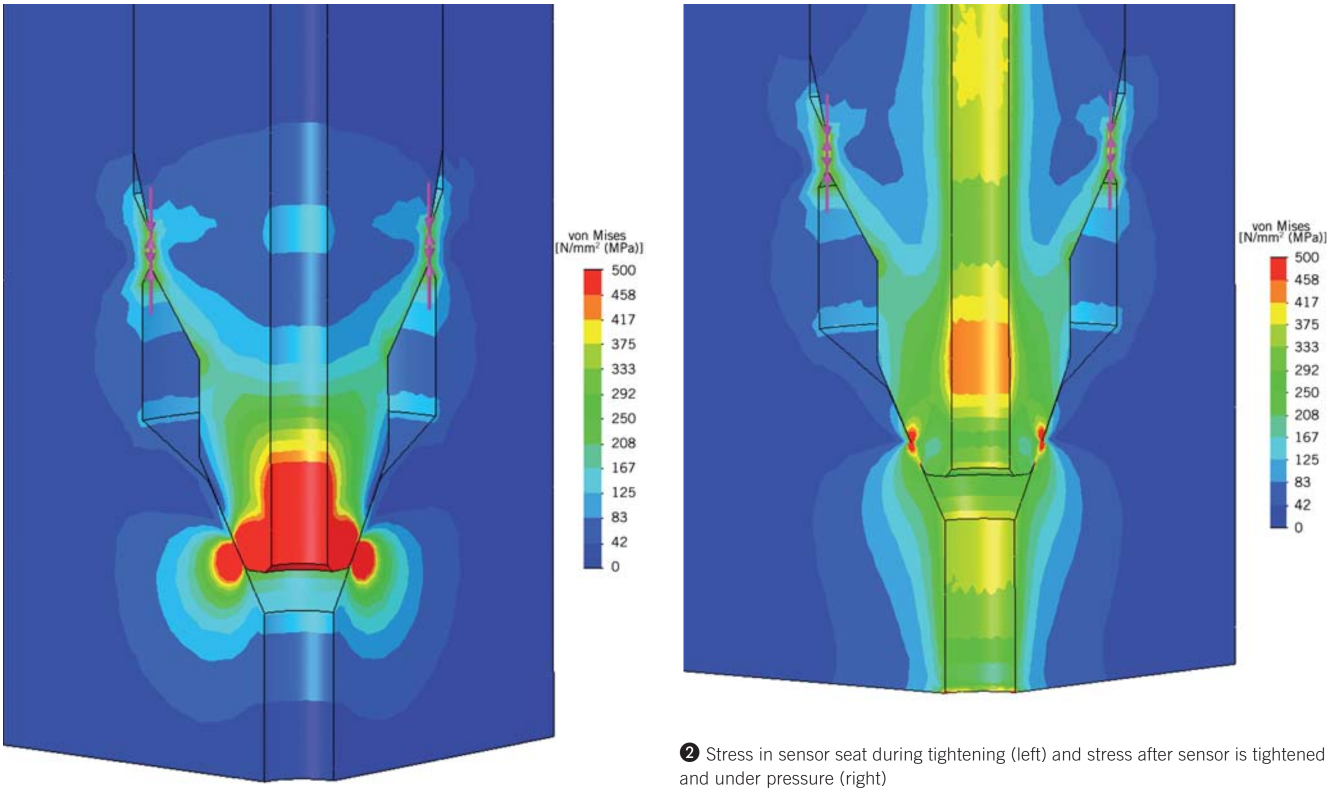
The electrical connection of the strain gauge on the cantilever beam to a printed circuit board (pcb) is made with the help of wire bonds in order to mechanically decouple the sensor element and electronics. In the latest generation of sensors only one pcb is required which, because of the stringent electromagnetic compatibility (EMC) and vibration requirements, is mounted directly onto the metallic sensor housing. The customer specific interface normally includes a connector integrated into the housing or an appropriate cable module.

SIGNAL PROCESSING WITH PRODUCT SPECIFIC ASIC

The output signal from the Wheatstone bridge which is generated by the very slight stretching of the diaphragm under pressure is, as already demonstrated, ①, extremely stable. On the other hand, the signal level is rather low – with a k-factor

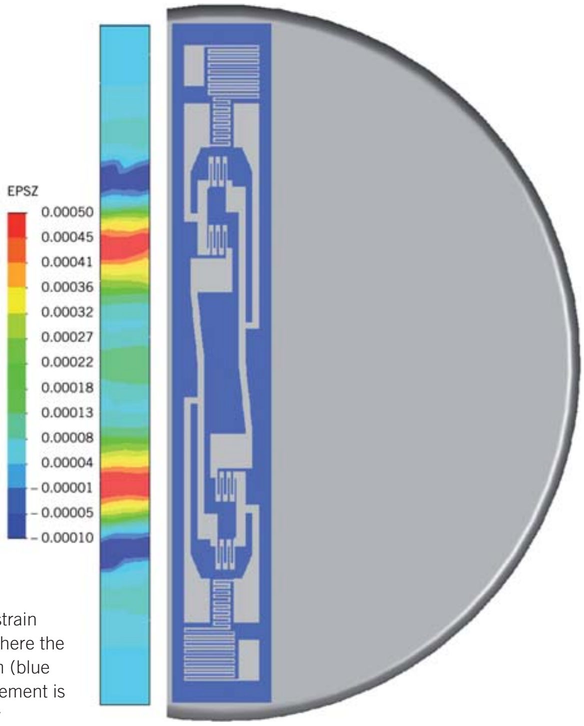


❶ Comparison of the long-term stability of two different resistive sensor technologies top: strain gauges sputtered onto steel; bottom: strain gauges printed on Al_2O_3 ceramic, then fired

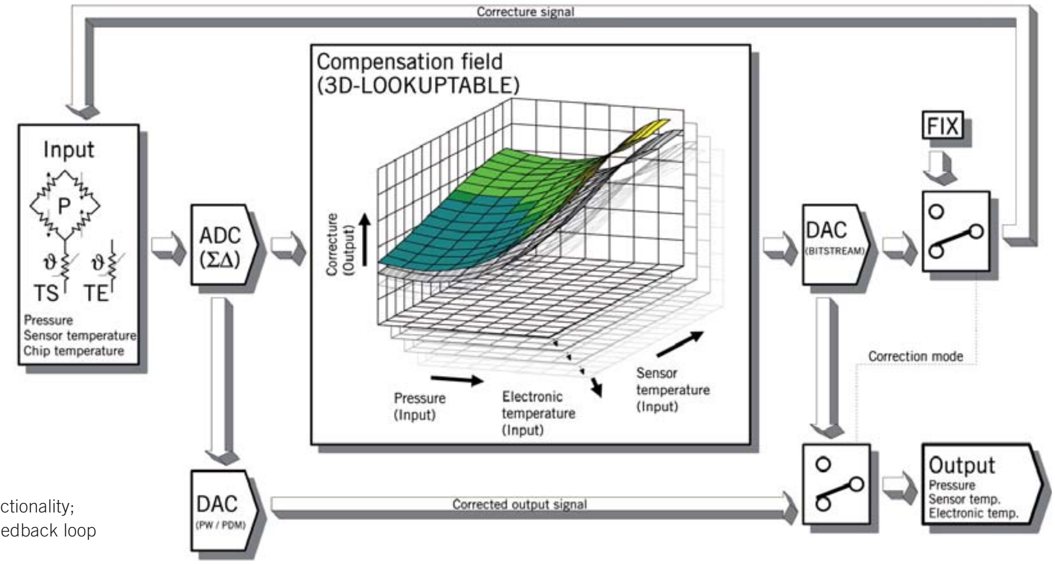


❷ Stress in sensor seat during tightening (left) and stress after sensor is tightened and under pressure (right)

of two for NiCr strain gauges, outputs of 2 mV/V are measured. This disadvantage can be made good with the help of the latest Application Specific Integrated Circuit (ASIC) technology. The IC used in the sensor features an offset-free amplifier which operates in a closed control loop, thereby compensating for any offset drift. This allows even small output signals below 2 mV to be amplified with a high signal-to-noise ratio and compensated, at 5 V supply voltage. In order to meet specific customer requirements zoomed (i.e. partial) measurement ranges may be selected, offering increased security against excess pressure (typically a factor of four to six times measuring range). Noise levels of ~ 40 nV/√Hz, equivalent to 0.6 μV_{eff} at 300 Hz bandwidth are achieved. ❹ shows a block diagram of the ASIC circuitry. Analogue to digital conversion is performed by a sigma-delta converter. Error compensation is effected by means of a three-dimensional lookup table – the error is evaluated and fed back via a fast pulse-width modulated (PWM) signal. Temperature is measured either by the ASIC's on-chip sensor or directly by a nickel resistor on the strain gauge itself, the latter giving a very good indication of the temperature of the pressure medium. The signal is measured with a bandwidth of 10 kHz, so that very fast transient effects in the fuel injection process can be recorded. The sensor electronics meet all EMC requirements as per IEC 61000 (level 4) as well as current marine and railway standards. According to DIN 16086 the total



❸ Finite element simulation shows strain zones in the x direction in the area where the cantilever is welded to the diaphragm (blue compression, red strain); the displacement is enlarged by a factor of 100 for clarity



❹ Schematic diagram of ASIC functionality; compensation is performed by a feedback loop at up to 10 kHz

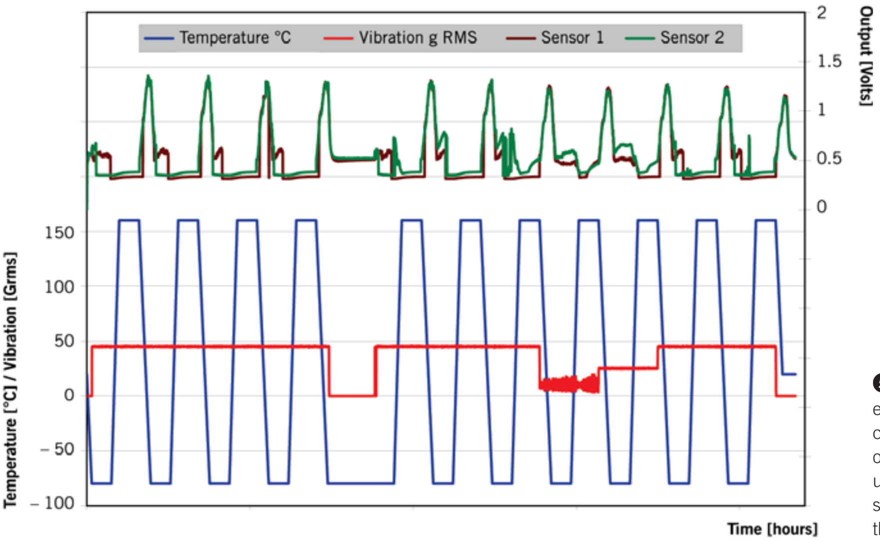
error shown by a pressure sensor is the combination of the non-linearity and hysteresis (NLH), the temperature error and the sensor drift. The total error of the Trafag high pressure sensor in the temperature range between -20 and 135 °C has been kept very low, so that generally sensors show a total error of just 0.3 to 0.5 % FS. This is equivalent to about 10 bar error in the 2500 bar measuring range.

SENSOR QUALIFICATION THROUGH EXTENDED TESTS

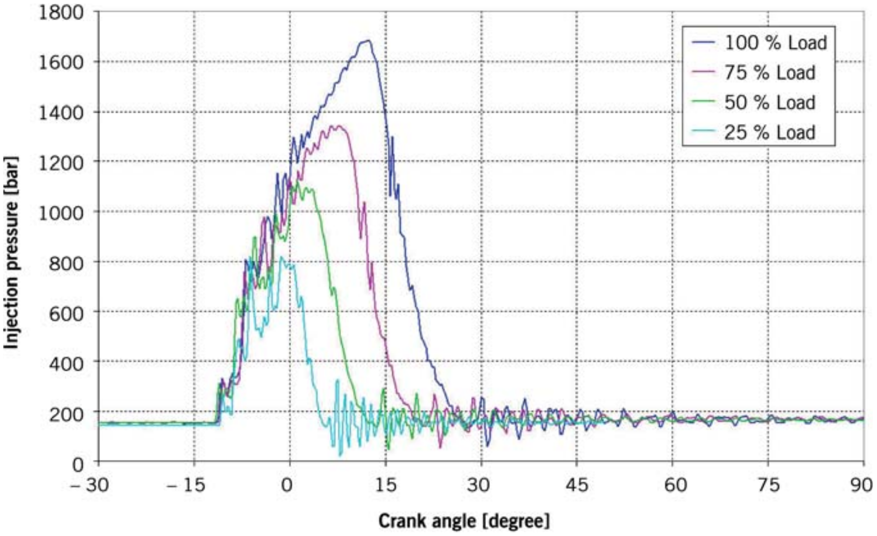
Both elaborate simulated lifetime tests and intentionally destructive tests were undertaken in order to test the robustness of the design, identify weak points and enable these to be corrected. The initial tests involved exposing sensors to high operating temperatures for extended periods, as already mentioned, ①. In addition, the combination of constant, high nominal pressure and exposure to maximum operating temperature quickly provides data on the stability of a particular sensor technology. In this regard, a typical test run involved exposing the sensors for 2000 hrs to 120 to 140 °C, during which time, the offset drift values should be less than 0.5 % of the nominal pressure range.

Increasing the frequency of temperature cycles provides temperature shock data (duration of temperature change less than 10 s, hold time typically 30 to 60 mins) which often gives precise information on sensor drift, possible short circuits, soldering failures or bond wire breakage. Extended vibration testing (400 hrs) with simultaneous temperature variation from to 40 to 135 °C represents another important part of sensor qualification. This test tends to uncover weaknesses in assembly and connection techniques such as poor electrical interconnects, loose parts etc. An excellent insight into this subject is given by Wulpi et al. [4].

Finally, highly accelerated lifetime testing (HALT) was also employed to definitively evaluate the design. ❺ shows an example of one such test



❺ Combined environmental HALT tests deliberately exceeding sensor specifications (-80 °C / 160 °C at constant vibration level of 50 g RMS, lower traces); output signals (upper traces) of the pressure sensors show uncompensated response to temperature shocks but also signal stability i.e. return to specified output at the end of the tests



❻ Injection pressure curves recorded with an 8 kHz pressure sensor

which quite intentionally exceeded the sensor specifications. Here, sensors with a specified vibration tolerance of 25 Grms within a temperature range of -40 to 125 °C are subject to a 50 Grms vibration test. At the same time the temperature in the test chamber is raised within a few seconds from -80 °C to 160 °C. The output signals of the sensors are recorded in real time to identify the beginning of a potential wear pattern. In the example shown the cable connectors represented the limiting factors. A particular response curve of the sensors can be recognized in reaction to the external thermal effects, since the short term transient errors which appear during the test are not compensated away. Elsewhere an increase in the signal-to-noise ratios, originating from wear in an external connector, can be seen. Essential for the evaluation of the test result is that at the conclusion of the selected test series, or for as long as possible during the tests, the sensors continue to function within specification. In the case of the Trafag high-pressure sensors, valid output signals were still measured at the end of the tests (0.5 V at ambient pressure).

SENSOR VALIDATION BY OPERATION ON LARGE ENGINES

Thin film technology with its inherent media-compatible design (no O-rings) allows sensors to operate on large engines using heavy fuel oil (HFO) where the viscous oil is preheated to up to 150 °C before injection (IFO 700 containing 2 % sulphur). After 3000 hrs operation on a large, nine-cylinder engine with common rail fuel injection only a very slight offset drift (< 0.5 % FS) was observed.

❻ shows the output of a high pressure sensor located near to the injectors of a large motor. Several such tests on various customer engines show that the injection pressure curve is measured exactly at different engine loads. The rapid, high amplitude changes in pressure as well as the easily recognised oscillations in the injector pressure tubing are reproduced without error or delay. In contrast to piezoelectric measurement techniques, the static pressure is measured relative to the ambient value. The peak pressures of up to 1600 bar generated by a unit pump system were faithfully measured and monitored.

CONCLUSION AND FUTURE PROSPECTS

The non-welded high-pressure sensor design described above allows reliable operation for the direct measurement of pulsating injection pressures in large internal combustion engines. The fast signal processing electronics with 10 kHz bandwidth permits optimization of the fuel injection modulation process by the motor control system. By using in addition new, economically priced sensors to monitor injector needle lift and cylinder pressure, the combustion process in each cylinder can be individually optimized, thereby allowing operators to reduce emissions, increase fuel efficiency and monitor engine health more closely.

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H70637 Trafag AG 07/2010

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