

Cylinder Head Gasket with Integrated Combustion Pressure Sensors for Advanced Engine Controls

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ABSTRACT

The cylinder head gasket with integrated combustion pressure sensors (CHGICPS) reported here targets advanced engine controls and in particular those based on the HCCI, PCCI, or LTC combustion principles, for gasoline, diesel, and alternative fuel engines. Due to the fiber optic combustion pressure sensor's (CPS) accuracy at low pressure during compression integrated into the CHGICPS, this device aims at in-cylinder prediction of mass air flow as well as in-cycle closed loop control of pilot fuel injection in a diesel engine. This paper reports on a replaceable CPS which allows installation and removal from the cylinder head gasket (CHG) without the need for removing the engine head. At the same time the distance layer thickness of CHGICPS is minimized to 2.5 mm and 3.4 mm, depending on the access ability and space constraints around coolant and lubrication ports in the engine. A multilayer steel CHGICPS prototype is constructed with replaceable fiber optic combustion pressure sensors (CPS) that operate on the principle of modulation of light reflected from a metal diaphragm deflecting under effect of cylinder pressure. The signal conditioners are remotely located from the CHGICPS in the tested design. The initial test results of the combustion pressure measurement CHGICPS demonstrated high fidelity pressure traces at low and high engine speeds for various throttle positions for the CPS using a heat shield as compared to a recessed and exposed fiber-

optic CPS. The difference between the reference sensor and the fiber-optic CPS is less than 0.1 bar during compression below 5 bar and .5 bar for a cylinder pressure range from 0 to 50 bar. The fiber-optic CPS removal and installation was performed successfully on the engine without removing the head with no signs of observable leakage. The measured pressure difference error between reference sensor and the fiber-optic sensor at peak power 2900 rpm and wide open throttle (170 bar peak cylinder pressure) shows a 2.3% error as compared to the water cooled reference sensor. Calibration adjustment of the fiber-optic CPS is shown to improve this performance. Future design considerations for integrating the signal conditioners into the CHGICPS and improved sensor performance are discussed. Overall, combining the pressure performance capabilities of a replaceable fiber-optic CPS that does not require removing the engine head, the suitability of the CHG location for all engine types, and the economic advantages of design simplicity, makes the CHGICPS a viable solution for combustion control technology in the future.

INTRODUCTION

Cylinder pressure is the fundamental engine parameter that provides the most direct and valuable information for advanced control and monitoring systems of internal combustion engines [1]. For the last 25 years numerous

manufacturers of light duty engines have been developing control strategies based on a Cylinder Pressure Sensor (CPS), which has culminated in the introduction in 2008 of the first cylinder pressure-controlled clean diesel 4-cylinder and 6-cylinder engines [2].

The primary reason the first commercial CPS-based engine control has been in a diesel engine is due to the unique benefits such a control offers for substantially reducing NO_x and soot emissions, lowering engine noise levels, and improving fuel economy and drivability [3], [4]. Other benefits of cylinder pressure-based closed loop combustion controls include: stability over lifetime (tolerances, emissions), elimination and/or simplification of other engine sensors, reduction application effort (simplified engine maps), enabling highest power-density, on-board diagnostics (OBD), compensation for fuel quality, torque feedback and control, improved cold-starting and engine warm-up, and enabling new combustion concepts such as homogenous charge compression ignition (HCCI) or premixed charge compression ignition (PCCI) [5]-[6].

CURRENT USE CPS IN GLOW PLUGS

The present diesel engines with cylinder pressure feedback use a CPS integrated with a glow plug in what has been called, by the device manufacturer, pressure sensor glow plug (PSG) [7]. The PSG is mounted either in all cylinders of a 4-cylinder engine or two cylinders of a 6-cylinder engine [2] - one per bank. A piezoresistive silicon strain gauge used in the PSG is glass bonded to a metal diaphragm located in the sensor signal conditioner enclosure attached to the top of the glow plug body, instead of the heating rod being immobilized in the glow plug body as done in a conventional design. The PSG heating rod moves axially under changing cylinder pressure transmitting the motion to the “cold pin” to deflect the device diaphragm. While the PSG offers good performance at high pressures its spring-mass principle is inherently prone to errors associated with engine vibrations and valve actuation. Despite an electronic filter, tuned for each engine type, to dampen the heater axial resonance, the PSG accuracy at low pressure is insufficient for a number of important engine control strategies including closed-loop pilot regulation and virtual in-cylinder sensing of mass air flow. Finally, there are also some concerns about PSG's long-term accuracy/reliability due to the potential of soot accumulation in the area where the heater rod enters the glow plug body.

The glow plug designs with integrated piezoceramic load cells [8],[9],[10] are considerably less accurate than the PSG due to strong susceptibility to engine valve actuation and vibration artifacts, sensitivity to sealing torque, and temperature and drift errors. So far these devices have not been used in production engines.

In contrast to the glow plug designs with either moving heater rod and piezoresistive sensor or piezoceramic load cell, the design employing a miniature fiber-optic-based sensor welded into the glow plug heater [11] offers high accuracy at all pressures. Also, the device is corrected against temperature errors associated with changing engine load or glow plug heating. Furthermore, the sensor is uniquely free of drift offering performance comparable to that of a water-cooled piezoelectric quartz reference transducer. Finally, the device is “self-cleaning” during glow plug actuation eliminating the risk of soot fouling. However, the device is not yet available commercially.

CPS INTEGRATION INTO CHG

An alternative approach to the glow plugs with integrated CPS considered for cylinder pressure-based engine controls relies on integration of either a strain gauge [12] or pressure sensor [13], [14] with an engine cylinder head gasket (CHG). Some inherent advantages of such integration over glow plug mounted sensors include suitability for use in all types and sizes of engines and different fuels, considerably lower cost especially in engines with a large number of cylinders, and compactness of the solution with a minimum number of connectors and harnesses needed. However, the cylinder head gasket with built-in strain gauges [12] has demonstrated poor correlation between the strain gauge output and cylinder pressure and large vibration artifacts. In contrast, the gasket based on a piezoelectric quartz sensor [13] has offered good performance. However, due to the sensor diameter of 3.5 mm the gasket thickness had to be increased from a typical ~1mm to 5mm making the design not suitable for a majority of engines, in particular the small ones recently of great interest to the automotive industry.

The previously reported [14] CHG with integrated CPS design based on a 1.7 mm diameter fiber-optic pressure sensor [15] requires a 2.5 mm thick gasket, which meets the industry expectations. Furthermore, the device accuracy is comparable to that of the same 1.7 mm diameter sensor mounted in the glow plug heater. However, this gasket design [14] relies on sensors that are permanently fixed to the gasket requiring engine head removal to replace the gasket in case a sensor failure occurs. The replacement of CHG with integrated CPS for a malfunction sensor is presently an undesirable service solution.

In this paper we report initial engine performance results on a CHGICPS that addresses potential service issues with replaceable CPSs in the CHG that can be easily removed while installed on the engine. This replaceable feature eliminates the laborious effort and cost associated with removing the cylinder head to address sensor performance issues.

METHOD- IMPROVED CHGICPS WITH REPLACEABLE CPS

COMBUSTION PRESSURE SENSOR ACCURACY CONSIDERATIONS

The CHGICPS reported in this paper targets advanced engine control and monitoring applications which require the CPS accuracy of $\pm 1.2\%$ of FSO at pressures above 5 bar and 0.3 bar or less thermal error, as measured against a water cooled piezoelectric quartz transducer. Such a very high accuracy needs to be realized for peak firing pressures ranging from 100 bar to 350 bar, under all engine load and RPM conditions, under hood temperatures ranging from -50°C to 150°C , and high levels of engine vibrations and EMI. In addition, the accuracy has to be retained over the device's lifetime of up to 15 years, 20 thousand hours, or 5 Billion pressure cycles, depending on the engine type and application.

In order to meet the target accuracy, an un-cooled CPS used in the CHGICPS needs to offer the following specifications. (1) Calibration accuracy, at room temperature, of $\pm 0.2\%$. (2) Sensitivity changes less than $\pm 0.5\%$ under engine load changes from idle to full load, corresponding in sensor head temperature changes as high as 200°C . (3) Offset changes less than 1 bar under an engine load change from idle to full load. (4) Maximum non-linearity and hysteresis less than $\pm 0.2\%$ of the FSO. (5). Sensor sensitivity changes less than $\pm 0.5\%$ for an under hood temperature change by 150°C . (6) Thermal error, related to the sensor diaphragm instantaneous distortion due to the effect of combustion gasses, less than 0.3 bar. (7) Sensor's response insensitive to engine head vibrations associated with valve or fuel injector actuation, as well as spark ignition related EMI. (8) Signal to Noise Ratio of 500:1 to 1000:1 at a 25 kHz bandwidth. (9) Sensor sensitivity and offset drift free over the device lifetime.

DESCRIPTION OF FIBER-OPTIC CPS USED IN CHGICPS

The CPS technology selected to develop the CHGICPS is the fiber-optic pressure sensor [15] shown in the schematic below (figure 1). The main advantages of this technology are its compact size, ability to operate at high temperatures, and low cost making it the preferred solution for CHGICPS.

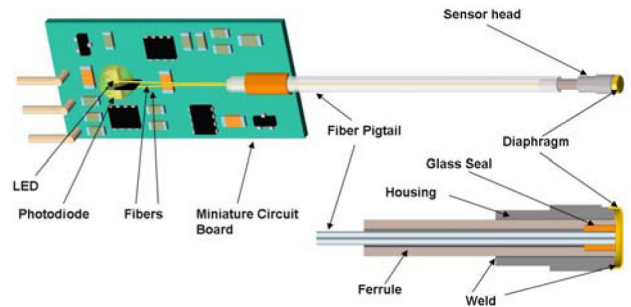


Figure 1. Schematic diagram of fiber-optic combustion pressure sensor

The sensor head 1.8mm in diameter consists of stainless steel housing with a welded hat-shaped diaphragm made of inconel 718 alloy and a metal ferrule with two optical fibers bonded inside. The other fiber ends are connected to the sensor signal conditioner. The diaphragm's inside surface is illuminated by the "delivering" fiber connected to a light source while the "receiving" fiber transmits light reflected from the diaphragm to a light detector. During sensor assembly the ferrule is advanced toward the diaphragm until the target gap is reached, at which time the ferrule is welded to the housing. Figure 2 shows the dependence of reflected light intensity as a function of the diaphragm to fiber gap. The red line shows the reflected light intensity changes resulting from the diaphragm's deflection on the order of 10 microns from its rest position D_0 to the position of peak pressure D_p .

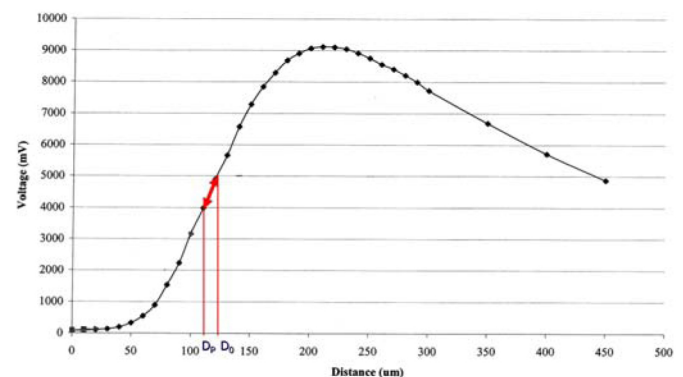


Figure 2. Reflected signal intensity as a function of fiber to diaphragm gap

The sensor signal conditioner board contains the LED and photodiode chips and the sensor circuitry. While the present prototypes use the SMD electronic parts, the mass production sensors will have most of the circuitry in the form of an ASIC so all the circuitry can fit on a 20 mm^2 board. The illumination-type, large core fibers are permanently bonded to the LED (850 nm wavelength, 150 micron emitting area, point-source type) and photodiode (silicon) chips. These low cost (encoder type) chips are mounted onto miniature, side-looking SMD packages.



The fiber-optic CPS described in this paper has been designed to meet all target specifications listed in this section. In particular, the non-linearity of $\pm 0.2\%$ of FSO or less is obtained by selecting the position D_0 near the inflection point of the response curves, where its second derivative goes through a zero value. The required minimum temperature dependence of the sensor sensitivity and offset, due to sensor head and signal conditioner temperature changes, are accomplished by the Auto-Reference technique [15] and its associated circuitry shown schematically in figure 3.

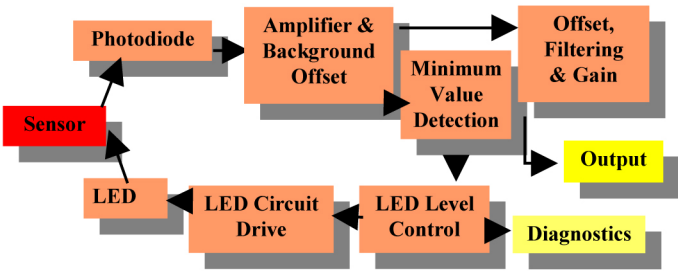


Figure 3. Block diagram of Auto-Referencing circuitry for closed loop control of LED drive current

The Auto-Referencing circuitry regulates the LED light intensity in a closed-loop control scheme so that the sensor offset is kept constant as the sensor head and signal conditioner temperatures change. In combination with the Temperature Compensation technique [15], the closed loop LED control also corrects for the temperature dependence of sensor sensitivity associated with the diaphragm's deflection temperature dependence [16]. The temperature compensation technique relies on an optimum selection of the sensor housing and ferrule thermal expansion coefficients and their lengths resulting in an increased diaphragm-to-ferrule gap with increasing sensor head temperature. The resulting increase in the reflected signal at minimum pressure is compensated by reducing the LED output by the auto-referencing circuitry, effectively reducing the sensor gain. This reduction is optimized to offset the effect of increased diaphragm deflection at increased temperature. It is to be noted that the compensation of both effects of sensor head and signal conditioner temperature on the sensor offset and sensitivity is implemented without any temperature sensors, either in the sensor head or its signal conditioner. Another advantage of the auto-referencing circuitry is its ability to maintain drift-free sensor offset under engine load changes and over the device's lifetime. Finally, the thermal error is kept at a low level owing to a heat shield installed in the CHG distance layer in front of the sensor diaphragm.

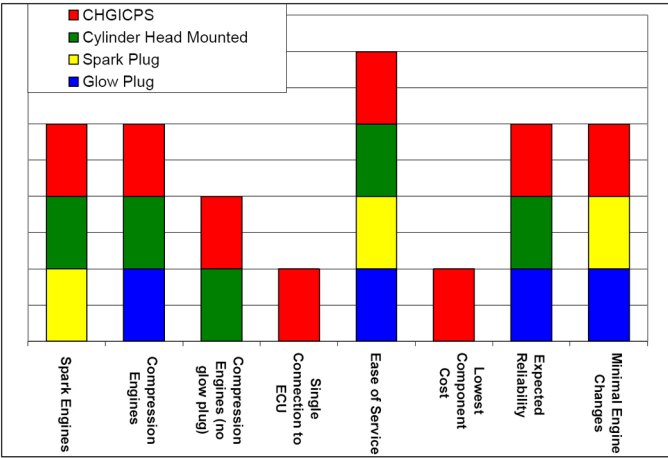
The fiber-optic CPS is inherently free of any hysteresis due to the “non contact” device principle, in which the diaphragm does not contact the fibers. The sensor is also free of any engine vibration artifacts that typically plug other types of CPSs. Reaching the maximum SNR target is relatively

difficult due to the use of high gain circuitry needed to amplify the low LED intensity and due to the circuitry high upper frequency of 30 kHz. Finally, the fiber-optic principle eliminates any EMI effects in the sensor head, but care needs to be exercised to shield the sensor electronic circuitry.

CHGIPS WITH REPLACEABLE CPS VS OTHER CPS ACCESS

There are many ways to effectively measure combustion pressure on internal combustion engines through a port in the cylinder head, spark plug, glow plug, or CHG, which are summarized in table 1. The cylinder head, using a dedicated port, is an obvious solution and works for all internal combustion engines with space permitting, but with compromise of structural rigidity. The economic negative is the additional machining and the expense of multiple rugged independent CPS components. The spark plug offers an opportunity for ignition type engines as an integrated product. Design challenges for this solution are the high temperature exposure of the CPS due to the location and the close proximity to high electromagnetic noise. As for the glow plug solution, as described earlier, it is currently in production and has its own its own specific design challenges. The CHG has the advantage of being a component that is used on all engine types and sizes at a location in the engine where the temperature is moderate. The economic advantage of this design solution is its simplicity, while providing an on engine replaceable sensor and a single connection to the ECU with minimal changes to the engine.

Table 1. Comparison of CPS Access Technologies



CHGICPS WITH REPLACEABLE CPS - PROTOTYPE FEATURES

To address the complicated servicing procedure of a permanently mounted CPS design, a more efficient servicing approach is being developed, which is termed CHGICPS with replaceable CPS as shown schematically in figure 4. This new design, figure 5, uses the same 1.7 mm diameter fiber-