FIBER OPTICS-BASED CYLINDER PRESSURE SENSORS FOR ADVANCED ENGINE CONTROLS

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Abstract

This paper presents the design, applications, and performance of the miniature fiber optic-based cylinder pressure sensor which has targeted advanced engine controls requiring high accuracy pressure information. Three types of sensor packages are described currently utilized in prototype closed loop control systems for diesel, gasoline, and dual fuel engines: glow plug with the heater-mounted sensor, spark plug with removable sensor, and a stand alone package. All these packages are based on the 1.7mm diameter sensor which has been validated in various combustion engines over the last ten years. This robust low cost sensor operates on the principle of light intensity changes due varying reflection from a flexing metal diaphragm, monitored by two optical fibres. The sensor is compensated for all major temperature errors encountered in internal combustion engines. (1) The auto-referencing technique maintains sensor calibration compensating for temperature effects on the sensor signal conditioner over the range of –40ºC to +150ºC. (2) In a reliable design the sensor head materials and dimensions are optimized to compensate for the mid-term thermal errors associated with engine load changes over a temperature range of –40ºC and 380ºC, resulting in the thermal coefficient of sensitivity as low as 0.005%/ºC. (3) Due to minimal heat flux associated with the sensor's small diameter the thermal shock error is minimized such that the total accuracy is typically in the range of 1- 2%, dependent on sensor package and application. Close to a hundred glow plug-integrated sensors have been used in on-road tests over several hundreds of hours without sensor performance degradation or soot fouling. Tens of spark plug mounted sensors have been utilized to control engine knocking in aircraft engines fueled by automotive gasoline. Finally, several tens of stand alone sensors have been used to control heavily knocking diesel-natural gas engines operating in the Homogenous Charge Compression Ignited mode.

1. Introduction

Cylinder pressure is the fundamental engine parameter that offers the most direct and valuable input information for advanced control systems [1]. Such systems are needed to meet ever stricter emission regulations that now affect, with a varying degree of severity, all types of internal combustion engines including those used in passenger cars, trucks, off-road vehicles, marine, watercraft, locomotives, and aircraft as well as stationary engines used in gas and oil pipelines or electricity generation. Based on cylinder-specific pressure information, closed-loop control strategies have been demonstrated for power balancing in large-bore natural gas engines, lean burn combustion in passenger cars and air-fuel control in natural gas engines [2]. The most advanced controls allow for both fuel delivery and ignition control in each cylinder and during each combustion cycle in what has been termed the Controlled Combustion Engine (CCE) [3].

The two critical combustion attributes that are of interest in the engine control of a spark-ignited engine are air-fuel charge delivery and ignition timing. Closed-loop spark control techniques provide timing that is optimized in the presence of different fuels, changing engine and environmental conditions. Such approaches provide optimum performance under all conditions and are able to adapt to varying knocking conditions in each cylinder. Based on cylinder pressure information, air-fuel ratio can be estimated to provide the best possible transient control in individual cylinders during cold-start and in lean-burn region.

In diesel engines the detection of the start of combustion has attracted the most attention to reduce NOx and soot emissions. In recently popular direct injection engines as much as 15% and 12% reduction in soot and NOx emissions, respectively, have been already demonstrated through the closed loop control of fuel injection based on the IMEP and 50% mass fraction burned values calculated from pressure information provided by glow plug-mounted sensors located in one [4] or all engine cylinders [5].

Optical fiber-based sensors are very well suited for applications characterized by high temperatures and high levels of EMI encountered in combustion engines [6]. These benefits combined with exceptional durability and very low cost make fiber optic sensors prime candidates for use in automotive production engines. Due to their miniature sizes, resistance to high temperatures, and immunity to EMI, these sensors can be combined with existing engine components such as ignition spark plugs, fuel injectors, glow plugs, or head gaskets. Such multifunctional devices with an embedded pressure sensor offer numerous advantages for practical and low-cost automotive systems not only from the point of view of sensor expense alone but also on the account of minimum total installation and operational cost. An embedded sensor does not require a separate access point into the engine and the device that the sensor is integrated with can be conventionally installed. No additional cable or connector is needed since the pressure sensor information is sent via the existing cable and connector.

2. Sensor description

The "generic" transducer used in various sensor packages consist of three basic components: a sensing head, a fiber optic cable, and a signal conditioner containing sensor optical and electronic components, as shown in Figs. 1 & 2.

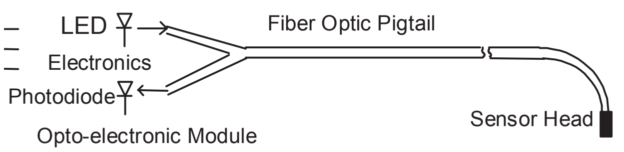

Fig. 1. Schematic sensor construction

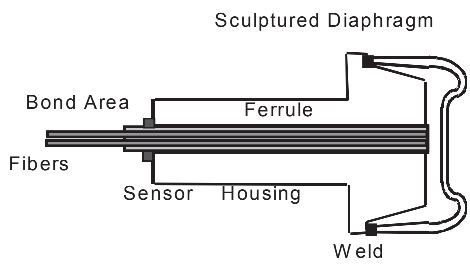

Fig. 2. Sensor head construction

The simple and robust design of the sensor head consists of a metal housing with a welded sensing diaphragm, a fiber holding ferrule, and two fibers bonded inside the ferrule, as schematically shown in Fig. 2. The sensor's response results from the pressure-induced diaphragm displacement that changes the optical signal transmitted from the sending to the receiving fiber [6]. For a given diaphragm displacement due to pressure change the sensor response, i.e. sensitivity and linearity, can be adjusted by a suitable choice of optical fiber core diameters and numerical apertures, as well as adjusting the relative position of the fibers in respect to the diaphragm. The linearity is affected by the diaphragm's mechanical stiffness as well as the linearity of the light intensity change due to diaphragm movement. With a typical fiber Numerical Aperture of 0.32 and core and cladding diameters of 100 and 140 micron, respectively, and full scale deflection of 10-15 microns of the Inconel 718 diaphragm, the pressure response linearity may be as low as 0.05% FSO, with a typical value +/-0.5% FSO. To ensure durable operation the present sensor uses a sculptured, hat-shape Inconel diaphragm with a varying thickness across its diameter. The diaphragm shape and material have been selected to meet the requirement of high strength at combustion temperatures, low creep, and fatigue life of hundreds of millions of pressure cycles. Preferably, the diaphragm has to be as small as possible so that the sensor requires the least space for mounting. At present, the smallest sensor has the diaphragm diameter of 1.7 mm making it suitable for integration into engine components such as spark plugs, glow plugs, head gaskets, or fuel injectors. However, a very small diameter creates a significant design challenge due to the simultaneous requirement of large diaphragm deflection (for high signal to noise ratio) and low stresses required for long lifetime. In a typical passenger car application the sensor has to function reliably over hundreds of millions of pressure cycles while in diesel truck engines the lifetime has to approach 2 Billion cycles.

Perhaps the most challenging aspect of a cylinder pressure sensor is the requirement of low thermal errors. A combustion-cylinder pressure sensor installed under-hood of a car or truck is subject to three types of temperature errors:

1. Shortest time-constant error (of the order of a few milliseconds): Associated with diaphragm distortion due to the exposure to combustion gasses. While this exposure lasts only a few milliseconds, it occurs with a time constant comparable of that of the pressure waveform. As a result, the diaphragm's position at minimum cylinder pressure is different during the compression and expansion parts of the combustion cycle.
2. Medium time-constant error (of the order of a few seconds): Associated with increasing average diaphragm temperature during increased engine load due to an average diaphragm temperature exceeding that of the engine head. For a typical application when the engine-head cooling effect limits the maximum diaphragm temperature to less than 500ºC, this error if not compensated for can be as high as 12% FSO. In engine R&D applications this error is minimized by using water-cooling, which essentially keeps the sensor average temperature constant. The water-cooling approach is however not suitable for use in production engines.
3. The long time-constant error: Associated with varying underhood engine temperature ranging from –40ºC to 140ºC (as high as 150ºC under hot shot down conditions). Such changes result in changing efficiency of the electronic and opto-electronic components of the sensor signal conditioner which when not compensated for may lead to several tens of percent measurement errors.

The temperature compensation technique used in the present sensor provides accurate pressure data under changing engine load conditions without the use of a separate temperature sensor. The thermal expansion coefficients and dimensions of the sensor are optimized in such a way that fiber-to-diaphragm distance increases with increasing temperature. The ferrule and housing elements are bonded certain distance away from the diaphragm (as shown in Fig. 2) so that the difference in the thermally induced part elongation with temperature may be significant. When temperature increases and the minimum distance between the diaphragm and the fibers increases, the auto-referencing circuitry reduces LED forward current - effectively reducing the sensor gain. The rate of gain reduction occurs in such a way that it compensates for the increase in the diaphragm's deflection with temperature; for the diaphragm made of Inconel 718 super alloy the uncompensated temperature coefficient of the diaphragm deflection of approximately +0.03%/°C is then reduced to the value as low as +/-0.005%/°C, typically +/-0.01%/°C [7].

The second critical sensor component significantly affected by temperature is the opto-electronic signal conditioner (as schematically shown in Fig. 1) containing a photodiode, an LED, and an associated electronic circuitry. The circuitry controls LED light intensity, amplifies and filters photodiode signal, and provides the auto referencing function. In a powerful yet inexpensive design this technique [6] regulates LED light intensity in response to any undesirable environmental conditions that may alter minimum detected light intensity. Baseline light intensity in fiber optic sensors may vary due to the light source or detector temperature dependence, optical link transmission fluctuations resulting from connectors' mechanical and thermal instabilities, fiber bending, or their aging over time. The auto-referencing approach corrects for both the sensor offset and gain drift. A side benefit of the technique is the availability of sensor health monitoring output. By continuously monitoring the LED current level or its rate of change, one can identify potential sensor failure before it occurs.

In order to meet the lifetime requirement of approximately 10 thousand hours at the signal conditioner temperatures typically as high +140^{o}C and occasionally at +150^{o}C, the LED driving current is kept at the maximum DC value of 15mA at 150^{o}C. Alternatively, the driving current is pulsed allowing operation at a higher peak current and the use of inexpensive LED chips.

In the present design the signal conditioner is mounted inside a metal protective shell, as shown in Fig. 3. In the mass production version the conditioner will be drastically reduced in size by replacing the current discrete LED and photodiode parts and conventional electronic components by a custom opto-electronic transceiver and a dedicated Application Specific Integrated Circuit (ASIC), respectively. All these parts will be sufficiently small so they can fit inside a typical electrical connector used in automotive or truck applications, as shown in Figs. 5 & 8.

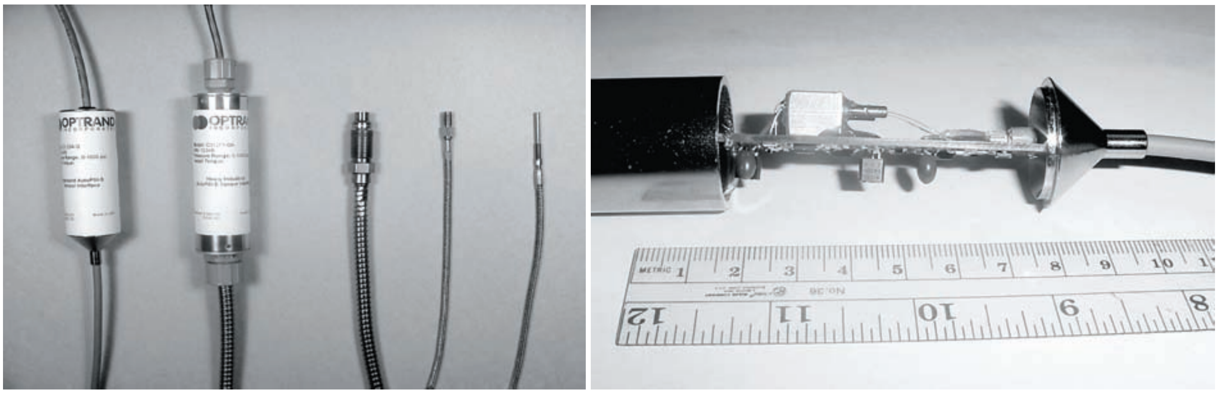

Fig. 3. Photographs of current cylinder pressure sensors used in engine R & D/monitoring

3. Sensor packages targeted for production engines

Due to its miniature size, resistance to high temperatures, and non-electrical nature, the sensor can be installed into a variety of packages ranging from conventional designs intended for head-mounted applications to higher-functionality pressure sensing spark plugs or glow plugs. For spark ignited engines the sensor can be permanently sealed inside a conventional spark plug with the sensing diaphragm semi-flush mounted with the spark plug front surface, as shown in Fig. 4. Alternatively a detachable sensor can be threaded into a modified spark plug, as shown in Fig. 6 for a spark plug used in aviation engines. In the ultimate design of the spark plug-integrated sensor, targeted for mass production, a signal conditioner is mounted on the top of an ignition coil allowing one cable to be connected to the sensor and the coil. The spark plug, the ignition coil, and the sensor are preferably integrated into a single, non-detachable device, the PressureSense Igniter, as shown in Fig. 5.

Fig. 4. Instrumented spark

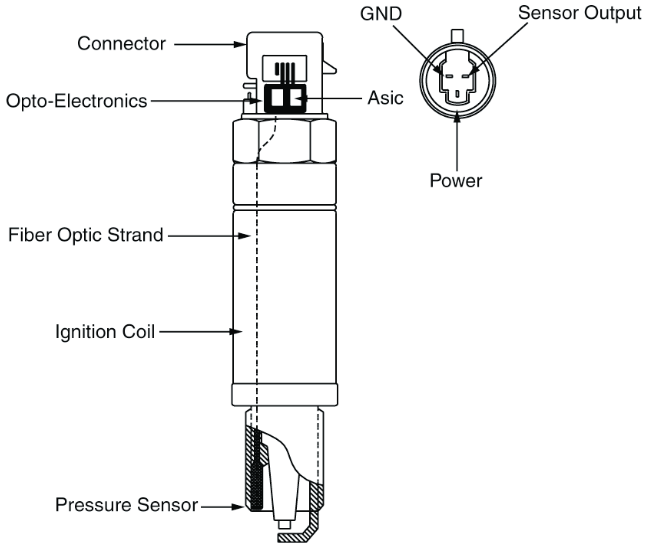

Fig. 5. PressureSense Igniter targeted for production engines

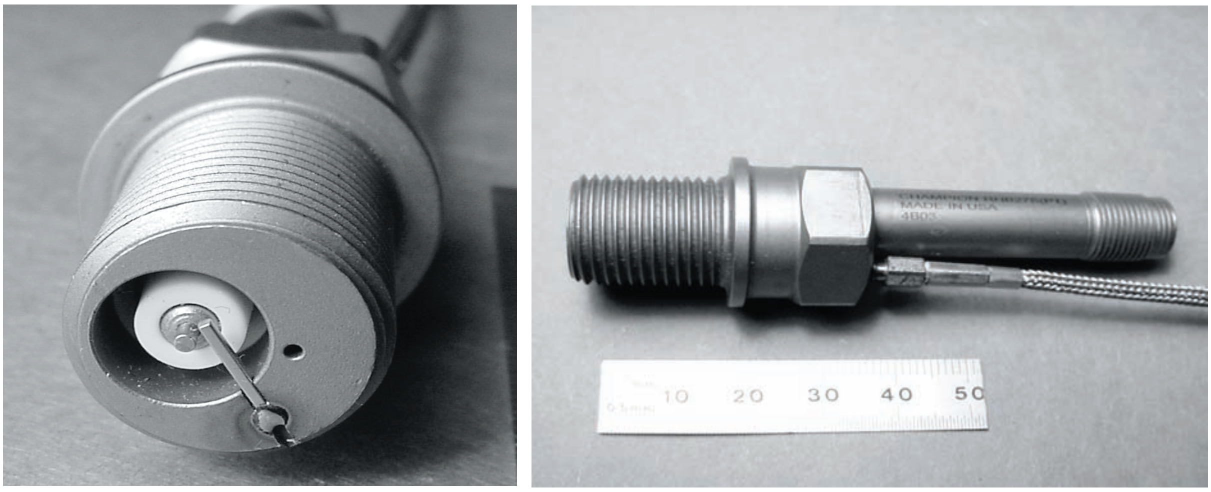

Fig. 6. PSIplug: Spark plug with removable sensor used in airplane engines

For use in passenger car diesel engines a number of packages have been developed in which the pressure sensor is integrated with a glow plug, the PressureSense Glow Plug^{TM} (PSGP), as shown in Figs. 7 & 8. In a design only possible with a non-electrical sensor, like a fiber optic one, the sensor diaphragm is welded into the glow plug heater electrical pole with and the pressure access channel formed in the heater. Due to the location of the pressure access orifices near the heater coils the device “self-cleans” during glow plug activation, when the pressure passage temperature reaches the temperature of ~650^{o}C and any potential deposits burn off. Fig. 7 shows a prototype device assembled from the parts of a conventional glow plug. The signal conditioner, as shown in Fig. 3 is attached at the end of a ~2m-lonng fiber optic cable. Fig. 8 shows the PSGP design targeted for production engines (based on a glow plug with a metal sheath heater). The sensor signal conditioner is encapsulated in an automotive-like connector directly attached to the glow plug body with 3 smaller sensor pins and the fourth (largest) pin dedicated to the glow plug heater.

Since the design shown in Fig. 8 is not yet in production, prototype devices, as shown in Fig. 7, have been used in engine tests and development of closed loop engine control strategies.

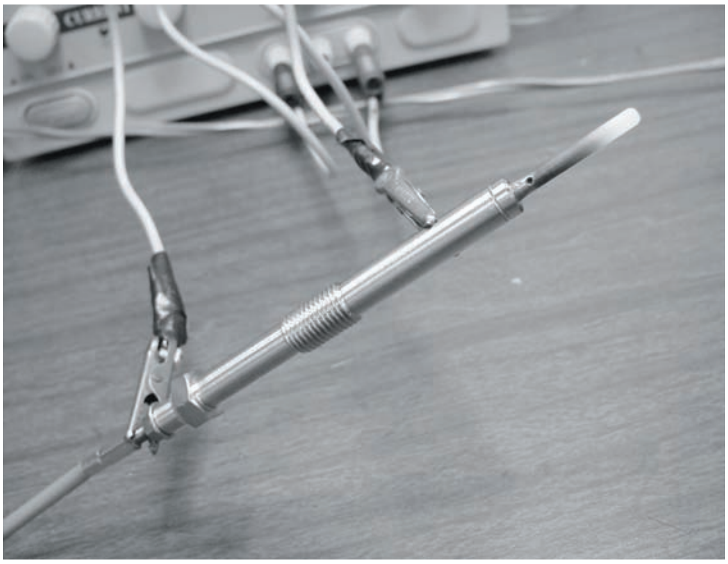

Fig. 7. Prototype PSGP

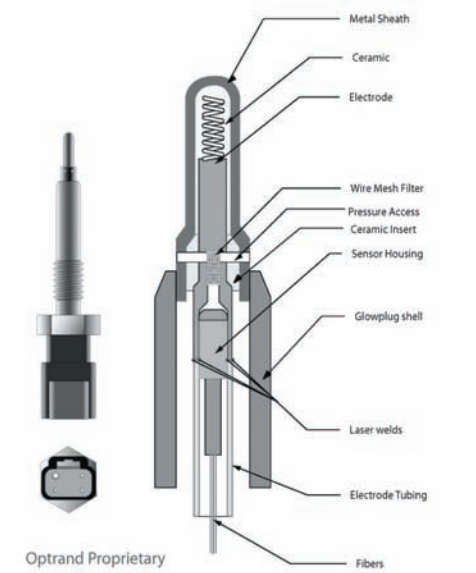

Fig. 8. PSGP targeted for use in production engines

4. Specifications and performance

The present cylinder pressure sensor targets those engine control and monitoring applications that require relatively high accuracy over the full pressure cycle and at low pressures in particular. Other critical sensor features are long life, high reliability, and low cost. Good linearity, low thermal shock error, and overall high accuracy at low pressures are required within a single combustion cycle so that the sensor output can be sufficiently accurate for mass air flow calculations. Basic specifications of the sensors intended for production engine applications are summarized in Table 1.

Table 1. Specifications of pressure sensors targeting production engine use

Pressure range:	0 – 100 bar or 0-200 bar
Over-pressure range:	1.5 x pressure range
Linearity & hysteresis – non combustion:	0.5% FSO
Linearity, hysteresis, thermal shock	1 - 2% FSO
Frequency response:	0.1-1Hz to 20-30 kHz
Minimum Sensor diameter:	1.7 mm
Signal to Noise Ratio (@ 20 kHz)	1000:1
Sensor housing continuous temperature:	-40 to 380ºC
Connector continuous temperature range:	-40 to 150ºC
Sensor Output:	0.5(0.3) -4.5 (3.5) V
Power consumption:	Max 20mA @ 5V supply
Life time:	0.5B -2 B, 5k-20k hours

Fig. 9 demonstrates the performance of the M5x0.5 thread sensor mounted directly in an engine head. The engine was a single cylinder, air-cooled, gasoline fueled engine attached to an electricity generator. A Kistler 6061water-cooled piezoelectric transducer was used as a reference. The Optrand sensor package included a “heat shield” disk welded in front of the diaphragm, aimed at reducing the effect of thermal shock. The sensor demonstrates excellent linearity and minimum thermal shock error in spite of the relatively low peak pressure of only ¼ of the sensor pressure range. The data shown was obtained over one cycle but a running average of 5 points was used for the display purpose.

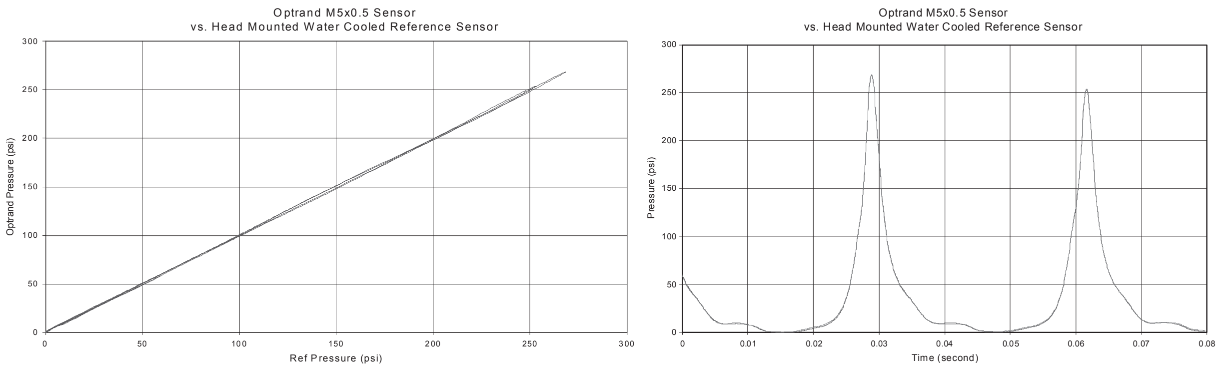

Fig. 9. Head-Mounted Sensor Performance: Total Non-Linearity\ Thermal shock +/- 0.44%

The performance of a spark plug-mounted sensor in is shown in Fig. 10. To mount the sensor, as shown in Fig. 4, a minimal modification to a production spark plug with M14x1.25 thread involved machining a sensor cavity and a fiber passage in the shell area. It is to be noted that a spark plug-mounted combustion pressure sensor is subject to potential errors compared to a head-mounted location. First, a spark plug sensor needs to be extremely small to fit into the spark plug shell. However, small diameter reduces diaphragm deflection resulting in lower detection sensitivity and Signal to Noise Ratio. Second, a spark plug-mounted sensor does not benefit from the same degree of cooling available to a head-mounted device since the spark plug body temperature is considerably higher than that of a water-cooled engine head. Third, unless the sensor diaphragm is flush-mounted, the potential for pressure waveform distortion and phase delay exists due to Helmholtz and standing wave resonance. Figs. 10 & 11 demonstrate that in spite of its miniature size a spark plug-mounted sensor can be highly accurate, within 1-2% of an uncooled piezoelectric transducer (Kistler 6051). At low pressures, Optrand sensor performance was actually superior to that of an uncooled piezoelectric reference due to the lower thermal shock error. Similar flat response at low pressures is observed in a passenger car test data shown in Fig.11.

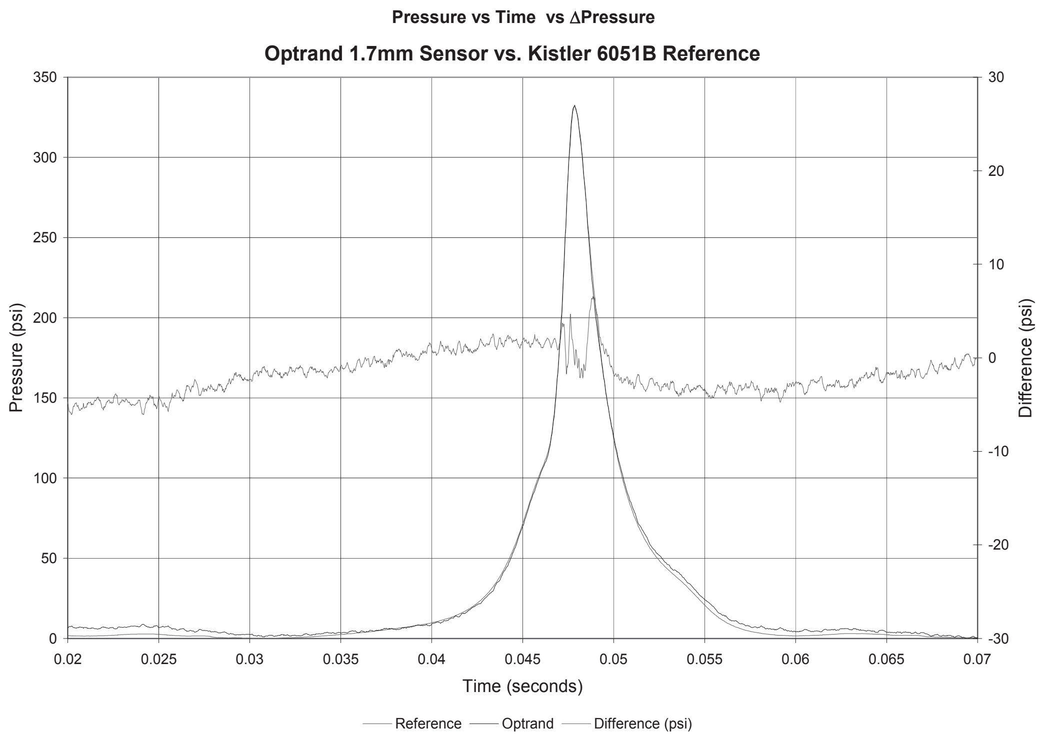

Fig. 10. CALplug single cylinder performance

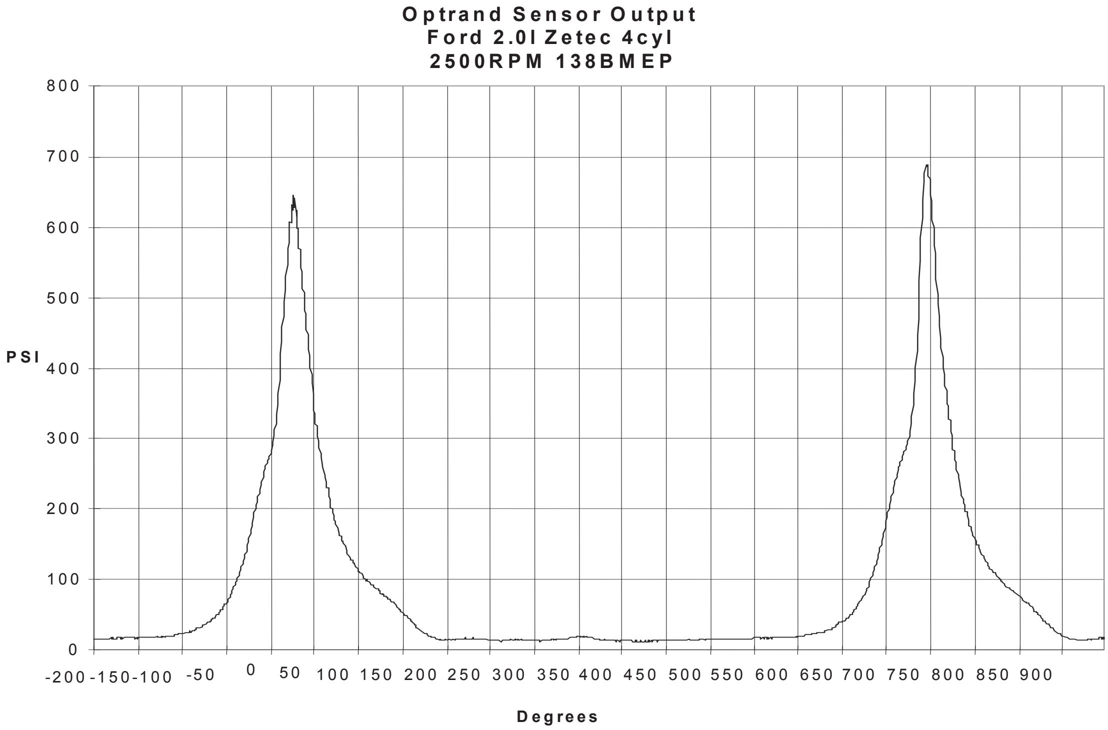

Fig. 11. CALplug automotive engine performance

Figs. 12a & 12b demonstrate typical performance of the PSGP as tested on a single cylinder genset engine. Kistler 6061water-cooled piezoelectric transducer was used as references. As seen in both figures the sensor demonstrates excellent linearity and minimum thermal shock error. It is to be noted that the pressure response show some small "ringing" effect at maximum pressures due to the PSGP pressure passages. However, this ringing can be easily filtered as the characteristics frequencies of interest in diesel engines are below the ringing frequency.

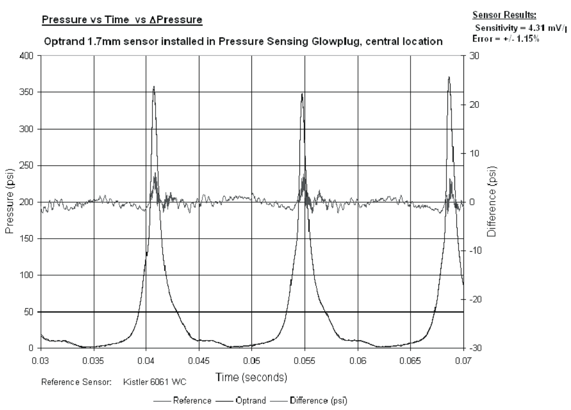

Fig. 12a. Pressure vs. time performance comparison

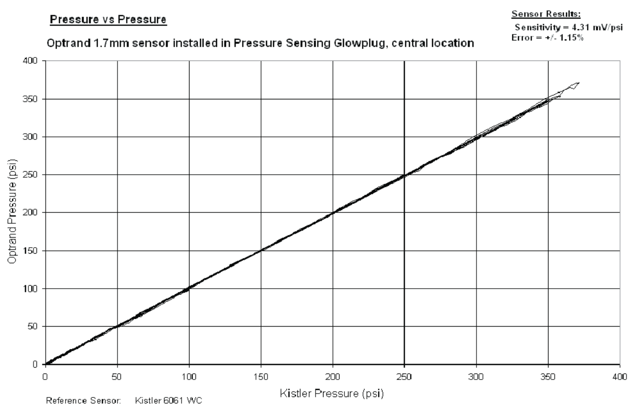

Fig. 12b. Pressure vs. pressure comparison

Figs. 13 & 14 show the comparisons between the Indicated Mean Effective Pressure (IMEP) and 50% mass burn (MFB) values calculated based on the PSGP output versus those obtained with the Kistler 6053 reference transducer. The data was collected in all four cylinders of a 1.9l common rail passenger car diesel engine. Notice that the accuracy of the calculated IMEP and MFB values is exceptionally good, within 1% of the values obtained with the reference transducer.

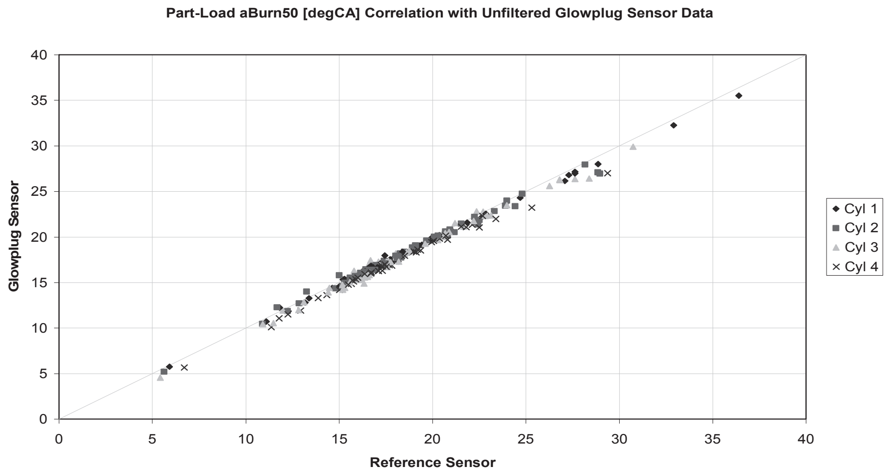

Fig. 13. 50% mass fraction burned comparison between PSGP and reference transducer

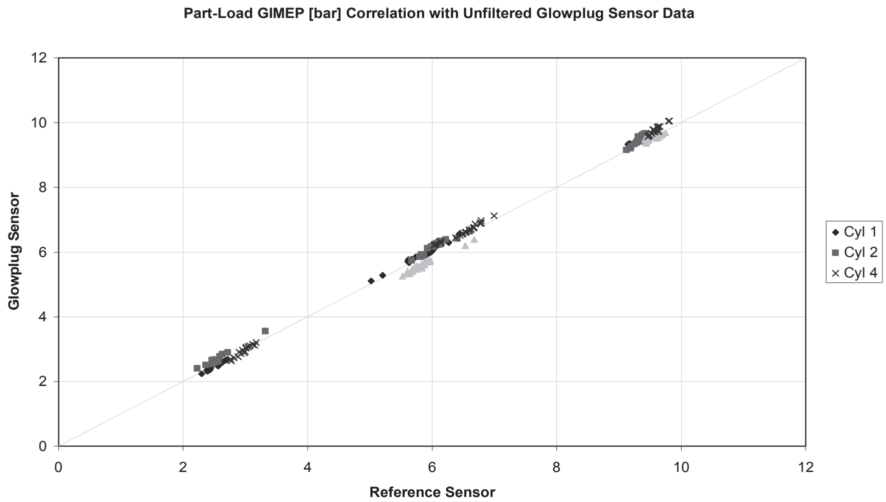

Fig. 14. IMEP comparison between PSGP and reference transducer

Over the last 8 years a few thousands of Optrand sensors have been subjected to endurance and calibration stability tests in gasoline, hydrogen, diesel, and natural gas engines. Most of the long term applications have been in large-bore natural gas stationary engines and have demonstrated durability of as much as 40 thousand hours. In addition to the endurance tests, hundreds of sensors have been subjected to long-term calibration stability tests. Periodically, every few to several months, the sensors were re-calibrated using air or water-cooled reference transducers (strain gauges or piezoelectric sensors) in natural gas and diesel. During a 6 to 12 month period the sensors demonstrated excellent calibration stability (compared to the initial values), ranging from a non-detectable to +/-0.1% change in the sensor sensitivity value.

Close to a hundred of glow plug-integrated mounted have been used in road tests over several hundreds of hours without sensor performance degradation or soot fouling. Tens of spark plug mounted sensors have been used to control engine knocking in aircraft engines fueled by regular automotive gasoline. Finally, several tens of stand alone sensors have been utilized to control heavily knocking diesel-natural gas engines operating in a partial Homogenous Charge Compression Ignited mode.

5. Summary and conclusions

The 1.7 mm diameter fiber optics-based cylinder pressure sensor utilizes the principle of light reflection from a flexing metal diaphragm, monitored by two optical fibers. A hat-shape Inconel diaphragm meets the requirement of high strength at combustion temperatures, low creep, and the fatigue life of up to 2 Billions (10E9) of pressure cycles.

The sensor as small as 1.7mm in diameter is suitable for integration into such engine components as spark plugs or glow plugs. Sensor's simple opto-electronic signal conditioner contains a photodiode, an LED, and an associated all-analog electronic circuitry. The sensor is compensated for varying gas temperatures, engine load changes, and under-hood ambient temperature changes. The auto-referencing technique maintains sensor calibration compensating for temperature effects on the sensor signal conditioner over the range of –40º to +150^{o}C. The sensor head materials and dimensions are optimized to compensate for the mid-term thermal errors associated with engine load changes, resulting in the thermal coefficient of sensitivity as low as 0.005%/^{o}C over a temperature range of –40 to 380ºC. Due to the miniature diaphragm size the sensor features very small thermal shock error resulting in high accuracy at low pressures. The sensor has been used in gasoline, natural gas, diesel, and hydrogen engines demonstrating the total error in the 1-2% range depending on sensor package, mounting, and application.

Over the last 8 years a few thousands of Optrand sensors have been subjected to endurance and calibration stability tests in gasoline, diesel, and natural gas engines and demonstrated durability of as much as 40 thousand hours in stationary natural gas engines. The designs targeted for mass production included sensors integrated with glow plugs and spark plugs as well as stand alone devices. Close to a hundred of glow plug-integrated sensors have been used in the development of closed loop controls for automotive diesel engines; in road tests over several hundreds of hours sensors performed without any degradation or soot fouling. Tens of spark plug mounted sensors have been used to control engine knocking in aircraft engines fueled by regular automotive gasoline. Finally, several tens of stand alone sensors have been utilized to control heavily knocking diesel-natural gas engines operating in a partial Homogenous Charge Compression Ignited mode.

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