A Fiber-Optic Pressure Sensor for Internal Combustion Engines

A multiplexed fiber-optic pressure sensor system has proved accurate and durable at high temperatures in extended engine tests.

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Photo 1. *Fiber-optic pressure sensors have* been extensively field tested in large stationary *reciprocating engines used* in gas *transmission. Shown here is a Clark* TLA-6 engine in an El Paso *Natural Gas compressor station* in Win&ester, *Kentucky.*

The need for improved in-cylinder pressure sensors for reciprocating engines is widely recognized in both user and R&D communities. The ideal sensor would give accurate readings of combustion chamber gas pressure with high temporal resolution within each engine cycle. It would also operate reliably for several years-at least one year without calibration-and be affordable (i.e., cost a few hundred dollars per cylinder). Engine control systems incorporating these sensors could reduce harmful emissions levels and improve fuel economy, as well as perform parametric monitoring for predicting emission levels. They would also find immediate application in instrumentation for engine research and development (see Photo 1).

The present standard for in-cylinder pressure measurement is a piezoelectric transducer mounted in a special port in the cylinder head, or in the Kiene valve that provides direct access to the cylinder. Two types are used: in one, a piezoelectric element is directly exposed to the pressure; in the other, a piezoelectric strain gauge responds to the displacement of a piston exposed to the pressure.

During engine operation these transducers must be cooled by circulating air or water. Even then, frequent calibration is required and operating life is relatively short. Furthermore, piezoelectric transducers are fragile and expensive and are vulnerable to electromagnetic interference. They have proved essential in engine research and development but have not been widely incorporated into engine products.

Fiber-Optic Advantages

Emerging fiber-optic sensor technology may for the first time make continuous in-cylinder pressure monitoring cost-effective outside the R&D laboratory [1,2]. Fiber-optic sensors are:

- Extremely sensitive
- Capable of operation at elevated temperatures for extended time periods
- Capable of safe operation in the presence of volatile gases or liquids
- Immune to electromagnetic interference
- Mechanically flexible and rugged
- Amenable to being located several kilometers from monitoring electronics
- Capable of being multiplexed to dramatically reduce the average cost per cylinder

Sensor Description

The fiber Fabry-Perot interferometer (FFPI) sensing element, the basis for the in-cylinder pressure transducer described here, consists of two internal mirrors separated by a length, L, of single-mode optical fiber (see Figure 1). To monitor the FFPI element, light from a semiconductor laser is coupled into the fiber and a portion of the reflected optical power is converted to an electrical signal by a photodetector. A change in the measurand of interest (in this case, pres-

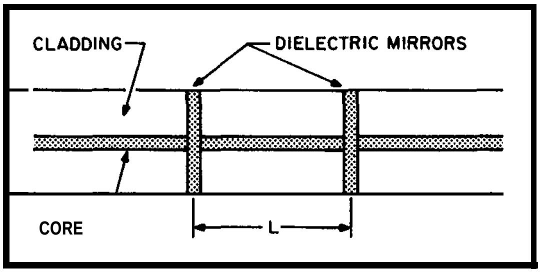

Figure 1. The fiber-optic *Fabry-Perot* interferometer is formed in a fused silica *fiber with a cladding diameter of 125 μm (0.005 in.) and a core diameter of 10 pm (0.0004* in.). For *the engine sensor, L = 1.2 cm.*

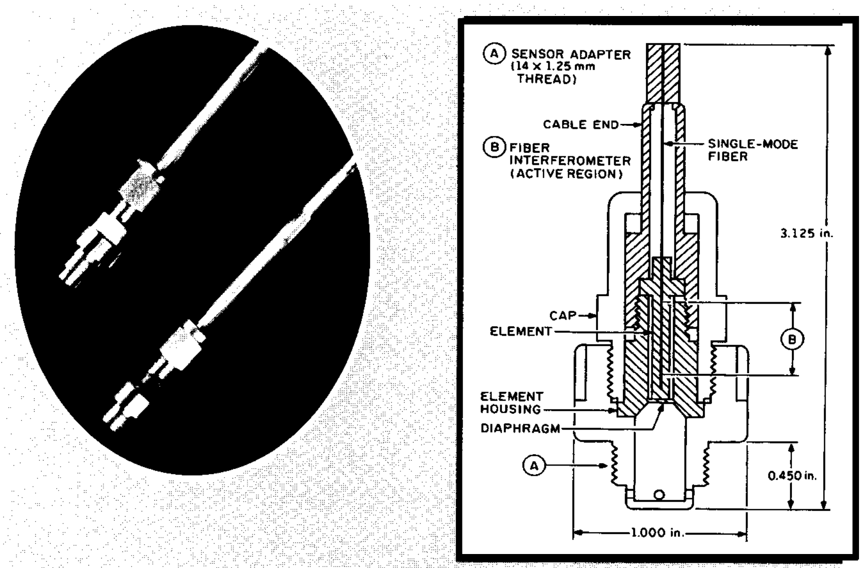

Photo 2 *and* **Figure 2.** ***Pressure on the diaphragm of this pressure sensor configuration causes a longitudina compression of the metal element in which the fiber interferometer is embedded.***

sure) results in a change in the length L of the interferometer. The reflected power level, as determined by coherent interference of light from the two mirrors, is very sensitive to small changes in L. (The ability of FFPI sensors to detect very small perturbations stems from the inherent sensitivity of interferometers to small displacements, a characteristic appreciated by optics researchers since the 19th century).

The mirrors are fabricated by vacuum deposition of a thin film of TiO_2 on the cleaved end of a fused silica fiber. Each has a reflectance of -5%. They are integrated by electric arc fusion into a continuous length of the fiber. In the engine sensor described here (see Photo 2 and Figure 2), the FFPI sensing element is embedded along the axis of a metal element that is then inserted into a metal housing with a 0.5 mm thick lower wall (diaphragm). A threaded cap at the top of the housing is torqued to produce a slight compression of the metal element. A stress-relief cable end with steel braid completes the assembly. The sensor is then mounted in a threaded port in an adapter that screws into a threaded port in the cylinder head, or in a Kiene valve. By allowing the gas to cool before it reaches the diaphragm, the adapter attenuates the effect of rapid temperature changes that occur during a combustion cycle. No thermal compensation is required, and none of the FFPI sensors is provided with external cooling.

The engine sensor is designed such that under typical operating conditions the in-cylinder pressure produces only a very small strain in the fiber (about 12 μstrain, or about 0.12 pm change in L). The raw sensor signal generated by the photodetector is processed electronically to determine the change in optical path length produced by he in-cylinder pressure. Change in pressure s derived by applying an appropriate calibration factor, with an assumed linear relaion between the pressure and the interferometer path length. As is true with other sensing technologies such as piezoelectric, semiconductor, micromachined IC, and surface acoustic wave, the FFPI can be configured to respond to different measurands (see sidebar).

The optical signal conditioning unit (SCU) can monitor up to 24 FFPI pressure sensors with a digital signal processor (see Figure 3) and a single distributed feedback (DFB) laser emitting at a wavelength of 1.3 pm. A grating integrated into the semiconductor diode causes the DFB laser to emit a single optical frequency at any given moment. The laser is driven with a periodic, slightly nonlinear sawtooth current waveform to give a linear chirp (i.e., a linear variation of the optical frequency with time) during each modulation period[2]. A Faraday isolator, a magneto-Optical one-way mirror, provides better than 30 dB suppression of optical feedback into the laser. Without an isolator, the feedback Causes instability in the laser's frequency and emitted power, with adverse consequences to sensor performance. A 1 by 25 "star" coupler distributes the laser light to the individual FFPI sensors; 2 by 1 directional couplers direct the reflected signals to an array of PIN photodetectors (see Figure 4). The photodetectors are reverse-biased InGaAs diodes; PIN refers to adjacent regions of p-type, intrinsic, and n-type material. A Motorola 68332 microprocessor uses a counting scheme to track the fringes (periodic variations in the photodetector signal) produced by each sensor; determines the phase shift in each fiber interferometer; and applies calibration factors to compute the pressure readings. Sensor calibration, a straightforward procedure requiring only a few minutes, is accomplished by means of a dead-weight tester with a quick pressure release valve. The normal sampling rate of 2 kHz, equal to the repetition frequency of the sawtooth waveform, is much greater than any frequency component in the pressure signal from the large, stationary engines used in natural gas transmission, which typically run at 300 rpm (5 Hz). For faster engines such as diesel locomotives, which run at -900 rpm, software changes allow the sampling rate to be increased to 8 kHz, with a corresponding reduction in the number of

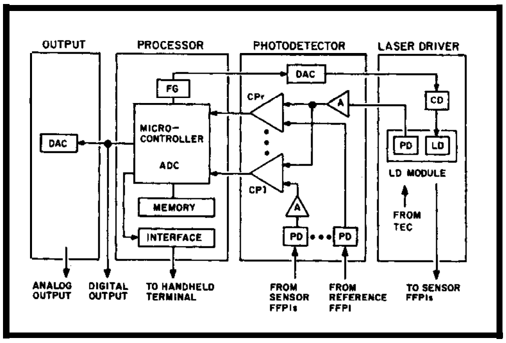

Figure 3. The components of the signal conditioning *unit are* D/A converter *(DAC); function generator (FG);* A/D converter *(ADC);* comparator *(CP); amplifier* (A); *photodetector (PD);* current *driver [CD); thermoelectric cooler (TEC); and laser diode (LD)*

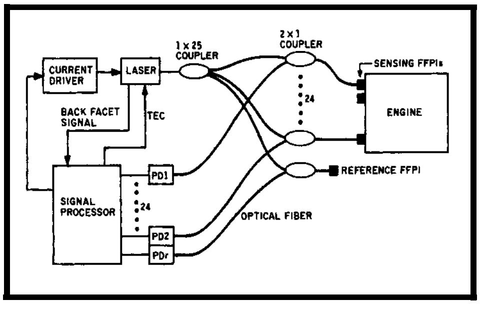

Figure 4. A *single laser provides frequency-modulated light to as many as 24 pressure sensors.* A *signal processor demodulates these signals to produce pressure vs. time outputs. (TEC = thermoelectric cooler and* PD = *photodetector.)*

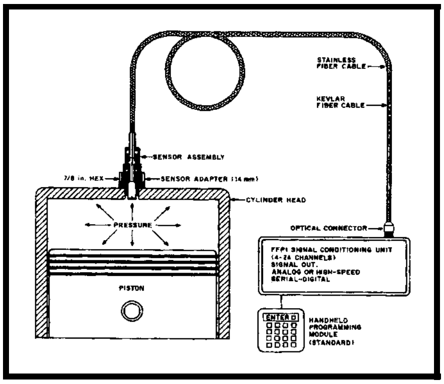

Figure 5. *Shown here configured for field tests, the cabled sensor assembly is mechanically rugged and suitable for use in the high-temperature engine environment,*

channels that can be monitored with one scu.

Because the adapter on the sensor head acts as a heat exchanger, the only form of active temperature compensation performed by the SCU is to peg (reset) the output pressure to the exhaust manifold pressure once each engine cycle, near the minimum pressure point. This pegging technique, also used in piezoelectric engine pressure sensors, removes the effect of slow temperature drifts on the sensor output signal.

Field Tests

Extensive field tests have been carried out in large (1000-3500 hp) stationary reciprocating gas-fueled engines of the type used in natural gas transmission (see Figure 5, page 26). The engines tested include a Cooper Bessemer GMV-4 at Colorado State University in Fort Collins, Colorado; a Cooper GMW-10 at a Transco compressor station in Sour Lake, Texas; a Clark TLA-6 in an El Paso Natural Gas (formerly Tenneco) compressor station in Winchester, Kentucky; a Clark TLA-6, a Worthington UTC-165T, and a Worthington ML-12 in an El Paso Natural Gas compressor station in West Winfield, New York; and a Cooper Ajax-Superior at a Union Pacific Resources compressor station in Bryan, Texas. Average temperatures at the sensor locations in these engines are generally in the 200°C–300°C range, with peak pressures between 400 psi and 1200 psi. After more than 150,000 sensor hours of in-cylinder operation, no mechanical failures of the sensor element have occurred.

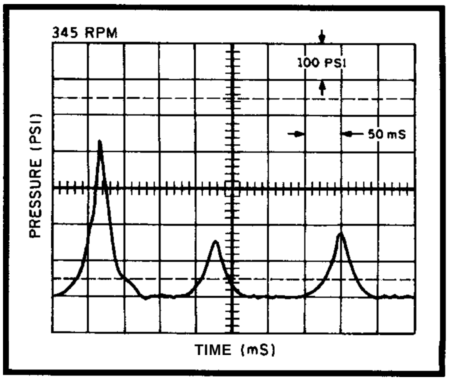

Figure 6. *When a pressure vs.* time *plot for an FFPI sensor is superimposed on a comparable trace for a piezoelectric reference (50 ms/div. horizontal, 100 psi/div. vertical), the data from the two sensors coincide exactly.*

Comparison of the uncooled FFPI sensors with a water-cooled piezoelectric reference sensor (Kistler Model 6061B) consistently shows better than ±1% agreement in peak pressure readings. There is a virtually perfect matching of the pressure waveforms over a wide range of engine types and oper-

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Although the most extensive use to date for the sensing element has been engine pressure measurement, several other applications have proven feasible. In one recent test, FFPI elements were installed on fatigue-critical components in the steel superstructure of a Union Pacific railroad bridge to measure dynamic strains caused by trains passing over it. Strain-induced changes in the interferometer's length were monitored and FFPI data proved in agreement with those from collocated resistive (foil) strain gauges. The benefits of the fiber-optic sensor in this application are deployment of the electronic monitoring equipment in a central location kilometers away from the sensors; immunity to lightning strikes and EMI; and inexpensive implementation through multiplexing.

The metal-embedded FFPI element is also a very sensitive strain sensor that can be used to detect and diagnose defects in rolling bearings, When the element is held in compression against or near a bearing casing, the passing of individual bearings can be readily detected. Defective bearings produce sharp spikes in the time domain and high-frequency content in the spectral-domain response of the sensor.

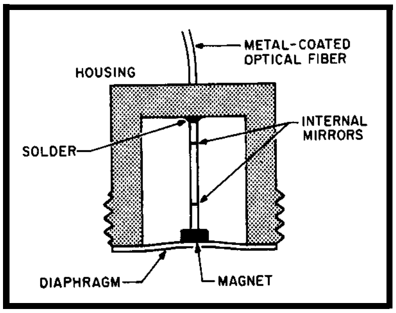

Figure 7. A *fiber-optic magnetometer based on the FFPI design can be used in rotating shaft monitoring schemes as a proximity probe to measure thrust and as a keyphasor to determine rate of rotation.*

The sensor design of Figure 2 has also, with slight modification, proved effective in measuring the pressure of high-temperature liquids in pumps, as demonstrated in field tests at the Citgo refinery in Corpus Christi, Texas, and the Flowserve (formerly BWIP International) plant in Tulsa, Oklahoma. In particular, the sensor was able to detect cavitation, a phenomenon that leads to blade damage and ultimately to failure in refinery and deep well pumps. By providing a cost-effective means for detecting cavitation and other pump anomalies, the FFPI sensor could lead to substantial savings in maintenance and repair costs as well as enhanced productivity in refineries, petrochemical plants, and oil and gas fields.

In a novel magnetometer design (see Figure 7), the single-mode fiber containing the FFPI is bonded at one end to a 0.005 in. diaphragm and also attached under longitudinal tension beyond the interferometer to the sensor housing. Force acting on a permanent magnet attached to the diaphragm causes a change in the length L of the interferometer. The optical signal from the sensor is processed by the SCU to determine the temporal dependence of magnetic field. The magnetometer has been used as a proximity probe to monitor thrust in a rotating shaft, and as a keyphasor to determine shaft rotation rate. A modification in which the permanent magnet is replaced by a proof mass converts this device to an accelerometer that can be used to monitor vibration in rotating equipment.

Finally, there is a widespread need to measure temperature over a wide range in environments characterized by EMI or flammable materials. The bare FFPI element is very sensitive to temperature over a -200°C to 1150°C operating range. Above this maximum, performance is found to degrade due to thermal diffusion of the mirror material. Because the size and thermal mass of the FFPI element are so small, its response as a temperature sensor is << 1 s). □

ating conditions. In a single-cylinder Ajax engine, for example, the piezoelectric and fiber-optic sensor traces are indistinguishable from each other (see Figure 6). In this case, the engine was run unloaded to give large cycle-to-cycle peak pressure variations. Similar results have been obtained on other engines as well.

Applications

The FFPI sensor has strong application potential in engine control and predictive emissions monitoring. The most sophisticated approach to optimizing engine performance uses pressure data for each cylinder in a closed-loop electronic fuel injection control system. Predictive emissions monitoring (PEM), which estimates pollutant concentrations in exhaust gas by software analysis of operating parameter data, represents a less expensive alternative to closed-loop control for many engine operators. High accuracy is needed in both control and PEM. One test using FFPI pressure sensor data as the key input to a PEM model showed "uniquely robust performance for determining NO, emissions from lean burn large bore pipeline engines. When properly applied, these models should satisfy the full gamut of possible regulatory requirements ."[3].

Conclusions

Field tests have shown that the FFPI fiber-optic sensor provides excellent lifetime and performance at high temperatures for continuous in-cylinder pressure monitoring in large, stationary engines fueled by natural gas. The sensors have performed reliably in an engine at temperatures >400°C and pressures >2500 psi. Since they pose no spark hazard, they can be safely deployed in environments such as natural gas compressor stations or refineries where volatile gases or vapors are present. The low optical loss in the fibers makes it possible to place the sensors at distances of several kilometers from monitoring electronics. Dramatic savings in the cost per sensor are realized through multiplexing. ■

References

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