Low-Cost Optical System for Pressure Measurements Within a Combustion Chamber of an Internal Combustion Engine

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***Abstract*— This contribution presents a novel low-cost approach to interrogation of short cavity Fabry-Perot optical fiber sensors and their use for pressure measurements in a combustion chamber of a petrol or diesel engine. The optical fiber sensor interrogation system is based on laser diodes with different wavelengths. Reflectance from Fabry-Perot sensors at three different wavelengths was observed to determine the cavity length, using specially developed signal processing algorithms. The interrogation system was evaluated statically and dynamically. It is shown that the interrogation system has a resolution of about 2 nm and bandwidth of 16 kHz. Two sensor designs were studied and evaluated in both the laboratory environment and in a combustion chamber of the engine. Both sensor designs are executed on the tip of the optical fiber, with etching, cleaving and splicing of special optical fibers.**

Keywords—Low-cost interrogator; optical fiber sensor; pressure measurement; internal combustion engine; signal processing algorithm

I. INTRODUCTION

Stricter ecological demands from the authorities and lower fuel consumption demands from the consumers of the cars with Internal Combustion Engines (ICE) are forcing the automotive industry into development and production of more efficient engines with lower emissions in the environment [1]. Research in both academia and industry is focused to achieve those goals [1]-[4], with, but not limited to: Downsizing of the engines, supercharging, variable controlled valves, novel fuels or their mixtures, etc. An important part of ICE are their sensors; information from them serves the electronic control unit for optimization of combustion and, consequently, lowering both consumption and emissions. In-cylinder pressure sensors have been investigated for a few decades, due to the rich nature of information that we can extract from the pressure curve. But, even after decades of research, the design of a low-cost pressure sensor, which would fulfil the price requirements of the automotive industry to implement it in the low and mid cost series production cars, which are responsible for a large part of global emissions, proved to be challenging. On the other hand, optical fiber sensors are known for their durability and reliability in harsh environments. Very often, they offer superior properties in terms of resolution and speed. Optical fiber sensors are connected to an interrogation unit, which is responsible for conversion of the measured parameter to a desired output, and is, as much as the sensors, responsible for the properties of the optical fiber measurement system. Commonly, the interrogation unit represents the bigger part of the cost of the optical fiber sensor system, and, due to its cost, optical fiber sensors have not made a breakthrough in consumer applications.

We present a new, low-cost method to interrogate a short cavity optical fiber Fabry-Perot (FP) sensor. While most of the reliable methods for interrogation of fiber FP sensors are based on wavelength sweep or wavelength filtering, our approach is based on only three different wavelengths. FP optical fiber sensors are involved in Metrology due to their low cost of production and a wide range of possible uses [5].

In Section 2 the theoretical background of the interrogation system will be presented, followed by the physical configuration of the system in Section 3. Section 4 will provide a short program description. Sensor mounting will be presented in section 5, followed by Results and Discussion in Section 6. Finally, in Section 7, conclusions and further work will be presented.

II. THEORETICAL BACKGROUND OF THE INTERROGATION SYSTEM

Interrogation of FP optical fiber sensors is a well-known problem, which is solved mainly with expensive equipment, inappropriate for our application. Most of them are based on a wavelength tuneable source or optical spectral analyzer. If we measure the wavelength response of an FP sensor, we get a "lifted sinusoid" response, from which we can determine

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with great accuracy the length of the interferometer. Our approach is based on three laser diodes with different wavelengths. We measure sensors` reflectance at different wavelengths with a photodiode, which is given by (1).

$$y_1 = A\left(1 + Bcos4\pi\frac{L}{\lambda_1}\right)$$

$$y_2 = A\left(1 + Bcos4\pi\frac{L}{\lambda_2}\right) \qquad (1)$$

$$y_3 = A\left(1 + Bcos4\pi\frac{L}{\lambda_3}\right)$$

y_x – response from a given wavelength
A – amplitude of the sinusoid
B – offset of the sinusoid
L – length of the FP cavity
λ_x – wavelength of the given laser diode

Solving (1) gives us (2) and (3) which are solutions for A, B:

$$A = \frac{y_1}{1 + Bcos4\pi\frac{L}{\lambda_1}} \qquad (2)$$

$$B = \frac{y_1 - y_2}{y_2 cos4\pi\frac{L}{\lambda_1} - y_1 cos4\pi\frac{L}{\lambda_2}} \qquad (3)$$

The length of the FP cavity is calculated with Newton's gradient method as seen in (4) and (5).

$$F(L) = k\left(cos4\pi\frac{L}{\lambda_1} - cos4\pi\frac{L}{\lambda_3}\right) - \left(cos4\pi\frac{L}{\lambda_1} - cos4\pi\frac{L}{\lambda_2}\right) \qquad (4)$$

$$L_k = L_{K-1} - F(L)/F(L)' \qquad (5)$$

For known wavelengths of the laser diodes, we can calculate the length of the FP interferometer.

III. PHYSICAL CONFIGURATION OF THE PROPOSED SYSTEM

The electro-optical configuration of the proposed interrogation system is presented in Figure 1. The system is built around a specially designed optical module consisting of three Fabry-Perot laser diodes, packed in a housing with optical elements providing good coupling into an SM fiber. The optical fiber is connected to the 50:50 2X2 optical fiber coupler, which splits the light into two equivalent parts. One part of the light goes to the photodetector for monitoring transmitted light, and the second goes to the sensor, which reflects some of the light back to the coupler. Half of the reflected light goes back to laser diodes and is lost, the other half goes to the second photo diode for monitoring reflected light.

The electronic part of the system is based on a microcontroller (PIC 32MZ family), which controls all the components described below. The design must provide us with sequential powering of the laser diodes with adjustable current. This is achieved with three equal electronic circuits consisting of a digital potentiometer, voltage buffer, digital switch, and a current driver with mosfet transistor. Such layout enables serial switching of the laser diodes on and off in the range of tens of microseconds. The detector side consists of two standard optical fiber coupled photodiodes and transimpedance

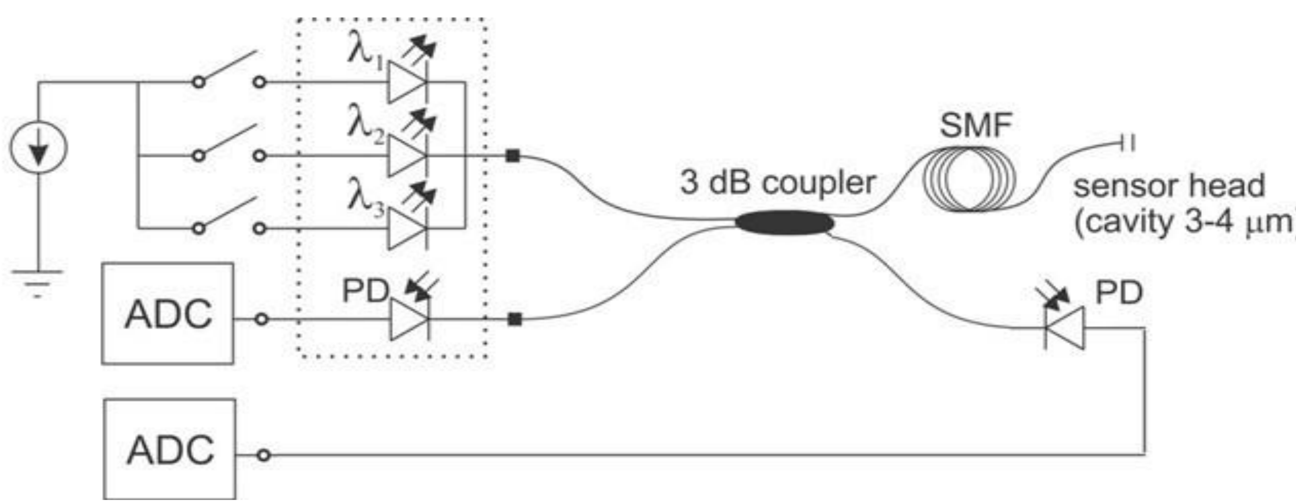

Figure 1: Electro- optical schematic

amplifiers with gains of 87 thousand and 2 million, for measuring the transmitted light and reflected light from the sensor, respectively. Signals from the amplifiers are routed to the microcontrollers` AD converter pins.

Two types of optical fiber pressure sensors are considered, both micromachined on the top of the standard SM optical fiber. First is the so-called needle sensor [6], as depicted in Figure 3 (b). The needle sensor was initially meant for strain measurements. Responsivity of a needle sensor with a 400 µm long gutter is about 2 nm/bar. Its production process is appropriate for massive production and, therefore, the needle is our first choice. The second sensor is a membrane pressure sensor [7], Figure 3 (a) . Its production process is more complex, but design of the structure is better, because it`s similar to some classical pressure sensors. Also, the responsivity can be set individually during the production process.

IV. Short program description

The program is a crucial part of the whole system because it must run fast enough to provide enough throughput of the whole system. Stable timing is achieved with timers and interrupts. Four switching states are implemented, as depicted in Figure 2, three for when each laser diode is turned on, and one when all diodes are turned off and we measure the dark optical power. This had to be implemented due to the optical power from combustion coupling into the fiber. Proper timing of the analog-digital conversion is also ensured with timers and interrupts. After all samples are taken, we start the algorithm for calculation of the length of the FP cavity. First, results are averaged with the number of samples taken in one state. After that they are “normalized”. Responses have undesired offsets and different amplitudes for different wavelengths, therefore, we must normalize all the signals to an even interval throughout the complete measuring range for all three wavelengths. Finally, we use equations 4 and 5 to determine the length of the cavity. With measured length of the cavity, responsivity of the sensor and initial length of the cavity, we calculate the pressure.

V. Sensor mounting

We designed a similar insert to the industry standard probe for measuring pressure in the combustion chamber (from the company AVL LIST GmbH). Redesigned and finished sensors are depicted in Figure 4. Bonding of fiber to the insert has proven to be difficult due to the high temperatures and pressures. Primarily, tests with two component epoxy adhesives were executed, but under high pressures the sensor fiber

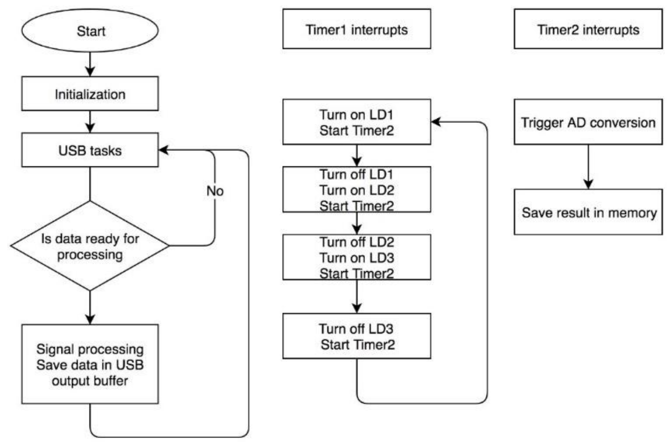

Figure 2: Program's flow chart

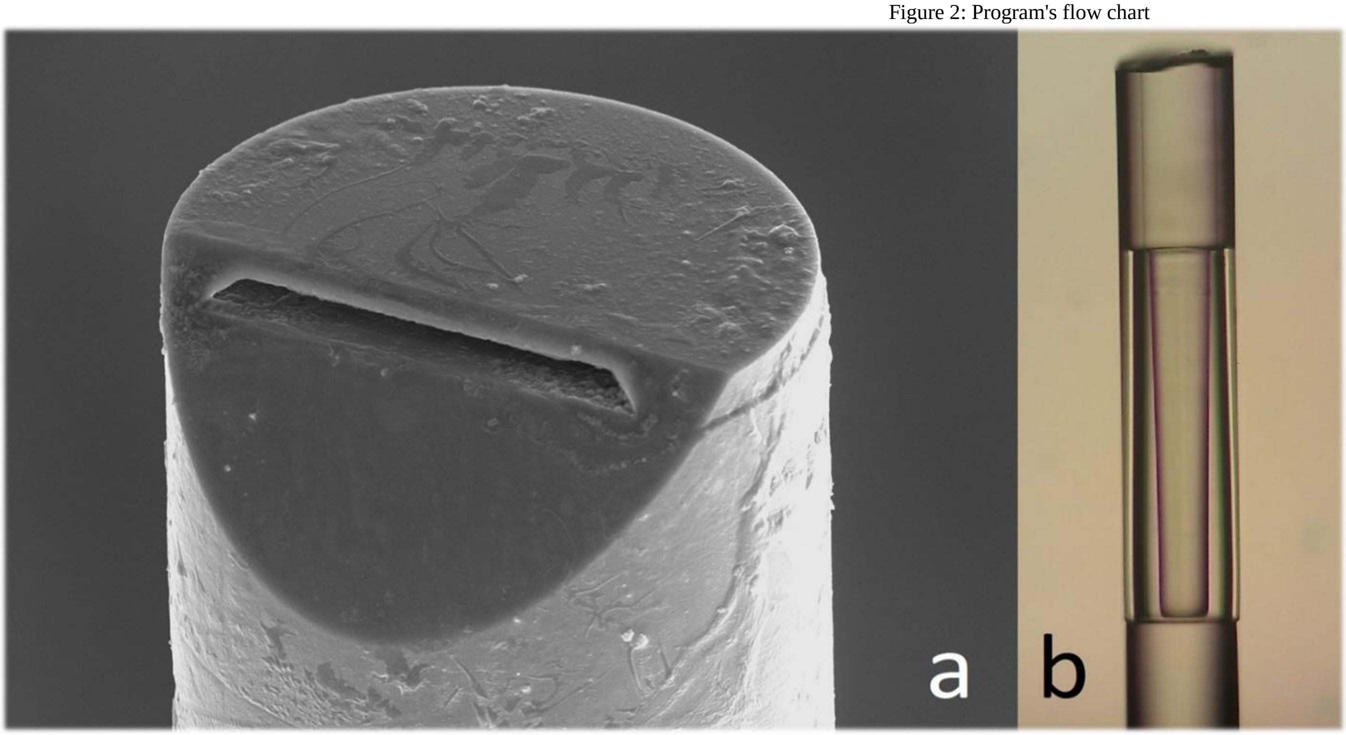

Figure 3: (a) Section view of membrane sensor (SEM), (b) Needle sensor (optical microscope), diameter of both is 125 µm

was excreted. Excretion was solved with usage of EPO-TEK 353ND. This joint has proven to be suitable for temperatures up to 350°C.

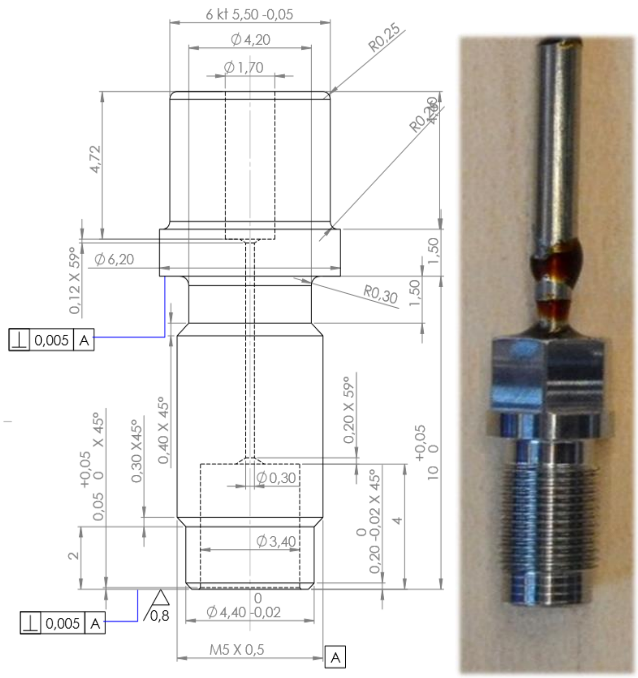

Figure 4: Redesigned insert for pressure measurement and finished insert

VI. Results and Discussion

The interrogation system was evaluated in laboratory conditions under both static and dynamic conditions. Static testing was performed with a needle sensor being stretched. The sensor forming fiber was left long enough to glue it to a linear stage, while the lead in fiber was glued to a stationary block of aluminum. The aluminum block and linear stage were secured on the optical table with screws. With moving of the linear stage, we got the results from the interrogation system given in the following graph. As seen in Figure 5, the interrogation system has a very good linearity over an almost 1 micrometre span.

Dynamic testing was performed with the needle sensor glued to a PZT stack. The PZT stack was excited with a 140 Hz square signal.As seen in Figure 6, 2, nanometres of noise are presented at 16 kHz sampling, considering the typical sensitivity of the membrane sensor we achieved noise of 500 mbar.After validation of the interrogation system, tests in the engine followed.

Test were performed on a Toyota 4Y ECS engine, fuelled with natural gas. This type of engine was developed for industrial forklifts. The engine was mounted on the test bench and coupled with an engine brake. We tested under different brake torques: 45 Nm, 100Nm and 115 Nm. Engine speed was 1500 rpm. The pressure curve acquired with the needle sensor is partially valid only during periods of high pressure, but in the periods of gas exchange, it is very distorted, due to rapid temperature changes, as the outer side of the structure got heated more than the inner pedestal. Therefore, false readings of pressure were acquired due to the uneven thermal expansion of the complete structure. Additionally, we had some difficulties with vibrations on the needle sensor due to high frequency vibrations introduced by the engine, so we needed

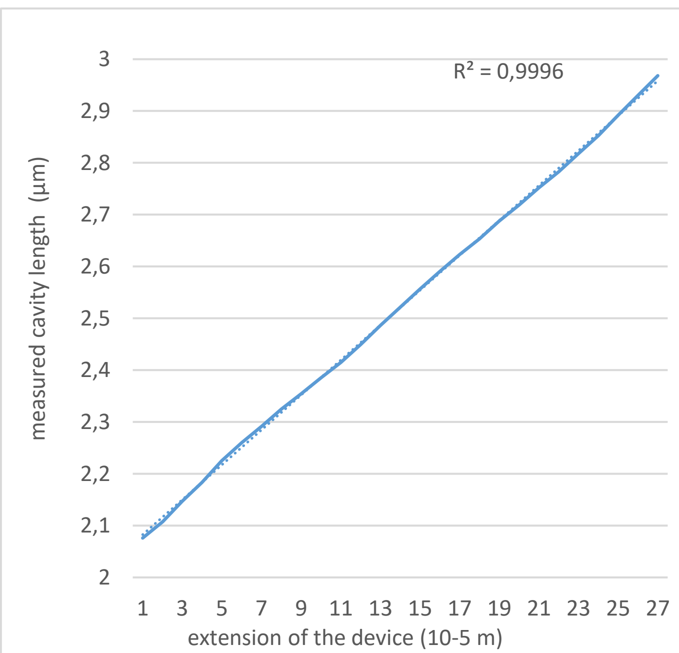

Figure 5: Linear response of the interrogation system

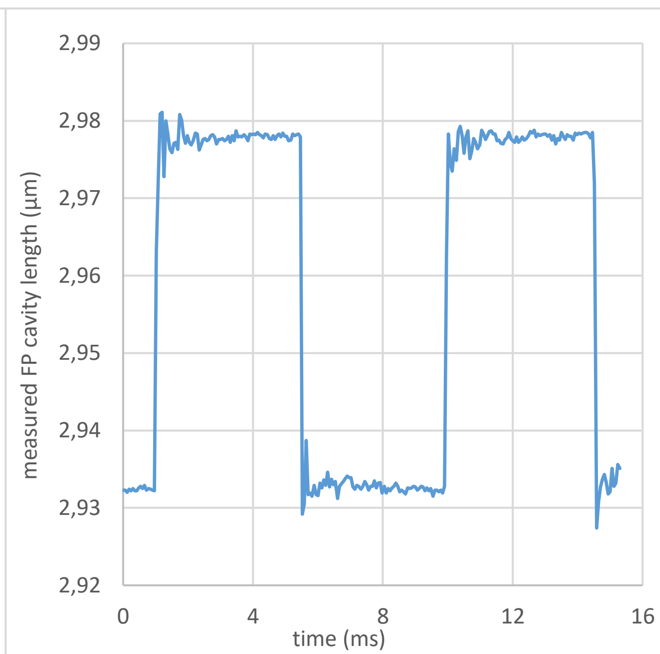

Figure 6: Dynamic response of the interrogation system

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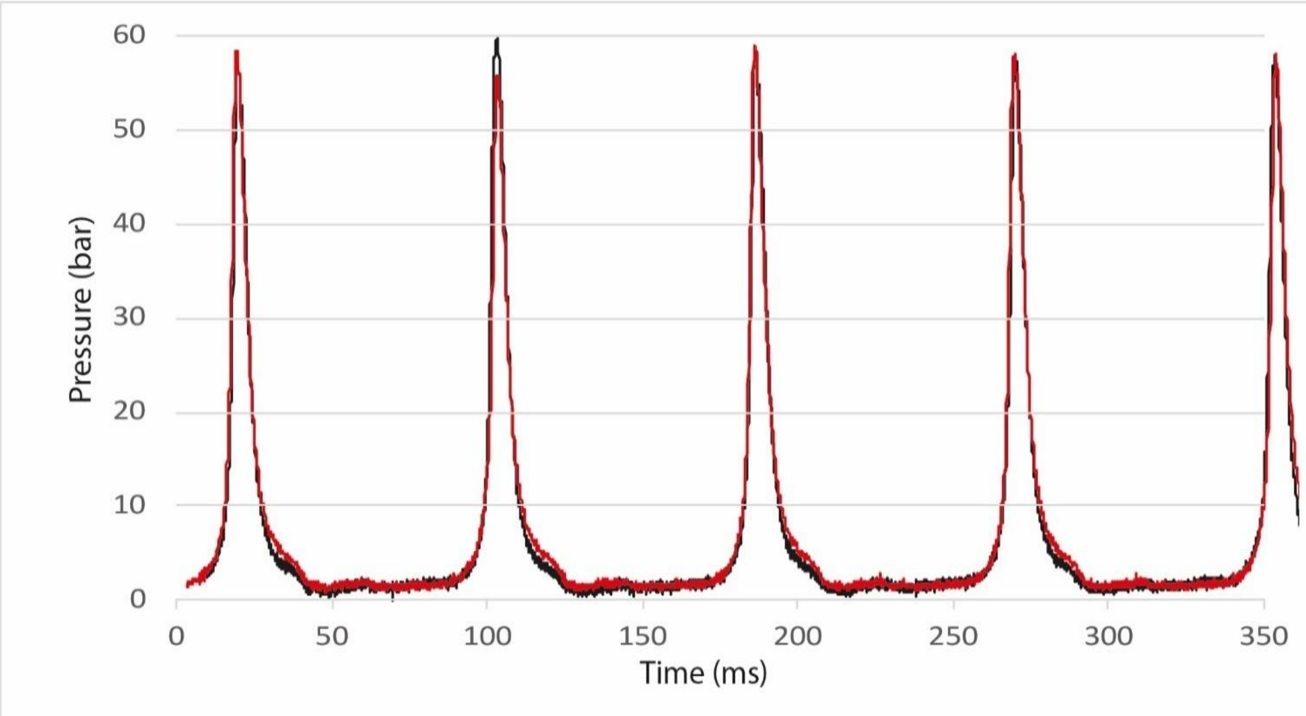

Figure 7: Pressure curves under work conditions at 1500 rpm and 115Nm braking torque. The red curve is measured with the proposed system, the black curve is a reference, measured with an AVL probe

to set the distance between the epoxy adhesive and the structure to such a length that those effects were minimized.

The following is the pressure measured with the membrane sensor after it has been inserted in the combustion chamber for 100 working hours. It has been observed that sensors do not age in this time period. The pressure curve in Figure 7 is valid throughout the complete combustion cycle.

VII. Conclusion and further work

This paper presented a low-cost interrogation system with corresponding sensors for pressure measurements under extreme conditions of a combustion chamber in automotive applications. Simple construction of the complete system and, therefore, minimum components, are used to achieve low cost design with good reliability.

The system was tested both under laboratory conditions and in a real engine. Resolution of 2 nm was shown, which matches 0.5 bar.

At the time, commercially available pressure sensors for combustion chambers were developed and manufactured by the company AVL LIST GmbH, for example GH15D, but, due to different approaches of measurement, additional work must be done in the direction of maturing of our solution. Further work must be done into research of dynamic temperature changes on the needle sensor to minimise those undesirable effects.

Acknowledgment

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