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Fiber Bragg Grating optical sensors for fast dynamic strain measurements in a Gasoline Direct Injector

L. Tozzetti^a, F. Gambini^a, T. Barsanti^b, L. Matteucci^b, I. Izzo^b, F. Di Pasquale^a, S. Faralli^{*a}

^a Scuola Superiore Sant'Anna, Istituto TeCIP, Pisa, Italy;

^bCPT Italy S.r.l., Pisa, Italy

ABSTRACT

Control systems for automotive applications have rapidly evolved introducing intelligence to address the increasing demand for pollution and oil consumption reduction. Fiber Bragg Grating (FBG) sensors are used in this work for monitoring Gasoline Direct Injectors (GDI) in order to optimize the engine performance and reduce the emissions. Several fast-acting solenoid injectors have been instrumented with FBG sensors and mounted in a test bench at the testing department of CPT Italy S.r.l to simulate the injector's behavior during the actuation phase. The FBG sensors, installed on the stem of the GDI, provide dynamic measurement of the strain variation during the injection process, pointing out the unwanted effects of the reopening, leading to injector tip wetting and consequent increased polluting emissions. The acquired data allows one to fully understand the GDI process and to optimize the injector design in order to reduce emissions, as required by recent European directives for the emission standards.

Keywords: Automotive Sensors, Automotive Sensor Applications, Optical Fiber Sensors, Fiber Bragg Grating, Fuel Injection System

1. INTRODUCTION

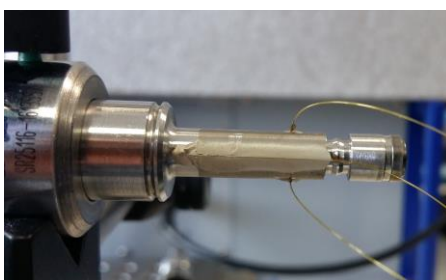


Fig. 1 Assembling of two FBGs on the stem of a Solenoid Injector.
The two FBGs are installed along the circumferential and the axial directions of the injector stem.

The increasing number of installed automotive sensors in powertrain systems are mainly driven by new legislations about pollution emissions and improved fuel economy. The reduction of the emitted particulate matter (PM), particulate number (PN) and Nitrogen oxides (NO_x) in gasoline direct injection (GDI) engine is becoming essential in order to fall within the increasingly stringent limits imposed by the Euro 6 and upcoming Euro 7 regulations; different emission reduction techniques have been proposed, including Nitrogen oxides (NO_x) after-treatment solutions, diesel oxidations catalysts and particulate filtering [1]. Moreover the control of the fuel injection system is becoming increasingly important for the development of advanced direct injection combustion technologies, where a large effort has been dedicated to the fuel rail pressure monitoring [2] and fine tuning of the injection timing by a feedback control of the cylinder pressure [3]. The large amount of data, to be processed in these control car systems, requires efficient and complex sensors that should be easy to fabricate, low cost, robust in harsh environment, and capable to provide accurate transduction of physical quantities such as temperature, pressure, torque, gas and air flow, distance and acceleration [4]. The performance of GDI systems strongly depends on the operation of the high pressure injectors; in particular, the functional characteristics of the injector and its design parameters play a key role in order to effectively control the engine performance. The unwanted reopening of the injector valve in the closing phase is a critical issue which causes an unsatisfactory atomization of the fuel and the injector tip wetting, resulting in an intake of petrol through a poor spray

quality and the consequent increase of polluting emissions. These phenomena need time-resolved and high frequency measurements in order to be identified and reduced, and they are usually investigated by measuring hydraulic pressure in dedicated fluid filled chambers [5] or through the visual observation of the spray process by a High Speed Video (HSV) technique [6].

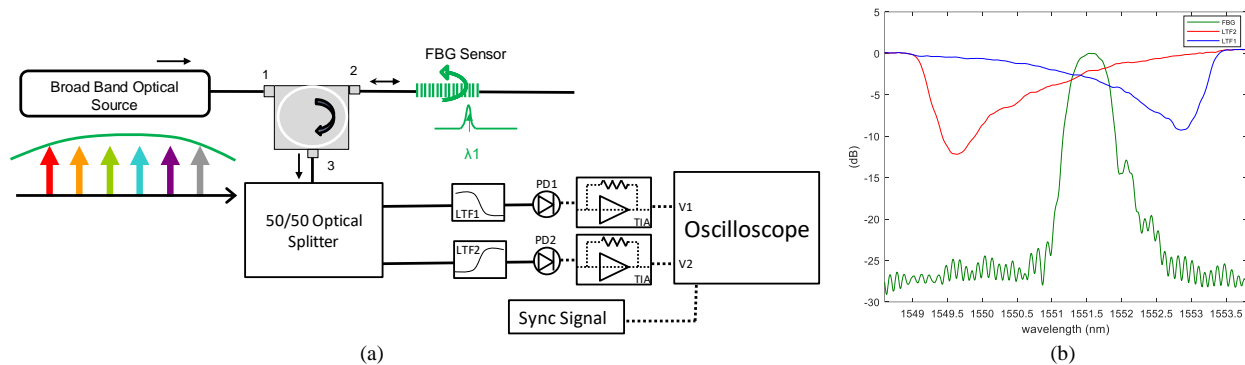


Fig. 2 (a) Schematic diagram of the optical setup for the interrogation of the FBG reflection spectra; (b) normalized spectrum of the FBG reflected light and the normalized transmitted spectra of the two optical linear transmission filter (LTF).

Optical fiber sensors are attracting attention from different industrial and research sectors ranging from structural health monitoring to energy production, from oil&gas to transportation, including automotive [7]. They provide significant advantages over conventional electrical sensors as they are electrically passive and immune to electromagnetic interference, small and light weight, chemically inert and suitable to harsh environments; these features make them very attractive for monitoring the behavior of GDI systems. In this paper we propose, for the first time to the best of our knowledge, a monitoring technique of the solenoid injector behavior, based on FBG optical fiber sensors, which can be correlated with high speed video monitoring of the spray process. Two FBG sensors have been installed on the surface of an injector stem, along both circumferential and axial directions, as shown in Fig.1, while the fast-acting solenoid injector was mounted in a dedicated test bench at the testing department of CPT Italy S.r.l. The dynamic strain of the FBG sensors due to the actuation of the injector was measured through a fast FBG interrogation technique based on linear filters and direct detection [8]; the fast injection opening and closing processes are fully identified with an acquisition rate up to 1 MS/s.

2. FBG SENSORS AND FAST INTERROGATION METHOD

Fiber Bragg Grating Sensors

Fiber Bragg Grating (FBG) sensor are widely used to measure physical quantities like stress, strain, temperature and vibration. In its simplest form a FBG sensor consists in a periodic variation of the core refractive index, induced in a specific section of an optical fiber; if a broadband light source is used to interrogate the FBG, the light will be reflected at a specific Bragg resonance wavelength [4]. The operating principle of the sensor is based on the real time tracking of the FBG resonance wavelength which is sensitive to changes in elongation and temperature variation. We used apodized FBG sensors written in a single mode bend-insensitive optical fiber, coated by a polyimide material; these characteristics allow to effectively install the sensors over bent surfaces, with a bending radius lower than 10 mm, to perform temperature measurements up to 300 °C and to accurately measure dynamic strain. As shown in Fig.1, we have installed two different FBGs on the injector stem, along both circumferential and axial directions respectively; the grating installed along the circumference has a length of 2 mm and a reflective wavelength of 1551.5 nm (3dB bandwidth = 0.55 nm, reflectivity > 70 %), while the FBG installed along the axial direction has a length of 4 mm and the same reflective wavelength of 1551.5 nm (3dB bandwidth = 0.50 nm, reflectivity > 70%). We assume that the minimum ultrasound wavelength detected by the FBG strain variation is much greater than the length of the FBG, and that the ultrasound wave effect on the dynamic response of the FBG can be considered linearly dependent on the strain wave amplitude detected by the FBG interrogator [9].

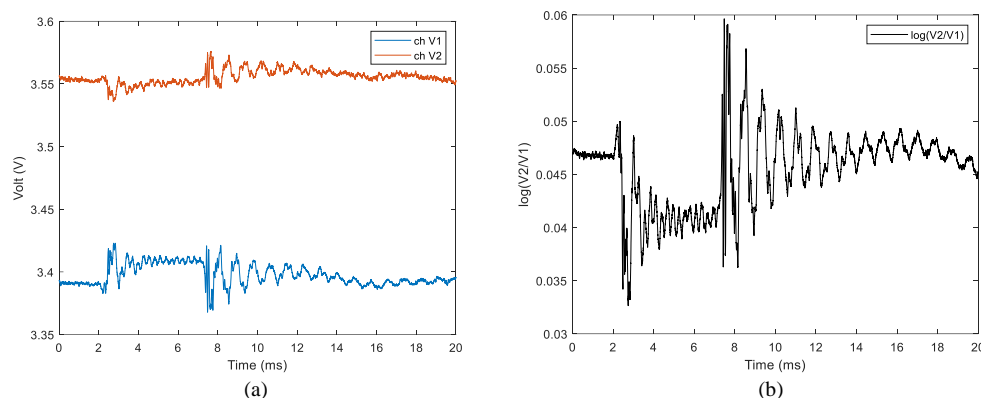


Fig. 3 Strain variation of the FBG sensor installed in the injector stem along the circumferential direction during a single injection process.

FBG Installation procedure

To achieve perfect strain transfer the FBG sensors must be bonded well and closely to the surface of the injector. The surface has been cleaned and degreased with isopropyl alcohol and striated with abrasive paper; the FBG sensors were placed on the injector surface in axial and circumferential directions, before applying an adhesive layer (Epoxy Technolgy EPO-TEK H20E metal glue) to cover it. After that, the adhesive was slightly pressed with a Teflon film covering it and finally, solidified by a thermal curing at 100 °C for 2 hours. Installation was done in a dust-free environment to avoid a negative influence on the fiber adhesion on the surface.

Fast Interrogation Method

A schematic diagram of the optical setup for FBG sensors interrogation is reported in Fig. 2. The system is based on a superluminescent light emitting diode (SLED) providing broadband incoherent light to illuminate the FBG sensors. The light waves reflected by the FBG, is sent to a 50/50 fiber optic beam splitters (BS) via port 3 of the optical circulator. Two linear transmission filters (LTF) convert the FBG wavelength peak variation in optical power variation. As shown in Fig. 2b, such filters are characterized by linearly shaped optical transmission spectra with a 10% to 90% transmission band of 3.3 nm, centered at 1551.5 nm and with opposite transmission slopes. The optical power at the output of the two LTFs is detected by two InGaAs PiN photodiodes with an analogue 3dB electrical bandwidth of 240MHz; the two PiN photocurrents I1 and I2 are then converted into voltages V1 and V2 by two transimpedance amplifiers within the receiver blocks. The electrical signal is recorded by a PicoScope USB PC oscilloscope with a sampling rate of 1 MS/s and processed by MatLab software tools. Thanks to the opposite transfer functions of the two LTFs, a shift of the FBG peak wavelength centered at 1551.5 nm induces opposite optical power variations at the two PDs; a simple interrogation function such as $\rho = \log(V1/V2)$ provides then a differential measurements of the FBG wavelength shift that cancels out all unwanted effects due to optical source power fluctuations or variation of the local fiber attenuation values.

3. EXPERIMENTAL RESULTS

The fast-acting solenoid injector was mounted in a test bench at CPT Italy S.p.A. and filled with a N-Heptane fluid. The fluid pressure is controlled by a pump in combination with a pressure multiplier and sensors that keep constant the inflow pressure of injector at 250 bar. The test bench permits to perform single injection by an electronic actuation control and to monitor the injector's behavior during the actuation. The tests were carried out at controlled constant room temperature and the FBG sensor strain variations were measured during single injection activation at 250 bar, with an actuation time of 5ms. Fig. 3 and Fig. 4 show the measured strain variation of the two FBG sensors installed in the injector stem respectively along the circumferential and axial directions. Fig. 3a and 4a report the measured voltages by each photoreceiver, during the injection activation; Fig. 3b and 4b show the corresponding interrogation function ρ . The measurements clearly show a decrease of the FBG reflection wavelength peak, corresponding to a strain decrease along the stem during the injector opening time window. Fig. 3 and 4 point out fast transients associated to both injector opening and closing phases. During the injector opening phase an undershoot in the interrogation function is observed, due to a pre-injection armature movement, which is responsible for the injector seat opening and the consequent fuel

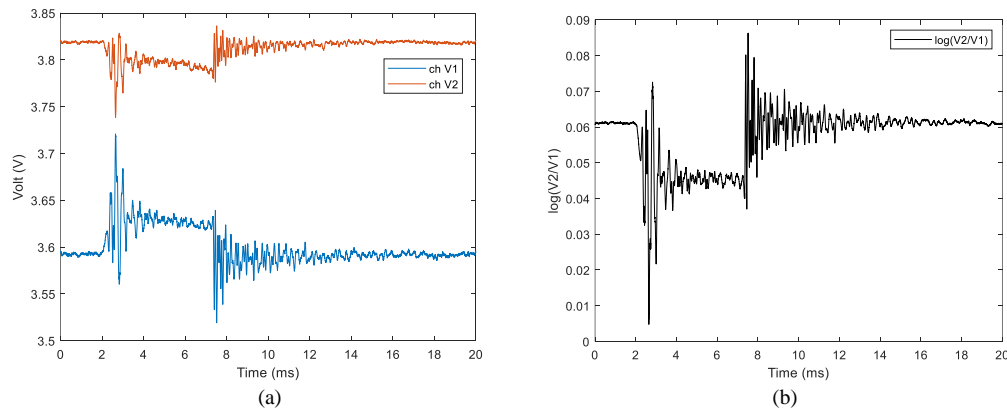


Fig. 4 Strain variation of the FBG sensor installed in the injector stem along the axial direction during a single injection process.

flow from the nozzle into the combustion chamber. At the end of the injector closing phase fast strain transients are clearly observed after the injector seat complete closing, characterized by a rather large oscillations. This behavior is mainly due to the unavoidable sudden transfer of kinetic energy from needle to seat and the related unwanted needle re-opening. The understanding of these unwanted phenomena is important to contain both unsatisfactory spray atomization and injector tip wetting, with the consequent limitation of polluting emissions. Only for circumferentially mounted FBG the low frequency oscillation after closing phase reported in Fig. 3 can be explained by the typical pressure oscillation corresponding to test bench hydraulic resonances excited by closing hit of needle against the injector seat.

4. CONCLUSIONS

FBG sensors have been installed on the stem of a GDI injector allowing to measure the injector deformation during its actuation. Dynamic measurements have been carried out demonstrating the possibility to monitor the injection behavior. The acquired data allows one to fully understand the GDI process and to optimize the injector design in order to reduce emissions, as required by recent European directives for the emission standards.

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