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Fiber Bragg Grating temperature monitoring of helicopter engine mechanical parts on an engine test bench

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Abstract: Fiber Bragg Grating temperature monitoring results of two mechanical parts located in the exhaust system of a helicopter engine test bench are reported and compared to thermocouple and SWIR camera measurements.

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1. Introduction

Fiber optic sensing offers multiple advantages in comparison to electronic sensors for a wide range of industrial applications due to its high wavelength-division-multiplexing (WDM) capability as well as its low intrusiveness and immunity to electro-magnetic interference. Aircraft engines will benefit from this technology that resists to harsh environments such as temperature up to several hundreds of degrees, thus allowing high spatial resolution temperature and strain measurements as well as pressure sensing in mechanical parts located deep inside the engine. That is the reason why the authors' respective organizations are conducting an industrial research partnership aiming at developing fiber optic sensing technology bricks integrated in next generation aircraft monitoring systems, including a number of test campaigns. The present paper describes experimental results of a test campaign on a helicopter engine test bench located at Safran Helicopter Engines site in France. Fiber Bragg Grating (FBG) temperature monitoring of two mechanical parts located in the engine exhaust system is presented, the first part being a cubic piece crossed by multiple air flows and the second one being an exhaust gas pipe. First, FBG temperature sensor fabrication and integration on the pieces are described (2) and measurement conditions, interrogation systems as well as other sensing technologies used for comparison are presented (3). Temperature monitoring results up to 600°C corresponding to eighteen sensors located on both mechanical parts and acquired during several test cycles are then exposed and a Fourier transformed 5-kHz signal is described (4). Finally, we sum up the main conclusions of this experimental work and discuss potential improvements for future test campaigns (5). Temperature, gradient and time scales are not represented on the figures for confidentiality purposes.

Table 1. Description of the three fiber optic section used for FBG temperature sensing

	Section 1F	Section 1B	Section 2
Number of sensors	7	5	6
Lowest wavelength (nm)	~1520	~1500	~1510
Channel spacing (nm)	10	15	15
Sensor distance (mm)	20	40	25

2. Fiber Bragg grating high-temperature sensor fabrication and fiber integration process

2.1 Inscription of high-temperature fiber Bragg gratings with femtosecond laser platform

Laboratoire Capteurs Fibre Optique (LCFO) is part of CEA (Commissariat à l'Énergie Atomique) LIST (Laboratoire d'Intégration des Systèmes et des Technologies) and is a research lab dedicated to innovation in fiber optic sensing technology, providing a wide expertise in fiber optic laser inscription platforms (KrF excimer lasers in the UV spectrum, femtosecond lasers at different wavelengths), fiber optic sensor interrogation systems as well as fiber optic integration. Fabrication of FBG sensors presented in this paper was performed with LCFO femtosecond platform on a standard single-mode optical fiber. Three fiber sections composed of seven, five, and six sensors respectively were produced for temperature monitoring of part 1 front (1F), part 1 back (1B) and part 2

(2) respectively. The different WDM interchannel spacings as well as the different spatial distance between sensors for each of the three sections are summarized in Table 1.

2.2 Fiber integration on mechanical parts for temperature measurements

Safran Tech is the corporate Research and Technology center of Safran. It is responsible for developing and building innovative technology bricks for the aeronautics of the future. As part of its activities, S3AR (Safran Sensing Systems Application and Research) focuses on sensing technologies. FOS (Fiber Optic Sensing) is part of S3AR activities. In the context of these tests, S3AR was involved in the definition of the FBG (spatial and spectral locations) as well as the packaging and the pre-integration of the fiber optic probes on the Exhaust Gas Pipe.

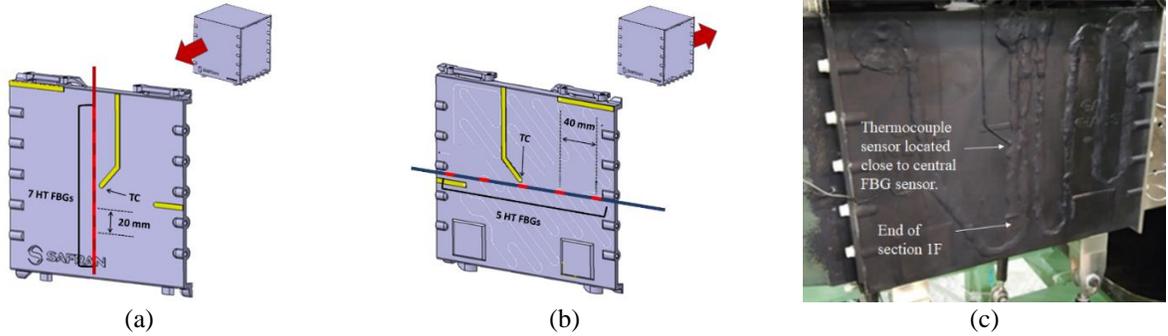


Fig. 1 Schematic of monitored piece 1 front and back and disposal of temperature sensors (a and b resp.). (c) photograph of piece 1 front (c).

After FBG inscription, the three sensor lines were inserted into metallic capillaries that were disposed on the two studied mechanical parts. Line 1F and 1B were glued at the surface of the front and the back of piece 1, which required a processing step in an oven for cementing of the glue at high temperature. Fig. 1 depicts schematic views of mechanical piece 1 front and back, including the disposition of the 12 FBG sensors and the 2 thermocouple sensors (TC) used for comparison. For both FBG lines 1F and 1B, the central sensor is disposed as close as possible to the TCs located at the center of piece 1 front and back. A photograph of piece 1 front is also provided in Fig. 1(c), where the TC sensor and the end of line 1F are indicated. Other fibers are visible but are out of the topic of this paper. On the other mechanical part, the capillary of line 2 is bridged to Inconel rods that cross the exhaust gas pipe, as depicted on Fig. 2, which exhibits a schematic view (a) and a photograph (b) of this piece. Those rods are meant to minimize the vibrations of the probes by applying intermediate holding points.

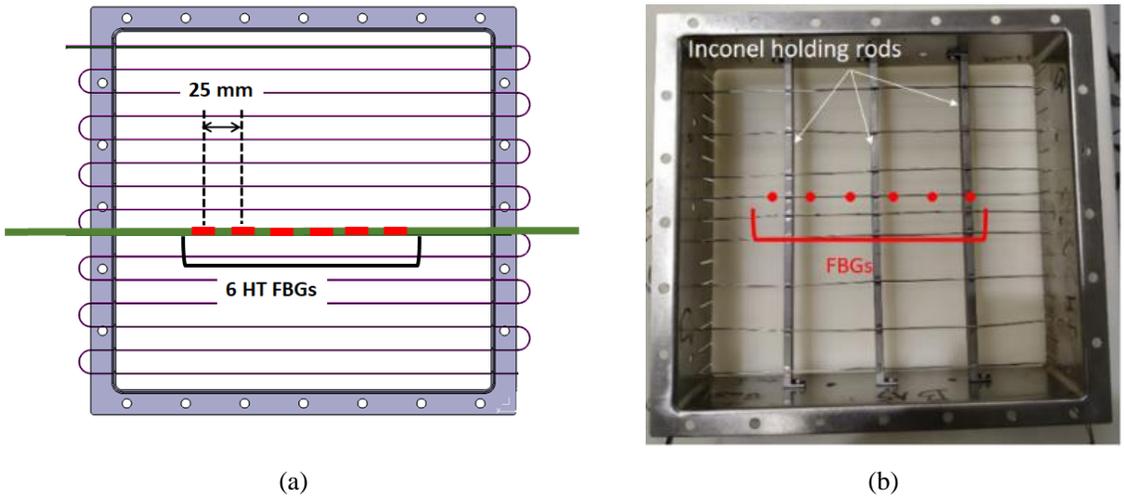


Fig. 2. Schematic of monitored piece 2, disposal of temperature sensors (a) and photograph of piece 2 (b).

3. Measurement conditions and fiber optic instrumentation system

After integration of optical sensors, those two mechanical parts were mounted on a helicopter engine test bench located at Safran Helicopter Engines site of Bordes in the south of France. Those optical fibers were alternatively connected to FBG interrogation systems [1] and [2], which main difference are their interrogation speeds (10 Hz vs 5 kHz resp.) and wavelength range (100 nm vs 80 nm resp.). As a result, measurements were acquired at different speeds during the different monitored test cycles, allowing Fourier transform of the signal at up to 2.5 kHz when acquired with [2], but with the drawback of only four monitored sensors out of five on line 1B due to limited range. The selected interrogation system was then connected to a computer located in the control room where the bench is operated. During the tests, the operators observed the evolution of FBG spectra during the phases of the cycle and recorded this data with software developed by CEA List (for the 10 Hz acquisition) and with commercial software [3] for the 5-kHz acquisitions. During a test cycle, hot and cold air flow rates are varied by steps of a few minutes depending on the selected engine rating, resulting in different average temperatures and gradients recorded on the two monitored mechanical parts. As stated below, the central optical sensors of both front and back of part 1 were disposed next to TC sensors. Those two sensors will enable the comparison with FBG technology in the next paragraph. In addition, an IR SWIR camera recorded images of the front of mechanical part 1 that were converted into 2D-temperature profiles after calibration. This gave us the opportunity to compare the thermal gradients recorded by this camera with the measured profiles obtained from FBG technology. Examples of obtained experimental results are presented hereafter.

4. Mechanical part temperature monitoring results during engine tests

4.1 Measured temperature and temperature gradients

After acquisition of data, wavelength variations of the FBGs were processed with the help of calibration data acquired previously in order to convert it into temperature signals. Fig. 3 depicts the temperatures acquired on both mechanical parts 1 and 2 by the 18 optical sensors (dashed lines) and the 2 TC sensors (solid lines) used during a given test cycle. One can observe the different steps of the cycle and temperature variations of several hundreds of degrees during the test, reaching temperatures as high as 600 °C. Fig. 4 axis 1 (left) represents the corresponding temperature difference between FBG sensors of lines 1F and 1B and TC sensors (dashed lines) while axis 2 plots the average temperature gradient computed from those values (solid lines). The expected high gradient difference between vertical (line 1F) and horizontal (line 1B) directions can be observed, with corresponding typical temperature gradients of 1 °C/cm and 10 °C/cm respectively.

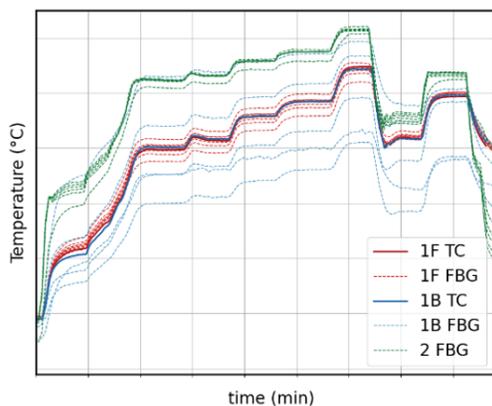


Fig. 3. Temperature variation measured during a test cycle vs time for different temperature sensors and different mechanical pieces. Red: part 1 front, blue: part 1 back, green: part 2. Solid lines: TC measurements. Dashed lines: FBG measurements.

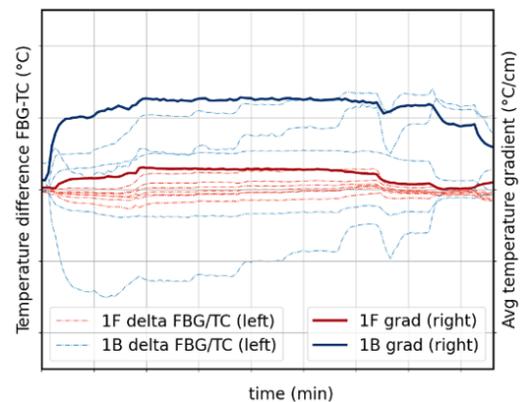


Fig. 4. Axis 1 (left, dashed lines) Temperature difference between FBG sensors and TC measurements and axis 2 (right, solid lines) average temperature gradient vs time during a test cycle. Red: piece 1 front, blue: piece 1 back.

One-dimensional temperature profiles corresponding to locations close to fiber line 1F were extracted from the 2-D profiles acquired with the SWIR camera, thus allowing direct comparison, as exposed in Fig. 5 at a given instant. The profile measured by the 7 FBGs (red dots on Fig. 5) keeps very close to the profiles defined on the glue and a few millimeters aside (blue and green curves) from the SWIR camera.

4.2 Acquisitions at 5 kHz and short-time Fourier transform

Finally, we present the data corresponding to one FBG on piece 1 and acquired at 5 kHz for another test cycle (Fig. 6). In addition to the measured temperature (Fig. 6(a)), fast variations of acquired wavelength resulting from convolution with rectangular window is represented (Fig. 6 (b)) as well as its short-time Fourier transform (Fig. 6(c)). One can observe that this signal exhibits different spectral contents depending on the test cycle step, providing additional relevant information to mechanical designers.

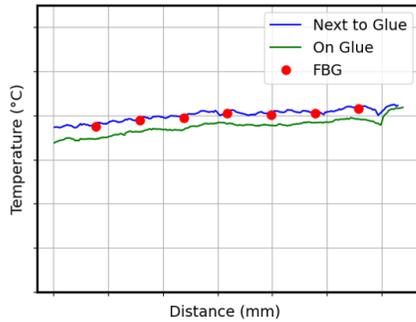


Fig. 5. Temperature at a given instant on piece 1 front. Red dots: FBG sensors. Blue and green lines: profiles extracted from SWIR images on the glue and a few millimeters aside respectively.

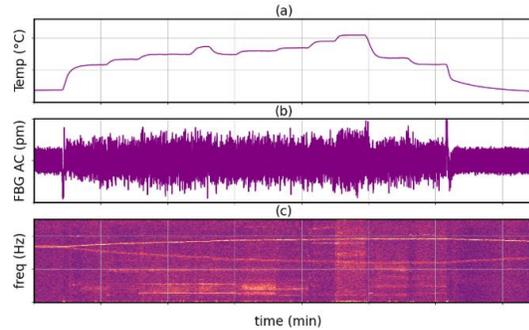


Fig. 6. FBG signal acquired at 5 kHz during a test: (a) temperature of sensor (b) FBG peak signal AC component obtained from difference between signal and signal convoluted by rectangular window (in pm) and (c) short-time Fourier transform of this signal.

5. Conclusion and perspectives

In this paper, we have presented temperature-monitoring results obtained from FBG sensors that were integrated in mechanical parts on an engine test bench. Temperature as high as 600°C was measured and temperature gradients were compared between horizontal and vertical directions of a given part of the exhaust system. In addition, we have compared temperature measured with those fiber optic sensors to data obtained from TC sensors and SWIR camera as well, which gave accurate and satisfying results. Finally, we present a short-time Fourier transform of an FBG signal at up to 2.5 kHz that exhibits different frequency contents depending on the step of the test cycle. Future test campaigns could potentially include novel fibers and coatings dedicated to engine measurements as well as a denser integration of FBGs.

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