HiTOS: A High-Temperature Optical Fibre-based sensor system for Space structures

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Space vehicles intended for transport applications like launchers, reusable modules, ATV’s and manned capsules demand increasing complexity and quality levels to face the growing market needs. With the goal to achieve a more reliable and affordable access to space, ESA started in 1999 the Future Launchers Technology Programme (FLTP) focused on the development of technologies related with re-usability of launchers and coordination of national efforts. Since then, the technologies applied to Health Monitoring Systems (HMS) for vehicle structures were strongly promoted as a fundamental tool to achieve an effective cost reduction without compromise of safety. To achieve the implementation of a reliable and effective Health Monitoring system, a broad range of sensors have to be distributed along the structure to measure different flight parameters like thermal profile, pressure and friction, strain etc. The goal of the HiTOS project was to propose a substitute of conventional temperature (thermocouples) and strain (strain gauges) sensors, thanks to the new generation of Optical Fibre-based sensors arising from an evolution of conventional Fibre Bragg Gratings: the so called Regenerated Fibre Bragg Gratings or rFBG. Along this contribution, the optical fibre temperature and strain sensors based in Bragg Gratings are introduced, and the different advantages and drawbacks are discussed for the specific case of structural monitoring in a Space vehicle. Experimental tests over a complete demonstration set-up are described together with the relevant results.

I. INTRODUCTION

The term Health Monitoring System (HMS) comprises the processes and techniques aimed to monitor and assess the status or condition of a space vehicle, collecting real-time data that enable the diagnosis and analysis of the status of each sub-system in order to improve the maintenance and the knowledge about the whole system operation.

For this purpose, the application of Optical Fibre based sensors carries significant advantages, including low electronic requirements (no need of numerous communication devices), multiplexing capabilities simplifying harness, EMI/EMC immunity and electrical safety, low weight, compactness (possible integration of sensing structures in the communication fibre lines), chemical compatibility, etc. On the other hand, different drawbacks appear, such us the susceptibility to mechanical damage, more difficult handling than their electrical counterparts such us thermocouples and lower temperature operation limits, conditioned by the melting temperature of the Optical Fibre material (in case of Silica, the melting point is 1600 ºC).

One of the most known of these Optical Fibre based sensors techniques is that based on the application of Fiber Bragg Gratings (FBGs) to sense Tº and strain. FBGs are one-dimensional multilayer filters inscribed inside an Optical Fibre line. The Tº and strain produce changes in its resonance wavelength, making possible to measure these parameters through the resonance characteristics over time. This technique is being currently used in health monitoring of civil structures as well as in space systems, such as PROBA II. Nevertheless, it has an intrinsic limitation in Tº, due to the fact that at high Tº (in the order of 600ºC) the FBG inscribed in the Optical Fibre is erased.

Fig. 1: Operation of a Bragg Grating. The FBG acts as a wavelength discriminator at the Bragg wavelength, which depends strongly on the grating length, and thus, on the temperature and strain over the fibre segment where the grating is inscribed.
One of the most interesting advantages of FBGs is that, since each FBG is resonant at its own wavelength, different FBG sensors can be deployed along the same optical line, implementing a sensor bus with many sensing elements along a single fibre line. This advantage supposes a key factor considering the reduction in mass and volume compared with the traditional approach based in a multi-line electrical harness connecting thermocouples along the vehicle’s structure. For this reason, the upgrade of the operation temperature limits of FBGs becomes an interesting challenge that was one of the leit-motif of HiTOS project

I.1 Regenerated FBGs

One of the most promising methods to increase the temperature of operation of FBG involves the use of Chemical-Composition Gratings, CCGs, here called Regenerated FBGs (rFBG) since its manufacturing is based in a subsequent annealing treatment at high temperature. During this annealing, the previous FBG is completely wiped out and a new refractive-index modulation grating appears in the zones that were previously exposed to UV radiation. These gratings are, eventually, resistant to temperatures up to 1200 °C, near the melting point of Silica. Once described this, the advantage of rFBGs towards other high temperature options such as those based in Fabry-Perot or Microstructured resonant cavities is that its spectral response is the same as the standard FBGs, therefore, the interrogation scheme is the same, which is highly mature in the industry thanks to the applications of FBGs in structural monitoring in civil engineering, off-shore, etc.

II. INTERROGATION SCHEME

The figure below shows the principle of operation of the rFBG based sensor system, which could be used to monitor temperature, strain or both on a Space structure. rFBGs are implemented) are thermally protected and then wired towards the hot elements of the vehicle (such as TPS tiles) and finally attached to them using high temperature fixing techniques, developed in the framework of this project. The HiTOS Interrogation unit is an optoelectronic compact system designed to take readouts of the central wavelengths of the different rFBGs distributed along the optical fiber. This instrument is commanded from an on-board computer through a simple yet compact set of commands implemented on a frame-structured communications protocol. This interrogation unit illuminates the optical bus with a broadband light source and then, in reflection, it detects and tracks the optical power peaks returned by the different rFBGs at their respective characteristic wavelengths. Tracking the position in the wavelength domain of those rFBGs, the respective local temperatures at such points of the optical fibre can be calculated.

III. PACKAGING AND INTERFACE

One of the most critical aspects of the HiTOS project, early so identified, is the packaging technique used to encapsulate the rFBG segment to withstand the demanding vibration and shock conditions during flight, and the interface method to attach the sensor element once packaged to the hot area in a reliable way, which could be either metallic or ceramic, materials that are common in re-entry thermal protection systems. Moreover, one of the challenging aspects when working with rFBGs is that, after the regeneration annealing process, the fibre segment becomes brittle, making impossible its use in the way that standard FBGs are packaged and connected to the measurement spots in, for example, civil structures. A specific packaging method was developed in the framework of the project to encapsulate the fiber segment where the rFBG sensor is inscribed, producing a metallic finishing that is compatible with common handling procedures and offering seamless interface properties with materials like the above mentioned.
Furthermore, the necessary interface techniques with TPS ceramic materials were developed and implemented in a test element as it can be appreciated in the figure below, manufactured to withstand temperatures above 1000 °C. The clamps were placed at the right distance to match with the rFBG sensors on the sensor bus, labelled as S in the figure, which served as the test elements in order to demonstrate the feasibility of the whole measurement concept during the test campaign.

![Test element with rFBG sensors](image)

Fig. 4: Photograph of two 1cm-long sensors (S1 and S2) attached to the piece of C/SIC as the final test element.

IV. EXPERIMENTAL TESTS

In order to demonstrate this technology and to validate the system concept, a whole representative demonstrator was build in laboratory, and extensive measurement campaigns were performed in order both the test the interrogation optoelectronic unit and to characterize the rFBG based sensors manufactured and packaged. In the figure below, the laboratory set-up can be appreciated, which corresponds with the complete interrogation scheme depicted in the figure 2.

![Laboratory set-up](image)

Fig. 5: Perspective of the HiTOS interrogation system set-up. The HiTOSManager running on the laptop shows the optical spectrum of the Broadband light source implemented, as sent by the HiTOS control electronics.

In addition, a complete software suite was developed (HiTOSManager) to interface with the interrogation unit and to visualize and store the measurement data. Functions for automatic spectral power peaks tracking, corresponding with the central wavelengths of the rFBG in the sensor bus, were implemented to demonstrate that this intensive signal processing task can be performed in the embedded Digital Signal Processor with no compromise of performance.

![HiTOSManager](image)

Fig. 6: Screenshot from HiTOSManager showing a detail of the HiTOS rFBGs array optical Spectrum acquired by HiTOS Interrogator in reflection mode.

Subsequent tests demonstrated the operation of the rFBG-based sensors, with their characteristic spectral response shifting to higher and lower wavelengths with increments and decreases of the temperature respectively.

V. RESULTS

In the figure below, plots corresponding to five temperature cycles are shown. In the plot A (wavelength vs. time), it can be appreciated that the time response of the rFBG sensors (red) is close to the reference thermocouple (black). In the plot B (Wavelength vs. temperature), a high linearity can be appreciated, validating this technology for temperature monitoring applications.

![Plot](image)
VI. CONCLUSIONS

Along the HiTOS project, different possibilities to address the most relevant technical issues were addressed and tested. Different packaging techniques and interface methods to join the sensors to the hot materials and different interrogation optical architectures were implemented and tested, reaching a final configuration that demonstrated to be suitable for its application in Structural Health Monitoring Systems for Space vehicles, as well as in other applications involving the measurement of high temperatures, such as propulsion.

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