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Feasibility study of FBG-based sensors for prognostics in aerospace applications

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Abstract. In recent years, aerospace systems have undergone a huge technical-scientific impulse, evolving new high-performance intelligent solutions able to perform diagnostic and prognostic functions autonomously. In this scenario, an important role is certainly played by the new types of sensors combining high performance (in terms of sensibility, accuracy, and reliability) with a marked resilience to external disturbances (e.g. EM noise or electrostatic discharges) and other environmental factors. Fiber Bragg Gratings (FBGs) sensors, suitable for measuring various engineering parameters in both static and dynamic modes, meet all these requirements; in aerospace, they could replace several traditional sensors, not only in structural monitoring but also in a much wider range of system applications including the diagnostic and prognostic of mechatronic devices. In this paper, the authors propose the first results of their investigation about the use of optical sensors for Electromechanical (EMA) and Electrohydrostatic Actuators (EHA). FBGs allow determination of aerodynamic hinge loads and minimally invasive measurements of local temperatures: the firsts are needed for in-flight model-based prognostics, whereas the detection of local heating allows to early infer an incipient partial short circuit of EM motor, a progressive power electronics failure or abnormal friction dissipation e.g. at bearing level. In order to assess the capabilities of optical sensors, evaluating different installation techniques and defining suitable configurations for the aforementioned mechatronic systems, a dedicated test bench has been developed and used for calibrating FBGs, analyzing their behaviour in different conditions of strain and temperature and conceiving a proper thermo-mechanical compensation strategy.

1. Introduction

Optical fibers are becoming more and more widely employed in aerospace application. Their ability to carry information with very high data rate, large bandwidth and low latency makes them suitable for the replacement of more common data buses based on electrical signals. Optical fibers feature several advantages over electrical data transmission. The weight of the system can be reduced, in particular if data is carried across long distances; the optical data transmission operated by the fibers is insensitive to electromagnetic disturbance generated by other systems, and this turns particularly useful for safety critical functions of aircraft, such as communication between flight control computer and actuators.

Additionally, optical fibers are highly resilient to hostile environments, characterized by extreme temperatures or presence of aggressive chemicals. However, some disadvantages are also introduced with optical systems: the installation is constrained by the minimum curvature radius that can be achieved without excessive optical losses; the components are highly vulnerable to mechanical damages, so the installation alongside with heavy mechanical systems can be difficult.



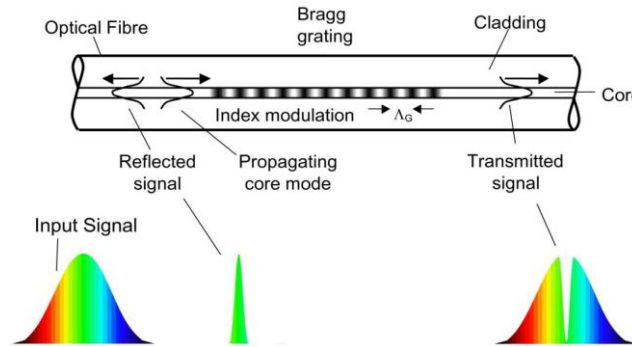


Figure 1. Schematic diagram of an FBG inside a single-mode optical fiber [1].

In addition, some of the equipment needed to translate optical data into electronic data is expensive because the some applications are still in development phase, and the production volume is therefore small. Aside from the simple data transmission, optical fibers can be used active components; in particular, their ability to modulate light intensity, polarization, phase shift, or spectrum can be leveraged to build robust and minimally invasive transducers of physical quantities [2-3]. In this work, we focus on a class of optical sensors known as the Fiber Bragg Gratings (FBGs) [1]. Those consist in a sensitive section of the fiber, built with a periodical modulation of the refractive index of the core, produced by a UV light laser which locally modifies the physical properties of the material printing a series of bands with higher refractive index. This modulation of the refractive index reflects a particular wavelength, called Bragg wavelength, following the equation:

$$\lambda_B = 2n\Lambda_G \quad (1)$$

where λ_B is the wavelength reflected by the FBG, n is the refractive index of the fibre, and Λ_G is the pitch of the grating as shown in figure 1. The linear relationship between the reflected wavelength λ_B and the grating pitch Λ_G is valid through all the field of measure; this allows to keep the same resolution and avoids dynamic calibrations of the sensors. The dependence of λ_B on the geometric pitch of the grating allows to use the FBG as a sensor for mechanical strain. Moreover, temperature influences both the refraction index and grating pitch (through thermal expansion), thus allowing to employ FBGs as temperature sensors. The behaviour of the FBG with respect to changes in temperature and strain is expressed by:

$$\Delta\lambda_B = K_\varepsilon\Delta\varepsilon + K_T\Delta T \quad (2)$$

where K_ε and K_T are the strain and temperature coefficients [4-6]. Clearly, if an FBG is used as a strain transducer, either its temperature shall be controlled or the effect of temperature change shall be accounted for, with a procedure called thermal compensation. The properties of FBG based sensor make them highly suitable for prognostic applications. Prognostics and Health Management (PHM) is a discipline aiming at the continuous estimation of a system remaining useful life, based on actual data measured by the system itself, with the purpose of optimally scheduling maintenance interventions and mission profiles. Clearly, a deep knowledge of a system is required to perform a useful prognostic monitoring; both precise sensor readings and a good understanding of the physical phenomena underlying the system are necessary. In this context, FBG-based sensors can provide accurate measurements of physical quantities related to the system performance and operation. For example, for the fault detection and estimation of remaining useful life of mechatronic systems, such as electromechanical and electrohydrostatic actuators, FBGs can be used as very sensitive strain sensors to determine the external load that acts on the actuator, modifies its dynamical response, and influences the rate of wear propagation. Additionally, minimally invasive and very accurate temperature measurements can be provided with a high spatial resolution, helping the detection of local overheatings that can indicate the presence of incipient faults of devices such as electrical motors

and coils of solenoid valves. Other PHM applications can be found in the vibration analysis of rotating equipment (such as turbomachinery and mechanical transmissions) and in health monitoring of composite structures, where high resolution strain measurements can help infer local damages such as delaminations [7]. In this work, we present an experimental campaign aiming at determining the performances of different installation techniques for FBG based strain sensors, relying either on gluing or mechanical clamping onto the surface of the monitored structure. Different off-the-shelf materials are tested, and their advantages and disadvantages are discussed, alongside with their applicability to different components and situations.

2. Test bench assembly

A test bench (shown in figure 2) has been developed to perform strain and thermal tests on FBG sensors, reducing as much as possible the errors due to external factors. The main critical factors to keep under control are vibrations and fiber locking systems. The tests and the result described in this paper aim to find the best locking solution to performing high precision strain test.

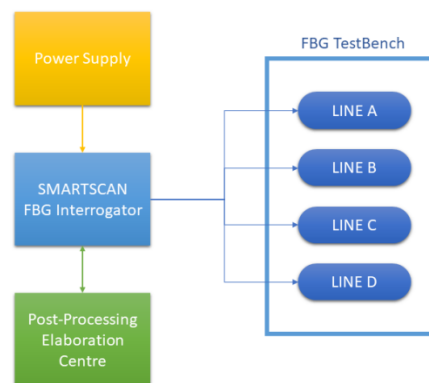


Figure 2. Schematic layout of the test bench.

The test items are optical fibers with a small sensitive region containing the Bragg grating. The fibers are clamped at both ends and tensioned by means of a small linear actuator, with a displacement resolution in the order of 10 microns. The free length l_0 of the fiber is variable from one test to another, but is kept in the order of tenths of centimeters, allowing a resolution for the strain in excess of 10^{-5} . One end of the fiber is equipped with an optical connector, allowing to couple it to the acquisition equipment, also referred to as the interrogator. The interrogator sends a variable wavelength light impulse along the fiber, and detects the wavelength reflected by the FBG section.

The shift in wavelength allows computing local deformation or temperature. Multiple measures are possible on the same fiber, by using FBG sensors with different base wavelengths; in an on field application, this allows to achieve high resolution measurements with compact and minimally invasive equipment. Vibrations made the first measurements unusable. Two main sources of vibration were identified in the test facility, specifically ground vibration (caused for example by road traffic and walking near the test stand) and room air circulation (due to temperature gradients). FBG sensors are highly sensitive to mechanical deformations, thus vibration causes a small but detectable additional deformation, reducing the accuracy of measurements. To minimize the effect of possible vibration sources, we adopted several strategies. The whole test stand was positioned on top of a pneumatic anti-vibration table; moreover, a set of passive sorbothane dampers, with a relaxation time of 2 seconds, were placed between the anti-vibration table and the breadboard.

Sorbothane is a visco-elastic urethane polymer, meaning that it exhibits properties of both liquids (viscous solutions) and solids (elastic materials) [8,9]. Additionally, the whole test bench was covered with a plexiglass enclosure, to isolate it from room air circulation, and a substantial low-pass filtering was applied to the measured data.

3. Locking techniques

The use of FBGs as strain sensors requires to secure the optical fiber to the structure to measure, with as rigid a connection as possible, such as the strain sensed by the fiber closely follows the local strain experienced by the structure. However, optical fibers are highly vulnerable to mechanical shear stresses, so the locking system shall be designed in a way not to damage the sensor itself. For example, a simple clamping between metal surfaces is not feasible, since the high local stress concentrations are likely to damage the fiber. The main aim of this experimental campaign is to investigate different locking solutions and characterize their performances, applicability, and ease of installation, in order to acquire the knowhow to develop FBG-based sensor packages suitable for prognostic applications.

We considered locking systems based on mechanical clamping, relying on a layer of soft material (typically synthetic rubber e.g. expanded neoprene or 1,3-butadiene) to distribute the load on the fiber and protect the sensor from concentrated shear stresses. In addition, we tested gluing of the fiber to a PLA holding plate, with various commercial epoxy resins.

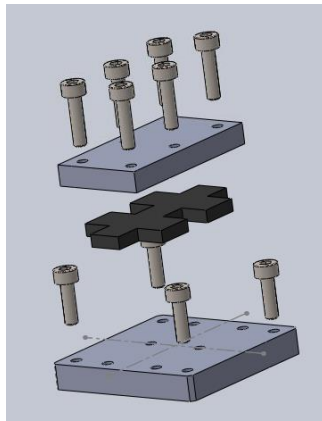


Figure 3. Locking system based on mechanical clamping.

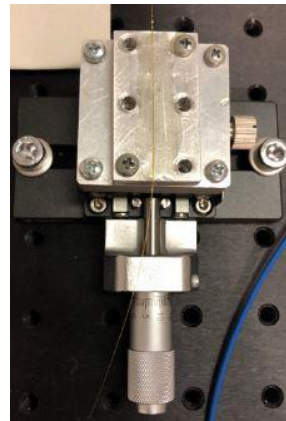


Figure 4. Locking system based on epoxy resins gluing.

Each clamping solution has its own advantages and disadvantages; for example, the mechanical clamping features a full reusability of all components, while the use of glue creates a permanent joint between the fiber and the holding plate (which is produced through additive manufacturing in order to have a quick availability of replacement parts for the experimental campaign). The mechanical locking shows a maximum strain value (much lower than the limit of the FBG sensor) for which the fiber slides from the clamp, producing an invalid measure. Conversely, the use of epoxy glue provides a stronger bond, eliminating the risk of slippage, but its stiffness is much lower and its response is characterized by a viscous-elastic behavior. Moreover, this behavior is greatly influenced by the temperature and humidity conditions experienced during glue application, and by the uniformity of mixing of the epoxy components.

4. Measurement strategy

In order to achieve a preliminary validation and evaluation of the considered technique to lock the FBG sensors, we proceeded with a simplified statistical approach. Our step procedure is summarized in figure 5 and briefly explained in the following.

- *Static strain measurements.* In this phase, the FBG sensor is set to a given strain, and kept in this condition for a time interval sufficient to acquire a statistically significant number of measurements with the interrogation system. The measures acquired with different imposed strain values are separated by an interval to allow the system to settle to the new condition, and avoid the acquisition of transient effects. Data points are stored in a log file by the interrogation system.

- *Data processing and filtering.* The log file is imported in the Matlab environment to be processed. The mean value and standard deviation of each set of measurements is computed. This process allows to filter virtually all the zero mean high frequency noise measured by the sensor: only the midpoint of each measurements set is used in the next phase.
- *Evaluation of a corrective coefficient and sensor calibration.* A linear regression, weighted by the standard deviation of the measures, is performed on the filtered data points for different strain values, to highlight the strain-wavelength characteristic of the FBG sensor in combination with a given locking method. The ratio between the theoretical slope Ke_{th} (from Equation 2) and the experimental slope Ke_{ex} is the corrective coefficient K to be used in the sensor calibration. The offset is an effect mainly related to the pre-tensioning of the sensor.

In order to have a better control of the accessible data we decided to work with Raw Data coming from the interrogation system without any filtering or elaboration from the software suite directly available on the system; then, all processing is performed by a Matlab script developed for the purpose. The discrepancy between the theoretical and experimental slope of the strain-wavelength curve can be mainly ascribed to the flexibility and slippage introduced of the different locking techniques that were tested. To evaluate the performance of the different solutions and calculate a corrective parameter that allows us to calibrate measurements come from the test bench, repeatability tests were performed, and an average corrective coefficient was computed for each locking system.

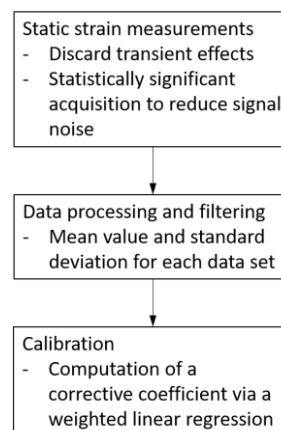


Figure 5. Step-by-step procedure for measurement and data processing.

5. Results

Several fibers were tested with different locking techniques. The sensor outputs in terms of center wavelength were acquired, filtered and converted into strain and displacement measures, according to section 4. As an example, figure 6 shows the imposed and measured displacement raw data as a function of time; in this case a 53.59 mm fiber was employed, with glued ends. The discrepancy between commanded and actual values is due to the flexible behavior of the glue locking system: part of the displacement of the linear actuator results in the elastic deformation of the glue and PLA locking plate, rather than in strain of the optical fiber. The irregular behavior during transient is due to the linear actuator being manually operated; however, those transient are excluded from the acquisition (dashed line in figure 6); conversely, only the static values are stored and processed in the following phases (highlighted by a thick line in figure 6). For each set of measures taken in steady state, the mean value and variance are computed according to section 4. The blue points in figure 7 are the mean values of each set of measures, represented alongside with its standard deviation in the measured displacement and the actuator resolution in the commanded displacement axis. The standard deviation of the measures is very small (barely visible in figure), and clearly a much larger part of the measurement error is due to the comparatively limited resolution of the linear actuation system.

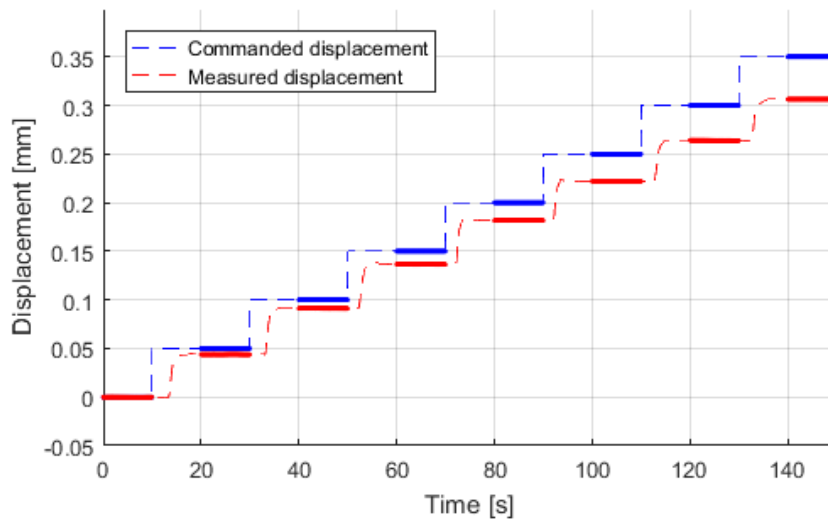


Figure 6. Imposed and measured displacement timeseries, for resin locking system and fiber length of 53.59 mm.

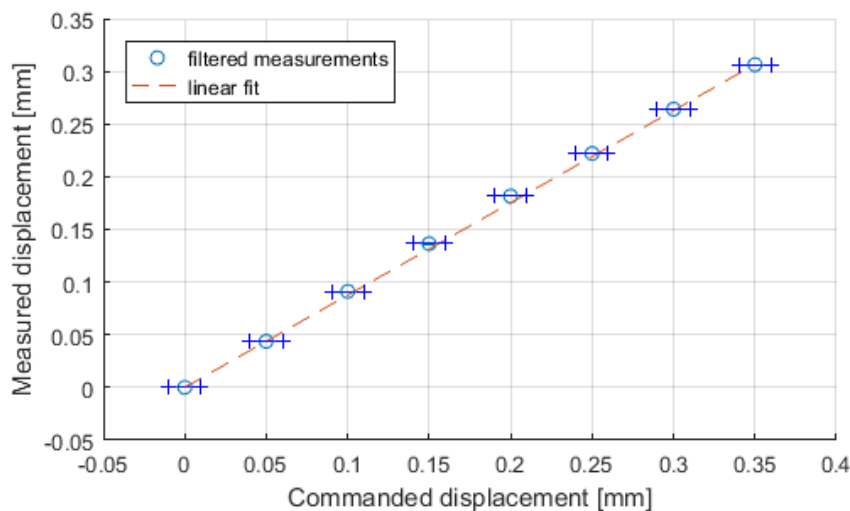


Figure 7. Imposed and measured displacements filtered values and linear fit for sensor calibration.

The red dashed line is the linear fit of the filtered points, weighted by their standard deviation; the inverse of its angular coefficient is the corrective coefficient needed to calibrate the sensor.

The glue locking technique behaves consistently in all the strain range of the FBG sensor (from zero to either the fiber breakage or the maximum wavelength detectable by the interrogation system). Conversely, the mechanical clamping is applicable only for strain lower than a certain value (depending on clamping pressure and friction coefficient between the fiber and the rubber layer).

Higher values of strain result in slipping of one end of the fiber from its lock. Figure 8 shows this behavior for a given clamping pressure and different fiber lengths (respectively FBG 1 = 53.59 mm, FBG 2 = 128.80 mm and FBG 3 = 228.94 mm). For a given displacement, a shorter fiber will experience a greater strain; for the clamping conditions considered in figure, a strain higher than $7e-3$ produces a slippage; aside from transient effects, the increase of displacement causes no additional strain on the sensor.

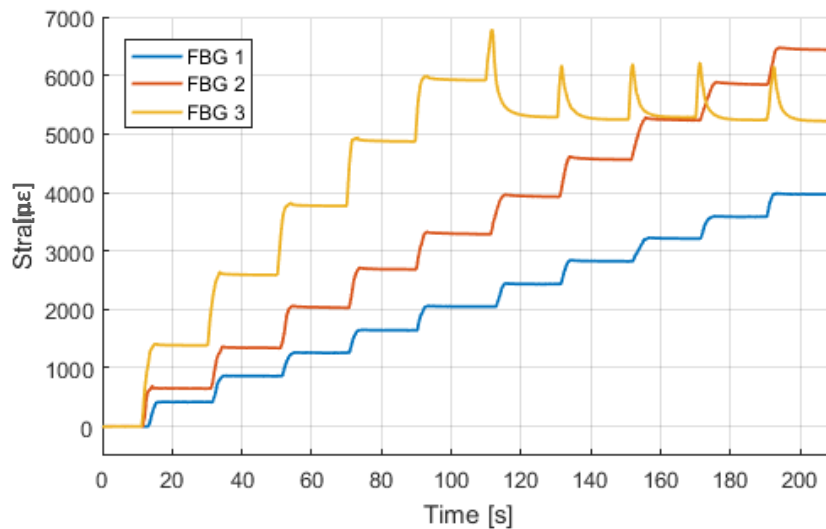


Figure 8. Behaviour of mechanical clamping for different strain values (FBG 1 = 53.59 mm - FBG 2 = 128.80 mm - FBG 3 = 228.94 mm).

Repeatability tests were performed to assess the presence of hysteresis or viscous shear phenomena within the different locking techniques; these consisted in repeatedly loading and unloading the sensor. In the case of fiber glued to the support, no significant hysteresis was detected: when the actuator returns to a null displacement, the FBG reading returns to the center wavelength corresponding to the initial preloading, even after several cycles. The mechanical clamping behaves differently: even a small displacement produces a local sliding on the rubber-fiber interface, and after the first loading cycle the sensor loosens slightly on the supports. Then, when the deformation is removed, the preloading on the fiber is reduced, and the FBG reading shifts accordingly.

These behaviors appear clearly from the strain-time curves of figure 9.

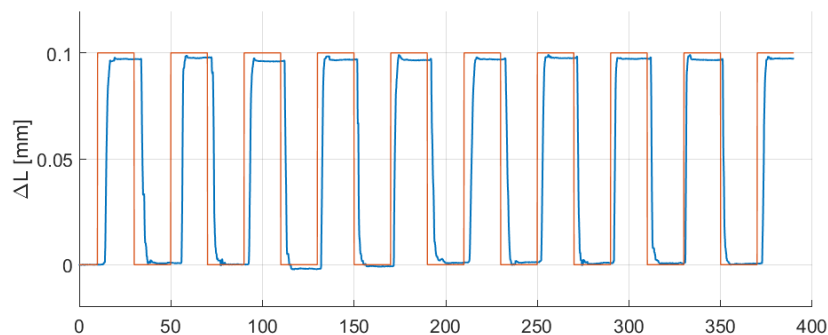


Figure 9. Time series of the applied and measured strain for repeatability tests.

Moreover, cyclic load and sliding causes the rubber layer to damage, producing a recess as a result of the permanent deformation caused by the high contact pressure in the fiber-rubber interface. This behavior has a negative effect on durability of this kind of locking techniques, as well as on repeatability of results. The hysteresis phenomena, alongside with the macroscopic slippage occurring for high strains, have a visible effect on the corrective coefficient K . Specifically, K increases because the locking system is not able to efficiently transfer the strain to the fiber. Moreover, the linearity of the sensor is compromised, resulting in a greater residual in the fitting and thus a greater dispersion of the K along different tests. Table 1 summarizes the corrective coefficients K for several test campaigns with different locking techniques, fiber lengths and applied displacements.

Table 1. Performance comparison of different FBG locking techniques.

Locking technique	Fiber lengths [mm]	Applied Strain [$\mu\epsilon$]	Corrective coefficient K	Dispersion
Hard rubber (1,3-butadiene)	228.94	4000	1.2135	0.064
Soft rubber (expanded neoprene)	228.94	4000	1.0769	0.021
Araldite	228.94	2000	1.0012	0.0013
Araldite	151.16	3000	1.0212	0.0045
Araldite	53.59	6000	1.1248	0.0132

From the test, the gluing with Araldite epoxy resin resulted as the best locking system in terms of stiffness, durability and repeatability. It features both the lowest dispersion and correction (that is, the corrective coefficient needed for calibration is the closest to unit).

6. Conclusions

Several locking techniques for the employ of FBGs as aerospace strain sensors for prognostic applications were investigated. The experimental campaign showed that gluing the sensor to the structure is an inherently better solution than mechanical clamping, in terms of both accuracy and durability. The use of these sensors allows precise and minimally invasive strain measurements with high spatial resolution and significantly more compact equipment than standard technologies, such as resistive strain gages. This will in turn enable to acquire the data needed for prognostic analysis of structures and actuation system, to compute informed estimates of remaining useful life of components, and to plan the maintenance schedule accordingly.

All the tests were carried out in a controlled environment, with constant temperature and humidity, so no thermal compensation was needed. Further studies are in progress to determine the effect of variable environmental conditions on the performance of the locking systems, as well as the applicability of FBG based sensor for highly dynamical measurements, such as mechanical vibrations.

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