FIBER OPTICS IN STRUCTURAL HEALTH MONITORING

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ABSTRACT

Structural Health Monitoring (SHM) has assumed a significant role in assessing the structures safety and integrity. SHM can be understood as the integration of sensing intelligence and possibly also actuation devices to allow the structure loading and damaging conditions to be recorded, analyzed, localized and predicted in such a way that non-destructive testing becomes an integral part of the structure. SHM sensing requirements are very well suited for fiber optic sensing technology. So in this paper, after a very brief introduction of the basic SHM concepts, the main fiber optic technologies for this application will be reviewed, several examples and the main current technical challenges will be addressed and, finally, the conclusions summarized.

Keywords: Optical Fiber Sensors, Fiber Optics, Optical Transducers, Optoelectronic Units, Structural health building monitoring.

1. INTRODUCTION

It could be very interesting to determine if structures are safe for reusing after a significant overload or to know if the current infrastructures are approaching or exceeding their initial designed life period. On the other hand, it is known that sudden collapses of representative structures with all the troubles and costs (even with losses of human lives) such the crashed AA587 flight (on November 12th of 2001) [1], the collapse of the I35W Minneapolis Bridge [2] or the Belfast Railway Line viaduct Collapse in Dublin (on 21st August 2009) have unfortunately happened. They could have been determined or evenavoided, if they had been equipped with *Structural Health Monitoring systems (SHM).* It must be remarked that modern structures should be equipped with monitoring systems able to automatically detect the damage, characterize it (recognize, localize, quantify or rate), and report it, providing important input for structure managers or for the *system intelligence*. According to the functionality and degree of complexity, the SHM systems can be classified in five levels, following what can be named the *staircase of the SHM systems* [3]: the higher the level, the higher the complexity and functionality. In fact, it is a logical consequence of the example described using the human body to depict the SHM concept. Level I SHM systems (the simpler ones) only detect the presence of damage without locating it on the structure. However, the level V are constituted by very complex hardware, custom algorithms and the software to enable, by itself, the diagnosis and/or the prognosis and even the healing functions.

A key item or subsystem of the SHM systems is its sensing part for what OFS technologies suit properly the main technical requirements.

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Understood as the set of techniques and scientific knowledge which are applied to the generation, propagation, control, amplification, detection, storage and processing of signals of the optical spectrum, along with their technologies and derived uses, the Photonics field can be divided into several areas. The Optical Fiber Sensing Technology can be considered a sub-area of the Photonic Sensing Technology one [4]. A Photonic/Optical Sensor can be considered as a photonic system where the measured object magnitude (measurand) or input signal (O_i), introduces modifications or modulations in some of the characteristics of the light in an optical system. After being detected, processed and conditioned, the system will deliver an output signal (O_e), usually in the electric domain, which will be a valid reproduction of the object variable. The transmitted or reflected light can be modulated by the measurand or modulating signal in its amplitude, phase, frequency or polarization characteristics. In accordance with this concept, if any of the processes or parts uses fibre-optic technology, a subdivision of OS known as Fiber/Fibre Optic Sensors (FOS), or Optical Fiber/Fibre Sensors (OFS), is created [3-5].

In this paper, the more successful fiber optic technologies for SHM will be reviewed, several examples and the main current technical challenges will be addressed and, finally, the conclusions summarized.

2. OFS SUCCESFUL TECHNIQUES FOR SHM

In near 3 decades a very wide number or techniques and approaches have been presented to measure a very wide set of measurands in not a less wide number of sectors of application. Many companies were created to exploit commercially the new OFS technologies. However not all of them have followed the proper path and survived successfully [6]. In the following lines a very brief review of some of the most successful techniques used will be addressed. They will be structured regarding the fiber structure employed in the transducer.

2.1.- Long transducers for elongation measurements

Several approaches have been tested for measuring the integral elongation of a structure using long fiber gauges. Typically, these kind of transducers are useful to measure the structural integrity of structures in a wide set of application sectors including architectural heritage and civil engineering applications [3,4,5]. When long gauge transducers are required, the most successful technology in the recent years has been the SOFO system. The transducer consists of a pair of single-mode fibres installed in the structure to be monitored (Figure 1).

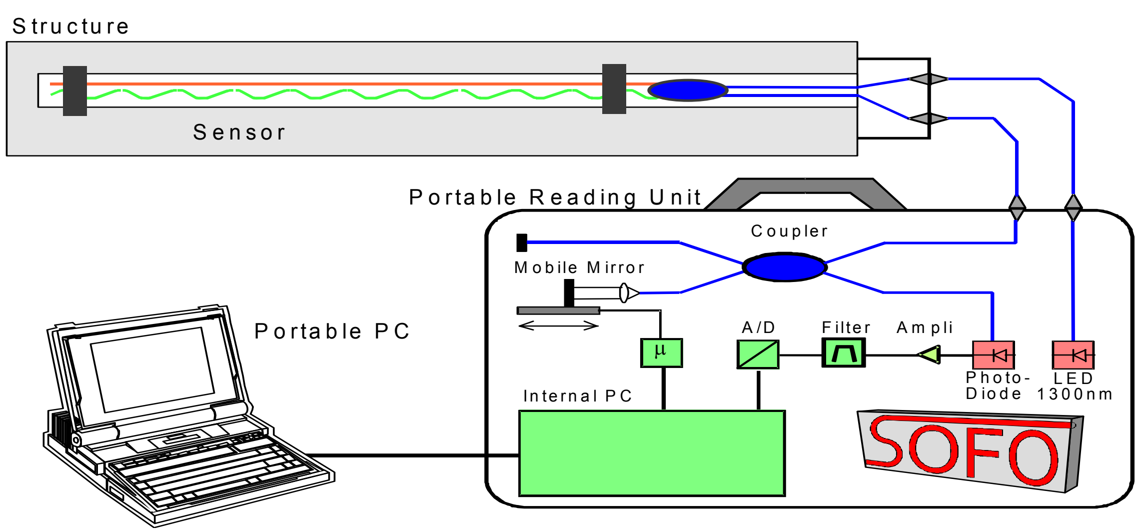


Figure. 1. Setup of the SOFO system. Courtesy of SMARTECH.

One of the fibres, called measurement fibre, is in mechanical contact with the host structure itself. It is attached to it at its two extremities and pre-stressed in-between. On the other hand, the other fibre, the reference fibre, is placed loose in the same pipe. To make an absolute measurement of this path unbalance, a low-coherence double Michelson interferometer is used. The first interferometer is made of the measurement and reference fibres, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-defined path unbalance between its two arms [5].

The precision and stability obtained by this set-up has been quantified in laboratory and field tests to be 2 micron, independently from the sensor length over more than one year. Even a change in the fibre transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity. Since the measurement of the length difference between the fibres is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors [7].

Five improved generations of the SOFO system for static measurements have been developed and commercialized being now also available the version for dynamic measurements [8]. It is based on the same transducer approach, but the reading or optoelectronic unit is based on a Mach-Zehnder interferometer instead of a mobile mirror used on the static SOFO unit.

The SOFO system was developed at the IMAC laboratory of the Swiss Federal Institute of Technology in Lausanne (EPFL) and is commercialized by SMARTEC SA (www.smartec.ch) .

2.2.-In-fibre gratings for quasi-distributed measurements

Gratings written in the core of optical fibres are one of the more intensively studied structures because of their great possibilities to create devices for both sensing and telecommunication applications [3-5]. Their optical, mechanical and environmental (in wide sense) behaviors, among others, were studied both as a base for transducers and/or as a base for optical devices for optoelectronic units or optical communications systems or subsystems [9,10,13,14].

In sensing, both short period (Bragg) and long period (period much longer than the wavelength of the light) are used [5,11]. The first ones because of their capability to measure both the strain and temperature of the structure (and an ample variety of indirect measurands). Besides, they are also widely used because of their ability to create tunable filters, and for their multiplexing capabilities. Long period gratings [12] are used because of their high sensitivity to the cladding modes (among others).

An Optical Fiber Grating, FBG, can be understood as an optical fiber with a periodic refractive index perturbation pattern inscribed in the core such that it diffracts the optical signal in the guided mode at specific wavelengths into other core-bounded modes, cladding modes, or radiation modes [10].

The peak of mode coupling in the reflected-spectrum occurs at the resonant wavelength λ_B given by [9]:

$$\lambda_B = 2\, n_{eff}\, \Lambda$$

Where, n_{eff} is the effective index of the mode in the grating. Measurement of the peak reflected wavelength results in the direct measurement of the optical product $n_{eff}\Lambda$ of the grating. Any perturbation that modifies the n_{eff} and/or the grating period Λ will alter the measured Bragg wavelength.

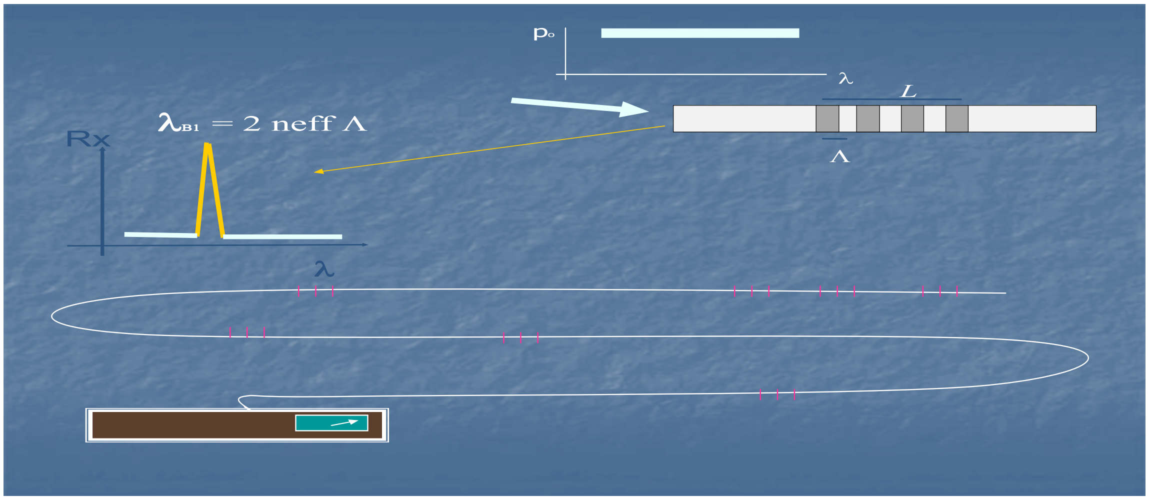


Figure. 2 Temperature and Strain Bragg grating Transducer and their WDM multiplexing capability.

As illustrated on figure 2 their in-line optical connection property enable the FBG´s feasibility to built-up fiber optic sensor networks using wavelength (WDM), time (TDM) and/or hybrid multiplexing schemes both active and passive [15].

This technology can be used in aerospace, medical, biomedical, environmental, electric power energy, and in military and civil engineering applications sectors [3,5,16]. In table I a summary of grating applications can be observed.

Table I Summary of potential sensing applications of various types of fibre gratings.

Gratings – Type	**Applications**
Fiber Bragg Gratings (FBGs)	• Strain and temperature sensors • Pressure sensors • Acceleration sensors • Ultrasound sensors • Mechanical load sensors • Gas detection sensors (e.g. hydrogen) • Extensometers • Electromagnetic field sensors • Reflection elements in interferometric sensors arrays
Fiber Bragg Grating Laser Sensors (FBGLS)	• Novel, compact hydrophones • Acoustic emission sensors for NDE
Long Period Gratings (LPGs)	• Bend sensors • Chemical sensors • Broadband source filters
Pi – Phase Shifted Gratings	• Transverse load sensing
Chirped Gratings	• Strain Sensing • FBG demodulation

A complete civil structure monitoring system fully designed, developed, in-laboratory and in-field tested system can be found in [17].

Despite of its relative novelty, the fibre grating technology is mature enough, and several sensing companies such as www.fos-s.be ; www.fibersensing ; www.micronoptics have their core business centred in this technology. New studies looking for new effects and structures continue nowadays [18,19].

2.3.-Distributed sensing

Due to optical fibre properties in addition to advanced interrogation techniques, distributed sensing in which the fibre acts, simultaneously, as optical channel and distributed transducer is, today, a reality. It can be said that the fibre plays the role of a "nerve" for materials and structures where the fibre is embedded. Distributed optical-fibre sensor systems have and, undoubtedly, will have a large role to play in the monitoring and diagnostics of what can be called "smart materials and structures" [20].

Linear backscattering and, overall, non-linear back-scattering and non-linear forward-scattering (having their own special advantages and disadvantages) can be used to match the specific requirements of length and resolution of the measurand. Raman scattering (for temperature) and Brillouin scattering (for strain and/or temperature) or their combination [21] using time, frequency, polarization, or correlation domain techniques (continuous or pulsed) including several variants [22], are used to interrogate the distributed transducer [26].

Distributed systems over larger distances (up to 100 km) [20] and special resolutions of 1cm have already [25] been demonstrated. Due to their relevance in sensing, works are in course to improve their main technical characteristics [25-28].

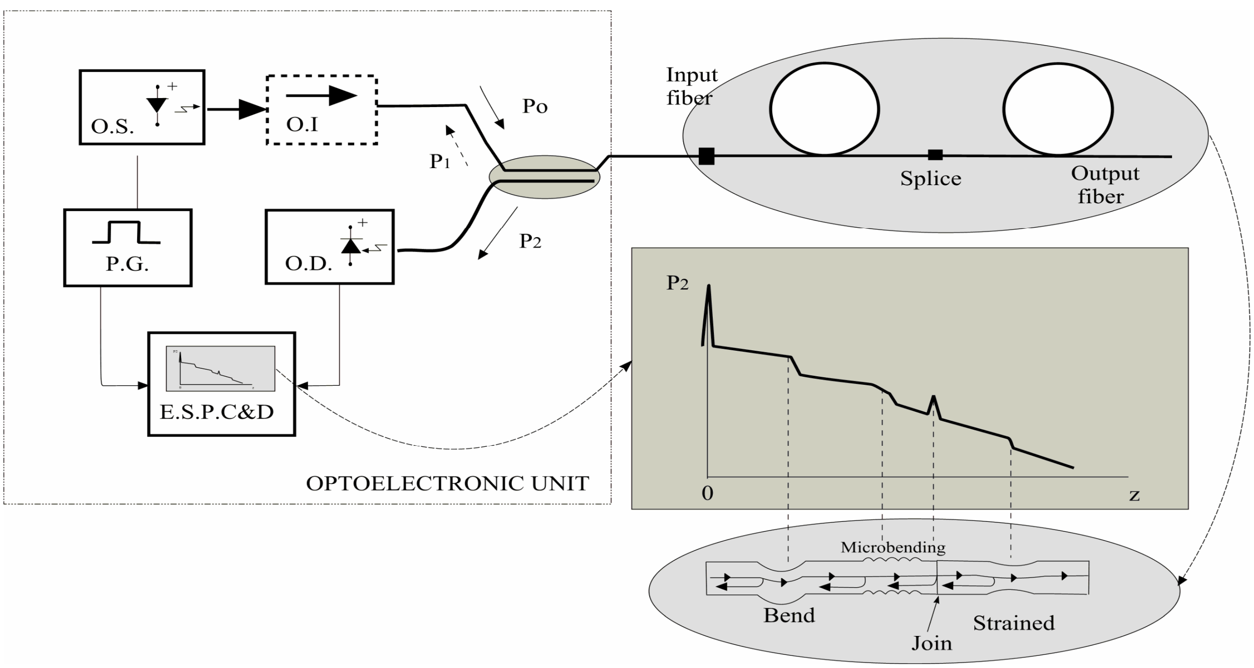


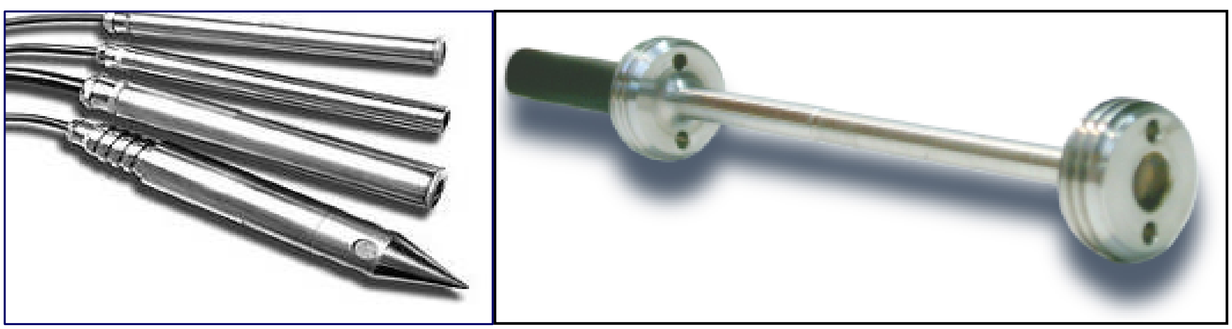
Figure 3.- Schematic illustration of a linear scattering based fibre distributed sensors system.

Despite the importance of this technology to solve real problems and in spite of the important flux of ideas coming from the research centers, their commercialization has not reach the expected level yet. However it is a key fiber sensing technology for the near future and despite the above mentioned, some companies such as http://www.sensornet.co.uk; http://www.sensa.org; http://www.weatherford.com; Omnisens (www.ommnisens.ch), ANDO (tmi.yokogawa.com); Neubrex (www.neubrex.com) and OZ Optics (www.ozoptics.com); are already offering some temperature and/or strain distributed systems nowadays.

2.4.- Other techniques for SHM: Fabry-Perot cavities

Fabry-Perot cavities (both passive and active) have been very successfully used in sensing applications exploiting measurand-induced changes in one of their cavity parameters. They can be used both as the basis for the transducer mechanism or as fixed or tunable devices in the optoelectronic unit. The cavity can be active, for instance integrating a fibre laser sensor, or passive. One very well tested approach is the Extrinsic Fabry-Perot Interferometers (EFPI's) that is constituted by a capillary silica tube containing two cleaved optical fibres facing each other, but leaving an air gap of a few microns or tens of microns between them. When light is launched into one of the fibres, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light onto the glass-to-air and on the air-to-glass interfaces.

This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fibre spacing [29]. These structures were used in a wide set of applications to measure an ample set of measurands. For instance in [30,31] a sensor head for long-term high-precision strain measurements of very small deformations of a mechanical diaphragm and in [32], a fiber-optic strain sensor an in-vitro and in-situ immunoassay biosensor based on fibre optic Fabry-Perot interferometer are described, respectively. Because of its nano-size and high sensitivity to many parameters (strain, pressure, vibration, chemical- humidity, breathing, etc,-) the FP cavities obtained by molecular self-assembly chemistry have obtained a special attention in the last decade [32,33]. Commercial FP transducers and devices can be found from several companies such as www.roctest; www.fiso.com; www.lunainovations.com; www.bam.de. In figure 4, several transducer or sensor heads based on EFPI's sensing structures able to be used on SHM applications can be observed.



a) b)

Figure 4. Commercial transducer for pressure (a) and for strain (b). Courtesy of Roctest.

3. SEVERAL EXAMPLES

The application of OFS in structural monitoring include civil or industrial structure monitoring (concrete beam tests, bridge girders, ore mines, nuclear containers, tunnels, hydroelectric dams…), for composite materials (spacecrafts, aircrafts tail spars, helicopters and windmill rotor blades, ship and submarine hulls, composite cure monitoring, composite girders for bridges…). OFS Technology can also be employed on acoustic sensing (towed hydrophone arrays, down-hole sensors for oil wells) on in-plant or distribution of electric power utilities, for gas pipelines and, in general, for industrial control, monitoring and processes; and even with potential environmental applications .

Just to illustrate the potential of the OFS in SHM applications, three examples framed on renewable energies, and civil engineering will be very briefly mentioned.

Figure 5. Installation wind turbine and detail on Cañoneras courtesy of COPSESA.. Sea-wave turbine in experimental phase in Santoña Spain. Placed at 10 km from the coast, the device converts the vertical movement of the sea waves in electric energy by means of a conventional generator. Courtesy of Sodercan.

SHM systems are being required and will play a key roll in established technologies such as wind turbines. The number of optical fiber monitoring systems applied to wind farms has increased during the last years, and the potential offered by these systems can be very attractive or crucial for off-shore renewable energy generation devices (Figure 5a). Initiatives such as Idermar Buoy in Spain driven by Iberdrola renewable and Sodercan just collecting data for environmental analysis or the Martifer Energy in Portugal instrumented with a quasidistributed system based on FBG technology (180 points) to assess its structural integrity are still in early stages (figure 5b) just collecting data for environmental analysis.

Las Navas viaduct can be used as an example of Civil engineering OFS monitoring. Las Navas viaduct is integrated by a symmetric and repetitive structure formed by ten identical sections, limited by two piles each. It was also instrumented with a SHM system developed by the University of Cantabria [17]. 42 FBG transducers (60 cm long) able to measure both the temperature and the elongation were placed on top of one pile and between two piles of sections. In each section the transducers were embedded inside the concrete structures in vertical, transversal and longitudinal positions (Figure 6).

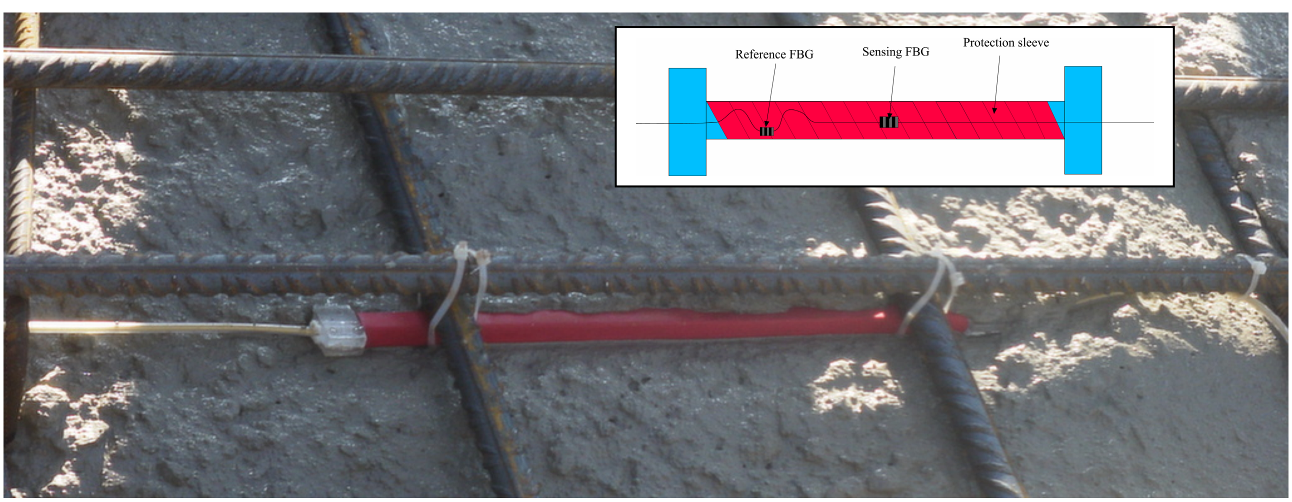


Figure. 6 Temperature and Strain grating Transducer being embedded in Concrete. Courtesy of the Photonic Engineering Group of the University of Cantabria.

4. MAIN CHALLENGE

The main challenge in Optical Fiber Sensors for SHM systems (common to all technologies) is to assure that the sensor system itself is not damaged both when deployed during the field and in the current working period of life. It is necessary to guarantee that the data from the sensors represent the real behavior of the material or the structure and are not corrupted due to a sensor malfunction. For that reason, it could be necessary to monitor the sensors themselves. This fact drives to the very challenging tasks of developing new techniques for:

a) *Sensor validation by itself or by means of reports on each other's condition.*
b) *'Fail-safe' sensor networks.*

If a sensor fails, the damage identification algorithms must be able to adapt the network. This adaptative capability implies that a certain amount of redundancy must be built into the sensor network [3].

3. SUMMARY & CONCLUSIONS

SHM is naturally linked to safe-working, maintenance, optimized technical and economic exploitation of the structures in addition to the minimization of the potential social, economical, and other impacts. With SHM systems unusual structural behaviors can be detected at an early stage decreasing the risks of sudden collapse and preserving nature, goods or even human lives.

After framing the fiber sensing technology as an area inside the photonic field, some key fiber sensors concepts have been stated. Then the most successful and mature techniques for SHM based on the architecture of the transducer, have been briefly presented. Using SOFO concept, Bragg grating technologies and Brillouin or Raman non linear effects, integral, quasi-distributed, and distribute measurands of interest on SHM applications can be successfully performed. The application areas for OFS in structural monitoring is vast, including civil or industrial structure monitoring (concrete beam tests, bridge girders, ore mines, nuclear containers, tunnels, hydroelectric dams), composite materials (spacecraft, aircraft tail spars, helicopter and windmill rotor blades, ship and submarine hulls, composite cure monitoring, composite girders for bridges), acoustic sensing (towed hydrophone arrays, down-hole sensors for oil wells); in-plant or distribution of electric power utilities, gas pipelines and, in general, industrial control, monitoring and processes. Some examples and the main challenge have been finally addressed.

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