Smart Sensing for Aeronautical Applications

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Smart sensing for aeronautical applications is a multidisciplinary process that involves the development of various sensor elements and advancements in the nanomaterials field. The expansion of research has fueled the development of commercial and military aircrafts in the aeronautical field. Optical technology is one of the supporting pillars for this, as well as the fact that the unique high-tech qualities of aircrafts align with sustainability criteria.

structural health monitoring | aviation | smart materials | optical fiber sensors

1. Flight Environment Sensing

1.1. Critical Environmental Sensing

Different engineering structures are exposed to environmental conditions related to the operation, or even the natural aspects, of the environment. The environmental sensing plays an important role not only on the structural analysis, but also in the navigation and control systems [1]. It is also important to mention that the dynamics of the environmental conditions (such as temperature and relative humidity) directly affect the operational and structural analysis in aircrafts in both corrective and predictive maintenance conditions [2]. Furthermore, the environmental monitoring is critical for the stress/strain sensors, since many sensors present temperature cross-sensitivity, where the structural failures can be also related to the temperature distribution dynamics [3].

In aircraft operation, the environmental monitoring is crucial for the navigation and instrumentation equipment, where the Air Data System is responsible to provide the flight data to the crew [4]. Considering an important technology for the system's navigation, especially on the external measurements of speed, the Pitot tube technology is widely employed [5]. Such a sensor uses the air pressure in dynamic and static intake conditions, in which the operation in the harsh environments of the flight conditions can lead to freezing of the device's orifice that can ultimately lead to critical issues in the sensor reading and even accidents [4]. To that extent, the Federal Aviation Administration provides instructions for the atmospheric conditions that can lead to such critical issues in the instrumentation, which also indicates the necessity of measuring the atmospheric/environmental conditions in-flight [4].

It is also important to notice that the environmental conditions, including temperature, moisture concentration, and pH, can lead to increases in maintenance costs and downtime, due to corrosion in different parts of the aircraft [6]. For this reason, environmental analysis also plays an important role in the structural defects, due to environmental effects, mainly the corrosion of the aircraft structure and components [7]. In summary, the corrosion is an electrochemical deterioration of metallic structures, which is caused by the chemical reactions of the material with the environmental conditions [8]. The extreme environmental conditions in aircraft operation (such as the freezing conditions in conjunction with extreme heating of some parts) exposes the aircraft structure and components to a variety of corrosion mechanisms [7]. Such a scenario includes additional criteria on the aircraft materials selections, where the design can be performed while also considering the corrosion resistance [6]. However, achieving such corrosion resistance in conjunction with the critical performance aspects, such as stiffness, weight, and strength, lead to the multi-objective problem of optimization in the material features that may not be completely fulfilled with a single material.

To that extent, the corrosion detection on the structures and components have been investigated [6]. In general, the detection is based on vision systems, which have drawbacks on the analysis of inaccessible areas. For this reason, the use of environmental sensors for indirect corrosion detection, where the environmental or local conditions can be used to correlate the corrosion parameters, such as location, time, and rates [9]. In this case, the environmental parameters monitoring, namely temperature, humidity, and even chemical compounds concentration, can be associated with corrosion, as well as its early detection or estimation [10]. Despite the influence of the atmospheric pollutants and compounds, such as acid sulfates and acid chlorides, as well as sea salts diffused into the moisture, the moisture detection and temperature play critical role in the corrosion analysis [6]. In the dynamic measurement of moisture, the time at which there are atmospheric conditions for surface layer of moisture is known as the time of wetness, and it is used as a factor for corrosion growth and initiation [10]. In addition, the temperature is an important parameter in the corrosion analysis, since it not only relates to the corrosion initiation, but also on the type of the corrosion [6]. Different temperature thresholds were analyzed in the literature for their correlation with the type of corrosion, which indicate the necessity of continuous temperature monitoring in aircraft structures and components, especially the ones with direct contact with moisture or atmospheric pollutants [6].

It is also important to mention that the climate conditions are important in the aircraft applications, not only on the external environmental conditions' assessment, but also the internal environmental conditions, since the thermal comfort in cockpit or by the crew members and passengers (in the case of commercial flights) are important parameters [11]. In many cases, there is the exposure to long periods at a seated position for the crew members and passengers, which can lead to skin maceration and general injuries, due to the microclimate conditions [12]. In the literature, three regions of thermal comfort in microclimate conditions (i.e., interface between the limb and the seat) were defined, and such regions include the comfort (temperatures from 29 °C to 34 °C and relative humidity below 70%), neutral comfort (temperatures from 27 °C to 36 °C with relative humidity below 80%), and discomfort (temperatures lower than 27 °C or higher than 36 °C with humidity higher than 80%) [13]. Therefore, the applications of temperature and humidity sensors can be used as important indicators of the thermal comfort in the cabin or in the interface between the limb and the seat.

Among different sensors technologies, optical fiber-based sensors are a growing research field in the sensor community, due to their advantages, such as compactness, electromagnetic fields immunity, passive operation, multiplexing capabilities, chemical stability, and biocompatibility [14], as mentioned before. For these reasons, they are used for applications in different areas, such as industry [15], SHM [16], biochemical [17], and medicine [18]. A high versatility is found in OFS, since many approaches were employed throughout the years, where the intensity variation [19], fluorescence/absorbance [20], long period gratings [21], FBGs [22][23], non-uniform gratings [24], nonlinear effects [25], specklegrams [26], interferometers [27], and surface plasmon resonance [28] sensors are generally employed. As an important advantage of optical fiber sensing approaches (related to their material features, which include a flexibility, compactness, and chemical stability), such sensors are able of being embedded in rigid and flexible structures [29], as well as the integration in different dyes [30] and dopants [31]. The embedment or integration of different materials in OFS is especially important in humidity sensors development using silica optical fibers, since such an optical material is not intrinsically sensitive to humidity/moisture absorption [32].

An interferometer-based approach for humidity assessment uses a Mach–Zehnder interferometer (MZI) fabricated from a taper, where a composite film composed of graphene oxide and PVA is coated on the optical fiber sensor [33]. The applied coating is sensitive to relative humidity variation, in which there is a RI variation as a function of the environmental humidity, which leads to the possibility of humidity sensing, due to MZI transmitted spectrum variation as a function of the RI. In another interferometer sensor for humidity measurement, a Fabry–Perot interferometer (FPI) is proposed in [34]. In this case, the interferometer's cavity is obtained on the tip of the fiber, where a Ti_3O_5 thin film (168 nm thickness) with an additional humidity-sensitive film with 1621 nm thickness made of SiO_2, which is enclosed with another Ti_3O_5 film with 168 nm thickness. Thus, the Ti_3O_5 films are used as reflective surfaces to create the FPI cavity, whereas the SiO_2 film presents variations in the RI as a function of the relative humidity, where such RI variations lead to a wavelength shift on the FPI's reflected spectrum. Similarly, the use of extrinsic FPI for humidity measurement can also be achieved using optical adhesive or polymer films that present swelling with the moisture absorption, which also lead to spectral variations of the FPI [35].

Considering the FBG sensors developments in humidity assessment, the use of silica optical fibers is also related to the optical fiber coating with different humidity-sensitive materials [36]. To that extent, the FBG can be coated with polymer films with humidity sensitivity, where the film swelling due to the moisture absorption leads to an increase in the strain on the fiber, which leads to a Bragg wavelength shift in the FBG. In this case, the use of PEG/PVA composite was investigated in [37] for the humidity sensitivity using the aforementioned principle. It is also worth noting that the cladding removal of the FBG (using chemical process such as the etching [38]) results in a sensitivity of the FBG with the external RI, which leads to the possibility of using thin films with RI variation as a function of the relative humidity for FBG-based humidity/moisture assessment approach.

In contrast with the humidity sensing principles using silica optical fibers, the use of polymer optical fibers (POFs) provides advantageous features in some applications, due to their inherent sensitivity to humidity [39]. For this reason, intensity variation-based sensors for humidity assessment were evaluated using the polymer swelling and material features dependency as a function of the humidity as the sensing principle [40]. In addition, the advances in polymer processing and major breakthroughs in FBG inscription led to the development of FBGs in POFs, the so-called POFBGs [41]. In such developments, the use of FBGs in polymethyl methacrylate (PMMA) POFs result in a sensor intrinsically sensitive to relative humidity and moisture, where there is no need for coating the optical fiber with sensitive materials [42]. It is also important to mention that etching treatments, as well as the diameter reduction of POFs, can lead to the improvement on the response time of these sensors in which the real-time moisture and humidity assessment can be achieved [43]. Furthermore, heat treatments can be applied in the POFs to obtain an insensitivity to temperature variations, as well as hysteresis reduction, in order to extend the performance of POFBG-based humidity sensors [44]. Moreover, the flexibility in POFs fabrication resulted in the possibility of developing POFs with different transparent polymers [45][46]. For this reason, POFBGs with tailored properties were developed to achieve high humidity sensitivity using intrinsic POFBG sensors [32].

As another critical parameter for environmental sensing, temperature sensors are mandatory for such assessment. If the aircraft applications are considered, there is a high range of temperatures for the sensors, where there are temperatures above 1000 °C in regions close to the engines and thermal equipment and temperatures below 0 °C for structural analysis for in-flight conditions [47]. In both scenarios (high and low temperatures), the OFS were already employed, where the stability of material properties at low temperatures already shows the possibility of using such fibers even in cryogenic applications [48]. Considering the low temperatures obtained on in-flight conditions, conventional OFS, such as interferometers [49], distributed temperature sensing [50], and FBGs [51], can be used using their intrinsic sensitivity to temperature variations along the fiber. In addition, the embedment of the optical fibers in different materials (with high thermal expansion coefficient) can extend the temperature sensor performance, especially in terms of sensitivity and resolution [52].

If high temperature applications are concerned, applications with temperatures close to the glass transition temperature or the processing temperatures of glass material (silica optical fibers) need the evaluation of the sensors, due to the variations in silica material features at such temperatures [53]. To that extent, the application of sensors based on fluorescence was proposed using the optical fiber coating in different photoluminescent materials, such as yttrium aluminum garnet (YAG), sapphire, and $MgAl_2O_4$, due to their resistance to high temperatures [54]. The fluorescence intensity ratio is commonly used in such applications, where the photoluminescent materials present fluorescence as a function of the temperature at a specific wavelength [55]. In this approach, a ratio between the intensity in the wavelength at which the fluorescence occurs and the intensity of a reference wavelength (without the fluorescence) is obtained and analyzed as a function of the temperature [56].

Another important breakthrough in high temperature development is micromachining, especially using the femtosecond (fs) laser for the fabrication of micro-structured devices in optical fibers, such as interferometers [57]. These devices can be used in high temperatures, but below the silica optical fiber processing temperatures. In addition, the encapsulation with different materials, as well as the use of air cavities, can extend the temperature application range of such sensors' devices [58]. In this approach, there is the application of sapphire wafers for the FPI cavity development [59]. Thus, the use of sapphire optical fibers is generally used in sensors devices for high temperature assessment, due to the temperature resistance that make them suitable for temperature applications in a range higher than 1000 °C, since the melting point of such materials is around 2045 °C [54].

The temperature sensors applications using optical fiber-based approaches are generally related to FBG sensors, due to their inherent sensitivity to temperature variations. In general, the FBGs are inscribed using UV lasers with holographic/interferometric/phase mask techniques [60], which typically result in type I gratings that operate in temperatures below around 450 °C, since higher temperatures lead to the erasing of the grating [61]. To address this issue in high temperature operations, the direct inscription using fs lasers result in the possibility of using such sensors in temperatures close to the ones of the material processing [62]. In addition, the annealing treatments in silica optical fibers for grating regeneration lead to changes in the FBG that enable its applications in temperatures higher than 1000 °C, due to the changes in the optical fiber material and grating structures [61]. Another straightforward approach for FBG-based high temperature sensing is the use of sapphire optical fibers, due to their high temperature resistance. To that extent, fs lasers were used in the FBG inscription in sapphire fibers using direct inscription [63] and phase mask [64] inscription methods, which result in a temperature sensor able to withstand temperatures higher than 1500 °C.

1.2. Pressure Sensing

Pressure assessment is critical in different fields for structural condition monitoring, environmental assessment, control units, and health monitoring. Therefore, pressure assessment is used in applications ranging from industrial measurements [65] to medicine [66] and biomechanics [67], just to name a few. In aerospace, pressure sensing can influence the predictive maintenance and optimization of its costs [68], structural health monitoring of aerospace and aeronautics assets [69], fuel economy, and even in the flight navigation [70].

The pressure measurements in engines stages of aircrafts are an important field of investigation, where the pressure assessment in turbine airfoils, as well as the effects of position and dynamics variations in aerodynamic structures, can be obtained [47]. In addition, the pressure assessment in the cabin and cockpit is related to the safety of the crew members and early detection of components malfunction [5].

Considering the applications and physical properties related to the pressure sensing, turbulence is an important phenomenon with some unsolved features for quantitative predictions of structures under turbulent flow [70]. In this case, there are variations in the pressures and velocities, which need to be dynamically and precisely measured, since they result in the possibility of obtaining temporal and spatial variations related to the Reynolds number in turbulence [5]. Despite the large dimensions of aircrafts, the aerodynamics of their components generally result in a microfluidics study, since there is the necessity of thin boundary layers investigation to evaluate critical effects, such as flow separation and friction drag [70]. The pressure assessment in such small layers is important on the assessment of such effects for proper design and mitigation.

The optical fiber-based sensors for pressure sensing generally employ the advantages of small dimensions, flexibility, and multiplexing capabilities of such devices for their embedment in different structures, considering a variety of geometries and configurations [45]. In this context, the assessment of mechanical parameters (e.g., pressure, force, and displacement) usually requires the integration of the optical fiber sensor in different structures, which include cantilevers [71], diaphragms [72], or platforms [73]. In general, diaphragm-embedded structure lead to a compact sensor device, with the possibility of customizing the sensor performance using different diaphragm materials, geometry, and assembly methods [74]. In the diaphragm configuration, there are two major geometric assemblies for the optical fiber integration in such scenarios, where the diaphragm can be positioned on the tip of the optical fiber [75] (perpendicular configuration) or along the optical fiber (parallel configuration) [76].

Considering the case with the diaphragm on the tip of the optical fiber, the advantages are the possibility of a miniature sensor development and the possibility of high-resolution measurements, where the diaphragm has the same dimensions as the cross-sectional area of the optical fiber [77]. In this configuration, the intensity variation-based sensors and interferometers (especially the FPIs) are used with micromachined flexible diaphragms positioned in a hollow structure [74]. In the case of FPI sensors using the diaphragm on the tip of the optical fiber, there is an extrinsic FPI formed in the region between the optical fiber tip (which is used as a reflector) and the tip of the diaphragm that can also include a reflective surface [78]. In this case, the sensor sensitivity is related to the diaphragm mechanical properties, since the spectral variations on the FPI are due to the cavity length variation with the diaphragm deformation. Thus, the use of flexible diaphragms with elastomers or other materials lead to a highly sensitive device, as discussed in [79], which make them suitable for the measurement of small pressure variations. In addition, the possibility of increasing the dynamic range, as well as the possibility of measuring higher pressures, is achieved by optimizing the diaphragm material properties, which make it suitable for gas pressure sensing [75]. Despite the difficulties and higher demands on the fabrication tolerance of such small diaphragms, the configuration using diaphragm on the tip of the optical fiber also inhibit the multiplexing capability of the OFS using a single fiber cable, since there is only one diaphragm at each fiber [74].

In another configuration for optical fiber pressure sensors, the diaphragm positioned along the optical fiber enables the development of diaphragm-embedded OFS based on intensity variation [80], interferometers [81], and FBGs [82]. Due to larger dimensions of the diaphragm in this configuration, the fabrication tolerances are smaller (when compared with the diaphragm on the tip of optical fibers) and the multiplexing capabilities are favorable, since many diaphragms can be employed along the optical fiber [83]. It is also important to mention that such a configuration leads to the possibility of positioning the optical fiber in different regions of the diaphragm, considering different planes, i.e., related to the position on different thickness [84], as well as the transverse area positioning, such as the fiber in the edge of the diaphragm [85]. For these reasons, it is possible to use this approach on the development of distributed systems for density profiling [86] and pressure mapping [87]. The operation principle of such sensors is based on the diaphragm strain, due to the pressure applied on the sensor assembly, which is transmitted to the optical fiber, leading to spectral variations in the sensors [65]. To that extent, not only the diaphragm properties are important on the sensors' performance, but also the optical fiber mechanical properties, since the sensor is based on the strain transmitted to the optical fiber. Thus, the use of POFs generally leads to higher sensitivity and resolution in the pressure sensors, due to their lower Young's modulus (when compared with conventional silica optical fibers) [82].

It is worth mentioning that such pressure sensors, irrespective of the configuration, are generally sensitive to temperature variations, not only due to inherent temperature sensitivity of the OFS, but also the thermal expansion and mechanical properties variations of the diaphragms [88]. In addition, there is a temperature variation on aircraft applications, as mentioned above, which increases the demands of temperature insensitivity on the OFS for pressure sensing applications. For this reason, different temperature compensation techniques have been proposed throughout the literature [89]. Such techniques include the use of a temperature sensor without pressure sensitivity to obtain a temperature reference system, which is compared with the results of the pressure sensor using the direct difference between both sensors signals considering their sensitivities. This approach can be used with different OFS approaches including FBGs (uniform and non-uniform) [90], different interferometers [91], and intensity variation-based sensors [92]. Furthermore, the use of mechanical structures for the development of temperature-insensitive pressure sensors, which include the application of a metallic sheet in the diaphragm region for the positioning of the temperature compensation/reference system [93]. It is also possible to position two FBGs in the same diaphragm for the simultaneous assessment of pressure and temperature, where the sensor system is characterized as a function of the pressure and temperature prior to its application in a real scenario, in which the temperature and pressure are simultaneously varied [94].

The intrinsic or extrinsic interferometric cavities along an optical channel generate an interferometric sensor [34][95]. Interferometric sensors with practical applications include FPI sensors and low coherent interferometric sensors (called as SOFO interferometric sensors) [96]. An FPI sensor may have a resolution as high as 0.15 µε, a strain measurement range of ±1000 µε that may be expanded to ±5000 µε, and the capacity to function at temperatures ranging from 40 °C to + 250 °C. FPI sensors are extremely compact, ranging in length from 1 mm to 20 mm, and can be incorporated in certain structural components without incurring any weight penalty or negative impacts. However, its low multiplexing capacity is a disadvantage.

It has been stated that SOFO interferometric sensors are the most successful low coherent interferometric sensors for structural health monitoring (SHM), having been successfully placed in hundreds of structures, including bridges, buildings, oil pipes, and tunnels. SOFO interferometric sensors are long-gauge sensors, in contrast to FPI sensors. They have a measurement range beginning at 0.25 m and extending to 10 m, or even 100 m, with a micrometer-level resolution and temperature insensitivity, high precision, and stability. However, they can only measure elongations and contractions at low speeds (0.1 Hz–1 Hz) and are unable to detect impact damage in aircraft structures.

There are three types of distributed fiber optic sensors: Rayleigh-based optical time-domain reflectometry (OTDR), Raman-based optical time-domain reflectometry (ROTDR), and Brillouin-based optical time-domain reflectometry (BOTDR).

OTDR is the first generation of distributed fiber optic sensors employing Rayleigh scattering to reflect the attenuation profiles of long-distance optical fiber networks [97]. An optical pulse is introduced into an optical fiber link, and the power of the Rayleigh backscattered light is measured by a photodetector as the light pulse propagates along the fiber link. This measurement is typically used to determine fiber loss and break locations, as well as to evaluate splices and connectors.

In recent years, ROTDR and BOTDR have been utilized for distributed sensing applications. Their operation methods rely on the nonlinearities of optical fibers, which generate additional spectral components. These additional spectral components are impacted by environmental conditions external to the system. Consequently, changes in external measurands can be determined by evaluating the spectral content appropriately. ROTDR is based on the Raman scattering phenomenon, which generates both anti-Stokes and Stokes components [98]. As the fiber connection itself is the sensor, the intensity ratio between these two components can provide temperature information at any point along the fiber link. Since the amplitude of the Stokes components is independent of temperature, ROTDR can only measure temperature with a temperature resolution of 0.2 °C, and not strain. With a spatial resolution of 1 m, the sensing distance of ROTDR is typically restricted to around 8 km.

In BOTDR, light is partially scattered back based on Brillouin-scattering phenomenon [99]. BOTDR can monitor both temperature and strain, since the frequency of the scattered light is dependent on the temperature and strain applied to the fiber link. The basic BOTDR measurement distance is 30 km and can be expanded to 200 km. The resolution ranges from 1 to 4 m.

2. Sensors for Navigation

Inertial navigation systems (INSs) are important systems for aircraft navigation that can also apply to personal navigation, car navigation, and unmanned aerial vehicles [100]. The continuous advances in autonomous vehicles and navigation systems place demands in the compactness, as well as the precision of such navigation systems [101]. These demands lead to developments in fiber optic gyroscopes (FOGs) and general MEMS in the development of systems with small errors in the position and attitude, due to the reduction of the sensors uncertainties and nonlinear signal processing approaches [102]. In this context, calibration methods and automatic error corrections increase the accuracy and general performance of INS. As another common approach for the development of reliable navigation systems, the INS can be integrated with the Global Positioning System (GPS), where the GPS enables the calibration and reduction of bias in INS [100]. In addition, the fusion between the INS and GPS enables the tracking performance of the GPS [103]. Such improvement is achieved using error calibration techniques based on feedforward or feedback methods. Moreover, the integration can be achieved by means of using only the GPS for the position and velocity calculations, whereas the navigation filters estimate the position, velocity, and attitude from the INS and the GPS’s position, and velocity data are used as the reference for calibration of the INS [100].

One of the sensors for the navigation system is the displacement sensors, where conventional linear variable differential transformers (LVDT) and rotary variable differential transformers (RVDT) can be employed [5]. Such displacement sensors are capable of operating in high temperature ranges (from below 0 °C to higher than 200 °C) and of the possibility of positioning in different regions of the aircraft, but at the cost of complex signal processing. To that extent, the development of optical fiber-based displacement sensors can address some of the issues of the electronic sensors, such as magnetic field immunity and potential applications in higher temperatures conditions [104].

Among the sensors for the inertial navigation systems, the continuous improvements in gyroscope technologies and rotation measurements are critical for the evolution in navigation systems [105]. In this case, the rotation rate indicates the variations in the heading and attitude of the system. Moreover, the accelerometers are also important in the navigation system for the assessment of acceleration amplitude and direction. If the gyroscopes are considered, such devices are positioned on a frame (or mechanical structure) to obtain the angular velocity of the rotating structure [106]. A typical classification of the gyroscopes includes the mechanical gyroscopes, optical gyroscopes, and MEMS gyroscopes [106].

Another approach for FOGs is based on the resonant structures, resulting in the so-called RFOGs [105]. In the last years, the use of novel optical fiber structures, e.g., the use of photonic crystal fibers (PCFs), has accelerated in order to obtain structural birefringence in the sensing structure [107]. If a hollow core PCF is used, the RFOG can even result in smaller cross-sensitivity as a function of temperature in conjunction with the lower backscatter and nonlinear effect, which increase the polarization noise controllability of the sensing structure [108]. For these reasons, the use of optical components in the coupling of hollow core PCFs with the resonator structure was proposed in [108], resulting in a high temperature stability of the device. In addition, a high finesse can be obtained in the resonant cavity using a PCF coupled with a single mode fiber, resulting in a hybrid PCF resonator structure, where such a structure resulted in a gyro bias stability of 0.5°/s [109]. It is also worth noting that the use of hollow-core PCF in the gyroscope prototype can reduce the polarization crosstalk of the structure [110]. Furthermore, the use of hollow-core anti-resonant fiber (NANF) structure resulted in the extended performance of the RFOGs, with the possibility of using a frequency differential RFOG structure to obtain a stability as high as 0.05°/h [111].

Optical fiber-based accelerometers have an even higher developments and applications, since they are not only used in navigation systems, but also in structural health monitoring [112] and physiological parameters monitoring [113]. To that extent, the optical fiber-based accelerometers were developed using different OFS approaches, as thoroughly discussed in [114]. The simplest approach for optical fiber accelerometers is the use of the intensity variation principle, where the transmitted optical power variation is analyzed as a function of the acceleration [115]. In this case, the sensor can operate in the coupling principle, where a fiber is positioned in a light source, whereas another fiber is positioned in a photodetector [116]. If this configuration is used, one of the fibers is isolated from the vibration/acceleration variation, and the other end is connected to the system with proof mass for the vibration transmission [117]. Some important drawbacks of this approach are that the sensors are sensitive to environmental variations and present low precision, due to the high sensitivity to misalignments.

As higher precision for optical fiber-based accelerometers, the interferometric-based accelerometers are developed using cavities, generally based on FPIs [114]. In general, cavity-based accelerometers use a movable structure connected to the cavity, in which the cavity length varies as a function of the acceleration. In this case, a sub-nanometer potential resolution can be achieved using such a configuration [118]. The application of micro-optical-electro-mechanical systems (MOEMS) resulted in the novel configurations for the optical accelerometers that can further increase the accelerometer performance [119]. In this approach, there is a microscale proof mass and a silicon frame to create the accelerometer structure, where the displacement and acceleration are obtained from the spectral features' variation of the cavity, with the possibility of tuning the accelerometer parameters (such as proof mass and stiffness) to achieve high resonant frequencies and small noise. In another MOEMS accelerometer, the bioinspired shape was proposed in [120], where a battery was used as proof mass and the sensors were embedded in a transparent web-like structure for movement analysis and highly sensitive displacement measurements.

One of the most common optical fiber-based approaches for accelerometers development is the integration of FBGs in mechanical structures [121]. In this context, many different approaches using single [122] and double [123] cantilevers, as well as diaphragm [124] and flexible hinge [125] structures, were proposed. This approach is based on the strain produced in the FBG, due to the inertial displacement of the proof mass under acceleration [126]. For this reason, it is possible to develop 2- and 3-axis [127] accelerometers using different assembly conditions and using the multiplexing capabilities of the FBGs. Thus, it is possible to develop FBG-based accelerometers for multipoint measurement, which play an important role not only in navigation systems, but also in structural monitoring in aircrafts. Furthermore, such devices are able of measuring tilt angles by means of embedment in mechanical structures and using different types of FBGs, such as the tilted FBGs [128] that can measure such parameters, with the additional advantages of self-referencing signals using the spectral features of the gratings. Such gratings-based devices can also include additional information for the navigation systems and enable novel data fusion approaches for ever higher accuracy and reliability of in-flight data.

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