Chapter 54
Low-Cost Fiber Sensors for Displacement and Vibration Monitoring

Alberto Vallan, Maria Luisa Casalicchio, Renato Orta, Marco Parvis, and Guido Perrone

Abstract The paper presents some fiber optic sensors that have been devised to provide a low-cost solution to monitor mechanical quantities, such as displacement, vibration amplitude and acceleration, in applications where fire safety or electromagnetic immunity are of primary concern. The proposed sensors are based on plastic optical fibers and require simplified interrogation systems since they relate the quantity under measurement with changes in the received optical power. Both contact and non-contact sensors have been developed in order to cover a vast range of applications.

Introduction

Fiber Optic Sensors (FOS) for the measurement of mechanical quantities, such as displacement, vibration amplitude and frequency or acceleration, find their most relevant applications in harsh environments or when intrinsic fire safety is required (e.g. in industrial plants and in cultural heritage preservation). Indeed, fibers are immune from electromagnetic interferences and discharges, do not form conductive paths and cannot start fires. Moreover, they can be easily embedded into concrete or composite materials and, due to their small mass, they often produce negligible perturbation on the quantity under measurement. Despite all these advantages, however, the diffusion of FOS is still limited mainly due to the costs of interrogation systems and the poor familiarity with the installation care required by optical fibers. Today, the majority of the fiber-based sensing systems on the market are based on fiber Bragg gratings, although many other principles have been investigated in the literature. In general, these commercial sensors use single mode glass

A. Vallan (✉) • M.L. Casalicchio • R. Orta • M. Parvis • G. Perrone
Department of Electronics and Telecommunications, Politecnico di Torino, C.so Duca degli Abruzzi 24, Torino, Italy
e-mail: alberto.vallan@polito.it

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fibers, so they take advantage of the large number of high performance devices originally developed for the optical communication market. On the other hand, Plastic Optical Fibers (POF) are emerging as an alternative technology that allows the fabrication of fiber sensors with all the most important pros typical of fibers, but with simplified installation procedures and reduced interrogator costs. POF have typically a large core diameter (from 0.25 mm to about 1 mm, instead of 9 μm of common glass fibers) and high numerical aperture (NA ≈ 0.5 instead of NA ≈ 0.11) [1], and these values make it possible to realize cheap transducers that relate the measure of displacements and vibrations to the variation of light collected from a fiber or transmitted in a fiber link (intensiometric sensors).

The aim of the research activity presented in this paper is to investigate the feasibility and the technical performance of these intensiometric low-cost plastic fiber sensors for displacement, vibration and acceleration monitoring.

Contact and Non-Contact Displacement Sensors

The proposed displacement sensors are based on a pair of transmitting – receiving plastic optical fibers, as shown in Fig. 54.1, in two configurations, namely one in transmission and one in reflection. In the transmission setup in Fig. 54.1a the fibers are facing each other and their free tips are separated by a distance *d*, whereas for the reflection setup in Fig. 54.1b the fibers are parallel and facing a movable mirror. In both cases the light collected by the receiving fiber depends on the distance *d*.

Both configurations have been employed to develop displacement sensors for crack evolution monitoring, especially suited for cases in which traditional electrical displacement sensors (e.g. potentiometers and LVDTs) cannot be used because of their potential fire risk [2]. Figure 54.2 shows two prototypes based on the transmission (a) and reflection (b) schemes, respectively, in which the fibers are inserted in a metallic embodiment that is used both for protection and to allow fixing the sensor across the crack. In-field tests carried out in some relevant historical buildings have shown that the sensors present a good resolution (better than 10 μm) in the short term (days), but in the medium and long term (months, years) the displacement measurements are significantly affected by unpredictable changes of the fiber losses, so compensation techniques must be used to guarantee an accuracy of at least 100 μm.

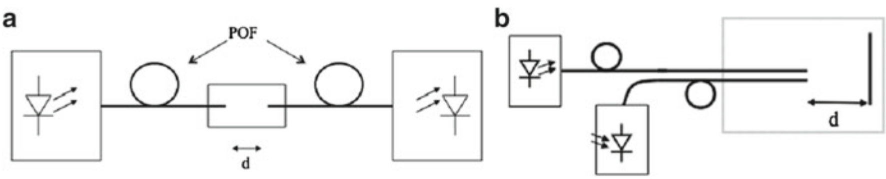

Fig. 54.1 Intensiometric sensor structures: transmission (**a**) and reflection (**b**) arrangements

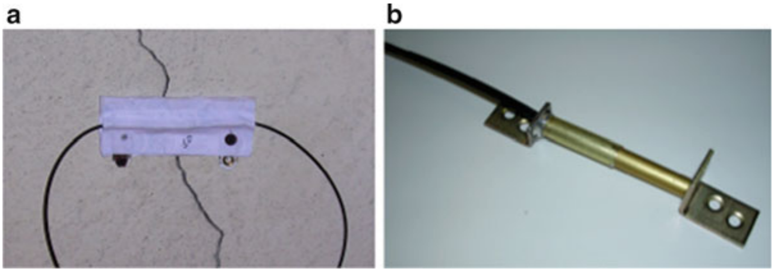

Fig. 54.2 Sensor embodiments based on the schemes of Fig. 54.1

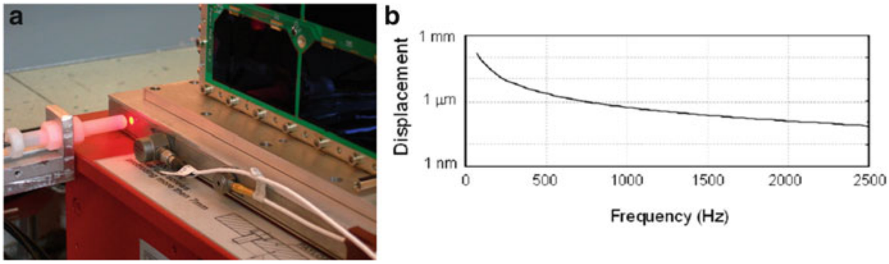

Fig. 54.3 An application of the non-contact POF displacement sensor in vibration tests: photo of the setup (**a**) and example of the measured displacement as a function of the vibration frequency (**b**)

The sensor scheme in Fig. 54.1b has been also implemented in form suitable to monitor vibration amplitudes during vibration tests [3]. In this application the mirror is replaced with the vibrating surface of the device that has to be monitored, such as the slip table shown in Fig. 54.3a. The sensor has shown a remarkable resolution, about 10 nm, even in the presence of diffusive targets and when high frequency vibrations (kilohertz) are measured, as shown in the result of Fig. 54.3b. However, this sensor presents high sensibility to the target distance and optical behavior, so it must be calibrated immediately before its usage. To overcome this drawback, a straightforward calibration procedure based on a piezoelectric accelerometer, has been developed [3].

Acceleration Sensor

Measuring the vibration amplitude of a target provides useful information about its mechanical deformation, but in many cases the quantity of interest is rather the acceleration. Acceleration can be indirectly obtained processing the displacement, but noise prevents obtaining meaningful results above few hundreds of hertz. For this reason, in literature inertial acceleration sensors based on fibers are investigated [4].

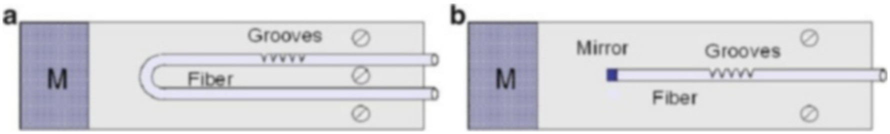

Fig. 54.4 Acceleration POF sensor exploiting the variation of micro-bending induced loss: transmission (**a**) and reflection (**b**) schemes

A POF acceleration sensor can be realized exploiting the dependency of the propagation loss with the fiber curvature induced by a cantilever loaded with a seismic mass [5]. The fiber sensitivity to bending can be increased by grooving the fiber surface in order to modify the core/cladding interface. Two sensor structures have been investigated: the configuration in transmission, shown in Fig. 54.4a, requires a large cantilever to accommodate the fiber so a small bandwidth of the resulting sensor is expected. On the contrary, the structure in reflection of Fig. 54.4b is more promising because it can be arranged using a smaller cantilever, and thus it can be designed to have a larger bandwidth. In this configuration a mirror is fixed on the fiber tip to reflect the optical power back to the detector and a coupler is used to separate forward and backward propagating signals.

Preliminary prototypes of both structures have been designed and tested, evidencing the feasibility of the proposed approach, at least for frequencies up to 2 kHz.

Conclusions

Low cost fiber sensors have been developed to measure displacements, vibrations and accelerations, in different configurations. The sensors are based on plastic optical fibers and exploit the light intensity changes due to variations of the quantity of interest, an approach that allows maintaining the costs low.

The developed contact displacement sensors are currently employed to monitor crack displacement in some buildings where the intrinsic safety is mandatory, while a non-contact version exploiting the same working principle has been successfully employed to monitor vibration tests. Furthermore, an innovative fiber accelerometer designed to monitor the vibration of moving parts of industrial machines is currently under investigation.

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