A low-cost intensity-based plastic optical fiber sensing system for permanent structural health monitoring

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An optical-fiber displacement measurement system devised for crack monitoring in cultural heritage preservation is presented and tested in a long term application. Low ownership and installation costs have been obtained using plastic optical fibers and an intensity-based transducer.

1 Introduction

Fiber optic sensors are attracting an increasing interest in many applications because of their high sensitivity combined with other unique properties such as immunity to electrostatic discharges, intrinsic fire safety and minimum invasiveness. However, their wide diffusion in structural permanent monitoring is still hampered by costs, especially those related to the interrogators and installation: hence the necessity of providing Municipalities and other Authorities with low-cost fiber-based measuring setups to widen their deployment also in structures those are relevant for the local community only. This is particularly important in cultural heritage preservation applications, such as the monitoring of the crack evolution of ancient buildings. Among the solutions that have been proposed in the literature [1], this paper discusses a simple and cost effective fiber displacement measurement system. This system, which employs plastic optical fibers (POF) for the displacement transducer has already been successfully employed to monitor the evolutions of cracks in different cases. In particular, the results of an almost two-year in-situ test in a prestigious monument in Venice are given, highlighting the impact of perturbing effects in long term measurements and suggesting compensation techniques. The usage of POF accounts for having most of the advantages of fiber sensors without their usual costs and complexities, since it is possible to use cheap sources and to simplify the connectors, given the larger core diameter and the much higher numerical aperture typical of POF.

2 The transducer

Very low cost displacement transducers with peculiarities suitable for crack monitoring applications (displacements up ± 5 mm, resolution better than 0.1 mm) can be developed using POF simply exploiting the variation of attenuation with distance between two facing fibers or between two fibers facing a mirror (Fig. 1). One of the fibers is fed by a LED (transmitted power Pin), while the other collects the light (received power P_{out}) and feeds a receiver that employs a standard photodiode-transimpedance amplifier configuration. The relationship between P_{out} and P_{in} depends on the configuration and can be theoretically approximated considering Gaussian beams, although in practice a calibration is necessary to improve the accuracy and also to take the parasitic effects due to hand-made fabrication of the sensors into account [2]. Several embodiments can be devised to implement the scheme of Fig. 1, going from bare fibers with just a thin plastic protecting sleeve to more mechanically stable metal housings, such as those shown in Fig. 2.

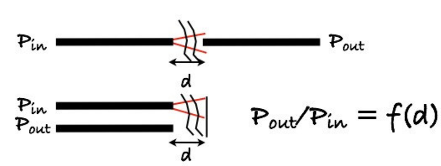

Fig. 1 *Schematic representation of the fiber transducer; transmission (above) and reflection (below) based setups.*

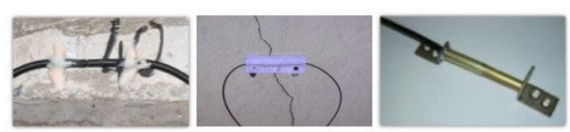

Fig. 2 *Photos of some embodiments of the sensors implementing the principles shown in Fig. 1.*

All the developed sensors have been characterized using a computer controlled micro-positioning system with a resolution better than 1 µm. The obtained results showed that intensity based sensors are very simple, but they are sensitive to external disturbances, such as temperature, unwanted strains occurring along the fiber connecting the transducer to the control unit, and drifts in the electronic circuitry. This means that high resolution can be achieved only in short (≈ 10 nm within few minutes) and medium (≈ 10 µm within few hours) terms, while long term measurements, like those necessary for crack permanent monitoring, require suitable compensation technique to be implemented to meet the specifications, as described in the following.

3 Reference sensor compensation technique

The proposed compensation technique makes use of a “dummy” reference sensor, which is a sensor identical to the other ones but not fixed to edges of the crack under measure. This approach, which is common to most types of the sensors, is effective provided that the reference sensor is exposed to the same kind of disturbances as the measuring sensor. An example of the results achieved using the reference sensor compensation technique during a two-year in-situ assessment test in a prestigious monument in Venice is reported in Fig. 3: the blue curve shows the raw data coming from the readings of the sensor during the first 18 months of the test, while the red one shows the same data after correction for the parasitic effects using the reference sensor. The latter curve fits well the expected crack behavior: considering the variation of the environmental temperature in the same period (Fig. 4), it is possible to note that only the curve after compensation has a correlation with temperature. In particular as the temperature raises, the crack closes due to the elongation of the two edges and vice versa when the temperature lowers.

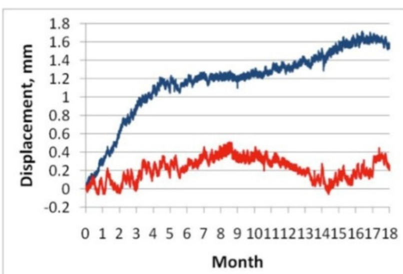

Fig. 3 *Evolution of crack: raw readings (blue curve) and after compensation using a reference sensor (red curve).*

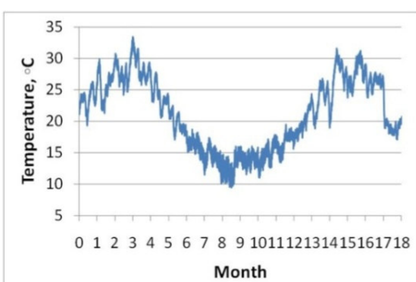

Fig. 4 *Environmental temperature during the period considered in the monitoring reported in Fig. 3.*

4 Dual wavelength compensation technique

A more efficient compensation technique is based on two different wavelengths. Considering a reflection-based setup as schematized in Fig. 5, the reference and the measurement signals at two different wavelengths are coupled into the fiber sensor; then the reference signal is reflected at the fiber tip by a dichroic mirror and used to compensate the sensor reading for environmental errors.

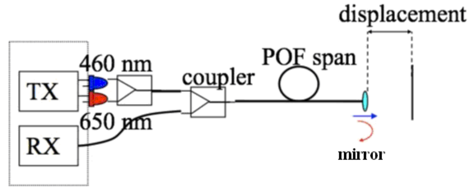

Fig. 5 *Scheme of the dual wavelength compensation technique using a reflection-based setup.*

The two signals travel along the fiber span experiencing always the same environmental conditions, thus allowing a higher accuracy after compensation. The ability to compensate for mechanical stress has been measured by bending a fiber span of ~5 m to different radii in order to simulate a typical installation (Fig. 6) where the fiber could be exposed to unwanted stresses. The experiment has been repeated three times to get little statistics on the repeatability. The ratio of the two signals is always within a 4% mismatch even for tight bending, and repeatability is always within 1%.

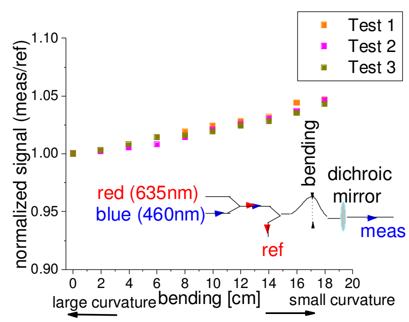

Fig. 6 *Example of the tests evidencing the possibility to compensate for perturbations due to unwanted strains using the dual wavelength setup.*

5 Conclusions

The prototype of a fiber sensing system for crack monitoring with costs/performances comparable to conventional systems has been presented and two perturbation compensation techniques have been studied. Current work includes the circuitry miniaturization and the development of a system to lower the power consumption in order to allow battery operation.

References

[1] B. Glisic and D. Inaudi: „Fibre Optic Methods for Structural Health“Wiley and Sons Ltd, 2007

[2] G. Perrone, A. Vallan: „A Low-Cost Optical Sensor for Non contact Vibration Measurements“ IEEE Transactions on instrumentation and measurement, vol. 58, no. 5, May 2009