

SOFO Sensors for Static and Dynamic Measurements

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Key words: fiber optic sensors, monitoring, static, dynamics, structural health monitoring.

SUMMARY

From many points of view, fiber optic sensors are the ideal transducers for civil structural monitoring. Being durable, stable and insensitive to external perturbations, they are particularly interesting for the long-term health assessment of civil structures.

Long-gauge interferometric SOFO sensors have been in use for the last 10 years for the monitoring of civil, geotechnical, oil & gas and other structures. The sensors are based on an all-fiber Michelson interferometer with one arm mechanically coupled to the structure and one used as reference. The original demodulation system is based on low-coherence interferometry and features excellent long-term stability and precision, but is not suitable for dynamic measurements. In order to allow the use of the same sensors for the measurement of dynamic events, a new demodulator was developed. It is based on the coherent demodulation of a coherence-collapsed laser source and is able to demodulate 8 SOFO sensors at frequencies of up to 1 kHz with resolutions of 0.01 microns. This system is particularly adapted for the analysis of dynamic structural deformations produced traffic, wind, seismic and impacts. The use of long-gauge sensors allows a direct measurement of the dynamic strains and the calculation of modal strains and curvatures.

This contribution presents the main features of the SOFO static and dynamic system and selected applications examples.

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1. INTRODUCTION

The construction and maintenance of the civil infrastructure represents between 10% and 20% of the public investment in most European countries. In the last decade we have however witnessed an increasing shift from investments in the construction of new structures to the maintenance and the lifetime extension of the existing ones. With the exception of the high-speed train lines, most of the transportation network, including highways and railway, is completed and in service. However, the steady increase of the passengers and goods circulating in the continent, amplified by the free circulation policy introduced by the European Community, is putting the civil infrastructure under a rude test. Many bridges and tunnels built a few tens of years ago need repair and in many case an extension of their bearing capacity and lifetime that exceed the original plans. Besides the direct costs associated with these interventions, the disruption to the normal use of the structures causes additional inconvenience including traffic jams and accidents that carry additional hidden costs.

The authorities managing the civil infrastructures face the challenge of maintaining the transportation network in a satisfactory state using a limited budget and with little perturbation to its normal use. This task is far more complex than that of building new structures and requires new management instruments.

Structural health monitoring is certainly one of the most powerful management tools and is therefore gaining in importance in the civil engineering community. Monitoring is often and mistakenly presented as a security tool. This is however only the case for the few structures that present a high potential danger such as nuclear power plants and dams. For most other structures the security risks are very limited and fortunately we rarely witness casualties due to a structural collapse. For all other structures, monitoring should be seen as management tool delivering information on the state of a single structure or on a network of structures. In what we call the in-formation age, structural health monitoring closes the gap between the seemingly inert world of structures and the frenetic one of information technology.

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. For civil structures such as bridges, tunnels, dams, geostructures, power plants, high-rise buildings and historical monuments, the most relevant parameters are:

- Physical quantities: position, deformations, inclinations, strains, forces, pressures, accelerations, and vibrations.
- Temperatures.
- Chemical quantities: humidity, pH, and chlorine concentration.
- Environmental parameters: air temperature, wind speed and direction, irradiation, precipitation, snow accumulation, water levels and flow, pollutant concentration.

Conventional sensors based on mechanical and/or electrical transducers are able to measure most of these parameters. In the last few years, fiber optic sensors have made a slow but significant entrance in the sensor panorama. After an initial euphoric phase when optical fiber sensors seemed on the verge of invading the whole world of sensing, it now appears that this technology is only attractive in the cases where it offers superior performance compared to the more proven conventional sensors. The additional value can include an improved quality of the measurements, a better reliability, the possibility of replacing manual readings and operator judgment with automatic measurements, an easier installation and maintenance or a lower lifetime cost. The first successful industrial applications of fiber optic sensors to civil structural monitoring demonstrate that this technology is now sufficiently mature for a routine use and that it can compete as a peer with conventional instrumentation.

2. SOFO SYSTEM

The SOFO system (Figure 1 and 2) is a fiber optic displacement sensor with a resolution in the micrometer range and an excellent long-term stability. It was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) and is now commercialized by SMARTEC in Switzerland (Inaudi et al. 1994, Inaudi 1997b, Inaudi et al. 1997).



Figure 1: SOFO system reading unit and SOFO sensor installed on a rebar

The SOFO static measuring system is based on the principle of low-coherence interferometry (see Figure 3). The infrared emission of a light emitting diode (LED) is launched into a standard single mode fiber and directed, through a coupler, towards two optical fibers mounted on or embedded in the structure to be monitored. The measurement fiber is in mechanical contact with the structure itself and will therefore follow its deformations in both elongation and shortening. The second fiber, called reference fiber, is installed free in the same pipe. Mirrors, placed at the end of both fibers, reflect the light back to the coupler that recombines the two beams and directs them towards the analyzer. This is also made of two fiber lines and can introduce a well-known path difference between them by means of a mobile mirror. On moving this mirror, a modulated signal is obtained on the photodiode only when the length difference between the fibers in the analyzer compensates the length

difference between the fibers in the structure to better than the coherence length of the source (in our case some hundreds of mm). Each measurement gives a new compensation position reflecting the deformation undergone by the structure relatively to the previous measurement points.



Fig. 2: SOFO system for static and dynamic measurements.

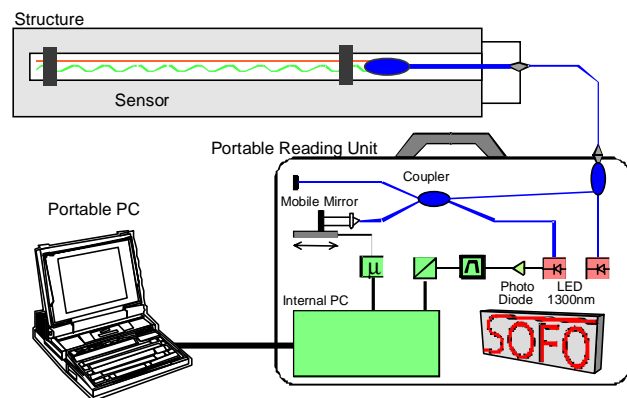


Fig. 3: Setup of the SOFO system used for static measurements.

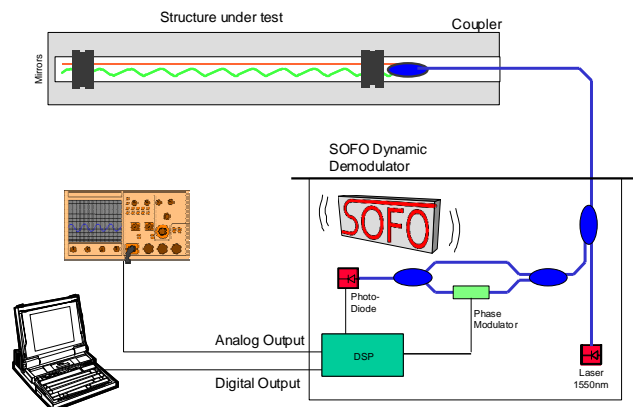


Fig. 4: Setup of the SOFO system used for dynamic measurements.

The Reading Unit can therefore be disconnected and used to monitor other fiber sensors and other structures. If multiple sensors need to be measured automatically, an optical switch is installed. The SOFO unit is capable of storing measurements and later transfers them to the data acquisition PC via a cable or a modem.

The SOFO Dynamic reading unit allows measuring SOFO sensors at high frequencies. One reading unit can be used to demodulate up to 8 channels. Multiple units can be combined when higher channel counts are needed. The SOFO Dynamic reading unit can be used in conjunction with the same SOFO sensors used for static measurements.

The SOFO Dynamic reading unit is based on a heterodyne low-coherence interferometer operating at 1550 nm (see Figure 4). The optical signal is phase modulated by the

demodulation interferometer. After detection, the reading unit tracks the phase modulation introduced by the sensors and converts it into a displacement. The resulting deformation is available in analog form on the analog outputs or in digital form on the USB connection that can be used to transfer the measurements directly to a PC for storage and further analysis. The measurements are relative and the zero point is lost on power off, but can be recalibrated using the SOFO Static reading unit.

The main characteristics of the SOFO system are:

Strain sensor technology	Fibre optic interferometric sensor
Strain sensor gauge length	0.2 m to 20m
Maximum cable length	10 km
Strain range	-5'000 to + 10'000 $\mu\epsilon$
Strain resolution for dynamic measures	0.2 μm @ 10 mHz, 0.01 μm @ 1 Hz and higher
Dynamic range for dynamic measurements	1 mHz to 10'000 Hz
Strain resolution for static measurements	2 μm
Temperature sensitivity	<1 μm / $^{\circ}\text{C}$ / m

3. APPLICATION EXAMPLES

This section will introduce a few projects showing an effective use of fiber optic technology for the health monitoring of different types of structures, with different aims and during different phases of the structure's lifetime.

3.1 Expo.02 Piazza Pinocchio

Once every generation, Switzerland treats itself to a National Exhibition commissioned by the Swiss Confederation. Expo 02 was spread out in five "Arteplage" over a whole region: the land of the three lakes, on the shores of the lakes of Biel, Murten and Neuchâtel, which are located in the northwest of Switzerland. Each "Arteplage" relates to a theme, which is reflected in its architectures and exhibitions. The "Arteplage" of Neuchâtel was related to "Nature and Artificiality"; a big steel-wood whale eating a village represents the fairy tale "Pinocchio" from the Italian writer Collodi. The "Piazza Pinocchio" was built together with other exposition buildings on one large artificial peninsula.



Fig. 5: Piazza Pinocchio and the big wooden whale

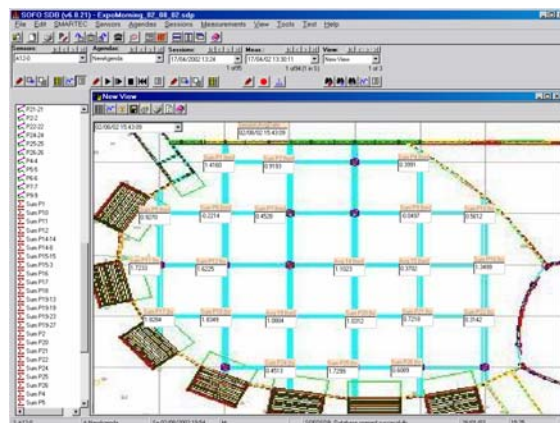


Fig. 6: Piazza Pinocchio control center with load indicators

The belly of the whale (Figure 5) holds the exposition dedicated to robotic and artificial intelligence, while the rest of the village was developed on two floors with steel piles / beams and wood walls and floors.

To guarantee that the life loads generated by the visitors accessing the platform would never exceed the design loads, it was decided to install a real-time monitoring system that would guide the exhibition personnel in granting or not the access to additional visitors. The SOFO system based on low coherence fiber optic deformation sensors was selected for this project. 31 SOFO sensors and 31 thermocouples were installed on steel piles to monitor real time visitor's live loads. The main requirements were: real-time computer results display of the live loads during 18 hours a day (Figure 6), automatic thermal-induced strain compensation, real-time warnings and pre-warnings for each single pile, automatic phone calls produced when reaching warning thresholds and remote monitoring for complete management of the monitoring system. The system operated flawlessly during 6 months and generated a few pre-warning, no warning and no false alerts. This project is a nice example of real-time monitoring with integration in a facility management system. If the selective access of the visitors can be considered a form of actuation, we can even describe the Piazza Pinocchio as a true "Smart Structure".

3.2 Colle Isarco Bridge

The development of a life extension and/or replacement strategy for highway structures is a crucial point in an effective bridge management system. An example of a global monitoring approach in establishing a bridge management system is represented by the project of the Colle d'Isarco viaduct on the Italian Brenner-Highway A22. The section of the highway that is subject to monitoring activities includes four columns, each of them supporting asymmetrical cantilevers in the north and south direction as can be seen in Figure 7.



Fig. 7: View of the Colle Isarco Bridge on the Brennero Highway in Italy

The overall length of this section is 378 m. The height of the girders near the supports number 8 and 9 is 11 m, at the supports 7 and 10 the height is 4.50 m. The girders have a uniform width of 6 m, the arrangement for each road bed is approximately 11 m wide. A wide set of sensors have been installed, including both traditional and SOFO fiber optic sensors and, due to the large dimensions of the section, a data acquisition system able to collect widely distributed sensing units was also installed (Figure 8). Wireless serial communication is used to transfer the measured data from the almost inaccessible locations on the bridge to the location of the personal computer used to evaluate the measured data.

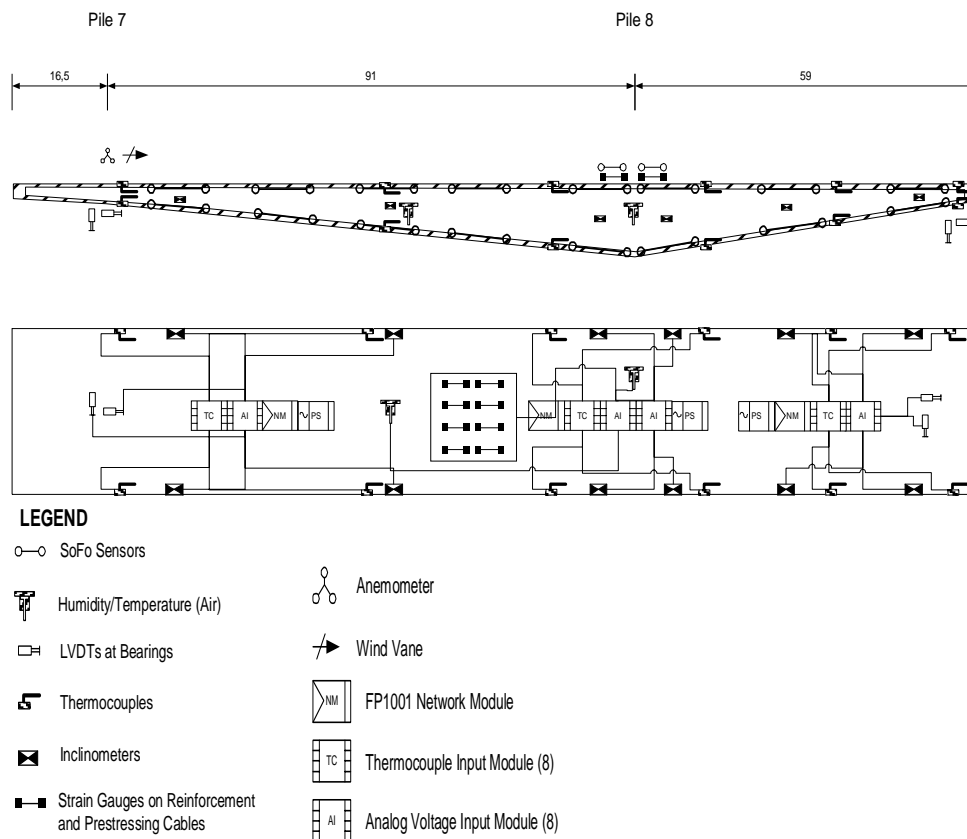


Figure 8: Layout of the Colle Isarco Bridge Instrumentation (courtesy of K. Bergmeister)

Data evaluation is performed by a combination of analytical modeling and fine-tuning of the system parameters. The system aims to the creation of the appropriate match between the non-linear simulation and the measured data. Since the measurement processes usually introduce a certain amount of variability and uncertainty into the results due to the limited number of measurement points and the partial knowledge on the actions, this randomness can affect the conclusions drawn from measurements. Randomness in measured variables can however be accounted for by their probability density functions. Once a model and its calibration has gained a certain level of completeness, analytical prediction provides a quantitative knowledge and hence it becomes a useful tool to support structural evaluation, decision making, and maintenance strategies. This ambitious project aims to a full integration of instrumentation into the decision-support system for structural maintenance.

3.3 Alptransit Tunnel

Switzerland is currently building a new railway line across the Alps. The Alptransit project is intended to make goods transport more economical and passenger transport faster (up to 250 km/h). The most impressive works of this new line will be the Gotthard base tunnel with its two tubes of 57 km each. The construction of these tunnels presents unparalleled challenges due to their exceptional length and the difficult geological conditions found in some areas along the route. The Gotthard base tunnel must pass through a vast range of layers, from the very hard Gotthard granite, through the high-stress pennine gneiss of the Leventina, to the butter-soft rock of the Tavetsch Intermediate Massif. One of the difficult areas is the south portal in Bodio. Due to constraints in the layout of the tunnel and the necessity to cope with the existing railway line, highway and roads, it is necessary to build the portal and the first 300m of tunnel in a loose stone formation. In order to optimize the support and confining structures in this area, SMARTEC SA was asked to install SOFO sensors to monitor the buttresses at the tunnel entrance and the concrete lining inside the tunnel (Figure 9). The sensors give quantitative information on the real loads that are carried by these structures in the short and long term. An automatic monitoring system records deformations and temperatures continuously and enables a correlation with the different construction phases.



Figure 9: Support Buttresses at the south portal of the new Alptransit Gotthard tunnel

In this case, monitoring concentrated mainly during construction, as it is often the case for geotechnical projects. Once the measurement systems are removed, the installed sensors remain however available for future manual measurements or to restore permanent monitoring if new unforeseen events occur.

4. CONCLUSIONS

The monitoring of new and existing structures is one of the essential tools for a modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. Progress in the sensing technology can therefore be produced by more accurate measurements, but also

from systems that are easier to install, use and maintain. In the recent years, fiber optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and quite a few have evolved into commercial products.

It is difficult to find a common reason for the success of so diverse types of sensors, each one seems to have found a niche where it can offer performance that surpass or complement the ones of the more traditional sensors. If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, I would cite the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements. Furthermore, the much larger market of fiber optic telecommunication offers an interesting potential for cost reduction in most components used for sensing applications.

In the near future it is therefore to expect that fiber optic sensors will consolidate their presence in the structural sensing industry.

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REFERENCES

- Brönnimann R. et al. 1998. Packaging of Fiber Optic Sensors for Civil Engineering Applications", Symposium DD, Reliability of Photonics Materials and Structures, San Francisco, paper DD7.2
- Inaudi D. 1997a. Fiber optic smart sensing, Optical Measurement techniques and applications, P. K. Rastogi editor, Artech House, pp. 255-275
- Inaudi D. 1997b. Field testing and application of fiber op-tic displacement sensors in civil structures, 12th International conference on OFS '97- Optical Fiber Sensors, Williamsburg, OSA Technical Digest Series, Vol. 16, pp. 596-599
- Inaudi D. et al. 1994. Low-coherence deformation sensors for the monitoring of civil-engineering structures, Sensor and Actuators A, Vol. 44, pp. 125-130
- Inaudi D. et al. 1997. Embedded and surface mounted fiber optic sensors for civil structural monitoring, Smart Structures and Materials Conference, San Diego, SPIE Volume 3044, pp. 236-243
- Kersey A. 1997. Optical Fiber Sensors, Optical Measurement techniques and applications, P. K. Rastogi editor, Artech House, pp. 217-254
- Udd E 1995. Fiber optic smart structures, Wiley, New York, 1995
- Udd E. 1991. Fiber Optic Sensors, Wiley

BIOGRAPHICAL NOTES

Daniele Inaudi received a degree in physics at the Swiss Federal Institute of Technology in Zurich (ETHZ). His graduation work was centered on the theoretical and experimental study of the polarization state of the emission of external grating diode lasers and was prized with the ETHZ medal. In 1997 he obtained his Ph.D. in civil engineering at the Laboratory of Stress Analysis (IMAC) of the Swiss Federal Institute of Technology in Lausanne for his work on the development of a fiber optic deformation sensing system for civil engineering structural monitoring. In 2004 he obtained a Maser in Business Administration from the Swiss Italian Technical University.

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He is an active member of OSA, SPIE, IABSE, fib, chairman of the Sensor conference at the annual "SPIE International Symposium on Smart Structures and Materials", member of the organizing committee of the annual "International conference on Optical Fiber Sensors" and member of the board of the International Society for Structural Health Monitoring of Intelligent Infrastructures. Daniele Inaudi is author of more than 100 papers, three book chapters, editor of a book on Optical Nondestructive Testing and member of the editorial board of "Optics and Lasers in Engineering" journal.

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