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Field Tests of Distributed Temperature and Strain Measurement for Smart Structures

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Brillouin time-domain analysis in optical fibres is a novel technique making possible a distributed measurement of temperature and strain over long distance and will deeply modify our view about monitoring large structures, such as dams, bridges, tunnels and pipelines.

Optical fibre sensors based on stimulated Brillouin scattering have now clearly demonstrated their excellent capability for long-range distributed strain and temperature measurements [1-3]. The Brillouin interaction causes the coupling between optical and acoustical waves when a resonance condition is fulfilled. It turns out that this resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain.

The resonance frequency is an intrinsic property of the material that may be observed in any silica fibre. This is very attractive since the bare fibre itself acts as sensing element without any special fibre processing or preparation. Standard optical cables may thus be used, resulting in a low-cost sensing element that may be left in the structure. Since the optical effect only depends on the fibre material, it is absolutely stable in time and independent of the instrument. Different measurements performed over a long-term period are thus fully comparable.

Instead of using the now traditional configuration using two laser sources [1,2], a novel experimental configuration has been developed by our team [3], shown in Fig. 1.

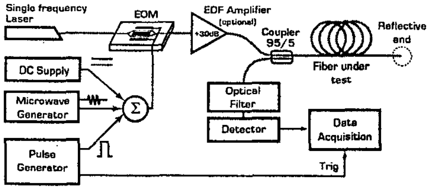

Fig.1 Configuration of the highly stable Brillouin distributed sensor used for field tests.

Its main original feature is the presence of a single laser source that is modulated through a Mach-Zehnder electro-optic modulator (EOM). This electro-optic modulator is the key element of the set-up since it is used on the one hand for pulsing the CW light from a single frequency laser to form the pump signal, and on the other hand for the generation and frequency tuning of the probe signal. The frequency shift on the laser light is achieved by simply applying a microwave signal on the electro-optic modulator electrodes, which creates a sideband at the proper frequency in the laser spectrum. This gives to the system an inherent stability, as far as frequency drifts of the laser are concerned.

The spatial resolution obtained with this equipment is 1 meter for a 10 km range. The physical limit for spatial resolution, that is just below 1 meter and results from the acoustic properties of silica, is actually reached by the equipment for short measurement range (< 1 km) [4]. This configuration of the sensor is thus definitely dedicated for long range measurements with meter resolution and is not suitable for centimeter resolution. It must be pointed out that a novel and very inventive configuration was recently reported [5], based on a correlation technique, that achieved measurements with a 1 cm spatial resolution, but the range of this technique is also reduced to less than 1 km, accordingly.

The accuracy on the determination of the Brillouin shift ν_B depends on the amplification contrast and the probe signal intensity. In standard fibres an accuracy of 1 MHz is observed. This approximately corresponds to a 1 K temperature resolution and to a 2×10^{-5} strain resolution. The Brillouin shift accuracy can be improved to 250 kHz, corresponding to a 0.25 degC temperature and 5×10^{-6} strain resolutions, respectively, at the expense of either a worse spatial resolution or a longer measurement time.

The Brillouin time-domain analysis was first developed to detect local strains in telecommunication cables [1], which may cause early failure due to fibre breaking. It turned out that this application has gained little interest, the manufacturing quality of telecom cables making the optical fibre to show practically no strain. We performed many measurements in critical installations such as underwater and aerial cables in mountain environment and no strain was detected at all in those special conditions.

But the special threadlike geometry of the optical fibre makes it an excellent candidate for monitoring large structures and installations. This property clearly opens new opportunities for a better control of the natural or built environment. The distributed nature of the sensing element offers the possibility to densely control a structure over its entire length, surface or volume, which would be impossible using point sensors.

We had the opportunity these past few years to perform many measurements on different sites, mostly tentative to demonstrate the feasibility of the technique for very diverse monitoring applications. In all cases the sensor demonstrated its capability to perform the required measurements, in few cases at the expense of a special installation or packaging of the fibre. Here below are listed field tests for which the described Brillouin sensor was tested:

- Hot spot detection along an electrical power line.
- Strain in an aerial telecommunication cable.
- Water temperature over a lake floor.
- Temperature monitoring during the setting of a large concrete structure.
- Temperature gradient measurement in a forest.
- Temperature monitoring in a large waste disposal.
- Pipe leakage detection.
- Intrusion detection over a sandy ground.
- Early detection of ground slides and soil movement.
- Marine rope elongation monitoring.
- Pipe leakage detection (oil, water, steam, brine, etc).
- Deformation of beams and pipes.

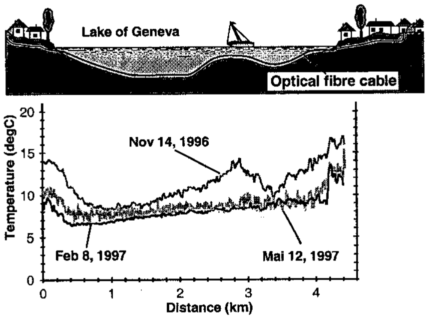

Fig.2 *Measurement of temperature over a lake bed showing seasonal changes. A spare fibre in an installed telecom cable was used for this measurement.*

Fig. 2 shows a temperature measurement along an optical fibre installed on the floor of the Lake of Geneva, demonstrating the fully distributed nature of the measurement. It is possible to take advantage of the long sensing range of the technique to monitor the surface or the volume of a structure, by installing the fibre following a mesh pattern. Such a possibility is shown in Fig. 3 in which a measurement of concrete temperature is performed showing the effect of the chemical exothermal process during setting.

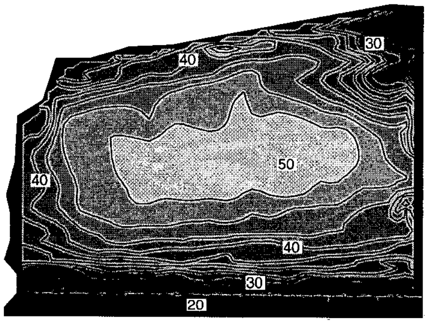

Fig.3 *Temperature of a 20x13x3m concrete structure in a dam, performed 30 days after concreting. Fibre was installed following a serpentine pattern, so that a 2D temperature distribution can be obtained. Isotherms are shown in degree centigrade.*

A problem that is often pointed out is the impossibility to discriminate between temperature and strain effects using the Brillouin sensing technique. In most situations the issue is irrelevant since in real conditions the problem turns out to be easily worked out by combining loose-tubed and tight cables. In a loose tube the fibre is granted to be unstrained and is therefore only sensitive to temperature. To obtain strain information a parallel tight cable must be installed that is fixed on the structure, so that the fibre will experience strain. The drawback of a double-length sensor is widely balanced by the very long range capability of such a sensor. Only this double-length configuration may grant a maintained accuracy for temperature and strain so far. Other configuration using only temperature-dependent characteristics of the Brillouin interaction (amplitude, linewidth) to separate strain and temperature effects would result in an unacceptable accuracy for most applications.

1. *T.Horigushi, T.Kurashima, M.Tateda, IEEE Photonics Technology Letters, 2, p.352, 1990.*
2. *.X. Bao, J. Dhliwayo, N. Heron, D.J. Webb, D.A. Jackson, J. Lightwave Technol., **13**, p. 1340, 1995.*
3. *M.Niklès, L.Thévenaz, P.Robert, Optics Lett., **21**, pp. 758-760, 1995.*
4. *A.Fellay, L.Thévenaz, M.Facchini, M.Niklès, Ph.Robert, Proceedings of12th OFS, Williamsburg VA, OSA Publications, Washington DC, pp. 324-327, 1997*
5. *K.Hotate et al, IEICE Trans. on Electron., Vol.E83-C, No.3, pp.405-412, 2000*