Invited Paper

Applications of distributed Brillouin fibre sensing

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ABSTRACT

Long-range distributed strain and temperature measurements along an optical fiber is presented, using a novel optical sensor based on stimulated Brillouin scattering. The optical effect only depends on the fiber material, so that the bare fiber itself acts as sensing element without any special fiber processing or preparation. The sensor accuracy is ± 1°C for temperature and ± 20 $\mu\varepsilon$ for deformation. The spatial resolution is 1 meter and the sensor range is more than 20 km. Successful monitoring of a concrete dam element has been performed using an embedded standard cabled fiber. The temperature dynamics of lake waters have been also observed by simply laying a cable over the lake bed.

Keywords: distributed sensor, optical fiber, strain sensor, temperature sensor

1. INTRODUCTION

A novel optical sensor for long-range distributed strain and temperature measurements along an optical fiber is presented, based on a nonlinear effect called stimulated Brillouin scattering. This interaction causes the coupling between optical and acoustical waves when a resonance condition is fulfilled. It turns out that the resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain. Local information is obtained by using pulsed lightwaves and a classical time-of-flight technique like in radar systems.

The resonance frequency is an intrinsic property of the material that may be observed in any silica fiber. This is very attractive since the bare fiber itself acts as sensing element without any special fiber processing or preparation. Standard optical cables may thus be used, resulting in a low-cost sensing element that may be left in the structure and used for other purposes like telecommunications.

Since the optical effect only depends on the fiber material, it is absolutely stable in time and independent of the instrument. Different measurements performed over a long-term period are thus fully comparable.

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2. DESCRIPTION OF THE INSTRUMENT

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. 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 setup 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.

Another original feature is that pump and probe both propagate back and forth through the sensing fiber using a reflection at the far end, making the access to a single fiber end for the measurement possible. This is due to the directional property of the Brillouin gain that is only effective for contrapropagative waves, while no interaction takes place when the waves are copropagative. In other words the pump pulse provides gain to the probe signal during its forward propagation through the stimulated Brillouin scattering process while the CW probe is amplified on the way back. Only a few percent of reflection is necessary at the fiber far end, so that it turns out that Fresnel reflection is actually sufficient.

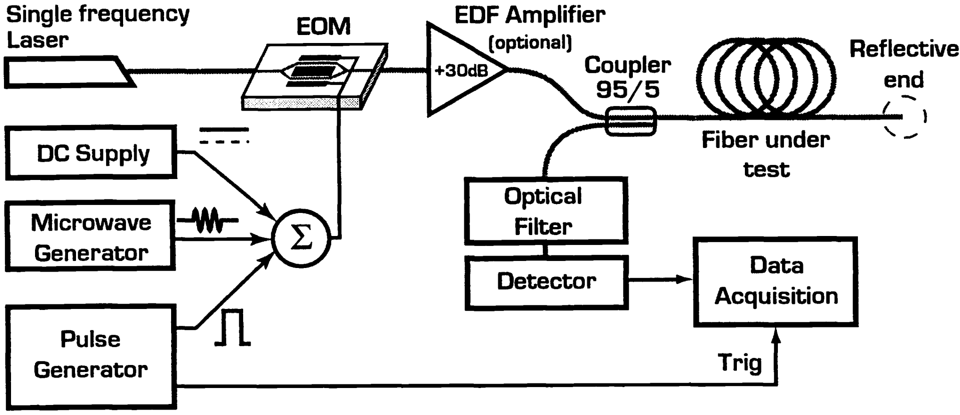


Fig. 1 Experimental setup for distributed Brillouin gain spectrum measurements, using an electro-optic modulator to generate the interacting signals.

The spatial resolution obtained with this equipment is 1 meter for a 10 km range and remains below 3 meters over 50 km. 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). This kind of sensors is thus definitely dedicated for long range measurements with meter resolution and is not suitable for centimeter resolution.

The accuracy on the determination of the Brillouin shift ν_B depends on the amplification contrast and the probe signal intensity. In standard fibers an accuracy of 1 MHz is observed. This approximately corresponds to a 1 degC temperature resolution and to a 2×10^{-5} strain resolution.[4,5] 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 a worse spatial resolution or a longer measurement time.

3. APPLICATIONS USING THE DISTRIBUTED BRILLOUIN SENSOR

This sensor has experienced many tests for different applications, some of them being directly performed in the field. The most significant are reviewed in this section.

3.1 Strain measurement

The equipment has been used to check the resistance of an experimental synthetic rope for marine applications. For this purpose a fiber was embedded in such a rope subjected to strong tensile stresses on a test bench. To simulate a possible damage 3 narrow cuts were superficially performed at a mid-length position. In Fig. 2 the damaged section can be clearly identified, the rope elongation – and the fiber strain, accordingly – being significantly larger at this position. Such a measurement also demonstrates that a meter spatial resolution is possible.

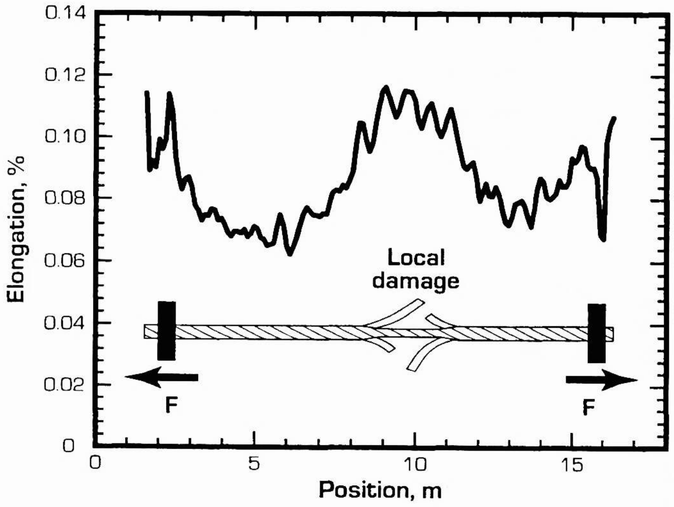


Fig. 2 *Measured elongation of a fiber embedded in a synthetic rope experiencing a strong tensile force. A local damage was intentionally made, so that it could be identified through an excess elongation.*

Another test was performed to check the resistance of a telecommunication cable wh[illegible] strong tensile load is applied. This classical test is achieved using a pulley system, as shown in Fig. 3, and provides significant information about the cable buffering capability regarding the fibers bundled in the cable. In particular this test is decisive to determine the critical pulling force at which the fibers start to be strained.

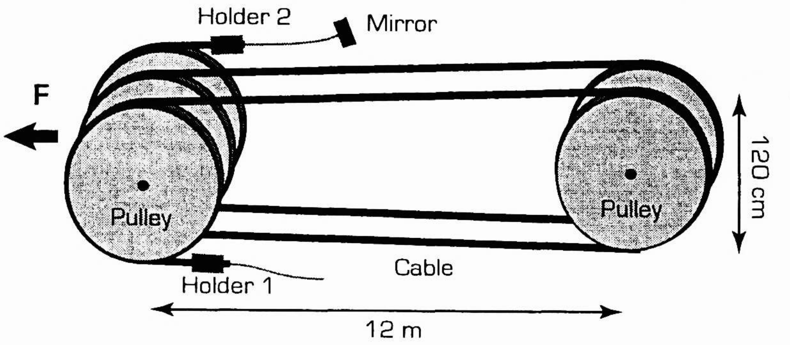


Fig. 3 *Traction bench for testing the cable resistance to a tensile force. Longer cable segment can be checked thanks to the pulley system.*

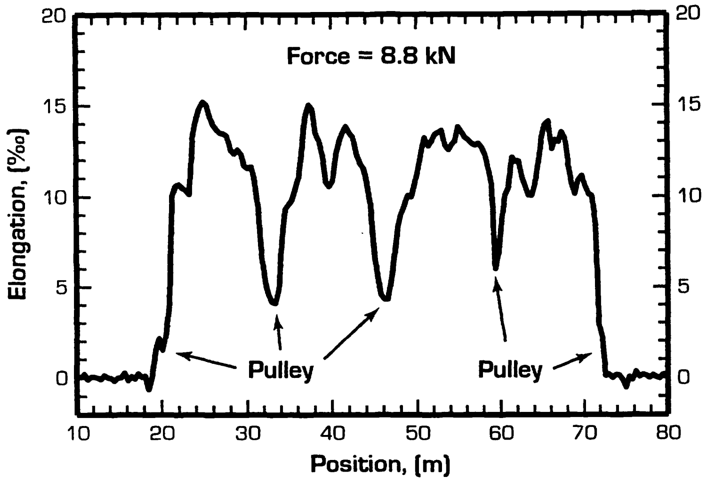


Fig. 4 Distributed measurement of the elongation of a fiber in a cable stressed by the system shown in Fig. 3.

In Fig. 4 the Brillouin distributed measurement using this pulley system shows an non-uniform fiber elongation over the cable length. The fiber is clearly less strained at the pulleys position. The total fiber elongation can be easily determined by integrating the local elongation over the entire cable length, as shown in Fig. 5 for different tensile forces. The critical pulling force is clearly observed and the fibers start to elongate linearly for a larger applied force. This is in perfect agreement with other measurement of the total elongation, performed using a classical technique based on phase delay measurements.

This result shows that the Brillouin sensor delivers a more complete information than classical techniques measuring the total elongation, since the local strain may differ significantly from the average strain. This is particularly important regarding the fiber breaking probability that is of course directly related to the local strain.

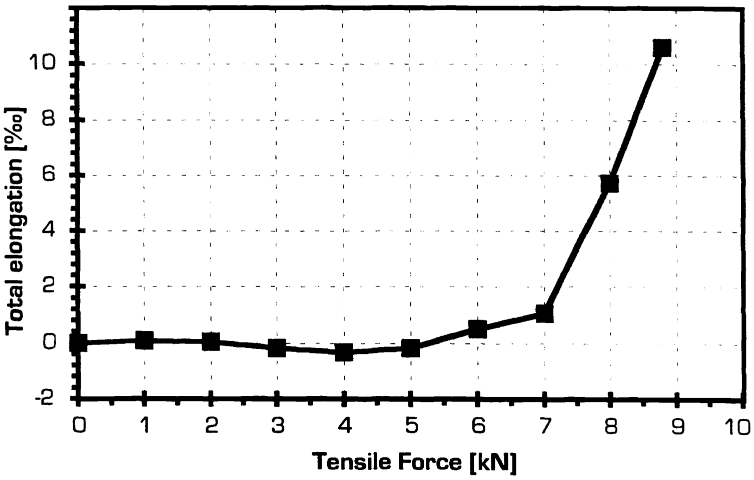
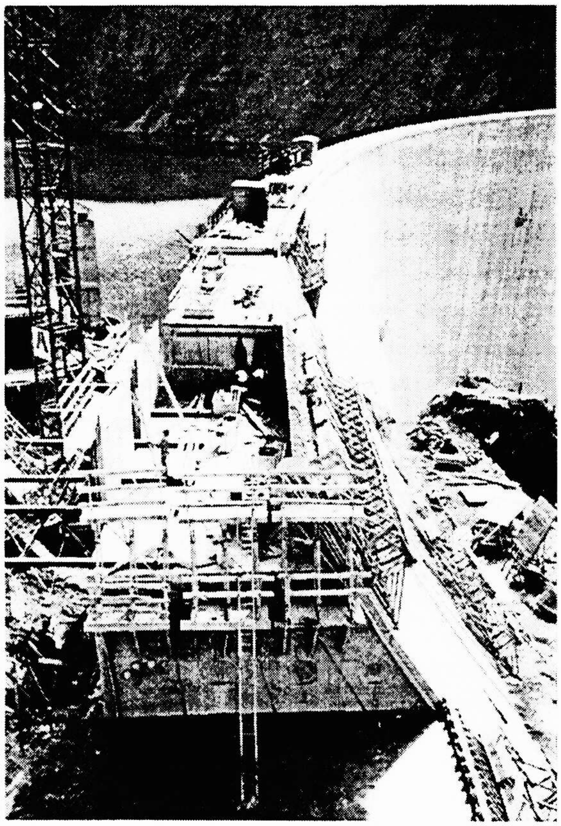


Fig. 5 Total fiber elongation over the full cable length for different tensile force, each point being calculated by integrating a measurement similar to Fig. 4.

3.2 Temperature measurement

Civil engineering is an important field of application for distributed Brillouin sensing, since it perfectly fulfills the requirement of long range measurements with meter spatial resolution. The equipment was used to monitor the concrete setting temperature in large structures. This monitoring is of prime importance in critical works, since the density and the importance of microcracks are directly related to the maximum temperature experienced by the concrete during the setting chemical process.



A major dam at Luzzone in the Swiss Alps was recently raised to increase the power capability of the associated hydroelectric plant. This raising was actually achieved by stacking gradually new concrete slabs of 15 m x 10 m average size for a 3 m thickness, as shown in Fig. 6. A small optical telecommunication cable was installed during the concreting over the central layer of the largest slab, so that the embedded cable makes a dense horizontal mat, necessary to obtain a two-dimensional temperature distribution of the whole central slab area. Fig. 7 shows the temperature distribution over the slab at different moment after concreting. It can be clearly seen that the temperature rises up to 50 degC in the central area and that it takes many weeks to cool down this region. The outer slab areas rapidly stabilize at the ambient temperature, so that an observer is totally unaware that the concrete is still fairly hot in the central region of the dam.

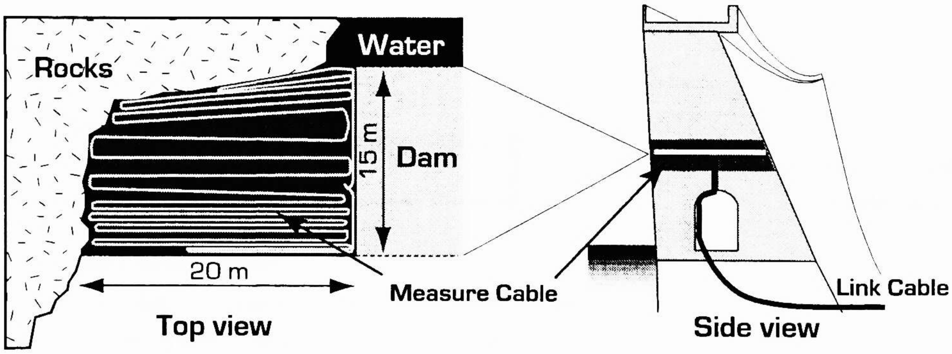
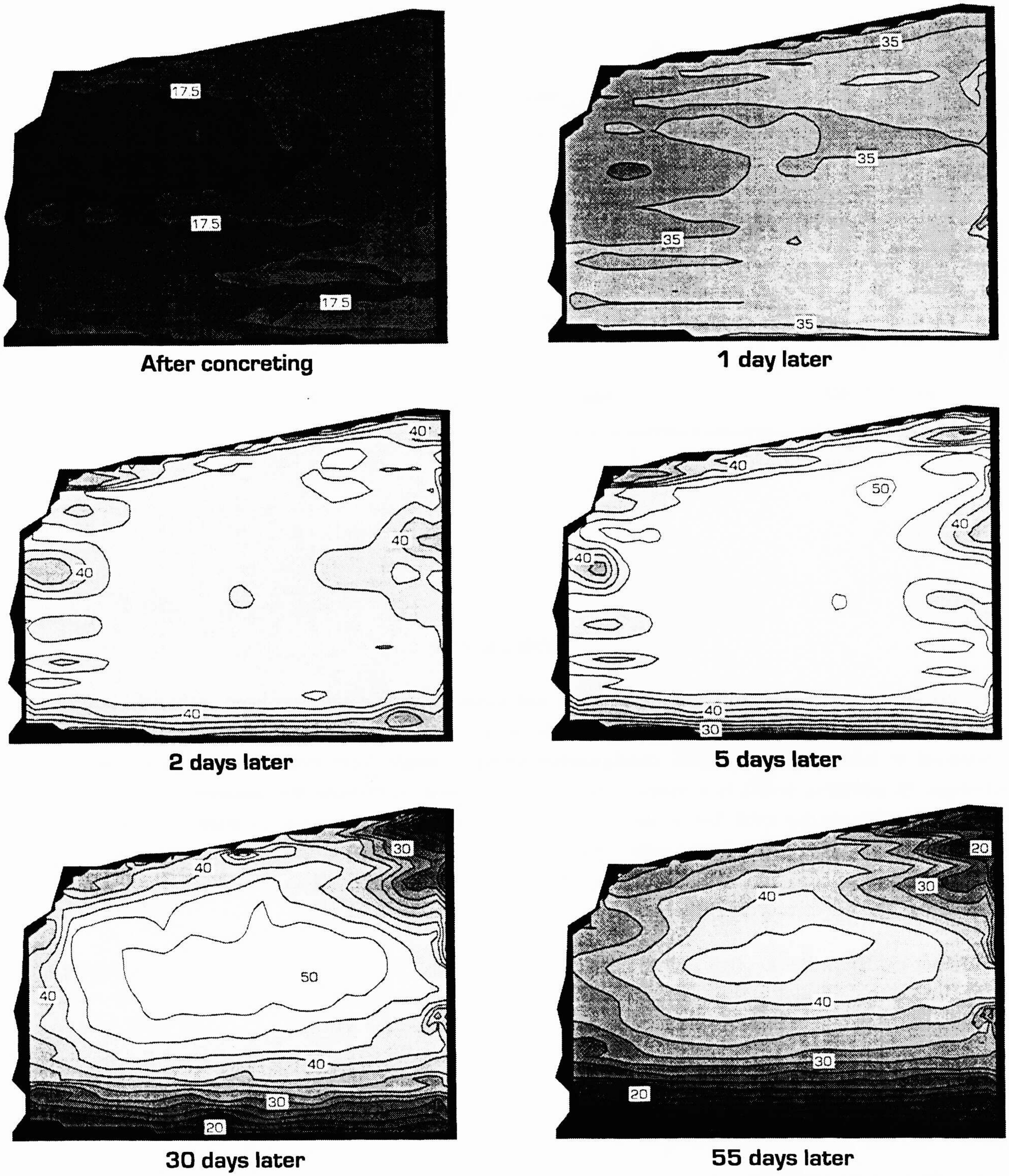


Fig 6 View of the concrete slab and of the mat-like installation of the measuring cable for concreting temperature monitoring, during the raising of Luzzone dam in the Swiss Alps.

Finally a cable installed by a telecommunication operator over the bed of the lake of Geneva in Switzerland was used to observe the temperature change of the deep waters in relation with seasonal conditions. Fig. 8 shows that the surface water moves down to the lake bed during the winter (November measurement), heating up the deep waters. This breaks the layered distribution of temperature and generates a complete water mixture essential for the lake oxygenation and the biological life, consequently.



After concreting

1 day later

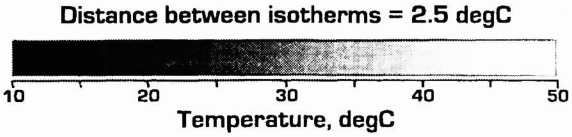
2 days later

5 days later

30 days later

55 days later

Fig. 7 *Two-dimensional temperature distribution in Luzzone dam during the setting of the concrete slab shown in Fig. 6, obtained by the distributed Brillouin sensor using an optical cable embedded within the concrete.*



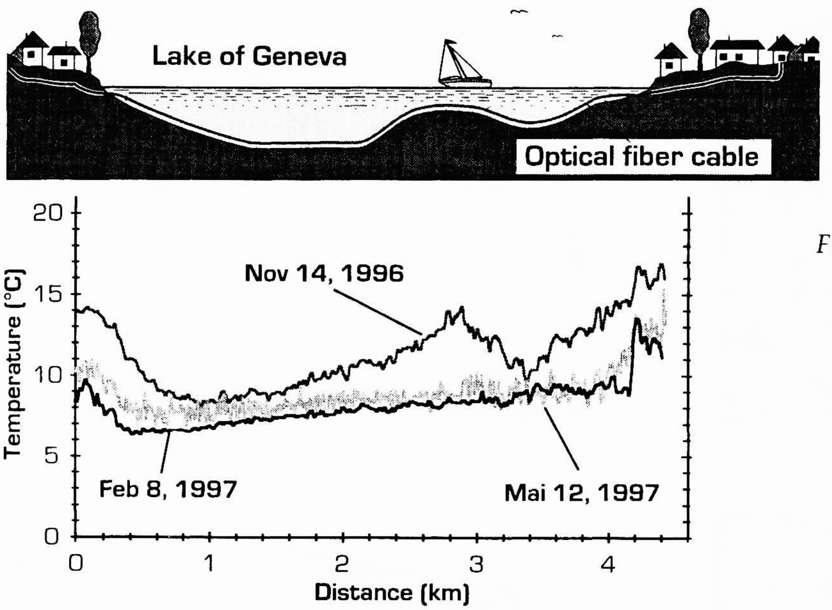


Fig. 8 *Temperature profile of the water on the bed of the Lake of Geneva, Switzerland, showing significant seasonal changes in the temperature distribution.*

6. CONCLUSION

Demonstrative tests of distributed temperature and strain measurements have been performed in the field using an instrument based on the local analysis of the stimulated Brillouin interaction (LASBI). This instrument is based on an original configuration using a single laser source and a pump and probe technique. In addition, access to a single fiber end is required to perform the measurements, what is an obvious advantage in the field. The nature of the Brillouin interaction makes such a sensor dedicated to long range measurements (up to 100 km) with a meter resolution. The physical limit for the spatial resolution is reached with this instrument and improvements are now rather expected in the temperature and strain resolution and in the acquisition time, that is currently 3 minutes for 1024 points.

Another problem that is often pointed out is the impossibility to discriminate between temperature and strain effect using a Brillouin shift measurement. To our opinion the problem can be in real conditions easily worked out by combining loose-tubed and tight cables. In a loose tube the fiber is granted to be unstrained and is therefore only sensitive to temperature. If strain information must be obtained a parallel tight cable must be installed that is fixed on the structure, so that the fiber can in addition experience strain. The drawback of a double-length sensor is widely canceled out by the very long range capability of such a sensor. Only this double-length configuration may grant a maintained accuracy for temperature and strain. Other configuration using the particularity that the Brillouin linewidth depends only on temperature and not on strain would result in an unacceptable accuracy for most applications.

7. ACKNOLEDGEMENTS

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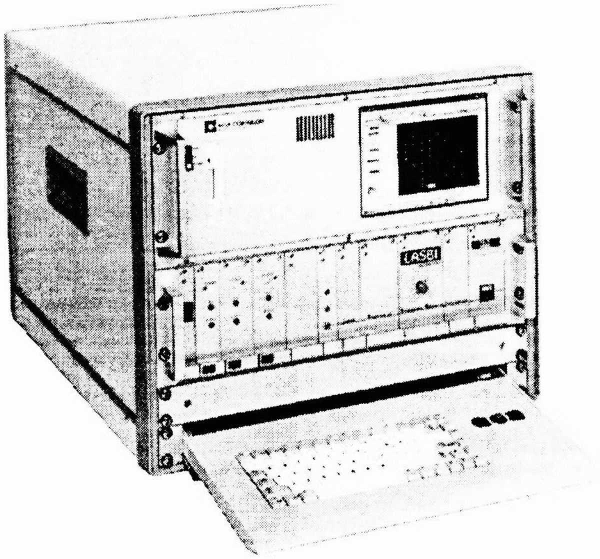

The Brillouin distributed fiber sensor *LASBI 9800*.