Lightning-safe diaphragm pressure gauge for geotechnical applications using a long-term reliable absolute EFPI sensor

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ABSTRACT

The paper describes a sensor head for long-term high-precision measurements of very small deflections of a diaphragm used for pressure gauges. High precision deformation measurement is assured by using a fibre Fabry-Pérot interferometer sensor; identification of zero-point changes, and thus, long-term stable measurement is achieved by a specially designed absolute interferometer sensor. Several fibre optic solutions based on fibre Fabry-Pérot technique have been investigated to find out a reliable sensor design. The presented sensor design has reached prototype status and allows to measure unambiguously static deformations with high precision. In order to evaluate repeatability and possible changes of zero-point reference if the head has been disconnected, validation of the described pressure gauge has been started. This validation work includes calibration and enables to evaluate possible drift effects, and to identify mechanical or thermal hysteresis.

Keywords: pressure sensor, fibre Fabry-Pérot interferometer, geotechnical application, precise deformation measurement, long-term stability

1. INTRODUCTION

In geotechnics compressive or tensile stresses are often measured by flat pressure pads (Flat Jacks) or by hydraulic concrete stress transducers using common pressure pads. The measurement principle is that a deformation of surrounding material, e.g. concrete, exert pressure on the pressure pad. The fluid in the pressure pad is compressed and the hydraulic pressure change is measured by scanning the deformation of an elastic acting diaphragm. This diaphragm is located in a cylindrical head connected to the pad. In order to achieve reliable measurement data over a long operation time, a high standard of quality is set concerning accuracy, repeatability, application technique, temperature influence, drifts and so on. In general, these requirements are very difficult to meet if atmospheric discharges or lightning strokes happen, e.g. in the vicinity of dams or bridges. Therefore, it was demanded to measure the deflection of a diaphragm inside the head without being influenced by electromagnetic interferences. Other requirements have to be considered, too:

- reproducibility of static measurement results over 20 years, at least;
- indication of zero-point drift over time because recalibration of the measuring head is not possible after installation respectively test loading;
- minimum of ageing;
- control of influences caused by leading cables or other components;
- water-tightly protected (IP 68), safe against aggressive media;
- compatible to fibre optic sensor networks.

In order to fulfil these requirements, a fibre optic sensing head has been developed to measure very small deformations of elastic diaphragms.

2. FIBRE OPTIC MEASUREMENT PRINCIPLE USED - GENERAL REMARKS

In order to measure precisely very small strain changes in industry or at university level, interferometric techniques are used. Fibre optic interferometric sensors are increasingly preferred because of their advantages: e.g. measurement resolution down to the picometer range, tiny sensing elements, almost no reaction to the measuring object. However, not

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yet completely solved are the problems arising from the fact that interferometric sensors deliver periodic signals. This feature makes the use of interferometric methods difficult for precise static and long-term displacement or strain measurements, if the sensor has to be disconnected. On the other hand, considering the continuously varying distance between two mirror planes in a fibre interferometer, especially for small distance changes, it is not possible to draw conclusions only from the cosine-like signal - which additionally decreases exponentially - to the direction of the mirror shift. The measurement result is then ambiguous. When the measurement device is switched off or disconnected, the zero-point reference is lost. This problem is not really significant for dynamic measurements, such as for measurement of acoustic emissions. However, measurement of static quantities is not easy to carry out. It requires sometimes extremely high signal resolution as well as unambiguity and zero-point reference.

Since about ten years, very different designs have been proposed to solve these problems. The basic idea in these proposals is to get or to create, at least, one more information, which can electronically or mathematically be combined with the original interferometer signal. From this, one can get unambiguous and absolute measurement information. The most interesting solutions, which solve these problems are: a) the current of the laser diode is driven by a feedback of the interferometric signal; a Serrodyn characteristics of the output signal is created from which the shift direction of the sensing interferometer arm can be detected unambiguously [1]; b) several defined laser wavelengths are used. An absolute measurement of distance changes is then possible by using the beat wavelength [2]. The cited methods suffer from two problems: either the signal resolution respectively the accuracy is not sufficiently high for some measurement tasks, or a reliable detection of absolute measurement signals is not really possible if the device or components of it have to be renewed. On the other hand, a re-calibration of embedded, that means, not any more reachable sensors is not possible, if the sensor-assembled structure component cannot be tested separately. These unsolved problems were the decisive factor to develop innovative and completely new solutions to get absolute and long-term stable measurement information from fibre Fabry-Pérot sensors. Following, one of the methods developed including first test results will be presented.

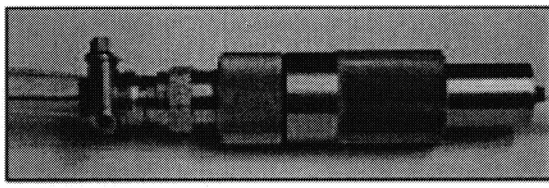
3. MEASUREMENT TASK AND REQUIREMENTS

The deformation of a metallic diaphragm has to be detected up to a deflection of 10 µm (rather less) perpendicularly to the plane of the membrane. Electric components are not accepted because of the probability of damage by lightning. Data recording is planned only from time to time, and long-term reproducibility of the deflection within a range of 5 % (full-scale) has to be ensured. Long-term measurement means, that the sensor has to work reliably for several years. Additionally, the diaphragm behaviour must not be influenced by stress-induced reactions of the sensing element to the tiny membrane. The sensing head including the read-out device should be not expensive. Finally, the data recording system should work automatically.

From the data scanning point of view, there is sufficient scanning time (about 5 min) because the measurement signal varies extremely slowly. The data scanning could run once per hour or once a day. A very important requirement is that the measurement device must be disconnected from the sensing head after each measuring event. A central data acquisition unit is not scheduled. Electric links between sensing head and device should strictly be avoided. On the other hand, non-electric auxiliary power supply, e.g. for calibration purposes, is allowed.

4. FIBRE OPTIC HEAD WITH ZERO-POINT IDENTIFICATION

In order to meet the measurement requirements and to enable a multiple calibration of irretrievable sensors (that means, the sensors are embedded or installed inside of large structures that the sensors are no longer attainable), a special compensation method has been developed. It uses an auxiliary energy. The principle of the measuring head is shown in Fig. 2. Inside the measuring head, a nearly reaction-free Fabry-Pérot interferometer (FPI) sensor, which is able to slide in a tiny capillary [3], is used as measuring interferometer. This movable fibre Fabry-Pérot sensor is driven by a change of the measurand (here: by deflection of the diaphragm). The calibration and measurement procedure is started by introduction of the auxiliary energy (in this case: compressed air) into the head. Due to this action, the elastic element (see Fig. 2) is slightly deformed and the measuring interferometer will be shifted back until a well-defined reference position. This position which represents the stable zero-point position is detected by a second interferometer sensor (stop trigger FPI). Finally, the evaluation of the interference signal of the measuring interferometer sensor delivers the difference between the value following from the actual measurement and the value defined by the reference point. Thus, measurement and calibration procedure is directly connected.



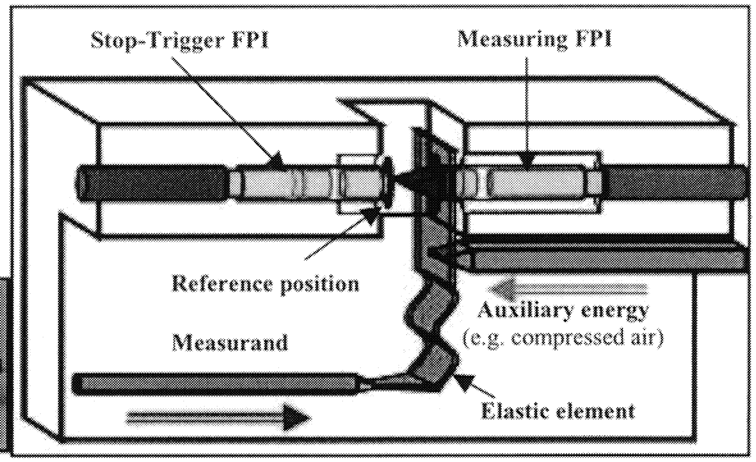


Fig. 1. Photograph of the sensing head

Fig.2. Scanning principle using fibre Fabry-Pérot sensors

5. TEST OF THE SENSING HEAD

In order to get reliable information about the performance of the scanning head, a test programme corresponding to the rules of validation [4] has been started. A number of tests has to carry out to verify whether the sensing head fulfils the requirements for the intended use. The most important questions concern:

- evidence of zero-point stability, that means, the estimation of the zero-point deviation from the original reference value; two test cycles are carried out: cyclic pressurisation for constant temperature with a certain stop time, and cyclic pressurisation at two temperature levels. All measured values are compared with a high-accuracy measuring device (reference standard);
- identification of sensor characteristic including existing hysteresis, drift, zero-point shift;
- evidence of precise functionality after disconnecting and reconnecting of the recording device;
- identification of possible influences on the sensor characteristic due to changes in temperature of leading fibre and components;
- evidence of mechanical stability.

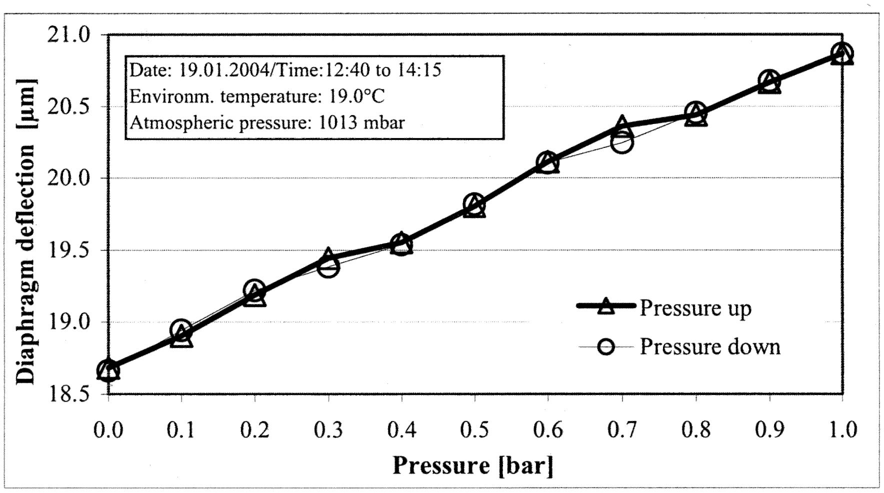


Fig. 3. Recording of the characteristic of the sensing element due to pressure changes

Following, a selection of achieved results of the validation are presented. The validation of the performance is being continued. The pressurisation up to a value of 1.0 bar as well as the pressure relief is made in 10 percent steps; the stop time is 2 minutes at each pressure level. After carrying out several cycles, power supply and fibre cable are disconnected. The further test cycles are made under nearly realistic conditions concerning disconnecting and reconnecting. Fig. 3 shows a calibration cycle in the above defined pressure range. Only a very small hysteresis effect can be observed between increasing and decreasing pressure load; the mean deviation is approximately 5.2 % related to the measurement range. The specification of a measurement uncertainty is, at the present stage of investigation, not yet possible. However, the uncertainty of the results has to be estimated, in any case, to give evidence that the sensor works reliably. Fig. 4 shows the drift of the sensing head under a permanent pressure load of 1.0 bar over 70 h. It is clearly to see that the drift is within a range of 0.44 μm of the diaphragm deflection.

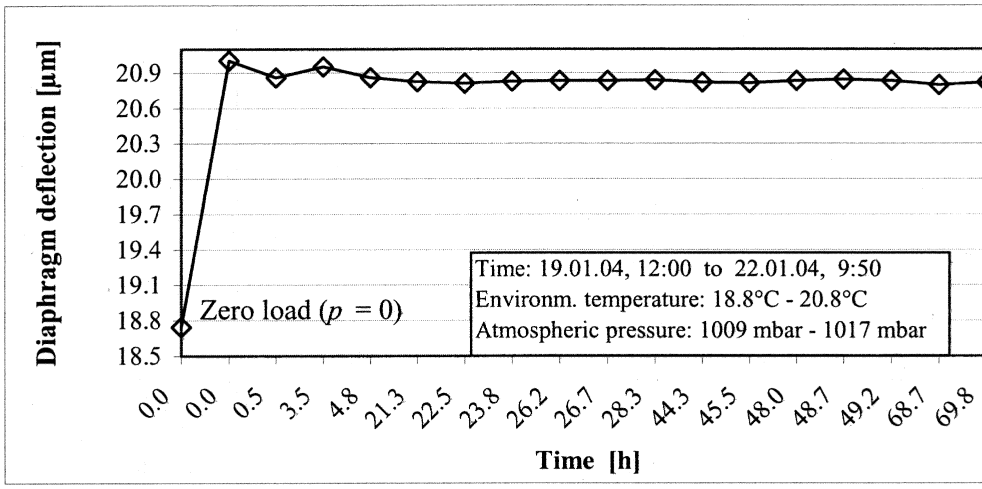


Fig. 4. Drift of the sensing head under permanent loading for 70 h.

6. CONCLUSIONS

A fibre optic sensor head based on a fibre Fabry-Pérot interferometer sensor has been developed. The sensing head can be used in hydraulic measurement systems for geotechnical applications to scan precisely very small deformations of a diaphragm. However, this head can also be used in other measurement systems. The special feature of this high-precision sensing head is its ability to enable long-term measurements with sensor-integrated zero-point reference, especially when the power supply is switched off between two measurement events or if components of the measurement system have to be exchanged.

One version of different solutions at laboratory level has been validated concerning repeatability of results, stability of zero-point reference, possible drift and hysteresis effects. It was shown that reliable long-term static or quasi-static measurements are possible and a zero-point stability information is available even if the recording device has been disconnected.

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