Fiber optic tiltmeter based on total internal reflection phenomenon

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ABSTRACT: Fiber optic tiltmeter has been developed based on total internal reflection at the interface between immiscible liquids with different refraction indexes. Multimode optical fibers have been used for optical signal transmission between the sensing element and light generation-processing units. The specifications of the measuring transducer are as follows: dynamic range – 59 dB, threshold sensitivity – 0.005 deg., sensing range can be adjusted within the limits of 1^0 to 10^0. The sensing element can be removed from the light generation and processing blocks to a distance of up to 1 km. High sensing performance and stability of the measuring transducer allow its wide application in real time tilt monitoring.

1 INTRODUCTION

As is known, operational safety of a wide range of civil infrastructures such as bridges, derricks, high-rise towers, buildings, tunnels, dams, etc. depends largely on the absolute angular position of its structural elements. Indeed, a slight, unrevealed in proper time slope of a column, retaining wall, or carcass element may lead to catastrophic consequences both to the people and environment, not to mention far-reaching economic effects. That's why tilt monitoring is worldwide regarded as an important aspect of structural health monitoring and a great deal of approaches has been implemented to address this problem (Erol et al. 2004, Chitaru & Enescu 2003, Dyshlyuk 2004, Kibrik et al. 1995).

Inclination measuring techniques range widely from mechanical pendulum protractors and bubble levels to electrolytic sensors and optical interferometric transducers. One of the most wide-spread nowadays types of tilt sensors is an electrolytic inclinometer (Puccio 2004). This kind of device provides highly accurate angular position read out over a wide sensing range, but it's electricity-based and therefore subject to electromagnetic interference. Most of the other conventional angular sensing techniques are either unsuitable for remote real-time monitoring or too bulk or sophisticated for mass application in health monitoring of large civil infrastructures.

Fiber optic sensors realizing up-to-date achievements of fiber optics, optoelectronics, and laser interferometry are being intensively developed nowadays. Among the primary advantages of this type of measuring elements are total immunity to electromagnetic interference, environmental ruggedness, multifunctional capabilities, durability, very small size and weight, high information bandwidth measuring and communication elements, and possibility to multiplex many sensors along one fiber optic line (Udd et al. 1998). That is why the introduction of fiber optic measuring techniques into SHM opens up exciting prospects of precision real time monitoring of civil infrastructures during their whole lifetime.

As it follows from the literature analysis some approaches to inclination monitoring based on fiber optics have been already undertaken (Dyshlyuk 2004, Inaudi & Glisic 2002). However most of them rest on mechanical suspensions, which results in the friction and may prevent a sensor from long ongoing operation without sensing performance deterioration. Besides some fiber optic inclinometry techniques are rather complex and expensive, which makes them cost-ineffective for the monitoring of huge structures when a large number of sensing elements is required. That is why the development of a simple, low-cost, and precision fiber optic tiltmeter free from moveable details and friction represents a topical and outstanding task of SHM.

2 OPERATION PRINCIPLE

Operation principle of the measuring transducer is based on the total internal reflection, which occurs at the interface between two immiscible liquids contained in the hermetical case of the sensor (fig.1). Light beam is emitted by optical fiber 3, which is

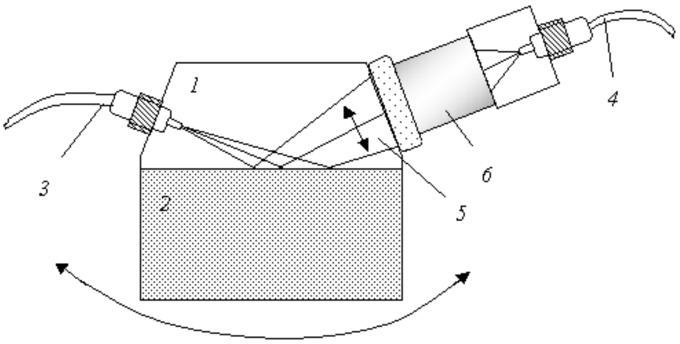

Figure 1. Fiber optic tiltmeter: construction and operation principle. 1, 2 – immiscible liquids with different refraction indexes ($n_1 > n_2$), 3 – emitting optical fiber, 4 – receiving optical fiber, 5 – reflected light beam, 6 – lens system.

mounted so as to ensure the incidence angle of the beam to the interface between the liquids to be larger than the critical angle of total internal reflection. In this case the light beam is totally reflected and launched into receiving optical fiber 4 by means of lens system 6. When any tilt occurs to the sensing element the interface between the liquids retains horizontal orientation, which results in the angular displacement of the reflected light beam relative to the body of the sensor and therefore in the intensity change of the light launched into the receiving fiber. This change is registered at the output of the sensor by means of a standard photodetector.

3 THEORY

In order to calculate the relationship between angular displacement of the sensor and its output optical signal intensity let's assume the intensity distribution in the cross section of the light beam to be a Gaussian function.

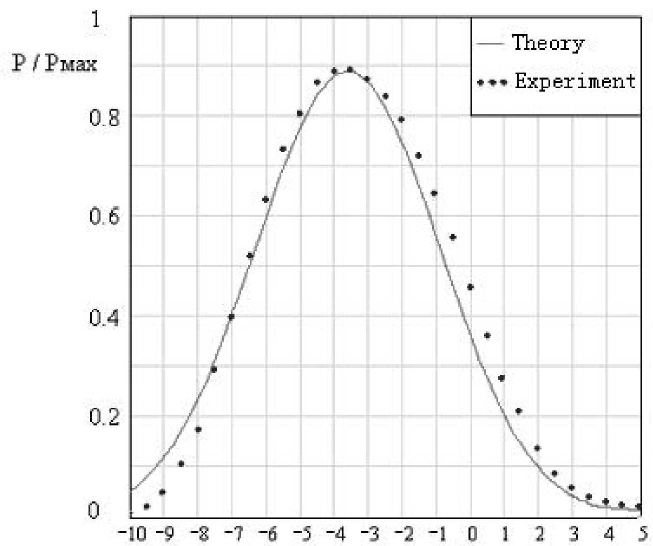

Figure 2. The dependence of the optical power integrated by the lens system on the sensor tilt angle.

It is then necessary to take into account two effects resulted from the tilt of the sensor and affecting its output signal. The first one consists in the movement of the reflected light intensity distribution in the input plane of the lens system, which leads to the change of the optical power integrated by the lens system.

The second effect deals with the displacement of the point where the reflected beam is focused to by the lens system. As far as the receiving fiber is positioned at the optical axes of the objective close to the focusing point, its displacement defines the intensity of the light launched into the receiving fiber.

Optical power integrated by the objective in dependence on the sensor angular displacement can be described by the following expression:

$$P(a) = \iint_S I(r, j, a) \cdot r \cdot dr \cdot dj \qquad (1)$$

where α = tilt angle, φ and r = polar coordinates in the input plane of the lens system, $I(r,\varphi,\alpha)$ = Gaussian distribution of the reflected light beam intensity in the input plane of the lens system in dependence on the sensor tilt angle.

Function $P(\alpha)$ calculated in accordance with expression (1) is presented in figure 2.

The next step is to compute the displacement of the reflected light beam focusing point and its influence on the output optical intensity of the sensor. For simplicity let's assume the objective to be a single lens with a focus distance equal to that of the lens system. Using geometry optics and actual dimensions of the sensing element one can easily obtain numerical simulation results for the relationship between sensor tilt angle and linear displacement of the focusing point in the plane of the receiving fiber input end face (fig. 3).

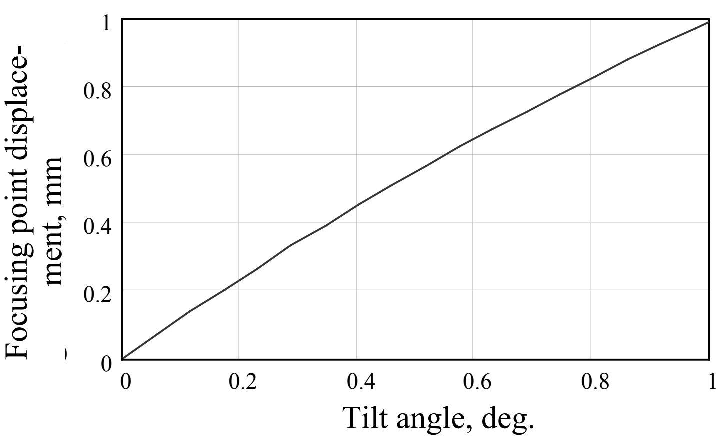

Figure 3. Numerical simulation results for the relationship between sensor tilt angle and linear displacement of the focusing point in the plane of the receiving fiber input end face。

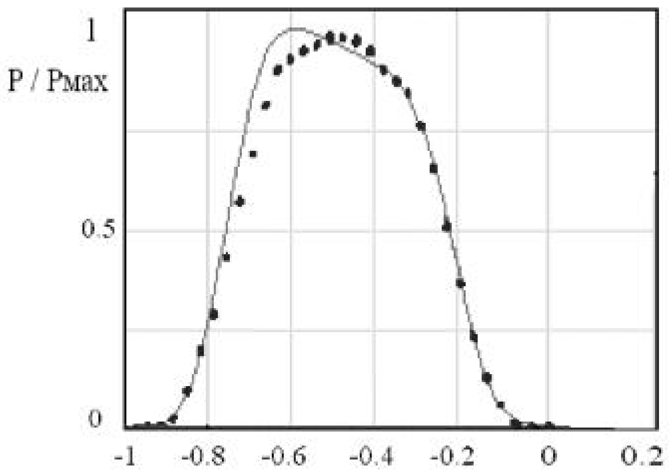

Figure 3. The dependence the sensor output optical power on the angle of its inclination.

Taking into consideration the relationship between sensor tilt angle and focusing point displacement, equations (1), actual parameters of the receiving optical fiber (in order to increase the sensor dynamic range and sensitivity, large core optical fibers (d = 500 µm) have been used), as well as Gauss light intensity distribution in the focusing point, the dependence of the relative optical power launched into the receiving fiber on the sensor tilt angle has been derived. It's graphically depicted in figure 3.

4 EXPERIMENTAL SETUP AND RESULTS

The diagram of the experimental setup is shown in figure 4. Sensing element 1 was mounted on precision positioning device 3 allowing graduated angular movement with an accuracy of 0.005^0.

The experimental results are presented in figure 5. Threshold sensitivity of the sensor was registered to be better than 0.005^0. The sensing range of the inclinometer amounted to about 0.7^0. It can be extended by moving the receiving optical fiber end face along the optical axes of the lens system slightly away from the focusing point.

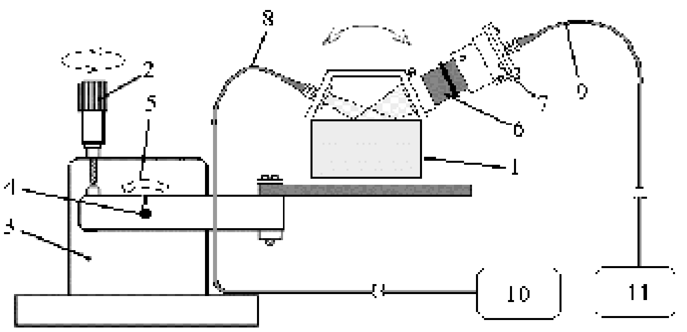

Figure 4. Experimental setup: 1 – sensing element, 2 – screw, 3 – angular positioning device, 4 – rotation axis, 5 – angular scale, 6 – lens system, 7 – receiving fiber positioning device, 8 – emitting optical fiber, 9 – receiving optical fiber.

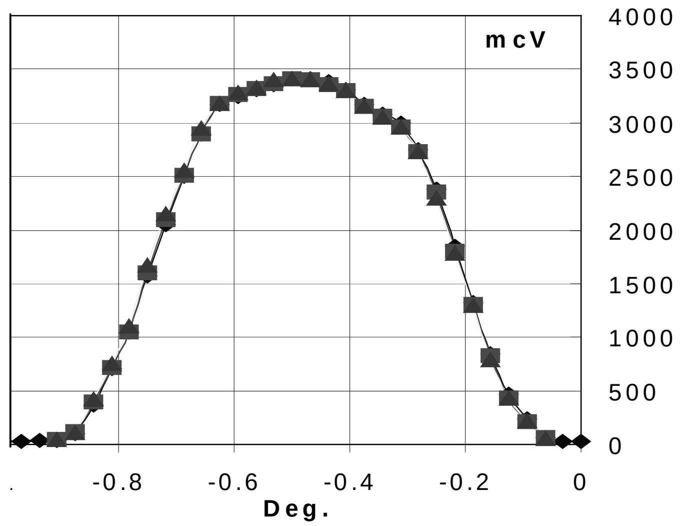

Figure 5. Experimental results for the sensor output signal on the tilt angle. To estimate the repeatability of the sensing performance several measurements were taken.

In this case the maximum output optical signal of the sensor is decreased, but the sensing range is expanded due to a larger radius of the light intensity distribution in the plane shifted form the focal one. Experimentally obtained dependences of the sensor's maximum output intensity and angular sensing range on the receiving fiber end face displacement from the focusing point are depicted in figure 6.

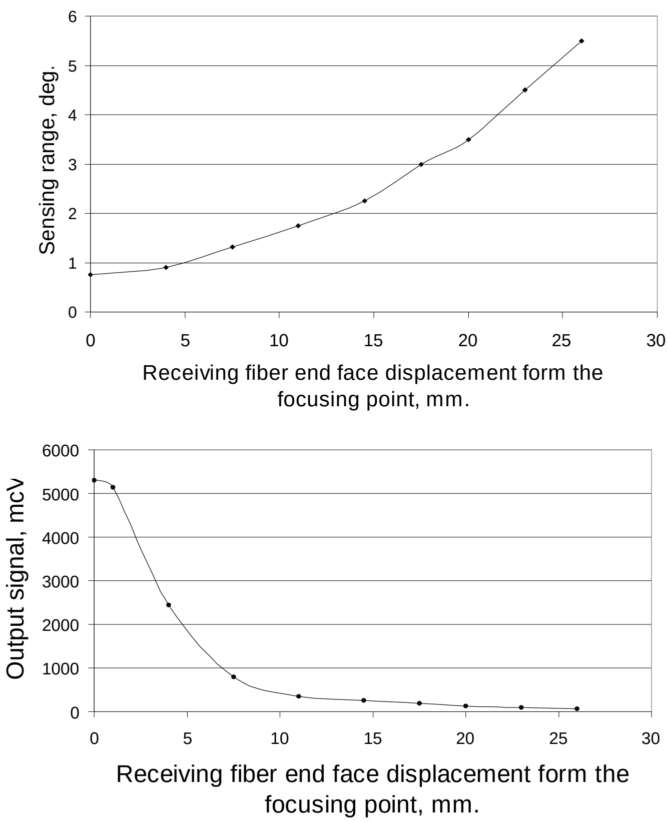

Figure 6. The dependence of the tiltmeter sensing range and maximum output intensity on the receiving fiber end face displacement from the focusing point.

5 CONCLUSION

Thus a fiber optic tiltmeter has been developed based on total internal reflection at the interface between two immiscible liquids with different refraction indexes. The sensing element contains no moveable details and is therefore free from friction, which makes it suitable for long-term ongoing operation without sensing performance degradation. The specifications of the measuring transducer are as follows: threshold sensitivity and dynamic range at 0.7^0 sensing range amount to 0.005^0 and 59 dB respectively. By adjusting the position of the receiving optical fiber end face the sensing range can be extended up to 5^0, which however brings about some lower accuracy specifications. Thus the sensor performance can be adjusted to meet the requirements of a specific SHM task. The sensing element can be removed from the light generation and processing blocks to a distance of up to 1 km.

The sensitivity, versatility and stability of the measuring transducer developed allow its wide application in long-term infrastructure health monitoring.

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