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# Applied Fiber Optic Measurement for Geohydraulic Engineering

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ABSTRACT.
Engineers have long sought the possibility of measuring parameters such as temperature and pressure continuously in the underground with high precision, high spatial resolution and high band width of parameters. Distributed fibre optic measurement offers the use of a very fast, robust, precise, light and small gauges with an high spatial resolution. In this paper we would like to compile fibre-optic measure-methods which are available now for projects in geohydraulical engineering. This paper will propose new problems for future research work on parameter identification for such parameters as conductivity and anisotropy .

## 1. INTRODUCTION

The application of an innovative measuring system, the distributed faser optic measurement offers new possibilities for monitoring and interpreteting the environmental and geohydraulical processes. By using solid substance effects, the fibre itself is used as a passive measure transducer. So it is possible to measure parameters along a fibre scope continuously with:

(1) very fast, very robust, precise, light and small gauge with high spatial resolution
(2) no influence on the measured area through the measurement process
(3) long time monitoring easily possible
(4) (because of special spatial arrangements of the fibre scope) the possibility of measuring parameters along a way in a plane or a volume.[17]

## 2. DISTRIBUTED SENSING

Optical Time Domain Reflectometry (OTDR) is used for distributed sensing of optic effects along fibre scopes. When light is launched into a fibre scope, loss occurs due to scattering effects. This arises as a result of light scattering on the fibre molecules. The wavelength of the launched light is long compared to the size of the radius of the molecules. A fraction of the launched light is reflected and is launched back to the light source. By pulsing the light beam and monitoring the variations in the backscattered intensity, the quantity and spatial resolution of the fibre variation can be determined. The intensity of the backscattered light changes with the kind and amount of impact on the fibre scope.

For homogenous fibres in a uniform environment, the backscattered intensity is a function of the loss in the fibre scope. By knowing the velocity of light and using a pulsed laser, the received backscattered light power $P_S(t)$ can be determined by:

$$P_S(t) = (1-\kappa)\kappa P_0 D r(z)\exp\{-\int_0^z 2\alpha_i(z)\,dz\} \qquad (1)$$

The location z of the forwardtraveling pulse at the time of generation of the detected backscatter signal $P_S(t)$ can be determined by:

$$z = \frac{ct}{2n} \qquad (2)$$

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*Key words and phrases.* OFDR, OTDR, intrinsic-pressure-sensing, Raman, Rayleigh, Brillouin.

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$\alpha_i(z)$ attenuation coefficient in neepers (natural exponential units: 1 neeper=4.34 dB)
$n$ the group index of the fibre core
$c$ velocity of light
$k$ the input fibre coupler power splitting ratio
$r(z)$ the effective backscatter reflection coefficient per unit length that takes into account the Rayleigh backscattering coefficient and fibre aperture
$D$ $(c\tau/n) = D$ the length of the optical pulse in the fibre at any instant of time

For practical use we assume that the loss experienced by the input is equal to the loss experienced by the backscattered light. So the slope of the logarithm of the detected signal is equal to the loss coefficient.

$$\frac{\partial(\ln P_S)}{\partial z} = -2\alpha_i(z) \tag{3}$$

The intensity of the localized perturbation is represented by the intensity of the loss and characterized by a higher slope in the OTDR trace. Spatial resolution, is for intrinsic fibre scope measurement a main property and it is the smallest distance between two scatters that can be resolved, and is determined by the input pulse according to:

$$\Delta z_{min} = \frac{c\tau}{2n} \tag{4}$$

The different OTDR Techniques have been compiled in [16]. This compilation is essentially compiled with the basic principle of OTDR, the optical radar system. Direct analogies between conventional radar and optical radar sensing have been found and utilized.

*Coherent OTDR.* The returned signal is weak and therefore mixed with a strong coherent local oscillator optical signal to provide coherent amplification.

*Optical Frequency Domain Reflectometry (OFDR).* A wide range of information is derived from the frequency distribution in the returned backscatter signal, but not its temporal decay. As is usually the case, this involves use of a chirped ratio frequency (RF)-modulated source.

*Coherent OFDR.* The emission frequency of a narrow linewidth (long coherence length) laser source is chirped and the returned backscatter signal is coherently mixed with an undelayed referential optical signal from the source.

*Pseudorandom Coded OTDR.* Correlation techniques are used in conjunction with pseudorandom input pulse sequences.

## 3. SENSING TECHNIQUES

**Rayleigh Backscatter Sensing.** Intrinsic sensors, based on the Rayleigh backscatter, utilize either measurand dependent loss $\alpha(z)$ or scattering mechanisms $r(z)$. Using the fibre for measurement only, the sensitvity of the fibre core may be enhanced to only this measurand. By using OTDR for interrogation of the external sensor, the spatial variation of the measurand along the fibre core is derived from the output information by using the determined parameters in equation (1-4).

The backscatter intensity, as described in eq. 1, is proportional to the backscatter reflection coefficient $r(z)$. The distributed sensing $r(z)$ is used, to determine measurand dependencies. The parameter $r(z)$ is uniform along the fibre and external perturbations are negligible. But the backscatter signal is temperature sensitive. Many experiments have been undertaken to increase the influence of temperature while determining the parameter by OTDR sensing. The temperature sensity of the gauge influids is much high than in solid fibre cores. The temperature sensitivity in solid fibre core by Rayleigh scattering is weak and not suitable for using this dependence for Rayleigh temperature sensing.

**Raman Backscatter Sensing.** Raman scattering is used in applications for distributed fibre optic temperature sensing. The Raman effect is a wave number shift of the exciting wavelength. The wave number shift comprises Stokes ($\lambda_s$ , lower photon energy) and anti-Stokes ( $\lambda_a$, higher photon energy) emissions. The peak intensity in the Raman spectrum, as shown in Figure 1, is at a wavenumber shift of $\pm \sim 400cm^{-1}$, at which the Ratio $R_r$ of anti-Stokes to Stokes intensity in the backscattered light is given by:

$$R_r = \frac{\lambda_s}{\lambda_a} \exp \frac{hcv}{kT} \tag{5}$$

$h$ Plancks constant
$c$ velocity of light
$v$ optical frequency of the exciting radiation
$k$ Boltzmans constant
$T$ absolute temperature which is sensed in the fibre

At a pump wavelength of $514nm$, the ratio has a magnitude of $\sim 0.15$ at room temperature and a temperature dependence of approximately 0.8% in the range of 0 to $100°C$.([16])

The backscattered Raman effect is launched through a filter in a OTDR electronic processing unit to determine the stroke/anti-stroke ratio. The Raman temperature scattering is very stable but the Raman scattering coefficient is very low and this necessitates the use of high input powers from the interrogating lasers and long signal representing the average of the detected backscatter signals. For applying Raman scattering normal Ge-doped telecommunications grade fibres are used.

Raman sensing allows the temperature sensing along a $20km$ fibre scope with a spatial resolution of $0.25m$ and a sensing range of $0.1°C$ (these are maximum limits which can not used at one time) [17].

**Mode-Coupling Distributed Sensing.** When the coupling between propagation modes in fibre is used the distributed sensing is called mode-coupling sensing. In this case the sensor is based on transmission of the fibre. For this type of distributed sensing the fibre must be capable of supporting two propagation modes as orthogonal polarization modes in high-birefringence, different propagation modes of a bimode fibre, or possibly spatially different fundamental modes of different propagation constants in a two-core fibre. After polarized light from a laser is launched in a polarizer to produce a one polarization mode, the light is carried via optical fibre with known length L to an other polarizer set 5° to the fibre eigenmode. If there is any perturbation of thefibre at a point p results in mode coupling, and a fraction of the light in the input mode couples to the orthogonal mode. This result causes an interference effect at the output. Frequency modulated continuous wave (FMCW) interrogation of the system delivers the location of the impact on the fibre.

$$f_p = \frac{\Delta v f_c B(L-p)}{c} \tag{6}$$

$Dv$ laser chirp
$fc$ repetition rate
$fp$ beat frequency
$L$ length of the fibre
$p$ localization of the perturbation
$B$ modal birefringence $(n_x - n_y)$

For distributed mode-coupling the laser is chirped. The detected output signal at the polarizer is heterodyned at a beat frequency which depends on the length $(L-p)$ and the mode propagation constant. The beat frequency corresponds to a unique mode-coupling location. For yielding mode coupling versus location information Fourier analysis of the output signal is used.

The reference papers are compiled in Appendix A together with the sensed parameters and the available accuracy. The performance of the used method depends mainly on the intensity of the launched laser light. However, increasing the laser intensity causes an increasing influence of temperature on the accuracy of the obtained measurand. Several investigations around the world have developed different methods of temperature compensation which all promise to be suitable for practical use.

## 4. APPLICATIONS

The progressive innovation of fibre optic technology enabled practical application of distributed fibre optic pressure sensing since the beginning of the 90's. Different methods of fibre optic distributed sensing have been applied for practical use.

The parameters which can be determined by intrinsic distributed sensing technique are compiled in [16] and shown in Table 1. Sensor types, which allow non-distributed intrinsic fibre optic sensing of geohydraulic parameters are compiled in [16] and shown in Table 2.

In 1992 the Intelligent Structural Research Institute at Vermont applied Multiplexed fibre optic pressure and vibration sensors for hydroelectric monitoring at the Winooski dam at Vermont. They modified photoelastic (or polarization) based fibre optic pressure sensors. Up to 10 sensors were attached onto each separate multimode fibre. The individual sensors were interrogated via optical frequency domain reflectometry. So a total of 50 discrete pressure readings were available along the dam ([11]). This quasi distributed sensing of separated sensors which are interrogated via one fibre scope is only useful for static sensing systems such as in concrete constructions. At the dam the water pressure excerted on the upstream face of the dam spillway and the vibration frequencies are measured. The fibre scope acts as a transmit-receive-light-pipe for the extrinsic sensor heads. Each sensor is interrogated by its special frequency $f_i$. The light intensity received at the frequency $f_i$ corresponds with the applied pressure at the sensor i. The result of these experiments verify the use of multifunctional fibres for pressure and vibration sensing. These experiments were applied at Winooski Dam at Vermont and the experimental results are available at the Internet (http://issri.emba.uvm.edu/). ([11])

In [12] the Texas A&M University published the results of an experiment with OFDR measurement at an 4-cylinder engine. The fibre scope launched the chirped laser light into the sensors. The sensors are low-finesse Fabry-Perot interferometers. The system has been used with FFPI transducers to monitor combustion-chamber pressure in real time. Their calculation indicated, that the optical noise in this system was low enough that more than 100 sensors could easily be operated from a single laser.

Fibre optic measurement of low hydrostatic pressure based on deformations induced in twisted nematic liquid crystal cells have been presented, and different methods of pressure measurement have been proposed:

(1) pressure measurement based on direct effect of hydrostatic stress on birefringence in highly birefringent (HB) fibres
(2) pressure measurement in the form of a fibre-optic strain gauge manometer
(3) fibre-optic measurement of low hydrostatic pressure based on deformations induced in twisted nematic liquid crystal cells.

A low hydrostatic pressure sensor based on deformations induced in twisted cells was presented in [13]. In this experiment the influence of temperature on the system was reduced and the results indicated, that this method offers high response to pressure. The experiment was carried out with $1/2\pi$ TN cells and $3/2\pi$ twisted STN cells ([13]). The authors suggest for this gauge potential applications for pipelines and mining instrumentation, process control technologies and environmental protection.

In 1995 the Department of Electronics and Computer Science at the University of Southampton presented a paper [14] which forms the basic of distributed OTDR strain sensing in a fibre scope with a layer of $TiO_2$. The sensing system detects either anti-Stroke Raman scatter or Brillouin scatter. The authors have shown, that the spatial resolution of an OTDR can be much higher than commonly assumed, particularly if strong reflections from reflective points are monitored. A better ranging system has been described, analyzed and demonstrated. The authors suggest this technique as a practical multiplexed high resolution ranging system that can be used for a strain sensor.

Distributed fibre-optic sensing is now also used for humidity, pH and water sensing. For that application the fibre core has to be modified with an fluorescent layer attached on the core. In [15] the method of distributed optical-fibre sensing system for multipoint humidity measurement is described. These methods are mainly based on one of the following phenomena: colormetric reagents that changes colour with relative humidity; changes in physical size with humidity; change of refractive index with humidity; change of reflectivity of thin metal films with humidity; change of fluorescent intensity with humidity ([15]). The sensor was placed in a chamber to keep the temperature constant at $36°C$. They obtained two different $RH\%$ values. The change of humidity effects the spectral absorption of the sensor at a wavelength region of 600-740nm. The experiment was carried out under different constant temperature conditions. The authors expect that more than 10 sensors can be sited at one the single multimode optical fibre. The sensors could be placed within several metres of one another, if necessary. For wide practical appication this method has to be further developed.

## 5. RESULTS

Three different methods are available for practical application.

**A** OFDR sensing. the fibre core is used as a light pipe, launching the light power in the sensors which are attached at the fibre core. The sensors are interrogated using different light frequencies for each sensor. The obtained datas are quasi distributed.

**B** OTDR/OFDR intrinsic distributed sensing with an $TiO_2$ layer. The sensing method uses the Fabry-Perot effect and the obtained signal is a Raman or Brillouin scatter.

**C** OFDR/OTDR interrogating pressure which causes bending effects on a fibre core. The obtained signal is an Raman or Brillouin scatter.

All three methods were proved to be suitable for practical use. However, since the high use of pressure is expected for geohydraulic applications, only methods A and B can be considered for practical applications. However, the need of continuous pressuredetection via a fibre scope still can not be fullfilled. Method A is proposed for measurand sensing at static structures such as dam constructions. The method B which was proposed for pH-, humidity- and water-sensing is also a promising sensing method for pressure. This method would offer the same fibre-optic gauge for pressure, as it is available for temperature by using the Raman backscatter effect. But when available, this method needs a period of system adaptation in the field. The fibre-optic pressure sensing would offer the following advantages:

(1) changeable location of measurement co-ordinates in the fibre core during the measuring process for better localisation of impact on the fibre core
(2) changeable spatial resolution within certain limits
(3) no interference to the environment under measurement
(4) the fibre core remains stable over a long period of time
(5) inert to chemical attack
(6) high accuracy and measure range
(7) matching exactly with the requirement of pressure sensing in the underground.

In our further work we will concentrate on the optimisation of strategy of fibre-optic measurement for temperature and pressure and research on the possibility of combining temperature and pressure measurement. There is also a need for new modelling programs which are capable to handle fibre-optic-measure-datas and their interpretation to determine anisotropy, conductivity and fractures in the underground.

Because the gauge using sensing method B will not be available before 1997 and so we propose using method A which is available today in combination with the common Raman backscatter temperature sensing for determination of underground parameters as described above.. This pre-investigation could be done at this time. When the method B will be available for practical use, it could be applied immediately with existing results of the pre-investigation. That would certainly shorten the time of development for a gauge.

## ***Appendix A** : Table of available parameter, measure band-wide and accuracy*

| *Reference* | *Parameter* | *Measure range* | *Accuracy* | *Application* |
|---|---|---|---|---|
| Birefringence Measurement Under Hydrostatic Pressure in Twisted Highly Birefringent Fibres; Tomasz R. Wolinski, Wojtek J. Bock,; IEEE Transactions on Instrumentation and Measurement; Vol. 44, No. 3; June 1995 | pressure | 0...105 MPa | 0.2%/MPa | Birefringent measurement method is based on twist-induced effects; twist and hydrostatic stress have been simultaneously applied in a special pressure chamber; temperature compensation at 20°C; *(no distributed intrinsic sensing)* |
| White-Light Interferometric Fibre-Optic Pressure Sensor; Wojtek J. Bock, Waclaw Urbanczyk, Jan Wojcik, Mario Beaulieu; IEEE Transactions on Instrumentation and Measurement; Vol. 44, No. 3; June 1995 | pressure | 0...40 MPa | <0.1% | fibre-optic white-light interferometric sensor is presented, allows absolute pressure measurement with improved operation range, two fibres used as sensing element (York bow-tie 800 and especially designed elliptical-core side-hole fibre), the system is temperature compensated; *(no distributed intrinsic sensing)* |
| Multiplexed Point and Stepwise-Continuous Fibre Grating Based Sensors: Practical Sensor Structural Monitoring?; M.G.Xu; H.Geiger , J.P. Dakin; Optoelectronics Research Centre, University of Southampton, Southampton SO171BJJ, UK; SPIE; Vol.2294, No. 69 | temperature<br>strain | 10...60°C<br>0...600 µstrain | 7.5 %<br>7.5 % | determination of distributed reflecting points via OTDR, |
| Prototype fibre-optic-based ultrahigh pressure sensor with built-in temperature compensation; Y.J. Rao, D.A. Jackson; Applied Optics Group, Physics Laboratory, University of Kent at Canterbury, Kent CT2, 7NR, UK; | pressure | 0...1000 bar | 0.7 % | remote sensor based on Fizeau cavity using a dual-wavelength coherence reading technique with built in temperature compensation. Operation distance up to 10 km |
| A distributed optical-fibre sensing system for multi-point humidity measurement; A. Kharaz, B.E. Jones; The Brunnel Centre for Manufacturing Metrology, Brunnel University, Uxbridge Middlesex UB8 3PH, UK; Elsevier Science, Sensors and Actors A 46-47; page 491-493 | humidity | Humidity<br>20...80%<br>temperature<br>25...50°C | <1...4 % | humidity sensing system, based on the absorption spectrum of a colormetric reagent (cobalt, chloride) immobilised on the surface of a core of a multimode optical fibre |
| Distributed pH and Water Detection Using Fibre-Optic Sensors and Hydrogels; W. Craig Michie, B. Culshaw, M. Konstantaki, I. McKenzie, S. Kelly, N.B. Graham and C. Moran | pH<br>water-detection | | | spatial resolution <50 cm over a length of 100m, the technique combines OTDR with chemically sensitive water swellable polymers (hydrogels). The sensor was applied for cement grouting process. |

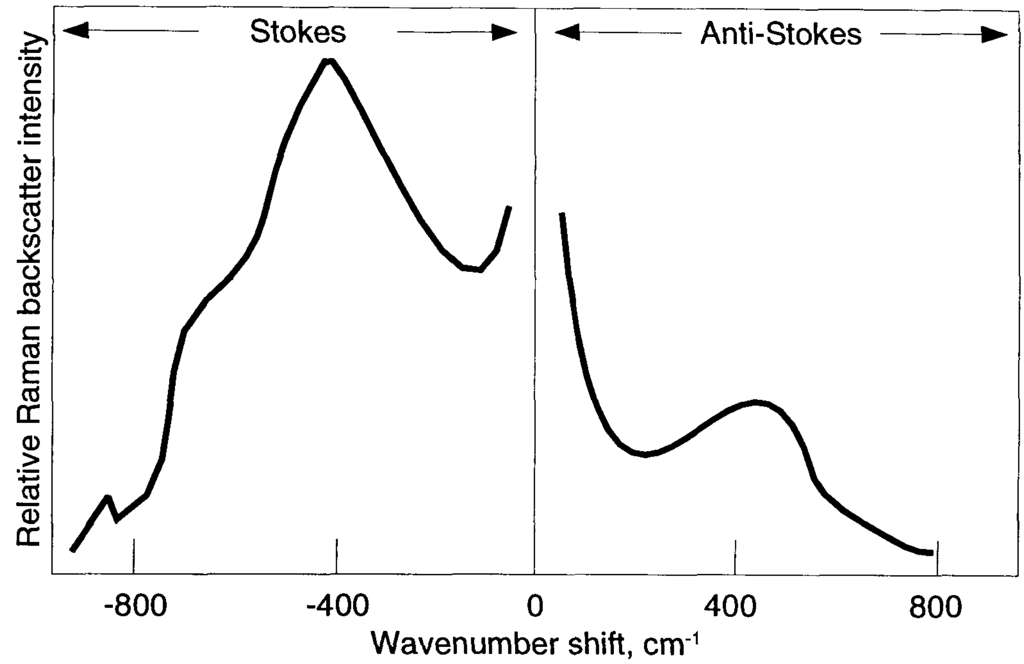

*Figure 1 Raman backscatter spectrum (l=514.5 nm, T=23°C). [11]*

*Tab. 1 : Intrinsic distributed sensing techniques and their determinable geohydraulic parameters*

| *Intrinsic Distributed Fibre Optic Sensing Technique* | | |
|---|---|---|
| *Rayleigh* | *Raman* | *Mode Coupling* |
| Strain Temperature | Temperature | Strain<br>Pressure<br>Temperature |

*Tab. 2 : Intrinsic sensors and their determinable geohydraulic parameters*

| *Intrinsic Fibre Optic Sensors* | | |
|---|---|---|
| *Microbend Sensors* | *Blackbody Sensors* | *Interferometric Sensors* |
| Strain<br>Pressure<br>Temperature | Temperature | Strain<br>Pressure<br>Temperature<br>Magnetic Fields<br>Electric Fields |

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