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Utilisation of pattern recognition techniques to interpret complex data from a multipoint optical fibre ethanol concentration sensor system

Damien King *, William B. Lyons, Colin Flanagan, Elfed Lewis

Optical Fibre Sensors Research Centre, Department of Electronic and Computer Engineering, University of Limerick, Castletroy, Limerick, Ireland

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Abstract

A multipoint optical fibre sensor system, capable of detecting various concentrations of ethanol in water is reported. The sensor system is based on a 500 m length of 62.5 μm diameter core silica clad silica core optical fibre and includes five sensing elements located along the fibre length. The sensing elements are based on evanescent wave absorption sensors and each sensor utilises a U-bend sensor configuration in order to maximise its sensitivity. The sensor system is interrogated using a technique known as optical time domain reflectometry, as this method is capable of measuring attenuation as a function of distance. Analysis of the data arising from the sensor system is performed using artificial neural network pattern recognition techniques, coupled with discrete Fourier transform-based signal processing. The signal processing techniques are applied to the obtained sensor system data, prior to the artificial neural network analysis, with the aim of reducing the computational resources required by the implemented artificial neural network in software.

Keywords: Artificial neural networks; Discrete Fourier transform; Measurement; Multipoint optical fibre sensor system; Optical time domain reflectometry; Pattern recognition

1. Introduction

The main drive of the present research in the area of optical fibre sensors in the water industry is to produce a range of optical fibre-based sensing techniques, preferably on a single optical fibre, which can be used for a variety of different sensing purposes and at the same time compete with existing conventional sensing methods. Optical fibre sensors also have a series of characteristics that are familiar: they are compact, lightweight and in general minimally invasive, as well as offering the prospect of multiplexing numerous sensors effectively onto a single fibre network. Additionally, all sensors should be immune to external electromagnetic interference as there are no electric signals present in the vicinity of the sensing points i.e. they are intrinsically safe. These properties, along with their capability for distributed or multipoint sensing, allow for the development of reliable and cost effective sensor systems that can be used in a wide range of application areas.

In this investigation, five evanescent field absorption sensors have been incorporated into a 500 m length of 62.5 μm core/125 μm cladding diameter silica clad silica (SCS) core optical fibre [1]. Each of the sensing elements comprises of a 3 cm section of the optical fibre for which the buffer and cladding have been removed and the core of the optical fibre is exposed directly to a measurand. In order to maximise the sensitivity of the sensing region of the fibre, a U-bend sensor configuration was utilised to increase the evanescent field penetration at the sensing region [2]. The U-bend sensors were located at 87 m, 215 m, 307 m, 397 m and 436 m, respectively, from the launch end of the fibre. This investigation is an advancement on work previously reported by King et al. [3], which was based on polymer clad silica (PCS) fibre in which the system attenuation losses were higher. With the reduced losses of the present system, the optical power budget available at the launch end of the fibre is capable of accommodating more sensors than previously implemented using the PCS fibre. The interrogation of such a sensor system uses an established technique known as Optical Time Domain Reflectometry (OTDR), which was first reported by Barnoski and Jensen in 1976 [4].

* Corresponding author. Tel.: +353 61 213558; fax: +353 61 202572.
E-mail address: damien.king@ul.ie (D. King).

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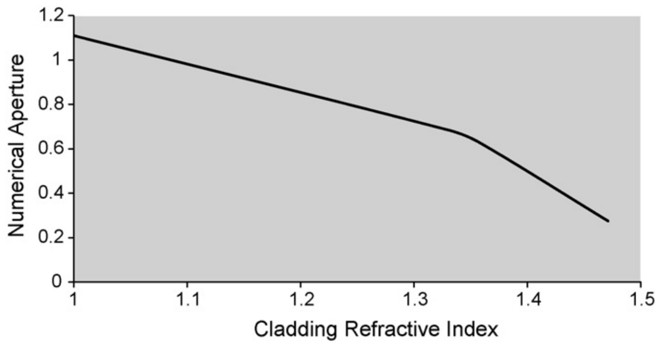

Fig. 1. Variation in numerical aperture caused by variation in the refractive index of the cladding due to the presence of a measurand. (a) Fibre bend mounting fixture used for the production of U-bend sensing elements, showing an initial wide bend as the first step of the U-bend sensor fabrication process. (b) Final stage of the bending procedure with the fixed and moveable ends of the fibre mounted parallel to each other.

Optical fibre sensor signals can often be complex and cross coupling of signals from external parameters e.g. temperature (the true measurand) and strain or microbending (interfering parameters in this case), adds to the difficulty interpreting data from such systems. It has been proposed that for many applications of optical fibre sensors, artificial neural network (ANN) pattern recognition techniques may be used to resolve the problems arising from cross-sensitivity to other parameters [5]. In this investigation, ANN pattern recognition techniques are coupled with signal processing techniques, based on the discrete Fourier transform (DFT), in order to accurately classify the sensor's test conditions. Test results and analysis are presented for multipoint sensor tests incorporating combinations of sensor immersion in 12.5% ethanol, 25% ethanol and 50% ethanol.

2. Sensor theory

In this investigation the sensors were incorporated on a 500 m length of 62.5 μm core diameter silica clad silica (SCS) optical fibre, where the cladding was removed and the core exposed directly to the measurand. In practice, however, the refractive index of the measurand in the sensing region (e.g. in this investigation, 12.5% ethanol ($n_2 = 1.3391$), 25% ethanol ($n_2 = 1.3462$) and 50% ethanol ($n_2 = 1.359$)) is less than the refractive index of the fibre's original cladding ($n_2 = 1.471$ and $n_1 = 1.496$ for the SCS fibre). This results in a sensing region with a numerical aperture[1] (NA) greater than that of the fibre, Fig. 1 and Table 1, for the fibre used in this investigation.

If the sensing region of the fibre remains straight and uniform in diameter, the critical angle (with respect to the normal in the core–cladding interface) of the fibre is higher than that for the sensing region of the fibre. This results in the inability of θ of a guided ray in the fibre to approach the critical angle, θ_c, within the sensing region. This limits the achievable evanescent field penetration in the sensing region and as a result also limits the sensitivity of the sensor.

[1] $\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$.

Table 1
Variation in numerical aperture caused by variation in the refractive index of the cladding due to the presence of a measurand

Cladding material	Cladding refractive index, n_2	Numerical aperture, NA
Silica	1.471	0.275
50% ethanol	1.359	0.625
25% ethanol	1.3462	0.653
12.5% ethanol	1.3391	0.666
Air	1	1.11

Numerous techniques have been reported that can increase the sensitivity at a sensing region:

- *selective launching conditions*: the sensitivity of the sensing region is increased by launching only those rays which make angles close to the critical angle of the sensing region [6];
- *tapering of the sensing region*: the angle of a ray approaches the critical angle at the sensing region of the fibre as it propagates [7,8];
- *bending of the sensing region*: the angle of a ray can be brought close to the critical angle of the sensing region if the sensing region of the fibre is curved in shape [2,9].

Although all three methods listed have been shown to offer sensitivity gains in comparison to a straight sensor configuration [6–9], the bending approach was selected in this investigation. Multimode graded index fibre is used in this investigation and due to the fact that modes within a graded index fibre settle down quickly with distance propagated (in comparison to a step index fibre); it was deemed that a selective launching configuration would not be advantageous in this research.

Gupta et al. [6] compared a straight sensing region to (a) a tapered sensing region, (b) selective launching conditions and (c) a combination of both tapering and selective launching conditions. It was noted that (a) a tapered sensing region offered 2.36 times the sensitivity of a straight sensing region, (b) selective launching offered a sensitivity gain of 2.89 and (c) a combination of both techniques provided a sensitivity increase of 7.55 times the sensitivity of a straight sensor. However, a further report by Gupta et al. [2,9] showed that a U-bend sensor configuration offered a sensitivity increase of approximately 70 times that of a straight sensing configuration, and due to this significant sensitivity increase provided by a U-bend sensor, the bending approach was adopted in this investigation.

The operation of the sensor is based on the modulation of the light intensity propagating in the fibre by the measurand as a result of the interaction with the evanescent field penetrating into the absorbing measurand. The evanescent field absorption, for a given length of the unclad fibre, depends on the number of ray reflections per unit length of the unclad fibre, N and the penetration depth of the evanescent field in the sensing region, d_p, which are defined as [10]:

$$N = \frac{\cot\theta}{2\rho} \tag{2.1}$$