Design of Hetero-core Smart Fiber Optic Macrobend Sensors

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Abstract

This paper presents a design technique for smart hetero-core fiber optic macrobend displacement sensors using Artificial Neural Networks. Experimental results for several macrobend displacement sensors are used for measuring the ability of Artificial Neural Networks (ANNs) to predict sensor measurand. Multilayer Perceptron algorithm was used as an ANN model. It is shown that all the algorithms are able to predict the displacement values with acceptable errors. Furthermore, a smart sensor architecture composed of multiple macrobend sensors using ANNs is proposed.

1. Introduction

Fiber optic sensors have been widely used and employed by many researchers in recent years. They can be used to observe different types of parameters such as strain, temperature, vibration, deformation etc. Fiber optic sensors have many advantages over traditional sensors. They have immunity to electromagnetic interference that eliminates the problems of lightning strikes and electrical hazards. Because of their small size, they can be placed in structural materials without degrading structural integrity. Also fiber sensors can run at high and low temperatures; therefore they can be embedded in composite materials. Moreover, a series of parameters can be sensed along the same fiber line.

Among many different fiber optic sensors, evanescent wave sensing is one of the successful ones. They are fabricated by etching some portion of the cladding layer. Despite its power to sense especially chemical measurands, it is very difficult to control the etching depth and length. Hetero-core fiber optic sensors are alternatives to etched structures with easy fabrication and ease of handling. Hetero-core fiber optic sensors, which have different applications in chemical measurement, displacement measurement and vibration measurement [1-3], have been developed in 2000s.

Fiber optic sensors based on bending effects are macrobending and microbending fiber optic sensors. In macrobending sensors radius of curvature of the fiber is relatively larger than the radius of curvature of the fiber as compared to microbending sensors. Macrobending sensors are used in a wide variety of applications including the measurement of displacement, pressure and temperature.

Due to their fast real-time operation and learning abilities, Artificial Neural Networks (ANNs) are preferred as a computational paradigm in which a deterministic description of the computation is either complex or difficult to identify [4, 5]. Because of these characteristics, ANNs are effectively used in optical fiber technology in the development of intelligent fiber optic sensors [6], calibration [7] and the prediction of sensing parameters [8, 9].

Problems may occur in any part of the fiber optic macrobend sensor system during long-term sensing. If the normal measurement values of the macrobend sensor can be predicted and compared with the measurement values, fault tolerance of the sensor can be decreased and more robust sensors can be designed. The ability of monitoring and predicting possible abnormalities enables immediate condition awareness and ability to take action against changing conditions.

In order to predict the sensor measurement values of fiber optic macrobend sensors, it is necessary to perform lengthy and complex mathematical computations. To overcome these problems ANNs can be used, because they can generate appropriate outputs for given inputs without any necessity to mathematical formulations between input and output data. Hence, this can greatly simplify prediction problem.

In this paper, a design technique for smart hetero-core fiber optic macrobend displacement sensors using Artificial Neural Networks (ANNs) is presented. Experimental results for several macrobend displacement sensors are used for measuring the ability of ANNs to predict sensor measurand.

2. An Overview of Optical Fiber Macrobend Sensors

Extensive research has been carried out about the macrobending loss since 1970s. The earlier research was based on a simplified model of a single-mode fiber with a core and an infinite cladding without any plastic jacket. With this model and assuming the weak-guidance approximation, the transversal field distribution Ψ in a curved fiber can be obtained from the scalar formula:

$$\left[\nabla_T^2 + k^2 n_{eff}^2(x,y) - \gamma_0^2\right]\Psi = 0 \quad (1)$$

where k is propagation constant; x and y are local Cartesian coordinates in the bent fiber; $n_{eff}^2(x,y) = n^2(x,y)(1+\frac{2x}{R})$; n(x,y) is the straight fiber refractive index and γ_0 is the straight fiber LP_{01} propagation constant [10].

Another approach suggests a model with finite cladding and infinite lossless coating. According to this approach, the field transversal distribution can be expressed as:

$$\Psi(x,y)\begin{cases}\sum_{p=1}^{N}\{C_pB_i[X_{2,p}(x)]+R_pA_i[X_{2,p}(x)]\}\cos\beta_p y & a\le x\le x_h\\ \sum_{p=1}^{N}\{D_pB_i[X_{3,p}(x)]-iA_i[X_{3,p}(x)]\}\cos\beta_p y & b\le x<\infty\end{cases} \quad (2)$$

where A_i, B_i are Airy functions, $\beta_p=(2p-1)\pi/2h$,

$$X_{j,p}(x)=\left(\frac{kR}{2n_j^2}\right)^{\frac{2}{3}}\left[\frac{\gamma_0^2-k^2n_j^2+\beta_p^2}{k^2}-n_j^2\frac{2x}{R}\right] \quad (3)$$

for j=2,3 and C_p, R_p, D_p are unknown coefficients to be determined. In this approach, a good agreement was achieved between the theory and experimental results. Including the cladding/coating boundary to the equation improves the validity of the formula [11].

One of the most recent approaches uses conformal mapping to calculate the bend loss in step-index, single-mode and multimode fibers to obtain a formula which is accurate if the mode field distribution of the bent waveguide is known. The first step is to express the curved fiber with an equivalent straight fiber by the conformal mapping method. After this, the modified refractive index becomes:

$$n' = n_{material}\exp\left(\frac{x}{R}\right)\cong n_{material}\left(1+\frac{x}{R}\right) \quad (4)$$

where $n_{material}(x,y)$ is the refractive index of the bent waveguide cross-section, and the exponential term expresses the increase in optical path length along the fiber with distance from the center of curvature. In addition, compression along the inner half of the fiber causes the refractive index to change according to the formula:

$$n_{material}=n\left[1-\frac{n^2x}{2R}[P_{12}-v(P_{11}+P_{12})]\right] \quad (5)$$

where v is Poisson's ratio, and P_{11} and P_{12} are components of the photoelastic tensor. Combining Eq. (4) and (5), we obtain:

$$R_{eff}\equiv\frac{R}{1-\frac{n^2}{2}[P_{12}-v(P_{11}+P_{12})]} \quad (6)$$

where R_{eff} is the equivalent bend radius. Simplifying Eq. (6) leads to:

$$n' = n\left(1+\frac{x}{R_{eff}}\right) \quad (7)$$

With this formula, it is not difficult to simulate the propagation of the modes. The theoretical results for both single-mode and multimode fibers have shown many agreements for high and fundamental modes with the experimental results [12].

3. Hetero-core Fiber Optic Macrobend Displacement Sensors

Hetero-core optical fibers are fabricated by inserting a small portion of fiber with a smaller core diameter into two identical fibers with larger core diameters which is illustrated in Fig. 1 The cladding diameters of the fibers should be the same. The insertion process is called splicing. Fusion splicing is the technique that uses heat to melt the fiber ends and glue them together. The device used for this purpose is fusion splicer. The evanescent field appearing in the hetero-core portion leaks from the cladding, when bending is given to the entrance or exit of the hetero-core region. The principle behind the phenomenon is the same with the evanescent wave sensors, but hetero-core optical fibers are easier to fabricate, since control of section length is easier compared to etching.

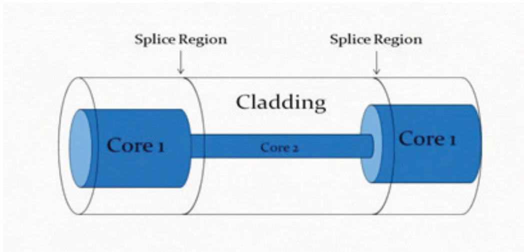

Fig. 1. Hetero-core optical fiber structure.

Using hetero-core phenomena hetero-core fiber optic sensors are designed. Hetero-core fiber optic sensors have great sensitivity because of the mode coupling taking place at the splice region. Since some of the power is coupled to the cladding, the leakage gets easier by an external effect which is to be detected. Since there is a great difference in core diameters, light can largely leak into the cladding part after the splice. Because of this structure, the light in the cladding may be affected by environmental conditions easily.

The experimental setup for the macrobend displacement sensor is shown in Figure 2. The macrobend sensor is composed of two wooden plates, and a rail system for adjusting displacement. The setup has been designed such that one of the wooden plates is stable and the other one is movable on the rail system. The inner section of the hetero-core fiber is fixed on the two wooden plates to form a half circle. The half circle establishes the desired macrobending.

Displacement measurements were accomplished by moving the movable plate on the rail system at 1 mm intervals and measuring the output light intensity at each interval as a function of applied displacement.

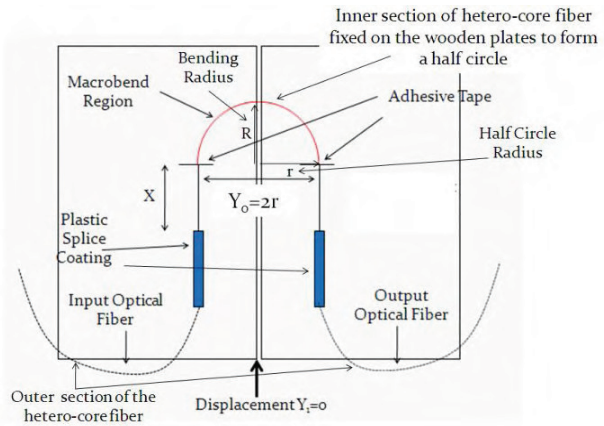

Fig. 2. Experimental setup for hetero-core fiber optic macrobend displacement sensor.

4. Design of Hetero-core Fiber Optic Macrobend Sensors Using Artificial Neural Networks

Problems may occur in the fiber optic macrobend sensor system during long-term sensing. If the normal measurement values of the macrobend sensor can be predicted and compared with the measurement values, fault tolerance of the sensor can be decreased and more robust sensors can be designed. The ability of monitoring and predicting possible abnormalities enables immediate condition awareness and ability to take action against changing conditions.

Artificial Neural Networks (ANNs) are one of the most useful predicting tools that have been widely used due to their computational speed, ability to handle complex functions, and great efficiency. ANNs are mainly used for classification, function approximation, clustering and regression. ANNs have different types of models. Feed forward neural networks, which are also called Multi Layer Perceptron (MLP), are the most popular model used in many applications. MLP is chosen in this work since it has many useful properties for prediction problems. It has a relatively simple structure and backpropagation algorithms are implemented in many problems [13]. Backpropagation is the generalization of the Widrow-Hoff learning rule to multiple layer networks and nonlinear differentiable transfer functions.

Standard backpropagation is a gradient descent algorithm. Backpropagation is the manner that gradient is computed for nonlinear multilayer networks. There are many algorithms based on other optimization techniques, such as conjugate gradient and Newton methods. In this work, conjugate gradient algorithms such as Fletcher-Reeves Update (FRU), Polak-Ribiere Update (PRU) and Powell-Beale Restart (PBR) are used. In the conjugate gradient algorithms, a search is executed along conjugate directions, which creates generally fast convergence [14].

These algorithms are utilized to predict displacement values measured by fiber optic hetero-core macrobend sensors. Normalized intensity and displacement are the input and output variables of ANN models, respectively. Displacement values can be predicted using normalized intensity values.

The network is trained and tested by training and testing dataset consisting of randomly selected experimental normalized intensity vs. displacement values. Displacement values are predicted for unseen normalized intensity values, after the training process. Equal numbers of hidden neurons are used in all process.

Each network was trained with eleven dataset before testing. The performance of the algorithms used in the network was compared in terms of their mean square errors (MSEs). The training MSEs results of MLP algorithms are shown in Table 1. These results show that Fletcher-Reeves Update algorithm has the smallest MSE value.

Table 1. The MSEs of different training algorithms.

Algorithm		Mean Square Error (MSE)
Multi Layer Perceptron	Fletcher-Reeves Update (FRU)	0.290
	Powell-Beale Restart (PBR)	0.291
	Polak-Ribiere Update (PRU)	0.293

The prediction performances of different ANN algorithms proposed in this work have been tested with four experimental dataset obtained from the experiments. The comparisons of the displacement values measured by fiber optic hetero-core macrobend sensor and the ANN model outputs (predicted displacement values) are shown in Table 2. From this comparison, it can be observed that PRU has the smallest test MSE value. The best (PRU) and the worst (FRU) ANN outputs with respect to MSEs are graphically compared with the experimental results shown in Figure 3. From these results, it can be observed that all the algorithms are able to predict displacement values with small errors.

Table 2. Comparison of the displacement values and the ANN outputs.

Normalized Intensity	Displacement (mm)	ANN Model Outputs		
		FRU	PBR	PRU
0.781	1	0.701	0.702	0.692
0.862	5	5.293	5.282	5.269
0.959	9	8.581	8.606	8.465
0.989	12	11.659	11.655	11.816
	MSE	**0.116**	**0.111**	**0.107**

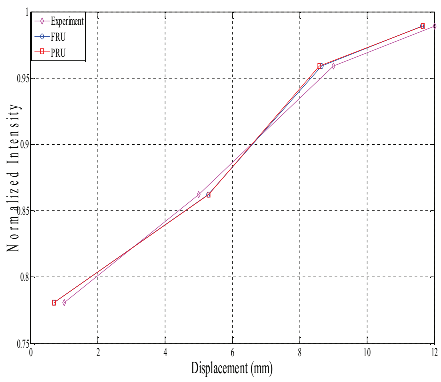

Fig. 3. Comparisons of the best and the worst ANN outputs with experimental displacement values.

From the above results, it can be concluded that ANNs can be used for designing smart sensors. Figure 4 shows a smart sensor architecture with multiple sensors. Using the smart sensor architecture, more reliable sensor measurand values can be obtained.

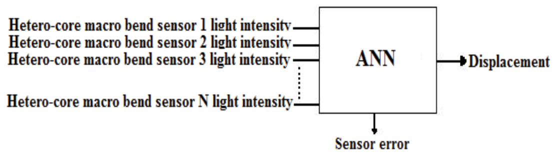

Fig. 4. Smart sensor architecture with multiple sensors.

5. Conclusions

In this paper, a design technique for smart hetero-core fiber optic macrobend displacement sensors using Artificial Neural Networks was presented. Experimental results for several macrobend displacement sensors were used for measuring the ability of Artificial Neural Networks (ANNs) to predict sensor measurand. It was shown that, the three conjugate gradient algorithms by Fletcher-Reeves Update (FRU), Polak-Ribiere Update (PRU) and Powell-Beale Restart (PBR) were able to predict the displacement values with acceptable errors.

5. References

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