AFRICAN MULTIDISCIPLINARY JOURNAL OF DEVELOPMENT (AMJD) VOL.10, ISSUE 3, 2021

The Optical Fibre Sensor: A Theoretical and Experimental View

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ABSTRACT

Fibre Optic Sensors are a fast-growing technology in recent years, and this area of photonics cuts across various aspects of life. Its prominent features enable it to stand out from other conventional methods of sensing, making them unique for various applications. In this study, a technique was developed to measure vibration along a fibre cable when there was an external/environmental perturbation. Metal analysis technique was employed which resulted in the derivation of the mathematical equation of light intensity in a fibre using the general Helmholtz equation. It was observed from the equation that light intensity, when perturbed, can cause a change in the phase as light travels through the fibre. The data obtained showed an increase in attenuation (loss) in the fibre cable when it undergoes perturbation, which is as a result of vibration. It is also observed that there is a phase shift, which is recorded by the OTDR as described in the theory (mathematical equation). The result obtained from this study shows that vibration can be measured by means of a fibre optic sensor using this technique, and the measured data obtained conforms with the theoretical result and is found to be successful. Although multimode fibre is preferred to single-mode fibre for short distances when taking measurements, this technique can also be used to achieve this and further measure the frequency of vibration using an OTDR.

Keywords: Optical Fibre Sensor, Optical Time Domain Reflectometer, Optical Fibre Cable, Light Intensity, Vibration Sensor

1.0 Introduction

Optical fibre over the years has been the medium in fibre optic communication but recently, the technological advancement in photonics is very rapid compared to other technologies (such as opto-mechanics, electro-optics, optoelectronics), which has led to the use of fibre optics in various areas in science besides telecommunication; hence it is used as a sensor.

The various types of fibre include; single-mode (used in long-distance telecommunications applications) and multi-mode (used mostly for short distances). These fibres are arranged in bundles known as optical cables and the bundles are protected by a jacket, the cable's outer covering. A single optical fibre consists of core (the central part where the light travels), cladding (special additives surrounding the core), and buffer coating (plastic coating that guards the fibre from break and moisture). The cladding has a high index of refraction when compared to the core and hence, gives rise to total internal reflection.

Fibre optic sensing is facilitated by its salient features, which make it prominent among other sensing methods because of its immunity to electromagnetic interference (EMI), tolerance to high temperatures and corrosive environments, greater sensitivity, light weight and compact size, multifunctional and wide dynamic measuring range, multiplexing capabilities, resistant to harsh environment (Environmental Ruggedness), remote sensing capability, inherent safety and suitability for extreme vibration and explosive environments and quick response in sensing different chemical and physical variables (Casalicchio, 2009). The fibre optic sensor system is classified into; Intrinsic optical sensor (an optical fibre core used directly as a sensing device) and Extrinsic optical sensor (an external optical device connected to a fibre cable, which serves as the sensor and fibre is used as a transmitting medium). The intrinsic sensors require a single mode fibre to perform its operation because it has a narrow core diameter, while a multimode fibre is mostly used for the extrinsic optical sensor. A sensing device that converts vibration into electrical signals is called as vibration sensor (Zhang, 2007).

Due to the versatility of an optical fibre, this research study focuses on using optical fibre as a vibration sensor. This technique requires using an Optical Time Domain Reflectometer for measurement and a vibrating mechanism. Although other techniques exist, none has been made researched using an OTDR. A summary of the different optical fibre classifications is shown in the Table1.

Table 1: Different classifications of optical fibre sensors (revised)

Classification Based on the Working Principle	**Classification Based on the Spatial Positioning**	**Classification Based on the Measurement Parameters**
Intensity-modulated sensors: Detection through light power	Point sensors: Discrete points, different channels for each measurement	Physical sensors: Temp., strain, pressure, force, speed and displacement (amplitude) sensors, Acoustic and vibration sensors, humidity etc.
Phase-modulated (interferometric) sensors: Detection using the phase of the light beam	Distributed: Measurement is determined along a path, surface, or volume	Chemical sensors: pH content, gas sensors, liquid level, spectroscopic study, etc.
Polarimetric sensors: Detection of changes in the state of polarization of the light	Quasi-distributed: Variable measured at discrete points along an optical link	Biosensors: DNA, blood flow, glucose sensors etc.
Spectrometric sensors: Detection of changes in the wavelength change of the light	Integrated: Measurement integrated along an optical link giving a single value output	Chemical and Biosensors

Sheng-he (2009) reviewed the trend of modern sensors; it was discovered that in practice, the optical fibre used as an intrinsic sensor for vibration proved difficult when separating the various changes encountered from other physical quantities. It was rather used as a medium of transmission of light and other sensitive device to detect changes of the measured physical quantity and the light parameter modulated by sensitive components. Hisham K.H. (2018) reviewed the trends in optical fibre sensing technology, which emphasis the current state of optical interferometry and modulation techniques. The optical fibre classification based on the working principle/modulation was reviewed, which requires an external perturbation as light propagates along the fibre as stated above. Yang (2014) reviewed on optical fibre sensing technologies for industrial applications at National Engineering laboratory for Optical Fibre Sensing Technology (NEL-FOST). They further described the various applications of optical fibre sensor for structural health monitoring, high-speed railway monitoring and transformer temperature monitoring, which can either be point, distributed, quasi-distributed sensors.

Structural Health monitoring is essential in dealing with environmental degradation in modern civilization. In other to eradicate these anomalies, proper environmental monitoring is necessary in order to curb efficiently, safely, and effectively with resources, such as petroleum, natural gas, cultivated land, and others. To this end, various green technologies have been developed. Hang-Eun Joe *et al* (2018) also reviewed the various principles of optical fibre sensors for environmental monitoring based on their spatial positioning in detecting changes in industrial facilities under severe (harsh) conditions. As light travels through the fibre cable, the intensity is altered as the cable is perturbed. This study shows that vibration can affect light intensity in an optical fibre, and the perturbation caused by the vibration of light is explicitly derived from the Helmholtz equation to light intensity in an optical fibre. Hence, the light intensity is measured using an Optical Time Domain Reflectometer (OTDR).

2.0 Methodology

2.1 Theoretical Framework

The theory of light propagation in an optical fibre is a well-known equation originating from Maxwell's equation, which gives the Helmholtz Equation as stated below

$$\nabla^2\vec{E}(r) + K^2\vec{E}(r) = 0 \qquad (1)$$

This is regarded as Helmholtz Equation

Light in fibre optics propagation in cylindrical coordinates, hence we have;

$$\frac{d^2E(r)}{dr^2} + \frac{1}{r}\frac{dE(r)}{dr} + \frac{1}{r^2}\frac{d^2E(r)}{d\theta^2} + \frac{d^2E(r)}{dZ^2} + K^2E(r) = 0 \qquad (2)$$

Let $E(r,\theta,z) = R_{(r)}\theta_{(\theta)}Z_{(z)}$

Equation (2) can be rewritten as

$$\theta Z\frac{d^2R}{dr^2} + \frac{1}{r}\theta Z\frac{dR}{dr} + \frac{1}{r^2}RZ\frac{d^2E}{d\theta^2} + R\theta\frac{d^2E}{dZ^2} + K^2 = 0 \qquad (3)$$

Dividing through by $R\theta Z$, we have

$$\frac{1}{R}\frac{d^2R}{dr^2} + \frac{1}{Rr}\frac{dR}{dr} + \frac{1}{r^2\theta}\frac{d^2E}{d\theta^2} + \frac{1}{Z}\frac{d^2E}{dZ^2} + K^2 = 0 \qquad (4)$$

Using differentiation by parts, we have the following

Let; $\frac{1}{\theta}\frac{d^2E}{d\theta^2} = -n^2;\ \frac{1}{Z}\frac{d^2E}{dZ^2} = -\rho^2;$ (5)

where Z is $e^{\pm i\beta z}$ and where θ is given by $e^{\pm in\theta}$. Therefore θ is $\cos n\theta \pm i\sin n\theta$

Therefore,

$$\frac{1}{R}\frac{d^2R}{dr^2} + \frac{1}{Rr}\frac{dR}{dr} - \frac{n^2}{r^2} - \beta^2 + K^2 = 0 \quad (6)$$

This gives;

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left(K^2 - \beta^2 - \frac{n^2}{r^2}\right)R = 0 \quad (7)$$

Let $K^2 - \beta^2 = \gamma^2$ (8)

$$\frac{d^2R}{dr^2} + \frac{1}{r}\frac{dR}{dr} + \left(\gamma^2 - \frac{n^2}{r^2}\right)R += 0 \quad (9)$$

This is not the pure form of the Bessel's equation; we can make the substitution.

Let $\gamma r = \delta$ (10)

Using partial derivatives and dividing through by γ^2, we have

$$\frac{d^2R}{d\delta^2} + \frac{1}{\delta}\frac{dR}{d\delta} + \left(1 - \frac{n^2}{\delta^2}\right)R = 0 \quad (11)$$

This is the general form of the Bessel's equation, which has the solution;

$$R = AJ_n(r\gamma) + BJ_{-n}(r\gamma) \quad (12)$$

As r tends to infinity, the second term of the Bessel's equation tends to infinity. That is, $BJ_{-n}(r\gamma) \rightarrow 0$, hence, we have

$$R = AJ_n(r\gamma)\cos n\theta e^{-i\beta z} \quad (13)$$

Let $E(r, \theta, Z)$ represent the m term and $B(r, \theta, Z)$ represent the l term

Therefore,

$$E = A_m J_{n_m}(u_m r)\cos n_m \theta e^{-i\beta_m z} \quad (14)$$

Similarly,

$$B = A_l J_{n_l}(u_l r)\cos n_l \theta e^{-i\beta_l z} \quad (15)$$

Introducing the Poynting vector to determine the light intensity in a fibre cable

$$I = S_{av} = \frac{cE_{max}{}^2}{2\mu} \quad (16)$$

where $B_{max} = cE_{max}$ (17)

$$I = \frac{\varepsilon_o C}{2} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \cos n_m \theta \cos n_l \theta e^{-\beta_{ml} z} \quad (18)$$

As m and l take several values, we have (Awodu *et al.*, 2019; Lujo and Klokoc, 2008)

$$I = \frac{\varepsilon_o C}{2} \sum_{m=0}^{N} \sum_{l=0}^{N} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \cos n_m \theta \cos n_l \theta e^{-\beta_{ml} z} \quad (19)$$

This is regarded as light intensity in fibre cable, which gives rise to equation (20)

$$I = \frac{\varepsilon_o C}{2} \sum_{m=0}^{N} \sum_{l=0}^{N} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) \cos n_m \theta \cos n_l \theta e^{[-i(\Delta\beta_{ml} z - \Delta\emptyset_{ml})]} \quad (20)$$

where $e^{[-i(\Delta\beta_{ml} z)]}$ is change in propagation const. along the fibre as it experience perturbation

$e^{[-i(\Delta\emptyset_{ml})]}$ is change in phase in the multi-mode fibre

Recall from equations (7) and (8), β is light propagating the fibre core in forward and backward direction. Therefore, detecting the changes of output light intensity, the light intensity inside a multi-mode fibre can be represented as (Lujo and Klokoc, 2008);

$$I_{(r,\emptyset)} = \frac{1}{2} Y \sum_{m=o}^{M} \sum_{N=0}^{N} A_m A_N J_{n_m}(U_m r) J_{n_l}(U_l r) . \cos(n_m \emptyset) \cos(n_l \emptyset) e^{[-i(\Delta\beta_{ml} z - \Delta\emptyset_{ml})]} \quad (22)$$

When forcing function F(t) is applied, equation can be rewritten as;

$$I_i = A_i\{1 + B_i[\cos\delta_i] - F(t)\theta_i \sin(\delta_i)]\} \quad (23)$$

Therefore, change in light intensity resulting from an applied forcing function is given as

$$\Delta I_T = \left[\sum_{i=0}^{N} |C_i \sin(\delta_i)|\right] \left|\frac{dF_{(T)}}{dt}\right| \quad (24)$$

As light travels through a fibre cable, the intensity can be altered by external perturbation/disturbance on the cable. The change in light intensity caused by the vehicular movement is derived in equation (24). It is possible by determining the backscatter level resulting from the forcing function. As light incident on the impression caused by vehicle tyre, the OTDR measures the Rayleigh backscatter along the fibre cable. This implies that vibration can affect light intensity in fibre optics, and the excitation caused by vehicular movement is explicitly derived in equation (24).

2.2 Experimental Setup

Vibration measurement was carried out using the following materials; optical fibre cable SM, optical time domain reflectometer (OTDR), heavy duty truck, gasoline generator (3.5kvA), and flask shaker in this study. The technique required using OTDR for measurement in the fibre optic sensor has never been used, which prompted this research.

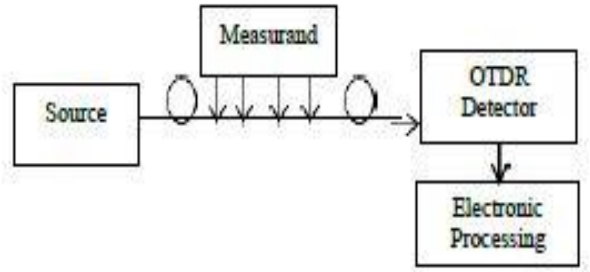

Figure 2.1: Schematic diagram of the setup

Light signal is sent through the fibre cable to the OTDR, which obtains the data, records the perturbed fibre. Data was recorded for fibre before and during perturbation, which are analyzed and duly shown in the results.

3.0 Results and Discussions

The data obtained showed the effect of environmental distortion causes a phase shift and a change in propagation in the fibre as light signal passes through it.

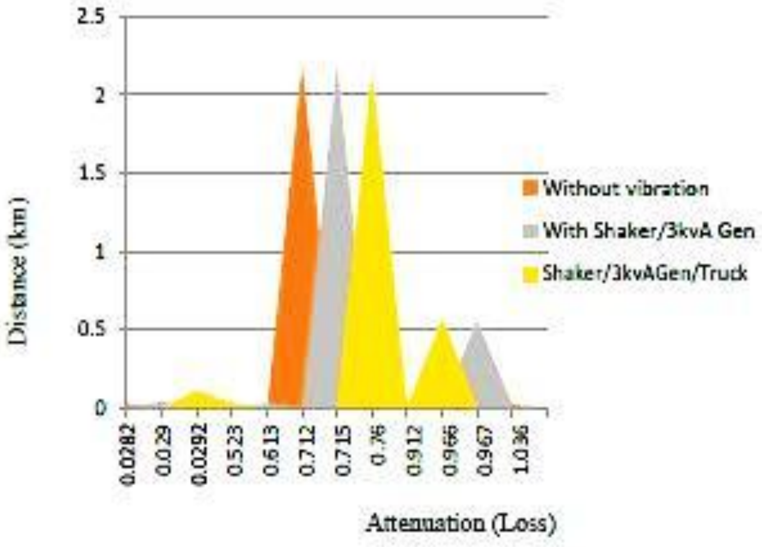

Figure 3.1: Graph showing the phase change caused by vibration

The data obtained showed increase in attenuation (loss) in the fibre cable when it under goes perturbation, which is as a result of vibration. It is also observed that there is a phase shift, which is recorded by the OTDR as described from the theory (mathematical equation).

4.0 Conclusion

- The result obtained from this study shows that vibration can be measured by means of a fibre optic sensor.
- This measured data obtained was compared with the theoretical result and found to be successful.
- Although multimode fibre is preferred to single-mode fibre for short distance when taken measurements, this study also showed that the technique can be possible to measure the frequency of vibration using an OTDR accurately.

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