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Vibration measurement of vehicular traffic at Oluku by Pass Bridge using Fibre Optic Sensor

Awodu OM[1], **Ukagwu KJ**[2], **Okuonghae T**[3], **Andikara JN**[4], **Azi SO**[5]

[1,3,4,5]Department of Physics, University of Benin, Benin City, Edo State, Nigeria.

[2]Kampala International University, Kampala, Uganda, Email: ceekay2yk@yahoo.com / ukagwu.john@kiu.ac.ug

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ABSTRACT

Optical fibres are made of silicon glass or plastic for transmitting light signal over long and short distances. Technological advancement in photonics has led to its use in fibre optic sensor (FOS), which has gained popularity in present day sensing technology due to its immunity to electromagnetic interference, resistance to environmental toughness, remote sensing capabilities amongst others. Fibre optic vibration sensor converts vibration signal to light signal. Although interest in FOS has greatly increased over the years in structural health monitoring and improved equipment maintenance, there are few publications in Africa and Nigeria to be specific in this area, hence the need to embark on this study.

A distributed fibre optic vibration measurement is employed to measure the frequency of vibration caused by uncontrolled vehicular movement at Oluku By-Pass Bridge. Optical Time Domain Reflectometer (OTDR) is used to obtain the nanoseconds snapshots of the stochastic signal arising there from. An expression for forced vibration on the multi-mode fibre caused by external perturbation was derived to obtain the phase shift and change in propagation of the signal. MATLAB software was used to transform the signal from space domain to frequency domain and hence carryout a comprehensive spectral analysis.

Data obtained show several frequency peaks at various corresponding backscatter level for high and low vehicular traffic. High attenuation contributed to low loss and low attenuation led to high loss. Two heavy trucks at opposite lanes indicate a large peak of

0.396Hz at backscatter level of -55dB, which corresponds to its high total loss. On the contrary, immense vehicular traffic resulted to several frequency peaks at backscatter level of -65dB and -70dB respectively. Conversely, trace signal with high reflectance had the signal buried in excess noise due to continuous excitation of the fibre.

Keywords: FOS, OTDR, Multimode fibre cable, stochastic signal, attenuation, spectral analysis

1. INTRODUCTION

Optical fibres are made of glass or plastic for transmitting light signal over long and short distances [1]. They are flexible strands, with the length roughly the diameter of a human hair. The various types of fibre include; single-mode which has a core to cladding diameter of 9/125microns in diameter (fibre that require a single propagation path and broadcast infrared laser light of wavelength 1300nm to 1550nm) and multi-mode has a core to cladding diameter of 62.5/125microns in diameter (fibres with several propagation paths or transverse modes and transmit infrared LED light of wavelength 850nm to 300nm) [2].

In recent years, fibre optics has found prominent use in sensor technology as an added advantage to its major applications in communication networks [3]. A sensing device that converts vibration into light signals is called as vibration sensor. Recently, FOS has gained increased popularity and market acceptance. In comparison to conventional sensors they offer a number of distinct advantages which makes them unique for certain types of applications, mainly areas where conventional sensors are difficult to function [4].

FOS is a sensor that uses an fibre optics as either a sensing element (Intrinsic sensor) or a means to transmits optical signal from a remote sensor to an electronic device (Extrinsic sensor) for processing [5][6]. It can be used to measure strain, temperature, pressure, and other quantities by modifying the fibre to suit the desired measurement in other to modulate light intensity, phase, polarization, wavelength and other parameters with fibre optic cable [7] (table 1).

Table 1 Fibre Optic Vibration Sensor Applications [7] [8] [9]

CLASSIFICATION	MEASUREMENT TECHNIQUE	MEASUREMENT PARAMETERS	WORKING PRINCIPLE	MEASURE TYPE	ADVANTAGES
Point Sensor	Interferometric: Fabry-Perot	Temperature, strain, pressure, displacement, refractive index etc.	Intensity/ phase	Intrinsic/ Extrinsic	High sensitivity but complex interrogation, limited multiplexing capacity, WDM is difficult.
	Mach-Zehnder	Temperature, strain, pressure, displacement, refractive index, etc.	Intensity/ phase	Intrinsic/ Extrinsic	Compactness and high efficiency combined with ease of fabrication, but complex interrogation
	Michelson	Temperature, strain, pressure, displacement, refractive index, etc.	Intensity/ phase	Intrinsic/ Extrinsic	High accuracy, compactness, good multiplexing capability, complex interrogation.
Quasi-distributed	Interferometric: Sagnac	Optical gyroscopes, strain, pressure, twist	Intensity/ phase	Intrinsic	Simple and easy to fabricate but suffer from the significant temperature strain cross-sensitivity.
	Fibre Bragg Gratings	Temperature, strain, pressure, can be configured to measure displacement, acceleration, etc.	Wavelength	Intrinsic	Excellent WDM capability, advantages of wavelength encoding but disadvantages of cross-sensitivity between strain and Temp.

Distributed	Rayleigh Scattering	Temperature, strain	Intensity (OTDR)	Intrinsic	High strain/temperature resolution and good spatial resolution, but limited length; Temp. compensation required
	Raman scattering	Temperature	Intensity (OTDR)	Intrinsic	Advantageous for temperature sensing only, since no particular packaging needed to make sensing fibre strain free
	Brillouin Scattering	Temperature, strain	Intensity (BOTDR)	Intrinsic	Advantage of relatively stronger signal but synchronization of two laser sources at the opposite ends of the fibre is required

Over the years, intensity-based sensor has evolved with several publications, which stimulates further interest. Due to the growing interest in structural health monitoring, the awareness of the dynamic characteristics of a bridge structure cannot be over-emphasized. The defects are as a result of heavy duty objects and wind constantly plying the bridge at certain momentum, which results to the deformation of the modal characteristics of the bridge structure. Hence the need for continuous monitoring of the bridge structure, as significant data obtained will contribute to a stable and safe operation of the bridge and can be used for the calibration of a structural numerical model [10] [11] [12].

In fibre optic sensor, phase OTDR has long been used to measure the vibration of a light signal. A phase OTDR and polarized OTDR has been used for vibration analysis to measure the signal to noise ratio, increased frequency response and phase signal demodulation [13] [14]. The data analyzed showed significant disturbance that resulted to variation in the analysis, with disturbance occurring at same and different frequencies over a long distance. FOS can also be used in for gas pipeline leakage monitoring in an oil and gas industry with the help of a Sagnac/Mach-Zehnder Interferometer configuration [15]. The design was used for a fibre length range of 1.5-9.5km, with the light intensity reducing to -56dB for pipeline with leakage and without leakage and the results yielded a positive response, with the vibration system having a sensitivity of 0.57Hz/m.

Conversely, most intensity based sensor are characterized using a fibre bragg grating but this work has shown that a conventional multimode fibre cable can be used along with an OTDR to measure vibration activities of an uncontrolled vehicular traffic at Oluku bypass bridge, Edo State, Nigeria.

2. METHODOLOGY

Theoretical Framework

In other to achieve a valid result, the light intensity propagation in a multimode fibre was derived from the well-known Helmholtz equation using the Bessel equation gives.

$$E = A_m J_{n_m}(u_m r) cos n_m \theta e^{-i\beta_m z} \quad (1)$$

Similarly,

$$B = A_l J_{n_l}(u_l r) cos n_l \theta e^{-i\beta_l z} \quad (2)$$

This gives the total light intensity in a multimode fibre as

$$I = \frac{\varepsilon_o C}{2} \sum_{m=0}^{N} \sum_{l=0}^{N} A_m A_l J_{n_m}(u_m r) J_{n_l}(u_l r) cos n_m \theta cos n_l \theta e^{[-i(\Delta\beta_{ml} z - \Delta\emptyset_{ml})]} \quad (3)$$

Therefore, detecting the changes of output light intensity, the light intensity inside a multimode fibre can be represented as [16];

$$I_{(r,\emptyset)} = \frac{1}{2} Y \sum_{m=o}^{M} \sum_{N=0}^{N} A_m A_N J_{n_m}(U_m r) J_{n_l}(U_l r) . \cos(n_m \emptyset) \cos(n_l \emptyset) e^{[-i(\Delta\beta_{ml} z - \Delta\emptyset_{ml})]} \quad (4)$$

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

$$I_i = A_i\{1 + B_i[cos\delta_i] - F(t)\theta_i \sin(\delta_i)]\} \quad (5)$$

Giving the change in detected intensity as

$$\Delta I_T = \left[\sum_{i=0}^{N} |C_i sin(\delta_i)|\right] \left|\frac{dF_{(T)}}{dt}\right| \quad (6)$$

As light travels through the fibre cable, the intensity is altered due to cable perturbation. This implies that vibration can affect light intensity in fibre optics, and the excitation caused by vehicular movement is explicitly derived in equation (6). Hence, the light intensity is measured using an OTDR. In other to calculate the power spectral density of the stochastic signal, a Parametric Model was used. This is considered when there is information about the signal being analyzed (examples include Yule-Walker model and Burg model). There are two (2) main methods, auto-regression (it assumes that the signal can be modeled as the output of an autoregressive filter) and subspace (it separates the signal into a signal subspace and noise subspace, thereby exploiting the orthogonality between the two subspaces which allows a pseudospectrum to be formed such that large peaks at narrowband components can appear) [17].

$$y(t) + \sum_{i=1}^{m} a_i y(t-i) = \sum_{j=0}^{m} b_j\, e(t-j), (b_0 = 1) \quad (7)$$

This gives an expectation value of;

$$r(k) + \sum_{i=1}^{m} a_i r(k-i) = \sum_{j=0}^{m} b_j\, E\{(t-j)y^*(t-k)\} \quad (8)$$

Equation gives rise to

$$r(k) + \sum_{i=1}^{n} a_i r(k-i) = \sigma^2 \sum_{j=0}^{m} b_j h_{j-k}^* \quad (9)$$

For Auto-regressive signal (AR), m = 0

Therefore; we have

$$r(k) + \sum_{i=1}^{n} a_i r(k-i) = \sigma^2 \quad (10)$$

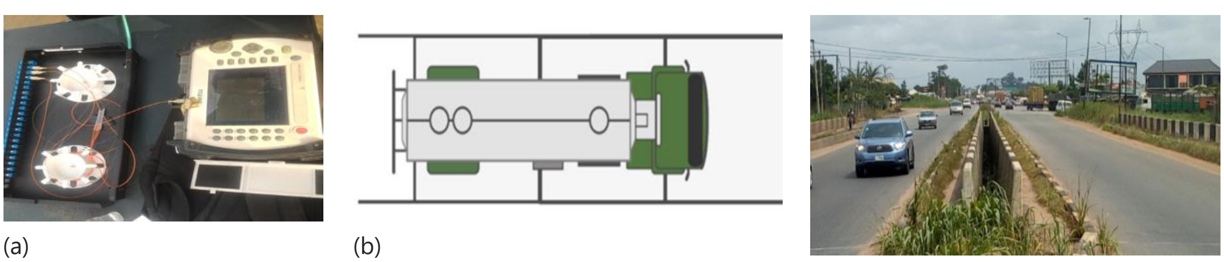
This gives a matrix set of$r_n + R_n\theta = 0$

The predicted coefficient θ = $(a_1, \ldots, a_n)$ and power, σ^2 = estimate of the spectrum

In determining the frequency of vibration caused by uncontrolled vehicular movement at distributed points of the fibre cable at Oluku By-Pass Bridge, a FOS technique is employed. Data were acquired using OTDR (Anritsu MT9083A1 Access Meter), a multimode fibre cable (of about 59 meters) and a patch panel.

Experiment

The experiment was carried out during a cycled Easter holiday, over a period of time and the results thereof (fig.1). This study is focused on the vibration measurement caused by vehicular movement using an OTDR to obtain the attenuation in an fibre optics. In other to achieve this, multimode fibre cable is attached to a patch panel and installed on a groove across the bridge.



(a) (b) (c)

Figure 1 Experimental setup

As light signal propagates through the fibre, vibration caused by vehicular movement creates a stochastic signal which is acquired with an OTDR and analyzed using appropriate software to calculate the power spectral density estimation (PSDE) of the stochastic signal. Multimode fibre cable (about 59m long) was attached to a patch panel and installed in the groove at the bridge. A short pulse of 10ns was sent from the OTDR into the fibre, while the vehicular movement OTDR recorded snapshots of the stochastic signal in the form of backscatter. The data was analyzed at every two (2) centimeters of the length laid across the bridge (about 32m) and the corresponding power level was obtained using Fiberizer Cloud software (163 data points) (fig. 2).

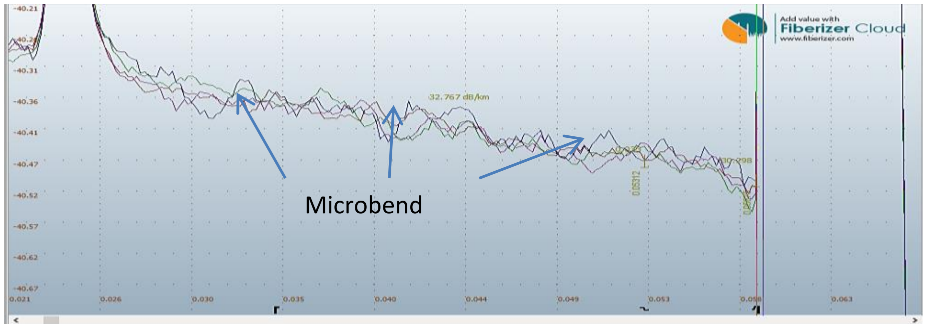


Figure 2 Fiberizer cloud indicating Backscatter (dB) level and distance (km)

3. RESULTS

Data obtained was characterized (low vehicular traffic, high vehicular traffic and heavy duty vehicles) and analyzed using MATLAB software to transform signals from space domain to frequency domain using the Fast Fourier Transform (FFT) as shown in the figure 3 & 4 below.

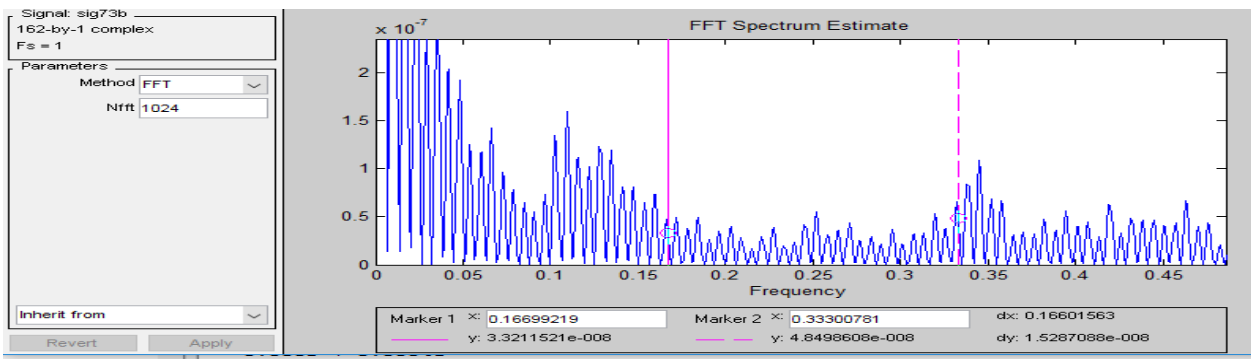
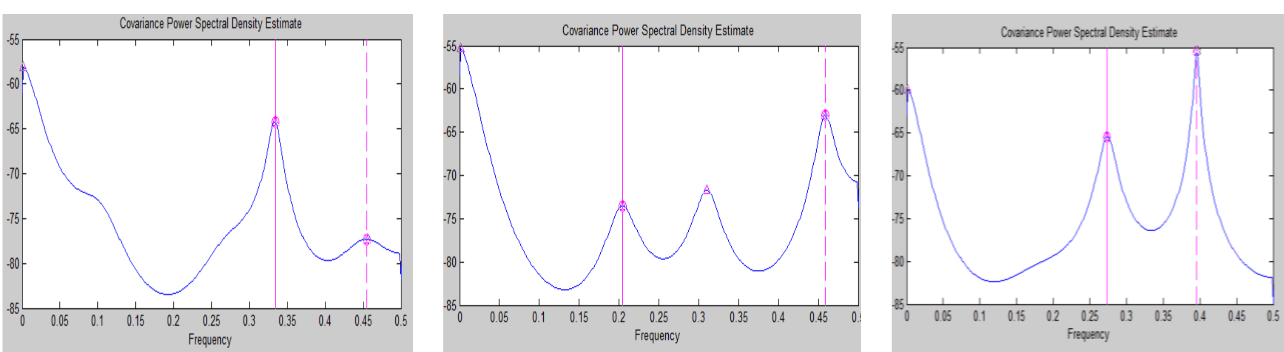


Figure 3 FFT of the signal

From the FFT, it is impossible to determine the dominant vibrating frequencies caused by vehicular movement, hence the need to carry out a comprehensive spectral analysis.



Low Vehicular Traffic High Vehicular Traffic Heavy Duty Vehicles

Figure 4 PSD for low and high vehicular traffic, heavy duty vehicles

This study shows that excitations caused by vehicular movement can be measured using OTDR in the form of backscatter. The measured reflectance range from -40.219dB and -40.535dB for different vehicular movements corresponds to the standard reflectance of -35dB or lower for a multimode fibre (FOA, 2015). The technique employed in this work measured the signal-to-noise ratio, frequency response and calculate the spectral analysis. In other to determine the spectral (frequency) content of the signal waveform, a covariance power spectral density with normalized sample frequency of 1Hz was used in this study and had dominant frequencies of 0.334, 0.395 and 0.455Hz for low vehicular traffic. Whereas, high vehicular traffic had frequency peaks of 0.204Hz, 0.311Hz and 0.459Hz at backscatter of -73.6dB, -75dB and -63dB respectively. Lastly, heavy duty vehicles had frequency peaks at 0.273Hz and 0.396Hz at backscatter levels of -65dB and -55dB respectively.

4. CONCLUSION

Most conventional vibration techniques have difficulty in detecting defaults using only its measured data due to its high signal-to-noise ratio and their limitation in frequency response. It is imperative to reduce the noise effect and obtain desired information of the measured signal. This study uses an OTDR to measure the attenuation of a stochastic signal caused by uncontrolled vehicular movement at distributed points on the fibre cable and calculated the spectral analysis of the signal. The power spectral density estimation (PSDE) characterizes the frequency content of the signal at corresponding backscatter level.

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