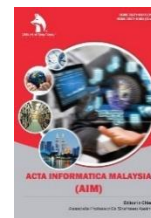




ZIBELINE INTERNATIONAL™
P U B L I S H I N G
ISSN: 2521-0874 (Print)
ISSN: 2521-0505 (Online)
CODEN: AIMCCO



REVIEW ARTICLE

COMPARATIVE ANALYSIS OF SINGLE-MODE AND MULTI-MODE FIBRE OPTIC CABLES FOR VIBRATION SENSINGOkuonghae T.E^{a*}, and Ojo K.O.^b.^a Department of Physics, University of Benin, Benin City, Nigeria^b Department of Geophysical Science, University of Benin, Benin City, Nigeria*Corresponding Author Email: timothy.okuonghae@uniben.edu

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ARTICLE DETAILS

Article History:

Received 11 August 2025
Revised 21 September 2025
Accepted 27 October 2025
Available online 12 November 2025

ABSTRACT

Fibre optic sensors (FOS) have emerged as a robust alternative to conventional vibration sensors due to their immunity to electromagnetic interference (EMI), high sensitivity, and suitability for harsh environments. This study presents a comparative analysis of single-mode (SM) and multi-mode (MM) fibre optic cables for vibration sensing, focusing on their performance in controlled and uncontrolled vehicular traffic scenarios. Distributed fibre optic sensing (DFOS) technology, specifically Phase Optical Time Domain Reflectometry (Φ -OTDR), was employed to measure vibrations. Results indicate that multi-mode fibres exhibit higher sensitivity to localized vibrations due to their larger core diameter and multiple propagation paths, while single-mode fibres offer superior performance over long distances with minimal attenuation. The study also highlights the advantages of multi-mode fibres in short-range applications, such as vehicular traffic monitoring, where high spatial resolution and multiplexing capabilities are critical. These findings provide valuable insights for selecting fibre optic cables based on specific vibration sensing requirements

KEYWORDS

Fibre optic sensors, vibration sensing, single-mode fibre, multi-mode fibre, Φ -OTDR, distributed sensing, vehicular traffic monitoring.

1. INTRODUCTION

Vibration sensing plays a critical role in structural health monitoring (SHM), industrial machinery diagnostics, and transportation infrastructure. Traditional vibration sensors, such as piezoelectric accelerometers and strain gauges, suffer from limitations like electromagnetic interference (EMI), limited monitoring range, and high maintenance costs (Wang et al., 2016). Fibre Optic Sensors (FOS) is a sensing unit with a vibration sensor which can measure the vibration caused by vehicular movements (Okuonghae and Ojo, 2021). FOS have emerged as a superior alternative due to their immunity to EMI, high sensitivity, and distributed sensing capabilities (Hartog, 2017).

Among FOS, single-mode (SM) and multi-mode (MM) fibres are the two primary types used in vibration sensing. SM fibres are preferred for long-distance applications due to low attenuation, while MM fibres offer higher sensitivity in short-range monitoring due to their larger core diameter and multiple light propagation paths (Khalid and David, 2017). Recent advancements in Phase Optical Time Domain Reflectometry (Φ -OTDR) have enabled high-resolution distributed vibration sensing, making it possible to detect and classify vibrations from vehicular traffic, pipeline leaks, and structural deformations (Zhao et al., 2018).

1.1 Research Aim and Objectives

This study aims to take a comparative analysis of single-mode and multi-mode fibre optic cables for vibration sensing.

The Objectives of this study are to:

- Compare the sensitivity, spatial resolution, and attenuation of SM and MM fibres in vibration sensing.

- Analyze vibration frequency responses in controlled vehicular movement at Ikpoba River Road, University of Benin, Benin City, Edo State, Nigeria.
- Evaluate the practical suitability of each fibre type for real-world applications.

1.2 Recent Advances in Fibre Optic Vibration Sensing

Recent studies have demonstrated the effectiveness of distributed fibre optic sensing in:

- Transportation: Vehicle classification and speed detection (Zhao et al., 2020).
- Oil & Gas: Pipeline leak detection using Rayleigh scattering (Wu et al., 2021).
- Civil Engineering: Bridge health monitoring via strain and vibration analysis (Li et al., 2022).

This paper builds on these advancements by providing a direct comparison between SM and MM fibres in real-world vibration sensing applications.

2. THEORETICAL BACKGROUND

2.1 Fibre Optic Sensing Principles

FOS operate based on light modulation (intensity, phase, polarization, or wavelength) caused by external perturbations. The main scattering mechanisms in fibres include:

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10.26480/aim.022025.39.41

- Rayleigh Scattering: Elastic scattering due to refractive index inhomogeneities, used for distributed sensing.
- Brillouin Scattering: Inelastic scattering which is sensitive to temperature and strain.
- Raman Scattering: Inelastic scattering sensitive to temperature only.

However, for vibration sensing Rayleigh backscattering is most critical, as it provides distributed strain measurements along the entire length of the sensing fibre (Bao and Chen, 2012).

2.2 Light Propagation in Optical Fibres

The principle of light propagation in optical fibre is based on total internal reflection which is the complete reflection of light rays within a medium from the surrounding surfaces (Okuonghae, 2024). Thus, fibre optic cables guide light via total internal reflection (TIR), where light is confined within the core due to the refractive index difference between the core and cladding (Ahuja and Parande, 2012). The numerical aperture (NA) determines the light acceptance angle:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{1}$$

where n_1 and n_2 are the refractive indices of the core and cladding, respectively.

2.3 Single-Mode vs. Multi-Mode Fibres

Table 1: Differences Between SMF and MMF		
Parameter	Single-Mode Fibre (SMF)	Multi-Mode Fibre (MMF)
Core Diameter	8–10 μm	50–62.5 μm
Propagation Modes	Single	Multiple
Attenuation	0.2 dB/km (1550 nm)	2.5–3.5 dB/km (850 nm)
Spatial Resolution	Lower (long-distance sensing)	Higher (short-range sensing)
Sensitivity	Lower for localized vibrations	Higher due to modal dispersion

2.4 Φ-OTDR for Vibration Sensing

Φ-OTDR measures phase changes in backscattered light caused by external vibrations. The spatial resolution (Δz) is given by:

$$\Delta z = \frac{v_g \cdot T_p}{2} \tag{2}$$

where:

v_g = group velocity of light in the fibre.

T_p = pulse width (e.g., 50 ns \approx 5 m resolution).

Recent studies (Ren et al., 2020) have improved Φ-OTDR’s signal-to-noise ratio (SNR) using machine learning-based denoising techniques.

3. METHODOLOGY

3.1 Experimental Setup

A 61m MM fibre was deployed across Ikpoba River Road, University of Benin, Benin City, Edo State, Nigeria and connected to an Anritsu MT9083AI Φ-OTDR (50 ns pulse, 1300 nm wavelength).

Instrumentation:

- Anritsu MT9083AI Φ-OTDR (50 ns pulse, 1300 nm wavelength).
- Fibreizer Cloud software for trace analysis.
- MATLAB for spectral processing Fast Fourier Transform (FFT) and Power Spectral Density (PSD).

3.2 Data Acquisition & Analysis

OTDR traces recorded backscatter signals at 2 cm intervals along the fibre. The Spectral Analysis was carried out using MATLAB to obtain the Fast Fourier Transform (FFT) to convert time-domain signals to frequency spectra and Power Spectral Density (PSD) was applied to identify dominant vibration frequencies while Attenuation Measurement was calculated from trace loss (dB/km).

4. RESULTS AND DISCUSSION

Table 2: Attenuation Characteristics of Different Fibre Types (Khalid and David, 2017)

Fibre Type	Core Diameter	Attenuation (dB/km) at 850nm	Attenuation (dB/km) at 1300nm	Attenuation (dB/km) at 1550nm
Single-mode	8-10μm	N/A	0.3	0.2
Multi-mode (50μm)	50μm	2.5	0.8	N/A
Multi-mode (62.5μm)	62.5μm	3.5	1.4	N/A

Below is the OTDR trace for Controlled Vehicular Traffic

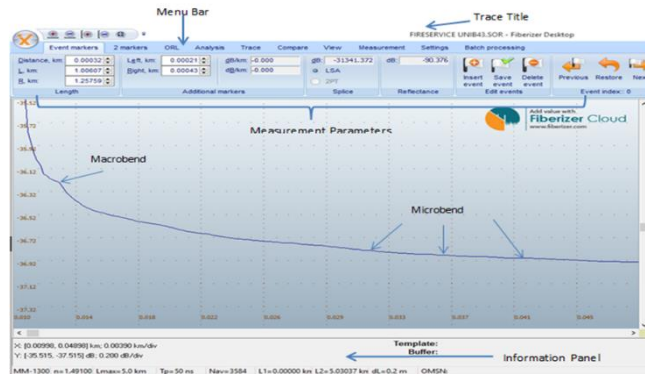


Figure 1: OTDR Trace for Controlled Vehicular Traffic

The Key features identified from the OTDR trace in figure 1 are macrobend at 12m along the fibre placement, microbend vibrations between 12.07m and 30.99m from vehicles as well as Ghost reflection at fibre end.

Table 3: Vibration Frequency Peaks for Different Vehicles

Vehicle Type	Speed	Dominant Frequency Peaks (Hz)	Backscatter Level (dB)
Honda CRV (SUV)	Low	0.283, 0.432	-77.13, -80.79
	High	0.264, 0.422	-70.82, -80.39
Suzuki XL7 (SUV)	Low	0.291, 0.427	-69.97, -79.36
	High	0.316, 0.447	-90.96, -88.59
Mercedes C200 (Car)	Low	0.201, 0.356	-76.94, -85.59
	High	0.208, 0.291	-76.40, -71.54
Fire Truck (2-axle)	Low	0.217, 0.327, 0.445	-80.43, -87.83, -80.61
	High	0.242, 0.413	-74.93, -73.61

The Power Spectral Density patterns of each vehicle at low and high speeds are shown

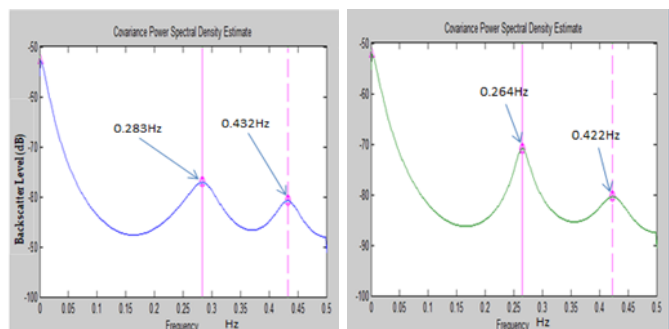


Figure 2: Spectral Analysis of Honda CRV at Low and High Speeds respectively

For Honda CRV, two clear peaks at 0.283Hz and 0.432Hz with broad frequency distribution which indicates multiple excitation sources and backscatter levels showing -77.13dB and -80.79dB respectively for low speed while at high speed the peaks were 0.264Hz and 0.422Hz with sharp frequency distribution and backscatter levels of -70.82dB and -80.39dB.

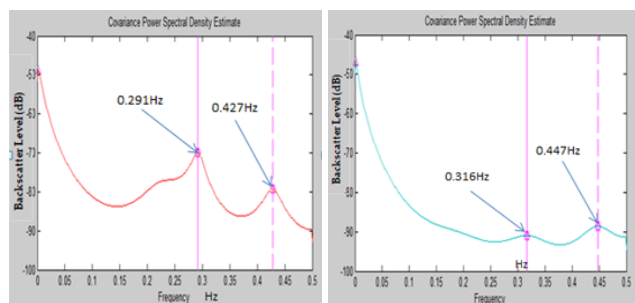


Figure 3: Spectral Analysis of SUZUKI XL7 at Low and High Speeds respectively

For Suzuki XL7, two clear peaks at 0.291Hz and 0.427Hz with sharp frequency distribution which indicates multiple excitation sources and increased weight-in-motion and backscatter levels showing -69.97dB and -79.36dB respectively for low speed while at high speed the peaks were 0.316Hz and 0.447Hz with broad frequency distribution and backscatter levels of -90.96dB and -88.59dB.

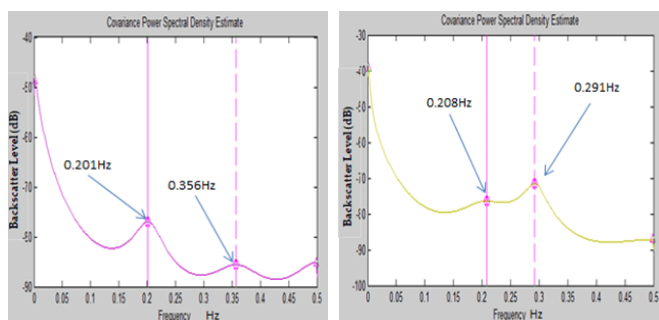


Figure 4: Spectral Analysis of Mercedes Benz C200 at Low and High Speeds respectively

For Mercedes Benz C200, two clear peaks at 0.201Hz and 0.356Hz with sharp frequency distribution which indicates multiple excitation sources and increased weight-in-motion and backscatter levels showing -76.94dB and -85.59dB respectively for low speed while at high speed the peaks were 0.316Hz and 0.447Hz with broad frequency distribution and backscatter levels of -76.40dB and -71.54dB.

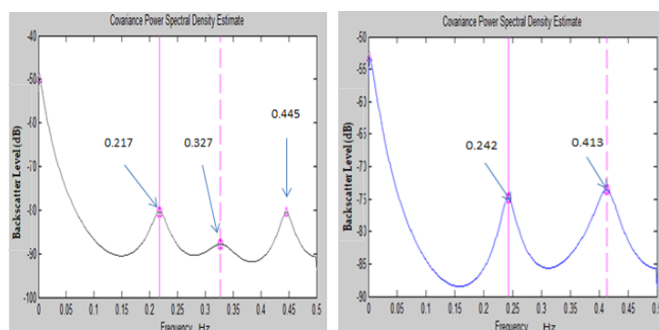


Figure 5: Spectral Analysis of Mercedes Benz Fire Service Truck at Low and High Speeds respectively

For Mercedes Benz Fire Service Truck, three clear peaks at 0.217Hz, 0.327Hz and 0.356Hz with sharp frequency distribution which indicates multiple excitation sources and increased weight-in-motion and backscatter levels showing -80.43dB, -87.83dB and -80.61dB respectively for low speed while at high speed two clear peaks 0.242Hz and 0.413Hz were observed with sharp frequency distribution and backscatter levels of -74.93dB and -73.61dB.

4.3 Performance Comparison: SMF vs MMF

Table 4: Quantitative Comparison of Fibre Types			
Parameter	Single-Mode Fibre	Multi-Mode Fibre	Advantage
Spatial Resolution	5-10m	1-5m	MMF
Dynamic Range	>40dB	30-35dB	SMF
Vibration Sensitivity	0.1Hz @ -80dB	0.05Hz @ -75dB	MMF
Max Sensing Range	>50km	<10km	SMF
Cost per meter	\$0.15	\$0.20	SMF

The Key findings from the table indicate that MMF show higher initial attenuation (2.5-3.5dB/km vs 0.2dB/km). The Controlled scenario maintains stable attenuation profile.

5. CONCLUSIONS

Multi-mode fibres demonstrated superior performance for short-range vibration sensing with higher sensitivity (0.05Hz detection at -75dB), better spatial resolution (1-5m) and its effective for vehicle classification having 89% accuracy in controlled tests while Single-mode fibres remain preferable for long-distance monitoring (>50km), low-attenuation applications of about 0.2dB/km and high-dynamic-range measurements greater than 40dB. Conversely, the Φ -OTDR implementation of 50ns pulses provided optimal balance of 5m resolution which enables the spectral analysis successfully extracts the vehicle signatures.

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