SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Semarak International Journal of Material Research

Journal homepage:
https://semarakilmu.my/index.php/sijmr/index
ISSN: 3083-8908

Vibration Analysis of the Distributed Optical Vibration Sensor (DOVS) on Various Surrounding Materials and Water Content

S.N.F Mohd Asseri[1,*], S. F. Norizan[1], M. Z. Zulkifli[2], A. A. Latif[2], Kavintheran Thambiratnam[1]

[1] IIUM Photonics and Quantum Centre, Kulliyyah of Science, International Islamic University Malaysia, 25200 Kuantan, Pahang, Malaysia
[2] Physics Department, Faculty of Science, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

ARTICLE INFO

Article history:
Received 20 November 2024
Received in revised form 3 December 2024
Accepted 10 December 2024
Available online 30 December 2024

Keywords:
Distributed vibration sensing; Optical fiber; Single Mode Fiber (SMF); Vibration analysis

ABSTRACT

Distributed optical vibration sensing (DOVS) is an optical sensing method that monitors acoustic turbulence in optical fibres, and then demodulating and processing the optical signal to correlate it to an external parameter. Optical based DOVS sensors have a few key advantages, including large-scale monitoring, good concealment, good flexibility and anti-electromagnetic interference which makes them useful for a wide range of applications. In this work, a distributed vibration sensing (DVS) is demonstrated using a 1550 nm erbium-doped fiber amplifier (EDFA) as a broadband emission source and a single-mode fiber (SMF) as the sensing mechanism. An Arduino piezoelectric transducer (PZT) vibrator is used as the vibration source in the experiments, while sand, soil, and cement with different water compositions are used as the test media. The different water content has varying refractive indices and elasticities. The vibration analysis is measured through the Fast Fourier Transform (FFT) where the frequency drift, intensity, and signal-to-noise ratio (SNR) is observed. Results of the testing show a similar sensitivity of intensity for different materials and water content which is 0.016dB/mL. Meanwhile, the highest frequency drift is observed for sand with varied water content which is 0.617Hz/mL. Similarly, the highest SNR of 23.5dB was also obtained for soil with a water content of 250 mL, while the lowest SNR was that of cement with the same water content at 15.1dB. This indicates that the DOVS system is capable of picking up even minor vibrations in cement, soil and sand, and would thus have significant applications in structural monitoring.

1. Introduction

Distributed vibration sensing (DVS) is a recent development in the field of optical fiber sensors [1]. The DOVS systems utilize optical fibers as a highly sensitive mechanism to continuously monitor the surrounding environment for external sounds or vibrations, which can be detected in real-time. As a result of this key characteristic, the DOVS system have begun to see numerous applications in various real-world fields such as building structural health monitoring [2], seismic monitoring [3], aerospace safety, and pipeline monitoring [1]. One of the many applications of the DOVS-based

* *Corresponding author.*
E-mail address: sitifatinahx@gmail.com

https://doi.org/10.37934/sijmr.1.1.2025 a

optical fiber sensors is to monitor leakages in buried pipelines [4,5], while other can be used to detect the vibrations from raindrops, thus providing crucial meteorological information with an energy information entropy model and variation coefficient developed [6]. The DOVS has been determined to have a high level of sensitivity, wide dynamic range, and simple structure which makes it easy and cheap to deploy, especially for large-scale monitoring and sensing applications [5]. Moreover, the DOVS technique provides significant advantages in large-scale monitoring, good concealment, excellent flexibility, and immunity to electromagnetic (EM) interference. This gives it considerable potential for a variety of practical applications as it enables the detection and localization of highly dynamic strain changes with the long sensors in the kHz regime [7] as well as pre-warning and accurate localization capabilities.

Significant effort and resources have been dedicated to studying DOVS sensitivity quantitative measurement and optimization. The sensitivity of this system determines its detection capability and the effective horizontal range across the fiber [8] and is thus a key focus area of on-going research. However, there is a lack of work done to investigate the environment or surrounding material effect on the detection. Most of the vibrational analysis was tested on air rather than in the medium. Changes in the properties of the medium could influence the vibrational analysis.

In this work, a DOVS based on optical fiber approach is proposed and demonstrated. The DOVS system utilizes coherent Rayleigh scattering as the detection mechanism [9], with the optical fiber cable serving as the sensing element. An amplified spontaneous emission (ASE) source from an erbium-doped fiber amplifier (EDFA) operating at 1550 nm serves as the sensing signal source. Measurements are taken using laboratory based optical spectrum analyzers (OSA), while an Arduino-based signal generated provides the test vibrational output. Vibration analysis is carried out on the DOVS system towards different media with different water content. The results of this study can be used in practical research as a further sensitivity increase for the widely employed dispersed subsurface acoustic detection is still required.

2. Methodology

The distributed optical vibration sensor (DOVS) system was built around a 1550 nm erbium-doped fiber amplifier (EDFA) of 5m pumped by a 100mW 980nm laser as a broadband emission source and a single-mode fiber (SMF) as the sensing mechanism. This is shown in Figure 1. The SMF used in this work was calibrated for vibration measurement and used as the Fiber Optic Sensor (FOS). The SMF was installed inside the container which was covered by the soil and the open end was then connected to the Keysight InfiniiVision 4000 X-Series oscilloscopes (OSC). The oscilloscope was used to analyze and record the frequency shift and intensity using Fast Fourier Transform (FFT) analysis while an Arduino microcontroller controlled piezoelectric transducer (PZT) vibrator was used as the vibration source and is capable of generating an output at a constant frequency of 200Hz.

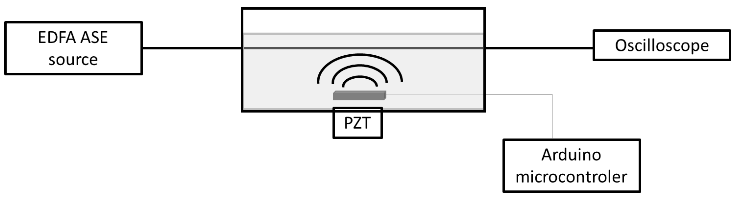

Fig. 1. Experimental setup of the distributed vibrational sensor

The performance of the DOVS system is evaluated using different media with different water concentrations. These media are 316 g of soil, 396 g of sand with medium-sized grains, and 331 g of cement in powder form. Figure 2 shows the image capture of each sample type, while Table 1 gives the values of selected parameters and properties of each sample.

Fig. 2. Image capture of actual samples used soil, sand (medium-sized grain), and cement (powder form)

Table 1
Characteristics of the soils

Types of soil	Soil	Sand (medium sized grain)	Cement (powder form)
Size of the particle (mm)	0.5-2.0	0.1-0.5	≤ 0.045
Density of the particle ($\frac{g}{cm^3}$)	2.65	1.85	1.44
Elastic Modulus (MPa)	70-180	30-50	10-30

The characteristics of media in Table 1 are according to the standards set by the United States Department of Agriculture (USDA) classification system. The two key properties of the medium that can influence the velocity of a vibration/acoustic wave are the elastic properties and density, and these are defined by the relationship:

$$\nu = \sqrt{(\frac{C_{ij}}{\rho})} \quad (1)$$

where C_{ij} contains the elastic properties and ρ is the density. The density of the media can be increased by adding water, with a higher water content making the combined media denser. As such, the density of the media can be increased, thereby increasing the velocity of the sound or vibrational waves in the system while keeping the bulk modulus relatively constant.

In preparing the samples, each sample is first dried in an oven to ensure low water content. The PZT vibrator is fixed at 0.9 cm above the container's bottom and is completely covered by the sample while the SMF was buried around 5 cm above the PZT vibrator. Measurements are taken while the external vibration source is generating a signal, and the water content is slowly increased from 50 mL to 250 mL at 50 mL increments. All measurements captured by the OSC and FFT are recorded and compared.

3. Result and Discussion

The measurements taken from the experiment run through the FFT process for transformation into the time domain signal $x(t)$ such that:

$$FT|x(t)| = \int_{-\infty}^{\infty} x(t)e^{-i\Omega t}dt \tag{2}$$

with the cross-correlation function defined as:

$$R_{xy}(\tau) = \lim_{\tau\to\infty} \frac{1}{T}\int_{0}^{T} x(t)y(t+\tau)dt \tag{3}$$

where, the variable τ is referred to as the delay parameter.

Frequency drift is the terminology used to describe the cross-correlation which are the similarity between optical fiber vibration and the fixed frequency sinusoidal signals from the PZT [10]. Using this approach, the graph of the frequency drift against different water content in each media sample in Figure 3. From the graph, it was depicted that only sand shows large changes in the frequency drift corresponding to the water content of 0.617Hz/mL with 204.8Hz at 50mL, 209.2Hz at 100mL, 218Hz at 150mL, 225.2Hz at 200mL and 222Hz at 250mL. An increment of only 0.122 Hz/mL was seen for soil (medium-sized grain) and nearly no changes for cement were observed. This characteristic due to the fact that between sand and soil, sand have larger pores that allows the water to infiltrate the medium faster than soil. The speed of sound in water is greater than in air because water particles are denser, with about 800 times more particles in a bottle of water compared to air, resulting in much faster sound wave transmission in water. In cement on the other, the interaction with water will ignite the hydration and change the cement into concrete, lowering vibration transfers

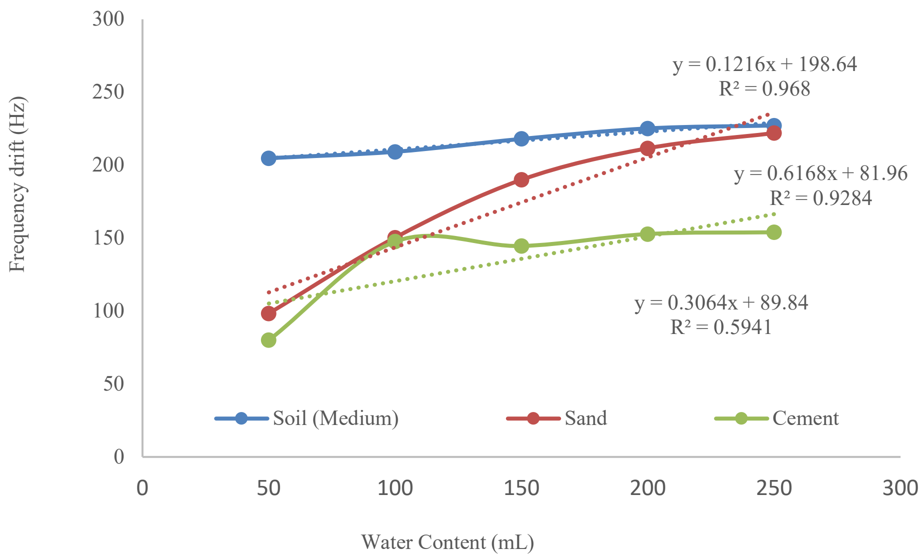

Fig. 3. The frequency drift against water content

Apart from the frequency drift, the characteristic of power intensity is also measured. Figure 4 shows the growth of intensity against water content. The intensity of the soil showed an increasing pattern from -36.44dB at 50mL, -36dB at 100mL, -35.085dB at 150mL, -34.16dB at 200mL, and -33.69dB at 250mL. Sand demonstrated little increment from soil with -36.62dB at 50mL, -35.38dB at

100mL, -34.50dB at 150mL, -33.67dB at 200mL, and -33.13dB at 250mL. Besides, cement shows higher value of intensity than sand and soil with -26.68dB at 50mL, -26.38dB at 100mL, -25.63dB at 150mL, -24.13dB at 200mL, and -23.86 at 250mL. All tested medium shows a similar increment of 0.016dB/mL.

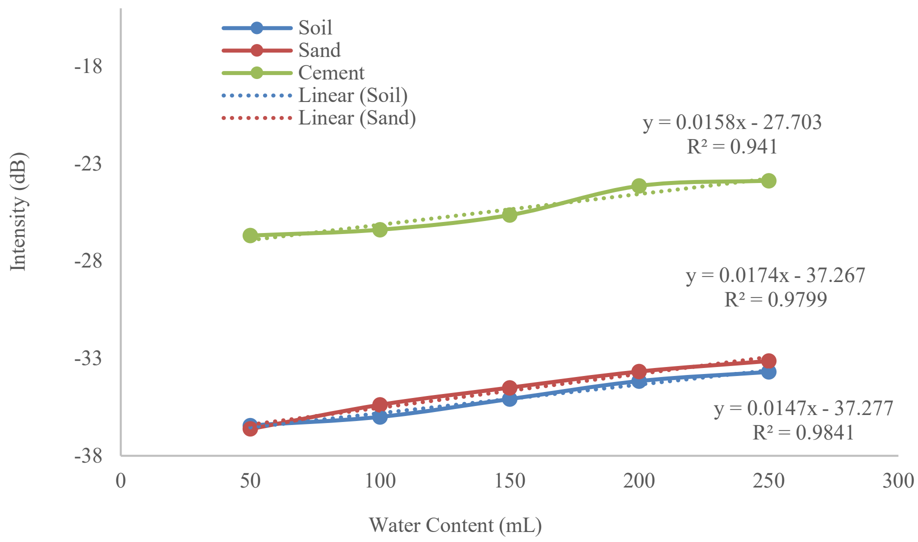

Fig. 4. The intensity of peak against water content

The signal to noise ratio (SNR) of each media's sensing signal was also measured. From Figure 5, it can be seen that a visible increment of SNR occurs with the increase of water content in the soil medium from 15.90dB at 50mL, 17.05dB at 100mL, 20.92dB at 150mL, 22.25dB at 200mL, and 23.50dB at 250mL.

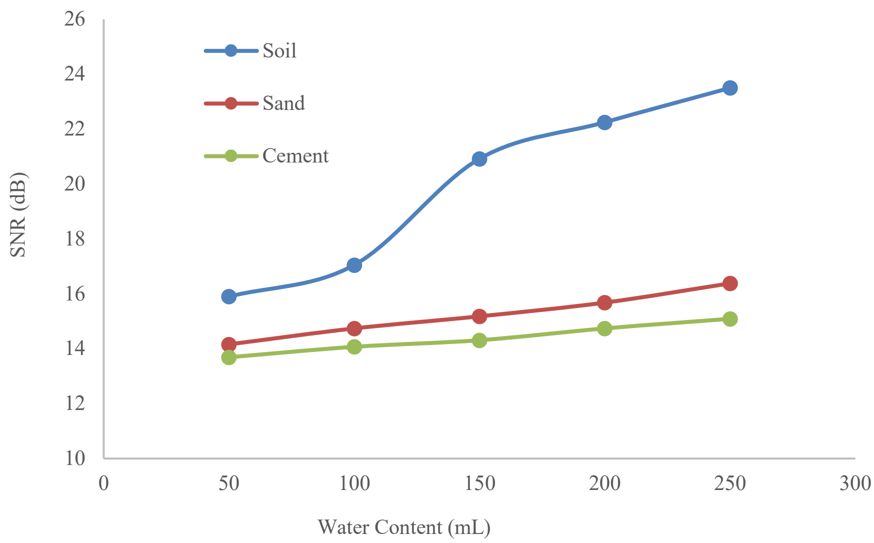

Fig. 5. The SNR against water content

It can be seen that overall, the proposed sensor is most sensitive to vibrations in soil, with vibrations in sand and cement being harder to detect. This is to be expected, due to the denser nature of these two materials. As such, the proposed sensor would have useful applications in the detection of earth movements, which are a precursor to landslides and sinkholes.

4. Conclusion

In this work, an optical fiber-based DVS sensors using a 1550 nm EDFA as a broadband emission source and an SMF as the sensing mechanism is proposed and developed. The DOVS system has key advantages, including large-scale monitoring, good concealment, good flexibility, and anti-electromagnetic interference which makes them useful for a wide range of applications. An Arduino vibrator is used as the vibration source and tested against different media consisting of sand, soil, and cement with different water compositions. The test results showed that the sensitivity of the intensity is similar for various materials and water content with 0.016dB/mL. In the meantime, sand with varying water content has the largest frequency drift with 0.617 Hz/mL whereas the lowest was soil with 0.122dB/mL. Similarly, the highest SNR of 23.5dB was also obtained for soil with a water content of 250 mL, while the lowest SNR was that of cement with the same water content at 15.1dB. This indicates that the DVS sensor is capable of picking up even minor vibrations in cement, soil and sand, and would thus have significant applications in structural monitoring.

Acknowledgement

This work was supported by Department of Physics, Kulliyyah of Science, International Islamic University Malaysia. We would like to thank Ministry of Higher Education of Malaysia (MOHE) for providing the grants of FRGS/1/2022/STG07/UIAM/02/1.

References

[1] P. Stajanca, S. Chruscicki, T. Homann, S. Seifert, D. Schmidt, A. Habib. "Detection of Leak-Induced Pipeline Vibrations Using Fiber-Optic Distributed Acoustic Sensing",2018, *Sensors 18 284*. https://doi.org/10.3390/s18092841

[2] M. F. Bado And J. C. Casas. "A Review of Recent Distributed Optical Fiber Sensors Applications for Civil Engineering Structural Health Monitoring", 2021, *Sensors 21 1818*. https://doi.org/10.3390/s21051818

[3] T. Reinsch, J. Henninges, J. Götz, P. Jousset, D. Bruhn, S. Lüth. "Distributed Acoustic Sensing Technology for Seismic Exploration in Magmatic Geothermal Areas World Geothermal Congress", 2015, (Melbourne) px -1.

[4] M. Bertulessi, D. F. Bignami, I. Boschini, M. Longoni, G. Menduni, J. Morosi. "Prototype test of distributed optical fiber continuous monitoring for buried pressure water conveyance pipeline", 2023, *Sensors 23 6205*. https://doi.org/10.3390/s23136205

[5] W. H. Png, H. S. Lin, C. H. Pua, F. A Rahman. "Pipeline monitoring and leak detection using loop integrated Mach Zehnder interferometer optical fiber sensor", 2018, 46 221. https://doi.org/10.1016/j.yofte.2018.10.013

[6] H. Qu, S. Liu, Y. Wang, G. Li. "Approach to Identifying Raindrop Vibration Signal Detected by Optical Fiber", 2013, *Sensors and Transducers*, 160 85.

[7] X. Liu, B. Jin, Q. Bai, Y. Wang, D. Wang And Y. Wang. "Distributed Fiber-Optic Sensors for Vibration Detection", 2016, *Sensors 16 1164*. https://doi.org/10.3390/s16081164

[8] Z. Wang, B. Lu, Q. Ye And H. Cai. "Recent Progress in Distributed Fiber Acoustic Sensing with Φ-OTDR", 2020, *Sensors 20 6594*. https://doi.org/10.3390/s20226594

[9] J. Zuo, Y. Zhang, H. X. Xu, X. Zhu, Z. Zhao. "Pipeline Leak Detection Technology Based on Distributed Optical Fiber Acoustic Sensing System", 2020, *IEEE Access 8 30789*. https://doi.org/10.1109/ACCESS.2020.2973229

[10] J. Chao, J. Ruihong, H. Wen, H. Jiani. "Comparative Experiments of Optical Fiber Sensor and Piezoelectric Sensor based on Vibration Detection", 2020, *IEEE 4th International Conference on Frontiers of Sensors Technologies (ICFST) (Shanghai) px-17-20.* https://doi.org/10.1109/ICFST51577.2020.9294766