Experimental Characterization of Macrobending Fiber Sensor Coupled via Vibrating Membrane for Acoustic Detection

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Abstract: This work investigates the application of a fiber-optic acoustic sensor based on macrobending loss for gas leakage detection, employing a membrane-coupled architecture to enhance acoustic sensitivity and directional selectivity. The proposed system integrates a single-mode fiber coiled inside a cylindrical structure sealed with thin membranes, which act as mechanical transducers by converting acoustic waves into localized perturbations along the fiber curvature. The experiments were conducted to evaluate the sensor's response under controlled excitation conditions, varying frequency, sound pressure level, source distance, and angular orientation. Results demonstrate that tighter curvature yields significantly higher optical attenuation. Spatial sensitivity was characterized by a nonlinear increase in attenuation with distance, and directional behavior was confirmed by enhanced attenuation under oblique wave incidence. The practical applications of the findings are diverse, with particular emphasis on gas leak monitoring in industrial settings.
Keywords: Acoustic sensor. Macrobending loss. Leak detection. Acoustic identification. Fiber optic sensor.
Abbreviations: DAS, Distributed Acoustic Sensing. FBG, Fiber Bragg Grating. FFT, Fast Fourier Transform.

1.Introduction

Detection and characterization of low-intensity vibration pose significant challenges across various scientific and engineering disciplines due to fluid flow's inherently chaotic and irregular nature. The advancement of acoustic sensing technologies is crucial for accurately capturing and quantifying these phenomena.

Optical fibers are recognized not only as the backbone of high-speed telecommunications but also as a versatile platform for advanced sensing applications. Their inherent properties, such as low attenuation, electromagnetic immunity, and high sensitivity, make them ideal candidates for structural health monitoring, environmental surveillance, and chemical or acoustic detection in harsh environments [1]. Distributed sensors, such as Distributed Acoustic Sensing (DAS), enable the detection of vibrations along extensive lengths of fiber, facilitating the identification of gas leaks in both urban and underground pipeline [2] [3] [4]. Interferometric techniques, such as Fabry-Perot [5] and Mach-Zehnder [6] have shown promising results, offering broad frequency response under adverse conditions. Fiber Bragg Grating (FBG) acoustic sensors have also demonstrated high sensitivity in detecting ultrasonic waves [7] [8]. However, these methods have certain limitations: they are primarily viable for new pipeline installations, require the integration of fiber throughout the pipeline network, are most effective for monitoring large leaks, demand sophisticated interrogation systems, and tend to be costly. Fiber optic sensors based on macrobending, intentionally inducing curvature in the optical fiber to cause light leakage, have emerged as a powerful technique for detecting mechanical perturbations, particularly acoustic vibrations. Traditionally viewed as a loss mechanism in telecommunications, macrobending can be harnessed to transduce acoustic or vibrational energy into measurable variations in optical power [9] [10]. When external acoustic fields induce dynamic strain on the bent section of the fiber, the resulting modulation in bending radius leads to variations in optical attenuation, which can be directly correlated with the incident acoustic signal.

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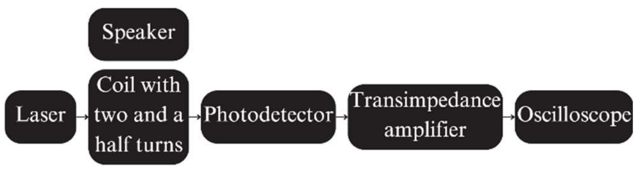
The present study explores the application of this macrobending phenomenon to develop an acoustic sensor aimed at detecting characteristic frequency signals associated with gas leaks in pipelines. This approach offers key advantages: passive and electrically safe operation in flammable or hazardous environments, robustness against electromagnetic interference and a promising and cost-effective solution. Specifically, the aim is to investigate the correlation between sound-induced optical attenuation and spatial parameters (e.g., coil diameter and excitation distance), and to assess the sensor's feasibility for gas leak detection applications.

2.Methodology

Figure 1 illustrates the schematic diagram of the experiment setup that comprised a 1550 nm laser, a Corning SMF-28e+ optical fiber, a speaker, a photodetector, a transimpedance amplifier, and an oscilloscope. The optical fiber was connected to the laser source and passed through the tube containing the coiled section. At the output, the fiber was connected to a photodetector that converted optical power fluctuations into an electrical current. This current was subsequently amplified by a transimpedance amplifier and monitored using an oscilloscope for temporal analysis.

The sensing head was composed of a 2.5-turn fiber coil enclosed within a cylindrical tube measuring 25.4 mm in diameter and 35.0 mm in length. To investigate the influence of curvature-induced loss, three different coil diameters were tested: 15 mm, 20 mm, and 25 mm.

Figure 1. Experiment setup.

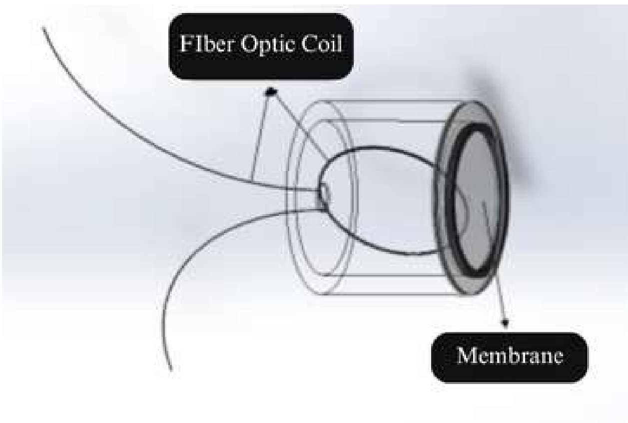


As depicted in Figure 2, both ends of the tube were sealed with thin membranes fabricated via 3D printing, designed with micro-apertures to permit fiber insertion. A segment of the coiled fiber maintained direct contact with the internal surface of the diaphragm, enabling efficient transmission of acoustic-induced displacements.

Acoustic excitation was applied using a commercially available speaker placed externally in front of the sensor head. The system was evaluated under both single-tone and dual-tone excitation protocols. In the single-frequency mode, isolated sinusoidal signals of 200 Hz, 440 Hz, and 500 Hz were applied individually. In the dual-frequency mode, simultaneous tones of 320 Hz and 325 Hz were employed to investigate the sensor's resolution in distinguishing closely spaced spectral features.

The first experimental phase focused on assessing the effect of coil diameter on sensor response, under varying acoustic frequencies at two discrete sound pressure levels.

Figure 2: Schematic representation of the sensor head



In a subsequent stage, the spatial configuration of the acoustic source relative to the sensor was systematically varied to evaluate directional sensitivity. The speaker was initially placed adjacent to the diaphragm and posteriorly moved to distances of 2 cm, 3 cm, and 4 cm along the fiber axis. Then, at a fixed distance, the speaker was rotated 30° from the central axis to introduce angular displacement.

For each combination of frequency, volume, distance, coil diameter, and angular position, the measurements presented in this paper represent the average result of ten repeated tests, ensuring statistical consistency and reliability

When the acoustic vibration reaches the membrane, it is transmitted to the fiber, causing deformation in the coils. These deformations manifest as variations in voltage, which is observed by the oscilloscope. Subsequently, the time-domain signal displayed on the oscilloscope was converted into a frequency spectrum using the Fast Fourier Transform (FFT), allowing the observation of the predominant frequency of the sound wave produced by the speaker. This approach provided a characterization of how periodic variations in coil radius, induced by acoustic stimuli of different frequencies, affect the optical attenuation and spectral sensitivity of the sensing system.

3. Results and discussion

The signal evaluated in the experiment was detected through the deformation of the optical fiber geometry, which induced macrobending effects. A similar result was reported by Wang et al. [10], who demonstrated that external vibrations could lead to variations in the macrobending loss, resulting in measurable changes in the transmitted signal.

In the initial phase of the experiment, the influence of fiber coil diameter on optical attenuation under acoustic excitation was systematically investigated using three configurations: 25 mm, 20 mm, and 15 mm. Each setup was subjected to sinusoidal excitation at 200 Hz, 440 Hz, and 550 Hz, under two distinct sound pressure levels, corresponding to 100% and 50% of the speaker's output volume, as illustrated in Figures 3, 4, and 5.

Figure 3. FFT of a 25mm fiber coil under varying acoustic excitation levels.

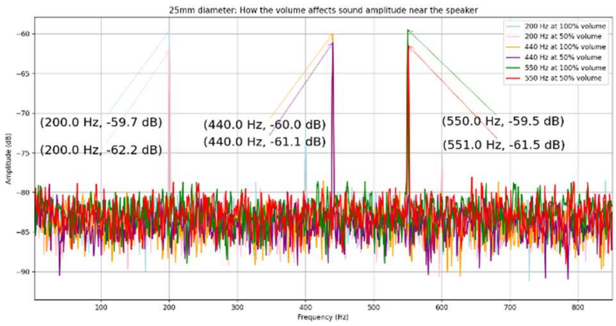


Figure 4. FFT of a 20mm fiber coil under varying acoustic excitation levels.

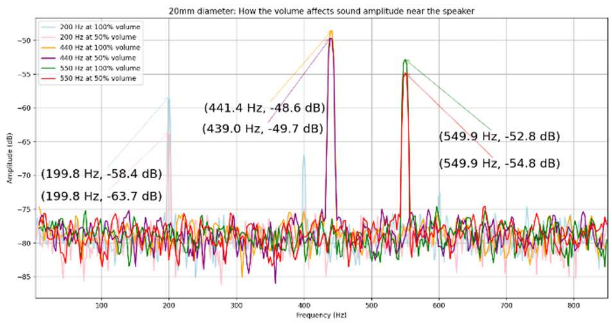
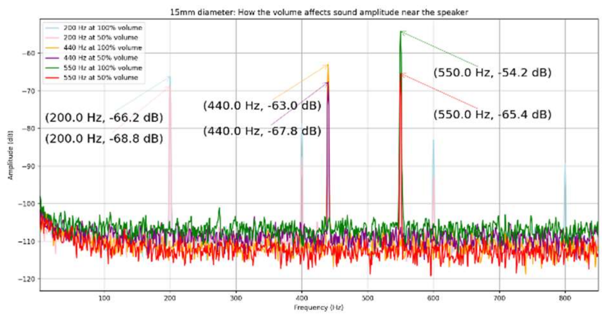


Figure 5. FFT of a 15mm fiber coil under varying acoustic excitation levels.



The results reveal a pronounced dependence of the optical attenuation on the coil diameter. Among the tested configurations, the 15 mm coil exhibited the highest attenuation across all frequencies. This behavior confirms that tighter curvatures enhance macrobending-induced losses, thereby increasing the sensitivity of the system to acoustic perturbations. The attenuation between the two sound pressure levels causes a significant change in the amount of light that is lost along the optical fiber, that is, the sensor responds sensitively to changes in sound, strongly modulating the transmitted optical intensity. The 25 mm coil exhibited more stable attenuation values with smaller amplitudes across all frequencies, indicating lower sensitivity to acoustic excitation. This relative insensitivity is consistent with the weaker perturbation of the guided mode expected at larger bending radius.

Since the system with the 15 mm coil diameter demonstrated higher sensitivity and was more responsive to changes, the subsequent results presented in this paper focus exclusively on this diameter, although the same tests were conducted for all coil sizes.

In the second experimental phase, the effect of the relative positioning between the acoustic source and the fiber coil was examined. This analysis was conducted using the configuration that exhibited the highest sensitivity in the initial tests, a 15 mm diameter coil operating under 100% excitation volume. Two key parameters were systematically varied: the linear distance between the sound source and the fiber coil and the angular orientation of the acoustic relative to the plane of the coil.

Figure 6. FFT of a 15mm fiber coil under varying acoustic excitation distance.

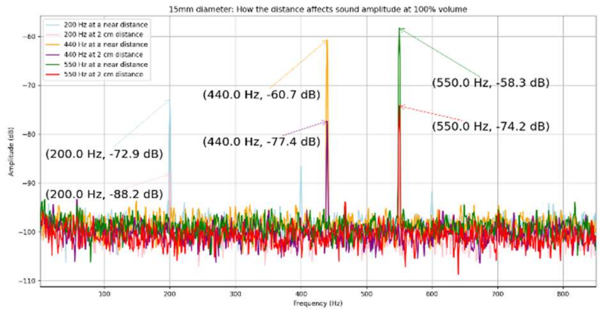
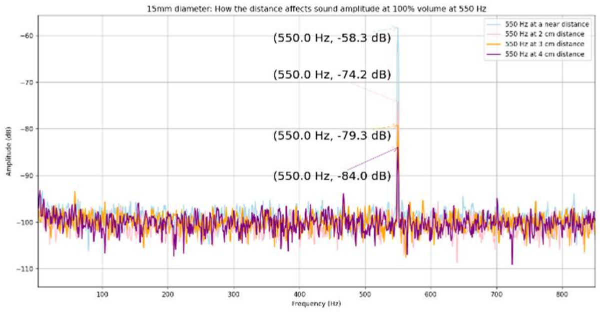


Figure 6 presents the optical attenuation data acquired with the acoustic source displaced by 2 cm from the coil, for three different frequencies. The results reveal a pronounced spatial dependence in acoustic sensitivity. In the sensing head employed in this study, the fiber does not interact directly with the acoustic field. Instead, the vibrating membrane acts as a transducer, converting acoustic pressure fluctuations into mechanical displacements that are coupled to the coiled fiber. As the source moves farther from the sensor, the sound intensity decreases, but the incident pressure field becomes more distributed due to diffraction and scattering in air, stimulating a broader region of the membrane. Therefore, the amplitude of the membrane's displacement is directly influenced by the incident sound pressure amplitude, which in turn is related to the square root of the sound intensity. This relationship is supported by classical acoustic theory [11]and confirmed in recent optical acoustic sensor models [6]. This behavior is further illustrated in Figure 7, which details the attenuation values for the 550 Hz excitation at increasing source distances. A similar result was discussed by Zhao et al. [12], where it was shown that the pressure of acoustic waves decays exponentially as they propagate along the pipeline, an attenuation behavior comparable to the inverse square law considered in this work.

Figure 7. FFT of fiber coil under different distances from acoustic excitation at 550Hz.



To assess directional sensitivity, the source was rotated 30° relative to the coil axis while maintaining its proximity and excitation level. Figure 8 shows the attenuation of all three frequencies. Angular displacement resulted in a substantial increase in attenuation, especially at higher frequencies. This may be attributed to the modification of the incident acoustic wavefront on the membrane surface, which alters the spatial distribution of induced vibrations.

Figure 8. FFT of a 15mm fiber coil under varying angular displacement

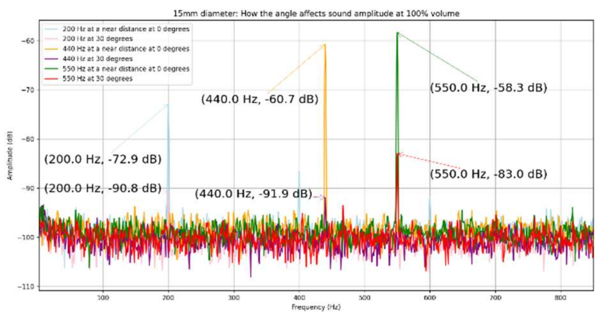
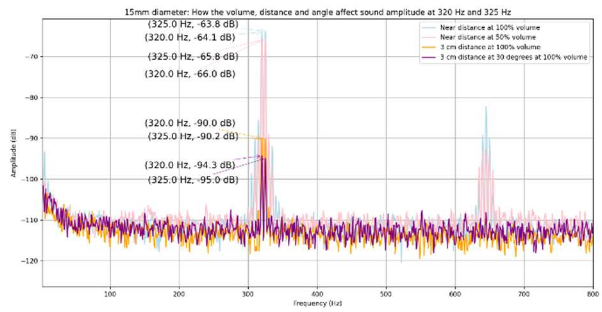


Figure 9 presents the results obtained from simultaneous excitation of two acoustic frequencies: 320 Hz and 325 Hz. The sensing system demonstrated the ability to resolve both frequency components independently. As in previous experiments, variations in sound pressure level, source distance, and angular orientation produced consistent effects on signal amplitude. A slight reduction in amplitude was observed when the volume was lowered, whereas increasing the distance between the sensing head and the speaker resulted in a more pronounced decline in signal strength, indicating once again the system's strong spatial dependence.

Figure 9. Frequency discrimination and spatial sensitivity of a 15 mm fiber coil sensor under dual acoustic excitation (320 Hz and 325 Hz).



4.Conclusion

This study provides a comprehensive demonstration of the viability and effectiveness of a compact fiber optic sensing architecture, based on macrobending loss, for the detection of acoustic phenomena. The experiments established that the diameter of the fiber coil plays a pivotal role in determining sensor sensitivity, with smaller radii yielding greater attenuation in response to acoustic excitation. These results affirm that tighter bending enhances interaction with guided optical modes under dynamic mechanical perturbation. The influence of spatial parameters such as source distance and angular incidence was investigated. The optical response exhibited a nonlinear dependence on distance, while also displaying directional sensitivity under oblique wave incidence. Notably, the sensor demonstrated the ability to resolve two simultaneous acoustic frequencies (320 Hz and 325 Hz), despite their narrow separation, underscoring its high spectral resolution and selectivity.

As demonstrated in this study, the proposed system offers operational advantages, recognizing variations in frequencies, sound pressure levels, distances, and angles. These findings position membrane-coupled fiber sensors as a cost-effective and scalable solution for acoustic monitoring applications. Moreover, they provide immediate detection without the risk of explosions or fires, which is highly beneficial in leak scenarios.

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