Sound Signal Potential for Visualization of Corrosion in Pipelines

Ryan Syuhada[a], Feblil Huda[a,*] and Nazaruddin

[a)]*Mechanical Engineering Department, Engineering Faculty, University of Riau, Indonesia*

*Corresponding author: feblil.huda@eng.unri.ac.id

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ABSTRACT

This study explores the potential of using sound signals to visualize corrosion within pipes. Early detection of pipe damage is crucial in preventing leaks and larger losses, especially in industries that rely on pipes for fluid distribution. Sound-based methods have advantages in detecting damage in hard-to-reach areas without direct contact with the pipe's surface. This study demonstrates that microphones mounted on the pipe surface can capture variations in sound signal characteristics related to corrosion conditions. To simulate corrosion in pipes, a layer of plasticine was applied to a specific area of the pipe's inner surface, creating a model of corrosion damage. The test results show that microphone positions aligned with the corroded area produce higher signal coefficients compared to non-corroded areas. With further processing, these signal data have the potential to be visualized as 3D images, providing a more detailed representation of the internal conditions of the pipe.

KEYWORDS: *Sound Signal, Pipelines Detection, Corrosion Visualization.*

NOMENCLATURE

CWT	Continues Wavelet Transform
DAQ	Data Acquisition
EA	Emission Acoustic
ToF	Time of Flight

1.0 INTRODUCTION

Pipes are essential components in numerous industries, such as oil and gas, petrochemicals, clean water, and drainage systems, with their primary role being the transportation of fluids like oil, gas, water, and chemicals[1]-[3]. Ensuring the reliability and integrity of these pipes is critical to maintaining the seamless functioning of production and distribution processes within these sectors [4],[5]. Damage to pipes, including corrosion, leaks, or other mechanical issues, can have serious consequences, leading to fluid leaks that may cause financial losses, safety hazards, and environmental harm [6]-[8]. As such, early detection of pipe damage is crucial to preventing more severe incidents and ensuring the safety of operations [9], [10].

Several techniques have been employed to detect pipe damage, such as visual inspections [11], [12], ultrasonic methods [13]-[16], radiography [17]-[19], electromagnetic techniques [20]-[23], and vibration analyst [20]-[25]. Each of these methods has its strengths and weaknesses. For instance, visual inspection might not be suitable for hidden or inaccessible areas [26], [27], while ultrasonic and radiographic methods require specialized equipment and trained personnel [28], [29]. Vibration analysis can indicate the presence of damage but often falls short in accurately identifying the type and location of the damage [30].

Methods based on sound signals present potential advantages in addressing some of these limitations. Sound signals can penetrate hard-to-reach areas and detect internal damage without the need for direct physical contact with the pipe surface. Furthermore, this approach has the capability to provide more comprehensive information about the internal state of pipes, facilitating more precise mapping of corrosion and other forms of damage. Previous studies have investigated the use of sound signals for detecting pipe damage, such as employing acoustic emission techniques to identify cracks or leaks, and frequency analysis methods to detect corrosion [31]-[33]. However, these studies have predominantly concentrated on detecting leaks and cracks, with limited focus on detailed corrosion mapping. Thus, additional research is necessary to improve the sensitivity and accuracy of these methods.

This research aims to find out the potential of using sound signals to visualize corrosion within pipes. By leveraging sound signals, the study seeks to achieve more accurate mapping of the internal conditions of pipes, particularly regarding corrosion contours. This approach is anticipated to enhance the reliability of pipe condition monitoring and boost operational efficiency across various industries.

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2.0 THEORY

2.1 Velocity and Reflection of Sound

The speed of sound in air at about 20°C is 343 meters per second (m/s), which depends on the density and elasticity of the air. When sound waves hit surfaces with different characteristics, such as corrosion or blockages in pipes, some of the energy will be reflected back [34]. In corrosion detection experiments, changes in the properties of the medium due to corrosion change the speed and characteristics of sound reflections. The Time of Flight (ToF) principle is used to detect corrosion by measuring the time it takes for sound waves to travel from the source to an obstacle and back again. The basic formula of ToF is:

$$ToF = \frac{L}{v} \, x \, 2 \qquad (1)$$

Where L is the distance from the source to the barrier, and v is the speed of sound. By analyzing this change in travel time, we can identify the location and severity of corrosion, enabling early detection and non-destructive treatment of the pipeline. The reflectometric acoustic scheme can be illustrated in Figure 1.

2.2 Continuous Wavelet Transform (CWT)

Continuous Wavelet Transform (CWT) is a signal analysis method that allows the separation of signals into different scales and frequencies, providing a more detailed analysis compared to the Fourier Transform, particularly in detecting sudden local changes [35]. In this study, CWT was used to analyze the sound signal generated from inside the pipe to detect corrosion or blockage. This method allows the identification of small changes in the signal that could indicate the presence of structural anomalies in the pipeline. Daubechies (db) wavelets were chosen for their ability to handle signals with sharp edges and non-stationary changes, as is often the case with vibration or sound signals in corroded pipes, enhancing the sensitivity of detection and improving the accuracy of identifying the severity and location of the anomalies. The Daubechies wavelet has a wavelet function expressed as follows:

$$\Psi(t) = \sum_{k=0}^{N-1} gk.\Psi(2t - k) \qquad (2)$$

Where, (gk) is the filter coefficient that determines the accuracy of the wavelet. The selection of *Daubechies* wavelets in this study is relevant due to their effective nature in detecting localized anomalies, enabling early and accurate identification of corrosion or blockages in pipes through analysis of changes in the sound signal.

Figure 1: Reflectometric acoustic scheme

3.0 METHODS

3.1 Testing Mechanism

Corrosion detection using sound signals involves transmitting acoustic or ultrasonic waves into a material such as a pipe or metal structure, in which case the sound transmitted is an impulse sound. As the sound waves propagate in the pipe, they interact with the surfaces and various obstacles present in the pipe. To create reflections and refractions that can indicate the presence of corrosion. By analyzing these sound signals, technicians can ultimately identify the extent and location of any corrosion damage within the structure. The sound mechanism in detecting corrosion is depicted in Figure 2.

Corrosion, sensor components, and pipe caps can obstruct sound waves as they travel through a pipeline. These obstructions can cause the sound waves to be reflected or absorbed, changing the pattern of the reflected or transmitted signal. This altered signal is then captured by a microphone and analyzed to detect potential corrosion. By analyzing the differences between the original and the returned signal that is gain insights into the location, size, and severity of corrosion damage. Advanced techniques like time analysis methods and wavelet transform can be employed to extract this information from the sound data

3.2 Test Procedure

The procedure for corrosion detection in PVC pipes using the thin plasticine approach as a corrosion simulation starts with preparing the PVC pipe and attaching a layer of plasticine to a certain part of the inner surface of the pipe to simulate the corrosion area. An acoustic transducer or impulse sound transmitter, in this case a speaker, is then attached to one side of the pipe to transmit the sound signal, while the receiver sensor (microphone) is placed 20 cm from the impulse source. Furthermore, the data collection step begins when the impulse sound is emitted into the pipe, the moment the impulse is emitted the sensor will record the sound response due to corrosion. The acquisition data is used to read the signal which will then be processed into CWT through the MATLAB application. This procedure is repeated in different positions as many as 8 points around the pipe. The test procedure scheme is shown in Figure 3.

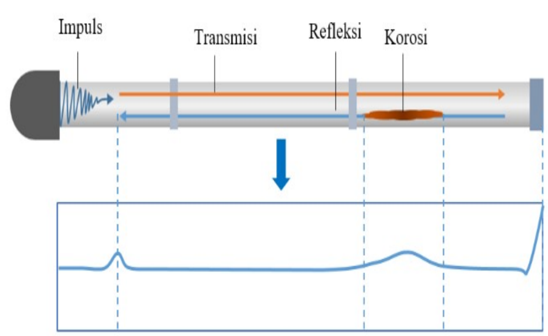

Figure 2: Sound mechanism in detecting corrosion

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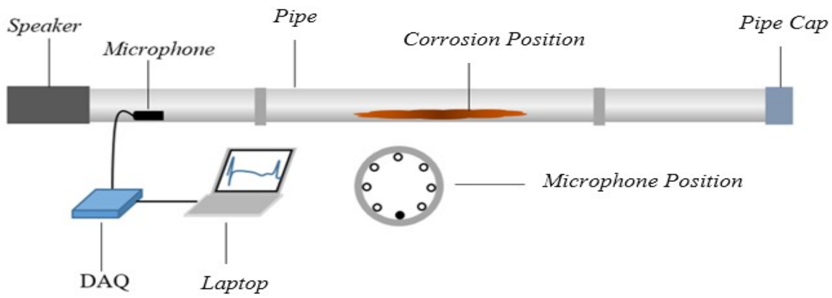

Figure 3: Test procedure scheme

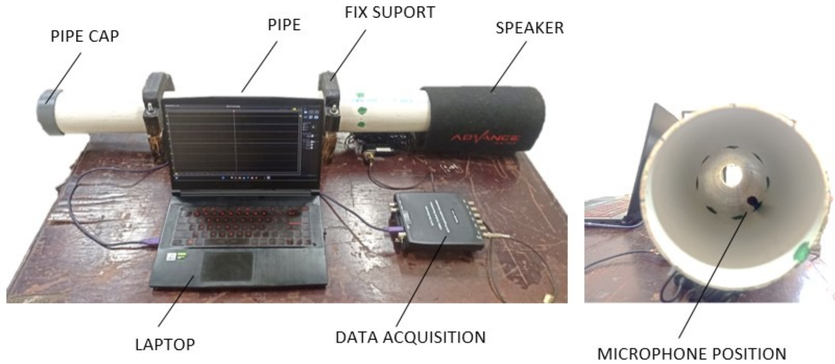

Figure 4: Test Setup

3.3 Test Setup

The setup of the pipeline corrosion detection test using sound signals involves several major components, each of which has a specific function. The laptop is used to control the test, process the received data, and display the analysis results. Data acquisition is a device that serves to connect between the laptop and the sensor, allowing the signal captured by the microphone to be recorded and analyzed digitally. The PVC pipe acts as the test object on which the corrosion simulation will be conducted. Pipe caps are used to cover both ends of the PVC pipe so that sound waves can be reflected and produce a measurable acoustic response. The speaker is used to emit sound signals into the pipe, serving as a source of sound waves that will propagate through the pipe. The microphone serves as a sensor to capture the sound signal that has propagated through the pipe and detect changes that occur due to interaction with areas of corrosion or imperfections. Finally, a pinch support is used to hold the PVC pipe steady and well-positioned during the test, ensuring consistent and accurate test results. Additionally, the entire setup is calibrated to ensure optimal signal transmission and reception for reliable measurements. This systematic arrangement enhances the overall effectiveness of the corrosion detection process, allowing for precise evaluation of the pipeline's condition.

The test setup consists of several components, each of which has its own function and specifications as shown in Table 1.

Table 1: Test setup components

Component	Function	Specification
Laptop	Display signals and process them	RAM: 8 Gb Processor: Core i5
DAQ (Data Acquisition)	Convert analog signal to digital signal	Mark: Hantek 1008C Channel: 8 Sensitivity:10mV/div to 5V/div Frekuensi : 0-250KHz
Microphone	Record sound signal	Merk : TOA ZM-360 Respon Frekuensi: 70-20.000Hz
Pipe	Test media	Type: PVC Diameter: 4” Length: 1.5m

3.4 Pipe Corrosion Testing Conditions

In this experiment, different corrosion variations were created using plasticine to simulate different conditions on the pipe. There were three main corrosion variations used. First, a circular corrosion variation of the pipe with three shapes: a full circle, a half circle, and a quarter circle, where the test was conducted at only one sensor position at a distance of 65 cm.

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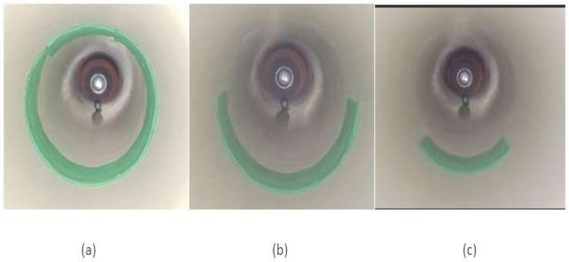

Figure 5: Circular corrosion condition (a) full circle (b) half circle (c) quarter circle

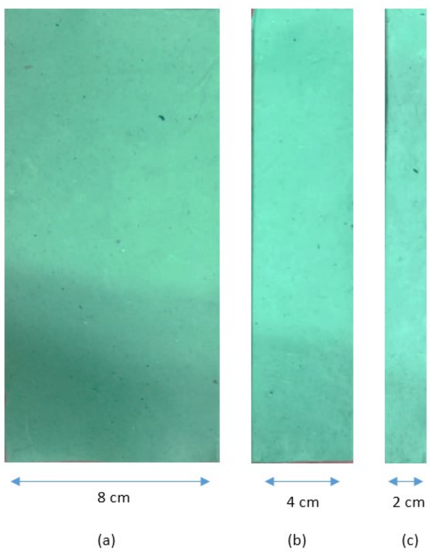

Figure 6: Depth corrosion: (a) 8cm, (b) 4cm (c), 2cm

Second, the variation of corrosion depth with depths of 8 cm, 4 cm, and 2 cm, the length of corrosion being ½ the pipe circumference, which was also tested at one sensor position with a distance of 55 cm.

Third, corrosion was placed at several points on the pipe in the shape of a half circle and a quarter circle, which was carried out at eight sensor positions at distances of 32 cm, 48 cm, 57 cm, and 75 cm. These variations aimed to understand the impact of the shape and depth of corrosion on the test results using sensors at various distances.

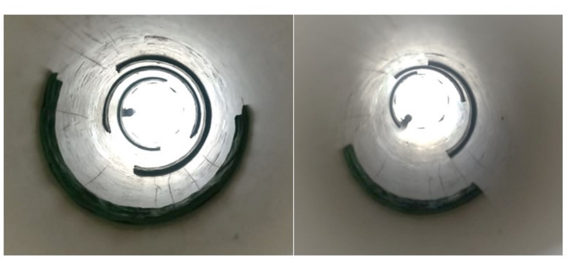

Figure 7: Multiple corrosion (a) half circle, (b) quarter circle

4.0 RESULT

4.1 Circular Corrosion Test Results

The testing results in this research consist of time-domain and wavelet-domain graphs, where the data was obtained by extracting the acquired data. The extracted data was then processed and transformed into time-domain and wavelet signals using MATLAB. This process involves a deeper analysis to identify relevant patterns from the data. Additionally, the time-domain graphs provide a clear representation of the signal variations over time, while the wavelet-domain graphs reveal frequency components at different scales. This dual approach enhances the understanding of how corrosion affects the acoustic signals, facilitating more accurate diagnosis and evaluation of pipeline integrity.

The test data shows the characteristics of the conditions in the pipe, such as the first amplitude at a distance of 20 cm shows the position of the microphone, then at a distance of 100 cm there is a characteristic of the pipe cap. The captured signal shows the corrosion characteristics shown in the red circle in Figure 8. It can be seen in Figure 8, there is a difference in signal between the 3 pipe corrosion conditions to illustrate the difference of them more clearly. From Figure 9, it can be seen that the corrosion ring affects the resulting signal. It can be seen that the blue signal line that shows the full corrosion ring has a higher amplitude peak than the others, both at the top of the hill and at the bottom of the valley of the wave.

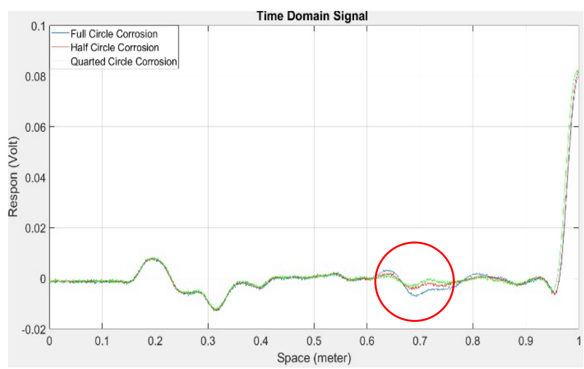

Figure 8: Circular corrosion time-domain signal

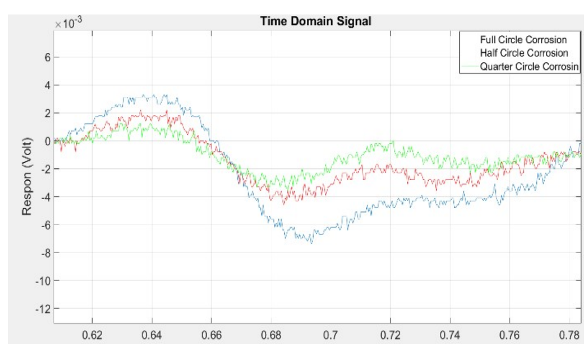

Figure 9: Time-domain signal zoom in circular corrosion.

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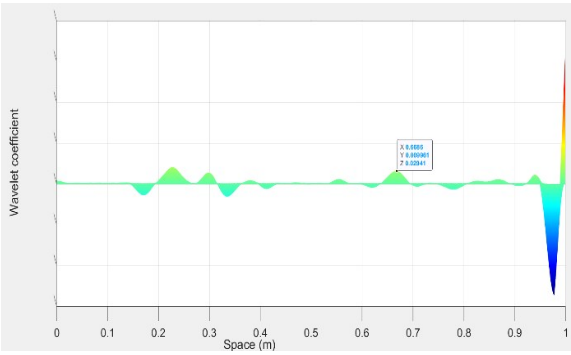

Figure 10: Wavelet of circular corrosion

The captured signals are then processed into wavelets to see changes in signal characteristics against wavelet coefficients. From Figure 10, it can be seen that corrosion placed inside the pipe provides a special image that explains that something is happening inside the pipe, in this case corrosion. To see the difference in values from variations in circular corrosion conditions is shown in Table 2.

Table 2: Wavelet coefficient of circular corrosion

No	Types of Corrosion	Coefficient
1	Full Circle Corrosion	0.02941
2	Half Circle Corrosion	0.01782
3	Quarter Circle Corrosion	0.01218

Table 2 summarizes the wavelet coefficients corresponding to each corrosion variation, highlighting the distinct signatures associated with different types of corrosion. By comparing these values, we can better understand the relationship between the corrosion characteristics and the resulting acoustic responses, leading to improved detection methods. From the table we know that circular corrosion gives the highest coefficient value which is 0.02941.

4.2 Pipe Depth Corrosion Test Results

This study also shows the signal results due to changes in longitudinal corrosion. It can be seen in figure 11, there are signal characteristics due to changes in corrosion to be clearer in distinguishing the signal. The signal was zoomed in on the part that indicates corrosion which is loaded in Figure 12.

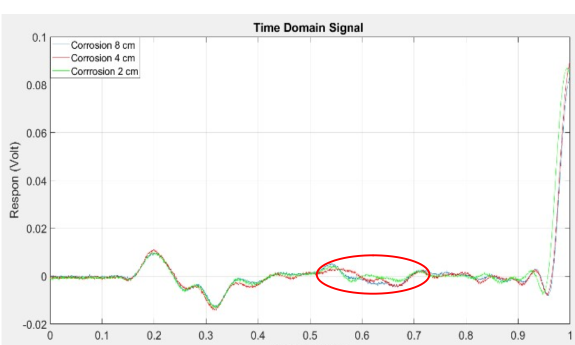

Figure 11: Depth-variation corrosion time-domain signal

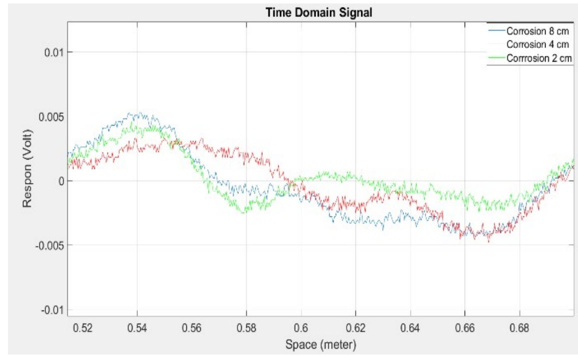

Figure 12: Depth-variation corrosion signal zoom

The signal from the depth variation indicates that the deeper the corrosion, the longer the signal captured in one wave, which consists of peaks and troughs. This is evident in Figure 12, where the blue line represents corrosion with a depth of 8 cm in the longitudinal direction. Upon close observation, the length of one wave is the longest among the other signals. In contrast, the green signal corresponds to corrosion with a depth of 2 cm, where the signal length is the shortest. This suggests that the signal's wave length is directly proportional to the depth of the corrosion, highlighting that deeper corrosion results in a more extended wave pattern due to the increased surface irregularities that affect the sound wave propagation.

The signal in this test is also converted into wavelet to see the change in wavelet coefficient to the change in corrosion. In order to see the difference in wavelet coefficient values from the three conditions, it is loaded into Table 3. The provided table 3 presents the results of a wavelet coefficient analysis on sound signals from corroded materials. The goal was to assess the relationship between the coefficient values and the depth of corrosion. The table 3 shows that the wavelet coefficient analysis can determine the depth of corrosion in sound signals. The coefficient value for a 2 cm corrosion depth was the highest at 0.02092, while the value for an 8 cm depth was lower at 0.01959. From the results of the wavelet coefficient of the sound signal, which is less responsive to the depth of corrosion, it can be seen that the coefficient value of 2 cm corrosion actually has a high coefficient value, namely 0.02092.

Table 3: Depth-variation corrosion wavelet coefficient

No	Type of corrosion	Coefficient
1	Corrosion 8 cm	0.01959
2	Corrosion 4 cm	0.01322
3	Corrosion 2 cm	0.02092

4.3 Corrosion Test Result at Several Points

The corrosion testing was designed to assess whether sound-based methods, such as acoustic testing, could reliably detect multiple corrosion points within pipes. To achieve this, the tests were conducted at various locations along the pipes, each at different angles within the pipe sheath. The purpose was to simulate real-world conditions where corrosion can occur at different spots, including areas that might be more difficult to detect. By placing microphones at multiple points, the goal was to evaluate whether the sound signals captured

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by these devices could effectively identify the presence and location of corrosion.

The results revealed significant variations in the data collected from each microphone position, suggesting that the ability of sound to detect corrosion is influenced by the specific location and angle of the microphones relative to the pipe. These differences highlight the complexities involved in using acoustic methods for corrosion detection, as the effectiveness can vary depending on factors such as the angle of the pipe and the positioning of the testing equipment. This implies that sound-based methods may need to be adapted or calibrated for different pipe configurations to ensure accurate and reliable corrosion detection. Figure 14 shows the wavelet results at microphone position 1.

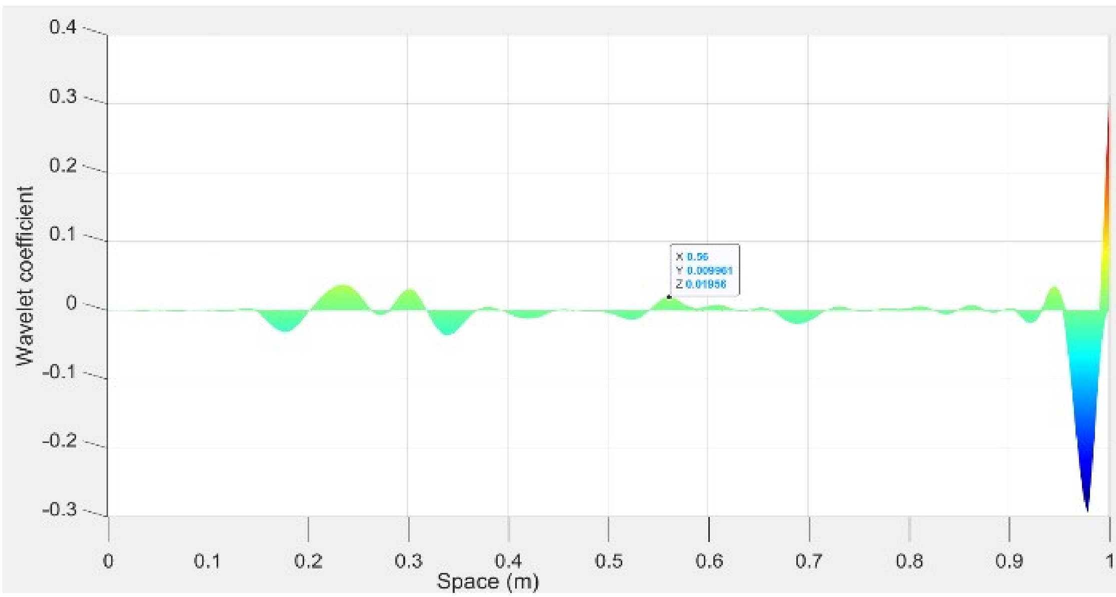

Figure 13: Depth-variation corrosion wavelet

Table 4: Coefficient of wavelet for multiple corrosion of the half circle

Mic Position	Coefficient			
	Corrosion 1 (90°, 45°, 0°, 315°, 270°)	Corrosion 2 (0°, 45°, 90°, 135°, 180°)	Corrosion 3 (90°, 135°, 180°, 225°, 270°)	Corrosion 4 (180°, 225°, 270°, 315°, 0°)
1 (0°)	0.02861	0.009649	0.009865	0.02512
2 (45°)	0.00902	0.00757	0.01113	0.01432
3 (90°)	0.01401	0.00859	0.00906	0.01213
4 (135°)	0.01474	0.00897	0.01036	0.01548
5 (180°)	0.01958	0.01933	0.01948	0.01292
6 (225°)	0.03909	0.01330	0.01895	0.01894
7 (270°)	0.04794	0.01480	0.01933	0.02813
8 (315°)	0.03824	0.01187	0.01188	0.02636

Table 5: Coefficient of wavelet for multiple corrosion of the quarter circle

Mic Position	Coefficient			
	Corrosion 1 (45°, 0°, 315°)	Corrosion 2 (90°, 135°, 180°)	Corrosion 3 (135°, 180°, 225°)	Corrosion 4 (225°, 270°, 315°)
1 (0°)	0.02718	0.0056	0.00861	0.01481
2 (45°)	0.01253	0.0163	0.01406	0.00919
3 (90°)	0.00489	0.0070	0.00692	0.00627
4 (135°)	0.00868	0.0020	0.00556	0.01066
5 (180°)	0.00028	0.0085	0.01075	0.00732
6 (225°)	0.00084	0.0066	0.00998	0.00735
7 (270°)	0.00052	0.0107	0.01115	0.01755
8 (315°)	0.03848	0.0091	0.00675	0.01970

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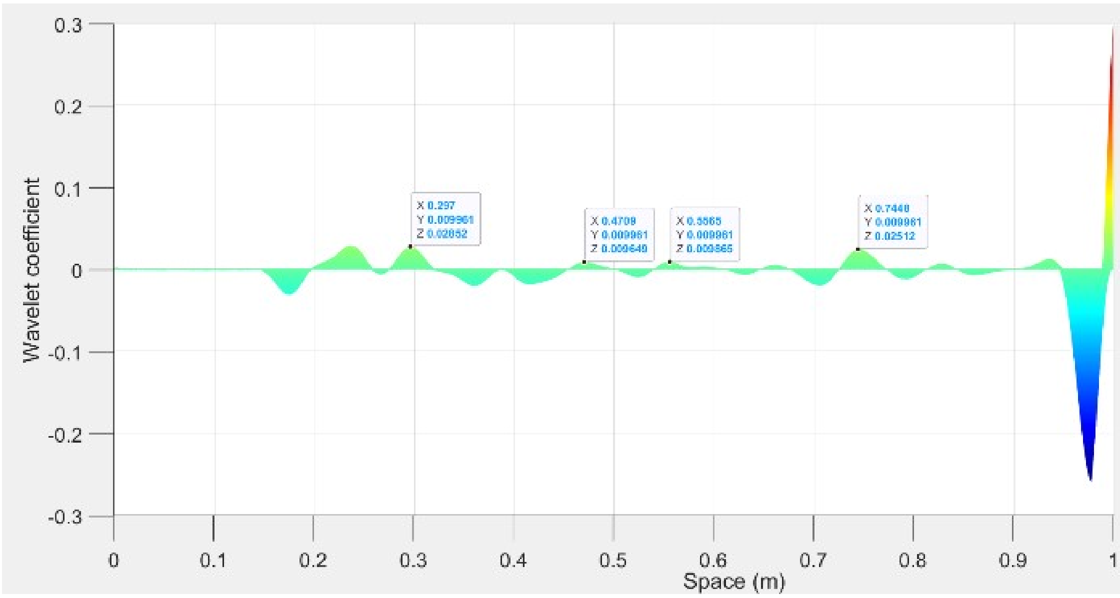

Figure 14: Wavelet multiple corrosion in a half circle

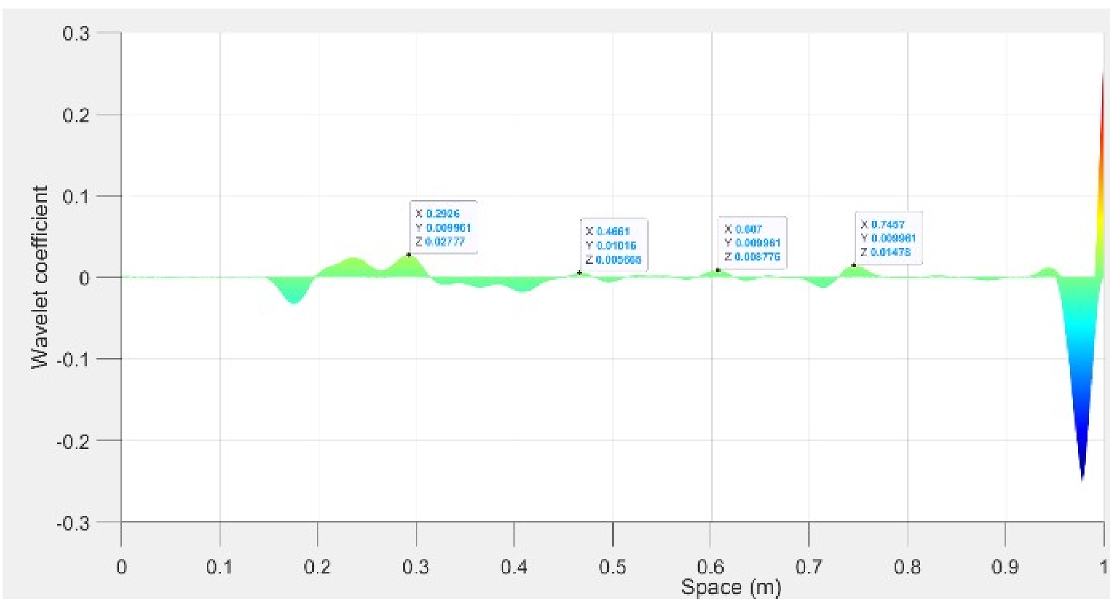

Figure 15: Wavelet of multiple corrosion of quarter circle

The test data is then summarized in Table 4. From Table 4, it can be concluded that the signal concludes that the microphone position that is parallel to the corrosion position will show a higher coefficient, which was not parallel to the corrosion. If traced further, referring to corrosion 1, which located along an angle of 90°, 45°, 0°, 315°, 270°. Ideally the microphone that was the right at that angle such as microphone positions 1,2,3,7 and 8 has the highest wavelet coefficient from other microphone positions. However, in the experimental data this did not happen or there were the ideal patterns. This happens because of the data misalignment. The data misalignment in question is that there is a difference in the amount of data for one cycle of pipe conditions.

Multiple corrosion testing was also performed with a smaller corrosion width to determine how sensitive and responsive the sound is to imaging corrosion. Figure 15 shows the results of the wavelet signal at microphone position 1. The results of this test are also loaded into the Table 5. The results show that the sound is still able to identify corrosion with a reduced width. In this case, it can be seen in Table 5, corrosion 1 which is at an angle of 45°, 0°, 315°, provides an appropriate response at the microphone position, where microphone positions 1, 2 and 8 show the highest coefficients from other microphone positions. The values of each

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coefficient were (0.02718), (0.01253) and (0.03848). This shows that the test result data is ideal for processing into corrosion visualization or data approaching data alignment.

Furthermore, these findings indicate that even minor corrosion can significantly impact sound propagation, making it a reliable indicator for early detection. The consistent responses across multiple microphone positions validate the effectiveness of the acoustic method in identifying varying corrosion widths. Ultimately, this enhances the potential for developing robust monitoring systems that can accurately assess pipeline integrity in real time.

5.0 CONCLUSION

The conclusion of this study reveals that sound signals have significant potential to provide detailed information about thin layers inside pipes, including various corrosion conditions. In the experiments, microphones mounted on the pipe's casing successfully captured different sound signal characteristics for each corrosion condition, indicating that physical changes within the pipe can be identified through acoustic signals. Furthermore, although the overall signal patterns were similar, variations in coefficient values suggest that further processing using signal processing techniques can transform this data into 3D imagery, providing a visualization of the pipe's internal conditions. However, to achieve a more accurate and representative visualization, advanced methods need to be developed to enhance the precision of translating these sound signals, especially concerning the complex physical and acoustic variations within the pipe environment.

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