FMDB *Transactions on Sustainable Energy Sequence*

Advanced Internal Corrosion Monitoring in Pipelines Using Magnetostrictive Sensors

G.V. Kanmani[1,*], D. Kerana Hanirex[2], S. Belina V. J. Sara[3], T. Shirley Devakirubai[4], M. Mohamed Sameer Ali[5], M. Mohamed Thariq[6], Saly Jaber[7]

[1]Department of Physics, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
[2]Department of Computer Science, Bharath Institute of Higher Education and Research, Chennai, Tamil Nadu, India.
[3]Department of Computer Applications, Faculty of Science and Humanities, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamil Nadu, India.
[4]Department of Commerce, Madras Christian College, East Tambaram, Chennai, Tamil Nadu, India.
[5,6]Department of Computer Science and Engineering, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
[7]Department of Analytical Chemistry, Saint Joseph University, Beirut, Lebanon.
kanmani@dhaanishcollege.in[1], keranahanirex.cse@bharathuniv.ac.in[2], sbelinav@srmist.edu.in[3], shirleydevakirubai@mcc.edu.in[4], sameerali7650@gmail.com[5], thariq10410@gmail.com[6], saly.jaber@usj.edu.lb[7]

Abstract: Economy and energy transportation infrastructure depend on transmission gas pipelines. Their safety and failure avoidance are national concerns. Coatings, cathodic protection, and advanced sensor checks maintain most underground pipes. The main pipeline inspection method is "smart pigging," where an inside inspection device goes through. Some pipelines are unsuitable for "pigging". These "unpiggable" cables may require excavation, making testing expensive and unfeasible. The pipelines' structural integrity must be tested using cheaper methods. This study examines the MsS for internal corrosion monitoring and detection in sensitive transmission pipeline sections in the lab and field. MsS uses guided mechanical waves below 100 kHz. These pulse-echo waves detect pipeline welds and problems. This approach lets you inspect long pipelines from one place. This approach detects circumferential cracking and corrosion. MsS examined refinery and chemical plant aboveground pipes. Torsional guided waves are used in MsS with a probe with a thin ferromagnetic strip (typically nickel) attached to the pipeline and twenty coil turns around it. The probe is cheaper than guided wave methods. It can collect data throughout time by being permanently mounted and buried on a pipeline at a low cost. Tracking condition changes over time would enable cost-effective pipeline integrity evaluation for crucial sections.

Keywords: Transmission Gas Pipelines; Magnetostrictive Sensor (Mss); Guided Wave Inspection; Pipeline Integrity Assessment; Internal Corrosion Detection, Unpiggable Pipelines; Transmission Gas.

Received on: 07/04/2024, **Revised on:** 21/06/2024, **Accepted on:** 15/08/2024, **Published on:** 07/12/2024

Journal Homepage: https://www.fmdbpub.com/user/journals/details/FTSES

DOI: https://doi.org/10.69888/FTSES.2024.000312

Cite as: G.V. Kanmani, D. K. Hanirex, S. B. V. J. Sara, T. S. Devakirubai, M. M. S. Ali, M. M. Thariq, and S. Jaber "Advanced Internal Corrosion Monitoring in Pipelines Using Magnetostrictive Sensors," *FMDB Transactions on Sustainable Energy Sequence*., vol. 2, no. 2, pp. 120–131, 2024.

1. Introduction

*Corresponding author.

Transmission gas pipelines are an integral part of the national energy-transportation infrastructure and, therefore, a lifeline for economic growth and energy security. Being operated at very high pressure, failure of such pipelines is dangerous to the public, property, and uninterrupted gas supply. Such failures can be prevented by periodical integrity assessment and maintenance [6]. While most transmission gas pipelines are underground and have various coatings and cathodic protection systems to protect from external corrosion, these methods cannot be failure-proof. Most ageing pipelines undergo internal and external corrosion and stress corrosion cracking, causing structural failures. Currently, pipeline health assessment through internal smart pigging is the common method used in the industry. However, such technology cannot be used to inspect many " undruggable " pipelines due to complex configurations, diameter variations, and intricate joints, which are considered too expensive for excavation and inspection. There's a need, therefore, to find cost-effective alternatives to make integrity assessments in such pipelines. Long-range guided wave technology looks promising for the inspection of unpiggable pipelines. This technology has already been implemented in refineries and chemical plants for inspecting long pipeline sections up to typically over 30 meters or 100 feet in each direction of a single sensor location.

Internal and external defects as small as 2-3% can be detected by this technology [2]. The commercially available two major systems are piezoelectric array sensors and magnetostrictive sensors (MsS). MsS technology involves a very thin ferromagnetic strip, usually nickel, bonded to the pipeline with coils wound around it. An electric pulse activates the coils, generating torsional-guided waves that travel along the pipeline and interact with the pipe wall. Reflections from welds or defects return to the sensor and create voltage signals that can be used to determine the location and severity of anomalies. Based on the magnetostrictive effect and its inverse, this system provides a non-invasive, cost-effective means for pipeline health assessment. It can inspect buried pipelines without excavation and monitor them for extended periods, a transformative capability in maintaining pipeline safety and reliability [3] (Figure 1).

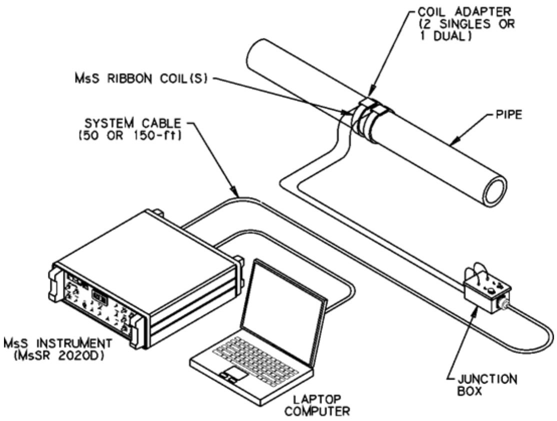

Figure 1: Schematic of MsS and instruments

This is MsS, Magnetostrictive Sensor, which will make a cost-effective inspection of and long-term monitoring of transmission gas pipelines, particularly where such susceptibility is reported, like being buried for long periods to the pipeline operators [1], thus specific areas that are low points in the pipeline and condensates collect the liquids are the concerned places especially to be susceptible to internal corrosion [4]. This MsS technology would effectively monitor these critical zones about the pipeline's structural integrity over the years. To enable focused monitoring, Ms's sensors could be installed 3.5 to 6 meters (10 to 20 feet) of these low points. The electrical leads from these sensors can be terminated at a connector box mounted at the surface, allowing inspectors to collect data without more significant interference with pipeline operations periodically. Inspection process. The inspection process collects and compares data sets taken at different time points to note the changes which might signify that defects have been initiated or have started to develop. This is one of the ways operators can sense slight changes in the conditions of the pipeline and, therefore, give advanced warning about probable internal corrosion and crack growths. Problems found early will allow operators to take preventive actions to eliminate costly repairs and avoid catastrophic failure. Therefore, the technology of MsS offers a trustworthy mechanism for monitoring the development and birth of defects, especially when it is hard to inspect pipelines [8].

Minimal excavation needs for installation is one of the benefits of MsS technology. This will help significantly cut the expense and the associated operational disturbance in deploying monitoring systems. Once installed, the MsS sensors become part of the pipeline system; therefore, it does not give way to short-term interruptions. This makes the technology very practical and able to harmonize with existing pipeline infrastructure and corrode engineering practices. Integrating MsS technology with pipeline corrosion management allows the operators to create an effective monitoring schedule and to determine the optimal sensor locations. Corrosion engineers can use the data obtained by MS's inspections to decide whether a pipeline needs maintenance, repair, or replacement [15]. This approach optimizes resource allocation and maximizes the service life of pipelines, hence contributing to increased operational efficiency and safety. The MsS technology is a major step forward in pipeline monitoring, combining affordability, ease of installation, and high performance. Its ability to provide continuous data on the condition of vulnerable pipeline areas ensures proactive pipeline integrity management. Integrating MsS technology with corrosion engineering strategies can enhance safety, reduce costs, and ensure the reliable operation of critical energy infrastructure. Such advanced monitoring emphasizes investing in up-to-date surveillance systems when coping with maturing pipelines and changing legislative provisions. These pipeline defects that were found early have now been manageable owing to such efficient MsS technology, guaranteeing long-run gas pipeline transport lines [12].

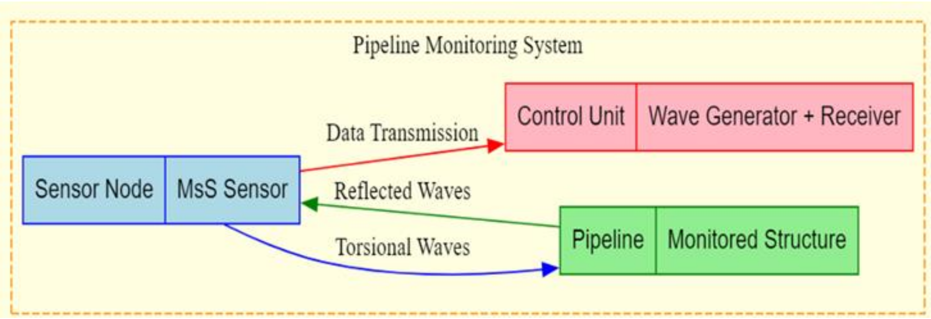

Figure 2: Illustration of MsS torsional wave technology for pipeline monitoring

Figure 2 represents a schematic diagram of streamlined pipeline monitoring with MsS torsional wave technology. Its core components are the sensor node, the pipeline as the monitored structure, and the control unit. In the streamlined concept here, the sensor node is painted light blue. It is the part responsible for generating and detecting torsional waves in MsS. The pipeline is the monitored structure, highlighted in light green. It has torsional waves propagating and finding any anomaly or flaw within it. The light pink control unit is both a source and receiver of the wave and data the sensor node gets. The three important interactions that this diagram is focused on are the torsional wave propagating from the sensor node to the pipeline through the blue arrow, the reflection of these waves back to the sensor node from the pipeline through the green arrow, and the data transmission from the sensor node to the control unit for further analysis through the red arrow. These constituents combine into an integrated "Pipeline Monitoring System" in the sense encapsulated by the dashed orange cluster boundary; they integrate the components to form one frame. It depicts, very efficiently, how the MsS technique may be adapted to pipeline integrity monitoring with the torsional wave propagation and reflection diagnostics that determine the defect, ensuring safe structure integrity and safe and efficient operations.

1.1. Objectives

The MsS technology has proven useful in detecting internal and external corrosion for various piping applications, including insulated and uninsulated aboveground piping networks in refineries and chemical plants. Its success in these environments makes it suitable for wider applications, such as long-term monitoring of buried pipelines. However, such technology may still involve technical and procedural demands to solve the potential problem it may be exposed to after being installed in an underground pipeline monitoring system environment. For example, the procedure for installing permanent sensors on a particular installation must take into account accessibility and soil conditions to ensure durability up to any given point in time in the future. Advancements in signal processing techniques, to be sensitive to small changes that may be apparent during the initiation and progression of defects, must be accompanied by noise reduction and increase signal clarity toward clear detection. Lastly, its sensitivity in detecting defects and the achieved monitoring range within the buried environments has to be accurately defined based on its operational scope and how optimal it will become upon deployment. These matters will have to do with MsS technology, which gives very early indications of defect possibility for reliable monitoring of integrity for buried pipelines and the means for proactive maintenance methods. With the above challenges overcome, the MsS technology can be a basis for efficient, cost-effective, long-term pipeline integrity management.

2. Literature Review

Transmission gas pipelines are important components of the energy transportation infrastructure, serving as lifelines to economic growth and energy security. As critical assets in the national economy, it is important that these pipelines operate safely and without interruptions [1]. These pipelines are primarily underground, and their anticorrosive protection is realized through coatings and cathodic protection systems, supplemented by periodic inspections [2]. "smart pigging," an internal device containing sensors that traverse the pipeline, is widely used among the inspection techniques [3]. However, some pipelines are less than ideal for smart pigging due to their design, including diameter changes, elbows, and complex configurations [4]. For these "unpiggable" pipelines, excavation for inspection is cost-prohibitive, thus requiring the development of cost-effective methodologies for structural integrity assessment [5]. MsS technology has proven to be a promising solution for the monitoring and early detection of internal corrosion in these pipelines. It uses guided mechanical waves of relatively low frequency, usually less than 100 kHz, to detect signs of defects or welds through pulse-echo testing [6]. It can efficiently examine long pipeline sections from a single location, identifying anomalies such as corrosion wastage and circumferential cracking [7]. MsS has been industrially used to scan aboveground piping in refineries and chemical plants, where its reliability and economy have been proved [8]. The mode of operation is mostly a torsional-guided wave using a probe that comprises a thin ferromagnetic strip (usually nickel) bonded on the pipe with multiple coil turns. These probes are less expensive than other guided wave systems and can be permanently mounted and buried for long-term monitoring [9].

This project aimed to demonstrate the feasibility of MsS technology for early corrosion detection in buried transmission pipelines. This was achieved in two phases. The first phase was the laboratory evaluation for the optimization of the technology, while the second phase was field demonstrations [10]. During the laboratory phase, several critical aspects were examined, including selecting adhesive bonding materials for permanent installation of sensors, testing on uncoated and coated pipelines above and below ground, and refinement of procedures for sensor installation and data analysis [11]. The key findings included the suitability of 5-minute epoxy to bond nickel strips and the capability of the technology to detect defects with about 0.5% pipe wall cross-sectional area loss over a 4.6-meter range in uncoated, aboveground pipelines [12]. The detection sensitivity did, however, drop to defects with a 2% wall loss over a 7.6-meter range due to wave attenuation from the soil for buried pipelines with 0.6 meters of soil cover. Besides increasing wave attenuation, the bitumen coatings lowered the detection sensitivity and range [13]. The two experiments on transmission gas pipelines were conducted on-site using bitumen coatings for corrosion protection. The first run was performed on a 610 mm (24-inch)-OD pipe having 6.4 mm (0.25-inch)-thick wall, and the second on a 762 mm (30-inch)-OD pipe having 11.4 mm (0.45-inch)-thick wall [14]. Both runs involved uncovering lengths of pipelines near supposed defect locations and then, after removing the coating in small areas, installing MsS probes. The probes were then tested, including after reburial in the case of the second pipeline [15]. The results showed that MsS probes could be permanently installed and buried for long-term monitoring of pipeline condition changes. However, a high attenuation wave caused by the bitumen coating and surrounding soil reduced the sensitivity and range of detection, thus limiting the effectiveness of the technology in such environments.

These results indicate that the MsS technology should be applied in benign, low-attenuation sections of pipelines, such as fusion-bonded epoxy or sleeved sections at road crossings [9]. In the case of bitumen-coated pipelines, the technology development at a higher level should include power output and attenuation problems [10]. Advanced sensor design or signal amplification may improve wave propagation to make MsS technology achieve reasonable detection and monitoring capabilities in high-attenuation environments [11]. In conclusion, this project demonstrated that MsS technology can become an inexpensive method for the long-term monitoring of transmission pipelines. Because it works well in low-attenuation environments, it still faces several challenges concerning operations in bitumen-coated pipelines, which will need further refinement [12]. When overcoming these challenges, MsS technology will become a robust tool in ensuring the integrity of critical pipeline infrastructure and supporting the safety and reliability of energy transportation systems [13].

3. Methodology

Pipelines represent critical industries of the petrochemical, nuclear, and electricity generation industries. Pipelines have also been part of the infrastructure for water supply, oil and gas transportation and distribution. They work with the most critical conditions: transferring energy products across hundreds of kilometres from production areas to processing or consumption points. Therefore, they must be near perfect to continue operations without mishaps, ensure safe operation and environmental protection, and continue their industrial processes. Internal corrosion detection can be a potent methodology for catastrophic failures and the best possible maintenance strategies. MsS technology is an advanced and cost-effective method for internal corrosion and flaw detection in pipelines. This begins with the observation of the operating conditions of the pipe and its environmental setting for the most susceptible to corrosion areas, mainly at the low spots where liquids would settle. Sensors such as the MsS are attached to the said strategic locations, either permanent or on-visit terms. The sensor has a ferromagnetic strip bonded to the pipe, and the coil is wound on it. This system uses an electric pulse that generates torsional-guided waves propagating along the pipeline. On reflection, any anomaly existing along the pipe, like corrosion or crack, will interact with the wave.

The processing of signals is of very high importance in this method. Further sophisticated algorithms are employed to process sensor data by cancelling noise that enhances the resolution of defect signals. Therefore, this technology will provide the most accurate detection of flaws like small wall thickness changes or incipient corrosion stages. The sensitivity and range of MsS technology are calibrated based on pipeline materials, size, and environmental application to ensure accuracy and results tailored for specific applications.

The methodology is based on generating a baseline dataset during the first inspection. Subsequently, inspections are performed with new data versus the baseline set to track progress in flaws or detect new anomalies. This offers pipeline operators a chance to visualize early-stage corrosion and take measures through preventive maintenance or repairs. Integration into pipeline management systems further enhances decisions by providing real-time pipeline health and facilitating predictive maintenance. This methodology deals with problems arising in buried pipelines when inspection using conventional techniques such as smart pigging is inapplicable. With less excavation need and the potential for long-range inspections from a single point, MsS technology brings forward a real way of pipeline inaccessible inspection. All-around process pipeline integrity management using MsS technology and traditional corrosion engineering practices can be provided. The MsS-based methodology will provide a reliable and scalable solution for early detection of internal corrosion inside the pipeline integrity assessment. This improves pipeline safety, operating reliability, and cost savings in inspecting and maintaining pipelines.

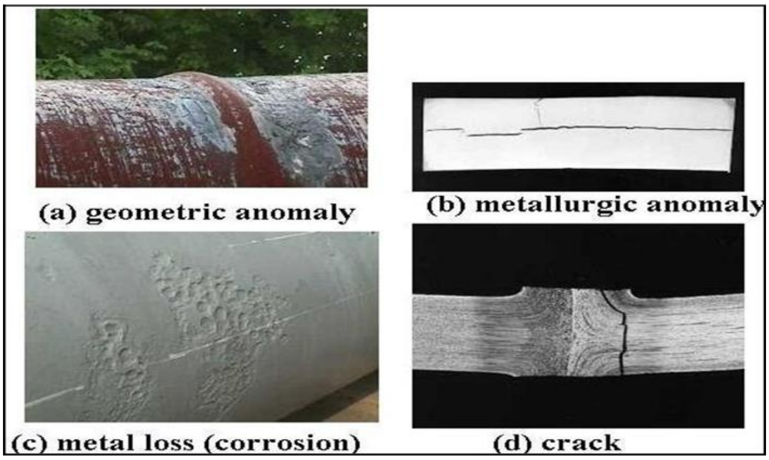

Figure 3: Common gas transmission pipeline flaws

Figure 3 displays four of the most common defects in pipelines. These can, indeed, have a tremendous impact on the pipeline's structural integrity and operating safety. In (a) geometric anomaly, it is a distortion in shape by deformation forces on the pipe due to applied external forces and improper handling and installation or from dents, buckles, or ovalities. Such anomalies create areas of stress concentrations that diminish the strength of the pipeline and open up potential secondary damage. Figure b is an image of metallurgical anomaly that mostly results from defects in manufacture, poor welding practices, or material faults, which are locations that become a failure area during the tension on the metal and pressure applied. The common and damaging problem with pipelines, as depicted in image (c), is corrosion through metal loss by chemical or electrochemical reaction with the environment. This damage weakens pipe walls and decreases their load-carrying capacities. There can also be a probable leakage or rupture due to large stress concentrations that might result from it. Image (d) is a crack, a critical flaw which may be caused by fatigue, stress corrosion, or impacts from the outside. Such flaws may propagate towards catastrophic failure with time if not detected and addressed in time. All of these images would tend to indicate the following: pipeline systems have to be periodically inspected and maintained using advanced techniques such as non-destructive testing for detecting, monitoring, and mitigating defects so that they would remain long-lasting, reliable, and safe.

The primary technique applied in pipe inspection is NDT. This scanning technique is fundamental in determining the pipeline conditions that ensure maintenance and safety. From the numerous journals and conferences held internationally, it is clear that the application of NDT in engineering is on the rise. Various NDT techniques are available, and each has different advantages and disadvantages, depending on the operating conditions of the pipe. Common methods rely on sensors to scan pipe integrity near the sensor. However, scanning long pipelines is time-consuming or dangerous unless the pipe is accessible or can accept a Pipeline Inspection Gauge. Smart PIGs, having high-tech sensors, can travel along pipelines and retrieve data over long distances.

Techniques such as UGW have gained much focus recently since they can scan over large distances over the pipeline from one application point. The challenges involved with UGW-based NDT inspection are the on-stream inspections under normal operating conditions in a plant at a reduced cost, periodic monitoring by probes installed within the test section to monitor changes over time, and the correct characterization of defects. Although obtaining data in NDT is simple, advanced methods may be used for defect dimension analysis and reconstruction. In most cases, the complete 3D flaw geometry cannot be obtained. The extensive usage of pressure vessels and pipelines in power, refining, and petrochemical industries places high risks like operational disturbances, loss of revenue, safety risks, and failure in a catastrophic form. Safety integrity must be maintained for the general public's and operator's safety. Therefore, defects and corrosion must be detected and analyzed through proper inspections. Onstream inspections are some of the most difficult because insulations complicate corrosion detection; it is equally challenging to have pipelines buried underground or beneath cities where the digging interferes with traffic and increases cost. Ultrasonic-guided waves could be the newest technology that makes the performance of tests from a single point possible while still monitoring the extent of corrosion or defects in a given pipeline. Annually, transmission pipelines that run through various parts of the globe span millions of kilometres and still grow yearly. Ensuring appropriate inspection technologies that promise safety, efficiency, and conformity can facilitate transportation services for energy products. In-line inspection tools carry out pipeline inspection operations at great distances. Among them is the smart pig that carries sensors. Pipeline threats, however, would have to calculate the length, pressure, flow rate, deformation, cleanliness, and inspection technology. Pipelines can only be safely operated if maximum maintenance is possible by providing proper and reliable inspection technologies.

Advanced in-line inspection tools have taken a long way from the challenge pipeline inspection posed earlier. Whereby formerly, a tool could not evaluate metal loss and cracks at once, runs required separate inspections with different tools, electronics and sensor carrier designs currently permit conducting both inspections in one go with one tool. It is not easy to integrate sensitive measurement technologies in the pipeline environment. Critical load-bearing components should be inspected to avoid failure. Their structural integrity and safety can be maintained through the periodical assessment of structural degradation and timely maintenance. For SHM and CBM to be economically and practically applicable to structures of the size of pipelines and pressure vessels, they must provide all condition information in real-time and on-stream at a minimal cost. One of the newer emerging technologies is the long-range ultrasonic guided-wave technology. This supports fast volumetric scanning of wide areas over the pipes and can detect internal and external defects. Small defects could be detected even at distances of one test position using the low-frequency guided wave application in a pulse-echo testing mode.

Advanced data processing systems are essential for meaningful information extraction from the inspection signals. These include methods that give the mean-squared error criteria for differentiating the echoes of defects from those produced by noise or signals created by pipeline features, welds and joints, and the geometry of flaws. This very hard inverse problem requires sophisticated techniques. Solutions of this type involve heuristic approaches like calibration, neural networks, and direct and iterative inversion physical models. Calibration is obtained by introducing known artificial defects with sizes on the pipes and recording the signals to establish calibration curves which predict the properties of the defect. Neural networks use regression techniques to map the signal from defects to actual sizes; hence, learning from the artificial defects allows estimation of the unknown geometries of defects. Direct inversion interprets the signals as a convolution of shapes of defects and transfer functions and then solves for characteristics of defects using de-convolution. The process of iterative inversion depends on forward modeling. Assumed geometries are used to compute signals and iteratively modified models to match measured data. Such methods are widely applied in industries like refineries and chemical plants to make pipeline inspection more efficient and reliable, hence safe for operations and integrity.

4. Result and Discussion

The article will discuss employing MsS technology to detect internal corrosion in pipelines early. It focuses on two factors: sensitivity to defects, guided wave behaviour, and pipeline coating and burial problems. Laboratory testing used a 0.25mm thick, 15.9mm wide annealed nickel strip bonded to the surfaces of the pipe to generate and capture the guided waves. The pipeline has an outer diameter of 610 mm with a wall thickness of 9.5 mm, artificially generated corrosion pits, and a corrosion pit comprised of 0.33-1% corrosion in the cross-sectional area. The internal surface of the inner surface of the pipeline's outer surfaces is intentionally inflicted by flaws. MsS is shown to be sensitive enough to measure even 0.33% for the monitoring mode; however, it resulted in some problems in differentiating the signal from the noise arising from its background, wherein the sizes of the defects were relatively smaller. Tested baseline data obtained for a defect-free pipe and then compared the results following the introduction of defects. These waveform differences clearly show that even much smaller defects could produce changes in the signal amplitude detectable for MsS. The current experiment clearly distinguished between the sizes of defects. The wave equation for guided wave propagation in cylindrical structures is:

$$\nabla^2 u(r,\theta,z,t) - \frac{1}{c^2}\frac{\partial^2 u(r,\theta,z,t)}{\partial t^2} = \frac{F(r,\theta,z,t)}{\rho} \quad (1)$$

Where:

$u(r,\theta,z,t)$ is the displacement field in cylindrical coordinates,
c is the phase velocity,
ρ is the material density,

$F(r,\theta,z,t)$ represents distributed forces acting on the system. The attenuation model for guided wave signals in coated or buried pipelines is:

$A([,x) = A_0(f) \cdot e^{-\alpha(j)x} \cdot \cos(2\pi f t - \beta x)$ (2)

Where:

$A(f,x)$ is the wave amplitude as a function of frequency f and distance x,
$A_0(f)$ is the initial amplitude at the source,
$cx(f)$ is the frequency-dependent attenuation coefficient,
β is the wave number.

Successively larger defects at 0.33%, 0.66%, and 1% of the wall cross-section of the pipeline were more detectable OD defects. The 0.33% defect produced a small signal change, whereas the 0.66% and 1% defects produced large differences. Waveforms at approximately 3 meters (10 feet) from the MsS sensor differentiated defects, and more significant defects resulted in greater signal loss under the scattering effect. For example, suppose the difference data adequately defined defects at 0.33% and 1%. In that case, it is difficult to envision any justification for why the same defect at 0.66% exhibited so little, if any, differences in signal. ID defects generally provided similar outputs, and MsS was suitable for internal corrosion monitoring. There also arose a challenge in environmental conditions by having a large variation in temperatures and slight deviations during signal subtraction, so refining the technology becomes quite important for it to give repeated results. The study extended its measurement capability to buried bitumen-coated pipelines for closer-to-reality field pipeline monitoring applications.

Table 1: Pipeline inspection data showing amplitude variations at different distances for various flaw intensities

Distance (ft)	Amplitude (0.2% Notch)	Amplitude (0.33%)	Amplitude (0.66%)	Amplitude (1.0%)
0	10	9	8.5	8
5	8	7	6.5	6
10	6	5	4.5	4
15	5	4	3.5	3
20	3	2.5	2	1.5
25	2	1.5	1	0.5

Table 1 displays the pipeline inspection data. There, it has been presented in terms of distance versus amplitude variation for different intensities of flaw. Here, distances are taken as zero and up to 25 feet, and their amplitude values at respective distances correspond to 0.2%, 0.33%, 0.66%, and 1.0% flaw intensity. Amplitude goes down with distance because the travelling signal from inspection gets attenuated while going through the pipeline. For instance, at 0 feet, the amplitude for the 0.2% notch starts with a value of 10 while reducing to 2 at 25 feet, indicating that the signal has become weaker. All flaw intensities have this tendency: a higher amplitude at a smaller distance indicates the reflection of ultrasonic waves from the flaws. Variation of amplitude due to the increase in intensity is found, as a high flaw percentage reflects the lower initial amplitudes with significant attenuation, and such variation indicates sensitivity for the inspection technique. It, therefore, brings crucial information that may be essential in defectivity assessment and its spatial distribution across the pipeline. A tabular representation for summarizing results will, however, enable detection and the locating of notches as well as other weld-related structural anomalies. Such information is critical to pipeline integrity because it can be used to determine areas of maintenance or repair crucial to the safe and efficient pipeline system operation.

For the 406-mm OD pipe with 1% defects at different axial positions, 10 kHz and 20 kHz guided wave frequencies were applied in the case of pipelines coated with bitumen. The data obtained at a higher frequency of 32 kHz could not propagate through the bitumen-coated surface. It was observed that waves of 10 kHz propagated well through the coated pipeline but suffered significant attenuation in waves of 20 kHz. Although the wave propagation at 10 kHz was successful, the MsS could not detect a 1% defect at 3 meters from the sensor in the bitumen-coated pipeline. Such a limitation reflects how pipeline coatings become a challenge against guided wave signal attenuation and, therefore, the effectiveness of current MsS technology. Further, such experiments also enlightened the possibility of the effect of coating thickness and properties on wave propagation; more work can be done to optimize sensor configurations and signal processing techniques in coated pipelines. Another challenge was the underground pipeline monitoring, as burials add complexity to the damping effect of the soil and environmental noises.

Preliminary results indicated that the attenuation of the signal in the buried pipelines was stronger than in the aboveground scenario and, thus, even harder to detect. Since bitumen coating and burial were combined to increase the attenuation on guided wave signals, the effective range of the MsS for detection was reduced. These results make the need even more evident to design high-sensitive sensor designs and amplification techniques that would apply to these limitations obtained in buried and coated pipeline scenarios. Research has also considered the reproducibility and reliability of MsS technology for monitoring pipelines.

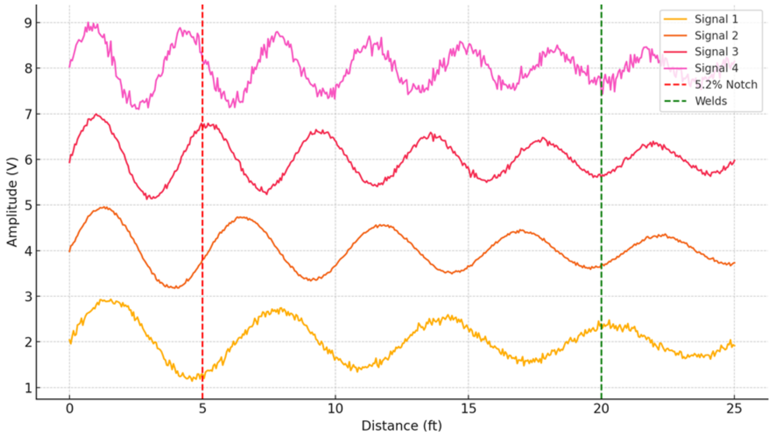

Figure 4: Inspection signals from Ms's pipeline inspection to detect flaws and structural anomalies

In Figure 4, several signals corresponding to various runs are shown. These signals are amplitudes versus distance along the pipeline. The features include an initial pulse, longitudinal modes, and reflected echoes resulting from defects or structural elements within the pipe. The features comprise the 5.2% notch, marked by a major signal amplitude change around 5 feet, and weld locations marked by clear reflections near 20 feet. The two features play an important role in understanding pipeline structural integrity. Signals attenuate gradually with distance, showing the energy dissipation as guided waves travel along the pipeline. The variations of the signals show the different flaw intensities and inspection conditions and highlight the method's sensitivity to defect size and type. The figure also shows the efficiency of ultrasonic-guided waves in identifying flaws and discontinuities over long distances from a single test point. This reduces the access directly to it, and because the pipeline could be fully checked, this further helps optimize inspection efficiency. Figure 4 depicts, in summary, how well the MsS inspection technique performed in finding the location of the notches and weld anomalies critical to pipe safety and reliability. The reflection coefficient for pipe wall thickness changes is:

$$R = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \quad (3)$$

Where:

R is the reflection coefficient for guided waves,
ρ_1, ρ_2 are the densities of the pipeline materials before and after the defect,
c_1, c_2 Do the wave velocities correspond to the two regions? Defect detection sensitivity based on cross-sectional area is given below:

$$S = \frac{\Delta A}{A_0} \times 100\% \quad (4)$$

Where:

S is the defect detection sensitivity,
$\Delta A = A_{defect} - A_{baseline}$ represents the change in cross-sectional area due to the defect,
A_0 is the original cross-sectional area of the pipeline.

Table 2: Comparison of baseline and monitoring data with subtracted RF and video signal amplitudes across pipeline distance

Distance (ft)	Baseline Data Amplitude (V)	Monitoring Data Amplitude (V)	Subtracted RF Signal Amplitude (V)	Subtracted Video Signal Amplitude (V)
0	0.5	0.48	0.02	0.01
10	0.4	0.38	0.02	0.015
20	0.3	0.28	0.02	0.01
30	0.25	0.23	0.02	0.008
40	0.2	0.18	0.02	0.006
50	0.15	0.13	0.02	0.005

Table 2 presents the baseline and monitoring data with subtracted RF and video signal amplitudes as a function of distance. Pipeline inspection baseline and monitoring data with distance measured at 10-foot intervals from 0 to 50 feet; amplitude variations in different conditions. The "Baseline Data Amplitude" column depicts the originally recorded signal amplitudes that are attenuated with distance, thereby illustrating signal attenuation along the pipeline length. The "Monitoring Data Amplitude" column depicts the recorded amplitudes during the monitoring phase, which is also attenuative but smaller in amplitude than baseline data, owing to the probable structural changes or anomalies in the pipeline. The "Subtracted RF Signal Amplitude" column is the difference between baseline and monitoring data in the RF range, equal to a small value, 0.02 V for all distances. This means there is not much change in this frequency range. Finally, the "Subtracted Video Signal Amplitude" column captures the difference in the amplitude of the video signals with slight fluctuations but generally decreases with distance. These differences will show anomalies or signals that could easily cause structural damage. Table 2 is significant to the pipeline for its integrity; it senses any minor differences in the amplitude of signals between the baseline and monitoring stages. These signal amplitudes will be subtracted from one another and interpreted by engineers as areas requiring particular attention or maintenance to maintain the pipeline safely and efficiently through service. Magneto constrictive transduction model is:

$$T = \frac{\mu_0 \cdot H^2 . \cdot (\Delta l)^2}{2E} \quad (5)$$

Where:

T is the energy of the transduced signal,
$\mu 0$ is the magnetic permeability of free space,
H is the magnetic field strength,
Δl is the change in the length of the magnetostrictive material,
E is the $Young^1s$ modulus of the material.

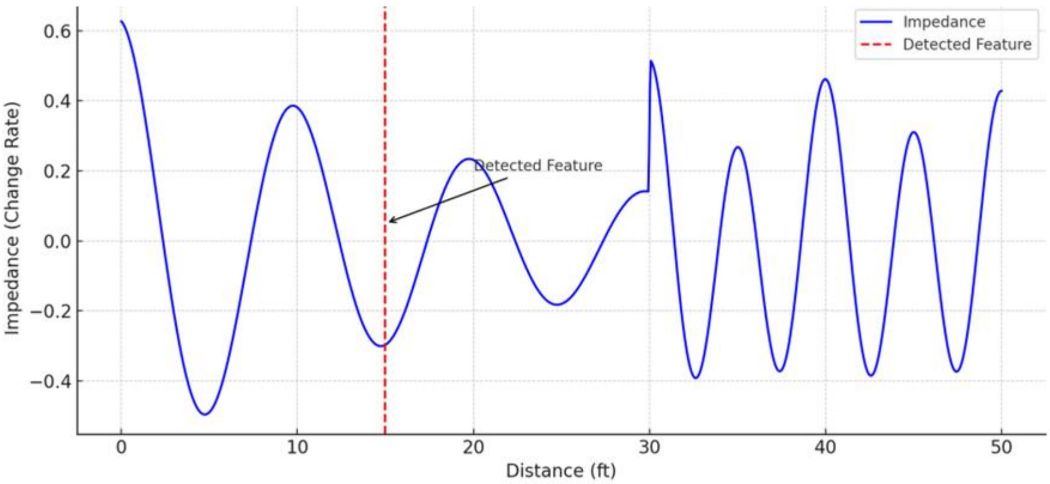

Figure 5: Representation of the rate of change of signal amplitude across pipeline distance

Figure 5 represents the gradient of signal strength with distance along the pipe, x-axis distance in feet, and y-axis impedance changes in the signal. A large signal is found at about 15 feet and indicated with a red dashed line. It is known as the "Detected Feature." This is a kind of big anomaly or change in structure, maybe a weld or defect or some other structural anomaly. Impedance varies along the pipeline with material properties, structural discontinuities, and energy losses. Shallow peaks and troughs indicate that the signals change quickly with features or flaws in the pipeline. After 30 feet, clear oscillations may be associated with other structural elements or geometric changes in the pipeline. This kind of analysis is crucial in pipeline inspection as it gives better insight into how the signal acts and where the anomalies are located. It then focuses on those areas with large changes in impedance. It draws them to operators' attention so they can draw their attention towards those regions for more investigation or maintenance. The simulated impedance graph is extremely important in non-destructive testing, as it makes it possible to monitor pipeline integrity efficiently and operate it safely.

Signals were collected repeatedly in identical scenarios to check for data integrity. It was found that even though MsS technology is extremely reliable for bigger-sized defects, it requires further calibration and signal processing for consistency even to identify smaller-sized defects that lie just above the detection threshold. The key factors affecting signal consistency were identified as temperature variations since small temperature changes critically affect both the amplitude and timing of guided wave signals. This demands temperature compensation algorithms and robust signal normalization methods to enhance the reliability of MsS technology in field applications. A significant feature of the work involved comparing the performance of MsS on uncoated versus coated pipelines.

The uncoated pipelines were better with clearer signal propagation and defect detection since the proposed technique could identify 0.33% defects in its monitoring mode. However, the bitumen-coated pipeline introduced significant signal attenuation, and the technology could not detect even larger defects. This difference illustrates that a certain approach has to be used according to the nature of the pipeline. One may need to adapt certain methods when applying MsS technology to coated pipelines, such as optimizing guided wave frequencies and sensor bonding techniques. A new achievement will be established regarding the possibility of using MsS technology to make very early internal corrosion to pipelines detectable based on aboveground uncoated installations wherein guided waves are transmitted quite satisfactorily throughout the cross-section of a pipeline. Indeed, the challenges that coatings, burials, and environmental conditions bring into play only emphasize existing possibilities that, even now, transcend the state of the art.

These problems should be overcome using a multiple-task approach to improve the sensor material, optimize the propagation frequencies for the guided wave mode, and create new data-processing algorithms. Research has to be developed in such directions that could achieve the creation of the MsS system in balance concerning environmental variables overcoming attenuation effects regarding coatings and burial to acquire a more holistic view of the possibilities and limitations for using MsS in monitoring the integrity of pipelines. These works form a foundation through which the further development of the MsS technology will make this technology much superior in fulfilling some of the dire needs in pipeline infrastructures. The relevance is related to the fact that through early detection of corrosion in pipelines and its usage, safe and dependable operation will always be possible. Pipelines need to be more innovative in their non-destructive testing methods to appropriately implement pipeline monitoring while solving emerging challenges in pipeline operations.

MsS technology was put through heavy laboratory and field testing to assess its feasibility for monitoring pipeline defects. MsS sensors with nickel strips glued onto pipelines collected guided wave data for uncoated, bitumen-coated, buried, and aboveground pipelines. Laboratory experiments also demonstrated the effectiveness of the MsS system at detecting defects ranging from 0.33% to 1% of the cross-section in the pipe walls, both externally and internally. The pipeline coatings using bitumen carried out the field test, which showed that for large attenuation values, it proved very difficult at higher detection frequencies. Although the guided waves of 10 kHz were partly successful, defects at the level of about 1% of the cross-section area of the wall could not be detected reliably over a distance of more than a few meters. The buried pipeline testing involved some extra complications due to wave attenuation and electronic noise, although MsS could detect defects from 1% to 1.5% in laboratory experiments.

Installation optimisation of MsS: Standardise bonding procedure for nickel strips, correct sensor positioning, and control the environmental issues such as condensation on-site during the application process. Laboratory experiments: Site selection and reference signals are two essential parameters because the attenuation of signals in the buried pipeline causes significant impacts on the detection of signals. It is highly significant in problems for which a laboratory environment poses less problem than having good access to practical implementations where installation pathways could determine field realization. Though it has the above limitations, it was deemed potentially useful for monitoring corrosion and structural changes in pipelines over time if installed with optimized configurations and validated for long-term use.

5. Discussions

Results from the study show the possibilities and drawbacks regarding using MsS in pipeline inspection for defective detection conditions in various operating mediums. Generally, results on laboratory experiments derived the capacity of MsS-based technology to discover small defection defects as small as 0.33% and 1% of pipe wall cross-section area by the high frequency propagative guided wave characteristics in guided pipeline structures, especially from uncoated aboveground locations. The amplitude data in Table 1 and Table 2 shows the signal differentiation method used in defect detection since there was a measurable increase in the defects involved in both baseline and monitoring data. Though this is more difficult to find at 0.33%, different amplitudes were realized for larger defects, such as 0.66% and 1%. The impedance graph of Figure 4 further emphasise that MsS technology can quickly follow varying signals in space, with locations and defects severity correlation; however, there are still obstacles like buried, which were with a bitumen coating. Wave attenuation is also highly recorded, which will cause some problems with detectable defects regarding the table and waveforms presented in Table 2 and Figure 4.

The results show that signal noise and environmental factors, such as bitumen coating and pipeline burial, greatly influence wave propagation and defect detection. The fact that signals could not be detected after 3 meters in buried lines and very high attenuation in lines coated with bitumen proves how optimized the MsS technology is to conquer such a problem. Practical lessons acquired were proper nickel strip bonding, proper frequencies used, which are 10 kHz for buried pipelines, and reliable reference signals. The improvement of practical lessons acquired must begin with improving the MsS application. Long-term monitoring pipelines would be possible if the strategic placement of sensors and reference signals could be established. The results emphasized that the preparation of surfaces and protection from environmental exposure, such as temperature and moisture, are crucial for deploying and operating sensors.

Field tests had promised promise for the potential of MsS technology under controlled conditions regarding the detection of corrosion and structural defects; however, the system's performance with buried and coated pipelines exposed major shortcomings. Tests conducted at several distances on both sides of the welds and known defects reflected that the system is not satisfactory enough to feel the presence of such occurrences at longer distances where the signal has attenuated. These limitations were of much greater significance for the scenario in which pipelines were covered by bitumen or significant soil covers, as heavy wave attenuation and noise proved to have quite strong effects on the system's efficiency. Though such limitations exist, the inherent merits of the MsS system have already begun to show through its ability to monitor generalized corrosion and structural anomalies in applications requiring real-time assessment and long-term performance tracking.

Hence, it is very useful for pipelines where continuous monitoring becomes a prerequisite for ensuring safety and a long period of operation. With an intent to make the MsS system fully available for practical utilization, most areas call for its optimization. In light of that, a call appears to improvise the installation procedure so the bonding increases while the sensor remains rightly positioned on the nickel strip. Installation, especially under high moisture and fluctuation in temperature and processing of signals, must be much more advanced, which would result in the elimination of much noise or effect of attenuation possible in obtaining the system as close to accuracy as possible. It would prove more applicable and practical if, for instance, it could stand on real-field validation, thereby broaching some of its difficulties, one of which is long-distance signal loss. These technologies are poised to revolutionize pipeline monitoring through the reliable and cost-effective detection of corrosion and structural defects in various environments.

6. Conclusions

The results revealed prospects and challenges with using MsS technology in pipeline monitoring, especially in finding corrosion and structural defects. Laboratory and field tests have validated the applicability of the technology to controlled environments where it could identify defects as small as 0.33% of the pipe wall cross-section in uncoated, aboveground pipelines. High wave attenuation and noise from buried and bitumen-coated pipelines greatly reduced the sensitivity and limited further the detection range. Pipe types tested in laboratory evaluations were the uncoated buried pipes, bitumen-coated pipes, and a wide range of sizes and configurations above ground. Artificial defects were made in simulating corrosion pits. The sensitivity in uncoated buried pipelines was down to 1% of the pipe wall cross-section using MsS sensors. Devcon 5-minute epoxy was also used. It proved important in providing reliable bonding of nickel foil sensors while ensuring durability even under harsh environmental conditions. Baseline and defect data were compared efficiently via signal processing algorithms that indicated improvements in such aspects as reduction in signal attenuation and enhancement in sensitivity for buried and coated pipelines are possible. This finding calls for optimization of the installation procedures and improved signal processing with field validation so that MsS can be more applicable under real conditions. Even though its present limitation is such applications requiring the real-time detection of defects, the MsS technique could be useful for long-term integrity monitoring of the pipeline, especially if it becomes necessary to monitor the progress of corrosion or track the environment very closely.

6.1. Limitations

MsS-based pipeline integrity-related internal corrosion detection at very early stages is highly limited in harsh environments. The signalling within a buried and coated pipeline is heavily attenuated; however, it is extreme in pipelines having bitumen-type coatings. Additionally, environmental variations such as thermal changes and soil conditions frequently complicate interpretation, as do noise interferences. Detection of defects whose sizes are less than 1% of the cross-section of buried pipelines is responsible for the limitation of system sensitivity. Therefore, it may be less effective in detecting corrosion at its incipient stages. Its performance is quite variable because field conditions are required to properly install nickel strips and maintain a good bond between them. For long-term monitoring applications, this failure to achieve uniform reference signals dampens the promise of MsS technology for monitoring the rate of progression corrosion. While successfully demonstrated in controlled environments, further improvement in signal-processing techniques is necessary to overcome real-world applications' inherent noise and attenuation problems. This is in terms of a lacuna in field validation of pipelines with complex geometries or surfaces corroded to such an extent that the technology will be limited to more considerable applications.

6.2. Future Scope

Some promising areas for future research in the early detection of internal corrosion in pipelines using MsS technology are further development of sensitive sensors and advanced algorithms for signal processing. With this, deficiencies due to noise and attenuation will be sufficiently counteracted, leading to reliable detection of defects from buried and coated pipelines.

Alternate sensor materials or bonding increase durability, especially under extreme environmental conditions. MsS technology, in combination with advanced data analytics, machine learning, and real-time monitoring systems, provides predictive capabilities for operators to measure corrosion risks before they become critical. Optimization of wave propagation in coated and buried pipelines and extension of the operational frequency range improves detection accuracy over longer distances. Several pipeline configurations, coatings, and environmental conditions will guarantee an increase in the reliability and applicability of the technology upon field validation under various configurations. Such MsS systems, when applied in fully integrative comprehensive programs of pipeline integrity management, make it one very effective tool in proactivity maintenance; therefore, the risk involved by operations of the pipeline is diminished by extension, as an extended lifespan could thereby make the MS technology of a safe option by ensuring a smooth operation process over pipelines close to the near future.

Acknowledgment: I am deeply grateful to my co-authors for their expertise and dedication, which greatly enriches this work.

Data Availability Statement: The data for this study can be made available upon request to the corresponding author.

Funding Statement: This manuscript and research paper were prepared without any financial support or funding.

Conflicts of Interest Statement: The authors have no conflicts of interest to declare.

Ethics and Consent Statement: This research adheres to ethical guidelines, obtaining informed consent from all participants.

References

1. J. B. Nestleroth, "Pipeline in-line inspection - challenges to NDT," in Proc. 9th European Conference on NDT (ECNDT), Berlin, Germany, vol. 48, no. 9, p. 524, 2006.
2. G. Acciani, G. Brunetti, G. Fornarelli, F. Bertoncini, M. Raugi, and F. Turcu, "3D-3 classification of defects for guided waves inspected pipes by a neural network approach," in 2007 IEEE Ultrasonics Symposium Proceedings, New York, United States of America, 2007.
3. J. B. Nestleroth and T. A. Bubenik, Document prepared for The Gas Research Institute, "Harvey Haines Project Manager," Batelle, Columbus, Ohio, United States of America, 1999.
4. H. Kwun, S.-Y. Kim, and G. M. Light, "Magnetostrictive sensor guided-wave probes for structural health monitoring of pipelines and pressure vessels," Applied Physics Division, vol. 61, no. 1, pp. 80–84, 2003.
5. H. Kwun, C. P. Dynes, and S. Y. Kim, "Evaluation of the magnetostrictive sensor (MSS)," vol. 36, no. 1–5, pp. 171–178, 1998.
6. Q. Zhou, W. Wu, D. Liu, K. Li, and Q. Qiao, "Estimation of corrosion failure likelihood of oil and gas pipeline based on fuzzy logic approach," Eng. Fail. Anal., vol. 70, no. 12, pp. 48–55, 2016.
7. C. I. Ossai, B. Boswell, and I. J. Davies, "Pipeline failures in corrosive environments—A conceptual analysis of trends and effects," Eng. Fail. Anal., vol. 53, no. 7, pp. 36–58, 2015.
8. H. R. Vanaei, A. Eslami, and A. Egbewande, "A review on pipeline corrosion, in-line inspection (ILI), and corrosion growth rate models," Int. J. Press. Vessel. Pip., vol. 149, no. 1, pp. 43–54, 2017.
9. M. Adegboye, W. K. Fung, and A. Karnik, "Recent advances in pipeline monitoring and oil leakage detection," Sensors, vol. 19, no. 11, p. 2548, 2019.
10. Z. Usarek and K. Warnke, "Inspection of gas pipelines using magnetic flux leakage technology," Adv. Mater. Sci., vol. 17, no. 5, pp. 37–45, 2017.
11. M. Coramik and Y. Ege, "Discontinuity inspection in pipelines: A comparison review," Measurement, vol. 111, no. 12, pp. 359–373, 2017.
12. X. Tan, F. Liang, Y. Huang, and B. Yi, "Detection, visualization, quantification, and warning of pipe corrosion using distributed fiber optic sensors," Autom. Constr., vol. 132, no. 12, p. 103953, 2021.
13. S. Oh, J. Kim, J. Lee, D. Kim, and K. Kim, "Analysis of pipe thickness reduction according to pH in FAC facility with In situ ultrasonic measurement real-time monitoring," Nucl. Eng. Technol., vol. 54, no. 1, pp. 186–192, 2022.
14. Y. Yang, S. Liang, B. Bijan, N. T. Thuc, C. Zhai, J. Li, and X. Xie, "Torsional capacity evaluation of RC beams using an improved bird swarm algorithm optimized 2D convolutional neural network," Eng. Struct., vol. 273, no. 12, p. 115066, 2022.
15. M. Zhang, X. Chen, and W. Li, "Hidden Markov models for pipeline damage detection using piezoelectric transducers," J. Civ. Struct. Health Monit., vol. 11, no. 4, pp. 745–755, 2021.