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CRACK TRACKING IN SMALL-DIAMETER METAL PIPE USING CONTROLLED MOTOR VIBRATIONS AND FLEXIBLE SENSOR

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ABSTRACT: Metal pipes are the most integral part of transporting water, gas, and other petrochemical substances over long distances. Higher strength, durability (along with wear and corrosion resistance), and lower cost make these pipes suitable for extreme weather conditions and hostile environments. Over time, these pipes experience significant impacts that may lead to defects such as holes, cracks, bends, corrosion, and finally component failure and property losses. Therefore, early detection of the defects in pipes is crucial to prevent such failures. There are several methods to detect defects in metal pipes, including non-destructive testing (NDT). However, high costs and declining performance are existing concerns for those NDTs. A motor-induced vibration source is more robust and reliable than a conventional vibration sensor. Thus, the feasibility of using a motor as a vibration source for metal pipe crack detection is studied in this work. To achieve this, a DC motor is placed on one side of the metal pipe and used as the vibration source. These vibrations are collected by a piezoelectric polymer, specifically a Polyvinylidene fluoride (PVDF) sensor, on the other side of the pipe. This work considers three types of pipe conditions: healthy pipe, bent pipe, and cracked pipe. Additionally, two different sensor locations (180-degree rotation) and sensor patterns (bent and not bent) are studied. From the studies, we can see that there are significant differences in pressure responses for healthy pipe and cracked pipe conditions. The maximum pressure response for a cracked pipe is 783 a.u. (intensity) whereas it is just 262 a.u. for a healthy pipe. Thus, the difference is sufficient to set a threshold margin. We have set 300 a.u. as the threshold margin and applied it to an algorithm. The algorithm can successfully detect a healthy or cracked pipe. However, it is very tricky in the case of a bent pipe, as the pressure differences are less than 300 a.u. for three conditions and above for only one. Hence, it might provoke an incorrect decision when detecting a bent pipe.

ABSTRAK: Paip logam adalah bahagian utama dalam mengangkut air, gas, dan bahan petrokimia lain dalam jarak jauh. Kekuatan dan ketahanan tinggi (bersama rintangan hakisan dan penggunaan), dan kos lebih rendah menjadikan paip logam sesuai bagi keadaan cuaca dan persekitaran melampau. Walau bagaimanapun, dari masa ke masa, paip logam mengalami kesan ketara seperti berlubang, retak, bengkok, hakisan dan akhirnya kegagalan komponen dan kehilangan harta benda. Oleh itu, pengesanan awal kecacatan pada paip adalah sangat penting bagi mengelakkan kegagalan tersebut. Terdapat kaedah tidak merosakkan (NDT) bagi mengesan kecacatan pada paip logam. Walau bagaimanapun, kos yang tinggi dan prestasi merosot adalah kebimbangan sedia ada pada NDT. Sumber getaran dari motor adalah lebih berdaya tahan dan lebih dipercayai berbanding pengesan getaran konvensional. Oleh itu, kebolehlaksanaan motor sebagai sumber getaran bagi mengesan paip logam yang retak dikaji dalam kajian ini. Bagi tujuan ini, motor DC diletakkan pada satu sisi paip logam dan digunakan sebagai sumber getaran. Getaran ini dikumpul oleh pengesan polimer piezoelektrik Poliviniliden Fluorida (PVDF) pada bahagian lain paip. Tiga jenis keadaan paip, iaitu paip sihat, paip bengkok dan paip retak dipertimbangkan dalam kajian ini. Tambahan, dua lokasi pengesan berbeza (pada putaran 180 darjah) dan corak pengesan (bengkok dan tidak bengkok) dikaji. Dapatan kajian menunjukkan terdapat perbezaan ketara dalam tindak balas tekanan bagi paip berkeadaan sihat dan retak. Malah, tindak balas tekanan maksimum bagi paip retak adalah 783 a.u. (intensiti) sedangkan hanya 262 a.u. bagi paip sihat. Oleh itu, perbezaan ini cukup bagi menetapkan margin ambang. Kajian ini telah menetapkan 300 a.u. sebagai margin ambang dan menggunakannya pada algoritma. Algoritma ini berjaya mengesan paip sihat atau retak. Walau bagaimanapun, adalah sangat rumit bagi mengesan paip bengkok kerana perbezaan tekanan adalah kurang daripada 300 a.u. bagi tiga syarat tersebut. Oleh itu, ia mungkin mencetuskan keputusan yang salah bagi mengesan paip bengkok.

KEYWORDS: *Guided wave; Pipe inspection; Metallic pipe structures; Non-destructive evaluation (NDE); Remaining useful life (RUL)*

1. INTRODUCTION

Pipelines are very crucial for resources like oil, gas, and water. Extracting these from underground to transporting them to the consumer ends requires a steady and reliable medium, and pipelines are the best solution. Resources can easily be transported over long distances or between countries using pipelines [1,2]. However, despite the improved quality and reliability, pipes are not meant to last a lifetime. Hence, quality and reliability both will degrade over time or due to influence. This can cause accidents with serious consequences and can cause fatalities, injuries, economic losses, and environmental damages [3]. According to the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) data, during 2002-2021, 680 pipeline incidents were recorded in the USA, with 260 fatalities, 1109 injuries, and over a billion dollars in damages [4]. Major reasons for these incidents are external interferences, corrosion, construction defects/material failures, hot taps, ground movements (earthquakes, landslides), and deformations [5].

Therefore, inspecting and monitoring the pipeline to maintain structural integrity is crucial. Various solutions are available to detect the unusual structural deformations of the pipes. However, sensor-based approaches have become the most convenient choice, along with magnetic flux leakage (MFL) testing, ultrasonic testing (UT), electromagnetic acoustic technology (EMAT), eddy current testing (EC), Electric Field Mapping (EFM), Eddy Current Inspections, sonar mapping, and guided waves [6-9]. These sensors are already available in the market and ready for use. Nevertheless, their functions are complex and multi-directional. Moreover, their larger geometry makes longer pipes necessary, impacting lab-based quality enhancements. On the contrary, we aim to investigate a more cost-effective and simpler solution.

Guided waves are a widely used technique for nondestructive testing (NDT). In this technique, waves produced by a vibration source are guided through the pipe to be inspected, and a sensor collects the waves. The pattern of the received waves can define the deformity in the pipe. These vibration sources (technically transducers) usually experience a decline in performance over time and during their life cycle. These factors make their performance unpredictable in the long run, especially when consistently influenced by temperature, humidity, vibration, and shock [10,11]. Declined performance can lead to incorrect results and, consequently, wrong recommendations [12]. Consequently, this makes them unsuitable as a vibration source for a sensory system, where the troubleshooting recommendation depends entirely on the received results.

A motor, on the other hand, is more reliable compared to a conventional vibration sensor. A motor's output, represented as Revolutions Per Minute (RPM), is fixed based on the input rating. Therefore, applying a specific voltage can only achieve a specific RPM. The combination of the motor's produced torque and RPM will create vibrations due to its rotation. These vibrations can be propagated to an attached surface. Hence, the motor acts as a vibration source. Motivated by this, we intend to investigate the feasibility of guided waves from motor vibrations. Therefore, we propose using a DC motor as a wave source. These motor vibrations can be guided through a metal pipe from one end and collected by a vibration sensor on the other. We have used a flexible piezoelectric polymer, Polyvinylidene fluoride (PVDF), as a sensor to collect the vibrations from the DC motor. In this work, we will focus on using guided waves to detect a crack in a metal pipe. To achieve this, we consider two pipe conditions: a healthy pipe and a deformed or cracked pipe. The characteristics of the received waves will indicate any deformations on the surface of the pipe.

The rest of the paper is organized as follows: Section 2 presents the related work. Section 3 describes the experimental design, while Section 4 presents the results and evaluation. Lastly, Sections 5 and 6 conclude this paper with some prospective future agendas and the limitations of the work.

2. RELATED WORKS

The best way to monitor pipelines is to use cost-effective and less invasive screening inspections that could provide a more global perspective of the pipeline while also suggesting which areas may require additional attention [13]. One very simplistic example of said screening inspections is sensors. Sensor technologies can include instruments that cover a wide range of physical principles, including electrical, optical, radiographic, chemical, and acoustic domains.

2.1. Magnetic Flux Leakage (MFL)

MFL inspection starts by saturating a magnetic field with a metallic surface, such as the pipe. Defects on the pipe's surface will disrupt the magnetic field's flux, leading to an aberration in the field outside the pipe surface. The aberration will indicate a pipe leakage, which is measured by the Hall effect sensor [13].

2.2. Electric Field Mapping (EFM)

The EFM method uses two electrodes in contact with the pipe. Current will pass through the pipe between the two electrodes, and the voltage drops between the two electrodes are measured. Any anomalies on the surface of the pipe, like cracks and corrosion, will alter that area of the pipe and thus the measured potential drop within the two electrodes [14, 15, 16].

2.3. Eddy Current Inspections

Eddy currents are structured electric currents that develop in a conductor due to changes in the magnetic field. During eddy current inspections, a magnetic field can be passed through the pipe, penetrating its surface, inducing current, and generating eddy currents on its surface. Any cracks and anomalies on the pipe's surface will be identified by the disturbance in the formation of eddy currents on the surface [17, 18].

2.4. Sonar Mapping

Sonar technology uses sound waves underwater to detect objects, aid navigation, and facilitate mapping. Multi-beam bathymetry and Side Scan Sonar (SSS) are commonly preferred methods for subsea pipeline inspections. By analyzing the seabed with sound waves, one can detect the return of the sonar pulse, the sea depth, and the position of anomalies by examining the amplitude of the sound wave reflections [19-21].

Moreover, guided waves benefit pipe inspections for various reasons [22-25]. This can be attributed to their long propagation and high sensitivity, but primarily, the interaction between guided waves and materials can effectively identify cracks in a pipe. Guided waves are particularly utilized in situations requiring high-sensitivity detection techniques. This includes microscale damage such as the initiation of fatigue cracks, early-stage corrosion, and material degradation. The excitation wavelength constrains the guided wave inspection technique, which can only detect significant damage.

3. SYSTEM DESIGN AND WORKING METHOD

Flexible sensors typically exhibit a broad range of pressure responses. Depending on the product definition and material volume, these responses range from very low to very high. A monitoring platform can also detect these responses. We chose the Arduino-based temporary monitoring system for its flexibility. Nevertheless, the limitation with Arduino is its inability to detect piezoelectric reactions in terms of voltages. Instead, it presents the responses in terms of sensor values. The highest value indicates the maximum voltage generated by the sensor. These sensor values are adjustable. We divided the total sensor values into 1024 units for our system. This implies that 1024 units will represent the highest pressure effect as the maximum sensor value. The fluctuation in these values will help identify the patterns for the pipe crack conditions.

Table 1. Experimental Setups Based on Pipe Conditions

Pipe condition	Sensor location	Sensor pattern
Healthy pipe	Top	Not bent
	Top	Bent
	Bottom (+180 deg)	Not bent
	Bottom (+180 deg)	Not bent
Bent pipe	Top	Not bent
	Top	Bent
	Bottom (+180 deg)	Not bent
	Bottom (+180 deg)	Not bent
Cracked pipe	Top	Not bent
	Top	Bent
	Bottom (+180 deg)	Not bent
	Bottom (+180 deg)	Not bent

Table 2. Mechanical properties of the pipe

Mechanical Properties	Metric
Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa
Modulus of Elasticity	68.9 GPa
Poisson's Ratio	0.33
Fatigue Strength	96.5 MPa
Shear Modulus	26 GPa

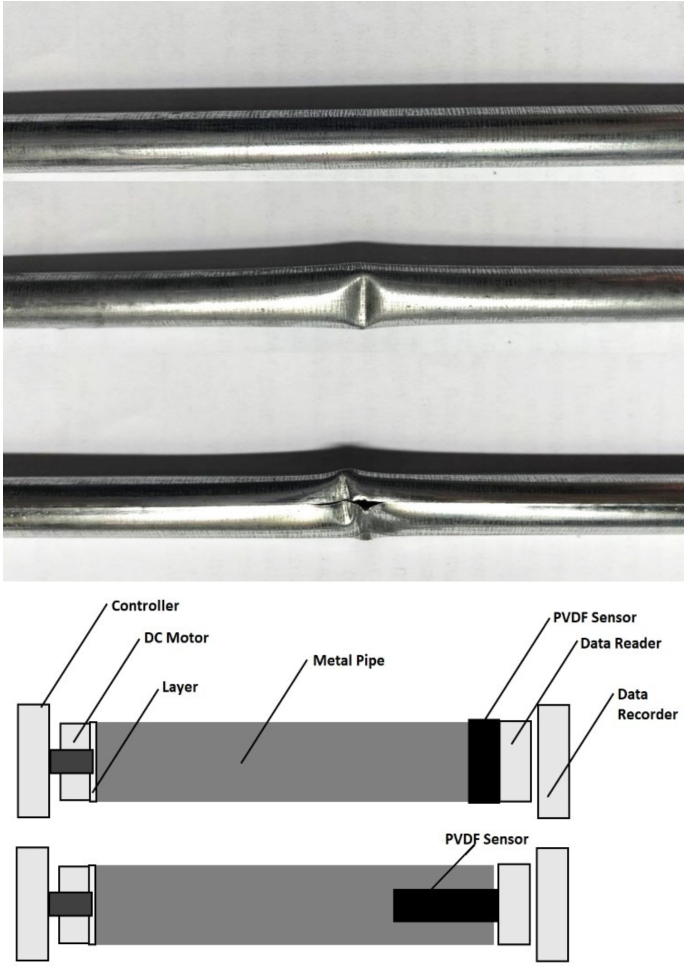

Figure 1. Considered cases of metal pipes. (a) a healthy pipe without any damage, (b) a bent pipe without an existing air hole, and (c) a cracked pipe with an existing air hole.

These fluctuations need to be stored as well for the sake of investigation. The data can be stored using Arduino since it connects to a data reader. Thus, the data is stored in memory.

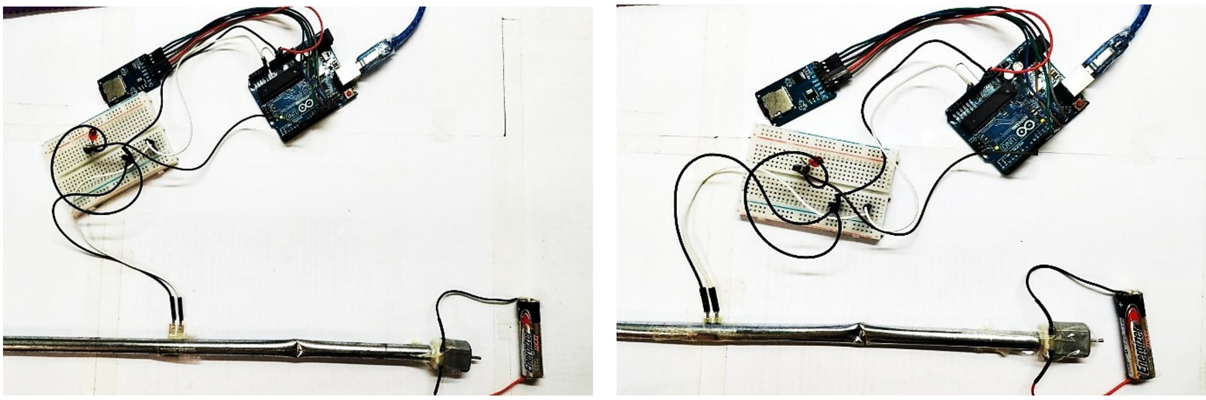

Figure 2. Experimental setup with a bent (left) and a cracked (right) pipe with damage.

3.1. Experimental Setups

Three types of pipe conditions are considered for the experiment. We have used aluminum pipes (6061 aluminum alloy tube (aluminum magnesium silicon alloy)) with an approximate diameter of 9 mm and 0.5 mm. Mechanical properties are mentioned in Table 2. First, we take a healthy pipe without deformation to find the threshold response values. These values will later be compared with the other cases. A bent pipe without any holes is then experimented on. Lastly, a cracked pipe is investigated to determine distinguishable differences. The pipe's bent length is approximately 7 mm. The open hole in the pipe is approximately 8.5 mm. The experimental setups are shown in Table 1 and demonstrated in Figure 2. All experiments are performed using two criteria: sensor location and sensor pattern. Sensor location reflects the position of the sensor with respect to the crack. Therefore, the top sensor location indicates that the sensor is positioned at the end of the pipe and aligned with the crack. Additionally, the sensor is attached to the pipe either parallel or bent according to the pipe surface, as illustrated in Table 1.

3.2. Components

This investigation utilizes three main component blocks: vibration sources, reading platforms, and recorders.

- *Vibration Source*: A vibration source will generate the prescribed vibrations. It is placed at one end of the investigated pipe. As previously mentioned, a DC motor has been utilized as the vibration source for this study. A power source is used to drive the vibration source. We have applied 3V DC to run the source; the rated RPM of the motor is approximately 13000 RPM, 3V.
- *Reading Platform*: A reading platform can read traveling vibrations through the pipe as responses. We have used Arduino Uno to read the pressure responses.
- *Recorder*: The pressure responses can be stored in memory. For this work, we have used a 16-gigabyte memory.
- *Definition*: The voltage presented in Section 4 (Results and Discussion) does not represent the real-time measured voltage. As previously mentioned, Arduino Uno cannot display the sensor output in volts. Therefore, we measured the supplied source voltage and distributed it based on the sensor value range. The sensor value range is 1-1024, and the measured voltage is 2 volts. Therefore, each sensor value represents (2000/1024) = 1.953 mV; the 1024 sensor value corresponds to 2 V.

3.3. Cases

Three types of cases are examined in the experiment based on the pipe's condition. In case 1, an intact pipe without any deformities is investigated. In cases 2 and 3, bent and cracked pipes are analyzed in the investigation. The bent and cracked pipes are intentionally deformed, not naturally occurring deformities. For all cases, 4 conditions are considered, with 2 kinds of sensor locations and 2 types of bending patterns. The conditions are described as follows:

- *Condition 1*: In this condition, the sensor is not bent and is attached in a parallel position with respect to the pipe. The sensor is located at the end of the pipe.
- *Condition 2*: In this condition, the sensor is bent and is attached to a vertical position with respect to the pipe. The sensor is located at the end of the pipe.
- *Condition 3*: Similar to condition 1, the sensor is not bent and is attached in a parallel position with respect to the pipe. However, compared to condition 1, the sensor is located at the end of the pipe with a 180-degree rotation.

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- *Condition 4*: Similar to condition 2, the sensor is not bent and is attached vertically to the pipe as well. However, compared to condition 2, the sensor is located at the end of the pipe with a 180-degree rotation.

4. RESULTS AND DISCUSSION

4.1. Case 1

In the first case, the pipe had no external damage. From the results, we can see that conditions 1 and 4 both have the highest sensor value of 244 a.u. (intensity) with averages of 179.33 a.u. and 175.51 a.u., respectively. Conditions 2 and 3 both show the highest value of 262 a.u., with average sensor values of 179.11 a.u. and 172.45 a.u., respectively. Hence, we can summarize that for case 1, the highest sensor value obtained was 262 a.u. The results are summarized in Figure 3.

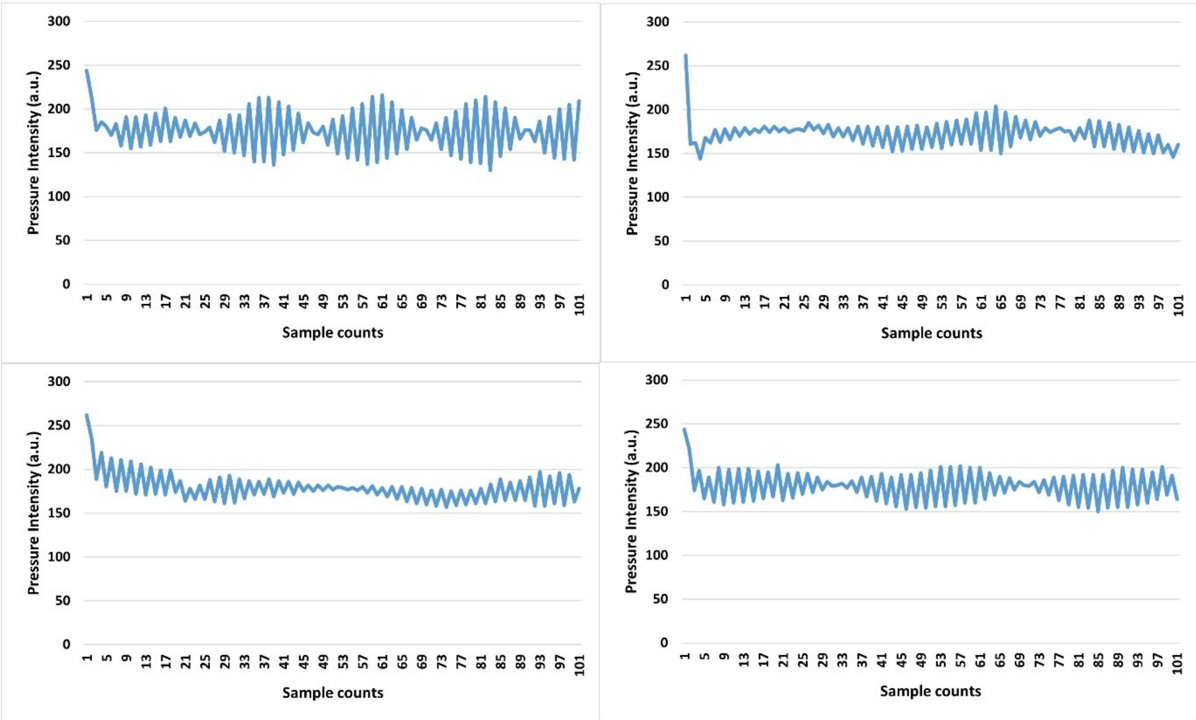

Figure 3. Pressure responses from pipe with no external damage (case 1)

4.2. Case 2

In the second case, the pipe is bent, so it has existing damage. As Figure 4 shows, condition 1 exhibits 300 a.u. of maximum values with an average of 177.21 a.u., while condition 2 has a maximum of 311 a.u. and an average of 190.54 a.u. It is 321 a.u. maximum and an average of 175.69 a.u., for condition 3 and a maximum of 590 a.u. with an average of 242.18 a.u. for condition 4. Hence, the highest sensor value recorded for this case is 590 a.u.

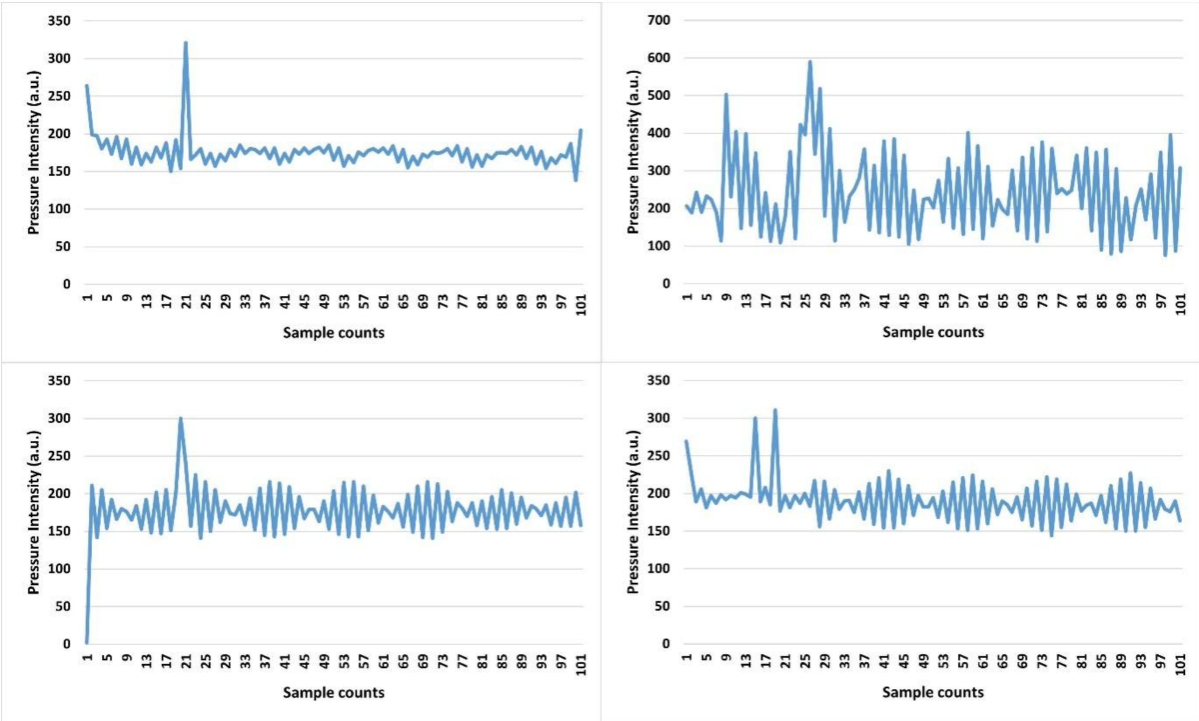

Figure 4. Pressure responses from a bent pipe without an existing air hole (case 2)

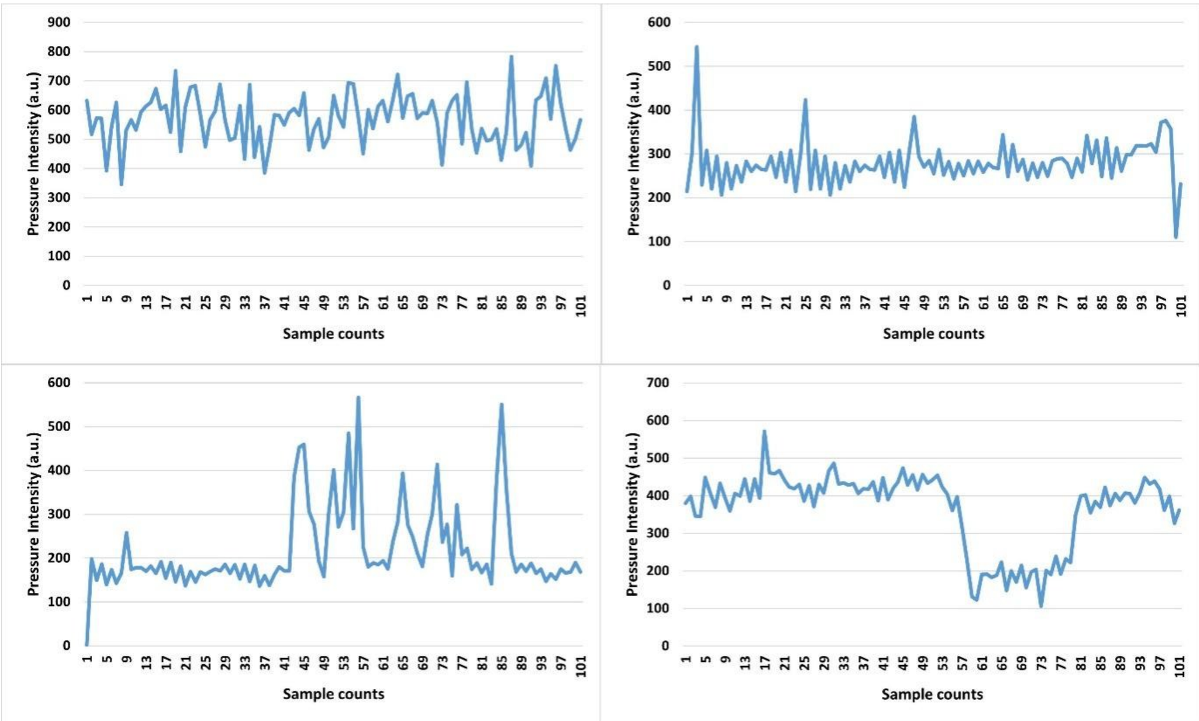

Figure 5. Pressure responses from the pipe with a crack and an existing air hole (case 3)

4.3. Case 3

In this case, the pipe is damaged with a crack. The results are depicted in Figure 5. In this case, condition 1 exhibits 566 a.u. as the maximum values with an average of 216.65 a.u., while condition 2 has a 572 a.u. and 363.49 a.u. average value. It is 783 a.u. and an average of 568.63

a.u. for condition 3 and a maximum of 544 a.u. with an average of 279.13 a.u. for condition 4. Hence, the highest sensor value recorded for this case is 783 a.u.

4.4. Discussion

Since we have the required values, we can now make the decisions from the aforementioned discussions and results presented in Figures 3, 4, and 5. We can see a maximum sensor value of 262 a.u. with an average of 179.11 a.u. indicates a healthy pipe response, as shown in Figure 3. Comparatively, a bent pipe will experience a maximum of 590 a.u. with an average of 242.18 a.u. of pressure responses. But for the case of a cracked pipe, a 783 a.u. maximum value and average of 568.63 a.u. is found.

The compiled results are presented in Figure 6. From the figure, we can see a better picture of the cases regarding distinguished responses. Figure 6 presents the received pressure responses for conditions 1, 2, 3, and 4, where the sensor is either not bent or bent, either aligned to the crack or not. Therefore, this number can be taken as a threshold value for the considered cases.

However, the differences between a healthy and a bent pipe are very difficult to distinguish. The maximum pressure responses are very close for conditions 1, 2, and 3, which are 56 a.u., 49 a.u., and 59 a.u. Interestingly, condition 4 exhibits 346 a.u. pressure differences, which are over the threshold value. Therefore, it might not be wise to consider all four conditions when evaluating the metal pipe deformation.

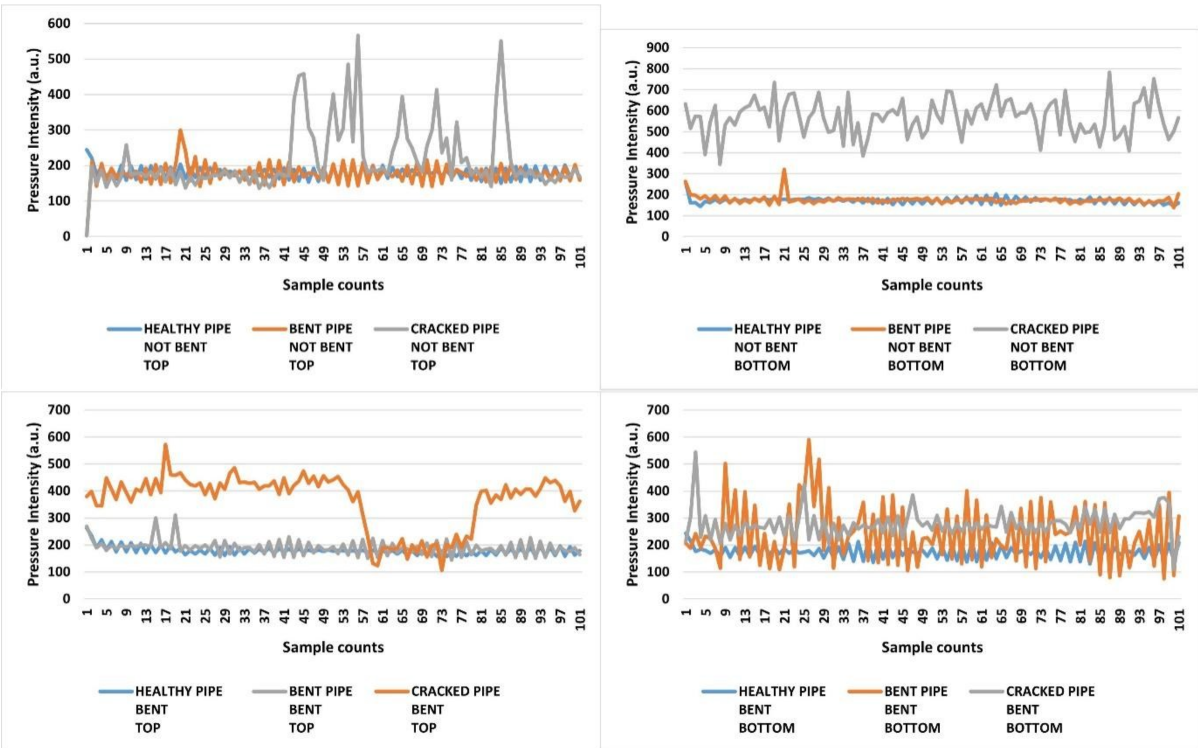

Figure 6. Cases and conditions comparison

We can now introduce an algorithm to determine the pipe health cases based on the aforementioned results and data summary from Table 2. The cases are differentiable based on the maximum sensor values in different conditions. Algorithm 1 presents the distinguishable differences among the three cases.

Table 2. Summary of all experiments

Experimental Setup	Maximum Sensor Value (a.u.)	Minimum Sensor Value (a.u.)	Threshold Value	Damage
Healthy pipe	262	244	No	No
Bent pipe without an air hole	590	300	Yes	Yes
Cracked pipe with an air hole	783	544	Yes	Yes

Algorithm 1 Pipe Health Algorithm

```
Pipe Deformation (Threshold Pressure, Max Pressure)
Pressure Values, ⌊0⌋ → ⌈1023⌉
Received Response, $R_R$ = ⌊0⌋ → ⌈Sensor Values⌉;
Max Pressure, $R_{max}$ = Max [$R_{R1}, R_{R2}, R_{R3}, ......R_{Rn}$]; where n = # of cases
Threshold Pressure, $T_R = \exists!|[R_{max}]|$;
Condition, $C = C_N$; where $N$ = # of conditions
while $R^{CN}_{max} \geq T_R$ do
    Pipe Deformation = EXISTS
    if $R^{CN}_{max} \geq T_R$ && $\not\forall N$ then
        STATUS = Deformation Identified [CRACK]
    else if $R^{CN}_{max} \geq T_R$ && $\neg \not\forall N$ then
        STATUS = Deformation Identified [OTHERWISE]
    end if
end while
if $R^{CN}_{max} < T_R$ then
    STATUS = HEALTHY PIPE
else
    STATUS = ERROR
end if
```

Algorithm 1 depicts the decision logic for the induced pressure in the range of 0 to 1023, as we designed it for the Arduino. Thus, the received responses will be recorded and compared later to the threshold values. From the four different experimental setups, it is noticeable that the sensor exhibits a distinct pattern when placed at the bottom of the existing crack. It remains above the threshold values for all the samples for a cracked pipe. Therefore, this case will be identified as a cracked pipe. However, all other cases for the bent pipe will show a significantly lesser number of samples below the threshold. This scenario will distinguish the bent pipe from the cracked pipe.

5. CONCLUSION

Non-destructive testing (NDT) is significant in structural health monitoring systems, especially in fluid transportation using metal pipes. However, the decaying performance of sensor-based systems at high costs poses a drawback. Therefore, a system with low cost and minimal performance decay is desirable. We have utilized a DC motor as a wave source, which offers significant advantages over traditional sensors. The primary objective of this study is to assess the viability of using a motor as a vibration source for detecting potential cracks in a metal pipe. A simple PVDF sensor was used at the pipe's other end to monitor the motor's pressure responses. An Arduino platform is used to read and record the collected responses afterward. Three types of scenarios are analyzed in this study. These scenarios include a healthy pipe, a bent pipe, and a cracked pipe. Furthermore, four different conditions are also considered, involving two sensor locations (180 degrees rotation) and sensor patterns (bent and not bent). The results reveal significant differences in pressure responses between healthy and cracked pipes. The maximum pressure response for a cracked pipe is 783 a.u. whereas it is just 262 a.u. for a healthy pipe. Hence, the differences are sufficient to set a threshold margin. We have set 300 a.u. as the threshold margin and applied it in an algorithm. However, it is very tricky in the case of a bent pipe, as the pressure differences are less than 300 a.u. for three conditions and above for only one. This could potentially result in an inaccurate decision when detecting a bent pipe.

As previously mentioned, the primary objective of this study is to assess the feasibility of a motor as a vibration source. Hence, no comparisons were made with existing NDTs in this study. Consequently, only open-ended pipes were tested. The prepared pipe damages are artificial (human-made) and not natural damages; hence, the crack pattern will be distinguishable.

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