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Numerical Study of Pipeline Leak Monitoring Based on Negative Pressure Wave Method

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ABSTRACT

Due to its potential as a sensor and actuator in the structural health monitoring sector, the piezoelectric material is widely used in monitoring the damage in pipelines. Monitoring pipeline damage is crucial since damage like fractures and leaks can result in significant losses if they go unreported for a long time. Numerous studies have used piezoelectric to examine the reliability of this sensor for locating pipeline defects and assessing their severity. However, there are limitations when it comes to the numerical research of piezoelectric sensors as global vibration analysis for damage monitoring in pipelines. Hence, the objective of this study is to conduct a numerical study of pipeline conveying fluid with different leak severity based on the negative pressure wave (NPW) for damage monitoring. The pipe's internal pressure fluctuation and surface strain are needed to obtain the PVDF voltage response. To determine the internal pressure fluctuation, the pipeline is first modelled with the turbulent fluid flow within and simulated in ANSYS Fluent. The surface strain is then obtained by exporting the pressure fluctuation data into ANSYS Transient Structural. The idea which includes piezoelectric as a leak detector and the procedure that may be used to determine the leak severity are also discussed in this study. A total of three pipeline models were examined, each with a healthy pipe as the baseline and a varied damage severity (i.e., 5 mm, and 10 mm leaks) at a location 0.3 m from the inlet. The result illustrates that when pipe damage increases, it creates a higher strain due to the fluid-structure interaction, thus increasing the PVDF voltage output. The proposed methodology has the potential as a leak detector in the pipeline and detects small-scale damages when combined with the impedance-based technique.

1. Introduction

1.1 Structure Health Monitoring

Damage to the pipeline is caused by a few factors such as vibration, external impact, and corrosion in and outside of the pipeline. A pipeline, clamps, valves, and other components make up most of a pipeline system. The maximum pressure in the system must be carried by the pipes, which are connected to each component. In the case of vibration, the pulsing excitation from the pump source and the structure's foundation both excite a pipeline when it is in operation [1]. The pipeline

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will be damaged and fail because of the long-term high stress. As for the external impact, it may occur due to construction activity where the workers unintentionally touch the pipeline and any other reasons. To help diagnose these problems, vibrations and defects in the pipes can be monitored with the appropriate damage detection technique.

The use of piezoelectric transducers such as lead-zirconate-titanite (PZT) and polyvinylidene fluoride (PVDF) has become popular over time due to its good application in low and high frequency [2-4]. Furthermore, active sensing with piezoelectric transducers is getting more attention for real-time damage detection and structural health monitoring, and passive sensing which utilizes the sensor only also famous in the detection of vibration caused by leakage especially in pipeline conveying fluid [5,6]. Thus, the direct piezoelectric effect has been deeply explored in the sensor development field.

When a pipeline is in use, defects might emerge that seriously harm the environment, lives, and property. These defects can lead to pollution, contamination of water sources, health risks, and even explosions or fires, depending on the nature of the transported materials [7]. Understanding the necessity of conducting pipeline monitoring and the safety concerns for personnel and communities nearby to the pipeline site highlighted the significance of creating a system for carrying out pipeline monitoring operations in real time.

A time-based monitoring approach is typically applied in pipeline monitoring. Depending on the method and equipment used for inspection, the frequency of time-based monitoring will vary. Patrolling, either through aerial or ground surveillance, is commonly used to assess pipeline conditions. Drones or helicopters can be employed for airborne surveillance over potentially compromised areas. On the other hand, ground surveys can be conducted using land vehicles or by foot, offering a comprehensive view of the situation [8]. Even though it is applicable, surveying by air or ground can only provide updated data about damage due to third parties such as excavation activity that leads to pipeline leaks. In addition, the damage found during inspections may not be recent, as inspections are scheduled or conducted in response to leakage reports.

In another study, researchers used a commonly available accelerometer as a sensor to detect pipe leaks through vibrations. However, there are some existing disadvantages to using them for such applications, ranging from their high cost, which requires an external power source to operate, to their general rigidity, which makes it difficult to achieve excellent conformance with the cylindrical pipes to which they are bonded [9]. The invention of piezoelectric patches as an alternative sensor to commercial accelerometers was prompted by the need for low-cost, output-only, and flexible vibration sensors for pipe leak detection.

Therefore, the industries need a real-time monitoring method and equipment that allows them to monitor the health of the pipeline externally and internally. To achieve that, ultrasonic testing is one of the effective methods that is being used to assess structural damage in structural health monitoring [10-13]. The method uses sound waves to find defects and measure thickness which is extremely useful in monitoring cracks and corrosion in the pipeline. To meet the real-time monitoring requirement, this method can be applied with any suitable sensor that is fixed onto the pipeline [14].

In addition, it would be interesting to perform a numerical analysis and compare the results with the previous experiment, as most experimental studies have been conducted over the past ten years while the numerical study which involves designing methods that give approximate but accurate numeric solutions is still limited. Numerical study is useful in cases where the exact solution is impossible to calculate or will cost a lot of money to construct. This paper aims to conduct a numerical study of pipeline conveying fluid with different leak severity based on the negative pressure wave (NPW) for damage monitoring and requires one to use computational fluid dynamics (CFD) simulations solver such as ANSYS Fluent to solve the complex equations that describe the fluid flow.

1.2 Negative Pressure Wave Leak Detection

The application of low frequency to piezoelectric materials is mostly achieved by utilizing passive sensing, where only the piezoelectric output is considered. Since the dynamic responses of the host structure to which piezoelectric materials are attached are related to the output energy from these materials, a relationship between the quantity of energy generated and the condition of the structure can be formed. Their output in the form of charge or voltage can be used independently to identify and track a circumstance that modifies this dynamic response.

Numerous pipeline structural health monitoring approaches have been utilized to track damage during the previous few decades [15,16]. The negative pressure wave (NPW) is one of the potential approaches as the vibration leak detection systems are useful for detecting early leaks in pipelines (see Figure 1). According to a study by Sheltami *et al*., [17], the idea of vibration-based leak detection is based on the Fluid-Structure Interaction (FSI) and NPW phenomena. The problem's initial stage emphasizes the dynamics of turbulent flow which is related to FSI that can cause vibrations that may lead to pipeline damage or failure, such as leaks. Then, when the pipeline leaks, the fluid escapes in the form of a high-velocity jet, and an NPW is produced at the leak spot caused by turbulence at a specific flow rate and results in an additional pressure fluctuation. These extra waves cause the pipe to vibrate more because they are transmitted through the pipe wall primarily through the junction connection. The NPWs will attenuate or diminish in both directions away from the leak point until they disappear.

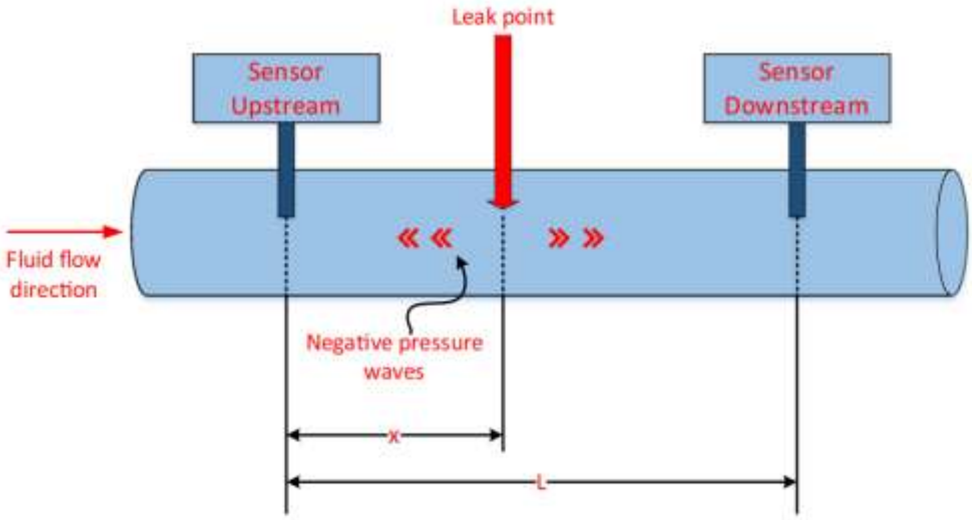

Fig. 1. Propagation of the negative pressure waves from the leak point [3]

Next, Zhu *et al*., [18] explain some theories about NPW where initially the internal pressure of the pipeline is relatively constant and significantly higher than the ambient, external pressure. As the pipe experiences leakage, the fluid inside the pipeline will escape through the leak and the pressure inside the pipe will drop significantly. The fluid that is escaping comes from both sides of the pipe to the point of leakage and generates the NPW at the leakage area. The NPW will propagate along the pipeline also toward both directions. Dropping in internal pressure leads to a decrease in the pipe's circumference strain and hoop strain. Thus, the PZT sensor will detect the change of hoop strain on the pipe wall as the NPW reaches the location of the PZT patch (see Figure 2).

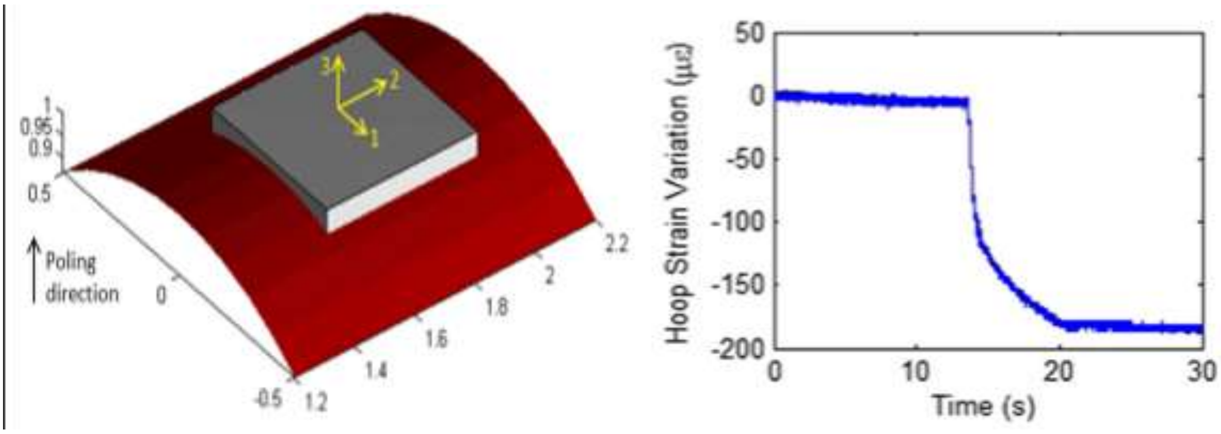

Fig. 2. The PZT patch attached to the pipe wall (left) and the hoop strain variation that happens when the leakage occurs (right) [4]

Another type of piezoelectric material that is flexible and suitable to be used on structures with the curved area such as pipes is polyvinylidene fluoride (PVDF) material [19]. PVDF patch transducers can be employed as passive sensors to detect acoustic sounds traveling through a pipeline and detect the NPW developed from the leakage. Numerical studies outlining characteristics related to varying pipe flow subjected to damage (mostly leaks) reveal that the pipe's vibration response is one of these parameters. This has resulted in the development of vibration-based fluid-pipeline damage detection systems. Although the results demonstrate the potential of this technology for pipeline leak detection, monitoring, and localization, it is yet to be seen if it can also be used to identify and monitor other defects, such as dents and pitting corrosion, which are typically precursors to these leaks.

2. Methodology

2.1 Overview

In this study, a two-phase approach was employed to determine both the fluctuation pressure, P_f, and the surface strain, ε. Fluctuating pressure, which refers to variations in pressure over time, can help identify anomalies such as instabilities that might occur during pipeline operation. Sudden changes or irregularities in pressure fluctuations can be indicative of leaks or breaches in the pipeline. Surface strain refers to the deformation or elongation experienced by the outer surface of the pipeline and measuring the surface strain of the pipeline, in which the PVDF patches can detect even small deformations caused by defects. As shown in Figure 3, the first phase involved CFD simulations using the commercial code ANSYS FLUENT, while the second phase utilized FE simulations with ANSYS Transient Structural. The Fluid Flow (FLUENT) was used as an analysis system in ANSYS. Several work steps need to be done such as defining the geometry, mesh, and setup to obtain the desired information, which is the fluctuation pressure along the pipe. The fluctuation pressure is then exported to the external data with the help of CFD-post and is directly exported to the Transient Structural to obtain the strain.

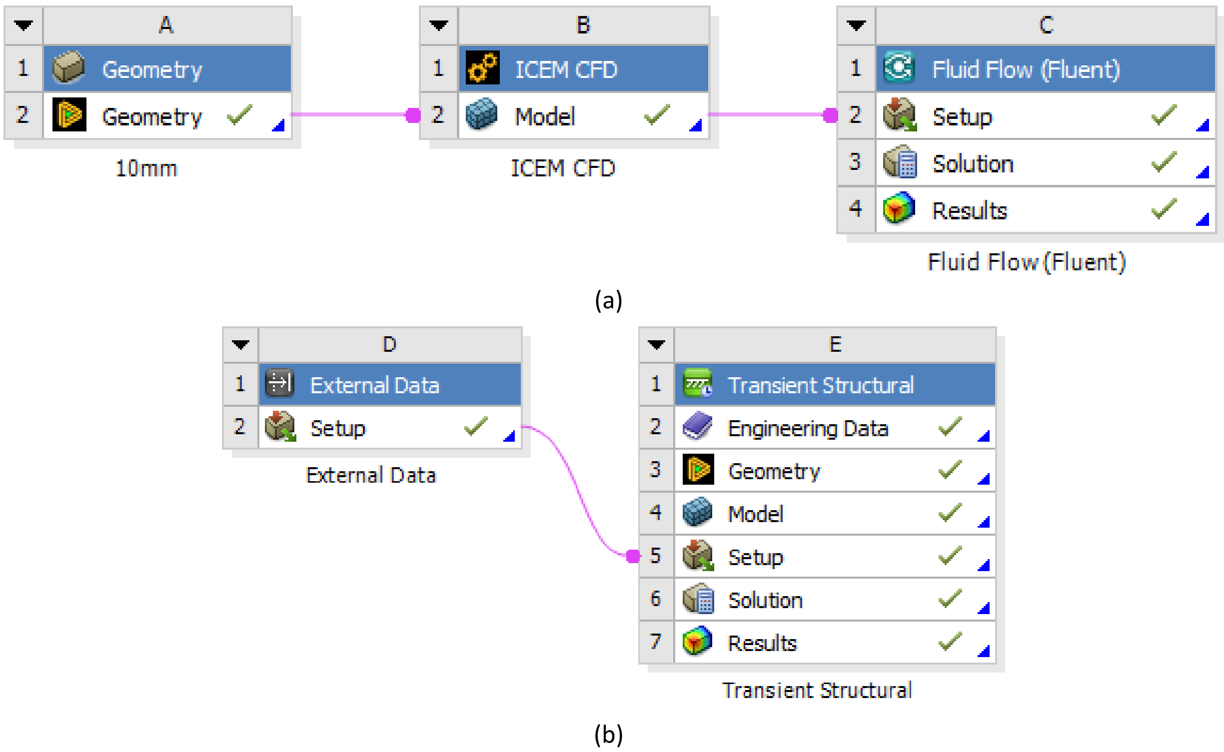

Fig. 3. Schematic of current study (a) First phase (b) Second Phase

2.2 CFD Simulation

The pressure fluctuation derived from CFD simulation is used to obtain the pipe surface strain by applying pressure on the interior wall surface in FE simulation. As the surface strain at all locations on the pipe is determined, the theoretical voltage output generated by the PVDF patch sensor at any point along the pipe wall can be calculated using Eq. (1) [20],

$$\varepsilon = \frac{V_p C_p}{S_q} \tag{1}$$

Where ε is the strain acting on the sensor, V_p represents the voltage generated by the sensor, C_p is the capacitance of the sensor and S_q is a sensitivity parameter = $d_{ij}YA$ (obtained from published data). Additionally, d_{ij} is a constant representing the piezo activity of the sensor in the poled direction, Y is the elastic modulus of the piezoelectric material, and A is the area of the sensor. The piezoelectric properties of the PVDF patch sensor used in this study can be seen in Table 1.

Table 1
Properties of PVDF patch sensor

Parameter	Value	Unit
Area, A_p	0.00175	m^2
Capacitance, C_p	Approximately 3.30	nF
Thickness, t_p	52	µm
Resistance, R	2.66	MΩ
Modulus of Elasticity, Y	8.3	GPa
Piezoelectric strain constant, d_{31}	30	PC/N

For the pipe geometry, a 1 m galvanized steel pipe was designed with an internal diameter of 37.3 mm and a wall thickness of 2.5 mm. The simulation will involve a comparison of three scenarios which are a healthy pipe (no leak), a pipe with a 5 mm leak, and a pipe with a 10 mm leak. The leak is located 0.3 m from the pipe inlet.

To obtain a good selection of mesh, the pressure gradient calculated from FLUENT must be close to the theoretical pressure gradient. As for the boundary condition, the velocity-inlet and outflow were set to the pipe's inlet and outlet, respectively. The leak pipe will have two additional boundary conditions which are the leak wall and the leak outlet. The mass flow outlet boundary condition is used for the leak outlet, and the leak wall's boundary condition is the same as the pipe wall. The atmospheric condition is chosen as the operational condition at the leak outlet since the leak discharges to the atmosphere as shown in Figure 4. A stationary wall with no-slip condition was fixed for the internal wall. The value for velocity at the inlet is calculated from the flow rate which is 90.85 L/min. The leak flow rate for a 5 mm leaked pipe is 0.026 Kg/s and for a 10 mm leaked pipe is 0.11 Kg/s.

To model the unsteady and turbulent flow, a Large Eddy Simulation (LES) setup was utilized. This setup is important to obtain internal pipe wall pressure fluctuations over time in a turbulent flow. The pressure fluctuation was then determined on the leak pipes and compared with that of the healthy state. For each case, the data of pressure fluctuation were extracted one by one from the CFD-Post and exported into a transient finite element model to obtain the external pipe surface strain. The fluctuating pressure can be defined in the CFD-Post by applying Eq. (2), where the pressure fluctuation at any point along the pipe is equal to the static pressure, at that point minus the mean pressure, of one simulation time.

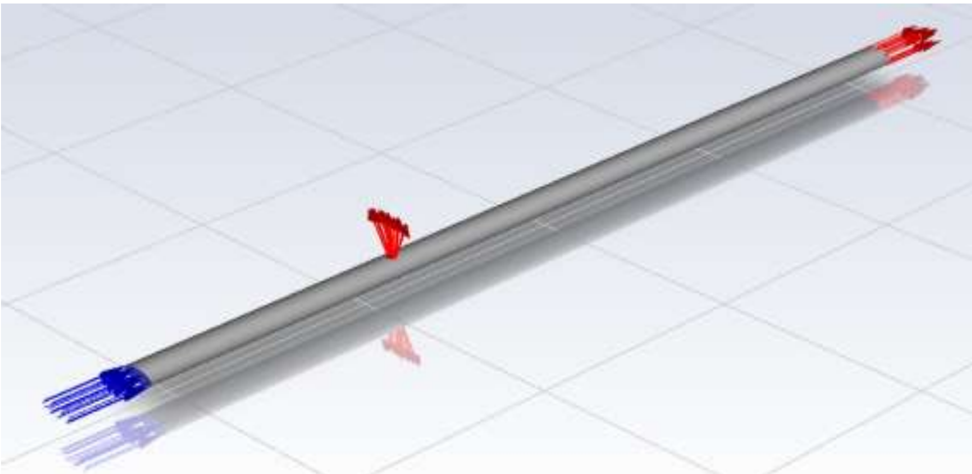

Fig. 4. Water flow through the 10 mm leak point located 0.3 m from the pipe inlet

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$$P_f = P - P_m \tag{2}$$

2.3 FE Simulation and Voltage Calculation

Next, the surface strain over the sampling time at every point of 0.2 m increment along the length of the 1-meter pipe including the leak point will be determined (Figure 5). For each point, the root mean square of the strain will be obtained, and then exported to Excel to calculate the theoretical voltage output of the PVDF piezoelectric patch using Eq. (1).

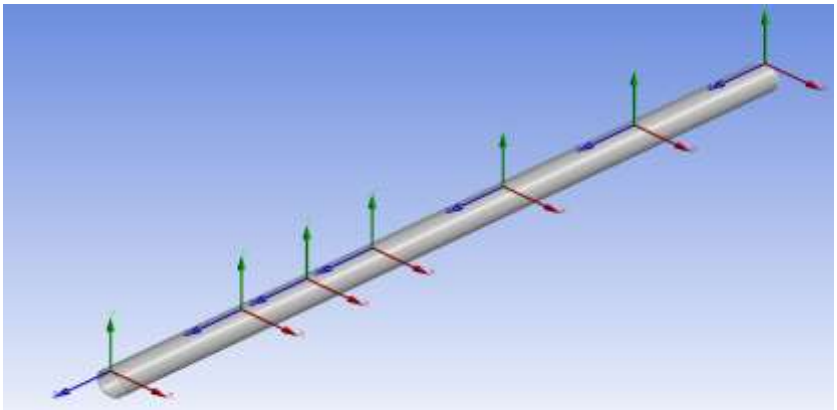

Fig. 5. Location of the 7 points on the pipe to obtain the surface strain

3. Results

3.1 Validation

A CFD simulation of flow in a healthy pipe was performed to validate the methodology with 1000-time step and 0.001 step size to determine the pressure fluctuation. The obtained result is then compared with the results from Okosun *et al*., [20]. As seen from the red lines of the current study in Figure 6, shows that the fluctuation pressure is fluctuated around 500 Pa. When compared with the previous study on the left figure, the pressure attained from 0 s to 1 s shows a similar trend. Thus, the setup for the simulation is carried forward to the next stage of the study for cases with different sizes of leakage.

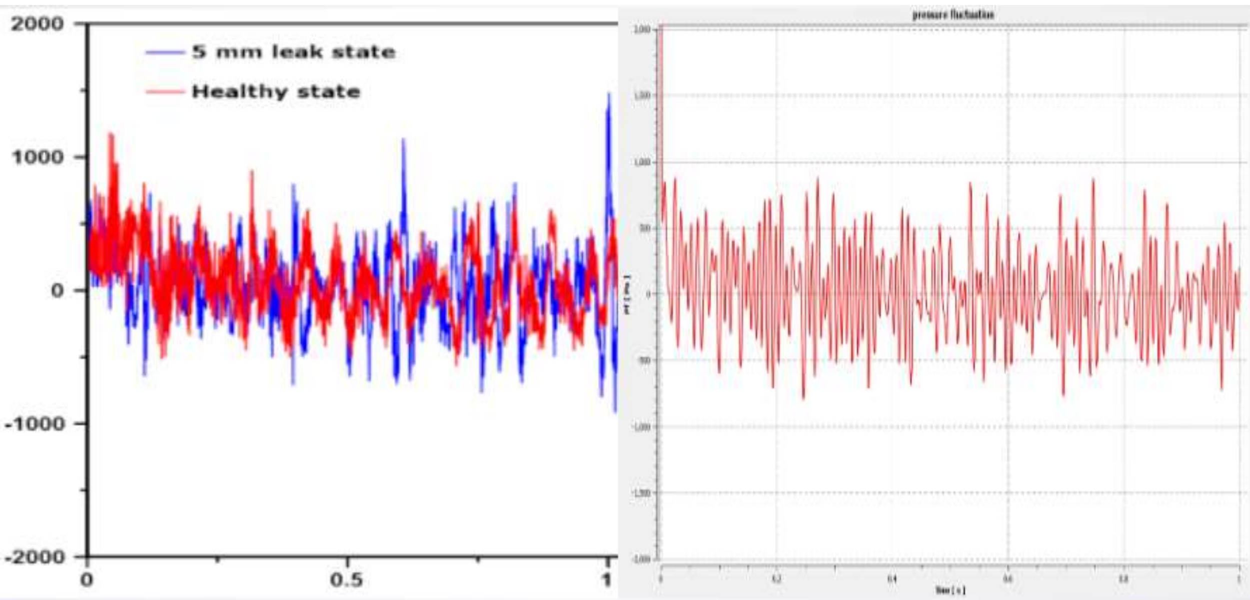

Fig. 6. Comparison of fluctuation pressure of healthy pipe against 2-second time between previous study by Okosun (left) and current study (right)

3.2 Pressure Fluctuation

Leakage with diameters of 5 mm and 10 mm leaks were introduced to the models located 0.3 m from the pipe inlet. The fluctuation pressure for the pipe with a 10 mm leak at the leak point and 0.6 m from the pipe inlet were extracted and shown in Figure 7 and 8 for comparison. The fluctuation in pressure shows how the pressure varies in its magnitude area over time. The pressure fluctuation at the leak point has a greater magnitude of pressure than that of the 0.6 m from the inlet due to the generated NPW at the leak area. As it propagates along the pipe, the magnitude of the NPW will reduce slowly and disappear. Thus, the leak area will have the highest value of NPW and at 0.6 m from the inlet will show a reduction in NPW. After the NPW disappears, the remaining pressure is only from the fluid-structure interaction between the pipe and the flowing fluid inside it. It is more evident based on the pressure contour shown in Figure 9 where the fluctuation pressure is higher in the vicinity of the leak point and near the pipe inlet.

3.3 Surface Strain

The pressure fluctuation from FLUENT was then imported to the interior pipe wall (Transient Structural) by using the CDF-post and External Data. Based on the strain analysis, it is found that the leaked pipe experienced higher strain than that of the healthy pipe due to the NPW generated from the leakage. A larger leak size leads to a larger generation of NPW, thus creating higher strain. When leakage is present, it forces the fluid inside the pipe to go out into the atmosphere, interrupts the flow, and makes it more turbulent, thus changing the pressure of the flow. It is seen that the highest strain value occurs in the leak area. The pressure fluctuations in the turbulent water flow will cause the strain on the pipe surface to fluctuate, as seen in Figure 10. As the water flows through the pipe, it exerts pressure on the interior wall of the pipe, causing the pipe to deform and creating strain on the surface.

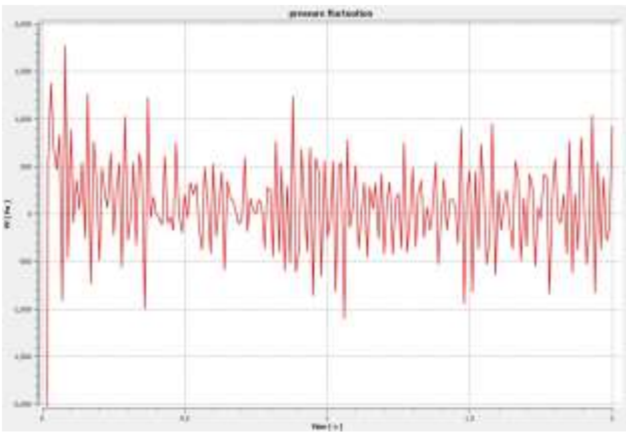

Fig. 7. Fluctuation pressure P_f against time for pipe with 10 mm leak: at the leak point

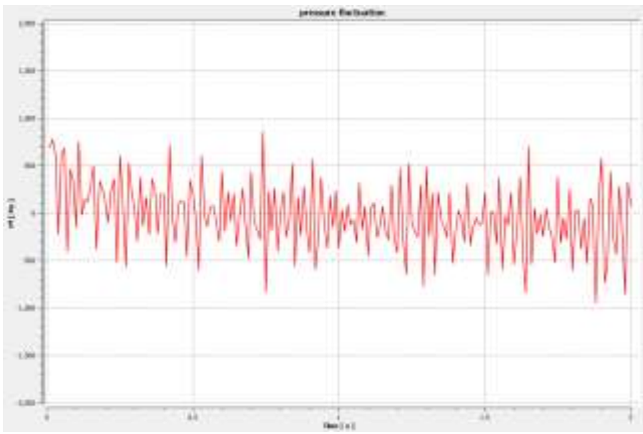

Fig. 8. Fluctuation pressure P_f against time for pipe with 10 mm leak: at 0.6 m from pipe inlet

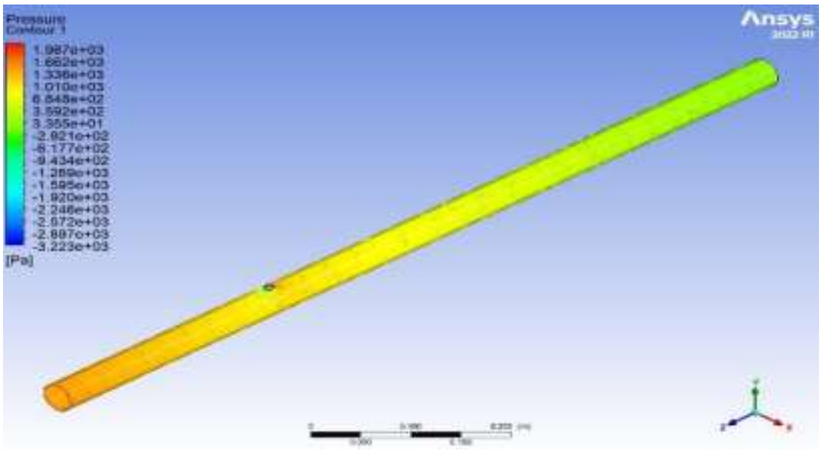

Fig. 9. Pressure contour of 10 mm leaked pipe at final time step (2s)

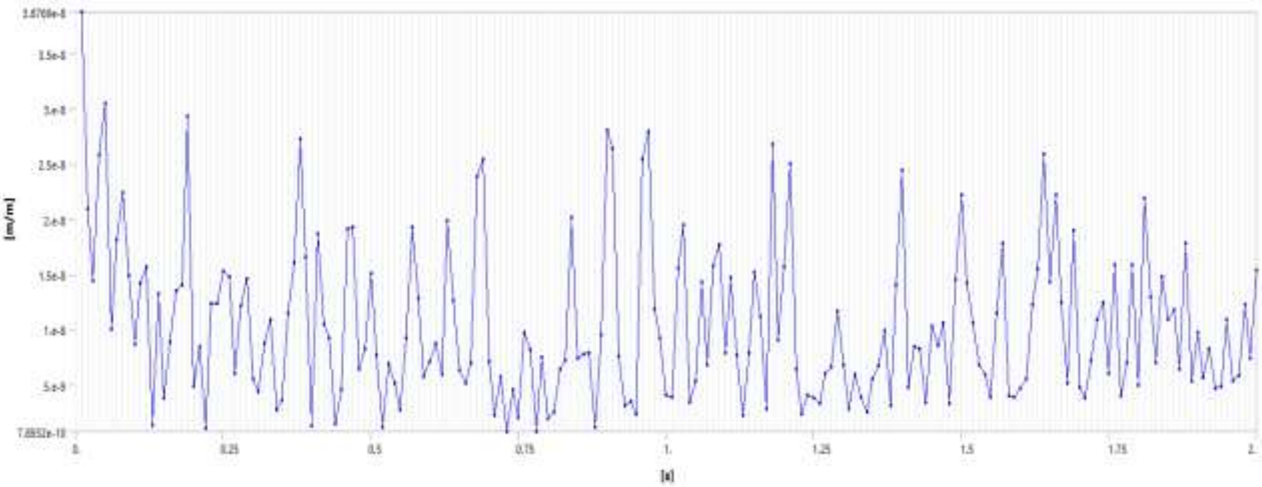

Fig. 10. Average strain experienced by the 5 mm leaked pipe over 2-s time

3.4 Theoretical Voltage

With the healthy pipeline as the baseline, the theoretical voltage magnitude generated by the PVDF piezoelectric patch for the leaked pipes can be analyzed. Essentially, the larger the leak on the pipe wall, the greater the generated NPW, thus the higher the voltage output generated by the PVDF piezoelectric patch. As seen in Figure 11, the voltage for the healthy pipe is decreasing slowly from the pipe inlet towards the outlet. A similar trend is seen for the 5 mm leak case, where the voltage decreases from the pipe inlet, however, the voltage shows an increase when it reaches the leak point at 0.3 m, then starts to decrease again. Compared to the 10 mm leak, the NPW generated by the 5 mm leak is lower and only has a small effect on the pipe strain. On the other hand, for the 10 mm leak case, the voltage is first increasing until it reaches the maximum at the leak point of 0.3 m. This voltage increase is the effect of NPW on the behavior of fluid flow and structures. After this point, the voltage has significantly decreased until it reaches a common voltage output for the healthy case at the pipe outlet. It can be concluded that the strain of the pipe is affected by the fluctuating pressure created by the unsteady and turbulent flow of the fluid inside the pipe. As the pipe leaks, the NPW appears and increases the fluctuation pressure and pipe strain. When the PVDF patch is attached to the pipe structure, the PVDF patch also will experience strain as the pipe does. However, how much the NPW is produced depends on the severity of the leakage, where a 5 mm leak is still considered small and hard to detect if there is any disturbance exists around the pipeline.

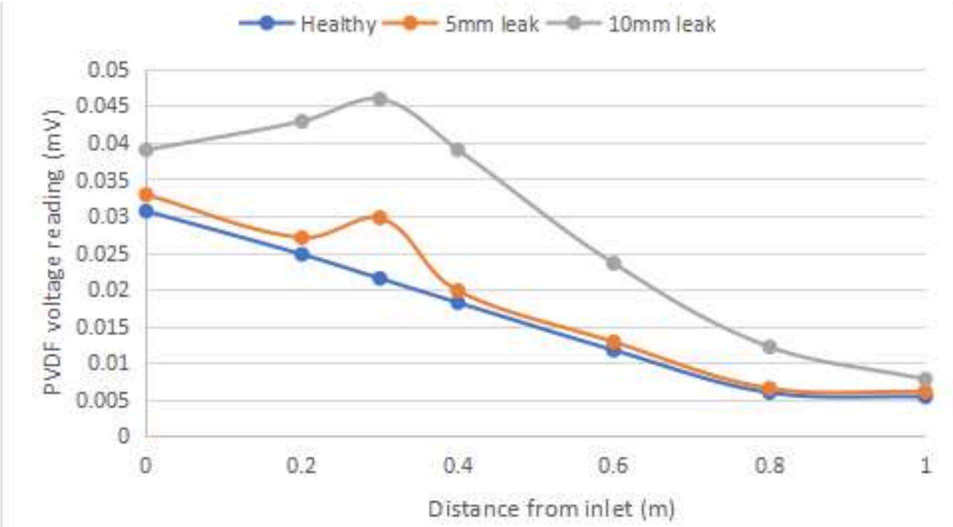

Fig. 11. PVDF voltage reading along the 1-m pipe for healthy, 5 mm-leak, and 10 mm-leak cases

4. Conclusions

The numerical study involving a PVDF piezoelectric patch as a sensor based on the negative pressure wave (NPW) has demonstrated the capabilities of the vibration method in detecting pipeline leaks. By studying the interactions between the fluid flow and structures, thus harnessing the responsive nature of these patches to vibrations, the study showcases the potential as a reliable leak detector. Changes in strain on the surface of the pipe were identified and the theoretical data were produced in terms of voltage magnitude. This technique offers a non-intrusive way to keep track of pipes and find leaks before they become a serious issue. Overall, the use of piezoelectric sensors to detect changes in strain on pipeline surfaces has significant potential for improving pipeline monitoring and maintenance. However, it is important to consider the limitations of the method such as their sensitivity to environmental factors and noise. External vibrations from sources other than leaks, such as nearby machinery or natural events like earthquakes, can potentially interfere with the accuracy of the readings. Very small leaks or leaks located far from the patches might pose challenges for detection.

Lastly, enhancing the study involves deploying multiple piezoelectric sensors at distinct pipeline locations to assess the vibration method's accuracy across varying flow conditions and fluid types. Additionally, conducting experimental studies on the piezoelectric sensors' performance in capturing leak-induced vibrations and exploring machine learning algorithms for data analysis could significantly enhance leak detection precision, especially in large pipeline networks. Integrating this methodology with electro-mechanical impedance techniques holds the potential for comprehensive damage identification, contributing to more effective pipeline maintenance and reducing the risk of costly leaks and environmental harm.

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