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Computational Study to Evaluate Vibration-Based Leak Detection Approach in Crude Oil Pipeline System

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الملخص

على مدى السنوات القليلة الماضية، كانت طريقة الكشف عن التسرب القائم على الاهتزاز (VBLD) في أنظمة خطوط أنابيب المياه موضوعًا للتركيز البحثي. تم تصنيفه كطريقة فعالة للكشف المبكر عن التسرب وخيار أفضل للمراقبة مقارنةً بالفحص الفني. هذه الطريقة VBLDباستخدام أنابيب مياه صغيرة في التجارب المعملية .المشروع الحالي (Computational Study) هذه الطريقة حسابيا و دالك بإستخدام الطرق الرياضية العددية في الأنابيب ذات قطر كبير في قطاع النفط و الغاز .

تم ربط ديناميكيات الموائع الحسابية (CFD) التي تستخدم نموذج إجهاد رينولدز (RSM) باستخدام نهج أحادي الاتجاه مع تحليل العناصر المحدودة (FEA) لمحاكاة تفاعل هيكل مع الموائع (FSI). كان هناك العديد من السيناريوهات التي تم فحصها وهي الأنبوب في حالة التشغيل العادي (بدون تسرب) وفي التشغيل غير الطبيعي (مع وجود تسربات). تمت دراسة ثلاثة تسريبات مختلفة الشدة صغيرة ومتوسطة وكبيرة على التوالي.

تم الحصول على جميع قياسات الاهتزاز لهذه السيناريوهات المذكورة ومقارنتها ببعضها. تشير النتائج إلى أن قياس الاهتزاز يزداد مع توسع حجم التسرب. هده الطريقة (VBLD) قادرة على الكشف عن التسربات لحالات المختلفة. يعد هذأ النموذج الحسابي (FSI) الذي تم تطويره في الدراسة الحالية مفيدًا لتصميم مزيد من التجارب المتعلقة بخط الأنابيب. توفر نتائج هذا البحث بعض قياسات الاهتزاز المختلفة التي يمكن استخدامها في دراسة حالات مماثلة.

Abstract

Over the last few years, Vibration-based leak detection (VBLD) method in water pipeline systems has been a subject of research focus. It is identified as an effective method for early leak detection and better choice for monitoring than inspection. Previous publications experimentally investigated VBLD method for small scale water pipeline systems. The current project computationally investigates this method for a large-scale crude oil pipeline system. Computational Fluid Dynamics (CFD) employing Reynolds Stress Model (RSM) was coupled using one-way approach with Finite Element Analysis (FEA) to simulate the Fluid-Structure Interaction (FSI). There were several case scenarios investigated namely the pipe in normal operation (without leak) and in abnormal operation (with leaks). Three different leaks with different severities, small, medium and large respectively were studied. The vibration measurements for these mentioned scenarios were all obtained and compared. The results indicate that vibration measurement increases as the leak size expands. The VBLD is found capable of detecting leakages with different damage severities. The FSI model developed in the current study is useful to design further experiments related to pipeline FSI. The findings provide some different vibration measurements that can be used for validation and verification for similar case studies.

***Keywords*:** Pipe flow, Leak detection, CFD, FSI, Pipeline system

1**. Introduction**

Over millions of miles around the world, pipelines are commonly used to carry hydrocarbon fluids. Pipeline accidents threaten and lead to economic and environmental issues, as well as the loss of human life [1]. There have been various incidents reported over the last few decades. In July 2004, an explosion caused by a leak in a gas pipeline inflicted injuries 132 people and killed 24 individuals. This leak, for example, existed for 14 days before the explosion of the gas. Furthermore, in March 2008, a leak in an ethylene pipeline caused a serious fire. In addition, an incident was reported in March 2012 about a pipeline leakage which resulted in a loss of one million liters of Kerosene due to the late discovery of the leak. At least two of these catastrophes could have been avoided using a “State-of-the-art vibration-based leak detection system” [2].

To reduce such risks and to keep pipeline facilities secure and reliable, the design of leak detection and localization using numerous methods has been the focus of many significant research studies. The pipeline monitoring system (PMS) most frequently utilized is based on flow rate, temperature, and pressure measurements. Usually, leaks are discovered via pipeline checks and patrols, or by monitoring pressures and flowrates quantities at a certain point such as the inlet and outlet of the oil pipeline system [1].

Recently, vibration-based leak detection method (VBLD) has become the topic of investigation by many engineers. The method is basically relying on field instruments called accelerometers (type of transducer used for measuring acceleration) that mounted on the outer surface of the pressurized pipeline to measure the flow-induced vibrations (FIV). The signals are then sent to a computer-based program for analysis and to keep the real-time condition monitoring running [3].

The advantages of using the vibration-based leak detection system far outweigh the demerits the other methods have, for instance, it does not require any hard effort to do the preventative maintenance, calibration, installation, and/or replacing the measuring device (accelerometer) when needed [3]. This is because the accelerometer used as a primary sensor to measure or detect the vibration in the pipeline is mounted on the outer pipeline surface which does not require stopping the flow rate or the production process [1].

Moreover, there are no moving parts on this system which means low maintenance and no room for errors along with easy troubleshooting installed and greater leak-detection sensitivities compared with the other approaches. For instance, the pressure point analysis (PPA) technique is not suitable in applications where the control valves open and close simultaneously. It also suffers from low system accuracy and false signals [1].

Although each method has it is own distinct and inherent benefits, the existing methods experience common drawbacks. This includes, incompatibility to detect small leaks, false alarms, high cost, entailing a highly skilled operator, significant electricity consumption, and poor accuracy. Therefore, the vibration-based approach is proposed to improve the limitations of the other techniques [4].

Versteeg and Malalasekera (2007) stated that, this technique (CFD) has recently become an interest to most of oil and gas companies considering its precision, time saving, the ability to give extensive details about the results, plus allowing simulation of the final product with real world physics and cheaper comparison to experimental works.

Abuhatira et al. [7] stated that numerical FSI simulations are mainly used to investigate the fundamental physics involved in the complicated interaction between fluids and solids. This is because analytical solutions are impossible to compute. Pipe flow simulations employing CFD tool are intensively conducted by Abuhatira et al. [8] to predict the turbulent pipe flow behaviour and different conditions. The main aim of this study is to computationally investigate the VBLD method in pipeline systems with applications in the oil and gas industry.

2. Methodology

2.1 Data Collection

Collecting data at an acceptable level of precision is the most important activity. It normally needs time to obtain trustworthy data that helps management goals to be achieved [5]. The data acquired, therefore, relies on the type of data and the data location using numerous approaches. For example, some of this data came from the operation department of Waha Oil Company (W.O.C) which owned by the National Oil Corporation (NOC) in Libya, while others were collected by engineering department of W.O.C. Pipeline information and fluid properties are illustrated in the tables 1 and 2, respectively.

In a real industrial life, pipelines usually have turbulent flows that makes them quite intricate/ complex. The difficulties with fluid dynamics or wall tension changes due to turbulence are exceedingly complicated and frequently difficult to predict and resolve.

2.1.1 Pipeline information and fluid properties

TABLE 1. Pipeline information (W.O.C, 2021)

Pipe Schedule	Material	Wall Thickness	Outer Diameter (O.D)
SCH100	Carbon Steel	0.02619 m	0.4064 m

TABLE 2. Fluid properties (W.O.C, 2021)

Parameter	Value	Unit
Specific gravity	0.696	N/A
Density	694	k_g/m^3
Viscosity	0.00122	Pa*s
Pressure	4e+6	Pascal
Flow velocity	0.5	m/s

This research was conducted in a large-scale real both ends supported crude pipeline system and was carried out in cooperation with Waha **O**il Company (**W.O.C**) in Libya.

2.3 Computational Modelling

The problem is the leak in oil and gas pipeline systems. This study proposes a novel vibration-based leak detection technique. The previous studies of this method were carried out experimentally in small diameter water pipeline systems which are expensive and require a great deal of effort to implement. Furthermore, data available in this regard is limited.

Although previous research revealed that the approach is appropriate for continuous pipeline monitoring, there is a need for more studies to be carried out (.i.e. the effect on pipeline geometry and fluid flow) to make it more reliable to be used not only in water side but also in oil and gas sectors, and that is what “Computational method by using Computational fluid dynamic (CFD) technique” is aimed too.

Therefore, a computational study was carried out to evaluate the vibration-based leak detection method in oil and gas sector due to the high cost of experiments as well as the lack of accessibility in large scale pipeline systems particularly in oil and gas industries. The computational study is useful for design experiments within the context of the Fluid–Structure Interaction (FSI) for pipeline systems, including the vibration leak detection method. The computational method conducted in a large-scale pipeline system using computational modeling techniques to evaluate the reliability of vibration-based leak detection methods in the oil and gas sector.

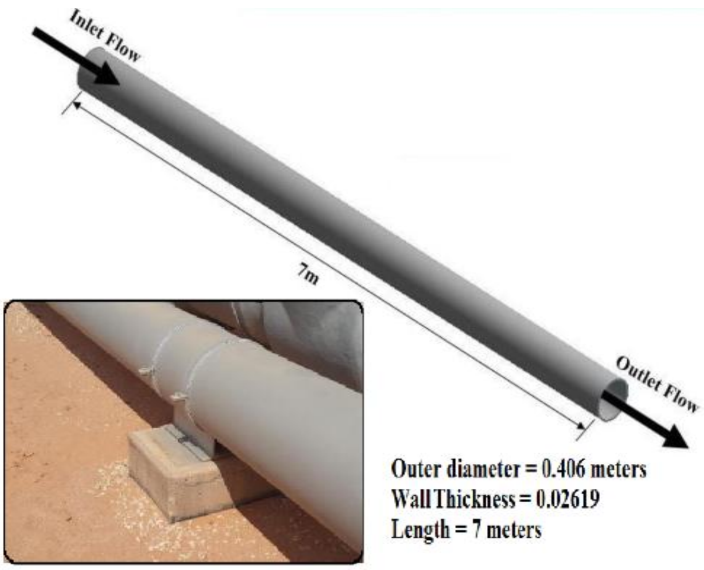

Figure 1. Both ends of the pipeline is supported

The pipe segment is **7 meters** in length and outer diameter of **0.4064 meters** as its clearly illustrates in the computational domain in figure 1 above. The pipe thickness is **0.02619 meters**. The pipeline system conveying a crude oil and used to transport this product. The arrows show the pipe inlet and outlet.

2.4 Numerical Method

Reynolds Stress Model (RSM) is coupled with a finite element structural model to simulate the fluid-structure interaction (FSI) using one-way coupling. The advantage of RSM is that, it is a reliable turbulence models that used for highly swirling flow [6] This model uses transport equations to solve all Reynolds stresses directly and avoid the isotropic viscosity assumption of the other models.

The pipe mesh illustrates in the **Figure 2**. The mesh structure was created to be very fine near the wall for capturing more details because the flow behavior near the wall is the region of interest. The pressure field floating in the internal pipe wall is considered the force that makes the vibration and hence an advantage is taken by very fine near the wall.

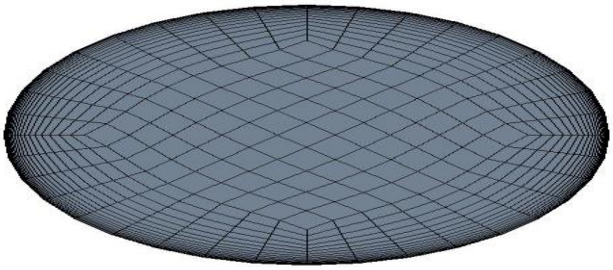

Figure 2. Pipe Mesh

3. Results and discussion

The vibration measurement analyses are performed across a straight 7 meters in length carbon steel both ended supported crude oil pipeline, and outer diameter of 0.4064 meters. The pipe thickness is 0.02619 meters. The pipeline system convey-s crude oil and is used to transport this product. The initial stage of the investigation involves the collection of measurements in various pipeline sections in order to first study the amplitude and frequency of vibration and then examine the changes in those signals caused by the change in the flow situation due to leaks.

Simulations of pipeline flow on 4 pipe situations, firstly, a healthy pipe (Normal operation "No Leak"), secondly, leak states (. i.e. small, medium, and /or large), were thus carried out as it is clearly demonstrated in the table and illustrated in the figures below for more clarifications.

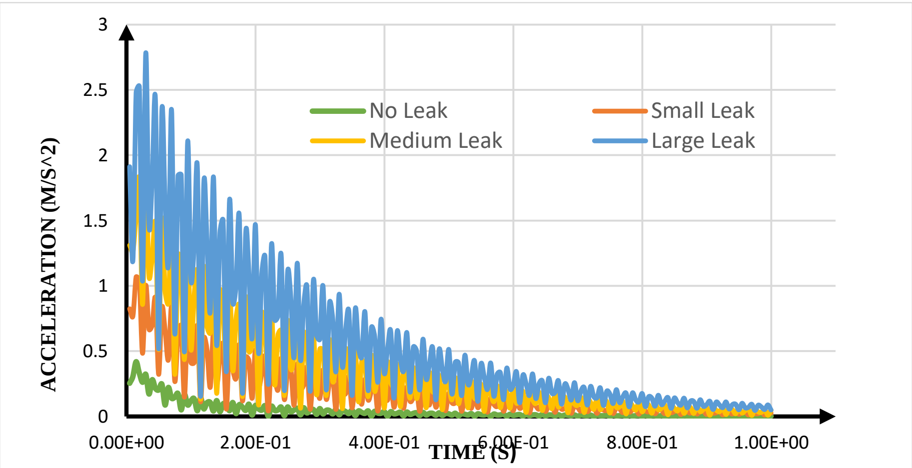

Figure 3. Leak countrification (Acceleration (m/s^2) & Time (sec))

The vibration measurement analyses are performed in one part; vibration across a straight 7 meters in length pipeline section is observed. **Figure 3** above demonstrates in the vertical axes (**Acceleration (m/s^2)**), while in the horizontal axes (**Time (sec)**) the average line chart for the whole case scenarios. The analyses are carried out to examine the effect of vibration levels on 4 pipeline situations; for instance, healthy pipeline (No leak), small leak (**0.005 meters**), medium leak (**0.0075 meters**), and large leak (**0.01 meters**).

These simulations were done at a constant fluid velocity of 0.5 m/s, and not at different flow rates because all the simulations were carried out on a real crude oil pipeline to maintain the real environment of the pipeline (as the crude oil passes through the horizontal pipeline on its way down to the tank, it undergoes at a constant flow rate maintained via a well-tuned closed-loop control system). It can be clearly noticed that the vibration magnitudes recorded for the small, medium and large leaks are significantly more than those obtained from no-leak conditions. Finally, more details about the results have been illustrated via a line chart for all case scenarios individually in the figures (**4, 5, 6 &7**).

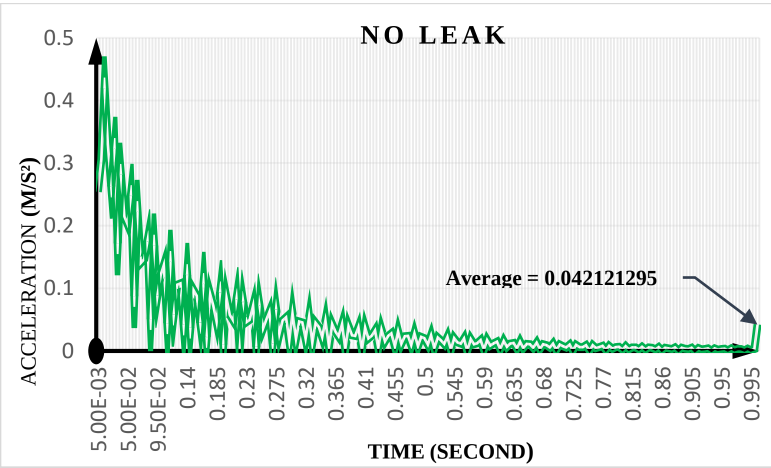

Figure 4. Line chart for No leak in the crude oil pipeline (Acceleration (m/s^2) & Time (s))

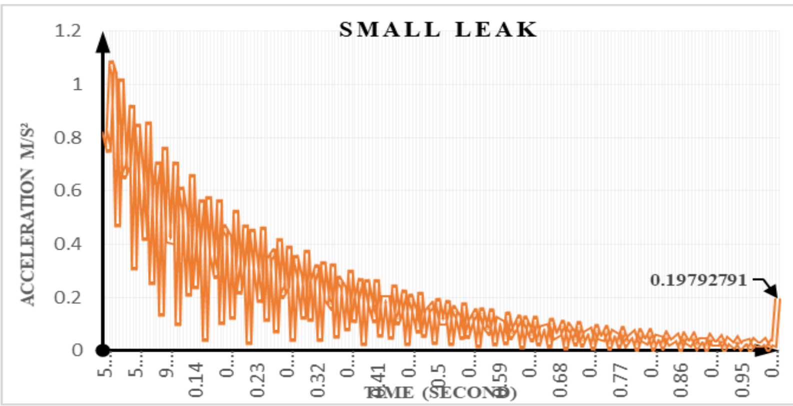

Figure 5. Line chart for Small leak scenario (Acceleration (m/s^2) & Time(sec))

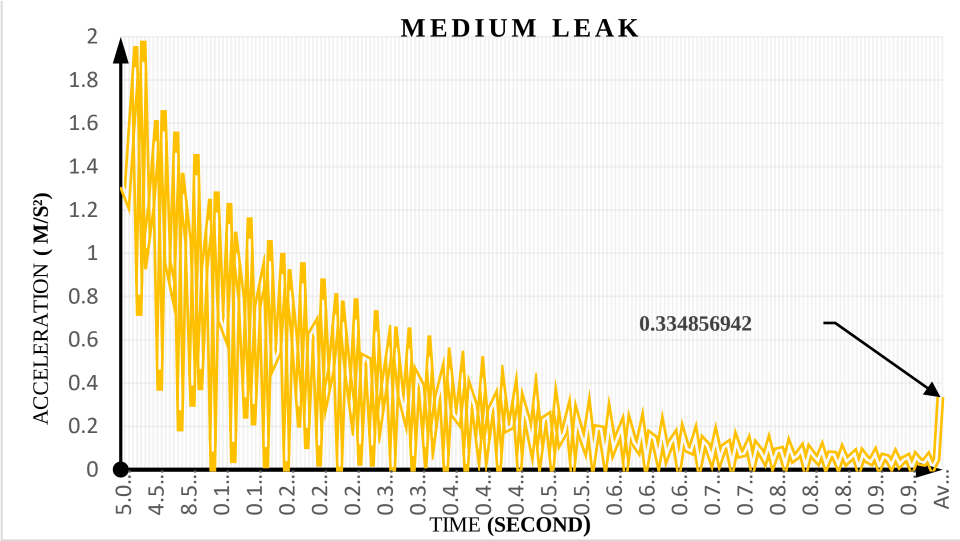

Figure 6. Line chart for Medium leak scenario (Acceleration (m/s^2) & Time (s))

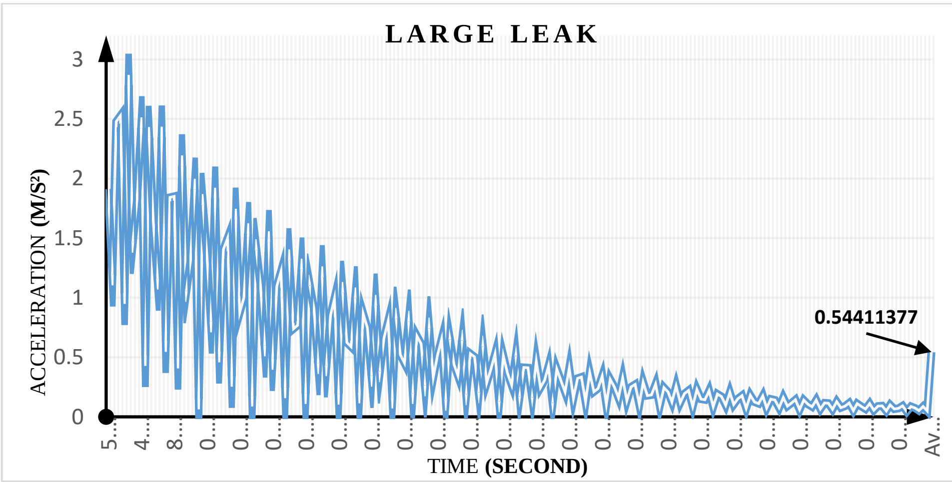

Figure 7. Line chart for Large leak scenario (Acceleration (m/s^2) & Time (s))

The vibration amplitude has been taken throughout the analyses as well as the average of each signal case. The results in **Fig. 8** show- a small increase in the vibration magnitude of roughly 0.19793 m/s^2 after making a small hole of 0.005 meters in the crude pipeline to simulate a small leak, the vibration magnitude rose to 0.334856942 m/s^2, when the size of the leak has increased by 0.0075 meters to simulate the medium leak. However, after completing the analysis on all pipe sections, it is found as shown in the line chart below that the vibrations are the highest at locations when the size of leaks is bigger.

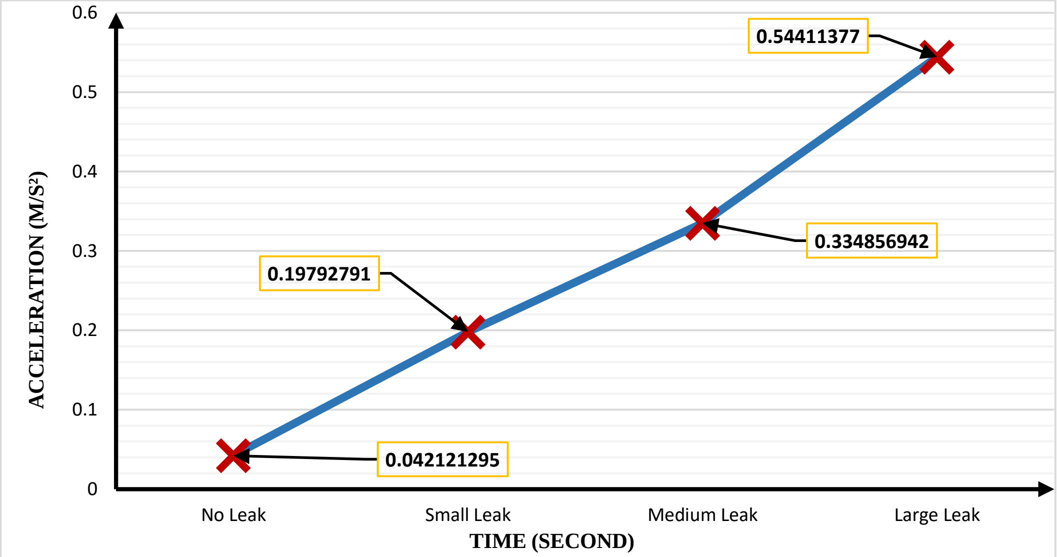

Figure 8: Line Chart for pipeline system cases (Acceleration (m/s^2) & Time (s))

The values for the whole case scenarios can be summarized from **table 3** below, furthermore the acceleration contours for each case scenario.

TABLE 3: All leak pipeline state simulation cases

Case	Value	Unit
No Leak	0.042121295 to 0.1113	m/s^2
Small Leak	0.19792791	m/s^2
Medium Leak	0.334856942	m/s^2
Large Leak	0.54411377	m/s^2

The last analysis is carried out to investigate the effect of the leak size of the supported straight pipeline on vibration levels. As it can be noticed (from the figures 5, 6, and 7, the small, medium, and large leaks, respectively), when the size of the leaks increase the vibration magnitude will gradually increase, which let the pipeline get the shape as it is clearly illustrated in figures 10, 11 and 12. Finally, the variations in the pressure due to leakage are followed by an amplitude shift in vibrating response in a complex pattern on the pipeline surface. Pressure variations/or fluctuations are directly proportional to the pipe's surface velocity/acceleration and could be determined by a speed/acceleration transducer [3].

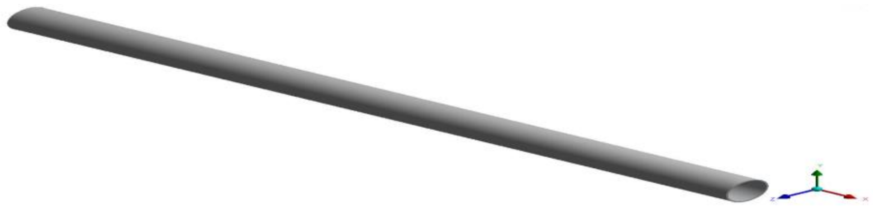

Figure 9. Healthy Pipeline (No leak scenario's)

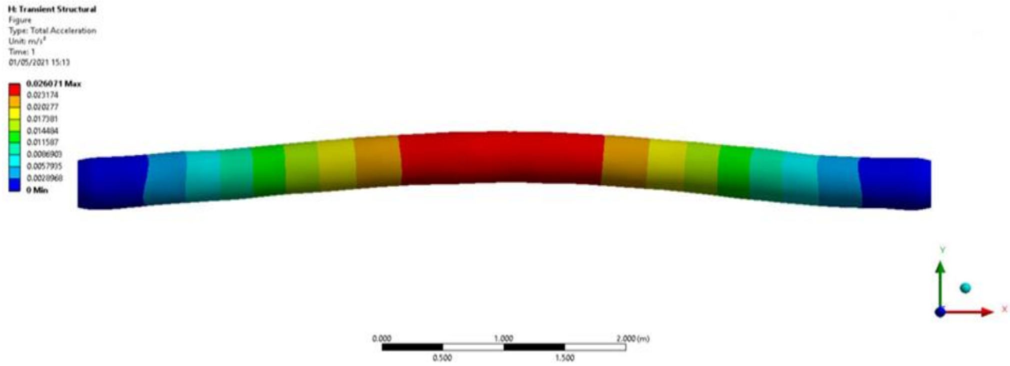

Figure 10. Small leak scenario's (0.005 meters)

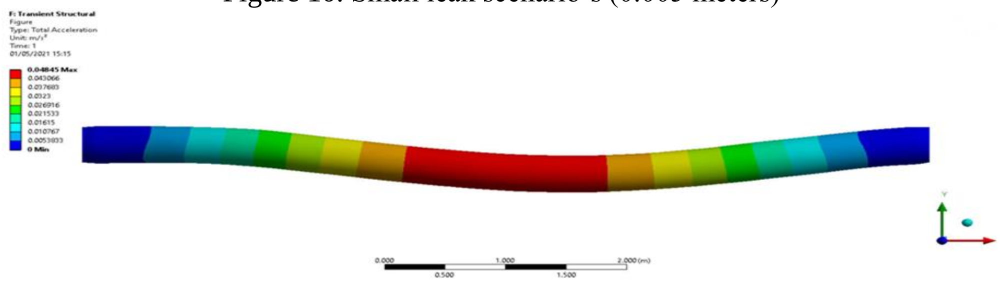

Figure 11. Medium leak scenario's (0.0075 meters)

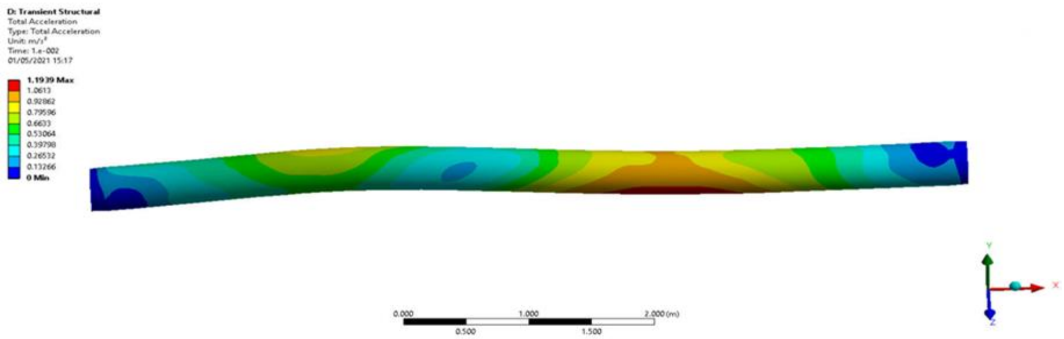

Figure 12. Large leak scenario's (0.01 meters)

4. Conclusion

Due to the high concentration of oil spillage via distribution pipelines, oil pipeline spillage must be detected, located, prevented, and controlled. Prior studies and the existing leak detection methods have been experimentally carried out on small water pipeline diameters.

Firstly, a computational study to evaluate leak detection in complex crude pipelines using vibration signals has been successfully carried out. This includes designing and analyzing of the computer research for fluid-conveying pipeline network using as earlier mentioned computational fluid dynamic (CFD), finite volume analysis (FVA) by the ANSYS Fluent package, and finite element analysis (FEA) by ANSYS Mechanical package. After completing the analysis on all pipe sections (Healthy pipe (no leak), and/or leak states (small, medium, and large)), it was found that this technique for pipeline leak detection is capable for detecting oil spillage in different leak size successfully.

Computer research has been conducted to assess the method of vibration-based leak detection of pipeline systems. The computer studies are chosen since previous studies have been experimentally carried out. Moreover, the time-saving and low-cost efficiency in comparison to laboratory/experimental work and difficult data getting are the reasons why this computer research is considered, as the experiments in the oil and gas sectors are costly and have limited accessibility.

Secondly, in order to secure the pipeline system in case of an occurrence of a leak, maintain a complete real industrial measurement and control package to be used in harsh environment (Oil & Gas sectors) to continuously monitor the crude pipeline, utilizing the vibration signal is an essential technique for leak detection. In this research, the Fluid-Structure Interaction (FSI) of a pipeline transporting fluid analyses, have been carried out. Furthermore, the vibration measurement of this scenario leak or no leak has been obtained for each leak scenario consideration.

To sum up, based on the Fluid-Structure Interaction (FSI) investigation of vibration-based leak detection system found capable of detecting leaks with different scenarios. In the next paper a **Programmable Logic Controller** (PLC Offline program) will be employed to be used as the main control to control, monitor, and troubleshoot the system at different mentioned scenarios, and also to maintain a complete real industrial measurement and control package to be used to monitor the crude oil pipeline, utilizing the vibration-based leak detection technique.

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