Leak Detection in Pipeline System Based on Flow Induced Vibration Methodology in Pipeline

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Abstract: ***The control of leaks in compressed gas and water distribution networks represents a critical issue. This paper deals with the detection of leaks by using vibration monitoring techniques. A Micro-Electro-Mechanical Systems (MEMS is developed for non invasive monitoring of pipeline systems. It incorporates MEMS accelerometers for measuring flow-induced vibration on the surface of a pipe to determine the change in fluid pressure caused by rupture and the damage location. This work presents an experimental investigation of the relationship between flow-induced vibration and the pressure fluctuations. Measurements of vibration were performed in pipe sections of a compressed gas filled loop subjected to a wide range of pressure. Experimental studies and observations shows that a sharp change in pressure is always accompanied by a sharp change of pipe surface acceleration at the corresponding locations along the pipe length. Therefore, pressure-monitoring can be transformed into acceleration cum vibration-monitoring of the pipe surface.***

Keywords: leak detection, acceleration, vibration, MEMS sensors

1. Introduction

Compressed and pressurised fluid carrying pipeline distribution systems, particularly underground pipeline networks, could be subjected to multiple damaged due to earthquake, pipe corrosion, man -made or natural hazards. In all these situations, the damage can be disastrous: leaks and ruptures in the pipeline carrying hazardous chemical gases would lead to major human health problems. Pipe damage may result in reduction in required demand supply at the destination point .compressed gases leakage at high pressure may threaten the safety of nearby environment. This paper demonstrates the use of a vibration monitoring sensor module for identification of location and extent of pipe ruptures in real-time so that emergency response measures can be rapidly implemented to minimize disaster consequences. Compressed and Pressurized pipeline systems such as a water distribution network and compressed gas filled pipeline network can be monitored non-destructively for the purpose of damage identification by measuring pipe surface acceleration at different positions. The change in pipe vibration value arises due to pipe acceleration can be primarily attributed to the sudden change in the compressed or pressurized fluid such as air or water caused by a rupture in the network. The damage identification can be analyzed using time domain history data vs acceleration data. Thepaper focuses on to demonstrate an experimental investigation on the relationship between piping vibration and the pressure fluctuations, such that water or compressed high pressure-monitoring can be transformed into acceleration-monitoring of the pipe surface. The implementation of MEMS (Micro-Electro-Mechanical Systems) sensor is significantly more economical approach leading to non-invasive measurement facilitates the simple and cost-effective identification of damaged pipe.

2. Related Works

Different methods are used to investigate the leaking and their location. It includes visual inspections, acoustic emission, and dynamic pressure measurement. The study on leak detection in acoustic before was done using cross-correlation analysis, cepstrum analysis, and also wavelet based-filtering.

Kim et al. [2009] proposed a low cost, unmanned, fully automated in-sewer gas monitoring system, called Sewer Snort. This system uses floating sensors for sewer gas concentration measurement. The floating sensors are introduced at the upstream station and drifted to the end pumping station, collecting location tagged gas measurements. The collected data provides gas exposure profiles to be used for preventive maintenance and/or repair. The localization of events detected by the sensors is based on the availability of fixed beacons set up on the manholes in the pipeline structure. The localization of the defects is simply determined by the identity of the manholes delimiting the segments containing the defects.

Stoianov et al. [2007] proposed wireless sensor network, called PipeNet, with fixed nodes. It integrates sensors that are able to generate acoustic vibration and collect hydraulic and acoustic/vibration data at high sampling rates. It also provides algorithms to analyze this data to detect and locate leaks.

Gao et al. (2005) uses correlation techniques for leak detection and location identification by analyzing the acoustic wave associated with leakage. These techniques are satisfactory for metal pipes, but they are unreliable for non-metallic pipes in which the acoustic signals attenuates very rapidly.

Misiunas et al [2005] validated and tested the use of pressure transient for detecting water pipe breaking in lab setting and real networks. The study adapted the continuous monitoring technique and used a modified two-sided cumulative sum algorithm to detect abrupt break-induced changes in the pressure data. Although the technique successfully detected the location of the break, this technique is applicable to single pipelines under two conditions, the side pipe has to be smaller in diameter than the pipeline and the reflection characteristics of the end boundaries can be derived, which limit its application in the real field.

Liggett and Chen (1994) calibrates and determines rupture or unauthorized use in the pipeline systems based on inverse transient analysis in the pipe networks. These techniques solve the inverseproblem from the measured pressure head data to detect the extent of rupture but involve extensive computational effort after the relevant data are collected.

3. Proposed Methodology

This experimental investigation study introduces a leak detection method based on a MEMS (Micro-Electro-Mechanical Systems)-sensor network that monitors the pipe surface acceleration in a non-invasive manner and computes in real-time a measure of acceleration-change. In the experiment, MEMS sensors are installed at all the different positions in the pipe network, so that the sensitivity of the MEMS sensor and change in acceleration value can be analyzed network. When a leak occurs in the network, the sudden disturbance in the fluid flow and pressure induces corresponding sudden change in the acceleration of pipe vibration. This change in the pipe acceleration is measured, and on the basis of these acceleration data, the location of the pipe leak can be found in the pipe network. For the field test, leak was simulated in the developed experimental pipeline testbed using a ball valve, the simulated events; include valve opening and closing at different range of high pressure compressed air.

4. The Correlation between Fluid Pressure Variation and Acceleration

Pressure variations and flow-induced pipe vibrations are two strongly correlated quantities. The internal pressure p of a pipe can be expressed as p = po+dp, where po is the nominal pressure and dp is the pressure variations.As,the nominal pressure po does not contribute to the flow-induced pipe vibrations only the pressure fluctuations dp will be considered. The pressure dp is balanced by the elastic stresses, pel , and the inertia stresses, pin, in the pipe wall, i.e., dp = pel + pin. Assuming Fel is the unidirectional force developed against the pipe wall, then:

$$\frac{Fel}{A} = \frac{PelDl}{2tl} = \frac{PelD}{2t} \qquad (1)$$

where A is the cross sectional area, D is the pipe diameter, l is arbitrary length of the pipe, and t is the pipe wall thickness. Hook's law declares:

$$\frac{Fel}{A} = E\varepsilon = \frac{E\pi\delta D}{\pi D} = \frac{E\delta D}{D} \qquad (2)$$

Where, E is pipe's elastic modulus, ε is strain, δD is pipe's diameter deformation. From Eqs. 1 and 2:

$$Pel = \frac{2tE\delta D}{D^2} = \frac{4tE\delta}{D^2} \qquad (3)$$

Where δ is the displacement of the pipe wall

The inertia force can be written as

$$Fin = ma = (\pi tlD\rho)a \qquad (4)$$

Where m is the mass, a is the acceleration, and ρ is the mass density of the pipe. From Eqs. 3 and 4 the pressure fluctuations dp can be expressed as

$$dp = Pel + Pin = \frac{4tE\delta}{D^2} + t\rho \qquad (5)$$

and thus the correlation between pressure variations and pipe wall acceleration becomes readily available. Further assuming:

$$\delta = \delta o(sin\omega t) \qquad (6)$$

Eq. 5 can be rewritten:

$$dp = \left(\rho - \frac{4E}{D^2\omega^2}\right) ta \; (7)$$

and the correlation is even more apparent. Another simple approach is to simulate the piping system as one dimensional beam model. Evans et al. (2004) took this approach and derived Eq. 8:

$$dp = -\frac{A\gamma}{g} a \qquad (8)$$

where g gravitational acceleration, A cross sectional area of the beam and γspecific weight of the beam. Eq. 8 again indicates that the acceleration of the pipe is proportional to the pressure fluctuations in the fluid. As seen from the above equations, analytical calculations, which are based on different simplifying assumptions and theoretical models, can be derived and can serve as a first basis in describing pipe vibrations due to pressure fluctuations in a pipeline system. In this background, we emphasize the use of acceleration data measured on the pipe surface as a measure of pipeline health. This study relies on the hypothesis that rupture of considerable size in the system causes sudden expulsion of water, resulting in abrupt change in force on the pipe internal wall to enhance the vibration of the system. Thus, a ruptured segment of the integrated system is expected to show a distinctly different transient response compared to the response associated with other common ambient forces.

5. Component Used

The hardware consists of: a sensing unit, a processing unit, display unit and a power unit. The Sensing unit is usually composed of two subunits: sensors and microcontroller. The analog signals obtained from the sensors are converted to digital signals by the ADC, and then fed into the processing unit. The processing unit is generally a microcontroller, we have used Arduino board(ATmega328) that fetched the required real time signal and then the real time signal is processed using the software used.Here,for our experimental studies we have used National instruments' labview 2012. The power unit is one of the most important components of a sensor node and is supported by 5V power supply.

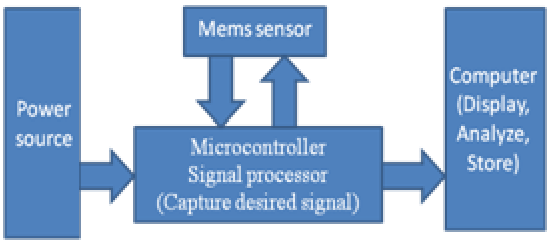

Figure1: Basic hardware block diagram

Hardware used:

- ArduinoATmega28 microcontroller
- Mems Accelerometer (adxl 335)
- Display unit(computer)
- 5v power supply

Software used:

- National instruments' labview 2012

6. Experimental Setup

To demonstrate the concept of Leak detection using the flow-induced vibrations on the pipe surface. A straight length of 1.6 meters of steel pipe having flanged rating of class 300 is used in the 20 bar high pressure laboratory. The test line has pipeline of 4 inch diameter with 2 simulated leaks of 6 mm. A quarter inch ball valve is mounted on to the leak to simulate leak manually. The acceleration-based sensor is attached on pipe surface and the ball valves are used to emulate multiple leaks. To verify the proposed methods explained above, simple experiments were carried out. In the experiments, leaks were simulated by the opening and closing of the valves. The valve is opened and closed suddenly. The corresponding signal is captured by the microcontroller and further analysed in the software used for this system that is lab view 2012.

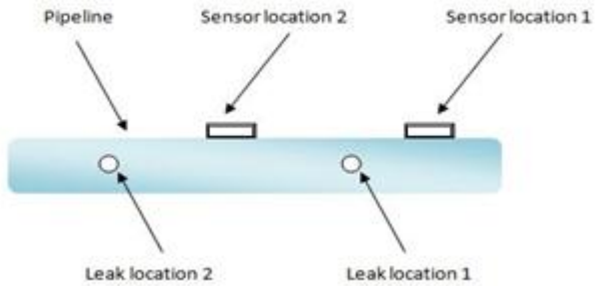

Figure 2: Basic experiment design

Figure3: Experiment test setup

The flow direction is from sensor location 1 to sensor location 2. This experimental study uses different line pressure with constant flow rate. The line pressure is varies from 10 bar to 3 bar with constant flow rate of 300 m^3/hr.

7. Results and Analysis

Output results show the measured data of rapidly changed acceleration using an acceleration based vibration sensor network. The sensor board is equipped with a three axis accelerometer and it transmitted samples data successfully in real time to a laptop computer. A sequence of Z-direction acceleration records is plotted and shown below. These plots show that the effect of simulated rupture measured in terms of the magnitude (intensity) of acceleration depends on the distance between the rupture location and the sensor locations under varying pressure conditions too. For example figure 4,5,6 and 7 represents the acceleration magnitude value for different line pressure corresponds to the event of opening of valve 1 (leak location 1) and sensor location 1.

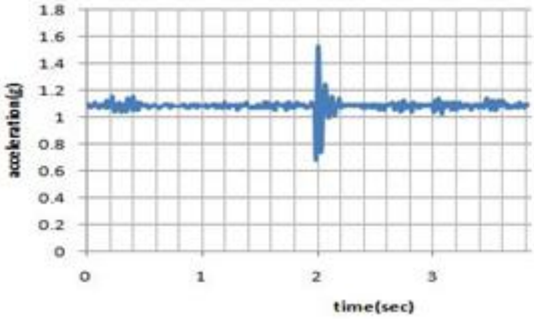

Figure 4: Pressure: 10 bar

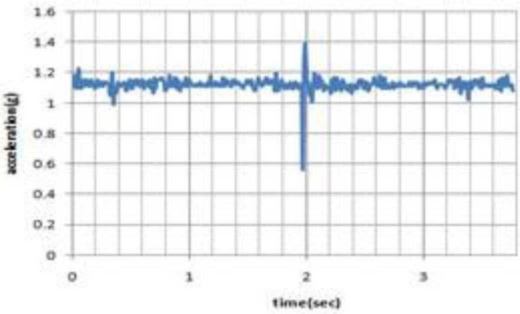

Figure 5: Pressure: 8 bar

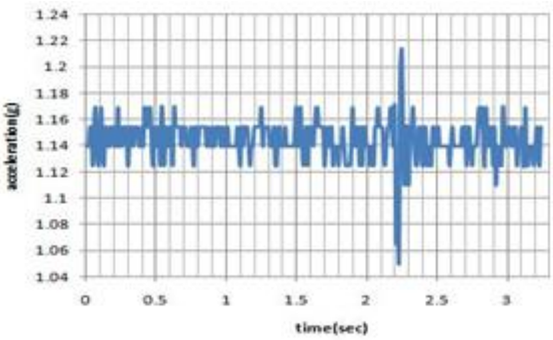

Figure 6: Pressure: 6 bar

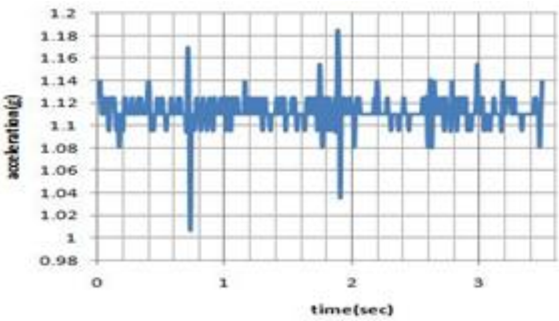

Figure 7: Pressure: 3 bar

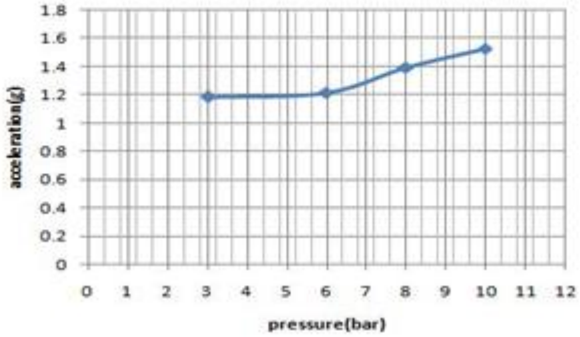

Figure 8: Combined analysis

Upon closer examination of plotted graphs, we observed that the amplitude of each peak is different for different line pressure. The accelerations value for 10 bar and 8 bar pressure are 1.52g and 1.39g respectively. Also, the acceleration value for 6 bar and 3 bar pressure are 1.21g and 1.18g respectively. These acceleration magnitudes are observed for sensor location 1 and leak location 1. These graphs reveal that the magnitude of the acceleration change increases as the line pressure increases as shown in Fig. 8 when we plotted the combined analysis curve result for different pressure value (bar) vs. acceleration (g).

Similarly, if we plot the graph for the other case when both leak 1 and leak 2 is open simultaneously and the sensor position is shifted to location 2.Then, upon closer examination of Fig. 9,10,11and 12, we observed that the amplitude of each peak is different for different line pressure. The accelerations value for 10 bar and 8 bar pressure are 1.57g and 1.48g respectively. Also, the acceleration value for 6 bar and 3 bar pressure are 1.24g and 1.21g respectively. These acceleration magnitudes are observed for sensor location 1 and leak location 1 and 2 both. These graphs reveal that the magnitude of the acceleration change increases as the line pressure increases as shown in Fig. 13 when we plotted the combined result for different pressure (bar) vs. acceleration (g).

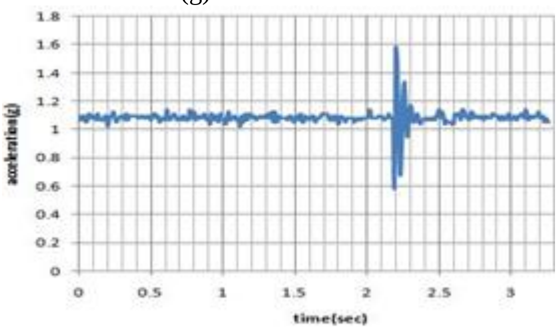

Figure 9: Pressure: 10 bar

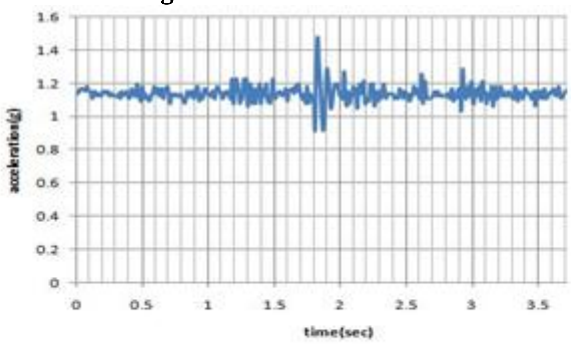

Figure10: Pressure: 8 bar

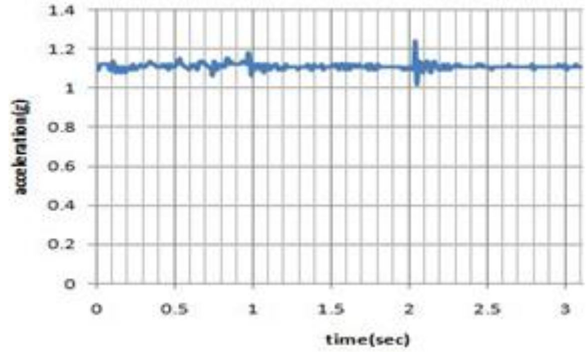

Figure11: Pressure: 6 bar

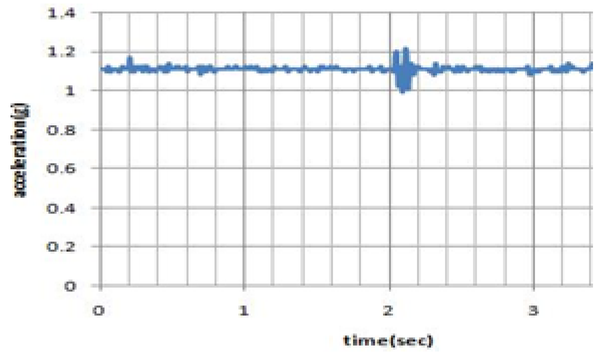

Figure12: Pressure: 3 bar

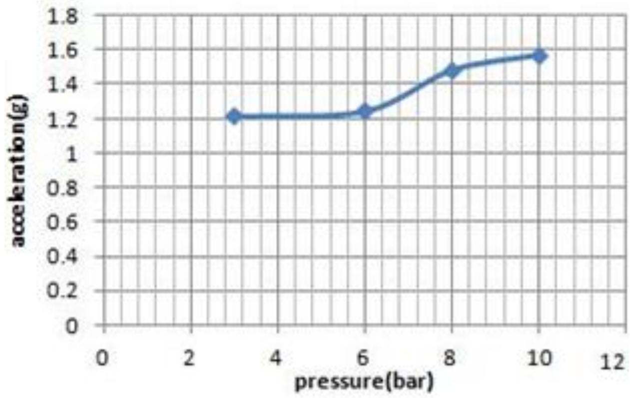

Figure13: Combined analysis

When the both valve is open i.e., when both leak is opened simultaneously at one time the change in acceleration magnitude is more when we compare it with acceleration magnitude value when there is only one leak. Also we can observed that the difference in acceleration magnitude is not much more in 3 and 6 bar pressure but when the pressure value increases from 8 bar to 10 bar a sharp change in acceleration value can be noticed. So, from these experimental studies we can conclude that pipe surface acceleration is useful in determining the damage or leak associated with the pipes under varying pressure conditions.

8. Conclusion

In these experimental studies, a novel pipe damage detection method based on flow induced vibration methodology in pipeline is studied and validated. It incorporates MEMS accelerometers for measuring pipe surface acceleration to determine the change in fluid pressure caused by leak and other damage. Experimental observations show that a sharp change in pressure is always accompanied by a sharp change of pipe surface acceleration at the corresponding locations along the pipe length.

9. Future Scope

- Further study is required to understand the pipe vibration under the ambient and transient hydraulic conditions and also for different structures such as t-joints and sharp bends.
- Also, the sensor directivity will be studied and will be implemented to enhance the leak locations accuracy using sensors location.

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