Monitoring Bending and Buckling of Long Pipelines due to Environmental Effects

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Abstract: Pipeline systems are widely used for distribution and transportation of petroleum, natural gas, water, and sewage. Pipeline operators face many threats to the integrity of pipelines. These include buckling and bending of the pipelines due to temperature changes, internal pressure or ground movement. Different types of sensors are used to monitor the stress in different directions of the pipe walls which include acoustic sensors, optical fiber sensors and strain gauges. In this paper a multi-node wireless sensor network that is distributed along the longitudinal axis of the pipeline is proposed. Bidirectional strain gauges connected to each node of the network measures the hoop and axial stresses along the pipeline. The data collected from each node is wirelessly transmitted through the network and processed at the receiving node. The data from individual nodes will be used to calculate the expansion due to internal pressure and temperature change, whereas the combined data from various strain gauges will be used to calculate the bending in pipe due to ground movement.

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1. Introduction

Underground piping systems plays a vital role in successful transportation of water, sewage, oils and gas resources. The network of pipe is buried underground to ensure their safety and to avoid any disruption that might occur because of their presence on ground. However, displacement and possible failure of the pipeline might result because of the displacement induced landslides. Currently many techniques exist for rapid detection of damage along a pipeline that can help to minimize interruption but underground pipelines are difficult to be inspected. The faults the pipeline can experience depends on variety of conditions including pipeline material (e.g. metallic, concrete and high-density polyethylene) and pipeline diameters as well as differing in geotechnical conditions (Bhalla, et al. 2005,Kishawy and Gabbar 2010,Sohn, et al. 2004).

Strain is an important measurement for pipelines structural integrity and condition monitoring. High magnitude, repetitive strains may lead to fatigue or yielding in the material. Permanent ground deformation imposes flexural bending and shear on the pipeline accompanied by axial compression or tension, depending on the orientation of the pipeline crossing an active fault. Under axial compression, the crushing of the joint bell is common while under axial tension, joint pullout is possible (Polak, et al. 2004). Due to the nonlinearity and uncertainty inherent to the joint, the behavior of non-continuous segmented pipes is considered to be a challenging engineering problem.

Pipelines nondestructive test is a technique that allows the examination of pipeline material properties without causing any damage to the material (Rizzo 2010). Recent advanced sensing technologies such as thermal imaging technique is used for detecting pipelines failure but it has its own limitations (Cho, et al. 2007). Other techniques such as ground penetrating radar and guided waves (Köppe, et al. 2012) can also detect subterranean conditions from the surface. However, these techniques are still unreliable for accurate characterization of pipeline damage.

Sensors integrated into pipelines coupled with a delivery of sensed information, could provide tremendous benefits for pipelines operators which include: fewer catastrophic failures, conservation of natural resources and improved emergency response. Because most pipelines are operated at high pressure, pipeline failure can cause severe damage to human health and property and interruption of water, gas or oil supplies (Guevara, et al. 2010).

One common sensor used in design to measure pipe bending is fiber-optic sensors (Zhang, et al. 2008). Recent studies have been conducted to monitor pipeline buckling with distributed Brillouin fiber sensor. Strains gauges can also be used to estimate a structure's loads, moments, and stresses. The sensors used to measure pipeline characteristics can be connected by wires or fiber optic. However these connecting wires are usually long and can be a subject to breakage or connector failures. Another disadvantage of long wiring that they need installation and long term maintenance cost which in turn limits the number of sensors that may be used which eventually affects the overall quality of reported data.

Using wireless networks for sensing eliminates these extra costs making installation much easier and more efficient. The wireless sensor network is a smart programmable solution that is capable of fast data acquisition (Guevara, et al. 2010, Kouche and Hassanein 2012). It is reliable and accurate over the long term, costs little to purchase and requires no real maintenance. Another advantage of using wireless sensor network that it can run on semi-active or even absolutely sleeping modes that can make it consumes very little power.

The technical system design and the experimental setup used to test network of pipelines using a smart damage monitoring technique are discussed in this paper. The proposed monitoring system is based on the development of sensor networks with event-driven triggering of the wireless data transmission. In this study, an experimental program focused on the behavior of commercial buried segmented pipelines is pursued. The results obtained from the array of strain gauges during pipeline faults are presented.

2 Methodology

The proposed wireless sensor network platform for pipelines structural monitoring consists of multiple nodes grouped in a star topology, as shown in Figure 1.A. Each of these groups can further form nodes in a two-peer network topology (Lynch and Loh 2006), as shown in Figure 1.B. The block diagram of the wireless sensor node is shown in Figure 2.

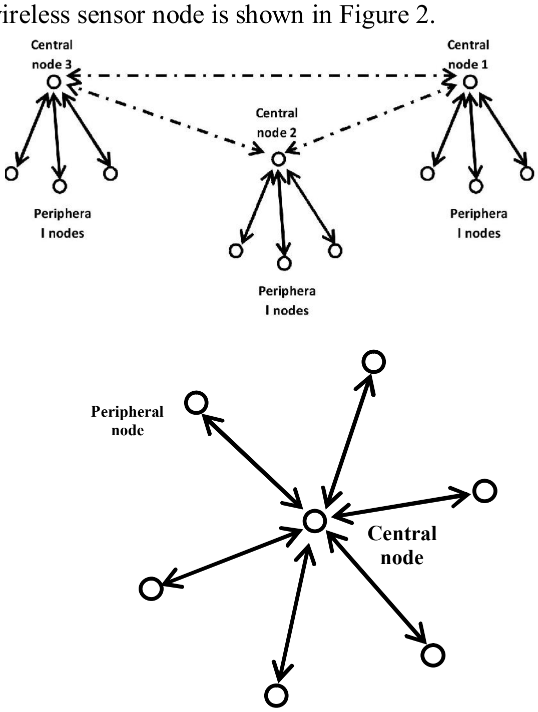

Figure 1: Wireless sensor network topology used; A. Star network and B. Two-peer network.

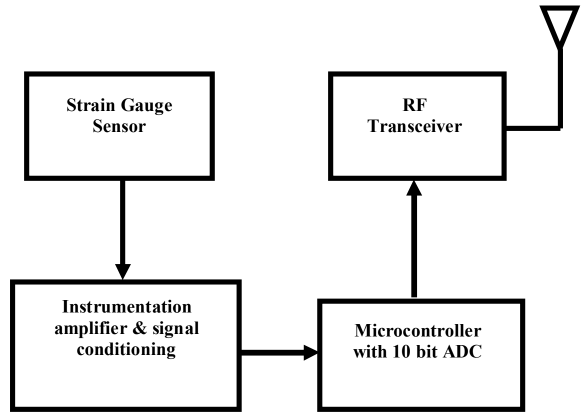

Figure 2: A wireless sensor node functional block diagram

Every sensor node comprises five strain gauges attached to one portion of the pipeline to detect stain change in three different directions. Each strain gauge is connected as a part of quarter-bridge circuit, as shown in Figure 3.

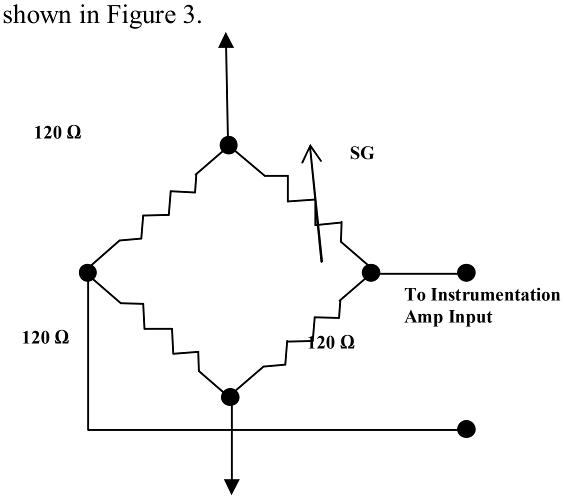

Figure 3: Quarter-bridge strain gauge circuit

Each of the quarter-bridge strain gauge circuit outputs are directly connected to the inputs of an AD8221 low offset instrumentation amplifier to amplify any change in the voltage due to changes in strain. Its low offset and high common mode rejection ratio over a wide frequency range make AD8221 an excellent candidate for bridge measurements.

At the core of each sensor node is the low-power Microchip PIC16f88 microcontroller. This 8-bit microcontroller has 4 KB of flash memory for storing embedded programs and 368 B of SRAM for temporary storing measurement data. In total, five sensing channels of the microcontroller are provided for the interface of sensor circuits to detect their signals and support the conversion from analog sensor outputs into digital formats with resolutions of 10 bits, which can be transmitted over the wireless network.

To provide wireless communication between sensor nodes, the RF solutions BRAVO 868 wireless transceiver in each node has been integrated. This radio frequency transceiver operates on the 868 MHz radio band and can communicate at a data rate of 9.6 kbps. The circuit diagram of the node is shown in Figure 4.

3 System Power Consumption

To prolong the battery life for buried wireless sensors a low power prototype was adopted. During the normal state without change in strain of the pipeline, the transceiver is "sleeping" and requires a standby current of approximately 6 µA per sensor node.

In order to best take advantage of these extremely low sleep currents, the microcontroller is programmed to operate in a mode which pulses power to the sensors' electronics, while synchronously performing analog to digital conversions. The RF communications is only used if there is any detected change in the data of a node. All internal units that do not have a power-save mode available will be deactivated for power saving purpose.

These advances have allowed batteries to be deployed in a wide range of wireless sensing applications, where the sensing nodes was placed in/out of sleep as required by the structure change. This is critical to squeeze most of the energy possible from remote batteries while still provide as high data acquisition rates as required. Using a lithium-ion battery with 200 mAh and five sensor nodes, the life cycle of the sensor network is calculated to be in the range of two years.

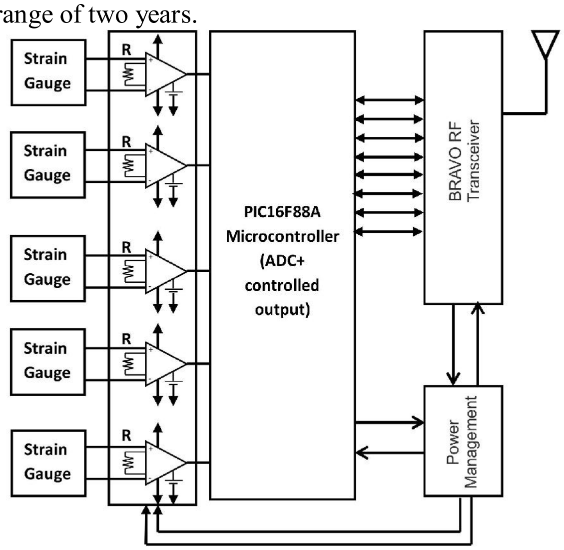

Figure 4: Wireless sensor node circuit diagram

4 System Setup

The strain gauges are installed on three axis of the pipeline, X, Y and R with their lead wires along the length of the pipeline to measure its response introduced during events of pipeline displacement. In total a set of five strain gauges are installed at each node; two strain gauges in the horizontal plan on the opposite faces, two in the vertical plan on the opposite faces and one along the R direction. Figure 5 shows the arrangement of strain gauge in each node. These results from the strain gauges can be interpreted individually for information like bending and pressure changes and collectively for information like thermal expansion, total bend and compression in the length of the pipe. The interpretation is listed as following

- If strain gauge N1X1 shows compression and N1X2 shows tension it is interpreted as the pipe is bending along the horizontal plan.
- If strain gauge N1Y1 shows compression and N1Y2 shows tension, it is interpreted as the pipe is bending along the vertical plan.
- If all the strain gauges (N1X1, N1X2, N1Y1 and N1Y2) show tension, it is interpreted as the pipe is undergoing expansion along the length.
- Any change in the reading from strain gauge N1R1 will be interpreted as a change in pressure inside the pipe.
- Tension in N1X1 and N1Y1 and compression in N1X2 and N1Y2 will predict the bending in both horizontal and vertical plane.

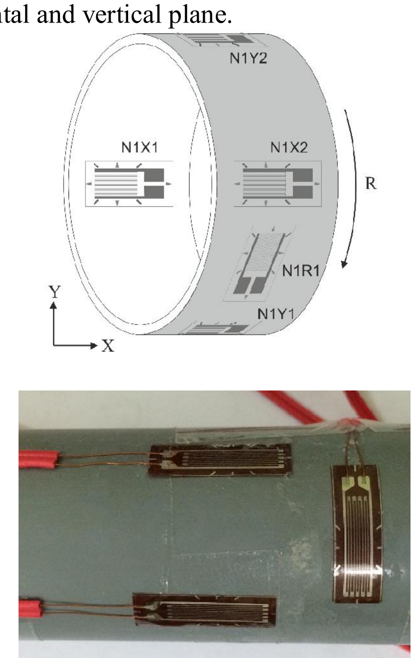

Figure 5: Schematic diagram and actual figure of strain gauge installation

By measuring the change in the strain gauge resistance, the output voltage V_0 of the strain gauge can be calculated as;

$$V_o = \left(\frac{R_3}{R_1+R_3} - \frac{R_4}{R_2+R_4}\right) V_i = \left(\frac{R}{(R-\Delta R)+R} - \frac{R}{R+R}\right) V_i \quad (1)$$

$$V_o = \left(\frac{R}{2R-\Delta R} - \frac{1}{2}\right) V_i = \left(\frac{2R-(2R-\Delta R)}{2(2R-\Delta R)}\right) V_i \quad (2)$$

$$V_o = \left(\frac{\Delta R/R}{2(2-\Delta R/R)}\right) V_i \quad (3)$$

$$V_o \approx \frac{\Delta R}{4R} V_i \quad (4)$$

The strain ϵ is calculated using:

$$\epsilon = \frac{-4V_r}{GF(1+2V_r)} \quad (5)$$

Where
GF = Gage Factor and

$$V_r = [(V_{OUT}/V_{IN})strained - (V_{OUT}/V_{IN})unstrained] \quad (6)$$

The strain gauges were calibrated by eliminating the lead wires and multiplying the output voltage by the amplification of the AD8221 instrumentation amplifier G where:

$$G = 1 + \frac{49.4k\Omega}{R_G} \quad (7)$$

Figure 6 shows the experimental setup where the pipe was subjected to controlled deformations (bending). For the current study, two nodes with 5 strain gauges each were prepared. The strain gauges were connected to a data logger for real time data collection. The responses from the strain gauges were recorded and interpreted for estimation of total bending along a certain direction.

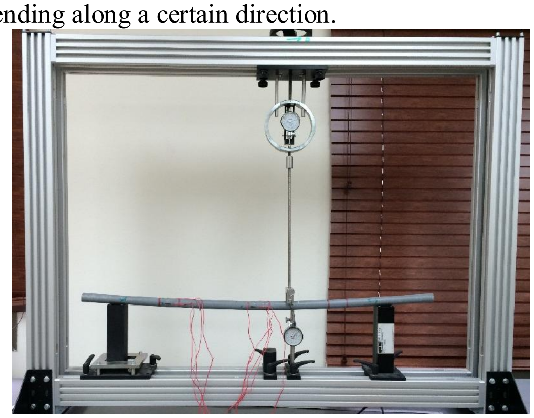

Figure 6: Experimental setup for radial bending

Figure 7 shows the experimental setup, where the test pipe is subjected to compressive loads, which eventually buckle the pipe. The sensing strategy utilized in this paper is optimized to provide real-time pipeline displacement data and to predict failure mechanisms of the pipeline during large displacements.

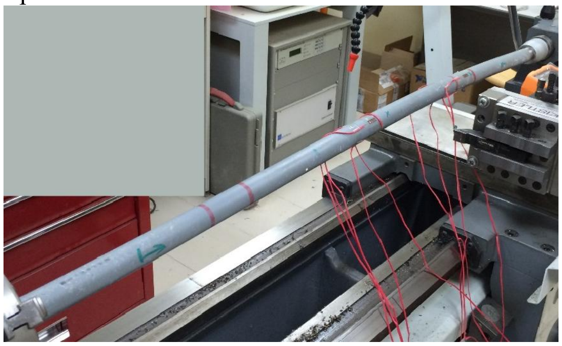

Figure 7: Experimental setup for axial compression

5 Results and discussion

Data collected during the three point bending is presented in Figure 8. The strain gauges showed the strain in the form of tension and compression as per their location. Because of the nature of load along the Y-axis, it can be seen that the tension and compression was sensed by gauges on the upper (N1Y1, N1Y2, N2Y1 and N2Y2) and lower surface of the pipe, whereas, the gauges on the side walls of the pipe (N1X1, N1X2, N2X1 and N2X2) did not reported any major strain. Also, the strain data showed difference in magnitude as per their distance from the point of application of displacement. This can be seen from the difference in magnitude of strain from the two nodes with node 1 being close to the point of application of displacement and node 2 away.

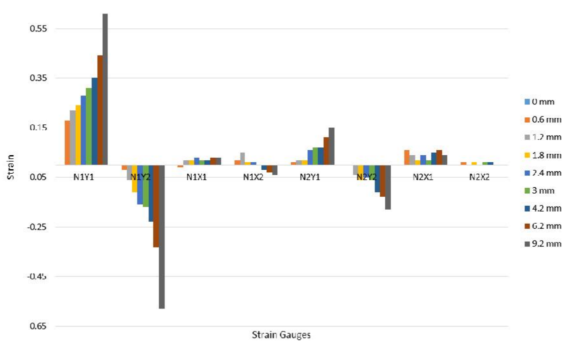

Figure 8: Strain at various locations during radial loading

The results of axial compression is presented in Figure 9. The pipe was compressed 1mm and 2mm along the length and it can be seen that all the gauges showed approximately similar change in strain.

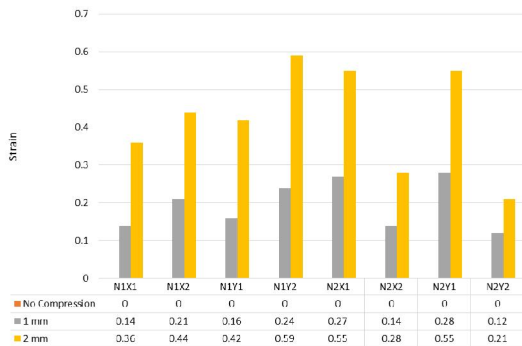

Figure 9: Strain in various gauges during axial compression

When the pipe was further compressed axially to about 5.5 mm, this resulted in sudden buckling and the gauges showed the effect in the form of strains which can be seen in Figure 10.

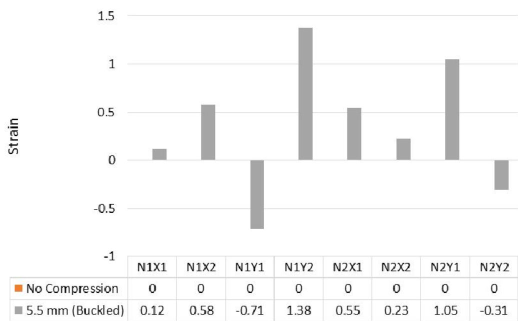

Figure 10: Strain in various gauges during buckling along the length

6 Conclusion

In this paper, a technique for predicting pipeline faults is proposed by continuously sensing the strain across the pipeline using wireless sensor network distributed along the longitudinal axis of the pipeline. A set of 5 strain gauges connected to each node of the network measures the hoop and axial strain along the pipeline. Each node contains strain gauge regulated sensor excitation, instrumentation amplifiers with programmable gains, microcontroller with10 bit A/D converter with an on-board memory, and bi-directional data logging RF serial data transceivers link. The nodes are capable of continuous RF transmission from over 70 nodes, over frequency bands of 868 MHz, at data rates of 9.6 Kbaud. Collected data from two points along the length of the pipeline helped in predicting the nature of bend, its direction, magnitude and location. The data was capable of predicting any change in pressure inside the pipe and the change in length either extension or contraction. The data was also helpful in showing buckling in the pipe.

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