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DESIGN AND DEVELOPMENT OF A NON INTRUSIVE PRESSURE MEASUREMENT SYSTEM FOR PIPELINE MONITORING

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In recent years wireless sensor network systems have increasingly been used to monitor infrastructure health. Advances in electronics and sensing systems have enabled the development of various pressure sensing methods for pipe pressure monitoring. This article presents laboratory based test results as part of the development and validation of a pipeline pressure monitoring method based on force sensitive resistors (FSR). Additionally, in order to validate the data, the proposed pressure sensing method is compared with a commercially available direct pressure sensor. Analysis of the data shows a significant correlation (correlation factor =0.9928) between the commercial sensor and the proposed sensor. These results showed that the proposed method has an acceptable accuracy and reliability even though it is not ultimately intended for absolute pressure measurements, but for monitoring relative pressure changes in pipes.

Keywords: Pressure monitoring, Non intrusive, Smart pipes.

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Introduction

During the period of 2009-2010 approximately 3 GL (3×10^9)of water was wasted in the UK every day (Department for Environment Food and Rural Affairs 2011). This includes both supply and distribution losses. Effective pipe monitoring systems can potentially help to reduce these losses, benefiting the water industry, consumers and the environment. Such a system should be able to be retrofitted to existing pipelines as well as being installed in new pipelines. Various pipeline monitoring systems have been developed over the past few years (Rizzo 2010). The first step towards pipe monitoring is to measure parameters which are related to the pipe condition. The sensing method should be preferably non intrusive to the pipe structure , low in cost and easy to fit. Different methods of leak and damage detection have been suggested in the literature (Hieu et al. 2011; Gao et al. 2005; Colombo et al. 2009; Dezfouli and Zabihollah 2010; Khulief et al. 2011). The main methods used in pipeline monitoring are: laser and vision based monitoring, acoustic and vibration monitoring, fibre optic monitoring, Robot/Smart PIG and multimodal monitoring.

Vision based systems use CCTV technology to detect and characterise pipeline defects. Similarly the laser scanning method uses a laser beam to investigate the integrity of the pipe structure (Kingajay and Jitson 2009). These technologies are also used in many robot based or smart pig based systems. Both of these methods exhibit various strengths and weaknesses. CCTV systems require a skilled operator to locate and characterise defects (Sinha 2004). Although automating the detection process by utilising image-processing techniques can solve some of these issues, they still require access to the interior of the pipe which is the main disadvantage of these systems.

Acoustic measurement can be used to detect and locate both bursts and leaks in pipes. These systems are based on the principal of Acoustic Emission (AE). Recent advances in the field of sensors such as hydrophones and MEMS (Micro Electro-Mechanical Systems) accelerometers have created many opportunities for these technologies to be utilised in infrastructure monitoring. A pipe leak will produce a vibration which can be detected using hydrophones or accelerometers. These acoustic measurements can then be cross correlated to pinpoint the location of the leak. An advantage of these sensors is that they do not require access to the interior of the pipe. However, in order to have a reliable system they need to run continuously at high sampling frequencies. These systems would therefore consume relatively high amounts of energy and therefore not suitable for long term (>20 years) pipeline monitoring. Another disadvantage of these systems is that the acoustic wave propagates differently in different pipe materials, making leak detection difficult in certain types of pipe material.

Fiber optic technology offers a potential solution to the problems associated with conventional acoustic measurements. Fiber optics are used in a variety of infra-structure monitoring systems. These systems exhibit major advantages over other systems, such as long range and independence of the sensor nodes to a power supply, which make fibre optic systems an attractive option for pipeline monitoring (Nikles 2009). However, they are not easy to fit/retro fit to pipelines. In some cases it is necessary to fit fibers and sensors to the pipe at the time of pipe manufacturing, which can be costly. Another disadvantage of these systems is their inability to easily recover from a failure. In the case of a burst or major defect, fibers attached to the pipes can be damaged which can disable the whole system from the point of the incident.

This paper reports on the design and development of a pressure measurement system for pipeline monitoring and presents laboratory based test results and validation experiments. The proposed system is based on the change in contact pressure between the pipe and a restraining clip, making it non intrusive to the pipe structure. Various sensors can be used to measure this contact pressure or alternatively measure the expansion of the pipe, however, most of these sensors require careful installation or complex circuitry. Force Sensitive Resistor (FSR, Interlink Electronics USA) can potentially solve these issues by their wide dynamic range and minimal signal conditioning circuitry. FSR sensors have demonstarted an acceptable performance in other applications such as finger motion tracking (Li *et al.* 2012). Additionally, the proposed pressure sensor assembly is non-intrusive to the structure of the pipe as it doesn't require access to the medium inside the pipe. Although these sensors exhibit lower precision than commercially available sensors they can potentially be used to provide non absolute pressure data, i.e. relative pressure changes, for pipeline monitoring. The proposed pressure sensor in this paper is based on these FSR sensors. Usage of these sensors for pipe monitoring is investigated and compared with an invasive commercial sensor.

System design and theory of operation

All pipes expand when they are pressurized. Although this expansion is very small at low pressures it can be used to detect the pressure changes occurring inside the pipe. Water distribution pipes can be modeled as a simple pressure vessel with open ends. The Hoop stress in the pipe, when modeled as a simple open ended pressure vessel, can be calculated using Equation 1, where σ_H is the Hoop stress, P is the internal pressure, r_0 is the initial radius of the pipe and t_0 is the initial pipe thickness.

$$\sigma_H = \frac{P.r_0}{t_0}, \tag{1}$$

The corresponding Hoop strain ε_H can then be calculated by Equation 2, where E is the

Young's modulus of elasticity of the pipe material.

$$\varepsilon_H = \frac{\sigma_H}{E} = \frac{P.r_0}{t_0.E}, \tag{2}$$

Since ε_H is change in circumference (δ_C), divided by the initial circumference (C), the change in circumference, δ_C, and radius, δ_r, can be found by Equations 3 and 4.

$$\delta_C = C.\varepsilon_H = 2\pi r_0 \frac{P.r_0}{t_0.E}, \tag{3}$$

$$\delta_r = \frac{P.r_0^2}{t_0.E}, \tag{4}$$

From Equation 4 it can be shown that $\frac{r_0^2}{t_0.E}$ is constant and therefore a change in pressure causes a linear change in radius. Figure 1 shows a schematic and an image of the sensor arrangement when attached to the pipe.

The FSR sensor is attached to the pipe with a high strength stainless steel clip. The pressure inside the pipe causes the pipe to expand and induces a contact force between the pipe and the clip. The contact pressure between the pipe and the clip can be modeled as two concentric pressure vessels with open ends. Since the clip and the pipe are in contact the radial expansion of pipe and jubilee are equal. Equation 5 can be used to calculate the contact pressure of two concentric pipes (clip and pipe).

$$\frac{(P-P_c).r_P^2}{t_P.E_P} = \frac{P_c.r_j^2}{t_j.E_j}, \tag{5}$$

Where P_C is the contact pressure between the pipe and the clip, r_j and r_p are the radii of the jubilee and the pipe, E_j and E_P are the respective material's Young's modulii of elasticity of the clip and pipe and t_j and t_p are the thickness of the clip and pipe respectively.

This contact pressure translates to a contact force on the FSR sensor. This change in contact force will alter the resistance between the two terminals of the FSR sensor. This contact force F_C can be calculated using Equation 6, where A_S is the sensing area of the sensor and K is a constant between 0 and 1 which indicates the ratio of the total contact pressure that is applied to the sensor.

$$F_c = K.P_c.A_s \,, \tag{6}$$

The change in resistance can then be measured by using a simple voltage divider circuit and a data acquisition device. The FSR sensor can be installed when there is no pressure inside the pipe and an initial contact force can be applied to the sensor by tightening the clip. At this stage the resistance of the FSR sensor can be measured and used as a reference for further measurements. Pressure measurements have previously been used to detect bursts in pipes (Stoianov *et al.* 2007). The indirect pressure data from the FSR sensor can also be used to detect bursts, blockage or any other type of failure, as long as it affects the pressure of the fluid in the pipe. The pressure transient profile signature of each failure then can be used to differentiate these defects from each other. The location of the burst can then be approximately determined from the pressure profile along the pipeline.

Experimental setup

A PVCU pipe with a diameter of 6 inches was used to test the sensor assembly. Both ends of the pipe were closed with flanges and an inlet/outlet and measurement valves were attached to the end plates. The inlet/outlet valve was used to pressurise the pipe up to 4 bar. The measurement valve was also connected to a commercially available direct pressure sensor in order to compare its results with the data obtained from the proposed FSR based sensor assembly. The output of both the commercial sensor and proposed FSR based sensor was measured at 100 samples/sec with a Labjak U3 data acquisition device. Figure 2 provides an overview of the experimental setup. The FSR sensor was attached to a voltage divider circuit in order to detect changes in its resistance. The signal conditioning circuit is illustrated in Figure 3.

During the experiment a cyclic pressure (0 to 3bar) is induced in the pipe. Data from both the commercial and proposed sensors were acquired simultaneously for further comparison and validation.

Results and discussion

Both sensors were successfully interrogated using the data acquisition device at 100 samples/second. During this experiment the pipe was pressurised up to approximately 3 bar by the compressor and then the pressure released manually through a valve located on the end plate. The raw output signal from the FSR sensor showed a very low noise to signal ratio. Moreover the proposed sensor assembly showed a high sensitivity to pressure change.

In order to measure the performance and linearity of the proposed sensor assembly the calculated pressure data has been plotted against the calibrated pressure measurements from the commercial sensor in Figure 4. In this experiment the pipe was pressured gradually up to 3 bar and reading are taken after the system had stabilised.

A first degree polynomial is fitted to the data points to assess the linearity of the FSR based pressure sensor. The R squared value of this linear fit showed an acceptable fit (R-squared= 0.9905). As was previously mentioned the proposed sensor assembly is not intended for absolute pressure measurements, therefore calibration is not critical. The dynamic performance of the sensor is presented in Figure 5. In this experiment the pipe was rapidly pressurised to 3 bars and then the pressure was released via a valve, this process was repeated multiple times to ensure repeatability. The pressure was measured at 100 samples per second from both the commercial and FSR based sensors.

Although the dynamic sensor performance during pressurisation is not linear it performs linearly during de-pressurisation. Linearity of the FSR based pressure sensor is mainly affected by the rate of pressure change. The raw data from both of the sensors were normalised in order to compare the data from the commercial sensor with the proposed sensor assembly in a dynamic test. The normalised dynamic response of both sensors to pressure change is demonstrated in Figure 6.

From Figure 6 it can be seen that the FSR based sensor assembly showed a high correlation with the commercial sensor. However, the FSR based sensor showed a small delay in response to a high pressure change. A correlation study also showed a high correlation between the two sensors (correlation factor=0.9928).

In practice, the clip and FSR sensor should be fixed to the pipe to avoid slipping of the sensor. The sensitivity of the FSR sensor assembly can be adjusted by changing the initial pressure applied by the clip. This is due to a change in the response behaviour of the FSR sensor in different load ranges. However, this doesn't affect the usability of the FSR sensors as they are to be used to measure relative pressure changes within the pipe such as those occurring as a result of a leak, and hence they they are not required to be calibrated on installation.

Conclusion

The proposed sensor assembly was successfully tested and the results compared to a commercial pressure sensor. The data from the FSR based pressure measurement system showed a very good correlation with the commercial sensor. The proposed system proved to be suitable for measuring relative pressure changes in plastic pipes. The main advantages of the proposed system over the conventional pressure monitoring system are low manufacturing monitoring system are low manufacturing cost and its non-intrusive nature of the monitoring, i.e. the structural intergrity of the pipe is not affected by the measurement device. The sensor has been deployed on a live water pipe for the past six months and hasn't shown any noticable degradation or loss of sensitivity. However it is intended to further investigate durability of the proposed system for long term usage for pipeline failure monitoring. More research also needs to be done to investigate new methods of retro fitting the sensor to the pipe without the need for complete excavation and trenching. The effect of background noise and soil around the pipe on the sensor output also need to be investigated by deploying the proposed pressure sensors on real life water distribution pipes. These FSR based pressure sensors can be used in conjunction with underground wireless sensor networks to provide useful data for pipeline monitoring. Moreover, these sensors can be connected to individual data loggers with analogue input capability for long term spot pressure monitoring.

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