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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

19   During the period of 2009-2010 approximately 3 GL (3×10^{9})of water was wasted in the UK

20   every day (Department for Environment Food and Rural Affairs 2011). This includes both

21   supply and distribution losses. Effective pipe monitoring systems can potentially help to reduce

22   these losses, benefiting the water industry, consumers and the environment. Such a system

23   should be able to be retrofitted to existing pipelines as well as being installed in new pipelines.

24   Various pipeline monitoring systems have been developed over the past few years (Rizzo 2010).

25   The first step towards pipe monitoring is to measure parameters which are related to the pipe

26   condition. The sensing method should be preferably non intrusive to the pipe structure , low in

27   cost and easy to fit. Different methods of leak and damage detection have been suggested in the

28   literature (Hieu et al. 2011; Gao et al. 2005; Colombo et al. 2009; Dezfouli and Zabihollah 2010;

29   Khulief et al. 2011). The main methods used in pipeline monitoring are: laser and vision based

30   monitoring, acoustic and vibration monitoring, fibre optic monitoring, Robot/Smart PIG and

31   multimodal monitoring.

32   Vision based systems use CCTV technology to detect and characterise pipeline defects.

33   Similarly the laser scanning method uses a laser beam to investigate the integrity of the pipe

34   structure (Kingajay and Jitson 2009). These technologies are also used in many robot based or

35   smart pig based systems. Both of these methods exhibit various strengths and weaknesses.

36   CCTV systems require a skilled operator to locate and characterise defects (Sinha 2004).

37   Although automating the detection process by utilising image-processing techniques can solve

38   some of these issues, they still require access to the interior of the pipe which is the main

39   disadvantage of these systems.

40 Acoustic measurement can be used to detect and locate both bursts and leaks in pipes. These

41 systems are based on the principal of Acoustic Emission (AE). Recent advances in the field of

42 sensors such as hydrophones and MEMS (Micro Electro-Mechanical Systems) accelerometers

43 have created many opportunities for these technologies to be utilised in infrastructure

44 monitoring. A pipe leak will produce a vibration which can be detected using hydrophones or

45 accelerometers. These acoustic measurements can then be cross correlated to pinpoint the

46 location of the leak. An advantage of these sensors is that they do not require access to the

47 interior of the pipe. However, in order to have a reliable system they need to run continuously at

48 high sampling frequencies. These systems would therefore consume relatively high amounts of

49 energy and therefore not suitable for long term (>20 years) pipeline monitoring. Another

50 disadvantage of these systems is that the acoustic wave propagates differently in different pipe

51 materials, making leak detection difficult in certain types of pipe material.

52 Fiber optic technology offers a potential solution to the problems associated with

53 conventional acoustic measurements. Fiber optics are used in a variety of infra-structure

54 monitoring systems. These systems exhibit major advantages over other systems, such as long

55 range and independence of the sensor nodes to a power supply, which make fibre optic systems

56 an attractive option for pipeline monitoring (Nikles 2009). However, they are not easy to fit/retro

57 fit to pipelines. In some cases it is necessary to fit fibers and sensors to the pipe at the time of

58 pipe manufacturing, which can be costly. Another disadvantage of these systems is their inability

59 to easily recover from a failure. In the case of a burst or major defect, fibers attached to the pipes

60 can be damaged which can disable the whole system from the point of the incident.

61 This paper reports on the design and development of a pressure measurement system for

62 pipeline monitoring and presents laboratory based test results and validation experiments. The

3

63 proposed system is based on the change in contact pressure between the pipe and a restraining

64 clip, making it non intrusive to the pipe structure. Various sensors can be used to measure this

65 contact pressure or alternatively measure the expansion of the pipe, however, most of these

66 sensors require careful installation or complex circuitry. Force Sensitive Resistor (FSR, Interlink

67 Electronics USA) can potentially solve these issues by their wide dynamic range and minimal

68 signal conditioning circuitry. FSR sensors have demonstarted an acceptable performance in other

69 applications such as finger motion tracking (Li *et al.* 2012). Additionally, the proposed pressure

70 sensor assembly is non-intrusive to the structure of the pipe as it doesn't require access to the

71 medium inside the pipe. Although these sensors exhibit lower precision than commercially

72 available sensors they can potentially be used to provide non absolute pressure data, i.e. relative

73 pressure changes, for pipeline monitoring. The proposed pressure sensor in this paper is based on

74 these FSR sensors. Usage of these sensors for pipe monitoring is investigated and compared with

75 an invasive commercial sensor.

76 **System design and theory of operation**

77 All pipes expand when they are pressurized. Although this expansion is very small at low

78 pressures it can be used to detect the pressure changes occurring inside the pipe. Water

79 distribution pipes can be modeled as a simple pressure vessel with open ends. The Hoop stress in

80 the pipe, when modeled as a simple open ended pressure vessel, can be calculated using

81 Equation 1, where σ_H is the Hoop stress, P is the internal pressure, r_0 is the initial radius of the

82 pipe and t_0 is the initial pipe thickness.

83
$$\sigma_H = \frac{P.r_0}{t_0},$$
(1)

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

4

85 Young's modulus of elasticity of the pipe material.

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

87 Since ε_H is change in circumference (δ_C), divided by the initial circumference (C), the change

88 in circumference, δ_C, and radius, δ_r, can be found by Equations 3 and 4.

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

90

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

92 From Equation 4 it can be shown that $\frac{r_0^2}{t_0.E}$ is constant and therefore a change in pressure causes

93 a linear change in radius. Figure 1 shows a schematic and an image of the sensor arrangement

94 when attached to the pipe.

95 The FSR sensor is attached to the pipe with a high strength stainless steel clip. The pressure

96 inside the pipe causes the pipe to expand and induces a contact force between the pipe and the

97 clip. The contact pressure between the pipe and the clip can be modeled as two concentric

98 pressure vessels with open ends. Since the clip and the pipe are in contact the radial expansion of

99 pipe and jubilee are equal. Equation 5 can be used to calculate the contact pressure of two

100 concentric pipes (clip and pipe).

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

102 Where P_C is the contact pressure between the pipe and the clip, r_j and r_p are the radii of the

103 jubilee and the pipe, E_j and E_P are the respective material's Young's modulii of elasticity of the

5

104 clip and pipe and t_j and t_p are the thickness of the clip and pipe respectively.

105   This contact pressure translates to a contact force on the FSR sensor. This change in contact

106 force will alter the resistance between the two terminals of the FSR sensor. This contact force F_C

107 can be calculated using Equation 6, where A_S is the sensing area of the sensor and K is a

108 constant between 0 and 1 which indicates the ratio of the total contact pressure that is applied to

109 the sensor.

110
$$F_c = K.P_c.A_s \, , \tag{6}$$

111   The change in resistance can then be measured by using a simple voltage divider circuit and a

112 data acquisition device. The FSR sensor can be installed when there is no pressure inside the

113 pipe and an initial contact force can be applied to the sensor by tightening the clip. At this stage

114 the resistance of the FSR sensor can be measured and used as a reference for further

115 measurements. Pressure measurements have previously been used to detect bursts in pipes

116 (Stoianov *et al.* 2007). The indirect pressure data from the FSR sensor can also be used to detect

117 bursts, blockage or any other type of failure, as long as it affects the pressure of the fluid in the

118 pipe. The pressure transient profile signature of each failure then can be used to differentiate

119 these defects from each other. The location of the burst can then be approximately determined

120 from the pressure profile along the pipeline.

121 **Experimental setup**

122   A PVCU pipe with a diameter of 6 inches was used to test the sensor assembly. Both ends of

123 the pipe were closed with flanges and an inlet/outlet and measurement valves were attached to

124 the end plates. The inlet/outlet valve was used to pressurise the pipe up to 4 bar. The

125 measurement valve was also connected to a commercially available direct pressure sensor in

6

126 order to compare its results with the data obtained from the proposed FSR based sensor

127 assembly. The output of both the commercial sensor and proposed FSR based sensor was

128 measured at 100 samples/sec with a Labjak U3 data acquisition device. Figure 2 provides an

129 overview of the experimental setup. The FSR sensor was attached to a voltage divider circuit in

130 order to detect changes in its resistance. The signal conditioning circuit is illustrated in Figure 3.

131   During the experiment a cyclic pressure (0 to 3bar) is induced in the pipe. Data from both the

132 commercial and proposed sensors were acquired simultaneously for further comparison and

133 validation.

Results and discussion

135   Both sensors were successfully interrogated using the data acquisition device at 100

136 samples/second. During this experiment the pipe was pressurised up to approximately 3 bar by

137 the compressor and then the pressure released manually through a valve located on the end plate.

138 The raw output signal from the FSR sensor showed a very low noise to signal ratio. Moreover

139 the proposed sensor assembly showed a high sensitivity to pressure change.

140   In order to measure the performance and linearity of the proposed sensor assembly the

141 calculated pressure data has been plotted against the calibrated pressure measurements from the

142 commercial sensor in Figure 4. In this experiment the pipe was pressured gradually up to 3 bar

143 and reading are taken after the system had stabilised.

144   A first degree polynomial is fitted to the data points to assess the linearity of the FSR based

145 pressure sensor. The R squared value of this linear fit showed an acceptable fit (R-squared=

146 0.9905). As was previously mentioned the proposed sensor assembly is not intended for absolute

147 pressure measurements, therefore calibration is not critical. The dynamic performance of the

148 sensor is presented in Figure 5. In this experiment the pipe was rapidly pressurised to 3 bars and

149 then the pressure was released via a valve, this process was repeated multiple times to ensure

150 repeatability. The pressure was measured at 100 samples per second from both the commercial

151 and FSR based sensors.

152 Although the dynamic sensor performance during pressurisation is not linear it performs

153 linearly during de-pressurisation. Linearity of the FSR based pressure sensor is mainly affected

154 by the rate of pressure change. The raw data from both of the sensors were normalised in order to

155 compare the data from the commercial sensor with the proposed sensor assembly in a dynamic

156 test. The normalised dynamic response of both sensors to pressure change is demonstrated in

157 Figure 6.

158 From Figure 6 it can be seen that the FSR based sensor assembly showed a high correlation

159 with the commercial sensor. However, the FSR based sensor showed a small delay in response to

160 a high pressure change. A correlation study also showed a high correlation between the two

161 sensors (correlation factor=0.9928).

162 In practice, the clip and FSR sensor should be fixed to the pipe to avoid slipping of the sensor.

163 The sensitivity of the FSR sensor assembly can be adjusted by changing the initial pressure

164 applied by the clip. This is due to a change in the response behaviour of the FSR sensor in

165 different load ranges. However, this doesn't affect the usability of the FSR sensors as they are to

166 be used to measure relative pressure changes within the pipe such as those occurring as a result

167 of a leak, and hence they they are not required to be calibrated on installation.

Conclusion

169 The proposed sensor assembly was successfully tested and the results compared to a

170 commercial pressure sensor. The data from the FSR based pressure measurement system showed

171 a very good correlation with the commercial sensor. The proposed system proved to be suitable

172 for measuring relative pressure changes in plastic pipes. The main advantages of the proposed

173 system over the conventional pressure monitoring system are low manufacturing monitoring

174 system are low manufacturing cost and its non-intrusive nature of the monitoring, i.e. the

175 structural intergrity of the pipe is not affected by the measurement device. The sensor has been

176 deployed on a live water pipe for the past six months and hasn't shown any noticable degradation

177 or loss of sensitivity. However it is intended to further investigate durability of the proposed

178 system for long term usage for pipeline failure monitoring. More research also needs to be done

179 to investigate new methods of retro fitting the sensor to the pipe without the need for complete

180 excavation and trenching. The effect of background noise and soil around the pipe on the sensor

181 output also need to be investigated by deploying the proposed pressure sensors on real life water

182 distribution pipes. These FSR based pressure sensors can be used in conjunction with

183 underground wireless sensor networks to provide useful data for pipeline monitoring. Moreover,

184 these sensors can be connected to individual data loggers with analogue input capability for long

185 term spot pressure monitoring.

Acknowledgments

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