TRANSIENT BASED METHOD & FORCE SENSITIVE RESISTOR FOR LEAK DETECTION IN WATER PIPELINE

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Abstract - *Pipeline systems are widely used for distribution and transportation of petroleum, natural gas, water, and sewage. Leaks and ruptures due to an aging and fast decaying pipeline system infrastructure cost millions of dollars a year; they also make clear the necessity for continuous, automatic monitoring systems that can provide early detection and early warning of defects, such as corrosion and leaks, before they reach the magnitude of a major disaster. This paper presents the design, development and testing of a smart wireless sensor network for leak detection in water pipelines, based on the measurement of relative indirect pressure changes in plastic pipes. Power consumption of the sensor nodes is minimized to 2.2 µw based on one measurement every 6 h in order to prolong the lifetime of the network and increase the sensor nodes' compatibility with current levels of power available by energy harvesting methods and long life batteries. The transient based method& force sensitive restior sensor were capable of measuring pressure changes due to leaks and its helps for leak detection in water pipeline*

Key Words*: *Pipe monitoring; leak detection; wireless sensor network; ultra-low power consumption; Transient reflection method (TRM), Underground Wireless Sensor Network (UWSN)

1.INTRODUCTION

Pipelines originated over 5,000 years ago by the Egyptians who used copper pipes to transport clean water to their cities. The first use of pipelines for transportation of hydrocarbons dates back to approximately 500 BC in China where bamboo pipes were used to transport natural gas for use as a fuel from drill holes near the grounds surface. The natural gas was then used as fuel to boil salt water, producing steam which was condensed into clean drinking water. It is said that as early as 400 BC wax-coated bamboo pipes were used to bring natural gas into cities, lighting up China's capital, Peking. Today's pipelines originated in the second half of the 19th century and since their adoption have grown drastically in size and number. While drilling for water, crude oil was accidentally discovered in underground reservoirs. This crude oil was not very popular until simple refineries came into existence. The oil was transported to these refineries in wooden vats that were even transported across rivers via barges pulled by horses. One alternative method of transport was by way of railway tanker cars. However, this meant that the oil supply was controlled by the large railway owners. So, to make transport independent and more reasonably priced, pipelines were adopted as a more economical means of transportation.

The transported oil was boiled off in refineries to obtain the by-products of naphtha, petroleum, heavy crude oil, coal tar and benzene. The petroleum was used as a fuel for lighting and the benzene produced was initially considered an unwanted by-product and was disposed of this situation changed drastically with the invention of the automobile which instantly increased the demand for consistent and reliable supplies of gasoline and resulted in the need for many more pipelines. Pipelines today transport a wide variety of materials including oil, crude oil, refined products, natural gases, condensate, process gases, as well as fresh and salt water. Today there are some 1.2 million miles of transport pipelines around the world, with some well over 1,000 miles in length. The total length of these pipelines lined up end to end would encircle the earth 50 times over. The construction of these longer pipelines with larger diameters also increased the need for more intelligent leak detection systems to better detect and localize accidental releases. Where it was once enough to have inspectors walk the length of pipelines and visually inspect for evidence of leaks, today this is no longer possible. In many cases, due to the longer lengths and the rigorous runs of remotely located pipelines, physical access may be limited. Pipelines can run through snowy landscapes, across mountain ranges, along bodies of water, or be located underground or subsea, even at depths exceeding 1 mile. This paper reports on the design and development of a multimodal Underground Wireless Sensor Network (UWSN) for pipeline structural health monitoring. A non-invasive method (to the structure of the pipe) of pressure monitoring is designed and developed based on Force Sensitive Resistor (FSR) technology. This method is then tested and validated in laboratory and field trials. Moreover, power consumption requirements of a suitable UWSN are identified and based on these findings an ultra-low power wireless sensor node is designed and developed.

2.SYSTEM DESIGN

A wireless sensor network can have different topologies and structures. The restrictive environment of a buried pipeline enforces many limitations on the overall structure of the UWSN. The RF transmission range in soil is significantly lower than in air, therefore communication between nodes is much more limited. This imposes limitations on routing protocols and the overall structure of the UWSN. Moreover, the topology of the network is restricted by the topology of the pipeline. Figure 1 illustrates the general schematics of the proposed UWSN for pipeline monitoring. In the proposed UWSN each node communicates with both nodes in front and behind itself via RF signals. For every 4–5 nodes (up to maximum of 10 nodes) there is a master node which has the capability to communicate with the sensor nodes via RF transmission. Moreover, these master nodes should be able to connect to the internet and transmit the received data from the nodes to the cloud. Data in the cloud can then be accessed via different devices with internet connectivity.

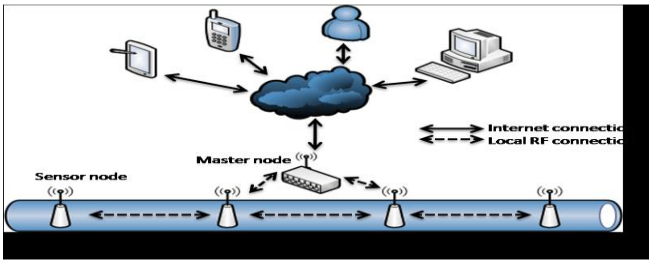

Figure 1. General schematic of the proposed Underground Wireless Sensor Network (UWSN) for a pipeline monitoring.

2. 1. Processing Unit and Transmission

Individual sensor nodes commonly have four main parts: a data gathering and processing unit, transmission unit, power management and sensors. Performance of each of these sections in terms of power consumption and reliability greatly affects the overall performance of the sensor nodes and network. Figure 2 illustrates a general schematic of different sections of the proposed sensor node for pipeline monitoring. The Micro Controller Unit (MCU) is responsible for gathering measurements from the sensors, processing data, managing the power regime of the nodes and sending data to the transmitter.

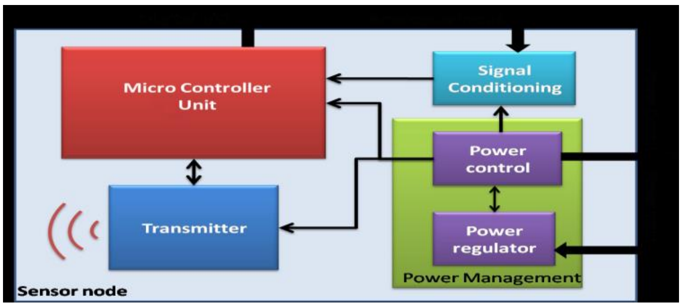

Figure 2. Schematic of the sensor node and its components.

The performance of the MCU highly affects the overall performance of the node. A careful balance between the processing capability and power consumption is required to achieve optimum overall performance.

The power management unit is responsible for converting the input voltage from the battery to a usable voltage for the MCU and other components. The Transmitter is one of the main parts of any sensor node. This unit is responsible for transmission of the data which is collected by MCU to other nodes via RF signals.

Signal conditioning is composed of a voltage divider circuitry and passive filters to regulate and condition the signals from the sensors before they are transferred to the analogue to digital converter in the MCU. Another aspect which affects the performance of the sensor node is its firmware. This can greatly affect both the power consumption and reliability. Figure 3 illustrates the latest version of the sensor node without packaging.

2.2. Power Consumption

Power consumption is the most challenging aspect of the UWSN. Ultra-low power consumption will allow the sensor node to operate for an extended period (in excess of the shelf life of the battery) of time without the need for battery replacement. Various parts of the UWSN can affect the power consumption

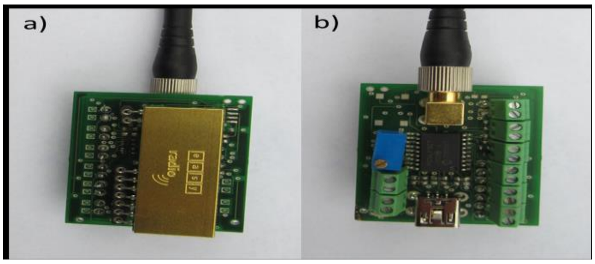

Figure 3. (**a**) Rear view of the sensor node; (**b**) Front view of the sensor node.

The environment in which the sensor nodes are being deployed also imposes restrictions on the design (*i.e.*, lack of maintainability, lack of access to common power supplies, *etc.*) Structural conditions of pipes change, in most cases very slowly so there is no need for a high sampling frequency; therefore these nodes will spend most of their time in sleep mode. This makes the sleep power consumption of the components very important [24]. Figure 4 shows a general schematic of the sensor node routine.

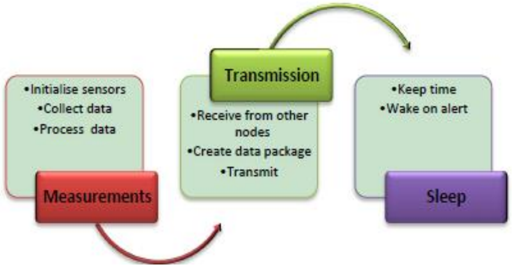

Figure 4. Schematic of the sensor node routine

During the sleep period the MCU of the sensor node cuts power to all components in order to minimize power consumption. Unnecessary internal functions of the MCU are also disabled during the sleep mode. The time the nodes spend in sleep mode is managed by a watchdog timer module in the MCU.This timer allows the MCU to keep time while it is in sleep mode and wakes up after a programmable interval.

2.3. Sensors

The ideal sensor for pipeline monitoring should be non-invasive to the pipe, low in power consumption and easy to install. Furthermore, they should be able to gather useful information without extensive data processing or high sampling rates. One of the key parameters in pipeline monitoring is the internal pressure of the pipe. Leaks or blockages can potentially alter the normal pressure in the pipe and hence monitoring the pressure can potentially help to identify these. Temperature measurements of a pipe and its surroundings can also provide useful data in pipeline monitoring. A slow leak might not have a major effect on the internal pressure of the pipe, but it can potentially change its surrounding temperature profile.

3.PROPOSED METHODOLOGY AND TECHNIQUES

In the proposed sensor node assembly the FSR sensor is attached to the outside of a pipe with a clip whose Young's modulus should be greater than that of the pipe. The clip is initially tightened to fix the FSR sensor to the pipe. All pipes expand to some extent when they force between the pipe and the clip. This contact force is then measured by the FSR sensor and relative internal pressure changes can be calculated from this force. This contact force is also dependent on the pipe diameter, pipe thickness, pipe material, clip material, clip diameter and clip thickness. Equation (1) can be used to calculate the contact pressure between the pipe and clip *Pc,* where *p*(Pa) is the internal pressure of the pipe, *rp*(m) is the radius of the pipe, *rj*(m) is the radius of theclip, *Ep*(Pa) is the Young's modulus of the pipe, *Ej*(Pa) is the Young's modulus of the clip, *tp*(m) and *tj*(m) are the thickness of the pipe and clip respectively.

$$Pc=P.rp2.Ej.tj \Box rp2.Ej.tj \Box +(rj2.tp.Ep) \quad (1)$$

The contact force on the sensor $Fc(N)$ can then be calculated from Equation (2), where *As*(m2) is the area of the sensor and K is a constant between 0 and 1 which indicates the fraction of the contact pressure which is applied to the sensor.

$$Fc=K.Pc.As \quad (2)$$

From Equations (1) and (2) it can be concluded that a change in pressure will result in a change in the force which is applied on the sensor. This will result in a change in resistance of the FSR. This change in resistance is then measured by the sensor nodes' analogue to digital converter through a voltage divider. The performance of the proposed pressure sensor assembly was compared to a commercial pressure sensor in order to validate its suitability and reliability in plastic pipes; which are currently the most common type of newly installed pipes in water distribution [25]. In these tests a 152 mm diameter PVC pipe was pressurized from 0 to 4 bars and the pressure was measured simultaneously using both a direct pressure sensor and the FSR based relative pressure assembly.

3.1 Transient Based Method

Transient-based methods for the purpose of pipe fault detection all employ the same principle, which is to extract information about potential pipe or system faults by analyzing the measured trace of fluid transient behavior.

The internal and external characteristics of the pipeline can affect the transient response by altering the flow and pressure in the system. Considering pipeline features such as constrictions, expansions, ends, branches, valves, junctions and bends, leaks, blockages and deteriorations, there are many faults that commonly exist in pipe systems. The occurrence of a leak is a hydraulic phenomenon but one associated with various troubles. An amount of pressurized fluid released from the leaks, providing transient protection for the system and modifying the character of transient pressure wave. The pressure fluctuations can be identified collectively in the time or frequency domain to determine the location and size of the leak. As the transient signal propagates throughout the pipe network, theoretically. The information concerning the integrity and features of the pipe system can be detected hydraulically by using the transient signal as a kind of probe. The reflected transient signal and its damping pattern are the critical properties to be accessed for achieving fault detection. Their magnitude is generally proportional to the level of deterioration at the fault. After measuring the transient response at accessible locations along the pipeline, potential fault information is extracted. Typically, pipe system behaviors are studied in order to infer the system state (e.g., flow or pressure) under the assumption that all system characteristics are known. By contrast, all fault detection techniques can be regarded as solving an inverse problem, in which the system state is analyzed to determine the unknown system parameters such as faults and pipeline features. Pipe fault detection techniques based on fluid transients have gained popularity over the last decades. Intensive numerical simulations, laboratory verifications and a few field tests have so far been conducted by researchers, generally based on the conviction that transient-based methods are superior to the other techniques. One reason for this belief is that they are nonintrusive and cost-effective. A nonintrusive technique used for evaluating the internal surface condition of pipelines is necessary for their planning and rehabilitation. When the fluid flow is in a transient state, the information about a long pipe can be obtained in a very short period of time at a great distance from the measurement point because the transient wave quickly travels through the fluid filled pipe

Another advantage is, compared to the performance of a pipe system under steady state, the system under transient state provides a vast amount of data, which is rewarding for the purpose of fault detection because the problem can be solved more accurately. Moreover, the results from fault detection. Using the transient are less susceptible to pipe friction factors. Theoretically at least, the fault detection and system calibration can be conducted simultaneously without knowing the precise friction value. Of course, these benefits are not the whole story, however.

3.2 Major Considerations and Categorizations

A number of transient-based techniques for pipeline fault detection have been developed in the last two decades (Wang et al. 2001; Colombo et al. 2009; Puust et al. 2010). These methods share some characteristics with each other but each has its own special advantages and disadvantages. Objectives-While developing transient fault detection techniques, it is vital to have a clear picture of the objectives that should be met. The possibility of balancing the expectations of all these objectives must be continually considered.

• Reliability—the technique is expected to show its effectiveness over time, and the performance of monitors should be stable in long-term identification of faults.

• Accuracy—it is evident that the errors in detecting and identifying false positives and negatives can lead to unnecessary pipe maintenance costs. Although developing a perfectly accurate fault detection method is difficult, a high degree of detection accuracy is obviously desirable.

• Cost—After completing the fault diagnostics, the economic aspect associated with the application of the proposed method is evaluated considering the costs of deployment, maintenance, and the management of diagnostic errors. One of the goals in developing a fault detection technique is to reduce the operational cost while improving the performance.

• Sensitivity—For the cost saving, developing an efficient method which can detect small anomalies from a long distance is important. The sensitivity of a fault detection method is optimized by increasing its sensitivity with respect to the target faults and by enhancing its ability to eliminate noise from other disturbances.

• Acceptance—Fault detection techniques are an application-oriented approach, which means the acceptance of the method must be established ideally both in the lab and in realistic field installations to prove its performance in laboratory or practical applications. The techniques should have simple and clear procedures, and be non-disruptive to the system. Based on these objectives, various transient fault detection techniques are presented, with the following major concerns addressed in different ways.

3.3 Transient Generation

The transient signal that is analyzed in the test can rely upon natural sources of fluid excitation, generated by an induced event (e.g., pump failure or pipe leak/burst) (Misiunas et al. 2005) or artificial events, such as injecting a prescribed transient signal into the pipe flow typically through valve operations. The subsequent behavior of the transient event is analyzed to acquire the system properties. The fault detection performed in passive systems obtain the transient signals directly from the system and exploit special features to detect and locate leaks and other faults. The systems that take advantage of information from transient events generated artificially are referred to as active systems, where the injected signals are customized and must be distinct from background noise.

3.4 Fault-induced effect

The transient signal contains two types of fault-induced effect. The reflection and damping effect, which can be utilized alone or can consider two types of information at the same time.

3.5 Domain type

After the time history of the pressure transient signal (i.e., the piezometric head) is measured by the transducers, the analysis of the data can be completed in the time domain or/and frequency domain.The time-domain methods analyze data straightforwardly in the time domain, while the frequency-domain methods require mathematical conversion.

3.6 Analysis approach

Signal processing and hydraulic transient model simulation are analysis approaches that are being onsidered. Signal processing is a method to extract information from measured data and compare it with the data sets from a fault-free benchmark on the basis of properties of leak-induced effect on a flow or pressure signal. Hydraulic transient models simulate data and reproduce pressure traces in the time or frequency domain. Based on the degree of coincidence between the data from accurately modeled systems with faults and measured data, information related to faults is determined. Two detection procedures with different configurations can be developed based on the propagation analysis of the pressure signal.

A signal processing approach locates the generator and the transducer of the transient at the end of a pipeline, and the inverse method using a hydraulic model generates the transient and measures the pressure response at multiple locations along the pipe.

In summary, according to the manner in which transient signals are utilized, the methods described in existing literature can be divided into four types: the transient reflection method (TRM), the transient damping method (TDM), the system response method (SRM), and the inverse transient method (ITM). These methods are briefly introduced in the following sections. Their key features and categorization are systematically summarized in Fig.5

4. TRANSIENT REFLECTION METHOD (TRM)

Generally, a transient pressure wave is partially reflected, partially transmitted and partially absorbed wherever the system shows discontinuity (Burn et al. 1999). Faults and pipeline features cause additional reflections of transient pressure waves as shown in Fig. 2.1 and may create multiple wave paths in the pipe system. Figure 2.6 shows the hypothetical pressure trace at a transducer. The transient wave is detected by the transducer at $t1$, and the passage of the reflected signal, normally the first signal reflected, is recorded at $t2$. In addition, the distance between measurement point and fault location can be given by multiplying the half wave traveling time T by the wave speed. The transient reflection method (TRM), often referred to as the time-domain reflectometry (TDR) technique, relies on differentiation of a reflected signal by identifying the discrepancies between measured results with the fault-free benchmark results. The benchmark results can be obtained from a fault-free laboratory system, or from an accurate numerical model of the pipe system. For a typical system with unknown characteristics, however, it is hard to determine the leak-free benchmark: only the changes from the benchmark results can be detected.

Jönsson and Larson (1992) were one of the first to use the generated transient to detect leaks by measuring the arrival time of a reflected wave. Brunone (1999) introduced the theory and verified it by an experiment in a single polyethylene pipe, while the background noise disturbed the identification of signals.

The experimental validationwas improved by Brunone and Ferrante (2001) to identify the leak location more accurately. Beck et al. (2005) used the cross-correlation method to reduce the problem of disturbance and detected more pipeline features in a T-junction network.

Meniconi et al. (2011a) applied the TRM to detect the location of illegal side branch in a laboratory complex pipe system. The experiment performed well, but uncertainty about factors like friction and unaccounted for reflections in real systems may complicate practical application. Recent studies have improved the application of TRM by utilizing methods and algorithms such as cepstrum analysis (Taghvaei et al. 2006), wavelet analysis (Ferrante and Brunone 2003; Ferrante et al. 2007), cumulative sum method (Lee et al. 2007), and artificial neural network (ANN) (Stoianov et al. 2001).

Artificial intelligence methods have also attracted attention. For example, an artificial neural network (ANN) constructs relations between input and output data without any explicit mathematical model and has been effectively used to solve many classification problems including transient fault diagnosis.

An ANN technique was applied for leak detection in a liquefied gas pipeline with 74,668m in length and 0.203m in diameter (Belsito et al. 1998).

The ANN training uses data generated by a transient model using different leak and flow conditions. The method could detect and locate leaks down to 1% of the total flow rate in about 100 s according to the numerical results. When using measured data, however, the average error of the detected leak locations increases to about 7000m for a leak of 1% of the total flow and 1645m for a leak of 10% of the total flow (Belsito et al. 1998).

Similarly to the problems that exist in the inverse methods, without the accurate simulation of the transients using a transient model, the information concerning leaks could be lost in the training process.

A novel leak detection method was developed by integrating the wavelet transforms with artificial neural networks for signal identification and leak feature extraction (Stoianov et al. 2001).

A supervised Kohonen network is applied to classify wavelet coefficients of the pressure response for transient events in a pipelinerig. Their potential has only been demonstrated using laboratory rigs, however.

The TRM has a basic concept and simple procedure, and previous works have also shown that the analysis of the reflected transient signal is effective in identifying pipeline features and faults (Beck et al. 2005; Lee et al. 2007; Ferrante et al. 2009; Gong et al. 2012b); nevertheless, its verification so far has rarely been extended to field tests.

The accuracy of the method would be much lower without the assumption of a single-phase flow and rigid pipes.

In addition, complicated geometries like loops in real complex pipe networks create complex reflected patterns that are less distinguishable. Therefore, it is difficult to obtain satisfactory results from pipe networks.

The TRM does not require a precise mathematical model; however, it requires fault-free benchmark data sets from the controlled pipe system to extract and classify signal features. Thus, its scheme is not applicable to existing real pipe systems because the faults in the system would particularly perturb the benchmark data sets. It is also difficult to detect the integrity of the system if the induced transient signals in a fault-free system are not perfectly regular and reproducible.

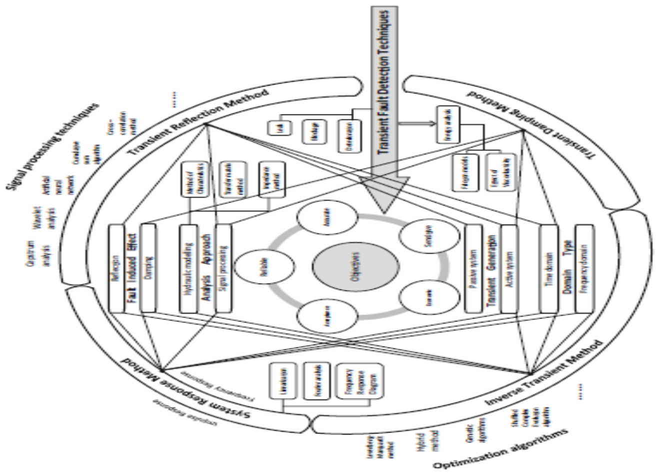

Figure: 5. Summary of current transient fault detection technique

5.RESULTS AND DISCUSSION

The proposed leak detection method is based on the relative pressure change profile in the pipe; therefore it is unnecessary to calibrate the sensors. Raw data from the sensors in laboratory tests are illustrated in Figure 10. As can be seen from this figure four main phases of the experiment (pump start, stabilization, leak, pump off) are clearly visible from the output of the pressure sensors. These include the pressure before the pump was switched on, the increase in pressure when the pump was switched on, the drop in pressure due to the development of the leak and finally the drop in pressure due to the switching off of the pump (shortly after development of the leak).

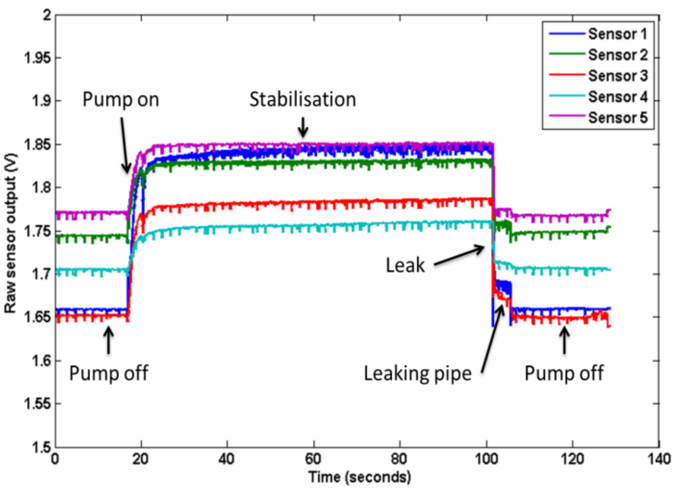

Figure: 6. Raw sensor output of laboratory experiment illustrating the pressure profiles for the five FSR sensors.

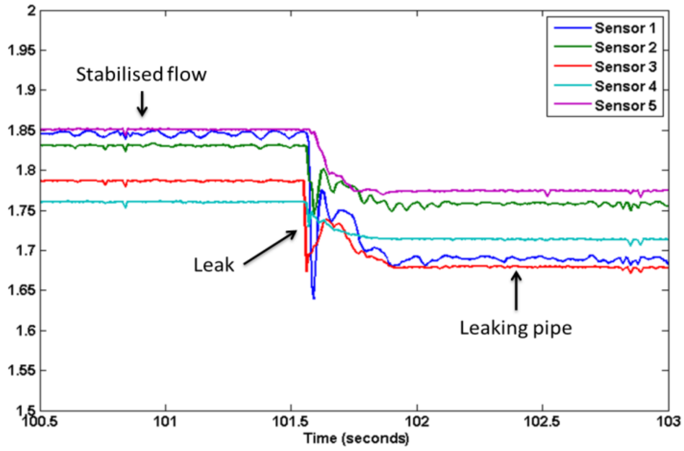

Figure: 7. Pressure drop measured by the five FSR sensors due to the occurrence of the leak.

It can be clearly seen from Figure 6 that the simulated burst can be detected from the sensors' raw output as a sudden pressure drop in the system. However, based on Figure 6 it is difficult to determine the exact position of the leak as all FSR sensors appear to respond similarly to the leak.

Figure 7 shows a close-up of the pressure drop due to the burst. It can be seen from this figure that the pressure profiles of Sensors 4 and 5, which are downstream to the leak point, are different to the ones upstream of the leak. The profile for theses sensors exhibit a more gradual pressure drop profile than the ones before the leak.

6.CONCLUSIONS

A non-invasive (to the pipe) pressure measurement method based on FSR sensors has been presented. This method allows easy installation of the sensor nodes on pipes without jeopardizing the pipes' structural integrity. The FSR sensors detected pressure changes both in the laboratory tests as well as in the field trials. The laboratory data showed that the profile of the pressure drop caused by the leak is different for the measurements before and after the leak. This might be used to determine the location of the leak. The sensor nodes were successfully deployed in field trials and they collected temperature and relative pressure data. Leak tests and daily pressure variations were clearly registered by the nodes showing a response in both the relative pressure sensor (FSR) as well as the temperature sensors. It is postulated that the temperature sensors have the potential to be combined with the FSR data to identify leaks as opposed to 'normal' pressure drops. This further validates the potential of UWSNs for pipeline monitoring. The fault detection principle and the method for analyzing the transient trace are presented. There is no unified framework for the identification and classification of these techniques. To tackle this problem, a systematic diagram is created to summarize the knowledge in the research area. The possible solutions with respect to the criterion of performance are different, since the selection of an optimal technique can only be performed considering the detection objectives, i.e., the need for reliable, economic, and robust methods applicable to complex and dynamic systems.

The main drawback to all the proposed fault detection techniques is that they are remain difficult to apply in real and complex systems. This is caused by the fact that for each method one must give ideal system assumptions prior to its deployment, which reduces the accuracy and generality of the method. In addition, the problem of signal attenuation and technical difficulty in transient excitation are always challenging in real applications.

The possibility of joining the frequency response method with inverse analysis has vital advantages, which will be a subject for further investigations. The process of developing pipe fault detection techniques is a complex optimization problem. Computational requirements and errors grow together with system complexity.

In this case, the fault detection is usually connected with the phenomenon of hydraulic impersonation. Further research on the techniques presented in the chapter is expected to address such issues, and certainly much research work still remains be done for minimizing the problem of both false positive and false negative field results.

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