A model for real time leakage detection in pipelines: A case of an integrated GPS receiver

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Abstract—Pipelines have been used to effectively transport essential commodities needed for human existence over a long distance. Examples of such commodities include water, natural gas, petroleum products and liquid hydrocarbons. Pipeline failure is most times caused by corrosion and wear, intentional damage, unintentional damage or operation outside design boundary. Such failures can lead to loss of life and property, and also monumental loss of revenue which can adversely affect national income. It is therefore imperative that pipelines are effectively monitored so as to accurately detect leakages in timely fashion. In the literature, several methods have been proposed and implemented to detect pipeline leakages and their possible location as well as the magnitude of the leakage; but these approaches have deficiencies in some ways. In this paper, we propose a model for real time leakage detection in pipelines based on integration of a detection subsystem and Global Positioning System (GPS) receiver. It is shown by the experimental results obtained, that the model can indeed be implemented to accurately detect location of leakage in pipelines and transmit location data to a microcomputer which represents the control centre in our model.

Keywords—Pipeline inspection gauge, GPS receiver, Leakage detection, Light dependent resistor

INTRODUCTION

Pipelines have traditionally been used to effectively transport essential commodities needed for human existence over a long distance. Examples of such commodities include water, natural gas, petroleum products and liquid hydrocarbons. Pipeline failure can be caused by corrosion and wear, intentional damage, unintentional damage or operation outside the design boundaries. Such failures can lead to loss of life and property, and also monumental loss in revenue which can adversely affect national income. Over the years, several methods have been proposed and implemented to detect pipeline leaks and their possible location and magnitude of such leaks. Some of these methods include: acoustic emissions, Fiber optic sensing, balancing systems, pressure analysis, Real Time Transient Method (RTTM), and others. The occurrence of a rupture, leak, or damage that could cause a leak usually generates an acoustic signal. These acoustic emissions are continuous and have a wide frequency spectrum, the majority of which is confined to the moderately high frequency portion (175 kHz – 750 kHz), (Shack et al. [1]). Leis et al [2] conducted an experiment to determine the distance in which an acoustic step function impact could be transmitted through the pipe wall in a 24-inch diameter pipeline. The researchers theorized that the impact could be detected as far as 25 miles away. They also indicated that signals with frequencies greater than 500 Hz were completely attenuated in their tests. Moreover Bassim and Tangri [3] had performed an earlier experiment to determine the effect of the attenuation of acoustic signals generated by strained/fractured pipe segments in a laboratory with both flowing and non-flowing helium gas. They also performed the experiments with a leak (hole) in the pipe segment. Transducers with a frequency range of 0.1MHz to 2 MHz were positioned along the pipe axis to record the acoustic signals. The results showed that the amplitude of the acoustic signal was not significantly affected by variations in the gas pressure up to 75 psi. The attenuation of the lower frequency signals were less than what was observed for the high frequency signals. They however concluded that the acoustic signal strength varied linearly with leak-hole size. Parker J.G [4], undertook studies (both theoretical and experimental) to identify factors of major importance in the operation of a system of active acoustic leak detection and then investigated in some detail the interrelation of these factors. To increase the signal to noise ratio, through the use of a correlation, only active methods were considered to detect the acoustic signal emitted by a 1/64” orifice in a pipeline buried 2 ft deep to the background noise. Verde [5], presented a method for leak location in a pipeline, using flow and pressure sensors only at the ends of the pipeline. According to Verde, the leak identification problem can be solved using a simple nonlinear model of the flow, assuming leak position with uncertainty, and combining static relationship between residual components and leak position error. The residual is the difference between the model predicted location and the location input into the model. This means that the locations of the leaks are inputs into the model, with a predetermined error, and a static relationship between each residual and position error derived to determine the position of the actual leakage. This method was tested and it was found that the greatest error

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in this model occurred when the leak was positioned near either end of the pipeline. The model was tested using real noise data and he was able to predict the location of a leak, provided that the location was not at the beginning or end of the pipeline. In [6] Misunas presented a new continuous monitoring approach for detecting and locating breaks in pipelines. This new technique falls under a classification known as time domain reflectometry. Misunas measured the pressure at one location in the pipeline to sense the negative pressure wave that was produced when a break occurred. The location of the break was determined by the timing of the initial and reflected transient waves produced by the break. The break size was estimated by the size of the magnitude of the transient wave. According to Misunas the limitation to this approach includes the speed of the break opening. When the speed of the break is not fast (that is, when the break opening time is longer than the wave travel time from the break point to the closest boundary and back), the accuracy of locating the leaks drops substantially and the proposed methods becomes unsatisfactory. Wang et al [7] developed a method of leak detection using the damping of fluid transients. According to Wang et al, the overall leak-induced damping could be divided into two separate parts. The size of the leak was indicated by the magnitude of the damping, while the location of the leak was determined from different damping ratios. After experimentation it was found that leaks of 0.1% of a pipeline’s cross sectional area, or smaller, could be detected and located using Wang’s proposed model. This model is only applicable in single transmission lines because more complex distribution systems introduce complex waveforms which may be falsely recognized as leaks. Kiuchi [8], developed a leak localization method in pipelines by using a fluid transient model. The model uses the continuity and momentum equations and the following assumptions are made: isothermal flow, steady-state friction, negligible pipe wall expansion and a constant slope over a pipe segment. The model computes the inlet and outlet flows, which are calculated from pressure measurements at the inlet and outlet of the pipeline. When there is no leak in the system the inlet and outlet flows from the model match the flows measured from the system. When a leak is present in the system the model computed pressure and flows do not change because the model assumes the pressure at the inlet and outlet is constant. The location of the leak is determined by integrating the pressure and flow profiles over the pipeline in two segments: from the beginning of the pipeline to the unknown leak location and from the unknown leak location to the end of the pipeline. The first segment uses the model flow outputs, as that section has no leak. The second segment uses the measured flows, as that section has the leak. Theoretically, Kiuchi showed that this method is capable of locating a leak in a pipeline; however, field applications showed that more work in the area of model tuning is necessary. Moreover, Benkherouf and Allidina [9], describe a method for detecting and locating leaks in long gas pipelines using the Extended Kalman Filter. The proposed model had artificial leakage states at predefined positions along the pipeline and the filter was implemented to detect the magnitude of these leakages. The location of the leakages was determined by linear interpolation from the magnitude and location of the artificial leakages. The model simulated a 90km pipeline and the filter was successful at locating a leak at 50km. No attempt was made to detect a leak closer to the boundaries of the pipeline or to experimentally verify the results. Results have shown that a large discretisation step can be used in the filter design without reducing the accuracy in the estimate of the leak position. Using a larger discretisation step reduces computational effort and allows the model to be implemented on a microcomputer. In their own contribution, Han et al [10] developed a pipeline inspection gauge system for determining position, orientation, curvature, and deformations such as dents and wrinkles of operating pipelines. Di and Muravchil [11] proposed a leak detection system that was a simplified statistical model for the pipeline operation allowing a simple implementation in the pipeline control system. By applying real time recursive linear regression to volume balance and average pipeline pressure signals, a statistically corrected volume balance signal with reduced variance was obtained. In the current work, we formulate an expression for computing pressure difference as a basis for leak detection. We further propose a hardware model for real time leakage detection based on an integrated detection and GPS receiver system. For industrial application, the integrated detection and GPS receiver system should be further integrated with the Pipeline Inspection Gauge (PIG) subsystem to constitute a single engineering system.

II. MATHEMATICAL MODELLING OF LEAKAGE DETECTION

The state of a pipeline is normally defined as a set of temperatures, pressures, flows, and densities that describe the fluid being transported at all points within the system. The pressure, density, temperature, etc are obtained as solutions to some set of equations describing the behavior of the pipeline or fluid. When leak occurs at any point in a pipeline, there is a sudden change in pressure and flow characteristics. For example, there is a sudden pressure drop in the pipe at the location of the leak followed by rapid line depressurization a few seconds (or milliseconds) later. To set up our mathematical model we consider two scenarios viz: no leakage in pipe and leakage in pipe. For the purpose of our model we assume as follows:

(a) no viscous forces,
(b) no frictional forces,
(c) variation in cross-sectional area over the length of the pipeline is negligible,
(d) the fluid is incompressible,
(e) the flow is steady,
(f) the integrated detection and GPS receiver subsystems are further integrated into the PIG system,
(g) the pipeline is horizontal,
(h) hole (leak) > 0.6cm, and
(i) the pipeline is not buried.
We note in Fig. 1 above that upon launching the integrated PIG, leak detection and GPS receiver system into the pipeline, the motion of the system derives from the driving force of the flowing fluid. For a steady, incompressible, non–viscous and frictionless flow, we invoke the Bernoulli’s equation \[12\] to model the motion of the fluid with the PIG-GPS system as follows:

\[ P_{x_i} + \frac{v_i^2}{2} + \frac{z_i}{g} = P_{x_j} + \frac{v_j^2}{2} + \frac{z_j}{g} + h_p \]  

This equation states that the sum of the pressure head, the potential head and the velocity head is constant. Since our pipeline is horizontal (i.e with no elevation), we can set \( z_i = z_j \). Thus

\[ P_{x_i} + \frac{v_i^2}{2} + h_p = P_{x_j} + \frac{v_j^2}{2} + h_l \]  

where

\[ P_{x_i} \] - the pressure at the inlet/upstream
\[ P_{x_j} \] - the pressure downstream (i.e. at all points before and including the outlet)
\( xi \) - all points before and including the outlet
\( z_i \) - elevation at the inlet
\( z_j \) - elevation at the outlet
\( v_i \) - velocity of fluid at the inlet
\( v_j \) - velocity of fluid at the outlet
\( h_p \) - head losses due to fitting, expansion/contraction, e.t.c
\( h_l \) - head loss in the pump

As the launched PIG-GPS system moves in the pipeline, there would be head loss due to the effect of the moving object (i.e. PIG-GPS) in the fluid.

Thus we can re-write equation (2) as:

\[ P_{x_i} + \frac{v_i^2}{2} + h_p = P_{x_j} + \frac{v_j^2}{2} + h_l - h_{P,GPS} \]  

where

\[ h_{P,GPS} \] - head loss due to the PIG-GPS system

Multiplying equation (3) by \( \rho g \), gives:

\[ \rho g P_{x_i} + \frac{\rho v_i^2}{2} + \rho g z_i = \rho g P_{x_j} + \frac{\rho v_j^2}{2} + \rho g z_j + \rho g h_p \]

\[ P_{x_i} - P_{x_j} = \frac{\rho v_i^2}{2} - (\rho g) h_l - (\rho g) h_{P,GPS} - \frac{\rho v_j^2}{2} + (\rho g) h_p \]

\[ P_{x_i} - P_{x_j} = \beta \]

where \( \beta = \frac{\rho v_i^2}{2} - (\rho g) h_l - (\rho g) h_{P,GPS} - \frac{\rho v_j^2}{2} + (\rho g) h_p \)

Subsequently, for a decision on occurrence of leakage, we have the conditions:

\[ \beta \leq 0 : \quad \text{No leakage} \]
\[ \beta > 0 : \quad \text{There is leakage} \]

Given the inlet pressure \( P_{x_i} \), we can compute pressure difference at every point since we can be assured of the value of \( P_{x_i} \) at every \( x_i \).

It then follows that a value of \( \beta > 0 \) indicates leakage at a location just before the point \( x_i \).

In subsequent sections, we present the design and implementation of a prototype integrated system consisting of a leakage detection subsystem, and GPS receiver subsystem (to obtain the accurate location of the leak) and an output subsystem.

III. SYSTEMS DESIGN AND IMPLEMENTATION

The integrated detection and GPS receiver system incorporates the following hardware components:

1. The Power Supply Module;
2. A Light Dependent Resistor (Leakage Detector);
3. A PIC18F2620 Microcontroller;
4. The MAX232 chip;
5. A Multiplexer- 74HC151;
6. A Demultiplexer – 74HC138;
7. 32- Channel LS20031 GPS 5Hz Receiver.

A. Overview of the operations of the integrated systems

In our model, we adopt a light-to-electricity sensing technique to detect leak in pipeline. To use light detection through a hole...
in a pipe to indicate the occurrence of a leak presents a challenge of how the circuit will measure light intensity. It is therefore imperative to choose an appropriate transducer (i.e. a light-to-electricity sensor) which for our case is a Light Dependent Resistor (LDR). Thus by connecting the LDR in a resistive divider network, we can achieve our objective. A typical biasing circuit for voltage divider circuit is shown below:

![Voltage Divider Circuit](image)

We note that the LDR’s resistance varies inversely to the light intensity. By replacing the \( R_{top} \) with the LDR and replacing the \( R_{bottom} \) with two resistors (variable: 100K\( \Omega \), fixed: 1k\( \Omega \)) in series, and setting \( V_{in} = 5V \) we obtain:

\[
V_{out} = \frac{R_{bottom}}{R_{bottom} + R_{LDR}} \cdot V_{in}
\]

By connecting the LDR as described above, the varying LDR resistance \( R_{LDR} \) is converted to a proportional varying voltage \( V_{out} \). The \( V_{out} \) is the proportional analog voltage of the light intensity that the Microcontroller can measure. This input is then read by the Microcontroller through the RA0/AN0 (analog channel) as shown in the circuit diagram. The Microcontroller has a 10-bit Analog-to-Digital (A/D) Converter. The resolution with a 5V reference is:

\[
\frac{5V}{2^{10}} = 4.89 \text{ mV}
\]

The Microcontroller will produce A/D output of 10-bit, which corresponds to the voltage being measured.

When light intensity varies within a specified range (so as to produce an output voltage of 3.6-5.0V: based on test experiment) falls on the photo-resistor, the Microcontroller senses the output voltage and performs an analog to digital conversion. The digital output is used to activate the GPS module to capture the geographical position of the leakage location.

Fig. 3 below shows the block diagram of our systems design, including the flow of signals among the subsystems. The LS20031 GPS receiver is a complete 5Hz GPS smart antenna receiver, which includes an embedded antenna and GPS receiver circuits.

![Block diagram of the integrated system](image)

To communicate with the GPS receiver, the Multiplexer and the De-multiplexer are configured to connect the GPS alone to the Microcontroller Unit (MCU) (i.e. TX - RX\(_2\), RX - TX\(_2\)). Similarly, when communicating with the PC, the Multiplexer and the De-multiplexer are configured to connect to the PC alone (i.e. TX - RX\(_1\), RX - TX\(_1\)).

Upon detection of leakage, the integrated system fetches the GPS coordinates from the GPS receiver and sends it to the serial port of the computer (via MAX232 module) for display. The mode of display/alert of a detected leakage is via Microsoft Windows Hyperterminal. Sample alert message on the computer is:

`ALERT! Leakage Detected at 0631.0559 N 00323.8814 E`

### B. Systems Implementation

We present the circuit diagram of the integrated system in Fig. 4. The integrated Detection and GPS receiver circuit board is presented in Fig.5, while the hardware implementation of the integrated system, including the output module is presented in Fig.6. The GPS receiver computes the latitude, longitude, altitude, and velocity. For this work, the useful parameters are the latitude and longitude.

Data collected in real time in a sample neighborhood in Lagos metropolis through which a pipe network runs are presented in Table I.
TABLE I
REAL TIME TEST RESULTS OBTAINED IN RESPECT OF LEAKAGES AT VARIOUS LOCATIONS IN AN AREA OF LAGOS

<table>
<thead>
<tr>
<th>S/N</th>
<th>Location</th>
<th>Leakage alert messages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Location 1</td>
<td>ALERT! Leakage Detected at 00323.8226 E</td>
</tr>
<tr>
<td>2</td>
<td>Location 2</td>
<td>ALERT! Leakage Detected at 00323.7948 E</td>
</tr>
<tr>
<td>3</td>
<td>Location 3</td>
<td>ALERT! Leakage Detected at 00323.5041 E</td>
</tr>
<tr>
<td>4</td>
<td>Location 4</td>
<td>ALERT! Leakage Detected at 00323.4249 E</td>
</tr>
<tr>
<td>5</td>
<td>Location 5</td>
<td>ALERT! Leakage Detected at 00323.4131 E</td>
</tr>
<tr>
<td>6</td>
<td>Location 6</td>
<td>ALERT! Leakage Detected at 00323.5227 E</td>
</tr>
<tr>
<td>7</td>
<td>Location 7</td>
<td>ALERT! Leakage Detected at 00323.3425 E</td>
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<tr>
<td>8</td>
<td>Location 8</td>
<td>ALERT! Leakage Detected at 00323.5053 E</td>
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<tr>
<td>9</td>
<td>Location 9</td>
<td>ALERT! Leakage Detected at 00323.5053 E</td>
</tr>
<tr>
<td>10</td>
<td>Location 10</td>
<td>ALERT! Leakage Detected at 00323.4886 E</td>
</tr>
<tr>
<td>11</td>
<td>Location 11</td>
<td>ALERT! Leakage Detected at 00323.4464 E</td>
</tr>
<tr>
<td>12</td>
<td>Location 12</td>
<td>ALERT! Leakage Detected at 00323.3905 E</td>
</tr>
<tr>
<td>13</td>
<td>Location 13</td>
<td>ALERT! Leakage Detected at 00323.3138 E</td>
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<td>14</td>
<td>Location 14</td>
<td>ALERT! Leakage Detected at 00323.2625 E</td>
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<td>ALERT! Leakage Detected at 00323.1338 E</td>
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<td>Location 16</td>
<td>ALERT! Leakage Detected at 00323.1366 E</td>
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<td>Location 17</td>
<td>ALERT! Leakage Detected at 00323.1025 E</td>
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<td>Location 18</td>
<td>ALERT! Leakage Detected at 00323.1130 E</td>
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<td>Location 19</td>
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<td>Location 21</td>
<td>ALERT! Leakage Detected at 00323.5034 E</td>
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<td>Location 24</td>
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<td>Location 25</td>
<td>ALERT! Leakage Detected at 00323.1173 N</td>
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<td>ALERT! Leakage Detected at 00323.7996 E</td>
</tr>
<tr>
<td>35</td>
<td>Location 35</td>
<td>ALERT! Leakage Detected at 00323.1033 N</td>
</tr>
</tbody>
</table>
IV. CONCLUSION AND RECOMMENDATION

Pipelines have been used to effectively transport essential commodities needed for human existence over short, medium and long distances. Examples of such commodities include water, natural gas, petroleum products and liquid hydrocarbons. Within this context, pipeline failure can be caused by corrosion and wear, intentional damage, unintentional damage or operation outside the design boundaries. Such failures can lead to loss of life and property, and also loss in revenue. For countries where crude oil, natural gas and petroleum products are the main sources of revenue, pipeline leakages would have adverse effect on economic growth and development. In view of the importance of pipeline as a means of transportation of valuable fluids, several research works have been done to address different challenges including leakage. Researchers have proposed several methods and techniques for leakage detection including acoustic emissions, Fiber optic cable sensing, pressure analysis, Real time transient method, pipeline inspection gauge, statistical models and others. However, a major challenge that remains is the cost-effective detection and accurate location of the point of leakage in a timely fashion.

In the current work we have modeled leakage detection using pressure analysis. Since the inlet pressure is normally known, our mathematical modeling is based on the availability of pressure data at some regular intervals on the pipeline. When leak occurs at any point in a pipeline there is usually a sudden change in pressure and flow characteristics. We subsequently used pressure dynamics to compute parameter value, which then form the basis for determining the occurrence of a leak. Furthermore, we presented a design and hardware implementation of our proposed approach. For this case, we use light sensing technique to detect leak and integrated that circuit with the GPS receiver’s circuit to get the accurate position of the leak. The Global Positioning System (GPS) provides reliable positioning to worldwide users on a continuous basis in all weather, day and night, anywhere on the Earth. To complete the process in terms of communicating the GPS receiver’s geographic data to a control centre in real time, we integrated the detection and the GPS receiver circuits with a personal computer. The geographic data corresponding to location of leak is displayed on the computer in real time.

From the data obtained in real time at different locations, it is shown that indeed the proposed model can be implemented for industrial application to detect and accurately provide location information on leakage(s) as to enable timely intervention. However, for such industrial application(s), the choice of components will depend to a large extent on the specific application area; for example, the choice of the light sensing device and the sensitivity requirements. Besides, the integration of the GPS receiver and detection hardware with the PIG electronics to form a single engineering system as well as the mode of communicating with the control centre will require further study. In terms of limitation, the proposed model can work only for exposed leakages. Most leakages resulting from intentional damage will fall into this category.

In conclusion, for countries where vandalisation of pipelines transporting valuable commodities (e.g. crude oil and petroleum products) is becoming a major concern, this proposed model would be very useful.

REFERENCES