A Leak Detecting Technique Utilizing an Abrupt and Large Pressure Drop

By

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Abstract

The distribution of clean, drinkable water is a problem that has been addressed in all civilizations. The most common form of transportation today, is the use of pressurized pipelines to carry the water long distances, but damage to the pipes, such as leaks, can cause considerable losses. The difficulty in detecting these leaks prompted this work, which attempts to find a reliable method of recognizing a leak and suggest possible designs that could be implemented on a pipe-navigating robot. This design would use thin flaps, or “leaves,” that would be forced outward by the rapid pressure drop formed in proximity to the leak. In order to determine the characteristic behavior of the system, several simulations, with a circular hole as the leak, were ran that showed that the significant pressure gradient existed only within distance on the order of the diameter of the leak. To validate these results, a high precision pressure sensor was used to try and measure the pressure gradient, but the pressure sensor was too large sense a pressure difference. Therefore, rubber strips were used to emulate the use of “leaves” to perceive the leak. This confirmed the simulation results, as the rubber strips had to be incredibly close to the leak in order to be affected. Furthermore, once the strip was pulled up against the leak, the friction created between the wall and the strip became strong enough that it could be utilized. Both the simulation and experimental results suggest that the leak detecting module should start near the leak. Next, instead of detecting the leak via a motion towards the leak, the module should instead take advantage of the large frictional force that occurs when the leaf has made contact with the leak. Further experiments could include testing the magnitude of the frictional force and creating a prototype.

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Table of Contents

1 Introduction .................................................. 11

2 Simulations .................................................. 13

3 Experiments .................................................. 19
   3.1 Pressure Sensor ........................................ 21
   3.2 Qualitative Experiment .................................. 23

4 Conclusion and Future Work .......................... 25
   4.1 Design Suggestions ....................................... 25
   4.2 Further Experiments ..................................... 28

Bibliography .................................................. 29
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>A diagram of the simulation setup</td>
<td>14</td>
</tr>
<tr>
<td>2-2</td>
<td>A sample result from the simulations with an outlet pressure of 5 bars</td>
<td>15</td>
</tr>
<tr>
<td>2-3</td>
<td>The maximum percentage pressure drop at various distances from the leak for various outlet pressures</td>
<td>16</td>
</tr>
<tr>
<td>2-4</td>
<td>The percentage pressure difference felt by a leaf with various thicknesses and initial positions</td>
<td>18</td>
</tr>
<tr>
<td>3-1</td>
<td>Plastic carriage used in experiments</td>
<td>20</td>
</tr>
<tr>
<td>3-2</td>
<td>The Omega pressure sensor held in the carriage measuring near the leak</td>
<td>21</td>
</tr>
<tr>
<td>3-3</td>
<td>The carriage with several rubber flaps at known distances from the leak</td>
<td>23</td>
</tr>
<tr>
<td>4-1</td>
<td>(a) A concept drawing of the suggested leak detecting module design, side view. (b) Same drawing, front view</td>
<td>27</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Clean water distribution is a critical issue all over the globe, particularly in regions where the nearest source is a significant distance away. Transporting water at higher pressures allows for greater possible ranges, but the pipelines that contain it are afflicted by leaks. The large distances water pipelines travel, along with their often inaccessible locations make leak detection a difficult, but still crucial, task. Robots are a logical possible solution but, their effectiveness is strongly dependent on their leak sensing capabilities.

Cheaper and more effective leak detecting capabilities are becoming increasingly important in countries where water sources are sparse. Current designs in use include using acoustics [1] or magnetic flux [2], however, these do not work as well in pipes made of PVC or other plastics. Visual inspection is also an option [3], but this often requires a tethered robot which limits mobility and can necessitate the pipeline being shut off during inspection. Also, these designs are generally used in larger diameter pipes.
Currently being researched by a joint group at MIT and King Fahd University of Petroleum and Minerals in Saudi Arabia is a technique that utilizes the strong pressure gradient that occurs near the leak to deflect a flat, long “leaf” that is made of rubber or plastic. Nominally this leaf, which could be a cantilever or a rigid hinged module, would be attached to the robot and held in its relative position by its inherent stiffness and the natural flow, however, when in the proximity of the leak the large pressure drop normal to the leaf would pull it away from the robot, which would be detectable.

In order to determine the feasibility of this technique, simulations and laboratory experiments were done to verify the expected phenomenon, quantify the design parameters, and test possible leaves. The objective of this work is to show the initial results of the experiments conducted and identify the parameters critical to making this design effective.

This work is divided into chapters. Chapter 2 will cover the simulations and the applicable results. Chapter 3 describes the setup and results from the experiments ran to verify the simulations. Finally, Chapter 4 contains the conclusion, design suggestions and future work proposals.
Simulations allow for reasonable conclusions to be made about complicated systems model that are impossible to solve analytically. To study the flow pattern around the system (shown in Figure 2-1) inside a 100 mm pipe, various computational fluid dynamic simulation studies have been performed with a well-tested CFD package. Steady state 3D turbulent flow simulations have been used to study the flow field, the pressure distribution around the body, velocity vectors and the calculation of drag coefficient. The standard k-e model is used for turbulence and the inlet velocity and pressure outlet boundary conditions are applied. The inlet velocity was 1 meter per second, there was a no slip boundary condition at the pipe walls, the outlet pressure was set between 2 – 5 bars, and the leak outlet pressure was set at 0 bars. The leak, a hole four millimeters in diameter, was half a meter away from its entrance. The steady state static pressures were measured at a range of positions along the x- and y-axes, where the x-axis is defined to be
parallel to the flow, the y-axis is defined to point away from the leak towards the centerline of the pipe, and the origin is located at the leak.

Figure 2-1: A diagram of the simulation setup, showing parameters and coordinates.

Inlet Flow 1 m/s

Outlet Pressure: 2 – 5 Bars

100 mm

Origin

External Pressure: 0 Bars

4 mm

Figure 2-2 shows a sample result from the simulation, where the outlet pressure was 5 bars, ranging x from -10 to 10 mm, and sampling at various y positions from 1 to 20 mm. The most significant and obvious result from this simulation is the incredibly quick reduction in the pressure drop from 1 to 5 mm away from the leak on the y axis. There is almost no noticeable pressure drop past 5 mm. Furthermore, the pressure difference is only significant within 4 mm of the leak along the x-axis. This small affected area, relative to the size of the pipe, makes it difficult utilize the pressure difference to sense the leak. This result was consistent across all of the sampled pressures.
One important result learned from the simulations is that the maximum pressure drop at a given y position is proportional to the outlet pressure; in other words, the maximum percentage pressure drop at a set distance away from the leak is constant. Figure 2-3 shows the ratio of the pressure drop to the outlet pressure, and fits the data to an exponential decay. This will become important later when problems with the pressure source become an issue. This is also beneficial because when applied to the leaf design, the optimality for any single pressure will be constant for all pressures, as the force causing the deflection is directly proportional to the outlet pressure. The fit shows that the overall pressure difference beyond 3 mm is insignificant, less than 5%.
Figure 2-3: (a) The maximum percentage pressure drop at various distances from the leak for various outlet pressures. (Note log scale on the y-axis) (b) A fit of the pressure drop data.

The fit for the percentage pressure drop can then be used to determine the relative effect on the deflecting force for the initial distance for the leak and the thickness of the leaf. Figure 2-4 shows the pressure drop ranging the thickness from 0.5 to 5 mm, and the distance to the leak from 1 to 5 mm. Under the assumption that the leaf (and robot) does not affect the flow field, the plot shows that there is a tipping point where a change in the
thickness of the leaf becomes less significant compared to a change in the initial position. After this tipping point, increasing the thickness does not significantly increase the force on the leaf. According to this plot, to get a desired pressure drop of 10 percent, the flap should have a thickness of around 1 – 1.5 mm and be at an initial position of about 1.5 mm. In fact, for a wide range of pressure drops, the thickness of 1 – 1.5 mm gives the best results, and increasing the thickness greater than 2 mm has little to no effect. Furthermore, these results support the previous conclusion that an initial position farther than 3 mm does not produce a large enough pressure difference to deflect the leaf.

Overall, the simulations gave insight into a complicated system, but require experimental verification. Additionally, there were several assumptions used during the analysis including that the leaves would not affect the flow field. The most crucial conclusion was that the pressure effects were only significant approximately within one diameter of the leak in any direction. For design criteria, this suggests that the leak detecting module should be as close to the leak as possible and does not gain any major benefit from being over 2 mm thick.
Figure 2-4: (a) The percentage pressure difference felt by a leaf with various thicknesses and initial positions. (b) Projection of the 3 dimensional plot into 2 dimensions, highlights the conclusion that a thickness greater than 2 mm does not significantly change the pressure difference.
Chapter 3

Experimental Setup & Results

In order to verify the simulation results and to gain further insight into a possible design for a leak detecting module, multiple experiments were conducted using a pressure sensor and qualitative observation. The piping system was simplistic, approximately a three foot long translucent PVC pipe with an inner diameter of four inches that had a hose attachment on one end, and an end cap on the other. The pipe had four holes drilled into it, varying from 2 – 5 mm in diameter, which could be individually sealed using rubber sleeves. The hose, with an inner diameter of one inch, connected the building water supply, nominally at ~65 psi; however, expectedly there were significant disturbances from the pressure source.

A plastic carriage (shown in Figure 3-1) was manufactured using 3D printing to house the pressure sensor and later simplistic rubber cantilevers within the pipe. The carriage had two slots, one on each side, which allowed high powered rare earth magnets
to be attached, which allowed the carriage to be manipulated and adjusted while the pipe was filled with pressurized water.

Figure 3-1: (a) Plastic carriage, top view. (b) Plastic carriage, front view. (c) Plastic carriage with pressure sensor, top view.
3.1 Pressure Sensor

The pressure sensor shown in Figure 3-1, a submersible water level transmitter (Omega PX437-100GI), was used due to its large pressure range, 0-100 psi, while maintaining a sufficiently high resolution, ± 0.1% or ± 0.1 psi. The pressure sensor was set in the carriage and placed in the pressurized pipe. The pressure was observed, first, far away from the leak, to establish a baseline pressure; and then brought close to the leak to attempt to measure a dip in pressure. Figure 3-2 shows one such trial where the pressure sensor is close to the leak, within the 4 mm range on the x-axis predicted by the simulations.

![Carriage Sensor Leak](image)

Figure 3-2: The Omega pressure sensor held in the carriage measuring near the leak.

The drawback in using this pressure sensor was its size. As discussed earlier, according to the simulations the noticeable pressure drop disappears past ~5 mm above the leak. The diameter of the pressure sensor was 1 inch, 25.4 mm. Not only was the
outer casing thicker than 5 mm, but furthermore, the silicon pressure cell that produced the signal was about half an inch in diameter, which caused an averaging effect of the measured pressure that dampened the already small signal to within the precision level of the sensor. This prevented any useful pressure measurement to be made about the leak. The pressure measured far from the leak was indistinguishable from the pressure measured near it. While this did not directly confirm the predictions made by the simulations, it did not give any evidence to refute the predictions either.

For this experimental setup, the static pressure, or pressure far from the leak, measured for the various hole diameters steadily declined as the size of the leak went up. This was most likely caused by the increased flow rate through the larger holes, which exaggerated the diffuser effect due to the rapid increase in the diameter from the hose to pipe. This brought the nominally ~65 psi pressure source down to ~60 psi for a 2 mm hole, ~54 psi for a 3 mm hole, ~46 psi for a 4 mm hole, and ~37 psi for a 5 mm hole. On top of the reduction in the source pressure, there were significant disturbances in from the building water supply due to the varying demand for water in the facility. These variances were random and had magnitudes up to 5 psi. Assuming the simulations provided a reasonable system model, the inconsistencies in pressure should not significantly affect the results of further experiments because the pressure difference scales linearly with the source pressure.
3.2 Qualitative Experiment

To verify that the expected pressure drop could produce a large enough force to pull a leaf, simple rubber flaps were used. They were placed on the plastic carriage from the previous experiment (shown in Figure 3-3) at a known distance to attempt to quantify approximately how far away the leak could affect the flaps. This distance was only an approximation due to the initial angle of the flaps. Furthermore, multiple different sizes of flaps were compared to utilize the greater area. These flaps were rigidly attached to the carriage, and because of this had an inherent stiffness that prevented them from being pulled by the leak sooner, which instead provided a more conservative estimate of the flaps maximum initial distance from the leak.

Figure 3-3: The carriage with several rubber flaps at known distances from the leak.

The simulation results were supported by the experiments using the rubber flaps. The flaps needed to be incredibly close to the leak, within 4 mm, to be affected by it, but once they started to be pulled towards the leak, the force pulling them became stronger.
In multiple cases, if the flap was large enough, it plugged the leak entirely and stopped all flow. This made the frictional force between the flap and the pipe strong enough to be used in the desired application. This was more common with the wider flaps, as the thinner flaps tended to get twisted, not allowing the entire leak to be covered.
Chapter 4

Conclusion and Future Work

Based on the simulations and the experiments, in order to receive the best results for detecting the leak, the leaf should be moved as close to the leak as possible. The small area that is affected by the leak limits the design of the leak sensing module. Furthermore, instead of utilizing the pressure drop to pull the leaf outward and detect this motion which would signal a leak; place the leaf outward and exploit the strong frictional force when the leak gets temporarily plugged by the leaf.

4.1 Design Suggestions

Both the simulations and the experiments showed that the initial distance was the most crucial parameter to ensure a leak was detected. That is why my suggestions for a design has the leaves connected to a flexure whose nominal distance from the centerline is greater than the radius of the pipe. The flexures should be weak and allow a large range
of motion to protect against damage when the robot has to navigate turns and obstacles. Furthermore, this will introduce another drag component that would need to be minimized.

The leaves themselves should have a thickness between 1 and 2 mm as shown by Figure 2-4, and be made of rubber or another soft material that would not corrode in water. A pre-existing curvature that would contour to the inside diameter of the pipe would minimize any gaps between the leaf and the wall. Multiple leaves evenly distributed around the robot would ensure that the full 360° range can be covered. Figure 4-1 shows a concept drawing of a single flexure and leaf.
Figure 4-1: (a) A concept drawing of the suggested leak detecting module design, side view. (b) Same drawing, front view.
4.2 Further Experiments

For further experimentation, I would attempt to find a better pressure sensor to verify the magnitude of the pressure drop near the leak. This was difficult to do because the high pressures, high degree of accuracy and small area limit which available sensors can be used. Furthermore, the experiments conducted above had no flow. It is important to determine how the existence of a flow would affect the leaves and the pressure profile, in general. In order to create this flow, a pump must be used because the building utilities cannot create a high enough pressure and flow rate.

Finally, the design suggestion I made utilized the large force created when the leaf was pulled tightly against the leak. Understanding this reaction could greatly improve the design, including the relative magnitudes of the force, which parameters most effectively increase the force, and how long does it take to grab. It is important to note that in the actual system, the robot will be moving with the flow, so understanding how that movement interacts with the leaf is important. Also, while a suggestion for the thickness of the leaf was given, the length and width were purposely left unspecified. These parameters should be determined by further testing.
Bibliography

