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DESIGN AND EVALUATION OF AN IN-PIPE LEAK DETECTION SENSING
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Leakage is the major factor for unaccounted fluid losses in almost every pipe network. In most cases the deleterious effects associated with the occurrence of leaks may present serious economical and health problems and therefore, leaks must be quickly detected, located and repaired. The problem of leakage becomes even more serious when it is concerned with the vital supply of fresh water to the community. Leaking water pipelines can develop large health threats to people mostly because of the infiltration of contaminants into the water network. Such possibilities of environmental health disasters have spurred research into the development of methods for pipeline leakage detection.

Most state of the art leak detection techniques have limited applicability, while some of them are not reliable enough and sometimes depend on user experience. Our goal in this work is to design and develop a reliable leak detection sensing system. The proposed technology utilizes the highly localized pressure gradient in the vicinity of a small opening due to leakage in a pressur-

ized pipeline. In this paper we study this local phenomenon in detail and try to understand it with the help of numerical simulations in leaking pipelines (CFD studies). Finally a new system for leak detection is presented.

The proposed system is designed in order to reduce the number of sensing elements required for detection. The main concept and detailed design are laid out. A prototype is fabricated and presented as a proof of concept. The prototype is tested in a simple experimental setup with artificial leakages for experimental evaluation. The sensing technique discussed in this work can be deployed in water, oil and gas pipelines without significant changes in the design, since the concepts remain the same in all cases.

INTRODUCTION

Leakage is the major factor for unaccounted water losses in almost every fluid distribution network worldwide; old or modern. It is reasonable to claim that almost 15 to 25% of the total water production is lost to soil due to pipe leaks [1]. A study on

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leakage assessment in Riyadh, Saudi Arabia shows the average leak percentage of the ten studied areas to rise up to 30% [2]. Losses through leaks represent a significant portion of the water supply, hence identification and elimination of leaks is imperative to efficient water resource management. Moreover, leaks in oil or gas pipes impose great environmental danger and also cause significant economic losses to the corresponding industries.

Pipeline leak may result, for example, from bad workmanship or from any destructive cause, due to sudden changes in pressure, corrosion, cracks, defects in pipes or lack of maintenance [3]. Thus, water authorities as well as gas and oil industries have been paying serious attention in preventing the loss of their product due to leakages in the pipe network. Over the last 20 years significant amount of research has been performed towards the development of novel leak detection techniques.

Mays [4] and Hunaidi [5] report various techniques for leak detection. First, water losses can be estimated from audits. The difference between the amounts of fluid distributed by the utility and the total amount of fluid recorded by usage meters indicates the amount of lost fluid. Acoustic leak detection can also be normally used not only to identify but also locate leaks. Acoustic methods consist of listening rods or aquaphones. These devices make contact with valves and/or hydrants in water networks. Acoustic techniques may also include geophones to listen for leaks on the ground directly above the pipes [5]. Chatzigeorgiou et. al. study the merits of an in-pipe acoustic leak detection sensor [6, 7] and propose the deployment of an in-pipe robot for leak detection [8].

More sophisticated techniques use acoustic correlation methods, where two sensors are placed on either side of the leak along a pipeline. The sensors bracket the leak and the time lag between the acoustic signals detected by the two sensors is used to identify and locate the leak [9]. Finally, several non-acoustic methods like infrared thermography, tracer gas technique and ground-penetrating radar (GPR) have been widely used for leak detection [10, 11]. **Nevertheless, all state-of-the-art leak detection techniques have limitations and drawbacks in terms of reliability, scalability and cost.**

Lately many robots have been developed for in-pipe inspection and used to identify corrosion, cracks or normal wear and damage. State of the art robots are usually wheeled, camera carrying and controlled via cables. Most of them are focused on oil or sewer-mains. One such robot was developed by Schempf at CMU [12] and was the untethered *Explorer robot*. The system is a long-range, leak-inspection robot, working in real-gas-pipeline conditions and is being controlled by an operator in real-time through wireless RF technology. The operator is constantly looking into a monitor as the robot is searching for leaks visually via a camera.

Past experience has shown that in-pipe inspection is much more accurate, less sensitive to random events and external noise

and less subjective to the user's experience. Moreover, pipe inspection from the inside brings the "sensing elements" closer to the leak source and consequently the system itself becomes capable of pinpointing very small leaks in a reliable fashion. In general such systems face major challenges associated with communication, powering and are expensive to deploy.

In this work we study the phenomenon of the leaking pipeline and propose a novel in-pipe leak detection methodology. Our goal is to design and prototype a novel and reliable leak detection system with the minimum number of sensing elements. Additionally, the system needs to be able to operate and sense leakages completely *autonomously*. Moreover our proposed system *will be deployable when the network is still operating*, which means supply to the community is preserved during inspection unlike most current methods, e.g. oil pipe inspection by wheeled robots and cameras is performed after pipes are drained. *Finally, all concepts discussed in this work and the proposed methodology are applicable to all kinds of fluid pipes, namely water, oil and gas.*

ANALYSIS

In this section we study the flow and pressure distribution inside a pipeline that is leaking. This is our first step towards understanding the phenomenon of a leaking pipeline and better support our proposed methodology in the coming sections. As it will be shown towards the end of this section, any leakage in a pipe is followed *by a highly localized pressure jump (pressure gradient)* happening very close to the opening. We are discussing this phenomenon throughout this work and try to utilize it in order to build a new and reliable leak sensing technique.

Pressure Gradient in the vicinity of a Leakage

For our analysis we consider the case of a straight pipe for simplicity. All results can be easily extended to bent sections, Y- and T-junctions and other complicated pipe configurations without major changes. So, let's consider the case of a straight pressurized pipe section as the one shown in the sketch of Fig.1. A planar sketch is presented here, although the real case extends in all three dimensions as a real pipeline does. Let's assume a leakage exists in the middle of the pipe. As one would expect due to the difference in inside to outside pressure ($\Delta p = p_{High} - p_{Low}$), fluid is escaping from the pipeline through the opening. Notice that the longitudinal axis of the pipe is z , while the transverse is y .

In our work we focus on small leaks only. By this we mean small compared to the pipe dimensions (less than 10% of ID). This enables us to assume that the line pressure is almost constant across a leakage (in the longitudinal dimension), which is a reasonable assumption for small openings. Not to mention that large leaks can easily be detected by other means. For instance

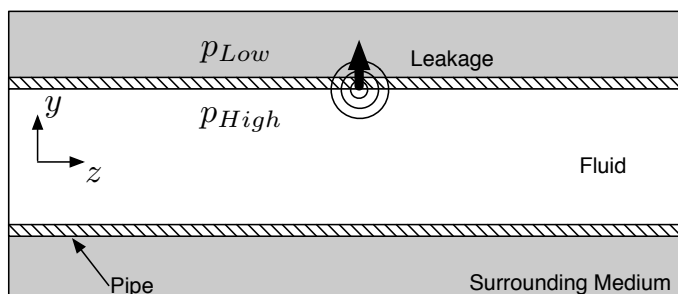


FIGURE 1. A simple sketch of a leaking pipe. A leak occurs in the middle of the pipe and thus, fluid is escaping through the opening. Notice the high line pressure, p_{High} , and the low outside pressure, p_{Low} .

installed pressure sensors around the network can easily sense the large drop in line pressure that such leaks impose to the network. Additionally a very large leak in a water pipe will be visible even by pedestrians as water reaches the surface quickly. Thus, our goal is to develop a system able to sense *small leaks* and prevent them from growing into large leaks with potential great social damage.

The drop in pressure (pressure jump) Δp as discussed before is occurring over a small distance close to leak opening. **The pressure jump/gradient is a highly localized phenomenon in the vicinity of the leakage.** Intuitively, we can guess that the volume of fluid that is affected by this phenomenon, namely this rapid local pressure gradient, depends on the fluid properties (density ρ , dynamic viscosity μ) and the magnitude of the pressure difference Δp .

Numerical Analysis of the Pressure Gradient near a Leakage

In this section we try to quantify and understand the phenomenon of the localized pressure gradient. More specifically we try to identify the size of the region that is affected by the pressure drop and understand what might be the optimal way to sense the leak.

For our initial numerical study we assume the case of a damaged pipeline with a $4mm$ circular leak. This is a very special case but nevertheless will give results not much different than a more realistic scenario, e.g. an opening of random shape. For our analysis we consider a pipe with ID equal to $100mm$, which happens to be a very common size in concurrent water distribution networks. Pipes of such size exist in almost all modern water distribution networks in major cities around the globe.

We perform a CFD study on this three dimensional leaking pipe problem and we use water as our working medium. We also apply a line pressure of $p_{High} = 5bars$ and an outside pressure of $p_{Low} = 0bars$. This is an extreme case since $5bars$ is considered a very high line pressure for water distribution networks but still

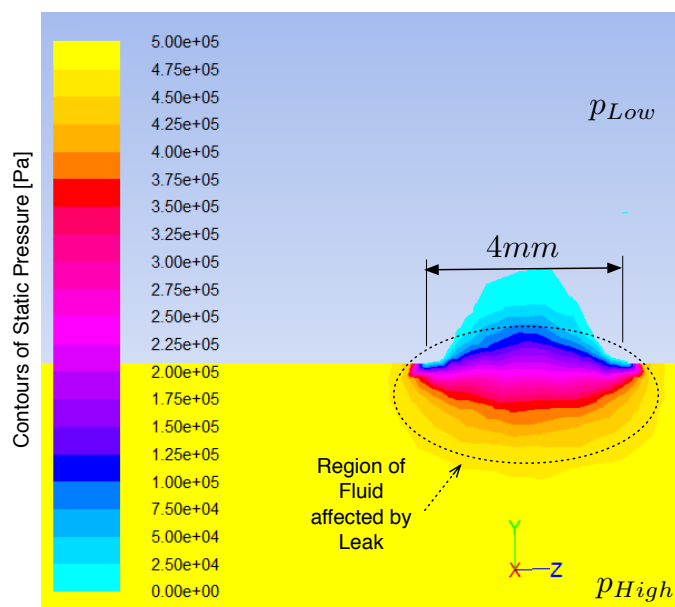


FIGURE 2. The static pressure distribution in the vicinity of the leak. A magnified version of a small leak is depicted. The fluid region as well as the surrounding medium are shown. The pipe material/wall is skipped on purpose. It is obvious that only a very small region of fluid is affected by the pressure drop. Contours of static pressure are shown in Pa.

remains a good value for an initial numerical study. Finally, for completeness we consider the case where water is also flowing with an average speed of $1m/s$ through the pipe. The direction of the ambient flow is from left to right towards the positive z -axis. As expected some of this fluid will escape the pipe through the opening.

Running a CFD case with the parameters specified above we get the pressure distribution shown in Fig.2. The image is zoomed in the region of interest, namely the vicinity of the $4mm$ opening. The localized drop in pressure is clearly depicted in this image. We observe from this figure that static pressure is dropping gradually from p_{High} to p_{Low} . We observe that there is a very small volume of fluid that is affected by this drop as shown in the figure.

From the CFD case we can extract the static pressure value for each point on the mesh. In Fig.3 we present the plots of the static pressure distribution along the z -direction for different heights y . The height here represents the normal distance from the leak. Thus, a height of $y = 49$ corresponds to a normal distance of $1mm$ from the leak for a $100mm$ diameter pipe (radius is $50mm$). Moreover $z = 0$ corresponds to the leak center location along the axis the symmetry of the pipe.

As one would expect the largest pressure jump occurs at $z = 0$. As one moves further downstream or upstream the pres-

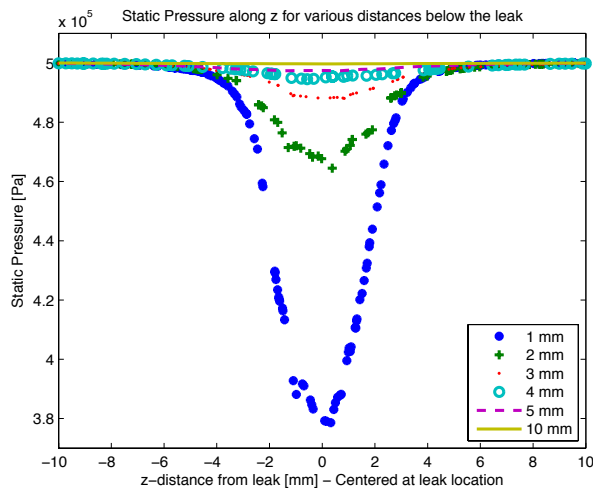


FIGURE 3. The static pressure along the z -axis for various distances from the opening. Each curve corresponds to a different normal distance from the leak opening.

sure increases again in an almost symmetric fashion as expected. Not surprisingly we observe that the region/volume of fluid that is affected by this pressure gradient is very small. Approximately a leak diameter away from the leak (4mm) the drop has disappeared and static pressure is back to $p_{High} = 5\text{bars} = 500.000\text{Pa}$.

In the previous case we studied the case of a very high value of line pressure. By repeating the simulations for different values of pressures we observe that the main trends and concepts remain the same in every case. In Fig.4 we summarize the results for four different cases of lower line pressures. Those plots show the pressure drop at the leak location ($z = 0$) as the normal distance from the opening increases from 1mm to 5mm (moving away from the opening).

It is quite common between all cases that the pressure drop is almost 0 at a normal distance of $3.5 - 4\text{mm}$ from the leak opening. Nevertheless, it is clear that if the sensor is close enough ($< 4\text{mm}$) **it will be able to pick this pressure drop and detect a potential leakage easily**. The closer the sensor finds itself to the pipe walls, the larger the magnitude of the pressure drop and the easier the sensor will be able to detect the leakage. Of course though the effectiveness of such a sensor depends very much on its sensitivity but nonetheless **it is clear that there is room here for creating a new sensing methodology by utilizing this localized pressure gradient**.

The cases presented here included a leak opening of 4mm . We observe that although this corresponds to a very small leak our measured quantity, although very localized, is significantly large and thus, could potentially be sensed efficiently. In this work we will try to utilize the large pressure gradient to design and fabricate a reliable mechanical leak detection sensor based

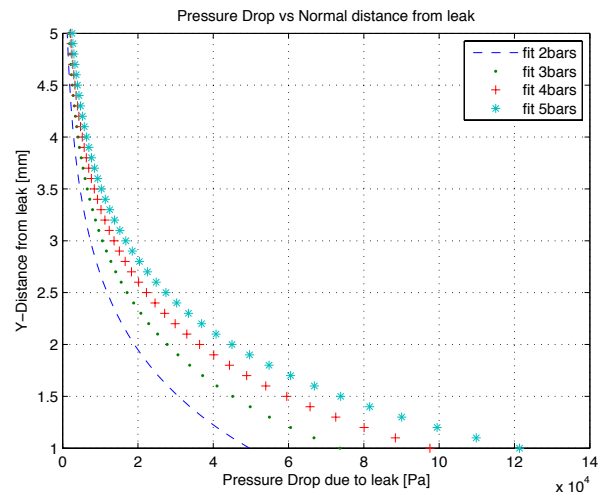


FIGURE 4. "Pressure Drop" for different values of line pressure p_{High} . Notice that after passing the "limit" of 4mm of normal distance from the leak opening the pressure has risen back to line pressure and the leak pressure drop is not sensible any more (0 Pressure Drop).

on force transduction. More details on the sensing methodology are discussed in the coming sections.

Repeating the cases for different sizes of leakages in similar pipes shows that although the values might change significantly, the trends and signatures remain the same in the pressure gradient [13]. More importantly, the signature of the large pressure gradient in the vicinity of the leak is always present in pressurized pipes independent from the size, the working medium or the surrounding medium.

OVERVIEW OF THE SENSING SYSTEM

We showed in the previous sections that each leak in a pressurized pipeline is accompanied by a highly localized pressure gradient. In this section we present a methodology that utilizes this very localized pressure gradient in an efficient way in order to sense leakages and provide information about the potential existence and magnitude of leakages along pipelines.

A very simple sensing implementation would be the use of a series of pressure sensors (differential or absolute) around the circumference of the pipe. In this embodiment one would have to put the array of sensors very close to the pipe wall. Thus, the system would be able to sense this localized pressure drop all over the circumference of the pipe. Nevertheless, such an implementation would be very costly and inefficient since it would include many sensors and significant amount of power to operate.

In order to minimize the number of sensing elements we can let a single body come very close to the opening. This body is then able to be displaced due to forces stemming from the pres-

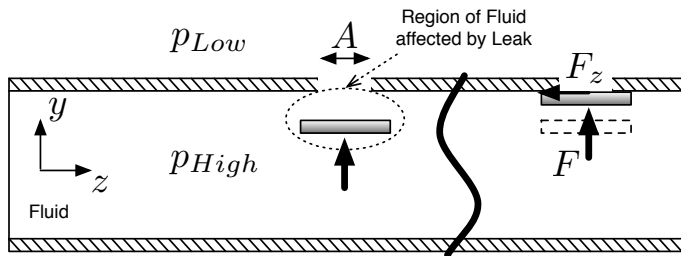


FIGURE 5. A body that is close to the leak opening is subject to a force because of the difference in pressure. The body is pulled closer to the leak and the pipe wall as it is sucked in by the pressure gradient. The whole system is supposed to be moving at a constant speed along z (from left to right). The carrier mechanism is skipped on purpose.

sure gradient and the leakage. In other words, the concept includes a system that is moving along the pipeline and a single body of this system is able to come close to a potential opening. This body is then displaced by the leak forces. This concept is presented in Fig.5. The system is supposed to be moving from left to right and the body, which is shown here as a small plate, is pulled upwards by the pressure gradient. This happens only if the plate comes close to the opening or if the body finds itself within the critical volume of fluid that is affected by the pressure gradient.

If the body has enough time to reach the wall it will touch the pipe wall and remain there. After this instant in time the force is equal to: $F = A\Delta p$, where A stands for the area of the leak opening and $\Delta p = p_{High} - p_{Low}$. We need to mention here that such a sensing body/system is moving inside the pipeline with the help of a carrier that could be an autonomous robot for instance. Details of the carrier are not discussed in this paper and a simple autonomous wheeled robot is used for experimentation later during this work.

The pulling force due to the pressure gradient will prove to be very useful in our leak detection methodology. A promising sensing approach would be to have some kind of either force or displacement sensors and thus be able to sense the movement of the body with respect to a fixed reference frame on the carrier.

Such an absolute radial/transversal displacement or force sensing technique would lead to false alarms very easily. In general, pipelines are not clean inside because of dirt, particles that sit on the bottom part and sometimes also due to corrosion. After some time of operation the effective diameter of a pipeline is not anymore equal to the nominal ID as it came off the factory. Sometimes the fluctuations in the ID can be very large. This said, such a sensor, that is based on the radial/transversal displacement of the body, would prove inefficient and unreliable. A small change in the diameter would push the body and "trigger" a false alarm, as this motion would be captured by appropriate sensors. This implication naturally leads us to the next design

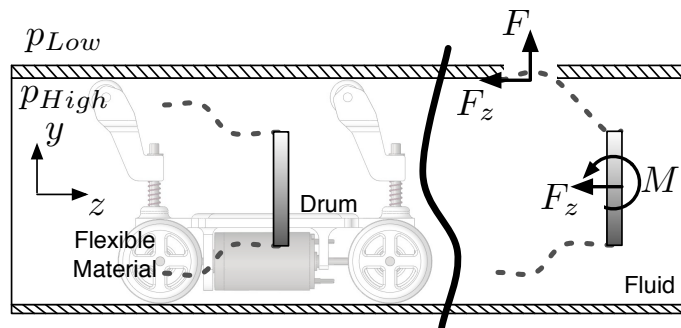


FIGURE 6. The main concept is presented here. A drum is moving from left to right with the help of a carrier robot. The flexible material (dotted line) is sucked by the leak due to the pressure gradient. Moreover, a friction force F_z is generated. As the carrier moves to the right a force and torque are transferred to the drum and can be sensed by appropriate sensing elements on the drum/carrier.

concept.

Sensing Concept

Our proposed methodology consists of a flexible body that moves close the pipe wall. This flexible body embraces the circumference of the pipe, finds itself within $2 - 3mm$ from the wall and also lets itself get displaced easily in case of a leak. Thus, almost any size of leak, small or large, will pull the flexible material towards the walls. This is more or less though dependent on the stiffness of the material, but we consider low stiffness materials in this work, e.g. thin soft polyurethane or multi-purpose neoprene rubber sheets (membranes). Finally, when the material touches the wall a corresponding normal force F is generated. This force gets larger as the size of the opening increases (it depends linearly on the area of the opening A).

As the carrier moves constantly to the right (Fig.6) another force is generated. This force, F_z , is now apparent because of friction between the flexible material and the pipe wall. A very significant portion of this friction force is due to the fact that the flexible material bends and confronts to the opening, making it more difficult to escape. When the flexible material detaches from the opening, as the carrier continues to move to the right, both forces disappear.

The flexible material is rigidly connected to the drum and the drum is allowed to move in specific directions. The modes corresponding to those directions can be observed with appropriate selection and placement of sensors. In our proposed system we measure the forces on this drum directly. The force F_z is transferred from the flexible material to the drum along with a torque (Fig.6).

We can also mention at this point that one can potentially design and optimize the shape and stiffness of the flexible body. By this one may make it less sensitive to fluctuations in pipe

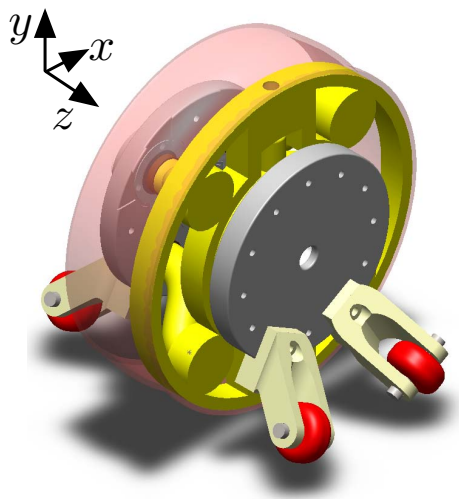


FIGURE 7. A 3D view of the proposed sensing system based on force transduction. The system is able to detect leaks anywhere around the circumference due to its ability to measure and sense longitudinal forces.

diameter and in general radial/transversal forces. Such a calibration/optimization will eliminate false alarms and will reduce the sensitivity of the sensing system to random events. The only way the drum needs to be generating an "alarm" is when there is a significant longitudinal force F_z that the sensors may feel because of the drum displacement.

Mechanical Design - Key Components

The proposed detailed design is presented in Fig.7. The sensing system is again supposed to be moving along the z -axis and sense any potential leakages at any angle θ around the circumference.

More details are presented in Fig.8 and 9 along with explanations on the main components of the system. The drum is depicted in yellow (solid color) and the flexible material in light red (transparent). The drum is suspended by a wheeled system and remains always in the middle of the pipe. A key fact with this proposed design is the gimbal mechanism consisting of different parts (parts [b] and [c] in Fig.9). Because of the existence of this mechanism the drum is allowed to pivot about two axes and thus respond to a torque (generated by an equivalent friction force at some angle at the circumference of the pipe) about any axis passing through its center point C .

More specifically, whenever the flexible material is pulled towards a leak because of a pressure gradient, a normal force F is generated because of Δp . As discussed before another force due to friction F_z is created. This force generates an equivalent force and a torque on the drum and forces it to rotate about some axis passing through its center C . This pair of force and torque can then be sensed by appropriate force and/or displacement sensors

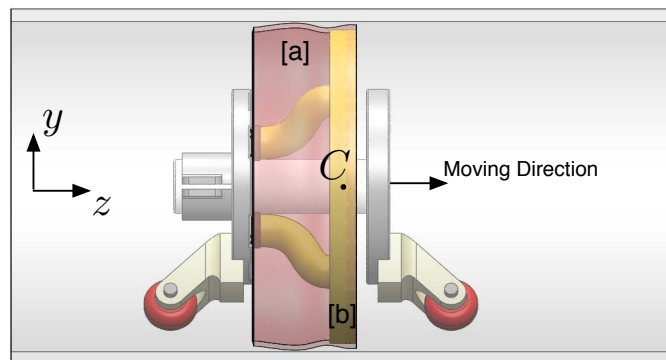


FIGURE 8. The left view of the proposed design. The sensor is moving to the right. Details: [a] Flexible material. [b] Drum.

mounted on the carrier.

In our proposed embodiment the sensors sit in the back plate of the carrier's chassis. Those sensors are capable of detecting forces normal to their surface. As the drum tends to move, a force normal to those sensors is applied and thus a signal is generated on each one of them.

By using one sensing element only the system would be able to estimate the existence of a leak and could potentially trigger an alarm based on the magnitude of the generated signal. But by appropriate selection of the position of two or more sensors we can get full observability for the leak detection problem. This means that we can not only pinpoint the existence of a leakage as the system moves, but also estimate its magnitude and its position/angle θ_{leak} around the circumference. To achieve full observability we need at least two sensors as used in Fig.9. Further discussion on this topic is outside the scope of this paper.

EXPERIMENTAL VALIDATION

In this section we present a prototype that we build as a proof-of-concept. Moreover we present initial experimental results on leak sensing for evaluation and completeness.

Proof of Concept Prototype

In this section a prototype of the proposed design is presented. More specifically we fabricated a first prototype of the sensing system in order to validate our design concept and test the sensing capabilities experimentally. All rigid parts were 3D printed using ABS material. For the flexible material we used thin sheets of flexible polyurethane that we attached around the circumference of the drum. The prototype is shown in Fig.10 where the assembled system is shown inside a 100mm ID pipe. The most critical part of the module, namely the gimbal mechanism, is shown in Fig.11.

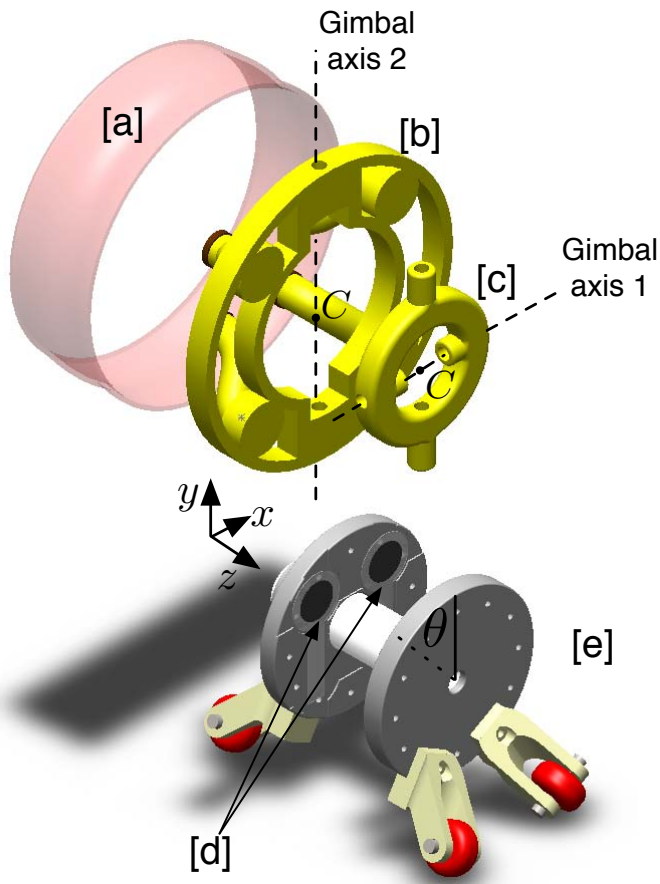


FIGURE 9. The exploded view of the proposed design. Notice how the angle θ is defined with respect to the vertical. All key components are visible. Details: [a] Flexible material, [b] Drum, [c] Gimbal part, [d] Sensors, [e] Carrier.

In this embodiment we installed the Force Sensing Resistors (FSR sensors) from Interlink Electronics as our sensing elements (force transducers). Moreover, we are using 2 separate sensors in order to get full observability as discussed in the previous section. Signals from the sensors are transmitted to the computer wirelessly with use of suitable RF modules and an "Arduino Mini" microprocessor.

Experimental Results

In order to validate the design and evaluate our sensing system we test the system in a simple experimental setup. In this case we present the results where the sensor will pass by consecutive openings/leaks of $2mm$ in diameter. The line pressure during the experimentation is always constant and equal to 20psi (1.38bars). The working medium in this case is air (gas).

During experimentation we observe that the sensing system is able to capture signals that clearly indicate the existence of

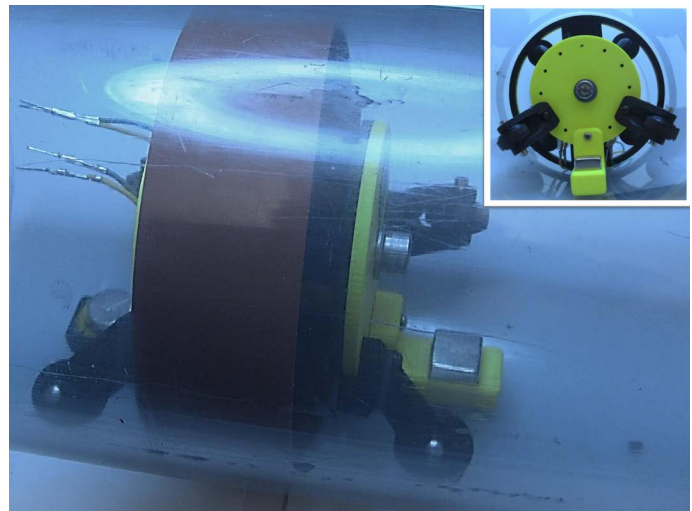


FIGURE 10. A prototype of the proposed sensing system. The system is deployed inside a 100mm ID pipe in this case. The FSR sensors on the back circular plate are not visible in this configuration. The side view of the sensor system is shown on the right.

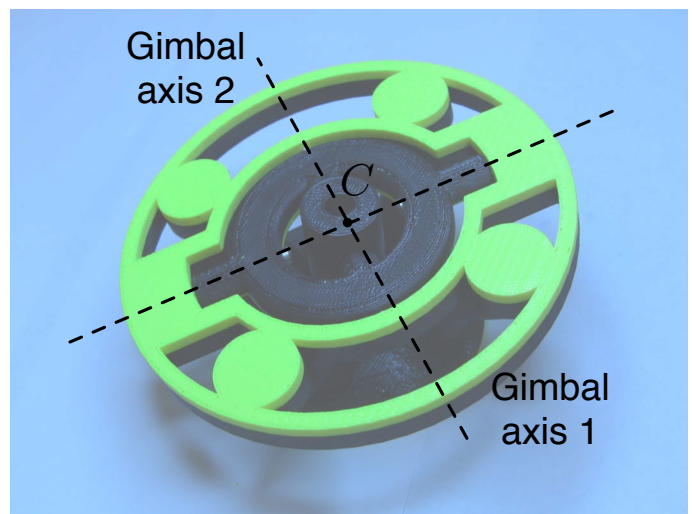


FIGURE 11. The gimbal mechanism at a random configuration. One can see the two axes of rotation. The flexible material is not presented in this photo and was later attached to the circumference of the drum.

leaks. The initial results are indeed very promising. Signals captured are presented in Fig.12 for two different cases. For those experiments the two sensors were placed on the back plate of the sensing systems along two vertical axes, i.e. off-center at 90° from each other. Sensor 1 is located at $\theta_1 = 45^\circ$ and sensor 2 is located at $\theta_2 = -45^\circ$.

In Fig.12(a) we present the signals captured by the two sensors when the system came across two similar leaks at an angle

$\theta = 0^\circ$. Whenever the system encounters a leak the response of the sensing elements and the force captured look similar. We can see that in this case the initial response of the signal to a leak is increasing in magnitude and when the flexible material detaches comes back to the dc value. This indicates that forces on both sensors are of pushing nature.

In Fig.12(b) we plot the signals captured by the two sensors when the system came across 2 similar leaks at an angle $\theta = 90^\circ$ around the circumference. Again the signals have the same trends between leak instances. In this case the signals captured by the two sensors seem to be behaving in an opposite manner, namely as the one drops the other rises in magnitude at each leak. This indicates that force on sensor 1 is pushing, while force on sensor 2 is pulling.

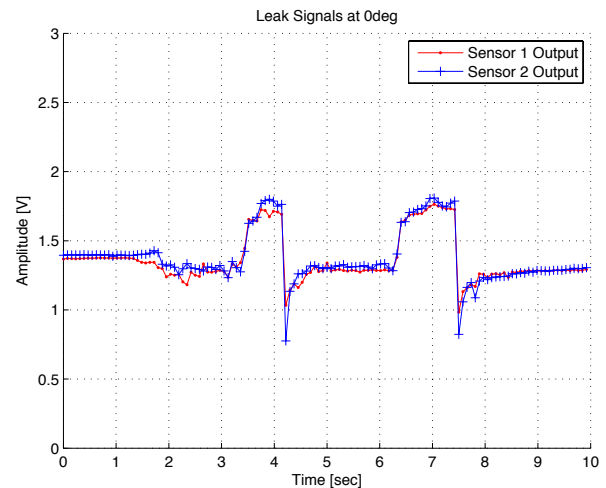
The differences between the two experiments exist due to the fact that each leak is at a different angle and this results in a different pair of F_z and M about C as discussed in the previous sections. Because the sensors are placed at different positions on the carrier's back plate one can use estimation algorithms for inference of the position and the magnitude of the leaks. *Nevertheless, it is also pretty clear that whenever the system passes by a leakage, a clear change in signal(s) will easily pinpoint the existence of a leakage, either by using one or more than one sensors on the back plate..*

CONCLUSIONS

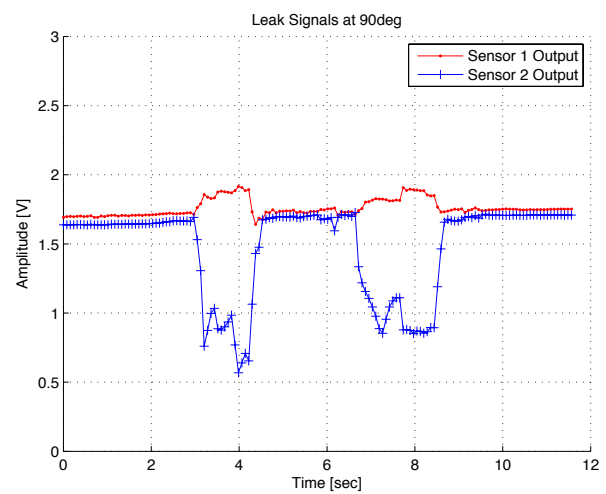
In this work a novel and reliable leak detection system is presented and evaluated. The fundamental principle of a leaking pipe is studied numerically using CFD simulations and a new sensing concept is presented. The mechanical design is shown in this paper and a prototype is built and presented as a proof of concept.

The prototype is tested under real conditions in the lab. The system is able to pinpoint leakages along the pipeline. The results presented in the last section of the paper seem to be very promising. More experimentation for careful calibration of the sensing parameters are now being carried out. This stage is crucial for accurate and reliable leak detection and for producing repeatable results.

Our future goals include the fabrication of even more prototypes and iterate the design for refinement. Moreover, some more experimentation is needed in order to evaluate the performance of the sensor under different conditions (pressure, flow, traveling speed, etc.). Finally, smart algorithms for the estimation of the position of the leak and its magnitude are under development. This will enable us to have a fully observable system, where leak magnitude and location will be able to be estimated via captured signals of two separate force/displacement sensors. Last but not least, we are planning to test our sensing system in other fluids, initially water but also oil and evaluate its performance there.



(a)



(b)

FIGURE 12. Signals captured by the 2 FSR sensors during initial experiments. (a) Sensor runs across two leaks at an angle of $\theta = 0^\circ$. (b) Sensor runs across two leaks at an angle of $\theta = 90^\circ$.

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