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Pipeline leak detection

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PIPELINE LEAK DETECTION

by

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A THESIS

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MASTER OF SCIENCE IN COMPUTER ENGINEERING

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Approved by

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ABSTRACT

In the present research two techniques are applied for leak detection in pipelines. The first method is a hardware-based technique which uses ultrasonic wave's emission for pipeline inspection. Ultrasonic waves are propagated in the pipe walls and reflected signal from leakage will be used for pipe analysis. Several Pipes with various dimensions and characteristics are modeled by finite element method using ANSYS. Second order longitudinal modes of ultrasonic waves are emitted in their walls. For this purpose, excited frequency is calculated such that it excites the second order longitude mode. In order to investigate the behavior of emitted wave in contact with leakage, four sensors are used in outer surface of pipe. Waves are reflected when encountering leakage and the leak location is recognized knowing the wave emission speed and flight time of backscattered signals. Wavelet transform is used for processing these signals and recognizing leak location. This method is tested on several pipe models and it presents satisfactory results for short pipes. The second approach is a software-based method which works based on the transient model of the pipeline. In this method the outputs from simulated pipeline are compared to those measured from flow meters and if their difference goes beyond a threshold value, leak is detected. For leak localization a gradient pressure technique is applied which needs pressure slope measurements at inlet and outlet of the pipeline. Several cases with leak at various positions are studied. This method works well with high accuracy for long pipelines.

ACKNOWLEDGMENTS

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1. INTRODUCTION

1.1. PROBLEM STATEMENT

Everything from water to crude oil even solid capsule is being transported through millions of miles of pipelines all over the world. Transport and distribution network is very elaborate and continuously growing. This network is prone to many risks .The pipelines are vulnerable to losing their functionality by internal and external corrosion, cracking, third party damage and manufacturing flaws[1]. However pipelines are among safest means for transportation. The major threat that occurs in pipelines is leakage. The effects of leakage go beyond repair expense and cost of lost oil or gas, it also significantly affects the human lives and environment. To impede these huge costs, designing a reliable leak detection technique is crucial. However, more information is required in order to achieve a reliable system. Before deciding on any corrective action the location and size of leakage should be known. Many researches have been done during last decades to find the location and size of the leakage with high accuracy.

1.2. SCOPE AND EMPHASIS

The scope for this thesis will be the design of a method for the detection and localization of a leak in a system consisting of a pipe. Two techniques are used for this purpose. The first one is a model-based approach that relies on the numerical model of pipe and flow and pressure measurements at both ends of pipeline. The second designed approach develops a finite difference model that captures guided wave excitation and sensing. The sensed waves are analyzed by wavelet transform for leak detection. The application areas of these two approach and their performances is discussed in chapter 5.

1.3. OUTLINE OF THESIS

Chapter 2 will present some of the earlier work done in leak detection; Chapter 3 will be dedicated to the theory behind the guided wave propagation along the pipeline and the simulation results obtained from this method. Chapter 4 gives a brief introduction to the mathematical pipe model and numerical method for solving fluid flow along a pipe, and then goes through the simulation results. Conclusion and discussion of the results and suggestions for further work are found in chapter 5.

2. LITERATURE REVIEW

2.1. INTRODUCTION

This chapter overviews different categories of leak detection techniques. In modern world, pipeline networks are an essential mode of transporting fluid from one place to another. Small percentages of loss can lead to significant economic impact, and potential risks to public health. The leak happens as a result of aging pipelines, deterioration or extreme pressure forced by operational error or valve rapid variation.

Removing leakage completely would be virtually impossible and very expensive. Thus, the development and implementation of an organized leakage control policy is one of the possible ways to reduce the leakage rates. In order to prevent further loss and public risk many techniques with different applicability have been proposed in following sections.

2.2. LEAK DETECTION TECHNIQUES

In this chapter we first looked at organizing the available leak detection methods. They could be classified based on their technical approach. There are two general way for leak detection: hardware based methods and software based methods [2]. These two groups are also named externally or internally based leak detection systems. Figure 2.1 illustrates classifying leak detection systems.

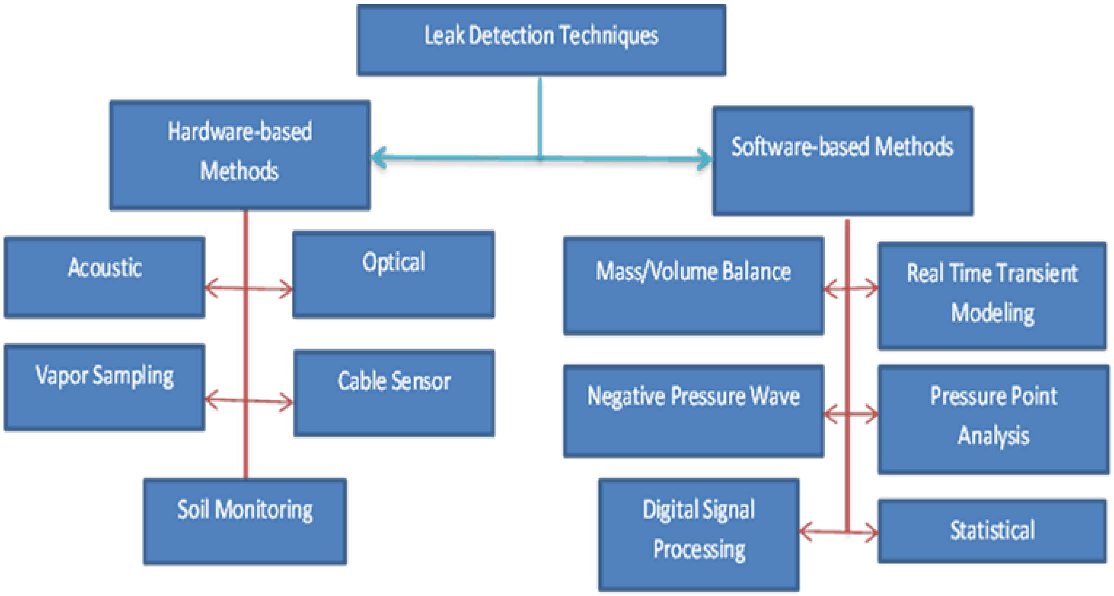


Figure 2.1. Classification of Leak Detection Techniques

2.2.1. Hardware Based Leak Detection. Hardware based methods for leak detection and localization detect the present of leaks from outside the pipeline by visual observation or by using appropriate equipment. These kinds of techniques are featured by a very good sensitivity to leaks and are very precise in finding the leak location. However, they are expensive and installation of their equipment is very complex task. As a result, their uses are restricted to places with high potential of risk like near rivers or nature protection areas or in conditions which pipe is transferring a hazardous material [2]. Examples of this method are acoustic leak detection, fiber optical sensing cable, vapor sensing cable and liquid sensing cable based systems.

2.2.1.1. Acoustic leak detection. The principle of this method is based on the fact that when a leak happens, it produces an acoustic noise around the place of leakage. Acoustic sensors which are installed outside the pipe track and detect internal noise level and create a baseline with specific features. The self-similarity of this signal is continuously analyzed by acoustic sensors. When a leak happens, produced low frequency acoustic signal is detected and investigated. If this signal ‘features differs from the baseline, an alarm will be activated [3]. The received signal is stronger near the leak site thus enabling leak localization. In the acoustic methods, the most common approach for detecting and localizing of leakage involves the cross-correlation. In general, the technique is based on detecting the noise that occurs when a leak exists in the pipeline. The method works by placing sensor devices on both sides of the pipes where the leak is suspected. The sensors can be placed on the road surface or directly on the particular point such as fire hydrants as shown by Figure 2.2.

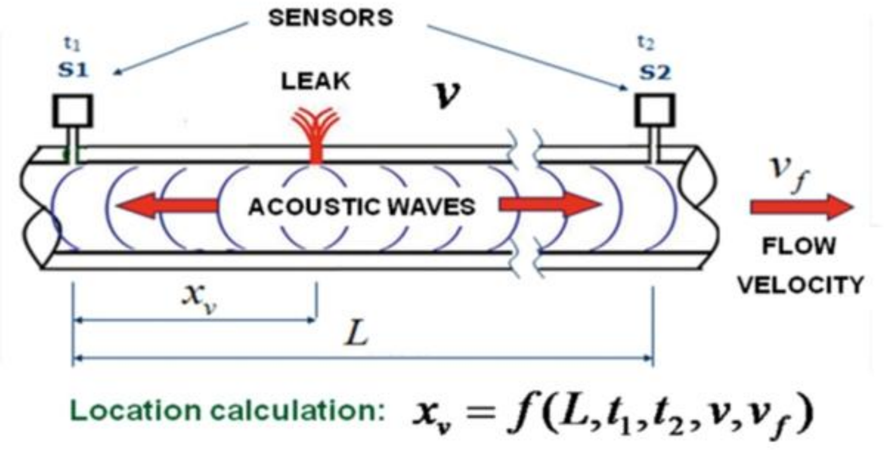


Figure 2.2. Leak Detection Using Acoustic Sensors

Location of the leak can be identified based on sound propagation velocity, time lag and distance between sensing points. It can be found by using the following equation [4]:

$$d_1 = \frac{d - ct_{peak}}{2} \tag{1}$$

Where $d_1$is the distance from the sensor 1 to the distance of the leak, d is a distance between two sensors, c is a sound wave propagation velocity and t_{peak} indicates time difference between the arrivals of identical frequencies to each sensor. The performance of the leak detection depends on the distance between the sensors, d. The shorter the distance between the sensors leads to higher accuracy. Obviously all variables of this equation can be found easily from the experiment. Thus, this technique can give results with a high accuracy level. The efficiency and accuracy of the method are dependent on the skills of the operators [5].

Acoustic sensors and computational systems based on artificial neural networks (ANN) are used for leak detection. The detection procedure was based on the fact that leakage could change the amplitude or speed of signal propagation [6]. Blesito [6] and Garcia [7] have used neural network for leak detection and have received flexible and promising results. Shibata [8] used ANN for leak detection. She gathered the sound noise data through some microphones inserted in a certain distances from the crash. Then a fast Fourier transform (FFT) was applied to the data and at last it fed forward to a neural network for final decision making. Zhao [9] applied neural networks for pattern recognition in oil pipelines. The experimental data from acoustic sensors preprocessed and got through a filter bank to extract frequencies of 1 kHz, 5 kHz and 9 kHz. The dynamic of these noises were used as input to neural networks. Neural training was carried out with database from an experimental pipeline in both states of healthy and with leak occurrence (transient and steady). The result was satisfactory for short pipelines up to 100 meters but since many microphones should be used along the pipeline which makes this method a very costly one, it is not an efficient approach for long pipelines. Avelino [10] proposed a real time leak detection system using sonic technology. He exploited wavelet transform for feature extraction and a neural network technique for decision making on leak occurrence in an oil pipeline. The system composed of two 32 bit DSP’s, four piezoresistive sensors, two global positioning system (GPS). The piezoresistive sensors were placed at both ends of the pipeline. These sensors are very sensitive to small changes and their mechanism is based on change of electrical resistance of the material due to variation of mechanical stress. Using two pressure sensors at each station provided the capability to identify the signal direction during a pressure fall caused by the leak. After preprocessing of the extracted signals from sensors, Wavelet decomposition was applied. And finally the outputs of wavelet decomposition were fed into the NN as its input. Leaks were identified by pressure fall. So situations where the pressure was rising or stable were discarded. The challenge of this work was finding an optimum sampling rate. After trying some sampling rate such as 100 Hz, 200 Hz and 500 Hz and 1 KHz, they come up with the sampling rate of 1 kHz. The advantage of this work was its ability of differentiating between leak occurrences and switching on/off pumps. However, it is not an efficient method for long pipeline and also location of leak could not be identified by this method.

In what regards the advantages of using this technique, it could be said that unceasing monitoring of the system is possible. Furthermore, acoustic signals are applicable in leak localization and also estimation of leak’s size [2]. However, sometimes high background or flow noise like noise produced by vehicles or valve or pump may cover the actual leak signal. An important factor of limited application of this technique for leak detection is associated with its financial drawback matters; installing plentiful sensors which are needed for long pipelines inspection based on this technique is significantly expensive.

2.2.1.2. Fiber optic sensors. The fiber optic sensing leak detection method relies on the installation of a fiber optic cable all along the pipeline. Its principle is as a leak occurs in pipeline the substance inside the pipeline gets in touch with fiber cable. So, the temperature of the cable changes due to this contact. By measuring the temperature changes in fiber cable leak could be detected.

This technique is based on the Raman Effect or Optical Time Domain Reflectometry (OTDR). The laser light is scattered as the laser pulse spreads through the fiber as a result of molecular vibrations. So, the backscattered light carries the information of local temperature along the pipeline. Indeed, Raman backscattered light has two frequency shifted components: the Stokes and the Anti-Stokes components. The amplitude of the Anti-Stokes component varies dramatically with regard of temperature variations. But the amplitude of the Stokes component is not affected by temperature. Therefore some filtering is needed to isolate Anti-stoke components from stokes components [11]. The problem associated with this technique is low magnitude of backscattered light. To overcome his issue high numerical aperture multimode fibers are used. However, another difficulty arises by using multimode fibers which is related to their severe attenuation features. Therefore the distance range Raman-based systems will be confined to approximately 10 km [12].

Brilloin scattering also happens due to interaction between propagation optical signals and thermally acoustic waves. This interaction leads to rise in frequency shifted components. Consequently, the Brilloin shift carries information of temperature and strain. On the other side, the Raman-based technique changes the intensity of the backscattered light. Brillouin based techniques are more accurate and more stable on the long term, since intensity-based systems suffer from a high sensitivity to drifts.

Figure 2.3 represents the spectrum of the scattered light in optical fibers when a single wavelength λ0 is propagated in the fiber to illustrate the difference between Raman-based techniques and Brillouin based techniques [13].

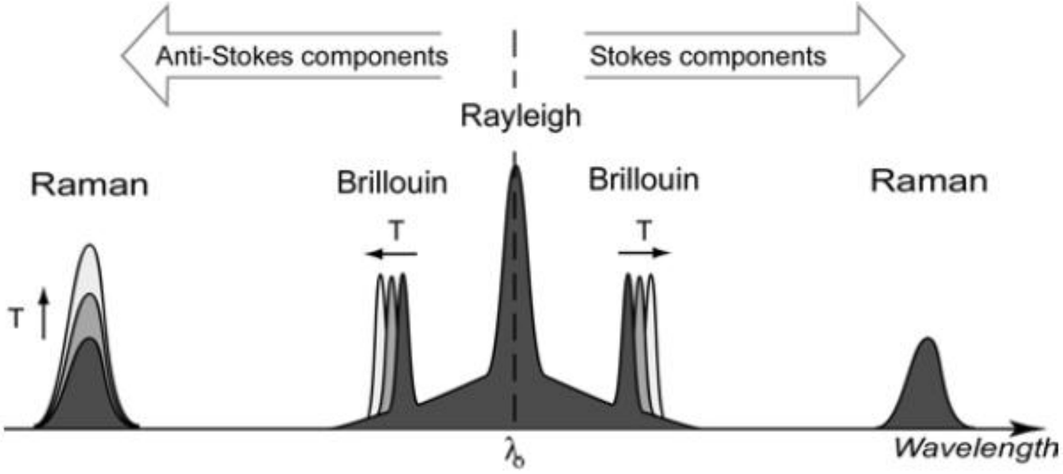


Figure 2.3. Schematic Representation Of The Scattered Light Spectrum From A Single Wavelength Signal Propagating In Optical Fibers [13]

In the north-east of Berlin a 55km pipeline was equipped with a fiber optics leakage detection system during the construction phase of the pipeline in 2002 by the company GESO. The reports till 2004 showed the leakage detection system has been in operation for and one leakage was detected [12].

One main benefit to using fiber optic is its insensitivity to electromagnetic interference. However, some disadvantages such as high costs and the stability over time limited wide range application of this method for pipeline monitoring. Moreover, this method could not be applied for existing buried pipelines. Consequently, it may need some excavation to reach the place where the optical cable should be installed for sensing purposes [2].

2.2.1.3. Vapor or liquid sensing tubes. The vapor or liquid sensing tube based leak detection method involves the installation of a tube along the entire length of the pipeline. If a leak happens, the content of pipe gets in touch of tube. The tube is full of air in atmospheric pressure. Once the leak occurs, the leaking substance penetrates into the tube. First of all, to assess the concentration distribution in the sensor tube, a column of air with constant speed is forced into the tube. There are gas sensors at the end of sensor tube. Every increase in gas concentration leads to a peak in gas concentration which its size is an indication of the size of the leak.

The detected line is equipped with an electrolytic cell. This cell diffuses an exact volume of test gas into the tube constantly. This gas along with air passes through the whole length of the sensor tube. When the test gas travels through the detector unit, it produces an end peak. So, the end peak is a sign of the whole length of the sensor tube. Leak localization is carried on by calculating the ratio of end peak arrival to leak peak arrival [12]. Figure 4.2 indicates this technique.

As shortcoming of this method, it could be mentioned that its speed of leak detection is very low. In addition it’s not very practical for applying in long pipelines as the cost of its equipment is very high. The other drawback of vapor sensing tubes is the difficulty of their application in pipelines above ground or in deep sites.

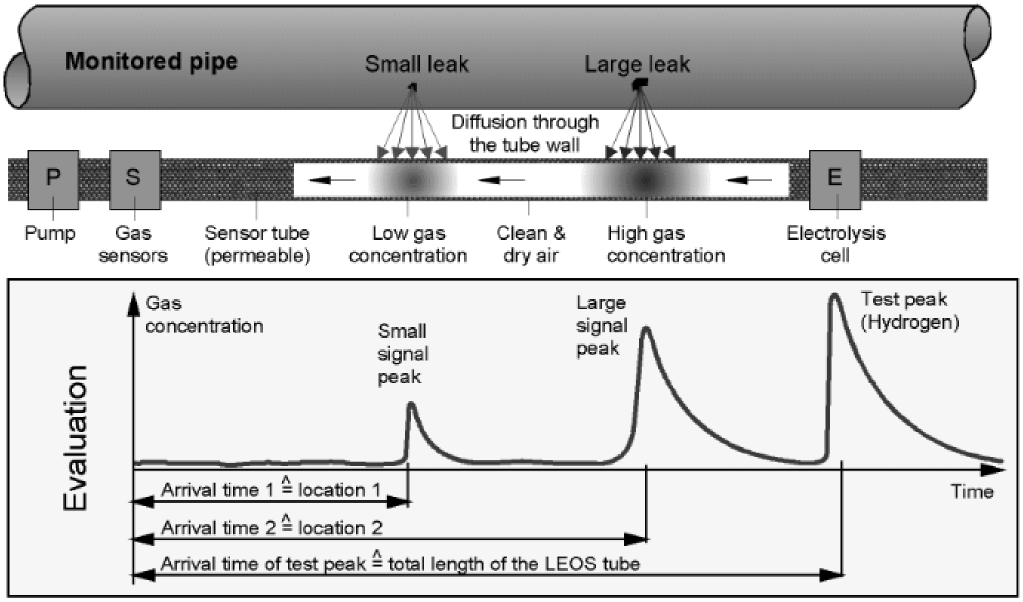


Figure 2.4. Leak Detection And Localization Using Vapor Sensing Tube [12]

2.2.1.4. Liquid sensing cables. Liquid sensing cables are placed near to a pipeline and their main function is representation of changes in transmitted energy pulses that has happened due to impedance differentials. Safe energy pulses are continually sent through the cable. As these energy pulses travel down the cable, reflections are returned to the monitoring unit and a "map" of the reflected energy from the cable is stored in memory. The presence of liquids on the sensor cable, in sufficient quantities to "wet" the cable, will alter its electrical properties. This alteration will cause a change of the reflection at that location. The alteration is then used to determine the location of a potential leak. For localization time delay between input pulse and reflected pulse are used [12]. This method works well for multiple leak detection and localization for short pipelines.

2.2.1.5. Soil monitoring. Soil monitoring technique exploits an inexpensive and non-hazardous gaseous tracer to be guided into pipeline. This tracer is featured as a very volatile gas which escapes from the pipeline at the exact location of leak. By analyzing the soil above the pipeline the presence of leakage and its location could be estimated [14]. Producing low false alarms along with detectability of very small leaks could be mentioned as advantages of this method. But on the other side the method is very expensive because the tracer should be injected into the pipe unceasingly in detection process. It also is not feasible in cases with uncovered pipelines.

2.2.2. Software Based Systems. The internal method is based on the monitoring of internal pipeline parameters (pressure, flow and temperature).

Generally, the effectiveness of the internal based methods depends on the uncertainties associated with the system's characteristics, operating conditions and collected data.

2.2.2.1. Mass-Volume balance. Mass balance (and volume balance) are, in effect the same method based on the principle of conservation of mass .The principle states that a fluid enters the pipe section either remains in the pipe section or leaves the pipe section. In standard pipeline networks the flow entering and leaving the pipes can be metered. A leak can be identified if the difference between upstream and downstream flow measurement changes by more than established threshold value [2].

This approach is already commercialized and has been used in the oil pipeline industry. This method is very sensitive to pipeline instrumentation accuracy. The main weakness of the mass balance method is the assumption of steady state. As a result of this assumption, the detection period has to be increased in order to prevent false alarms. Therefore, the response time to the leak will be delayed, which is undesirable. For instance, a 1% leak needs about 60 minutes to be detected [2]. Another significant disadvantage of mass balance method is location of the leak is unknown. Consequently, in real application other methods are required in conjunction with mass balance method after the leak has been detected to identify the location of the leak [5].

2.2.2.2. Real time transient modeling. This leak detection technique is based on pipe flow models which are constructed using equations of conservation of mass, conservation of momentum and conservation of energy. The difference between the measured value and the estimated value of the flow is used to determine the presence of leaks. For building this model flow, pressure and temperature measurements at both ends of the pipeline are necessary. Furthermore, to design a reliable system with minimum false alarm the noise level should be continuously inspected to modify the model [2].

Billman and Isermann [15] used this approach for leak detection and localization. Their leak detection method is based on mathematical dynamic models, nonlinear adaptive state observers and a correlation detection technique. The method was tested by Siebert [16] at a 68 km gasoline pipeline. The results revealed that detection of leakage with size of 0.2% of inlet flow was feasible in 90 second. And also leak location could be estimated with accuracy of 0.9%. Verde used a linearized pipe flow model on an N-node model for leak detection [17]. The only measurements were pressure and flow rate at both ends of the pipe. Since the fluid model in the pipe is given by a set of partial differential equations, a finite dimension nonlinear model was acquired by having pressure measurements as input. The output of the model is the estimated flow rate at extremes. Verde in another paper [18] extended his method for finding two simultaneous leakages in pipeline. Continuing to work on model-based leak detection and estimation, Verde designed a framework for leak reconstruction in pipelines using second-order sliding mode [19]. Single leak and multiple leaks are both studied in this paper. In the case of a single leak, the necessary and sufficient condition that allows estimating the position of the leak is determined and discussed. Under such a condition, an algorithm that determines the position and flow of the leak in finite-time is introduced. In the case of two leaks with known positions, a finite-time estimation of the leaks flow is obtained. Aamo designed [20] and later revised [21] a detection system that uses an adaptive Luenberger-type observer based system on two coupled partial differential equations of the fluid flow.

The main advantage of this method is that it has the ability to detect very small leaks (less than 1 percent of flow) and it could estimate the leak size accurately. In addition the delay of leak detection is negligible. However on the other hand, this method is very expensive as it should deal with processing of huge data sets in real [2].

2.2.2.3. Negative pressure wave. When the pipeline leak occurs, the fluid pressure drops suddenly at the position of the leak and generates negative pressure wave, which propagates with a certain speed towards both upstream and downstream of the pipeline. Two pressure sensors are installed at the beginning station and the end station of the pipeline respectively. The negative pressure wave received by the two sensors can identify pipeline leak and furthermore locate the leak by calculating the time difference between the arrival times of the negative wave at each end [22].

Literature [23] in 2002 introduced using negative pressure wave method and wavelet algorithm to detect and locate leaks. Since April 2001 till now, this method has been used in "island-Yongan" and "island-Jixian" line of victory oil field.

Support vector machine learning [24] was used to analyze the readings from pressure sensors and to make decision on the presence of leak in the pipe. In this work NPW detection was considered as a two-class pattern classification task. The two classes are "NPW present" and "NPW absent". With an SVM formulation, a nonlinear classifier is trained using supervised learning to automatically detect the presence of NPW in pressure curve. By this method, small or slow leak can be easily recognized out of noise.

A signal processing method that has been widely used along with negative pressure wave is wavelet transform. Li Yo bi [25] used the wavelet transform for leak detection. The monitoring system acquired internal parameters of the pipeline from the existing SCADA system. The reported time delay for leak detection by this method is 2 minutes and estimation error for leak localization is stated 2%.

Marco Ferrante [26] developed a transient based leak detection procedure based on extracted pressure signals which are prone to abnormality due to any fault in pipe. By processing these pressure signals using wavelet transform their sensitive feature are extracted. The rapid variation in signals leads to rise of local maxima in wavelet transform modulus. The sequence of modulus local maxima was constructed. Based on the properties of the random noise level, chains connected to false alarm were filtered. The amplitude of pressure signals is related to leak magnitude, while the arrival time of reflected signal is related to leak location.

Henrique V. da Silva [27] proposed a leak detection methodology based on clustering and classification. They used a fuzzy system for classifying the running mode. Four pressure transducers were connected to a computer and leak simulated at different locations along the pipeline. The position was calculated by estimating the arrival time of the negative wave at the transducers and the knowledge of the wave speed. The drawback of the method was its incapability of finding leak location. But, this method still has not exploited in long pipeline [2].

2.2.2.4. Pressure point analysis pressure. This method detects the occurrence of leaks by comparing the current pressure signal with a running statistical trend taken over a period of time along the pipeline by pressure monitoring and flow monitoring devices [5]. The principle of this method is based on the fact of pressure drop as a result of leak occurrence. Using an appropriate statistical analysis of most recent pressure measurements, a sudden change in statistic properties of pressure measurement such as their mean value is detected. If the mean of newer data is considerably smaller than the mean of older data, then a leak alarm is generated. This method may require sensitive high resolution but not necessarily very precise instrumentation. So, the lower overall installation costs are not very high. Furthermore, this method is able to identify the occurrence of leaks, but not necessarily the presence of them. Since this method use of pressure drop as a leak signature, it can yield false alarms as the pressure drop is not unique to the leak event.

2.2.2.5. Statistical. A statistical leak detection system uses advance statistical technique to analyze the flow rate, pressure and temperature measurements of a pipeline. This method is appropriate for complex pipe system as it can be monitored continuously for continual changes in the line and flow/pressure instruments. In addition, this technique could be used for leak localization. Using statistical analysis is also very easy and applicable into different pipeline systems [2]. The main objective of this system is to minimize the rate of false alarm. It is also suitable for real time application and has been successfully tested in oil pipeline systems [5]. The main disadvantage of statistical leak detection is that noise interferes in the statistical analyses, and some leaks were hidden in the noise which prevented them from being detected.

2.2.2.6. Digital signal processing. Another method for leak detection is using digital signal processing techniques. The procedure of this method is that the response of the pipeline to a known input is measured over a period of time. Afterwards, this response is compared with the later measurements. Based on comparison of their signal’s features like frequency response or wavelet transform coefficients a leak alarm could be generated. Similar to statistical methods this technique does not need a pipeline model. The problem associated with using this method for leak detection is only leak occurrence could be detected not leak presence unless the size of present leak increases considerably [2].

2.3. SUMMARY

In this chapter, many different methods for leak detection and location in pipelines networks have been described. These methods are divided into two main categories: hardware based methods and software based methods. The hardware based techniques detects the leaks from outside of the pipe using specific devices, in which some cases the cost is very high. On the other hand, there is the software based techniques, which deals with Software programs at their core implements algorithms continuously to monitor the state of pressure, temperature, flow rate or other pipeline parameters and can infer, based on the evolution of these quantities, if a leak has occurred [2]. This methodology is most popular among the researchers due to the cost effective. Hardware based leak detection systems are expensive. To install this kind of hardware along pipelines that expand over hundreds of miles is expensive regardless of where the pipe is situated or what elements it runs through. It also adds more equipment that needs service and repairs. The software based systems usually only need flow, pressure and maybe temperature measurements at the inlet and outlet. The proposed model-based approach does not have the complexities of most methods in this area and its accuracy in leak localization is very good.

3. GUIDED-WAVE BASED PIPELINE LEAK DETECTION

3.1. INTRODUCTION

Main challenges in pipeline leak detection are their long length and also lack of easy access in areas where the pipe passes from severe environmental conditions. One of the practical solution for these problems is using lamb waves which has been widely applied in pipeline monitoring [28,29,30]. Metal pipes can act as a waveguide and propagate wave into itself. Advantage of using guided waves over other methods like, acoustic waves or vibration analysis is their capability to transfer over long distances. By evaluating changes in propagated wave, the leakage could be detected.

Guided wave propagation in pipes is composed of three basic modes: longitudinal waves, torsional waves and flexural waves. Each of them has the ability of transfer specific amount of energy. In contrast of flexural waves Longitudinal and torsional wave are symmetrical to axis of pipe. Various systems and sensors have been proposed for propagation of ultrasonic waves.

To study the propagation of ultrasonic waves in pipes and evaluate the behavior of waves in dealing with the leakage, finite element analysis (FEM) is used. To model the propagation of waves along a pipeline, software ANSYS 11 is used .After analysis of transient behavior of pipeline, the extracted data from ANSYS is fed to MATLAB for analysis and applying damage detection algorithms.

The overall idea of lamb-wave based leak detection is as follows:

1. The pipe is modeled in ANSYS
2. Lamb waves were propagated through pipes
3. Signals are extracted from both “healthy” and “damaged” state
4. Detection algorithm for Lamb wave methods is based upon the Wavelet transform.
5. Leak detection index is extracted based on the difference between wavelet coefficients energies of “healthy” state and wavelet coefficients energies of “damaged” state

A diagram for the leak detection based on lamb-waves is given in Figure 3.1.

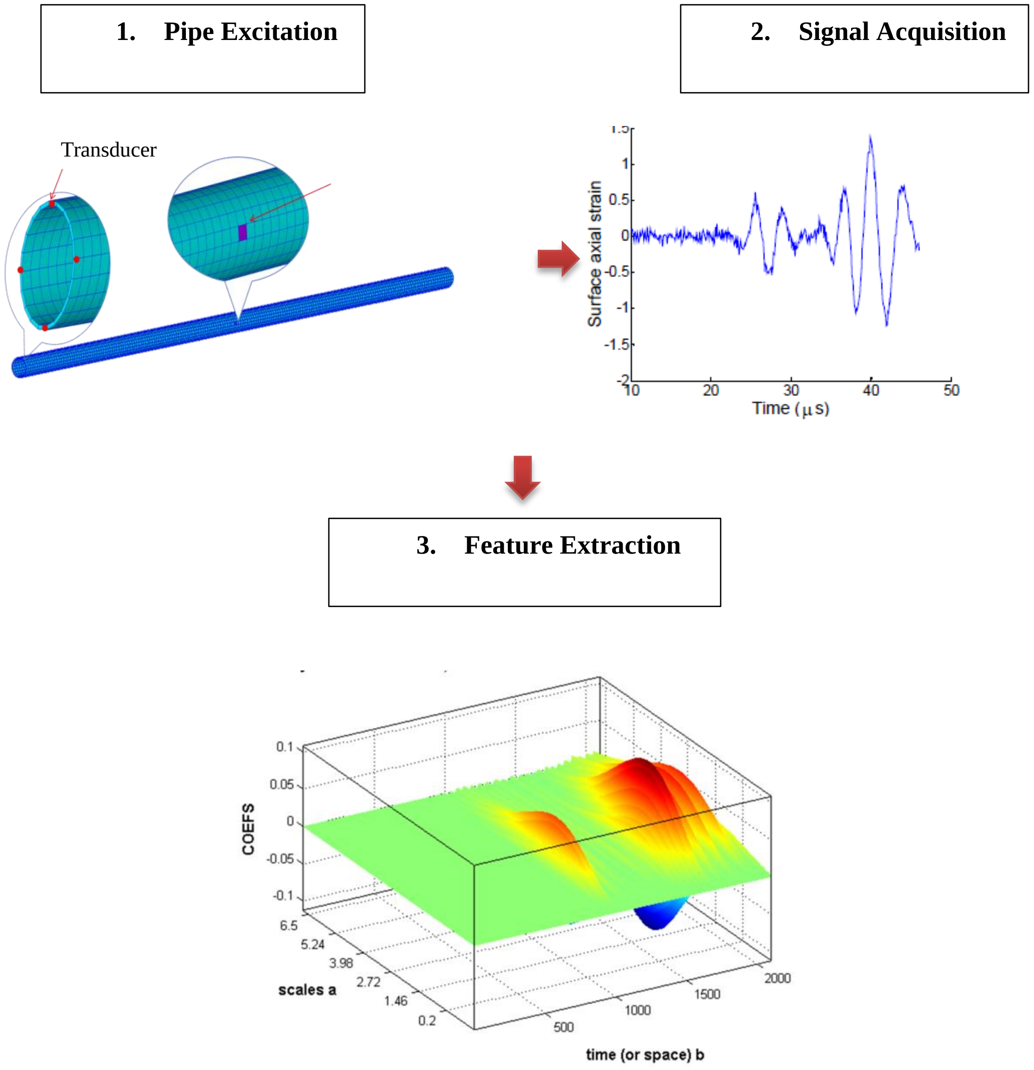


Figure 3.1. Overview Of The Lamb-Wave Leak Detection

Hypothesis for this work are as follows:

1. In this study, only the pipeline with free boundary conditions will be discussed.
2. It is assumed that piping network layout is available
3. There is no fluid inside the pipeline.

3.2. THREE-DIMENSIONAL MODEL OF THE LAMB WAVE PROPAGATION ALONG THE STRAIGHT PIPE

Structural elements of degree 2 are used for pipeline modeling to achieve maximum efficiency. The outer radius of the pipe is 6.03cm and its inner radius is 5.61 cm. Length of the pipe is 500cm and leakage is located at distance of 243.52 cm from the end point of the pipe. Leakage is assumed to affect the stiffness properties. In order to model the leakage in the pipe, the stiffness of elements at leak location is reduced by decreasing Young's modulus by 40 percent. Parameters for the pipeline are shown in the Table 3.1.

Table 3.1. Parameters For The Straight Pipeline

Symbol	Parameter	Value
E	Young's Modulus	200 GPa
υ	Poisson's ratio	0.3
ρ	Density	7860 kg/m^3
R_{out}	Outside diameter	6.03[cm]
R_{in}	Inner diameter	5.61[cm]
L	Length	500[cm]

3.2.1. Appropriate Mode Selection. The challenging part of using guided waves for pipe monitoring is selection an appropriate mode for wave propagation. Typically, an excitation source can provoke and propagate all existing modes in its bandwidth; as a consequence, it leads to producing a very complicated signal which is very difficult to interpret. Even with the release of a single mode of wave, it still remains hard to differentiate between changes due to echo of the inherent characteristics of the pipe, such as the welding points and those changes caused by leak in pipe wall. Since in addition to leakage, geometrical characteristics of the pipe change the propagated wave, we should have the power to control the received signal. The first step in having such control is to pick a narrow-band propagation signal. For getting minimum distortion the dispersion curves are used. To obtain dispersion curves for steel pipeline PCDISP Toolbox of

MATLAB program for solving the equations of motion is used [31]. Dispersion curves of phase group and velocity group for pipe with defined characteristics in Table 3.1 is shown in Figure 3.2 and Figure 3.3. The selected mode is indicated in bold lines

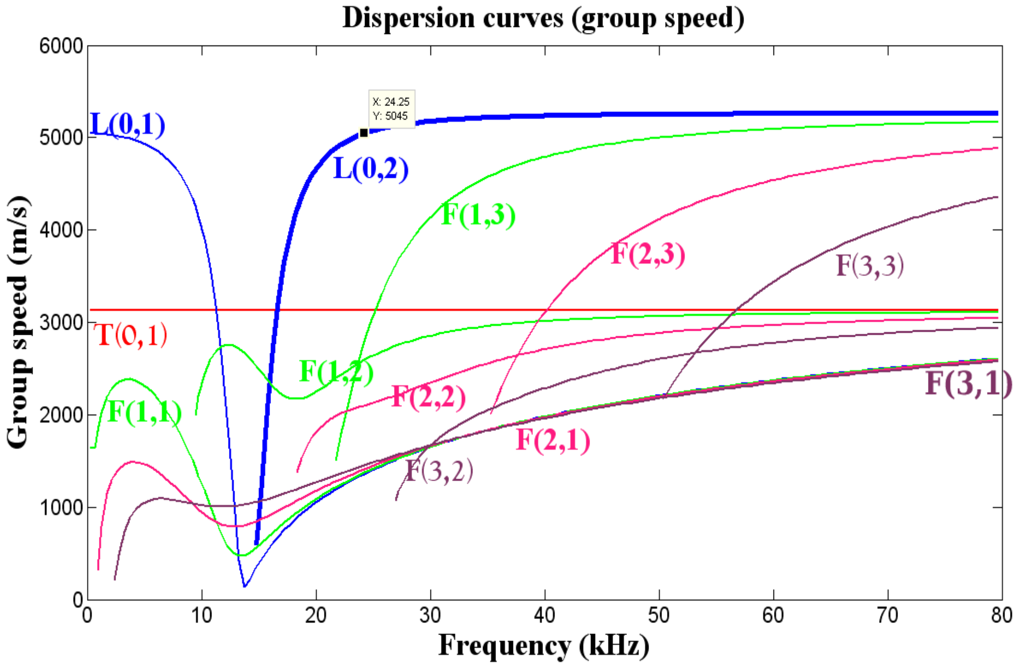


Figure 3.2. Dispersion Curves Of The Pipe: Velocity Group Versus Frequency [31]

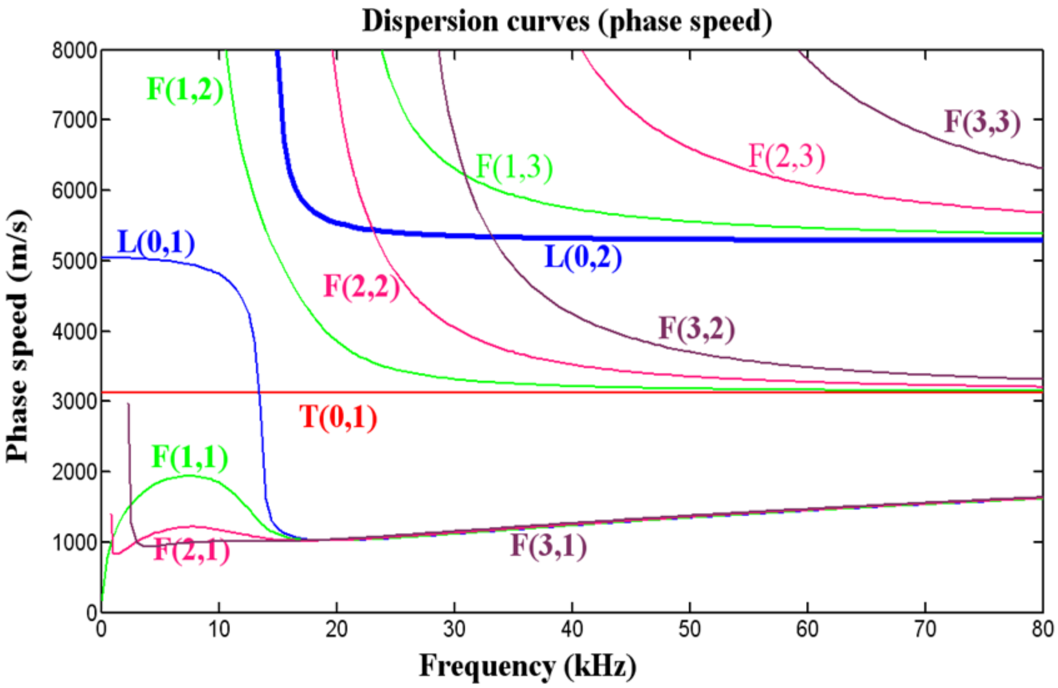


Figure 3.3. Dispersion Curves Of The Pipe: Phase Group Versus Frequency [31]

From the dispersion curves it is evident that the slope of curves for longitudinal mode is almost constant for frequency ranges more than 20 kHz, which means that speed of wave propagation is constant for frequencies more than 25 kHz. For this reason, the excitation frequency of 25.24 kHz is chosen for propagation along pipe wall. Longitudinal mode has some advantages over flexural and torsional waves, namely, higher speed and less deviation around selected frequency. In this work, the guided wave is a sinusoidal signal which has a central frequency of 25.4 KHz and 3 cycles of the guided wave are modulated by Hanning window. Since the longitudinal wave speed in this frequency is 5045 m/s, wavelength of transmitted signal is:

$$\lambda = \frac{c}{f} = \frac{5045\ (m/s)}{24.25\ (KHz)} = 0.208m \tag{1}$$

Considering the calculated value of wavelength, the meshing length is chosen as one-eighth of a wavelength which is 2.6 cm. Pipe cross section is composed of 20 elements. One end of the pipe is confined in three dimensions. At the other end a trigger function of f(t) is applied along z-axis while the other dimensions are remained motionless. The excitation signal of single-node is shown in Figure 3.4.

$$f\left(t\right)=0.26(1-\cos(2\pi \mathrm{f}\,\frac{\mathrm{t}}{3}))\sin(2\pi \mathrm{ft}) \qquad (2)$$

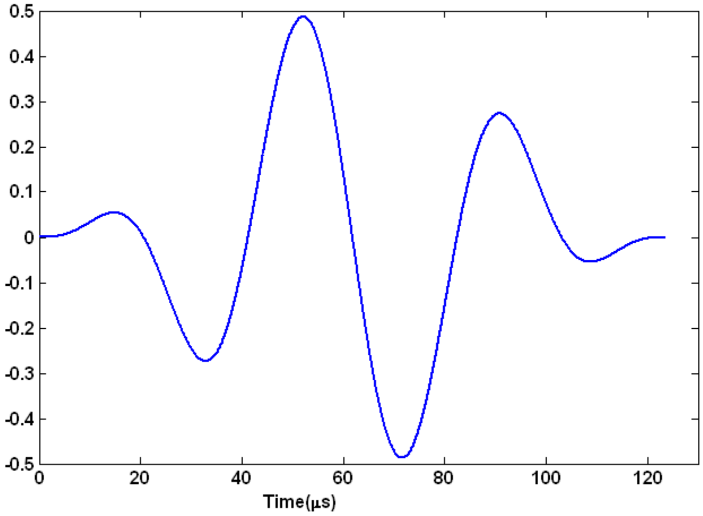


Figure 3.4. The Time Domain Excitation Signal With Center Frequency 25.4 kHz

The operating frequency in above equation is 25.24 kHz. The distribution of the energy density for this frequency is shown in figure 3.5.

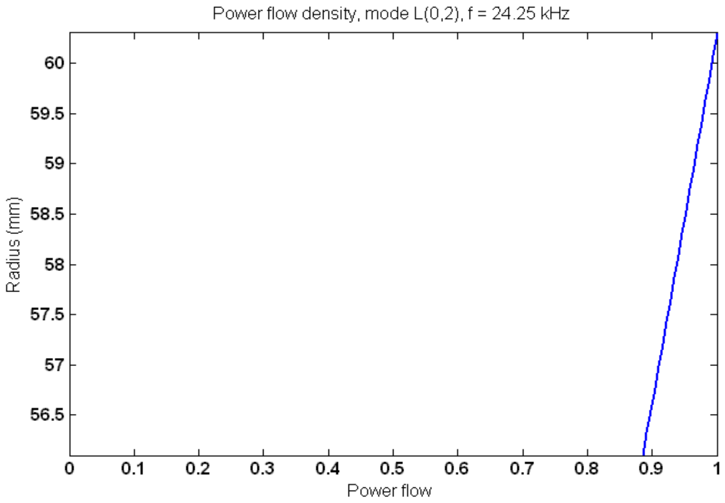


Figure 3.5. Energy Distribution in Frequency of 25.24 kHz Across the Thickness of the L(0,2) modes

Figure 3.6 shows the displacement and stress distribution of longitudinal mode along pipe thickness with outer radius of 6.03 cm and inner radius of 5.61 cm.

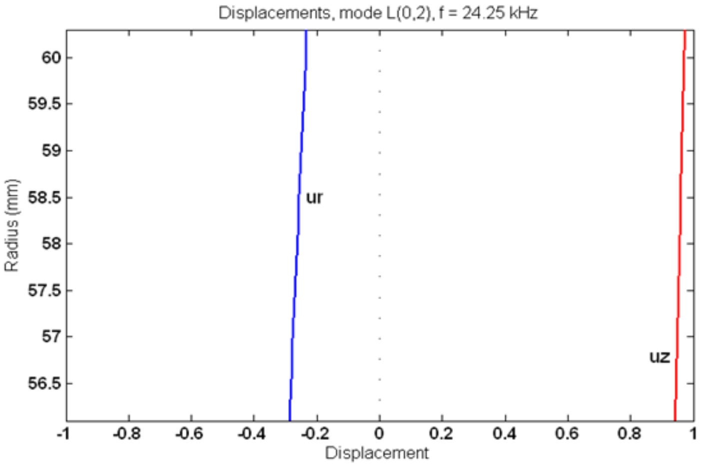


Figure 3.6. Displacement Across the Thickness of the L(0,2) modes

Figure 3.7 presents stress distribution along the thickness of pipe is shown.

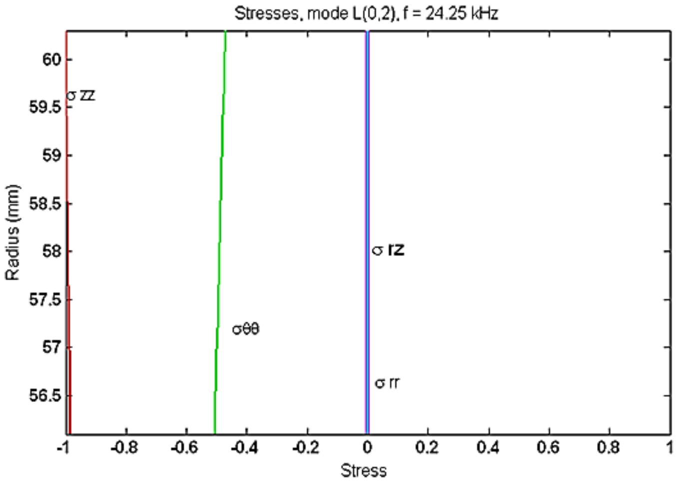


Figure 3.7. Stress Across the Thickness of the L(0,2) Modes

Then, transient analysis is conducted on the pipeline. Four sensors at the edge of the pipe are acted as sensing points. The signals were acquired using the pulse–echo setting as shown in Figure 3.8. Afterwards, the signal processing algorithms were designed in the Matlab programming environment to analyze the behavior of pipe.

Figure 3.8. Leak Location And Sensors Configuration At The End Of Pipeline

The finite element model of the straight pipe which is established in Ansys software is shown in Figure 3.9.

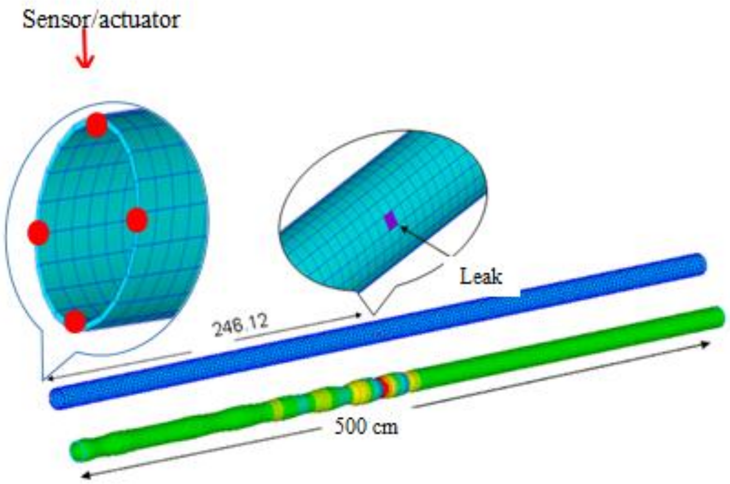


Figure 3.9. Finite Element Model Of Straight Pipe

Figure 3.10 shows the acquired signals in both states; with and without leak.

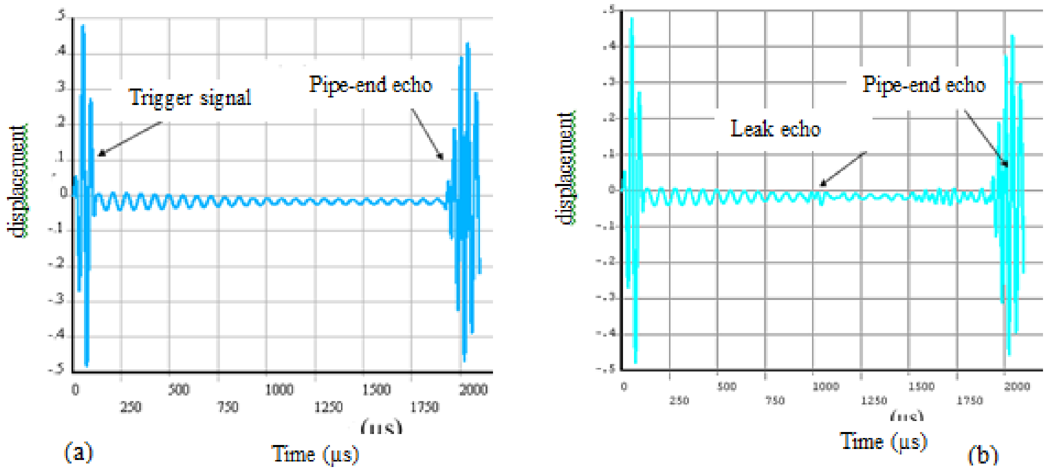


Figure 3.10. Received signal: (a) No leak, (b) With leak

The results show that the guided waves are an appropriate method for leak detection in straight pipelines. However, the behavior of the pipe at the knee bend pipes is slightly different. The propagated signal from the knee bend could cause misinterpretation of the signal. This problem is addressed in [32] by coating pipe with a soft cover which compensate the bad effect of distortion caused by the bend shape in pipe. The characteristics of pipe and its cover are presented in Table 3.2.

Table 3.2. Parameters for the Knee-Bend Pipeline

	Young's Modulus	Poisson's Ratio	Density
Metal Pipe	200 GPa	0.3	7860 kg/m^3
Shield	0.05 GPa	0.3	7860 kg/m^3

The finite element model of knee-bend pipe is presented in Figure 3.11.

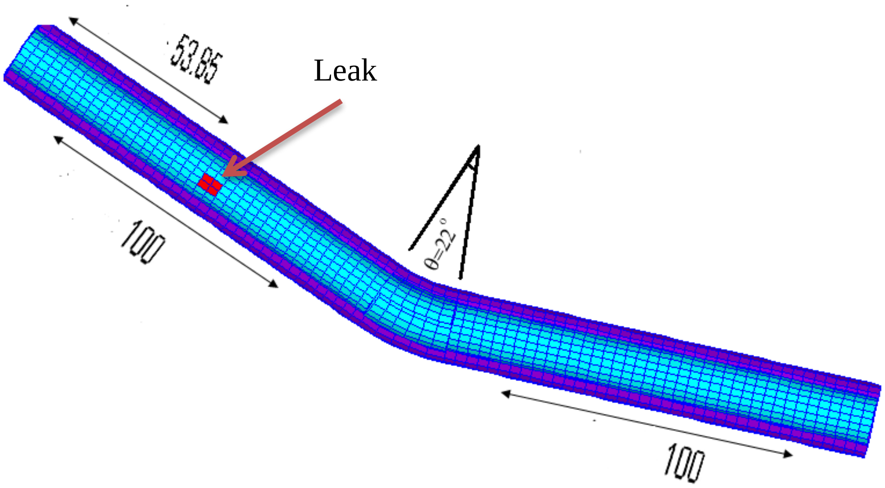


Figure 3.11. Finite Element Model of Knee-Bend Pipe

3.2.2. Wavelet Transform. Signal processing could be done by different tools. The Fourier transform is probably the most widely accepted signal processing tool in science and engineering which converts each signal to a series of sinusoidal signals with different frequencies. Indeed Fourier transform maps signal from the time domain to the frequency domain. But, if we take the Fourier transform over the whole time axis, it cannot been stated that at what time a specific frequency is risen. For overcoming this problem, Short-time Fourier transform (STFT) have been proposed. STFT uses a sliding window to find spectrogram, which gives the information of both time and frequency. But its problem is that the length of window which limits the resolution in frequency. So the Wavelet transform was suggested to overcome this problem. Wavelet transforms are based on small wavelets with limited duration. The translated-version wavelets locate where we concern. As a matter of fact, the wavelet transform is like the windowed Fourier transform with a completely different merit function. The main difference is this: Fourier transform decomposes the signal into sins and cosines, i.e. the functions localized in Fourier space; but the wavelet transforms uses functions that are localized in both the real and Fourier space. Generally, the wavelet transform can be expressed by the following equation [33]:

$$F(a,b) = \int_{-\infty}^{+\infty} f(x)\psi^{*}(\mathrm{a},\mathrm{b})dx \tag{3}$$

Where the * is the complex conjugate symbol and function ψ is some function. This function should have two important characteristics of oscillation and short duration. Therefore, $\psi(x)$ is the wavelet function, if the following condition are met by Its Fourier transform $\Psi(\omega)$:

$$\int_{-\infty}^{\infty} \frac{|\psi(\omega)|^{2}}{|\omega|^{2}} d\omega < \infty \tag{4}$$

This condition indicates that

$$\int_{-\infty}^{\infty} \psi(x)dx = 0 \tag{5}$$

This means that each wavelet function is an oscillatory function that its average value is zero. Wavelet function could be continuous or discrete. These two transforms have the following properties:

In following, the continuous wavelet transform which has been used in this work will be explained in more detail.

3.2.2.1. Continuous wavelet transforms. The continuous wavelet transform of a signal (CWT) is defined as the sum over all time of the signal multiplied by a scaled, shifted version of the wavelets function where both the time and frequency windows can be changed. The CWT is given

$$Q(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} y(t)\psi^{*}\left(\frac{t-b}{a}\right) dt \tag{6}$$

Where the index $Q(a,b)$ comprises the wavelet coefficients; a and b are the scale (dilation) and translation (position) parameters, respectively. “y(t)” is the vibration response signal. ψ^{*} is the complex conjugate of the basis function ψ (or mother wavelets function) [33].

In this study, Mexican Hat wavelet was used. This function is proportional to the second derivative of the Gaussian density function and is defined as following:

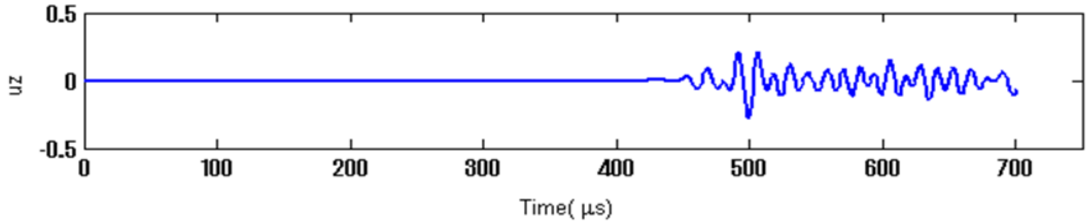
$$\psi(x) = \left(\frac{2}{\sqrt{3}}\pi^{-1/4}\right)\left(1 - x^{2}\right)e^{-x^{2}/2} \tag{7}$$

3.3. PIPE LEAK DETECTION

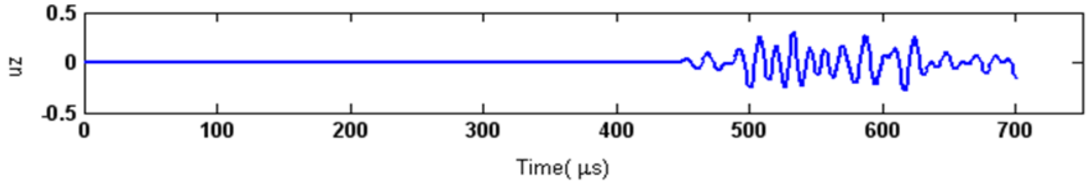
The first idea that comes to mind is to define leak index which is sensitive to leak occurrence. This index could be in various forms:

a) Calculating difference between signals measured from the normal pipe $z_u(t)$ and signals measured from the damaged pipe $z_d(t)$ seems to be the simplest solution: $DI = z_u(t) - z_d(t)$. The calculated leak index is shown in Figure 3.12.

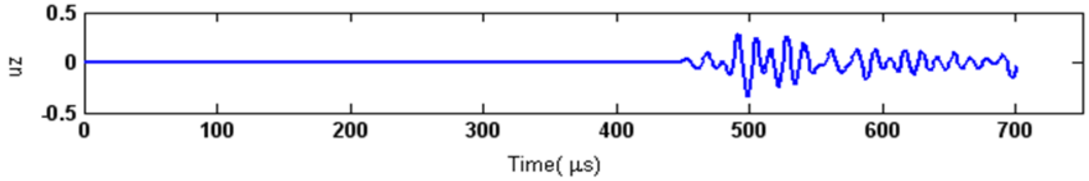
DI for sensor 1



DI for sensor 2



DI for sensor 3



DI for sensor 4

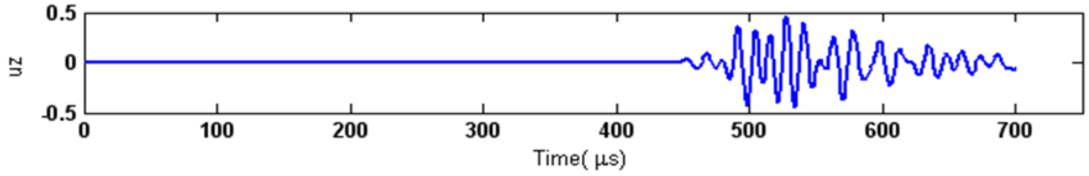
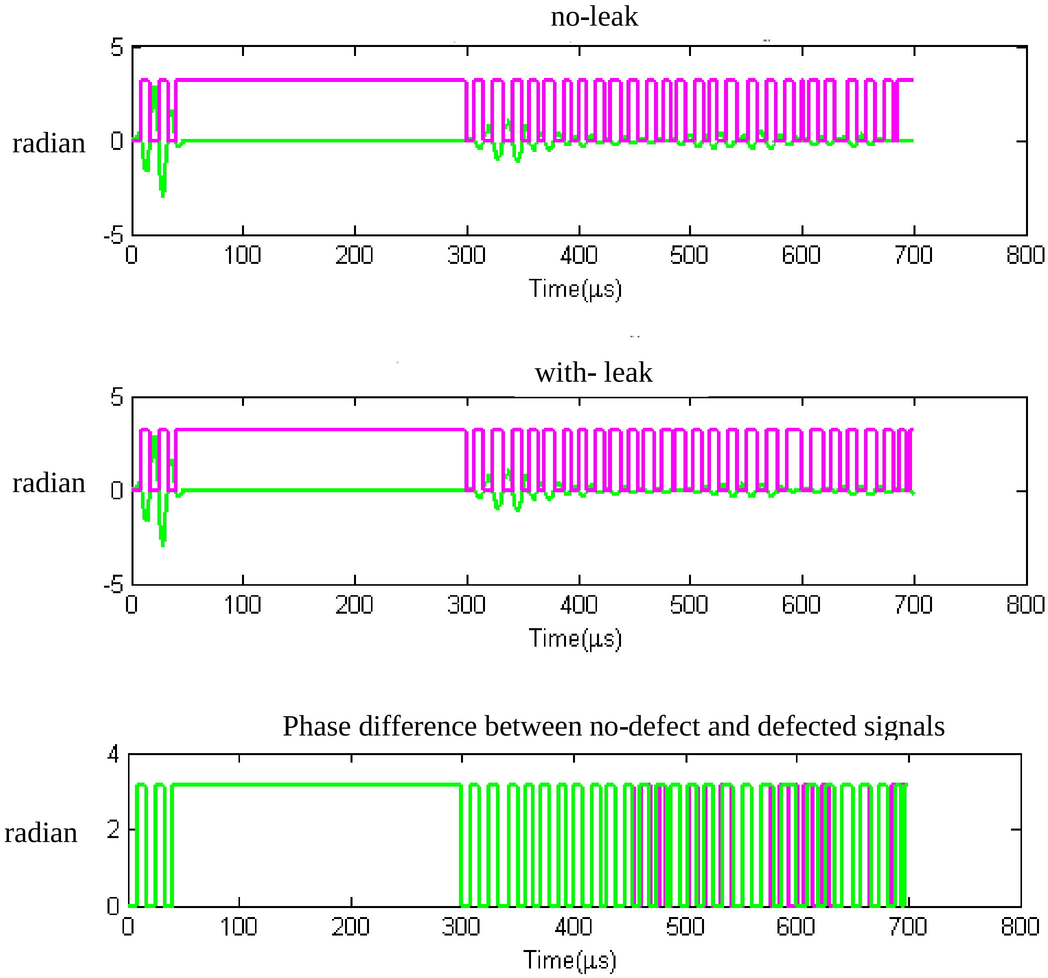


Figure 3.12. Calculated Damage Index DI For 4 Sensing Points

b) The second approach is to derive phase difference between healthy signals and defected signals. This methodology is more useful than first approach because this index could give some information regarding the position of leak. Figure 3.13 shows the phase difference of received signals at location of sensor 1.


no-leak

with- leak

Phase difference between no-defect and defected signals

Figure 3.13. Phase Difference Of Healthy And Defected Signals At Sensing Point 1

3.3.1. Fault Detection Using Wavelet Transform. The wavelet coefficients of the received signals at four sensing point in both healthy and damaged states is estimated. Afterwards, the percentage of energy of each coefficient is calculated using below equation.

$$S = |Coefs|^2 \tag{8}$$

$$Sc = 100 \times \frac{S}{\sum S_i} \tag{9}$$

“Coefs” is the matrix of continuous wavelet coefficients. Then difference between energy percentage of wavelet coefficients in healthy and defected states is defined as damage index.

Wavelet coefficients and scale parameters used in this work shown in Table 3.3.

Table 3.3. Wavelet Types And Ranges For Leak Detection

Pipe	Wavelet type	Scale range:
Straight	Mexican hat	2: 0.02:25
Knee-bend	Mexican hat	2: 0.02:30

Figure 3.14 presents the wavelet coefficients of defected signals. As it is clear from the figure the reflected wave from defect has high amplitude. In Figure 3.15 and Figure 3.16 the derived damage index at position of sensor 1 is shown for straight pipeline and knee-bend pip respectively.

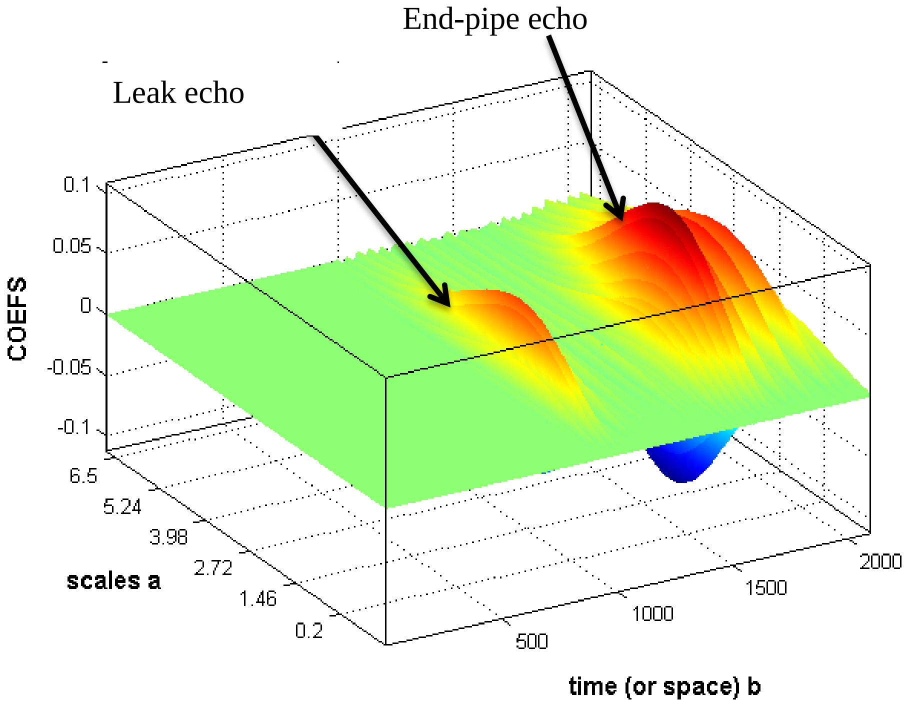


Figure 3.14. Wavelet Coefficients Of Signals Extracted From Defected Straight Pipe

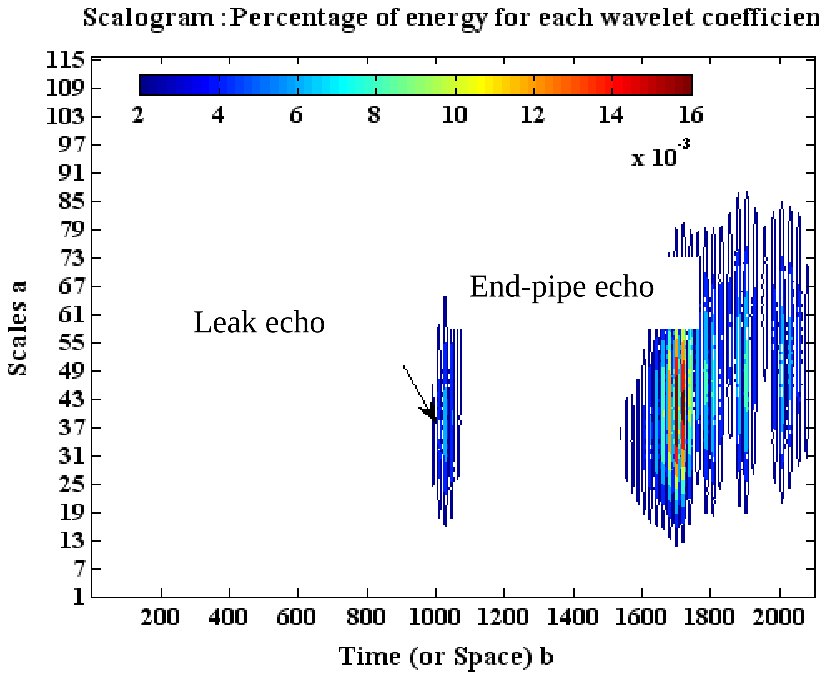


Figure 3.15. Damage Index For Straight Pipe

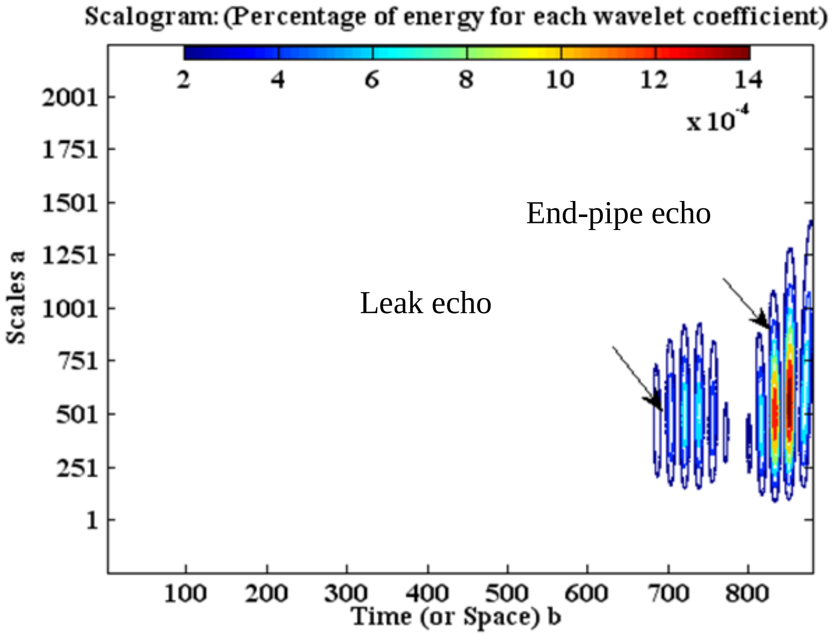


Figure 3.16. Damage Index For Knee Bend Pipe

3.3.1.1. Leak localization. According to Figure 3.15 and Figure 3.16 and by measuring the time of flight of the returned signal from the leakage point, the leak location could be estimated. Longitudinal wave propagation velocity for pipe with specifications listed in Table 3.1 can be obtained by following equation.

$$V_l = \sqrt{\frac{\mathrm{E}}{\rho}} = \sqrt{\frac{200Gpa}{7860kg/m^3}} = 0.5044\,{}^{cm}\!/_{\mu s} \tag{10}$$

$$d_l = 0.5044\,{}^{cm}\!/_{\mu s} \times 1050/2 = 264.81cm \tag{11}$$

Table 3.4. Leak Localization Results

	Exact leak location	Estimated leak location	Estimation error
Straight pipe	246.12 cm	264.81 cm	7.5 %
Knee-bend pipe	168.1	171.53	2%

4. MODEL BASED LEAK DETECTION

4.1. INTRODUCTION

This thesis aims to apply the observer design technique to leak detection for pipeline systems. The nonlinear model of a pipeline is first built up. This model is fed with pressure measurements at both ends of the pipeline. Then the flow rate at the outlet is compared between a real pipeline and simulated one. If the difference goes beyond a defined value, it is said that a leak is detected.

For leak localization a scheme based on the fact that pressure drop is linear along the pipeline, is used. Both extremes of the pipe are equipped with two pressure sensors. From their measurements slope at both ends could be calculated. Then the leak location will be estimated based on the intersection of lines with these two different slopes. The overview of the proposed method is shown in Figure 4.1.

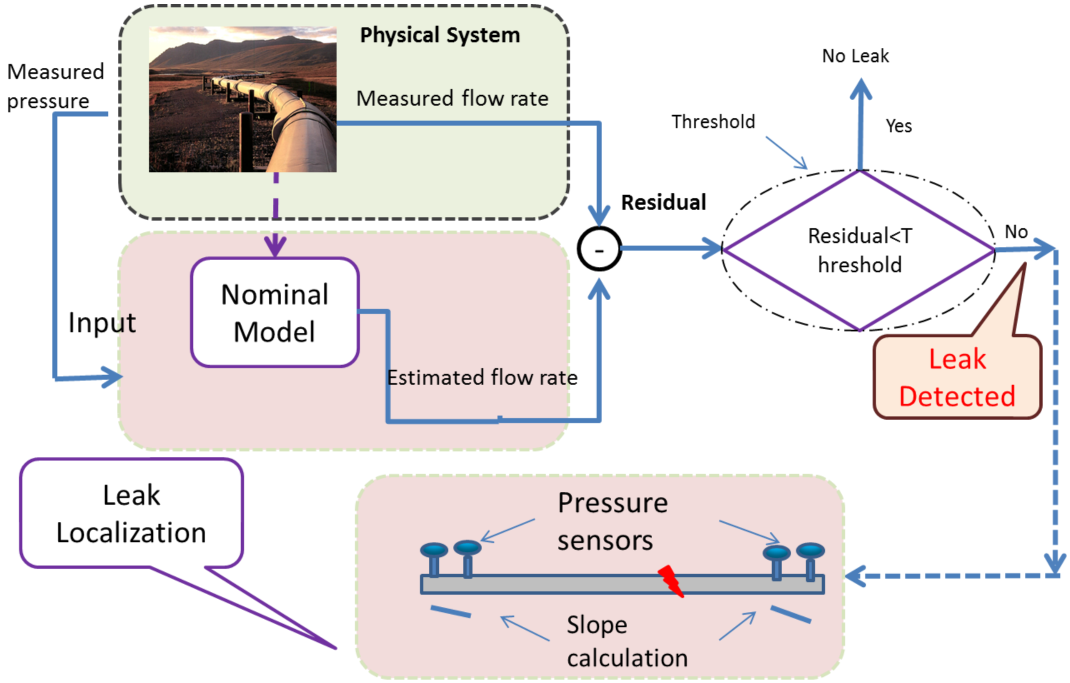


Figure 4.1. Overview Of The Proposed Scheme

4.2. MATHEMATICAL MODELS OF FLOW OF FLUID IN A PIPE

The intermediate-stage flow when the flow conditions change from one steady state to another is termed transient-state flow. In other words, the transient conditions are initiated whenever the steady state conditions are disturbed. Such a disturbance may be caused by planned or accidental changes in the settings of the control equipment of a man-made system or by changes in the inflow or outflow of a natural system.

Common causes of transients in engineering systems are:

- Opening, closing, or “chattering” of valves in a pipeline;
- Starting or stopping the pumps in a pumping system;
- Starting-up a hydraulic turbine, accepting or rejecting load;

Mathematically speaking, the transients in a distributed system are represented by partial differential equations, whereas the transients in a lumped system are described by ordinary differential equations. The system may be analyzed as a lumped system if $\omega L/a$ is significantly less than 1; otherwise, the system should be analyzed as a distributed system. In the preceding expression, ω = frequency of the flow oscillations, L = length of the pipeline, and a = wave velocity.

The model consists of two equations, the conservation of mass equation (continuity equation) and the momentum equation. These equations are a set of partial differential equations since the flow velocity and pressure in transient flow are functions of time as well as distance. The goal is to determine the dependent variables (pressure and flow) as a function of time and space.

Assuming the fluid to be slightly compressible and the duct walls slightly deformable; the convective changes in velocity to be negligible; the cross section area of the pipe and the fluid density to be constant, then the dynamics of the pipeline fluid can be described by [33]

Momentum Equation

$$\frac{\partial Q(z,t)}{\partial t} + gA\frac{\partial H(z,t)}{\partial t} + \mu Q(z,t)|Q(z,t)| = 0 \qquad (1)$$

Continuity Equation

$$c^2 \frac{\partial Q(z,t)}{\partial z} + gA \frac{\partial H(z,t)}{\partial t} = 0 \tag{2}$$

With $H(z,t)$ the pressure head (m), $Q(z,t)$ the flow rate (m^3/s), z the length coordinate (m), t the time coordinate (s), g the gravity $(m/s2)$, A the section cross-area (m^2), D the pipeline diameter (m), c the pressure wave speed (m/s) and $\mu = \frac{f}{2DA}$ where f is the Darcy-Weisbach friction coefficient.

Once the equations are derived a numerical methods are introduced for solving these equations. The methods currently in use in commercial software packages include:

- Finite difference
- Finite element
- Method of characteristics
- Frequency response/spatial discretization.

In this work finite difference method is applied for solving fluid flow partial differential equations.

4.3. DISCRETIZED MODEL

In order to simulate the leak detection system, a discretization of the pipeline and a numerical solver is needed. The pipeline is divided into by N-1 sections and N nodes where each section has a uniform lengthΔx. This is illustrated in Figure 4.2. Due to the separate direction of the flow of information, a finite difference method can be used to calculate values for the spatial derivatives. In the explicit finite-difference method, the partial derivatives are replaced by the finite-difference approximations such that the unknown conditions at a grid point at the end of time step are expressed in terms of the known conditions at the beginning of the time step.

Assume a pipeline of length L where

- the pipeline’s length is divided into n identical cells of size $\Delta = \frac{L}{n}$
- leak severity parameter is λ_i

- based on the definition of finite difference method for solving partial differential equations the fluid flow equations (1) and (2) are estimated by[17]:

$$\frac{\partial H(z,t)}{\partial z} \cong \frac{H_{i+1}(t)-H_i(t)}{\Delta} \qquad \forall\, i = 1, \dots, n-1 \qquad (3)$$

$$\frac{\partial Q(z,t)}{\partial z} \cong \frac{Q_i(t)-Q_{i-1}(t)}{\Delta} \qquad \forall\, i = 2, \dots, n \qquad (4)$$

Where i describes the space section of the pipe model. By substituting (3) & (4) in fluid equations, n pairs of ordinary differential equation are derived. A leak at point $P_i$of the pipeline which discharges into the atmosphere produces a discontinuity in fluid equations and as a result a boundary condition forms at P_i which is related to discharge outflow [17].

$$Q_{pi} = \lambda_i \sqrt{H(P_i, t)} \qquad (5)$$

Where the parameter λ_i is a function of leak size and gravity. then $\dot{Q}_i$ and $\dot{H}_i$ are described as follows:

$$\dot{Q}_i = \frac{gA}{\Delta}(H_i - H_{i+1}) - \mu Q_i |Q_i| \qquad \forall\, i = 1, \dots, n-1 \qquad (6)$$

$$\dot{H}_i = \frac{c^2}{gA}\left(Q_{i-1} - Q_i - u_{ti}\lambda_i\sqrt{H_i}\right) \qquad \forall\, i = 2, \dots, n \qquad (7)$$

u_{ti} is a step function which defines the leak occurrence time. Then these two partial differential equations of fluid flow in pipeline are transformed into 2n-1 ordinary differential equations:

$$\begin{bmatrix} \dot{Q}_1 \\ \dot{H}_2 \\ \dot{Q}_2 \\ \cdot \\ \cdot \\ \cdot \\ \dot{H}_{n_1} \\ \cdot \\ \cdot \\ \cdot \\ \dot{Q}_{n-1} \\ \dot{H}_n \\ \dot{Q}_n \end{bmatrix} = \begin{bmatrix} -\mu Q_1|Q_1| + \frac{gA}{\Delta}(H_1 - H_2) \\ \frac{c^2}{gA}(Q_1 - Q_2) \\ -\mu Q_2|Q_2| + \frac{gA}{\Delta}(H_2 - H_3) \\ \cdot \\ \cdot \\ \cdot \\ \frac{c^2}{gA}\left(Q_{n_1-1} - Q_{n_1} - u_{t1}\lambda_1\sqrt{H_{n_1}}\right) \\ \cdot \\ \cdot \\ \cdot \\ -\mu Q_{n-1}|Q_{n-1}| + \frac{gA}{\Delta}(H_{n-1} - H_n) \\ \frac{c^2}{gA}(Q_{n-1} - Q_n) \\ -\mu Q_n|Q_n| + \frac{gA}{\Delta}(H_n - H_{n+1}) \end{bmatrix} \tag{8}$$

Figure 4.2 shows the discretized pipeline model with one leakage.

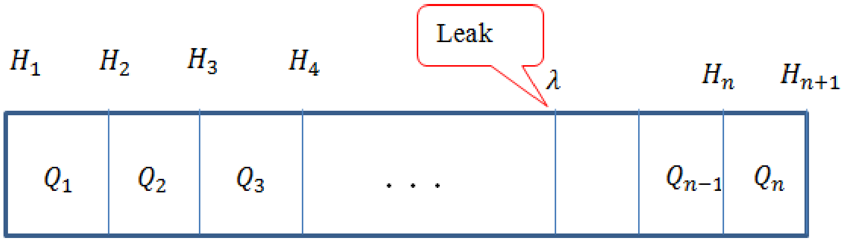


Figure 4.2. Discretized Pipeline Model

In this method the only available measurements are flows and pressures at the extremes of the line. Different mixture of these measurements could be applied as boundary conditions. In this thesis, the pressure at both ends of the pipeline is chosen as boundary conditions.

$$[H(t,0)\; H(t,L)] \tag{9}$$

And systems outputs are flow at inlet and outlet of the pipeline.

$$[Q(t,0)\ Q(t,L)] \tag{10}$$

4.4. PIPELINE MODEL

The simulated pipeline characteristics are summarized in Table 4.1.

Table 4.1. Pipeline Characteristics

Parameter	Symbol	Value	Unit
Pipe length	L	10	[km]
Pipe diameter	D	0.3	[m]
Velocity of sound	c	1000	[m/s]
Friction coefficient	f	0.04	

The initial conditions are needed to compute the transient conditions. Mostly the initial conditions correspond to the initial steady-state flows. So the model is fed with initial conditions computed from Eq.1 and Eq. 2.

4.5. LEAK DETECTION

The proposed leak detection algorithm is based on comparison of flow measurement at two extremes of the pipe with those acquired from the simulated model. In order to keep the model more realistic, a white noise with SNR=10 dB is added to its inputs. A leak with severity of one percent of inlet flow is injected to the model at time 50 second.

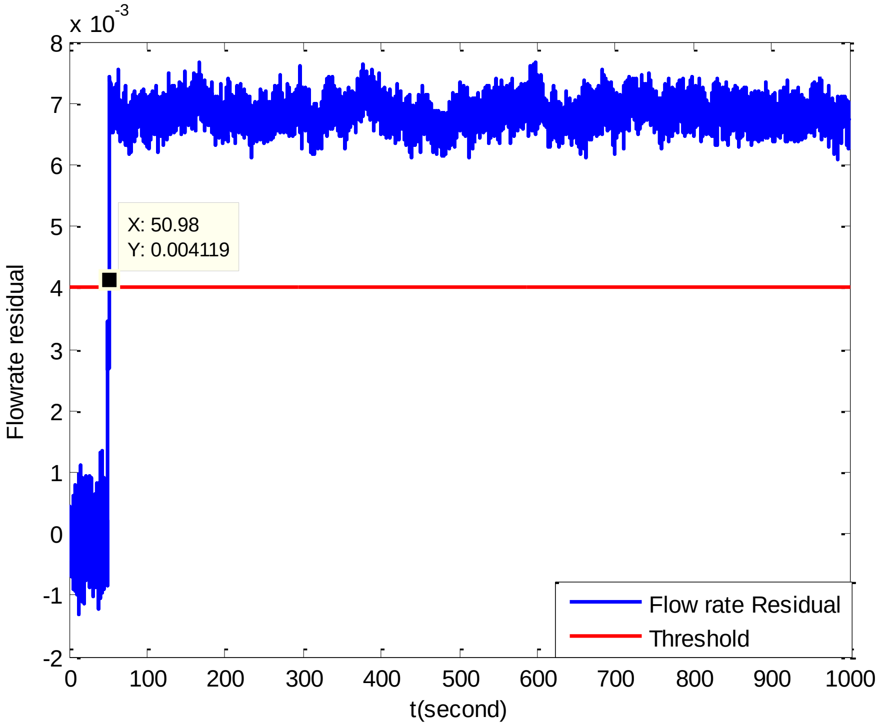


Figure 4.3. Flow Rate Residual At The Outlet; Pipe Length = 1km

As it is clear from the Figure 4.3, the leak is detected at 50.98 sec. so there is a delay of 0.98 second in leak detection. However, as the length of pipe increases this delay grows up. Figure 4.4 and Figure 4.5 show the flow residual for pipeline with length of 10 km and 100 km respectively.

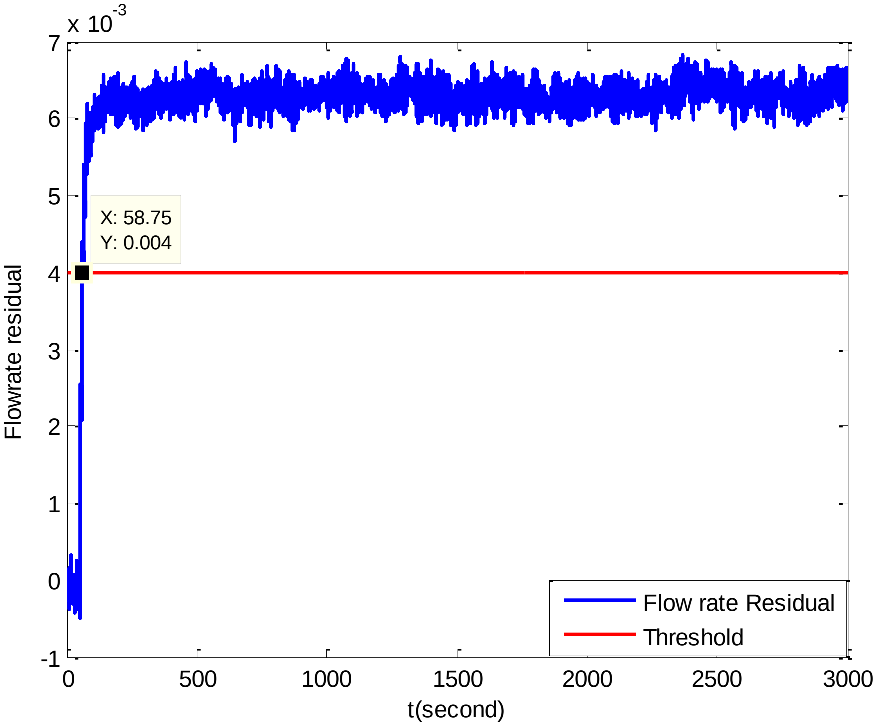


Figure 4.4. Flow Rate Residual At The Outlet; Pipe Length = 10km

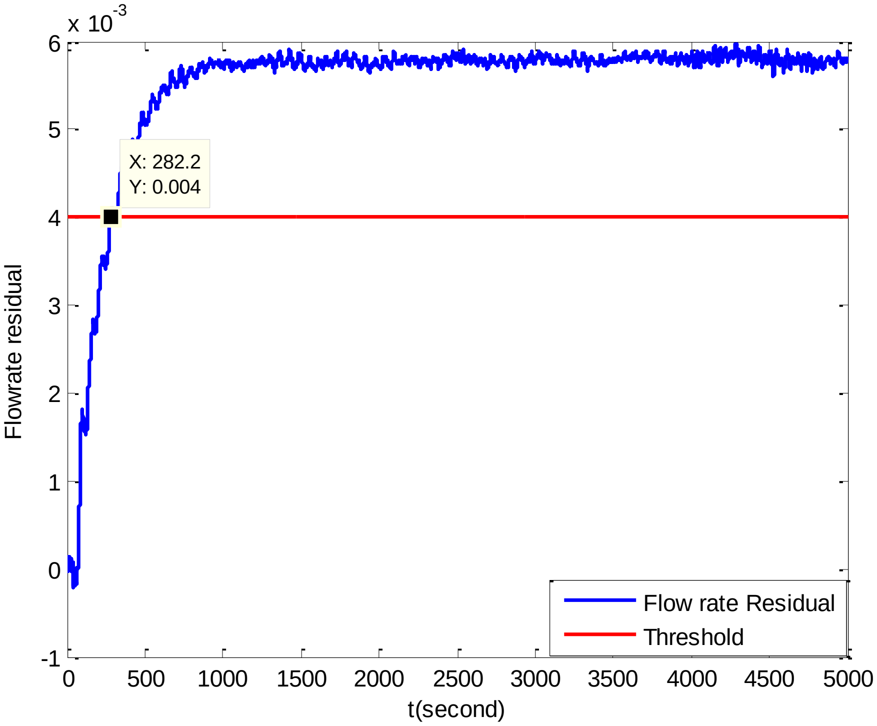


Figure 4.5. Flow Rate Residual At The Outlet; Pipe Length = 100km

The delay in case of 10 km pipe length is equal to 8 second and for pipe with 100 km length it is 232.2 second. This delay might be so severe in cases which pipe is transporting a dangerous fluid. However, in some cases like water transportation it should not make a severe concern. As a matter of fact, there is a trade-off between desired speed and cost. In applications which are very time-sensitive denser sensor networks is needed to fullfill their requirements. Figure 4.6 shows the detection delay vs pipe length.

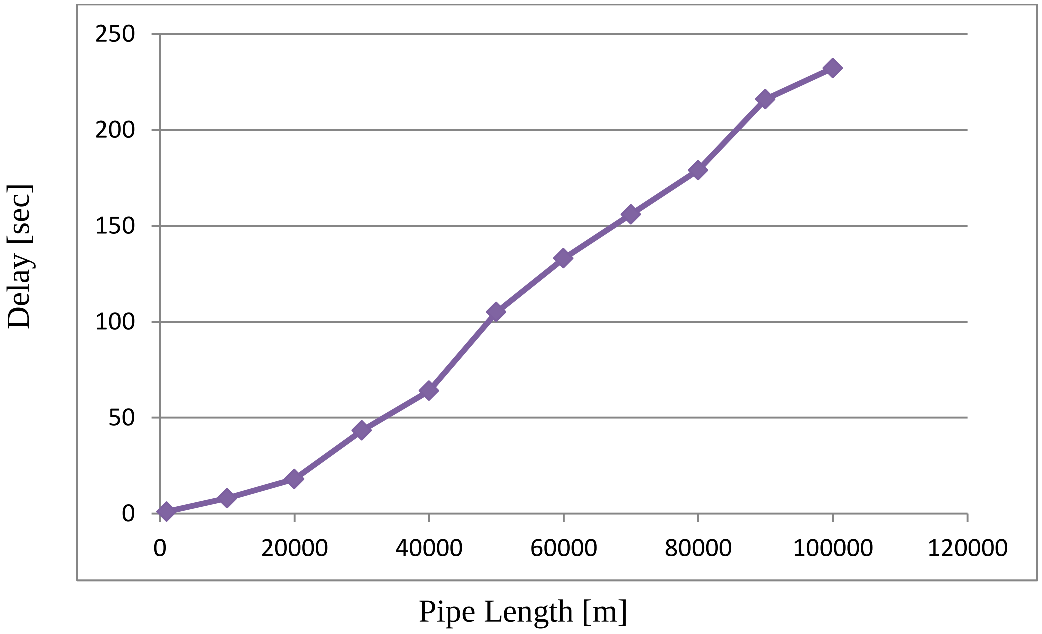


Figure 4.6. Leak Detection Delay Variation With Respect To Pipe Length

Another parameter which worthes to be noticed is threshold value. This parameter should be chosen based on the environmental noise and uncertainity in measurement instruments.

Figure 4.7 shows the pressure signals at the outlet for “with leak” and “without leak” cases. At time of occurrence of leak the pressure signals drops dramatically and the difference between two signals suddenly increases. But after a while, both signals lay down in a steady state situation.

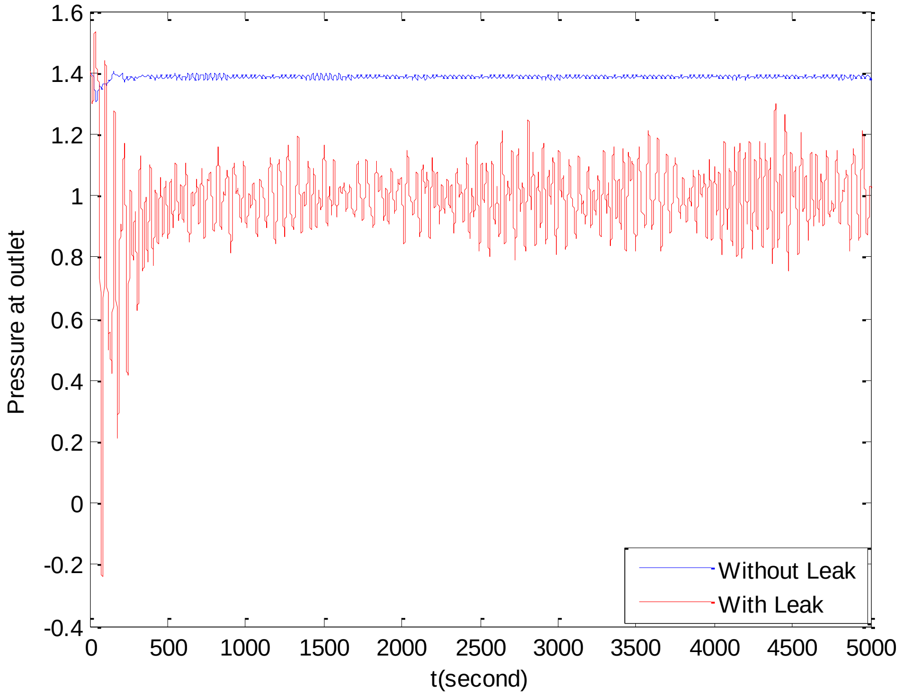


Figure 4.7. Pressure Signals At The Outlet

4.6. LEAK LOCALIZATION

The challenging part of pipeline monitoring is how accurate the location of leakage could be identified. Figure 4.8 describes the procedure of leak localization. Indeed this method works based on the fact that pressure variation along the pipeline is linear in steady state. Steady-state equations corresponding to Eqs. 1 and 2 may be obtained by substituting $\partial H/\partial t = 0$ and $\partial Q/\partial t = 0$. Hence, it follows from Eq. 1 that $\partial Q/\partial x = 0$; i.e., Q is constant along the pipe length. Substituting $\partial Q/\partial t = 0$ into Eq. 2, simplifying the resulting equation, and writing it in a finite-difference form, we obtain

$$\Delta H = \frac{\mu Q|Q|}{gA} \tag{11}$$

Where ΔH = head loss in pipe length Δx for a flow of Q. So, based on described steady state analysis, as long as there is no leak, the pressure drops with a constant slop along the pipeline. But once leak occurs, the slope will change after the leakage. The intersection of two lines could be used as an indicator of leak location.

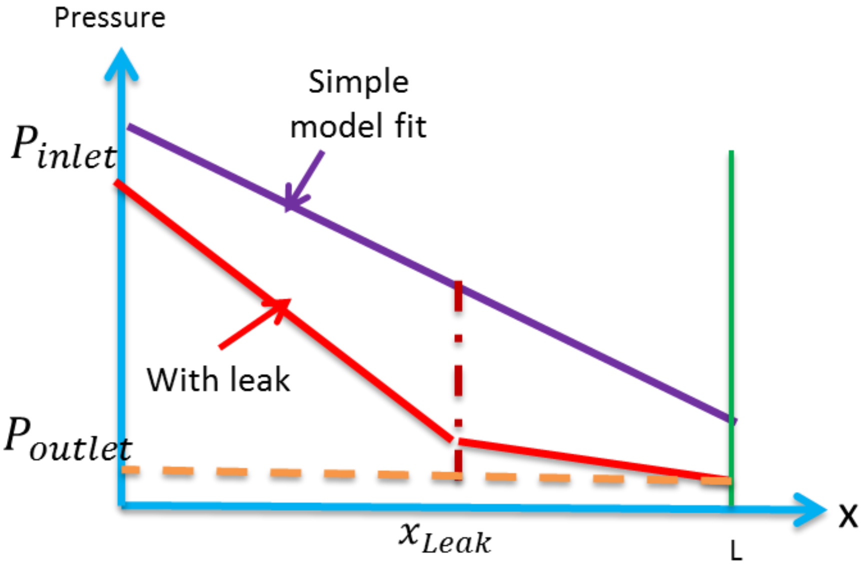


Figure 4.8. Leak Localization Procedure

Allying this method needs two pressure sensors at the inlet and two at the outlet. The distance between these two should be considered carefully. The pressure ‘gradient, before and after the leak point could be calculated as:

$$\frac{\partial P}{\partial x}\bigg| x \leq x_{Leak} = \frac{P_{xLeak}-P_i}{x_{Leak}} \tag{12}$$

$$\frac{\partial P}{\partial x}\bigg|_{x_{Leak}\leq x\leq L} = \frac{P_O-P_{xLeak}}{L-x_{Leak}} \tag{13}$$

where P_i , P_o and P_{xLeak} denote the pressure of the inlet, outlet and leak point in pipeline, respectively and L is the length of pipeline. The intersection point which is an estimation of leak location could be calculated as:

$$x_{Leak} = \frac{P_o - P_i - L\frac{\partial P}{\partial x}\Big|_{x_{Leak} \le x \le L}}{\frac{\partial P}{\partial x}\Big|_{x \le x_{Leak}} - \frac{\partial P}{\partial x}\Big|_{x_{Leak} \le x \le L}} \qquad (14)$$

The measured value of pressure is definitely prone to noise. To reduce the noise effect of estimation result it is more reasonable to compute gradient with a fixed length of pressure data near to the time leak detection. So each pressure in above equations will be replaced by its mean in a length of time [35].

Table 4.2 to Table 4.4 present the results for leak localization for pipe with length of 1 km, 10 km and 100 km respectively. The noise with SNR=15dB is added to the model inputs.

Table 4.2. Leak Localization Results For Pipe With Length of 1 km

Exact Leak Location [m]	Leak size	Estimated Leak Location [m]	Estimation Error
300	1%	311.6	3.8 %
300	5%	318.93	6.31 %
500	1%	525.46	5.09 %
500	5%	509.84	1.96 %
700	1%	702.038	0.29 %
700	5%	701.59	0.22 %

Table 4.3. Leak Localization Results For Pipe With Length of 10 km

Exact Leak Location [m]	Leak size	Estimated Leak Location [m]	Estimation Error
3000	1%	2991	0.3 %
3000	5%	2995	0.16 %
5000	1%	5048	0.96 %
5000	5%	4987	0.26 %
7000	1%	7015	0.21 %
7000	5%	6997	0.04 %

Table 4.4. Leak Localization Results For Pipe With Length of 100 Km

Exact Leak Location [m]	Leak size	Estimated Leak Location [m]	Estimation Error
30000	1%	29876	0.41 %
30000	5%	29925	0.25 %
50000	1%	50078	0.16 %
50000	5%	49925	0.15 %
70000	1%	69870	0.18 %
70000	5%	69760	0.34 %

As it could be seen from the Table 4.2 to Table 4.4, this method works well for pipelines with length up to 100 km and the maximum estimation error is 6.5%..

5. CONCLUSION AND FUTURE WORKS

5.1. SUMMARY

The reliable method for leak detection in pipelines is an important problem to be solved for preventing disastrous failures. Two leak detection methods are proposed and implemented. One is a hardware-based and the other one is software-based method

The first approach is based on the transmitting lamb-wave by a pizoresitive actuator along the pipeline and analysis of the received wave. A wavelet-transform approach is used to detect the fault in pipe. For leak localization time of travel of backscattered wave is used. The estimation error for leak localization in pipe with length of 500 is 7%. This method is very reliable in leak detection; however it is very expensive and is applicable in shorter ranges than model-based approach.

The second implemented technique is a model-based method which relies on a numerical model of pipe and flow and pressure measurements at both ends of the pipeline. The measured flow-rate at the outlet of pipe is compared to output from simulate pipeline. Their difference is an indicator of leak happening. This method is tested on pipelines with various lengths up to 100km. for leak localization a gradient pressure method is used. Single leak in pipeline is located precisely for pipelines of lengths up to 100 km. the maximum estimation error for leak localization by this method is 6.5%.

5.2. FUTURE WORKS

The future work of this research is as follows:

- ✓ In this study only longitudinal waves are analyzed and used for propagation. It would be better to examine the behavior of other wave modes such as flexural wave in reaction to leak.
- ✓ The simulated pipe in ANSYS is a boundary-free one. For getting more realistic results, it is required to simulate a pipe which is bounded by a material
- ✓ Experimental set-up for testing this methodology and using piezoresistor actuators for exciting pipe should be implemented to test it in real-world

- ✓ Threshold value should be chosen based on the time-history measurements from a pipe to reach a reliable decision making system
- ✓ For the model-based it is suggested to implement the method on an experimental set-up
- ✓ This method only works for localization of single leaks. So working on a method which could localize multiple leaks is suggested.

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