FINITE ELEMENT ANALYSIS OF PROPAGATING WAVES IN NON-DESTRUCTIVE TESTING FOR DEFECTS CHARACTERISATION IN PIPES

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ABSTRACT

Early detection of defects in commercial piping system is important in preventing enormous and expensive repair due to large unprecedented failure caused by corrosion, blockage or structural deformation. Over the years, various non-destructive inspection methods were used within the multimillion oil and gas industry to prevent losses of both human and money. Most of the research has been done within the solid isotropic media by mean of studying the ultrasonic guided test. The dispersive nature of propagation within solid media requires great experience from technicians in interpreting the signals acquired through the available sensors. There is an inevitable need for industry to interpret the signal easier with available artificial intelligent techniques; however this would require more data for training. In this research, the time domain reflectometry will be investigated for various acoustic wave reflections from defects within a pipeline system by means of 3-dimensional finite element modelling and experimental procedures. Artificial defects of different sizes will also be modelled to understand the propagation of acoustic wave within the pipe. An incident wave will be introduced at a point along the pipe and the travelling path of longitudinal wave within the pipe will be studied. The potential implementation of local mesh refinement in commercially available FE packages is considered and discussed in the context of the choices open to the modellers. The outcome of the techniques and information will be a significant improvement in FE modelling of acoustic wave in non-isotropic media. This method will be the potential solution to the current prediction method used in Support Vector Machine by simply reducing the needs to have physical experimental data of defects. Modelling of various defects and failures can be done with the method presented in this thesis, as an input to a greater work within non-destructive testing in pipe. In the experiment, we have validated the predicted results of Finite Element Analysis to the defects responses, confirming to the hypothesis of this research.

DECLARATION

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

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As this is the second submission, it has been a long 36 months for the author before this thesis can be completed to the desired standard.

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CHAPTER 1.

INTRODUCTION

1.1 Background of the Research

In the oil and gas industry, complex structural and piping system are exposed to various loads and conditions throughout the lifetime. The cost of these infrastructures can reach millions of dollars hence breakdown or disaster can be very costly as well as fatal. In the US alone the property damage within the period 1986-2003 due to accidents in hazardous gas pipelines was over USD850M while damages due to accidents in natural gas pipelines was over USD230M[1]. Flaws or defects in oil and gas pipes must be constantly investigated with accurate interpretation from any evidence gathered during examination to allow the prediction of future failure.

Failure detection using non-destructive methods (NDT) is inevitable within the multimillion oil and gas industry to prevent losses, in both human and money. In modern engineering, NDT is a widely recognised method for determining and evaluating the properties of material, component, or system without causing any damage to the assets. Among the commonly used tool for the exercise includes ultrasonic, magnetic-particle, liquid penetrant, radiographic and eddy current testing [2].

1.2 Guided wave pipeline Inspection

Predicting the type of failure in an ultrasonic detection often rely on complicated signal processing method. Experienced technicians and high-end signal processing methods are the two major requirements that makes interpretation of responses difficult and therefore can be very expensive [3].

The inspection of structures with guided waves method requires knowledge on how the waves propagate in the structure and its reflectometry characteristic. As early as 1959, the early work such as Gazis [4] have inspired researchers to use the understanding of 3-dimensional sound wave propagation in determining the responses of wave field to irregularities within the travelling path. The knowledge was later used in real life application such as determining defects within a pipeline structure. Non-destructive testing of pipelines is used to detect defects that are small in size before they lead to failures and has become an important discipline for oil and gas pipeline management.

Ultrasonic guided wave testing is a type of test commonly used in the longitudinal structural of non-destructive defect detection. Lately, this guided waves method has attracted the attention of many researchers, as it reduces the hassle of time consuming physical onsite inspection[5][6].

1.2.1 Localised Ultrasonic Guided Wave Method

In conventional ultrasonic inspection, the guided waves propagate along a single line across the cross sectional view of the pipe and therefore inspection time was not efficient. The probes will need to travel along the length of the pipe before detecting any disconformities within.[7]

Tone burst signal will be triggered on the outer circumference surface of the pipe along the thickness direction. As the wave propagates and reflected from surfaces within the pipe, responses were recorded and analysed. Reflections from defects within the travelling path can be observed between two peaks of pressure amplitude in time domain. The ratio of reflecting waves to the diameter of the pipe will be indicative values in determining the defect parameters [8].

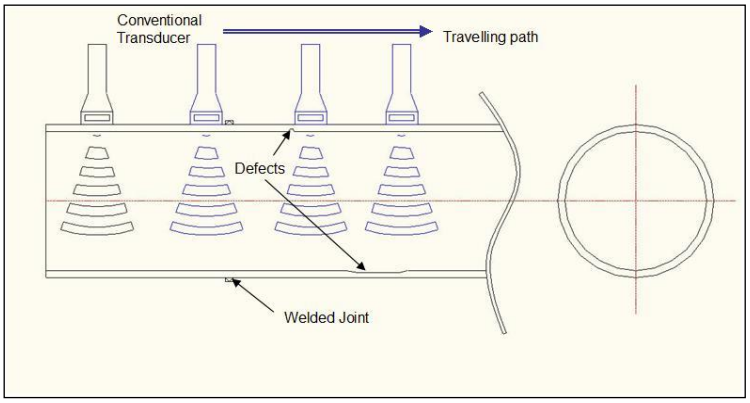


Figure 1.1: Conventional localised inspection method

The coverage area of the localised detection method are limited to the effective detection width of the sensor and limited to the pipe thickness. To allow bigger coverage area, the technicians will need to move along the longitudinal pipe length and around the circumference. Figure 1.1 visualised the movement of transducer and the coverage area of the inspection.

Although this method is much slower that the LRUT, the results are more accurate as the wave travelling distance is much shorter and less dispersive.

1.2.2 Long Range Ultrasonic Guided Wave Method

Long range ultrasonic transceiver is one of the latest methods used with commercially available equipment to the industry. As the acoustic impedance changes in the structure due cracks or deposit in the pipe wall, it will cause reflections of the guided waves.

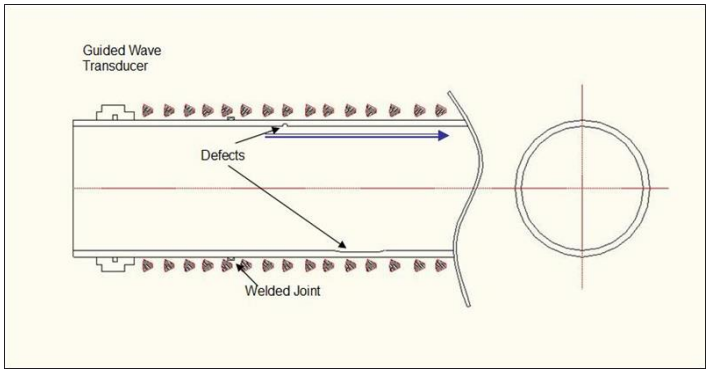


Figure 1.2: Long range inspection method

These reflections can be received by the same transducers used for excitation of the guided waves or another sensor. The scattered signals responses at the sensors contain information about the size and location of the pipe features that caused the reflections. By determining the theoretical travel period, the reflection arrival time gives an indication of the longitudinal location of the defect. Frequencies and the amplitude of the reflected signal will give an indication to the characteristic of the defect [8].

The LRUT method is a much faster method of detection due to the higher number of sensors used to transmit and received the ultrasonic signals. Figure 1.2 visualised the travelling direction of the sound wave. As the waves travel along the longitudinal direction of the pipe without the needs for sensors relocation, it reduces the inspection time. However, the various numbers of transceivers are creating dispersive travelling modes, therefore signal processing will be more complicated from the localised method discussed earlier [8].

1.3 Problem Statements

As discussed earlier in 1.1, defect detection using ultrasonic wave rely upon the reflected acoustic signal propagation from the investigated medium. In pipeline defect detection, it is the signal from defect's reflectometry that characterised the defect parameters and location within the pipeline structure [9].

Researchers are working on experimental and field data to provide the references for classification of failure based on the wave propagation signals. As most of the work are being done in the laboratory, modelling of the pipe and the defects are limited to laboratorial scale models which most of the time does not represent the real pipeline condition in the field.

With the availability of latest solution within artificial intelligent system such as the Support Vector Machine (SVM)[10], the gap of knowledge between the knowledge of field exercise and the laboratory data can be narrowed by providing the set of matching data of ultrasonic reflectometry within the pipe structure. Simply by matching the reflected signals from defects obtained on the field to the database of defect from experimental data [11].

Obtaining the defect characterisation from experimental data will require physical set-up of piping system in the laboratory and an accurate defect model that represent the common defect type within commercial pipeline. However, with the massive range of sizes and set-up within commercial pipeline, it will be impossible to have the complete database of defect type for training in the SVM.

Finite Element Modelling (FEM) is a popular method used within static and dynamic solution in structural analysis. With the available commercial packages, finite element analysis softwares are capable of modelling structural problem using both the explicit and implicit methods [12]. However identifying the key inputs to the 3-dimesional modelling in finite element analysis, with the propagation of wave in solid module is critical. It is an inevitable

process for researchers to understand in saving time and money, by having accurate modelling and result within the modelling space rather than building rigs in the laboratory [13]. Through modelling method of ultrasonic wave propagation in a pipeline structure within finite element module, the reflectometry from defects can be analysed and feed into the SVM. Creating model and executing the analysis in finite element method requires various discipline of knowledge such as precise definition of parameters and boundary conditions classifications. The challenge to this research is to obtain the modelling method in finite element analysis that accurately represents the propagation of ultrasonic waves in the physical pipeline and its defect reflectometry [14][15].

1.4 Research objectives

The current inspections in pipe failure using ultrasonic sensors are currently targeting the pipeline damaged and its faults. Currently the experiences of skilled technicians are the prime factor in determining the failure or defect in pipeline. It is a method that is prone to human interpretation therefore susceptible to errors. The speed of the data that is coming in from the numerous sensors requires constant monitoring and great amount of attention [16].

Demand for various failure investigation data are now very high as researchers are trying to move forward from existing non-destructive testing that not only identify defects characteristics but to perform a more complex prediction of failure occurrence [11].

This research proposed a comparative study between the results of propagating wave in laboratory set-up with the model in FEA software, which will be used as the input to pipeline failure prediction by the support vector machine (SVM).

The objectives of the research are:

1. To contribute the knowledge on propagation characteristic within a typical oil and gas pipeline through 3-D Finite Element Analysis.
2. To identify the node displacement amplitude responses for various condition of defects within the pipeline by understanding the acoustic reflectometry from defects in time domain.
3. To design, build, complete experimental procedures and investigate the acoustic impulse propagation characteristic.
4. To investigate and validate the results obtained from analysis with the results obtain through experimental data.

1.5 Brief Methodology

The work to date on the pipeline failure prediction rely on the data from experiments and knowledge of experienced technicians [13]. To overcome this issue, a clear modelling method of wave's propagation in pipe using Finite Element Analysis will be identified in this research.

Two clear path of the research were recognised to be the analysis of desired model in FEA and execution of laboratory experiment. Results from the main analysis exercise will be processed and comparatives analysis will be done to validate the method used within the FEA.

The research uses advance FEA modelling and piezoelectric sensors in investigating the signal responses within the pipeline structure. Three main parameters observed in both, the analysis and the experiments are;

1. The time domain reflectometry for selected nodes within the pipe during ultrasonic wave propagation with and without artificial defect.
2. The signal processing procedures in finding the relevant transient responses.
3. The characterisation of defects using the acquired signals.

Validation of the FEA method will be done by comparing the displacement amplitude in time domain with the signal acquired through experimental procedures. Qualification of this method will be the foundation in building 3-dimensional models of pipe with artificial failures as the potential training data to the available SVM.

1.6 Thesis Outline

This thesis is a culmination of approximately two years of research work done as part of research activities to develop a novel method of modelling various defects for industrial pipelines. This report looks at the background study on theory of ultrasonic wave propagation, finite element modelling, literature review on works being done related to the research topic, knowledge gap on existing research, design of research methodology and comparative results from finite element analysis and experimental works before embarking into further research within the topic.

In Chapter 1, we look at the thesis problem statements, objectives, preliminary information on the literature review and the brief methodology.

Chapter 2 is the literature review that summarised on going literature search with regards to the research. Current methods and its advantages and the disadvantages will be discussed and suggestions will be made on research directions. An executive summary of the literature review and discussions on knowledge gap will be presented as the foundation to the knowledge required in this research. The chapter ends with background theory that underlined the research works.

Chapter 3 represents a comprehensive report on the methodology chosen for the research. An outline of methods with Finite Element Analysis model will be presented with details on various input for the analysis, such as the boundary condition and the analysis step type. In the second part of the chapter, details of experimental design set-up of both mechanical and electrical discipline are presented.

After a clear direction to both experimental and simulations tasks, a quantitative display of the results will be displayed in Chapter 4. Being one of the critical task in the research, this chapter sums up the outcome of both experimental and simulation in Finite Element Analysis exercises.

The experiment validates results accomplished through the simulations of lamb waves with and without defect pipe structure.

In Chapter 5, the final chapter of this thesis, conclusions will be presented followed by the potential extensions to the works completed.

CHAPTER 2.

LITERATURE REVIEW

2.1 Ultrasonic Wave Guided Inspection

As one of the objective of this literature review is to look at available and current practices within specific pipeline failure detection knowledge, the review will start with works on popular ultrasonic method. Works on the wave propagation in failure detection for hollow cylinders was published as early as 1923 by Gosh[17] suggesting the first linear elastic solution. His work was then expanded by Ghazi in 1958[4] who embarked into the new journey by studying deeper into the wave propagation characteristic by solving the 3-dimensional waves propagation in hollow cylinder with linear elastic analytical methods for solving ultrasonic guided wave excitation problems. However, the preliminary study shows a great difficulty in identifying dispersed wave during that propagation. Only then the dispersion theory was taken as the critical knowledge in understanding the scattered propagation within the solid media.

Guided waves propagation (along the pipeline) since then has taken up interests from the later researchers as more pipelines were built globally. Mohr in 1976 performed a study on the longitudinal modes with particle displacements coupled in axial and radial directions for transverse failures and torsional modes[18], oscillating in the circumferential direction only, for longitudinal failures. Pulse was excited at one end of the pipe and received at the other end to determine the characteristic of travelling wave.

2.1.1 Guided Waves Principles

Ultrasonic guided wave principle of sound at frequency higher than 20 kHz lies on the ability of piezoelectric sensors to detect pressure change along the investigated media. The ability to detect responses is bounded by the media characteristic in which the signal to coherent noise ratio being a great determinant. Unwanted noise in the elastic waves often reduces the capability of inspection method to determine the representation of the signal. In order for the responses from defects be interpretable, it is necessary to use selected wave modes, which allow the signal to be simplified [5].

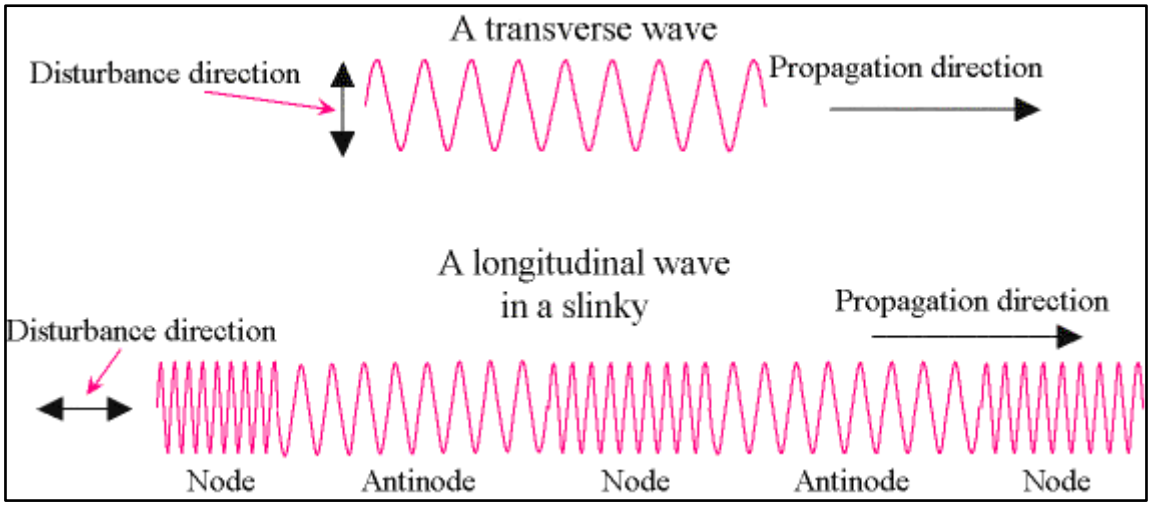


Figure 2.1: A representation of travelling wave modes

The propagation is a result of pressure changes (refer Figure 2.1). As pressure increases, molecules within the pipe move closer and packed, making it travel faster in a solid media and slower in more porous material.

These properties of ultrasound can be used to detect wall thinning by means of pressure change at different wall thickness. These waves are produced by ultrasonic transducers or transceiver. Ultrasonic transducers are very accurate transducers that can produce high frequency sound waves based on the piezoelectric effect. Piezoelectric transducers have a solid-state pressure sensitive element that will expand and contract in step with an input voltage that is applied across the opposite terminals of the quartz crystals with axes direction visualised in Figure 2.2.

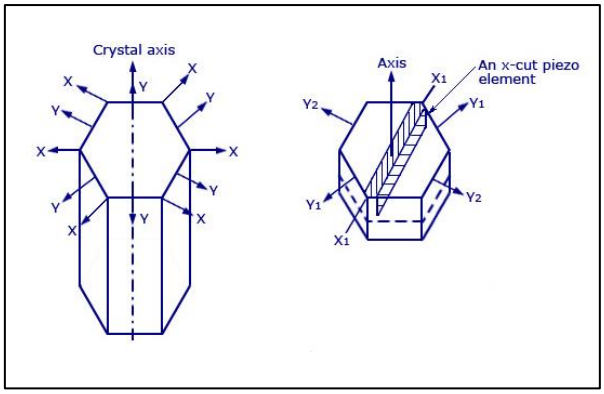


Figure 2.2: Axes of piezoelectric sensors

Researchers examined the effect of the defect size using a guided wave mode and the changes in frequency of the reflections coming from notches. The reflectometry were studied and relationship between the excited wave and the reflected wave in various modes were used to determine the type of defect. In practice, cylindrical ultrasonic transmitter provide a fast screening technique using waves that propagate along the pipe and that are partially reflected when met with defects.

The characterisation of defect was further investigated by Lin, through guided waves and electromagnetic acoustic transducers (EMATs) to measure wall thickness [19]. Wave propagation experiments were performed for a 10mm thick specimen, with different artificial defects used to imitate natural local wall thinning due to corrosion. In this experiment the intensity of the reflected wave were used as the criteria in determining the thinning wall character.

For typical conventional ultrasonic inspection, the guided waves propagate along a single line across the cross sectional view of the pipe and therefore inspection time was not efficient. The probes will need to travel along the length of the pipe before detecting any disconformities within.

To reduce the longitudinal travel of sensors requirement and to reduce the inspection time, long range ultrasonic (LRUT) or guided wave technique were introduced and it is capable of screening longer pipelines within shorter period of time [15].

Low frequencies guided sound are currently used in ultrasonic guided wave technique, travelling along the pipeline with 100% coverage of the pipe wall. Potentially effective areas are precisely located in terms of distance from the transducer ring and highlighted for local examination by visual or conventional NDT methods.

The response from the metal loss feature is a function of the depth and circumferential extent of the metal loss. Instead of scanning the region directly below or near to the transducers, guided waves travel down the length of the pipe and produced reading showing discontinuity within pipeline [20].

In Long Range Ultrasonic Transceivers (LRUT), an array of ultrasonic transducer elements is fitted around the pipe. From this single location, low frequency guided waves are transmitted in both directions along the length of the pipeline, screening non accessible areas remotely.

Various guided wave transducer rings and belts have been developed that are able to inspect pipe lengths of over 25 metre using dry-coupled piezoelectric transducers. These systems are designed to detect localized corrosion on the order of 10% the pipe cross sectional area [21].

Long-range ultrasonic inspection using dry coupled transducer techniques typically function as a screening tool for inspection. The technique can detect corrosion within several meters in both directions from the transducers. However, the technique requires the emptying of pipe during inspection in which this can be an expensive exercise for industry[2][22]. In embarking further into the study, we will need to further understand potential modes of travelling ultrasonic wave within the investigated pipe.

2.2 Understanding the Travelling Modes of Ultrasonic Waves

Ultrasonic waves propagate in multiple modes due the frequency and impedance. Therefore, the excitation of the desired mode is very important as this will allow the interpretation of response signal to be easier. In this section we will look into the understanding of dispersion and the critical incident pulse.

2.2.1 Dispersion of Ultrasonic Waves Propagation

In embarking into the study of guided wave propagation in solid media, one should look at the dispersion principles. Dispersion is a phenomenon of which a sound wave breaks up into its component frequencies as it passes through a material. The phase velocity of the sound wave is viewed as a function of frequency. Hence, separation of component frequencies is measured by the rate of change in phase velocities as the radiated waves pass through a given medium.

Guided waves propagate with very complicated wave structures due to a mixture of multi-modes and mode conversions. The typical modes are longitudinal, torsional and flexural labelled as L(0,n), T(0,n) and F(m,n) respectively. The first index 'm' indicates the order of harmonic variation of displacement and stresses around the circumference and the second index 'n' is a counter variable [23].

Modal analysis and simulation of guided wave propagation with computational solution are very useful for solving problems due to the complexity of the wave [24]. Dispersion curves were used to describe and predict the relationship between frequency, phase velocity, group velocity, propagation mode and its thickness.

Dispersion curves can be generated for all types of structure including plates, rods, tubes, multilayer structures, rails or any wave guide, whether isotropic or anisotropic. Any of the points on the dispersion curves could be used to carry out an ultrasonic guided wave test. Some

points, however, are much better than others for improved reception, sensitivity and penetration power.

One of the key variables associated with how good a particular point might be related to the wave structure is the displacement. The wave displacement characteristic across the thickness of the structure and within the cavity of the structure determines effectiveness of investigations.

Wave such as axisymmetric guided waves can propagate for long distances with little attenuation and regularly used for pipe NDT. Meanwhile, in some cases, flexural modes (non-axisymmetric) will be used together with axisymmetric modes for better detection. However, the signal identification and interpretation are more challenging [15].

In enabling the focusing of wave energy along the pipe, flexural modes can be modulated by time delays and amplitudes to constructively interfere with each other at pre-described positions. It is important to determine the mode of propagation existed from dispersion curves and relate it to mechanical function in finite element analysis.

2.2.2 Incident Pulse Type for Guided Wave inspection

As the main aim of the detection is to identify the reflected signal of ultrasonic signal from the defect location, the selection of excited signal is critical. It is clear from the dispersion theory discussed in the previous sub-section that many modes can potentially propagate at a given frequency [5].

From the literature search, it was found that one of the ways to reduce signal of irrelevant frequencies is by selecting single mode propagation. Exciting many modes will result in a signal that is too complicated to interpret. Even if a single mode is achieved, mode conversion will occur at boundaries and at any other discontinuities such as defects and welds, and

therefore correct interpretation of the reflections is necessary. Designing transducer that can produce excitation of the preferred mode is essential to the experimental set-up.

As the measurement of the amplitude is in time domain, the frequency of the excitation signal is critical in making sure that the propagating wave is non dispersive. However many researchers works further within the frequency domain in understanding the characteristic of reflection before applying the necessary filtration of time domain data and understand the reflectometry characteristic.

2.3 Three Dimensional Finite Element Modelling

Wave propagation problems in finite element analysis for structural problems are solved using both implicit and explicit solvers. These two time domain methods are available in commercial solvers for finite element analysis. In explicit model methods, the state of the system at a later time is calculated from the current state of the system. This section presents the details of research method using the numerical implementation for wave propagation problems [12].

FEA uses a complex system of points called nodes which make a grid called a mesh. This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress. Points of interest may consist of fracture point of previously tested material, fillets, corners, complex detail, and high stress areas. The mesh acts like a spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, hence creating many elements [25].

2.3.1 FEA Modelling of Ultrasonic Wave

The ability to understand various responses to the acoustic wave propagation are becoming very important for researcher in determining the type of failures or defects detected through the sensors. Demma[26] investigated the mode of propagation for guided waves through systematic analysis by studying the effect of pipe size, defect size, guided wave mode and frequency through detail analysis of notches reflection using computational model.

Two types of models were used in the analysis i.e. the axis symmetric and 3D analysis. In reducing the analysis time and the expensive computational analysis procedures, the researchers reduce part of wall thickness, but are axially symmetric to cover the whole pipe circumference.

Maps of reflection coefficient as a function of the circumferential extent and depth of the defect were presented for a 3 inch steel pipe with defects on the outer surface of the pipe. A more recent research classify the defect by getting the ratio of amplitude of reflected wave to the amplitude of the incident wave in frequency domain. However the finite element modelling method does not consider presence of any components within the pipeline structure or even the transported fluid.

Linear elasticity theory was often used in 3D modelling of elastic wave propagation along circular cylinder structures, by introducing Hanning window tone burst signal at one end of pipe with excitation frequency varying from 20-100 kHz. Commercially available finite element analysis software was used to run 3D finite element analysis for most validation to experimental work [27].

To validate the feasibility analysis in any modelling, theoretical group velocities of the wave propagating along the general experimental pipe set-up were compared to the group velocity of the models.

The parameters of concern for most of the computational analysis performed by researchers are often the amplitude of displacement (u) for specific nodes within the wave travel media. Readings from the available piezoelectric during laboratory experiment will provide the required data for comparison with initial identification on the mode of propagation.

A laser generated sound waves using numerical calculations in determining the vertical displacements of nodes within the media was introduced later. The element sizes use were very

course, however, results from the analysis shows that basic characteristics of sound waves can be model in finite element domain with proper meshing but the quantification of the defect was never investigated [28][16].

In the literature review, modelling of wave propagation were accomplished through a couple of popular methods i.e. the mathematical analysis programming and readily available finite element analysis softwares.

With the available softwares, new possibilities of modelling techniques emerged, the research community is no longer looking at simple experimental set-up but at a complex shape within the modelling discipline. These allow less investment needs to understand a complex characteristic of wave propagation, mainly due to the less amount of physical set-up as more of the analysis being done on computers.

With the countless number of computer package available, it is essential for researcher to interpret the data or the results intelligently and to use the data in more practical environment. Boundary layer problems and the dispersion of signal occur once the sound wave travels between different media [29].

2.3.2 Explicit FEA Method

Explicit dynamic analysis in FEA is a direct time stepping method based on the central-difference operator and the use of diagonal element mass matrices. Post millennium journal papers open up a new horizon of techniques for wave modelling due to the availability of commercial software such as SAFE, ABAQUS, ANSYS and other smaller software companies rising with the evolution of CAD/CAM technology [30].

Wave propagation occurs when the initial equilibrium is disturbed by the application of forces or displacement constraints on nodes. Commonly, these are applied in the form of a tone burst

or a pulse. The central difference operator links the displacement, velocity and acceleration in the following way:

$$u^{(i+0.5)} = \dot{u}^{(i-0.5)} + \frac{\Delta t^{(i+1)} + \Delta t^{i}}{2} \ddot{u}^{i} \quad (1)$$

$$u^{(i+1)} = u^{i} + \Delta t^{(i+1)} \dot{u}^{(i+0.5)}$$

with u being the displacement, $\dot{u}$ the velocity, $\ddot{u}$ the acceleration, Δt, the time increment and i, the time increment number.

The procedure is explicit because the process is advanced using known values from the previous time step. Drozdz modelled the wave propagation of ultrasonic waves within a plate structure using explicit method and the results of the analysis shows a clear qualification signal echoed from defect on the plate surface. Although the modelling was done in 2-dimensional model, it is viable to adopt the explicit method in this study as the element used can be extended to the thickness direction [25].

2.3.3 Incident Wave Loading in FEA

The excitation wave in ultrasonic pipeline testing is a dynamic loading problem that requires careful definition of force amplitude in time domain. In dynamic analysis of finite element solver, the force can be exerted on a point within the structure through its geometry set or the nodes within the element [31][32].

Tabular input of amplitude vs time in the load input allow the variation of frequencies for the incident wave. Most researchers working with ultrasonic testing are using 0.75 MHz excitation signal at the transmission point. The maximum distance that can be covered depends on the

attenuation of the material, transmitting transducer power and other factors such as uniformity of the structure.

To allow for better representation of the wave travelling in the structure, the CFL condition named after R. Courant, K. Friedrichs and H. Lewy must be considered. The actual time step used in a model can be expressed in terms of its ratio by the critical time step. This ratio is called the Courant (or CFL) number, which in this research model, a 10 element per wavelength rules shall be sufficient [33].

2.3.4 Analysis of Commercial Software Packages

As a strategic planning method in determining the FEA software that are available in the market, a SWOT analysis (shown in Table 1.0) was used to evaluate three major software in the market (ABAQUS, ANSYS and COMSOL). It involves the identification of internal and the external factors that are favourable or the opposite in achieving the project objectives. The results of the analysis for a number of most prominent software shows clear indication that the suitable tool for the finite element analysis in the research was ABAQUS Dynamic, Explicit solution.

ABAQUS	
Strengths	*Weaknesses*
1. Available at minimal cost at both research location	1. Limited features on 3D modelling
2. More reference available due to its earlier establishment	2. Hybrid meshing limited to just fluid structure interface
3. Commercial package availability	
Opportunities	*Threats*
1. Updates available online.	1. Discontinuation of licensing
2. Dynamic and static analysis availability	2. Limited size of meshing applied to education version
3. Multicore analysis	

ANSYS	
Strengths	*Weaknesses*
1. Ease of use and interfacing with multiple CAD 2. The ease of model building 3. Commercial package availability	1. Meshing process for complex assemblies and designs can be really difficult 2. No particular edit command to the analysis, will need to redo every time 3. Not available at research venue.
Opportunities	*Threats*
1. Available training module online 2. More reference available due to its earlier establishment 3. Commercial package availability	1. Few shared licensed 2. Heavy price tag
COMSOL	
Strengths	*Weaknesses*
1. Very easy to learn with theoretical knowledge 2. User friendly versions for Multiphysics modelling	1. Limited to mainly buildings model 2. No hybrid meshing for boundary condition
Opportunities	*Threats*
1. More features than the common FEA software 2. Commercial package availability	1. Unavailability locally 2. Less number of expert available in the region

Table 1: SWOT analysis for 3 major software of finite element analysis

2.4 Prediction of Failure Using Neural Network

The majority of reviewed papers described non-destructive testing (NDT) as techniques developed and used for detection, sizing and monitoring failure in pipes, cross country pipelines using on-site data acquisition [11].

Real time data monitoring can be the solution to prevent pipe failure, any potential damage from corrosion can be detected early and trigger the alarm bell for maintenance work on a pipeline [10][34].

The challenge with continuous monitoring is the method of which most neural networks work i.e. batch data acquisition. Set data must be trained within the neural network system to identify type of defects represented from the acquired signal.

Most publications on prediction and identification of defects within the pipeline shows the need for training's data and to date, the desired data is very limited. There is a need to validate the method of modelling defects in computer using finite element analysis and accumulate the database of defects respond signal for neural network training [10][11].

Researchers are in need of data to train but however, they will need to look on modelling techniques that simplify the interaction within various media in a typical piping structure before more models can be generated.

2.5 Background Theory

In executing the research, fundamental understanding on the theory supporting both the experimental and the finite element analysis will be greatly needed. This chapter will discuss the background theory for ultrasonic waves travelling in the pipe structure.

2.5.1 Ultrasonic Waves in Hollow Pipe

Derivation of governing equation of wave in solid media came from the simple governing equation in a taut spring element. As the wave travel in the pipe, the particles within the pipe vibrate due to changes in the pressure. Three different modes of propagation will be produced i.e. the longitudinal, torsional and the flexural modes labelled as $L\ (0,m), T\ (0,m)$ and $F\ (n,m)$ respectively. Where circumferential order $n\ =\ 1, 2, 3, \ldots$ and the mode $m\ = 1, 2, 3, \ldots$. There are infinite number of torsional modes but however in this research we concentrate on the longitudinal wave's propagation.

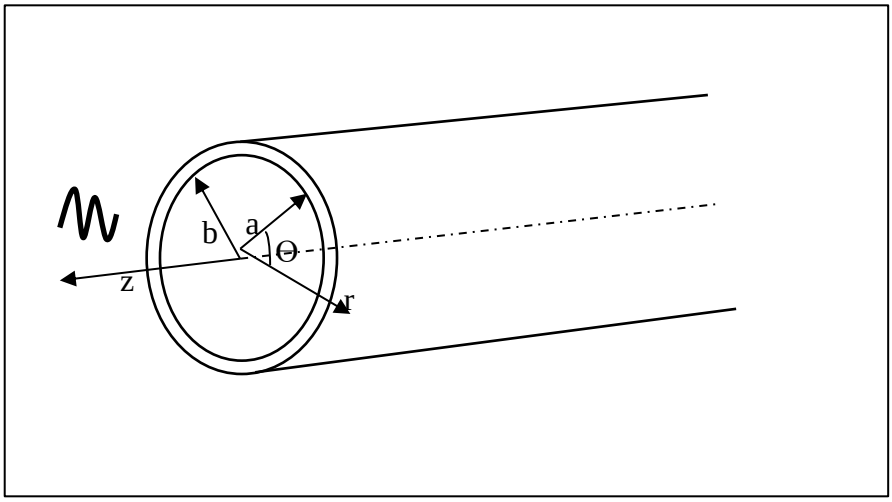


Figure 2.3: Vector component of travelling wave in hollow pipe

Consider a travelling wave in longitudinal direction z in an infinite cylinder in Figure 2.3; the cylindrical coordinate system can be simplified into three different directions;

$$u_r = U_r(r) \cos n\theta \cos(\omega t + \xi z) \qquad (2)$$

$$u_\theta = U_\theta(r)\cos n\theta\cos(\omega t + \xi z) \tag{3}$$

$$u_z = U_z(r)\cos n\theta\cos(\omega t + \xi z) \tag{4}$$

where n is the circumferential order, ω is angular frequency, ξ is wave number, $U_r(r), U_\theta(r)$ and $U_z(r)$ are constituted by Bessel function. For hollow cylindrical structure with homogeneous and isotropic elastic medium, the vector form of Navier's equation of wave motion is;

$$\mu\nabla^2 + (\lambda + \mu)\nabla\nabla u = \rho\frac{\partial^2 u}{\partial t} \tag{5}$$

where u is the displacement vector, λ and μ are Lame's constant for the material, ρ is the density, ∇^2 and ∇ being the Laplace and Hamilton operator, respectively. Introducing Helmholtz decomposition, the vector u is decomposed in terms of a scalar potential function $\emptyset$ and a vector potential function H as (with the additional constraint that $\nabla . H = 0$).

$$u = \nabla\emptyset + \nabla \times H \tag{6}$$

Substituting equation (6) into equation (5) produces scalar and vector wave equation:

$$\nabla^2\emptyset = \frac{1}{c_L^2}\frac{\partial^2\emptyset}{\partial t^2} \tag{7}$$

$$\nabla^2 H = \frac{1}{c_T^2} \frac{\partial^2 H}{\partial t^2} \quad (8)$$

Where $C_L = \sqrt{(\lambda + 2\mu)/\rho}$ and $C_T = \sqrt{\mu/\rho}$ are the two velocities of longitudinal and shear wave velocity. The two values will be critical in determining the period of wave travelling within the pipe and its longitudinal location [35].

2.5.2 Explicit Theory of Finite Element

Explicit dynamic analysis in ABAQUS/Explicit is a direct time stepping method based on the central-difference operator and the use of diagonal element mass matrices. Let us start with the equation of dynamic equilibrium:

$$[M]\ddot{u} + [C]\dot{u} + [K]u = F_a \quad (9)$$

$\ddot{u}, \dot{u}, u$ are the acceleration, velocity and displacement respectively. $[M]$ is the diagonal lumped mass matrix whose values are determined by the density of the material used. $[K]$ is the static stiffness matrix whose values are defined by the Young's modulus and Poisson's ratio. $[C]$ is the viscous damping matrix which is determined by the Rayleigh damping. Stiffness or mass proportional damping can be introduced:

$$[C] = C_M[M] + C_k[K] \quad (10)$$

Where C_m and $C_k$are the mass and stiffness proportional damping coefficient. $[F_a]$ is the external force.

Wave propagation occurs when the initial equilibrium is disturbed by the application of forces or displacement constraints on nodes. Commonly, these are applied in the form of a tone burst or a pulse. The central difference operator links the displacement, velocity and acceleration in the following way:

$$u^{(i+0.5)} = \dot{u}^{(i-0.5)} + \frac{\Delta t^{(i+1)} + \Delta t^{i}}{2}\ddot{u}^{i} \tag{11}$$

$$u^{(i+1)} = u^{i} + \Delta t^{(i+1)}\dot{u}^{(i+0.5)}$$

with Δt, the time increment and i, the time increment number.

The procedure is explicit because the process is advanced using known values from the previous time step.

The computational efficiency comes from two aspects of the explicit scheme. Firstly, unlike in the implicit scheme, there is no need to assemble and invert the global mass matrix. Secondly, the diagonal mass matrix is used when calculating the acceleration in the following way:

$$\ddot{u}^{i} = M^{-1}([F]^{i} - [I]^{i}) \tag{12}$$

where $[F]$ is the applied load vector and $[I]$ is the internal force vector. $[M]^{-1}$ is easily calculated because $[M]$ is diagonal.

This implementation is conditionally stable and the time step Δt has to be smaller than the critical time step Δt_{cr}which in an undamped system depends on the highest frequency in the smallest element [14]:

$$\Delta t \leq \Delta t_{cr} = \frac{2}{\omega_{max}} \tag{13}$$

In wave propagation modelling, as small deformations of elements are assumed, an approximation often used is that the critical time step is the transit time of a dilatational wave through the smallest element in the model [38]:

$$\Delta t \leq \Delta t_{cr} = \frac{\Delta L}{C_L} \tag{14}$$

where $\Delta L$the smallest element size and C_L is the velocity of the dilatational wave.

Figure 2.4 illustrates the value of ΔL for a linear square element, a linear equilateral triangular element and a quadratic equilateral-triangular element. It can be noted that this distance corresponds to the shortest distance between 2 nodes for a square element but this is not the case for triangular elements[12].

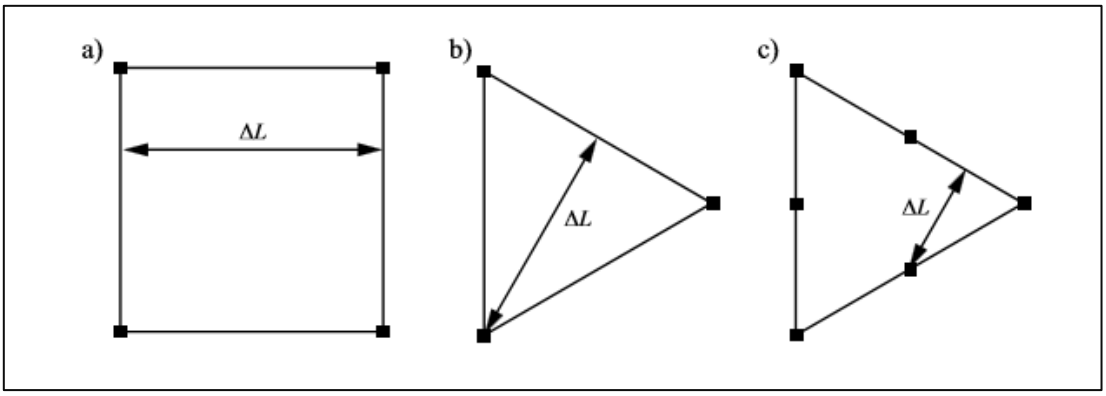


Figure 2.4: Illustration of ΔL for a a) linear square element, b) linear triangle element and c) quadratic triangle element

The condition in equation (14) is referred to as the CFL condition after R. Courant, K. Friedrichs, and H. Lewy. The actual time step used in a model can be expressed in terms of its ratio by the critical time step. This ratio is called the Courant (or CFL) number:

$$CFL = \frac{\Delta t}{\Delta t_{cr}} \tag{15}$$

Therefore the time increment is defined as:

$$\Delta t = CFL \Delta t_{cr} = CFL \frac{\Delta L}{C_L} \tag{16}$$

Given that the space usually needs to be discretized in such a way that the shortest wavelength in the model is finely discretized (usually, at least 10-20 nodes per shortest wavelength are used), a large number of increments is required to solve a model. The number of increment in an explicit scheme is larger than the one required with a time domain implicit scheme but, since global mass and stiffness matrices do not need to be formed nor inverted, each increment is computationally inexpensive. This makes the explicit scheme particularly attractive for wave propagation [36][37].

CHAPTER 3.

METHODOLOGY

3.1 Overview

In achieving the desired output of the research, a clear process flow was built from the knowledge acquired through the literature review. The research process in figure 3.1 summarised the key task within this research and was used as the main guideline in designing the overall methodology;

Two clear paths of the research was identified to be the analysis of desired model in FEA and the execution of laboratory experiment. Results from the main analysis exercise were processed and comparatives analysis was done with experimental model in validating the Finite Element Analysis method. The research uses advance FEA modelling and piezoelectric sensing technique in investigating the ultrasonic wave reflection on the pipeline. Four main parameters observed in both analysis and experiments are;

1. The time domain reflectometry for selected nodes within the solid media of pipe for ultrasonic wave propagation with and without artificial defect.
2. The signal processing procedures in finding the relevant transient responses.
3. The characterisation of defects using the acquired signals.
4. Boundary conditions of FE model.

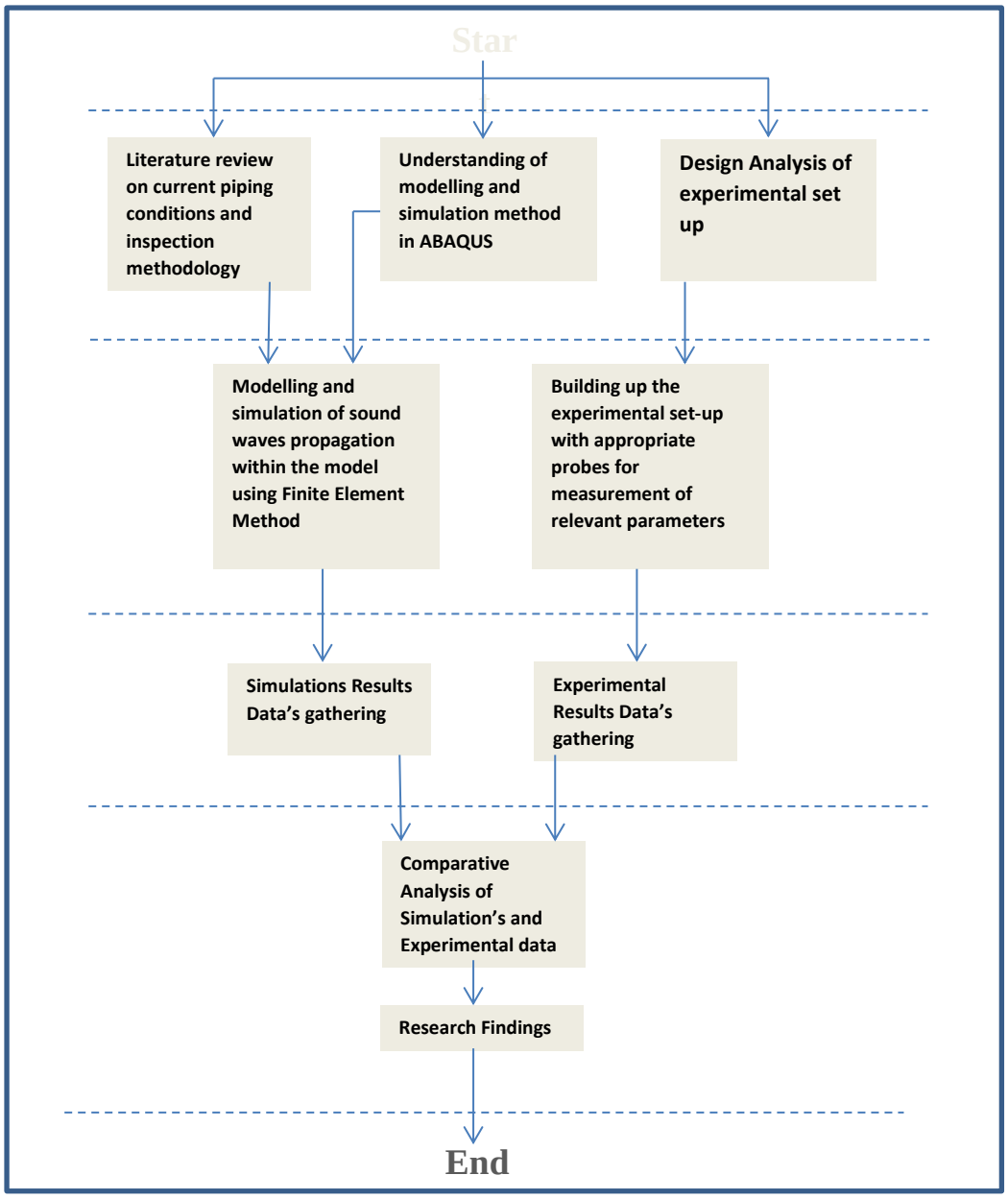


Figure 3.1: The research flowchart for the study of guided wave

Findings of time domain of lamb wave's displacement within the pipe structure at specifics location between the experimental and finite element analysis data were used to identify the correct modelling method and shall be the foundation to greater knowledge on defect characteristics [11]. With this knowledge one can built more database of defect modes and eventually be an input to failure prediction method such as the SVM.

3.2 Finite Element Analysis

As discussed earlier in the background theory, finite element method was identified to be the appropriate tool for the modelling of lamb wave propagation within the inspected pipe due to its' capability of iterating element by element of the pipe structure subjected to ultrasonic wave excitation.

3.2.1 Analysis Framework

In this thesis, ABAQUS Explicit was used as the analysis's tool for the research; the analysis framework is given in the figure 3.2.

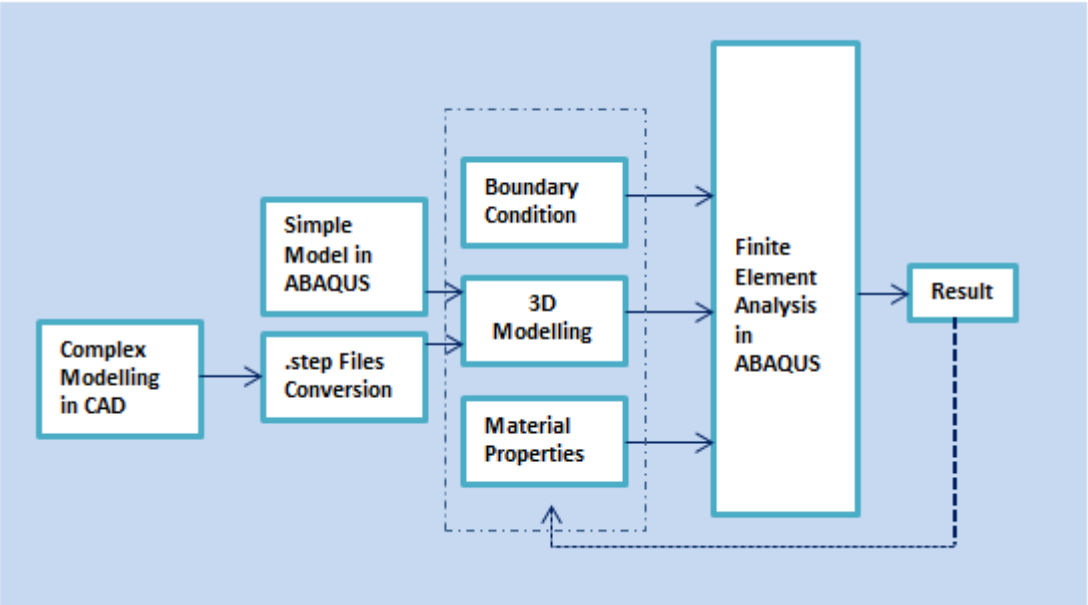


Figure 3.2: Finite element analysis workflow

For the analysis, 3 core inputs to the ABAQUS analysis interface were identified and those are the modelling, boundary conditions and the understanding of material properties. Interpretations of these data will be of important inputs in validating the wave theory travelling in solid media [31][36].

3.2.2 Model Database

Creation of model database within the ABAQUS interface is restricted due to the limited capability of the software. As an alternative to more complicated models, the modelling can be done in a more reliable modelling software such as Autodesk Inventor and Solidwork that are readily available within the university's and SIRIM Berhad's computer facilities. The exported model to be used in ABAQUS will be converted to .step extension prior to the analysis within the ABAQUS interface [38].

A standard stainless steel pipe available commercially will be used for the model. Although it is possible to complete assembly of 3 dimensional models, only the horizontal parts of the pipe will be used in the analysis. For the model pipe, length is 4 meter, with an outer diameter of 60.3mm and 2.5 in thickness. Initially, the fluid loading within the pipe will be restricted to air while other fluid presence will be introduced once simulation results comply to the theoretical travelling time period [39][40].

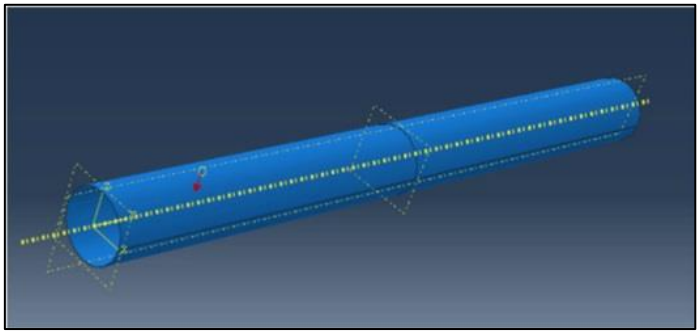


Figure 3.3: A 3 dimensional model built in ABAQUS

To replicate the real life defect condition identified in the literature review, various defects length of L_n were be introduce on the outer circumference (imitating the corrosion real life effect) build through plane offset along z-direction.

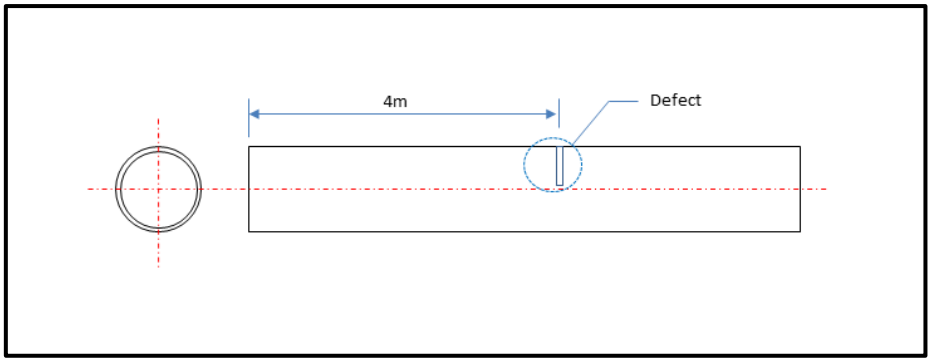


Figure 3.4: Artificial defect location representing material loss due to corrosion within typical pipeline.

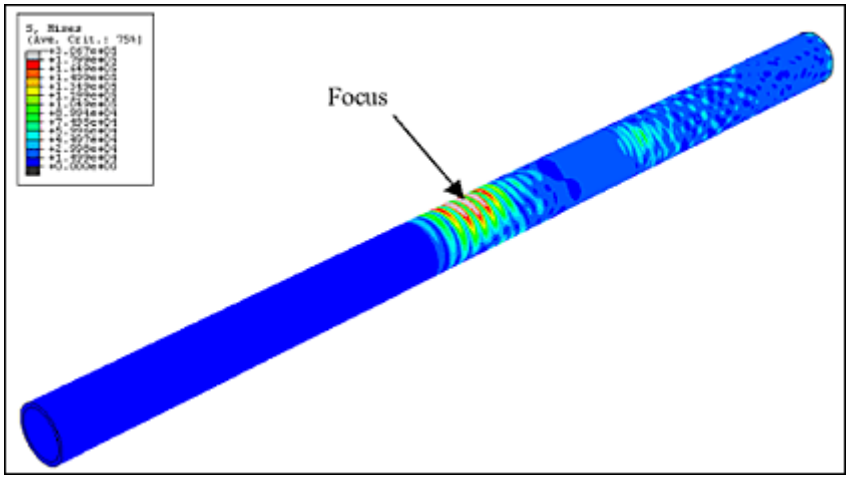


Figure 3.5: Showing focus area during FEA simulation

3.2.3 Solid and Fluids Material Properties

Material module in ABAQUS requires accurate definitions for better simulation. Therefore a detail material properties table will be used as a reference to the analysis. A solid and acoustic type material definition will be used in the simulation with fix determinants from second option user defined input. TABLE 1 & 2 are the proposed input properties; [41]

Material	*Density (kg/m^3)*	*Young Modulus (GPa)*	*Poisson's Ratio*
Stainless Steel	*min – 7.8x10^3*	*203*	*0.265*

Table 2: Solid media material properties

Medium	*Density (kg/m^3)*	*Bulk Modulus (Pa)*	*Speed of sound in medium, c (m/s)*	*Kinematic Viscosity*
Air	*1.205*	*1.01×10^5*	*343*	*15.11×10^6*
Water	*999.97*	*2.2×10^9*	*1,484*	*8.94×10^4*

Table 3: Acoustic media material properties

The solid media will be defined as homogeneous material while the fluids will be given acoustic definitions within the material input file. All properties of fluid are taken at atmospheric pressure and at a temperature of 28 degree Celsius.

3.2.4 Coupled Acoustic-Structure Constraint

ABAQUS is a flexible tool in modelling fluid displacement within the acoustic domain, however a proper definition to the initial interface condition between solid-fluid medium will be very important to the analysis.

TIE-Fluid Structure constraint was used for constraint at acoustic-structure boundary for the duration of simulation. This surface pairing would be able to perform translational and rotational motion for the surface pairs.

Slave Surface	*Master Surface*	*Degree of Freedom*
Acoustic	*Stress*	*Translation*
Stress	*Acoustic*	*Acoustic Pressure*

Table 4: Possible pair at surface boundary

3.2.5 Step Analysis

In obtaining the most efficient loading frequency of the incident wave, a wide range of frequency was introduced for the different modes of propagation. In doing so, the effective wavelength changed accordingly. Throughout the simulation, increment was based on the

effective wavelength and speed of propagation. Total step time was based on the theoretical travelling time using;

$$\lambda = \frac{velocity}{frequency} \tag{17}$$

The time obtained was used to predict the results before proceeding to the next step within the FE analysis.

3.2.6 History Output Database

A geometric or node set will be built within the solid region of the pipe, emulating the location of piezoelectric sensors in the experimental rig. History output database was acquired from the set location with the sampling rate of every step analysis increment value (based on the sampling frequency during experiment). The variables option is the subset of both displacement and velocity.

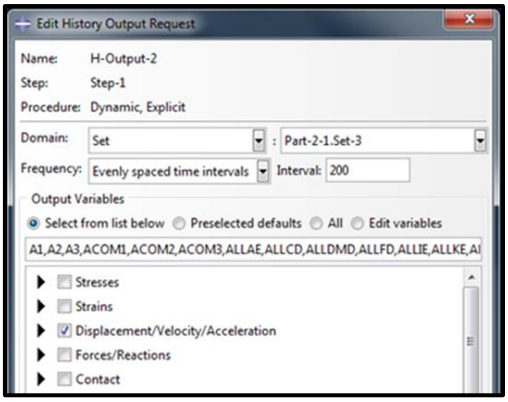


Figure 3.6: Cut out from the HOD window of ABAQUS

The iteration was obtained at every space time intervals of 200. As for the output variables, chosen parameters were displacements, velocity and acceleration.

3.2.7 Incident Wave Interaction

The incident wave within the FE model represent the excitation wave produced by the transceiver, the travelling modes were defined through the Cartesian origin at the set created within the structural model. Although the point load can both be defined through geometric set or the nodes, in this thesis the later was used throughout. Simulating an impulse incident within the acoustic fluid medium requires incident wave definition from a point source from within the solid region of the model.

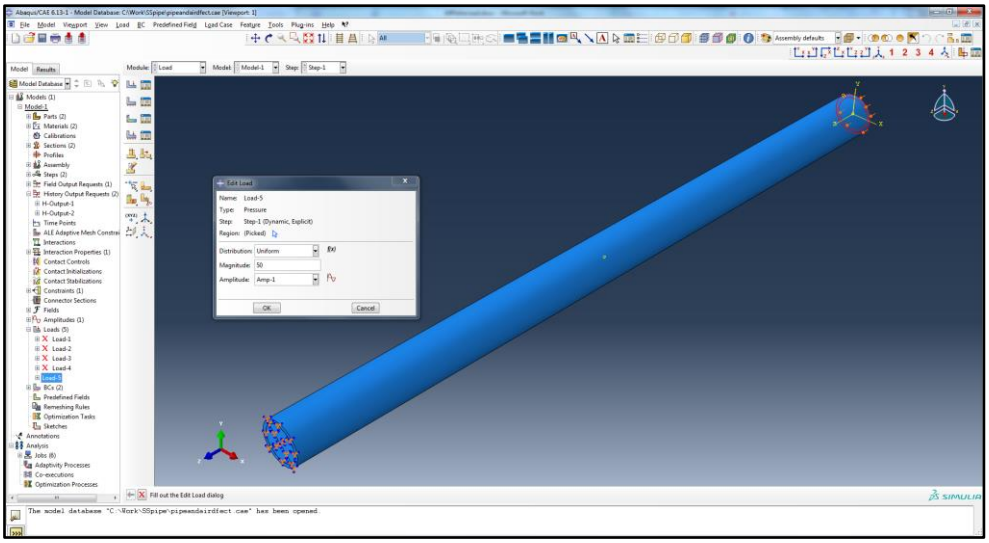


Figure 3.7: Showing incident wave loading example on solid media of pipe with the Cartesian cut out

3.2.8 Loading Amplitude

Propagation of waves occurred when the equilibrium is disturbed as it is subjected to loading condition i.e. the forces or displacement on nodes. In NDT cases the load often being the Henning window tone burst signal but in this research we introduced the 3 cycle's impulse loading for a period of 0.4×10^{-6}s [42].

Defining this window in the FEA domain requires modifications to the function, simply by creating tabular input method to the loading amplitude in ABAQUS.

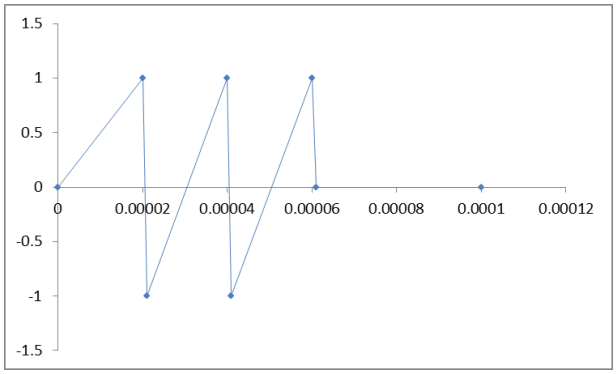


Figure 3.8: A typical mode pulse in the loading amplitude

3.2.9 Meshing Strategies

A meshing strategy of least 10 elements per wavelength longitudinally along the pipe length and 3 elements along the thickness should be deploy in making sure that the capturing of position is done properly.

$$l_{elem} = \frac{\lambda_{min}}{10}$$

(Where l_{elem} is the element length and λ_{min} is the shortest wavelength of interest)

Applying this rule to the meshing strategy will ensure that every interval of propagation will be captured by the history output database. The wavelength value for sound wave propagating through the solid media of the pipe was obtained through literature reviews available on acoustic wave properties [43][44].

Material	Speed of sound (C)
Stainless Steel	6400 m/s

Table 5: Speed of sound in the lamb wave travel media

The changes of wavelength for every variation of frequency in the analysis were based on the speed of sound, and the element size maintained below 1/10 of wavelength.

For general purpose of validation, the travelling period for acoustic wave in air was calculated based on the speed of sound wave at 28 degree Celsius temperature, travelling at 40 kHz i.e. at 6400 m/s [45].

To validate the feasibility of simulation data, the group velocity of the wave propagating in simulation shall not exceed 20% difference of the wave predicted based on the parameters above.

The time of flight for the pulse to travel from the source was determined and the predicted travelling time Δt_{Ln} can be obtained from the simple formulation below;

$$v = f\lambda \tag{18}$$

where v is the speed of sound in the media derived from frequency, f and the wavelength.

$$v = \frac{s}{t} \tag{19}$$

Expressing the equation in time domain,

$$t = s/v \tag{20}$$

The predicted time at location for various frequencies, at 28 degree Celsius are to 6.25 x 10^{-4}s for the defect and 12.5 x 10^{-4}s for echo coming from pipe end.

3.2.10 Signal Processing

For wave propagation problems with zero damping (C = 0), exact time may yield very inaccurate solutions of the original (due to large spurious high-frequency oscillations). At very small time increments, integration by a time-integration method with or without numerical dissipation may yield very inaccurate results due to spurious oscillations. Moreover, mesh refinement and small time increments can lead to divergent results. Therefore, the treatment of spurious oscillations is crucial for obtaining accurate numerical results. A low pass filter using MATLAB Butterworth filter was used in this research to eliminate the noise [46].

The time domain reflectometry (TDR) techniques were used to plot the incident and the reflected narrow band pulse propagating within the pipe. Identification were made to the single planar mode that best represent the reflection characteristic, simply by varying the frequency of the sampling [47].

3.3 Experimental Set-Up

The experimental set-up consist of two major topics i.e. the mechanical set-up and the electrical set-up. Both planning were done simultaneously, however the fabrications of parts have been the challenge throughout this research.

3.3.1 Mechanical Set-Up

This section details up the experimental setup that was used to simulate real pipeline conditions and also induce artificial defects into the pipelines. The first stage was to develop a system to demonstrate the working principles of the guided ultrasonic waves as a means of condition monitoring.

The experimental apparatus consists of 6 metre steel pipe (L), with optional diameter and thickness (refer block diagram in figure 3.10). This is to accommodate the availability of material within the dynamic lab and the ease of machining as well as the waiting time for fabrication. Any alterations with regards to the sizing in different research can be regularised in the finite element analysis.

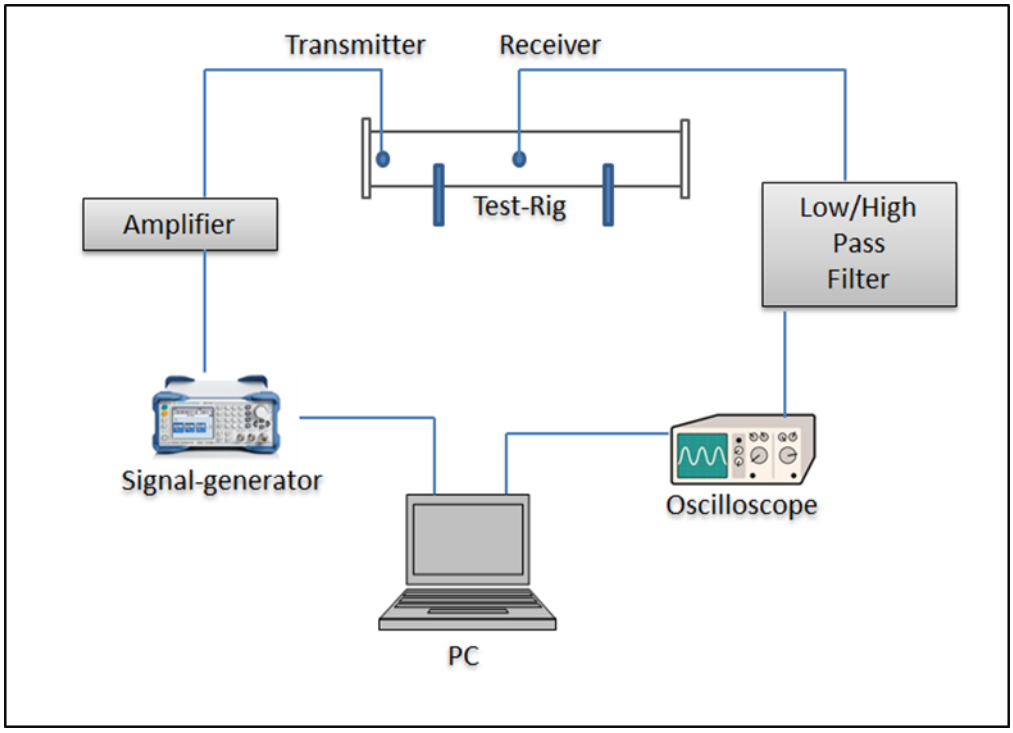


Figure 3.9 : Experimental rig ultrasonic system block diagram

The two main components for the experiment are the transducers and the receivers that was supported by all other research components to complete the system. The guided electronic system chosen was the Teletest LRUT system.

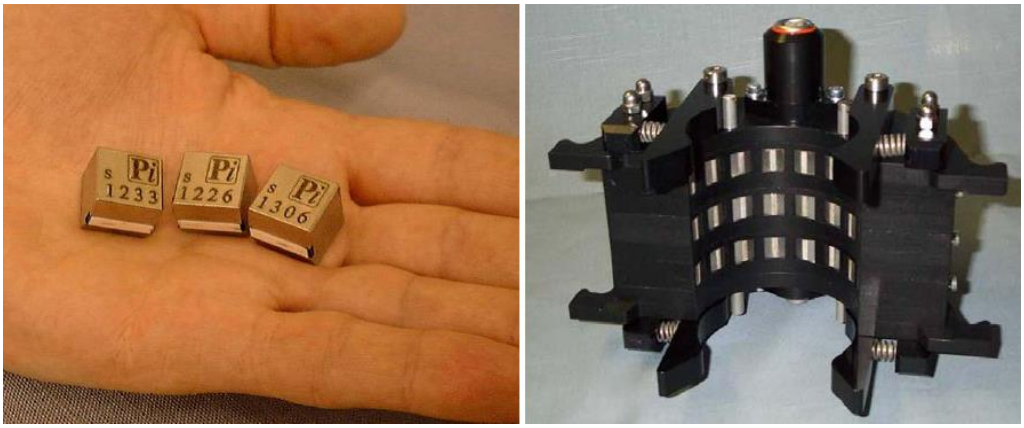


Figure 3.10: A complete set of Teletest LRUT system

After completing an extensive review of available system in the market (refer Table 5), the Teletest system has already been used in many research related to the transient response analysis of ultrasonic waves in various solid media.

System	Description	Year	Availability
Teletest	- Commercially available system to utilise long-range guided wave ultrasonic testing for detecting corrosion in pipelines. - Developed by TWI in response to requests from research institution. Industrial Members in the oil, gas and petrochemical industries. - Ultrasonic transceiver ring detector with transducer ring or tool that wraps around the pipe.	1992	Immediately
MSS	- The MsS System is composed of the MsSR3030R equipment, MsS Probe, and a laptop computer. - It utilizes the magnet effect to generate and detect ultrasonic waves affecting the small change in the physical dimensions of ferromagnetic material when an external magnetic field is applied to it.	1999	Procurement needed
GUL	- Detects low frequency as travelling along the pipe wall. Using three primary component i.e. transducers, wave makers and controller unit. - It used 100% volumetric inspection with pre design clamping unit.	1999	Procurement needed
TechCorr	- Works most effectively in straight sections of pipe. The ultrasonic signal will be attenuated or totally absorbed by elbows, flanges, tees, welded supports, socked welds, and other obstacles	1999	Procurement needed

Table 6 : Summary of available LRUT system available in the market

3.3.2 Mounting of Transducers

In this work, 16 transducers were used to excite the particle within the pipe. All the transducers used are non-resonant dry couple type with shear mode excitation operation. The transducers were mounted along the longitudinal length of the pipe with an array of positioning along the outer circumference, known as the collar. Pneumatic system was used to create the required forces at contact point between sensors and the pipe. Every longitudinal arrangement of the sensors is equipped with 5 pin LEMO. The effective diameters for the system are from minimum of 4 inch to a maximum of 6 inch outer diameter pipe. Adjustment to the size can be made using the two available bolts connection [31].



Figure 3.11: Experimental rig used in a common pipeline

3.3.3 Artificial Defects

Lathe machine will be use to clear around the circumference on the inner surface of the pipe as shown in Figure 3.4. This is to simulate a crack or corrosion at the outer surface of the pipe. The induce defect location will be machine at 4m of the excitation source. One point of the pipe will be closed with a flange to allow indicative reflection source.

3.3.4 Manufacturing & Assembly Procedures

The needs statement for experimental design will be the guideline to conceptual design analysis before proceeding into detail manufacturing design. All manufacturing and procurements procedure are to be aligned with the governing rules within the University of Nottingham guidelines [48].

As this thesis only looks at some part of a larger research that are already in place, the set-up for mechanical components were designed is such a way as presented in figure 3.13, complete with the presence of pump and internal fluid. The main concern of this thesis for the time being is the horizontal pipe shown in figure 3.12.

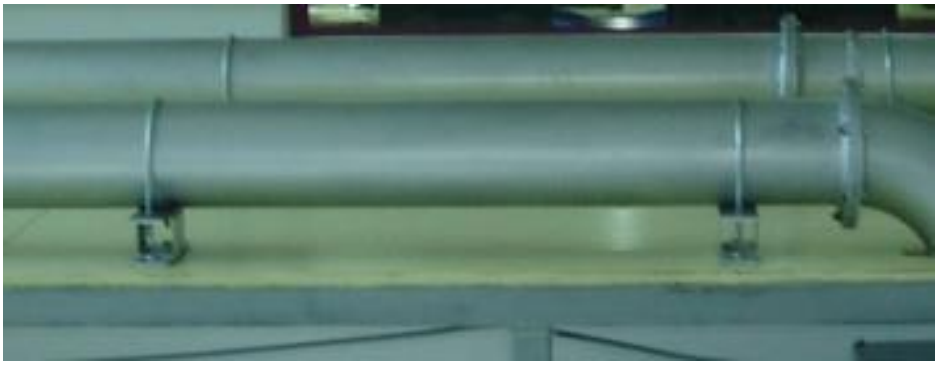


Figure 3.12 : Experimental pipe set up

Detail drawings were the reference documents for both the owner of the research and technicians that were handling the manufacturing processes. This is to make sure that a continuous improvement to the process can be achieved during the research period.

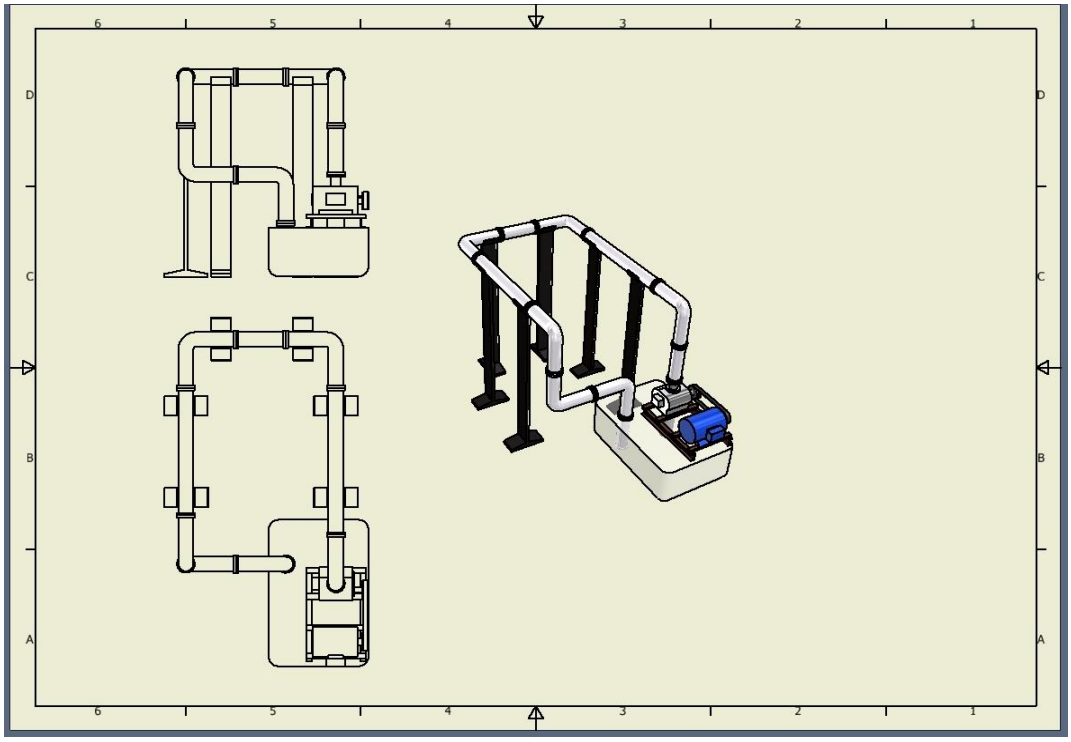


Figure 3.13 : Submitted design for laboratory set-up

Figure 3.13 shows the detail design submitted for the laboratory set-up and later fabricated for the experiment.

3.3.5 Electrical – Set Up

The aim of this set-up is to measure the signals on the nodes location within the pipe for the purpose of monitoring the reflectometry of acoustic wave echoed from the defects. A sound transmitter will be used to transmit a signal across the flowing pipe and through the defect area to see changes in the acoustic signal.

Changes in the acoustic signal voltage before and after the defect area were used to determine the time domain reflectometry of the defects. Initial stage of the experiment entails realisation and validation of the detection capabilities of the sensors to the analysis data acquired through finite element analysis. Understanding on signal processing method was important in finding the accurate reading parameters.

3.3.6 Amplifications of Power

In order for the sensors to function properly in detecting the tone burst signal, the signal requires amplification to a sufficient voltage level and subsequently increase the signal to noise ratio.

Of the shelf power amplifier from APEX (PA240) were used to execute the task of amplifying the voltage. With two ICs the amplifier is capable of generating up to 660Vpp.

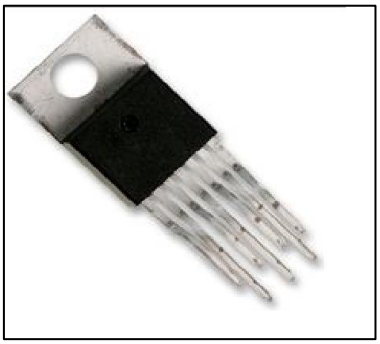


Figure 3.14: PA240 power amplifier

The circuit diagram used for the power amplifier design was based on the datasheet provided by the supplier. In the final design, 100 kΩ feedback resistor and 10 kΩ input resistor were used. Output voltage was adjusted to the required level by using variable resistor pot [49][50].

3.3.7 Signal Processing

Data acquisitions of the signal at sampling position were made using sensors discussed earlier in the chapter. The signals were acquired through a DAQ with 16-channel, 7 µs sinking digital inputs and 16-channel, 500 µs sourcing digital outputs. Compatibility of the DAQ is with 24V logic levels with the range of output up to 30V [51].



Figure 3.15: Labview 16 channel DAQ used for the research

Commercial ready data acquisition software by national instruments was used as the data acquisition software. These data were processed in MATLAB and filtrations of noise were made using built in filter in MATLAB.

CHAPTER 4.

RESULTS

4.1 Overview

In this chapter, we will be looking into the key results obtained throughout the research. Validation of the FE Analysis method was initially performed to identify the boundary condition that produce accurate wave reflection. The validations were made by comparing predictive theoretical time travel and the travelling time of wave within the FE model.

Once the technique identified to be the correct approach to FE solution, this chapter will unsolved the greater questions of this research by modelling the exact model with introduction of various defects. Displacements of nodes were obtained at the same positions to the one in experimental LRUT excitation [28].

Experimental results gathered through all 16 channels within the DAQ will be presented in the later part of this chapter. The conclusive comparative analysis of both experimental and finite element simulation i.e. the key findings to this research will be discussed at the end of the chapter.

4.2 3-D Finite Element Modelling

In this topic, step by step results from the validations of method to the final results of finite element method will be represented.

4.2.1 Validation of model

3-dimensional pipe models were built in ABAQUS for pipe and air element only. A partition was made at the opening end of the longitudinal length of the pipe to allow for a placement of sensors set point and defect modelling respectively (figure 4.1).

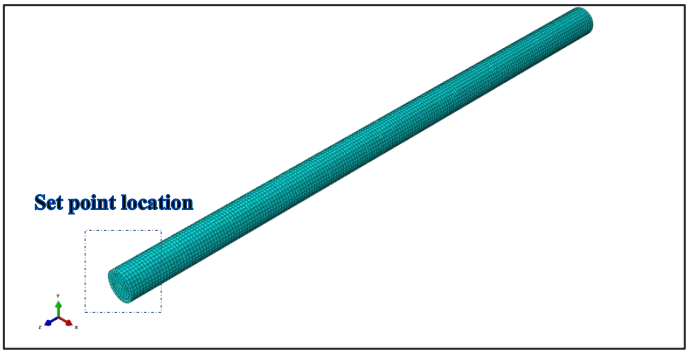


Figure 4.1 : Showing 3D modelling of pipe with meshing in iso view

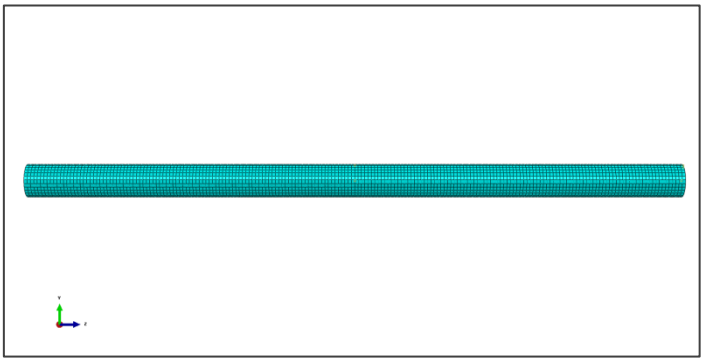


Figure 4.2 : Showing 3D modelling of pipe with meshing

Material assignment used for the pipe and air within the pipe are according to the material properties in Table 2.0 & 3.0. As this modelling being the maiden model for the purpose of qualifying a method, solid modelling was used for both materials. Only two surfaces defined

in all of the models i.e. the inner surface of pipe and the outer surface of air definition as those are the two interfacing surface, with frictionless interaction.

The objective of this analysis is to study the reflective acoustic signal travelling time within the solid element in pipes without defects within the pipe. A closed end pipe was used by simply applying fixed boundary condition to the closed end circumference.

A plot of displacement at U1 and U2 were extracted from history output database in ABAQUS and analysed using MATLAB, with built in low pass filtering. Detailing of test pipe parameters are given in the Figure 4.3 below.

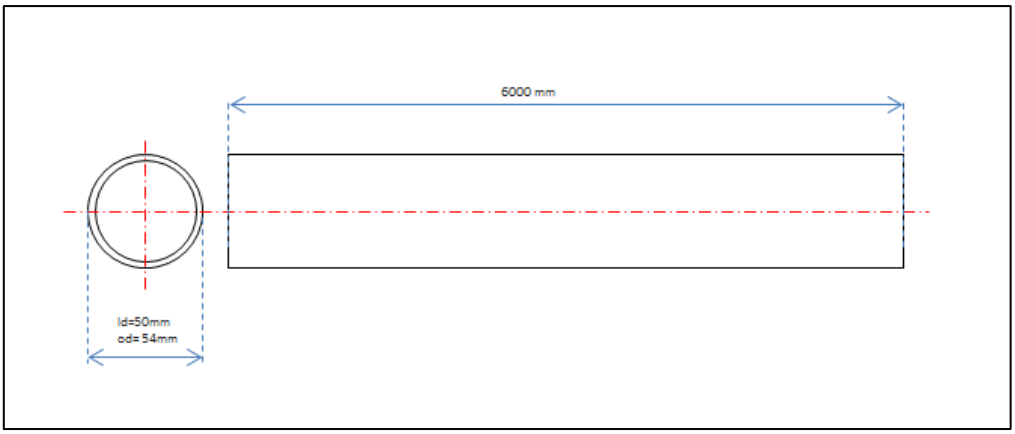


Figure 4.3: 2D representation of test pipe

A dynamic, explicit step was executed in this analysis. The time step was set at 1x10-7 interval. To monitor the responses on the node, a history output database was requested at the node selected at geometry set within the solid element at the incident wave source, for every interval of the step.

Pinned boundary condition was stated to be the boundary condition by selecting the open surface at pipe end. The opposite end of the pipe was subjected to an average pressure loading on the –z direction at a magnitude of 0.01N at a magnitude referred in the previous chapter.

The boundary layer condition between air and inner pipe surface was set to be frictionless for the entire step of the analysis. Assumption was made on the propagation to be an elastic laminar flow without energy losses during the propagation i.e. at zero damping.

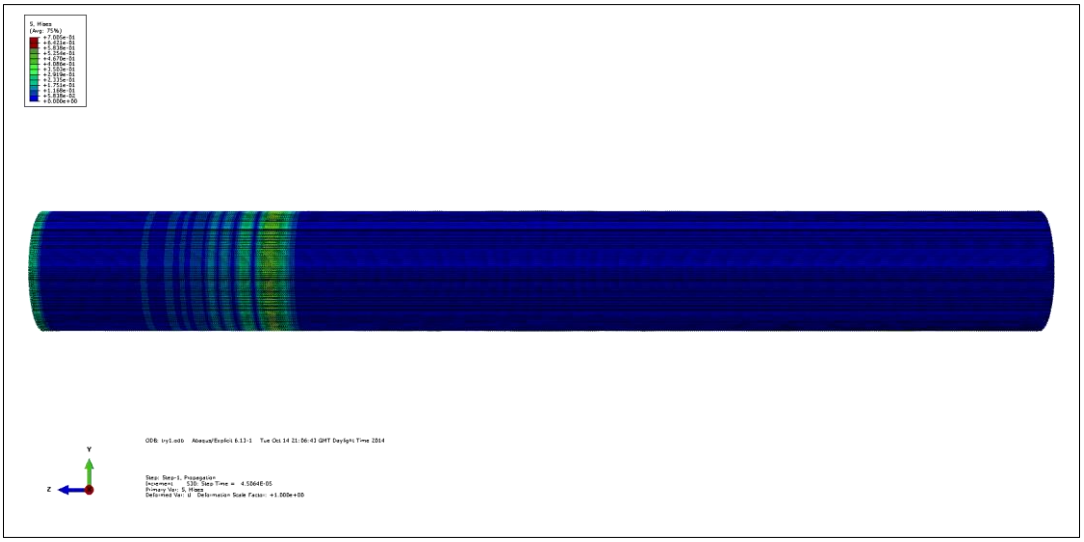


Figure 4.4: Screen shot showing propagation of lamb wave for test pipe

The study concentrates on the solid domain of the pipe rather than the acoustic inner air. Therefore a fine meshing was used on the pipe and coarse mesh size was chosen for the acoustic region. This technique allow for shorter period of analysis time due to less interpolation for nodes.

Figure 4.5 plot shows the trend of analysis period with accordance to the mesh sizing.

The time taken for analysis period increase as the size of element become smaller as this is mainly due to the higher number of iteration within the Finite Element Analysis. Although very few analysis were done at mesh size of below 0.05mm, it really shows that the analysis time is too long and would be suitable for larger structure.

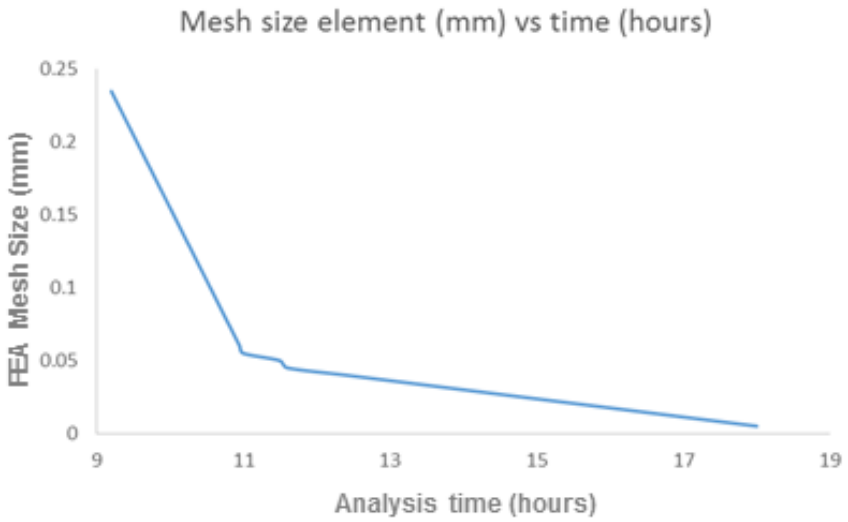


Figure 4.5: Plot of Analysis Period vs Mesh size

By observing the time domain plot of displacement of node 223 (shown in Figure 4.6), one can see the propagation of lamb wave within the pipe structure. The first peak in the beginning shows the incident wave excitation and the reflection can be seen clearly after certain interval. As the test model of the pipe is short, echo can be observed towards the end of the plot. This interval represented the travelling time of the propagated wave in the solid domain.

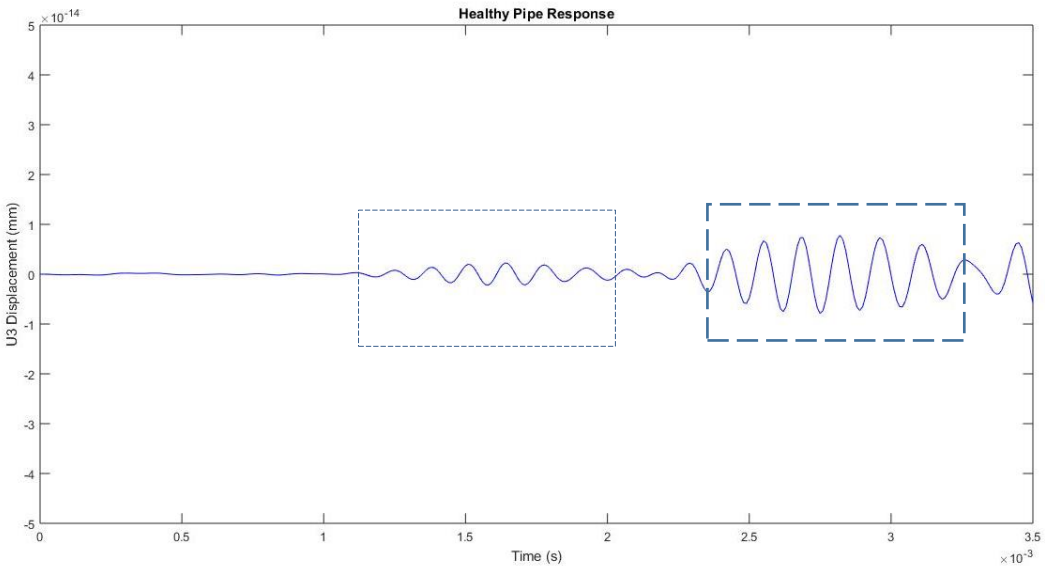


Figure 4.6: Plot of node displacement in time domain

Finding the sampling period was very critical, as the propagation of wave tend to be dispersed after certain period of time. The first interval of echo arrival was 10% slower than the theoretical travelling time of 2.36 x 10e-3s.

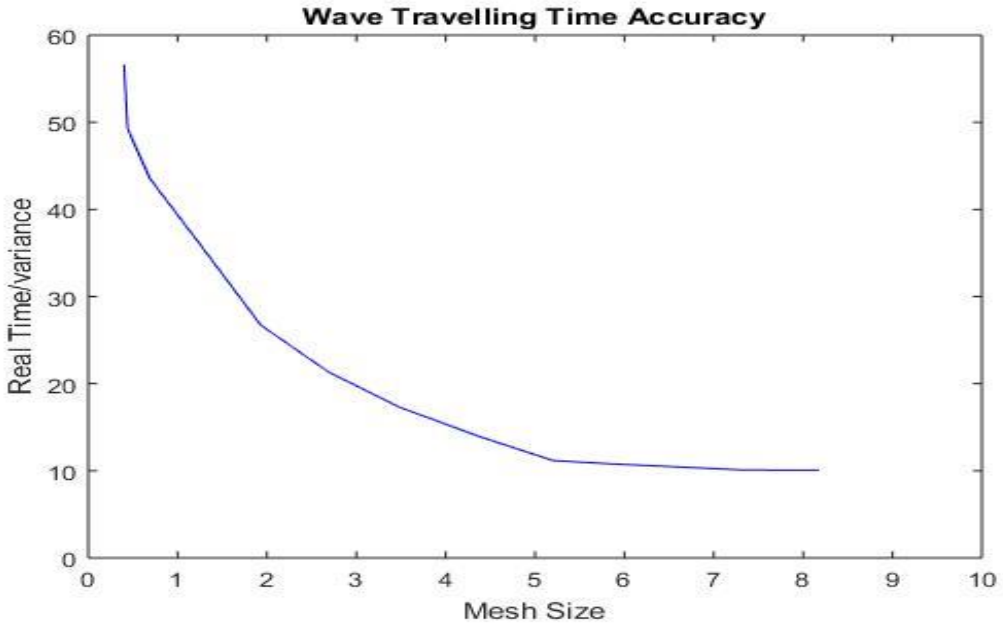


Figure 4.7: Travelling time accuracy for various mesh size

As the mesh size becomes smaller, the accuracy of time travel period increased (as shown in the previous plot in Figure 4.7). The accuracy does not improve as the mesh reduces to 1/10 of the length of the investigated lamb wave.

However, the test model showed reliability of the modelling technique and shall be an acceptable approach in determining the responses at all 16 locations within the full scale FEA model. In the next section we will discuss the result from full scale modelling in FEA with various modes of excitation.

4.2.2 Complete Model of 3D Finite Element Analysis

After completing the test model and validating the method, full scale model was built for all different defects situation. Meshing strategies of all models were maintained to be the same as the strategy used in the previous section; however due to the introduction of defects to the full model, partition were introduced at defects regions.

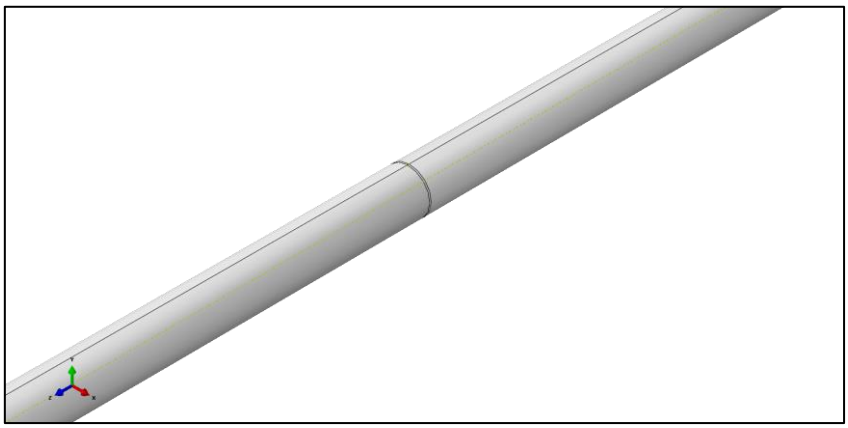


Figure 4.8 : Showing partitioned region on pipe

In representing the various modes of excitations, point loads were subjected to the nodes at the open end of the pipe. Cartesians loading placement were made according to the angle of incoming excitation signals coming from the LRUT.

A pinned boundary condition was introduced at the close end on pipe, with equally distributed force along x, y and z direction. Although this condition created a very dispersed propagation for the wave reflecting from it, the arrival of the end pipe echo is later than the echo from the defects itself, therefore the dispersion can be ignored.

The total STEP time for the analysis was fixed at 0.05s, a period that was long enough for the lamb wave to propagate and reflected by the discontinuity within the pipe. At a STEP time of 1E-7, the iteration captured almost every change to the node displacement [52].

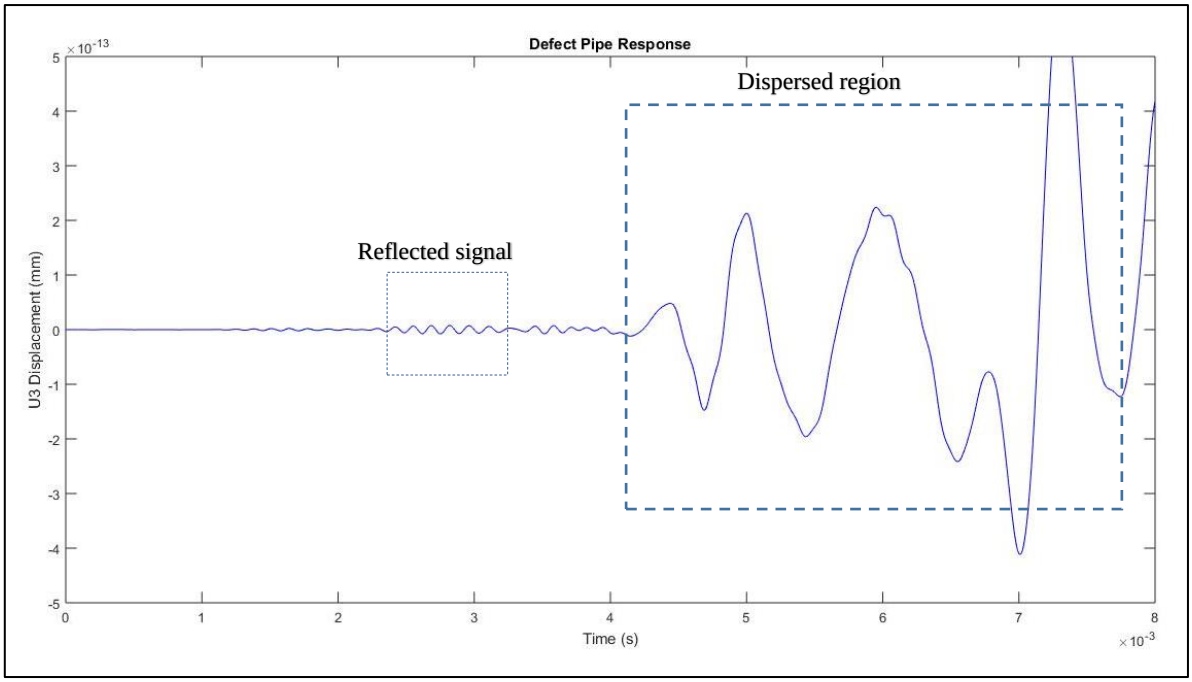


Figure 4.9: Plot of node displacement in time domain

All plots show a consistent reflectometry interval as the location of the defects was maintained within the models. However, the amplitude of displacement varies according to the size of defects. The bigger the defect width, higher amplitude is observed. This behaviour is due to the changes of the energy within the solid particles as it reaches the discontinuity within the pipeline. All of the characteristics of the propagation confirmed to the energy equation discussed in chapter 2.

Although 16 sensors point were taken to be the reading points of the nodes, only one of the less dispersed signals was taken as the reference point. Since the locations of sensors are symmetrical, the reading between reflections does not differ [53][54].

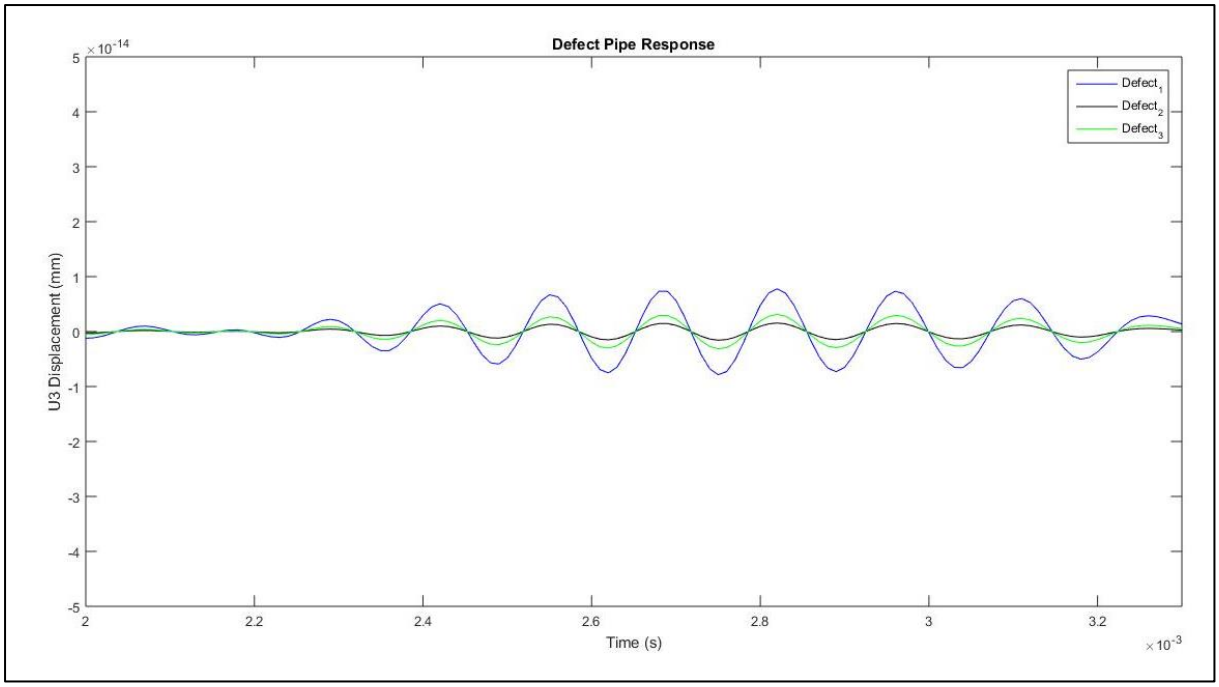


Figure 4.10: Plot of node displacement in time domain for various defect sizes

The finite element modelling method proven accomplishes the task of modelling the lamb wave propagation, within the solid domain of a pipeline. Although it is clear that the time interval confirmed to the theoretical time, there is a need to validate the amplitude of the signal itself by comparing to either theoretical or experimental data.

The calculation method with theoretical method can be time consuming and complicated. With the availability of equipment as describe earlier in chapter 3, validation of the finite element models can be made easier with experimental results.

In the next section, we will be looking into the result obtained through experimental works and will discussed in the following chapter.

4.3 Experimental results

Piezoelectric sensors within the transceivers convert the strain at the surface of the pipe to voltage output. The outputs from all 16 transceivers were then acquired via the DAQ and all the responses were recorded by the NI software.

Next, data were then transferred to MATLAB and processed, eliminating the unwanted signals. In determining the type of filtrations suitable, data was initially plotted in frequency domain through fast Fourier transform. From then onwards, either low pass, high pass or band pass filters was performed to the sets of data according to the suitability.

As the profiling of the reflectometry is the key to the comparative analysis between the simulation and experiment, time domain analysis was found to be better option. Once again the best signal out of the 16 channel was carefully chosen and identified for analysis.

4.3.1 Single Mode Excitation

Controlling the excitation pulse is very critical to the mode of propagation and the amount of noise produced by the propagation. Tone burst signal is the best option by implementing it within a Hanning window. This can be achieved by generating the signal with built in function within the Labview software. The frequency of excitation was 20 kHz at 180Vpp.

4.3.2 The Echo Signal

Echo signal coming from the output piezoelectric sensors are sampled by the DAQ. Although a sampling rate of 40 kHz will be enough to capture the echo and eliminate aliasing effect, 100 kHz sampling rate were used to capture higher resolution of data.

In the plot shown (Figure 4.11), clear echo signal can be seen within time domain. As the amplitude of the echo signal reduced from the initial incident wave, its frequency remains to be the same. The next plot will show changes to the echo signal due to induce defect to the pipe.

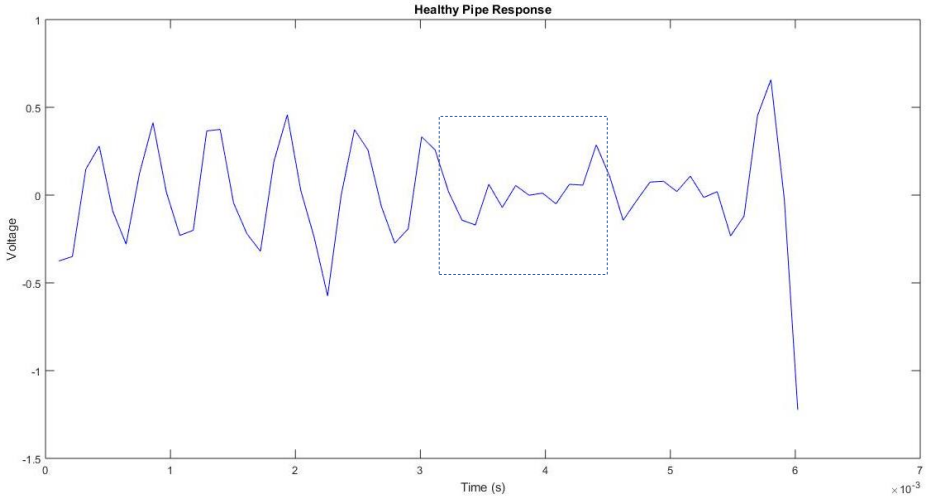


Figure 4.11 : Healthy pipe response signal

The classification of default can be made by monitoring variations of echo signals with respects to the changes to the size of defect. There is an unambiguous relationship between the defects and the amplitude of its echo signals. From the plot in Figure 4.11, it is apparent that the echo signal from the defects present in between the two peaks within the time domain signal.

With the identification of the pipe end reflective signal, variations to the size of defect were then introduced to exhibit the characteristic of reflectometry to changes in solid domain of the pipe structure.

In Figure 4.12, the time domain plot shows a peak occurring between the incident and pipe end reflection. The change was due to the introduction of 1mm defect, as the lamb wave propagates through the defect. Part of the lamb waves were reflected from the defect, while the larger part

of the wave propagate further towards the next changes in longitudinal structure i.e. the pipe end flange.

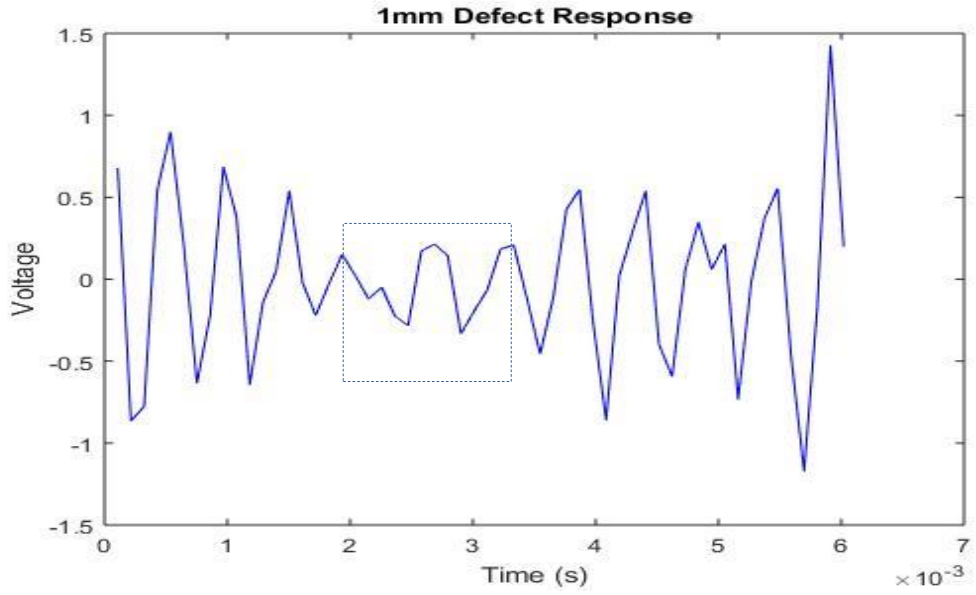


Figure 4.12 : 1mm defect size response

As the size of defect increases, a clear indication can be seen on the reflective signals (Figure 4.13 and Figure 4.14).

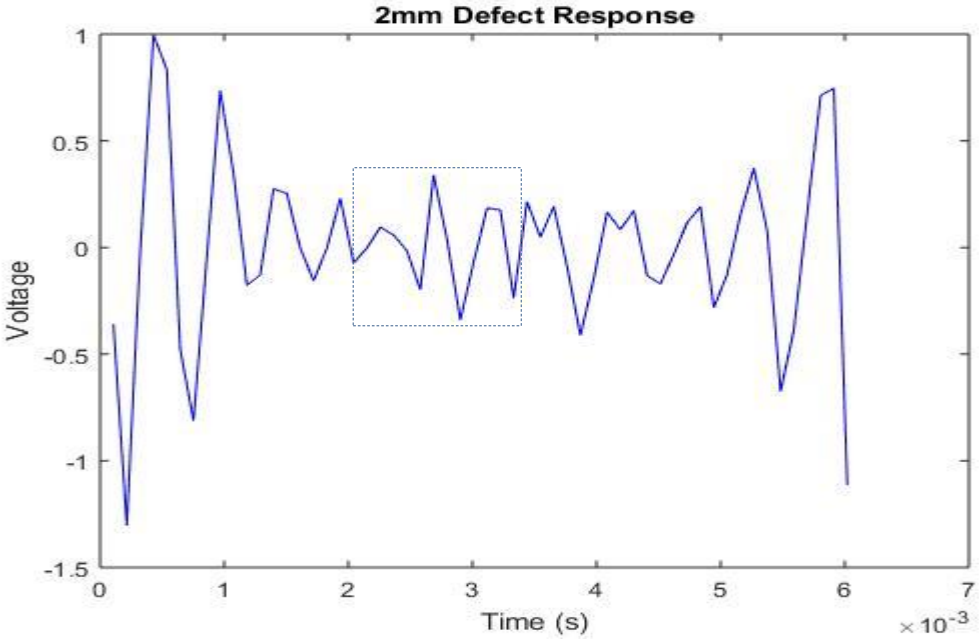


Figure 4.13 : 2mm defect size response

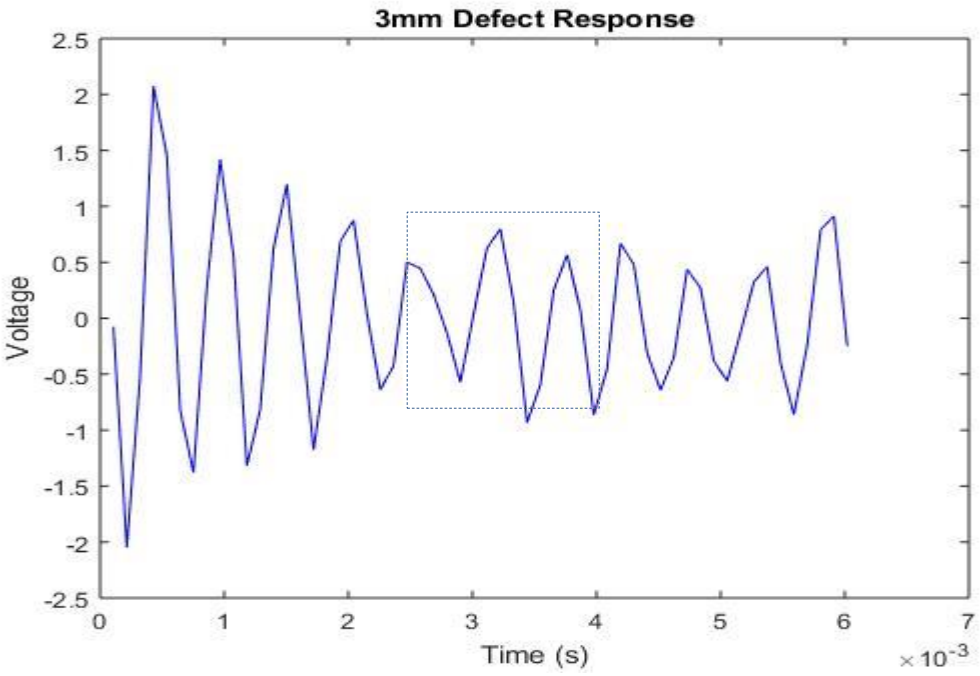


Figure 4.14 : 3mm defect size response

At 3mm defect size, the peak is once again observed between the arrivals of pipe end reflection. The results indicated that the relationship of defects to its reflectometry can be determined by both experimental and simulations. The next topic, therefore, moves on to discuss the comparative analysis of the results and the opportunity that lies ahead of this findings.

4.4 Discussions

The validation of method through experimental results is an important factor in qualifying Finite Element Method to be the correct method of modelling defects reflectometry in pipe. Modelling of greater data can only be built in Finite Element once the results confirmed to the experimental values.

In this topic we will be looking into both experimental and simulation data within its characterization values of defects. The aim is to look at viability of Finite Element Model.

4.4.1 Strain

The deformation reference position of material points in the pipe is the strain values of nodes used in the analysis. Such a measure does not distinguish between rigid body motions (translations and rotations) and changes in shape (and size) of the body.

As two tensor quantities can be obtained in experimental and FEA analysis, physical insight into strains within a node can define propagation of wave within. This could be applied as the common denominator, and eventually comparison can be made for each defect condition.

4.4.2 Comparative Analysis of Strain Value at Reflectometry's Peak

A comparison of the two results reveals the potential of the Finite Element Analysis Method to be adopted in the current prediction method produced by the University of Nottingham. Plot in figure 4.15 prove to be substantial evidence to the hypothesis.

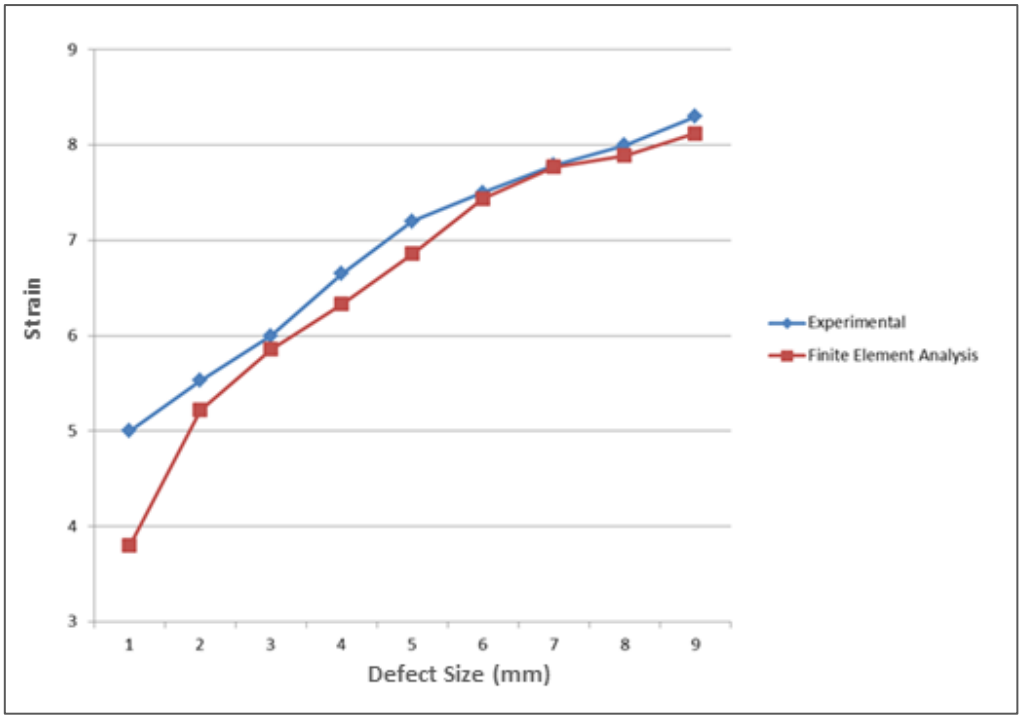


Figure 4.15: Typical plot of dimensionless strain of various defect sizes (mm) for both experimental and finite element analysis

It can be clearly seen that although the Finite Element Analysis data for this study is not perfectly representing the experimental results, the method will be able to give an indication to the reflectometry characteristic. Although it is very early to make conclusion that the Finite Element Analysis is a total solution to identifying type of failures or defects, the result offers great potential for greater development.

CHAPTER 5.

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

Four objectives of the research were achieved based on these statements;

1. An extension to the knowledge on propagation characteristic of a typical oil and gas pipeline through 3-D Finite Element Analysis was presented in the thesis.

2. In the results section, node displacement amplitude responses for various conditions of defects within the pipeline were discussed and greater understandings to the acoustic reflectometry from defects in time domain were unveiled.

3. A complete experimental design was built for the research and achieved the desired objectives of the experiment.

4. Investigation of Finite Element models and validation of the results were obtained confirming the potential of Finite Element Method in the build-up of training data for SVM.

Earlier in Chapter 2, the literature review shows a gap in the knowledge in finite element modelling of pipe with the presence of both defects and for the purpose failure detection using SVM.

In Chapter 3, a clear methodology was presented for both experimental and simulations work. The results in Chapter 4 shows a great potential of justifying the hypothesis of an online detection using long range detection via finite element model. It is a method that allows better understanding defect/failure detection in pipe.

From the simulations and experimental results in this research, conclusions can be made and discussed in this chapter.

5.1.1 Modelling of Finite Element Analysis

Finite Element Analysis is the potential tool in understanding the knowledge on propagation characteristic of within a typical oil and gas pipeline without having to build the physical models of long and expensive pipeline [11][2].

The value of amplitude responses for various conditions of defects within the pipeline in time domain can be acquired through the FEA model, with a certain degree of consideration to the boundary condition.

5.1.2 Defects Reflectometry Characterisation

From the time domain responses discussion in Chapter 4, a clear reflectometry characteristic can be seen for all different defects induced to the pipe for both experimental and simulation works. Those values will be the critical input to later analysis work of prediction using SVM.

The inputs to Finite Element Analysis solutions presented shall be the prime knowledge to other work related to lamb wave propagation. Meshing techniques, boundary condition and the other inputs offered in Chapter 4 can be replicated in solving other related models [34].

5.1.3 The Realistic Analysis Time

Performing the analysis as reported in Chapter 4 is a time consuming effort. Increasing the length of the pipe to a longer and more complicated structure will require a larger number of iteration within the FEA environment.

Better specifications for the hardware such as better processor will be important factor before engaging into more complex structure.

An introduction of multicore processor will be needed if the research team would to embark into the building of greater defect database for SVM.

5.2 Future Works

Work reported in this thesis opened new avenues for research and technology development and improvement as outlined below.

5.2.1 Modelling Of Multiple Defects and Components

Throughout this thesis, the works concentrated at only single defect type with multiples sizes. Artificial defect sizes were introduced to replicate thinning of pipeline, nothing further.

Numerous other components are used within a pipeline, along hundreds kilometres. Various number of defects, such as blockages or pits are often found in common pipeline.

In the future, works shall continue on the modelling of all the defects discussed in previous paragraph, with more research on the meshing techniques.

5.2.2 Training of data in SVM

As discussed in 2.4, the usage of neural network is the front in classifying defect signals from an LRUT. Support Vector Machine (SVM) being the tools, the work in this thesis can be the core to greater findings.

More data will be needed for SVM to train before any defect can be translated instantaneously by the field users. With Finite Element Analysis capacity of modelling without having to build physical rig, the number of defects that can be identified will be limitless for as long as the method of modelling it is suitable.

5.2.3 Working in the Acoustic Medium

The capability of solid medium of pipe analysis using Finite Element Method was evident in the thesis. However, there is a need to understand the characteristic of propagation from within the pipe.

An online detection method can be established from within the pipe although greater investigation will be needed to clarify the propagating wave criteria in the non-isotropic media.

Adding the presents of transported fluid can be the new challenge for researchers in detecting the blockages without having to empty a pipeline [37].

5.2.4 Improving the Analysis Time

Among the biggest obstacle stumbled upon by the author throughout the research is the capacity of processing within the commercial hardware.

The analysis time is in great need of a revisit, introduction of method such as sharing of multicore processors within an institution can be introduced to allow shorter analysis period [55].

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Appendix

```
  ABAQUS INP File

*Heading
** Job name: hp002run1 Model name: Model-1
** Generated by: Abaqus/CAE 6.13-1
*Preprint, echo=NO, model=NO, history=NO, contact=NO
**
** PARTS
**
*Part, name=Part-1
*Elset,    elset=_s_Surf-1_S6,    internal,    instance=water-1,
generate
    4,  6593,    11
*Surface, type=ELEMENT, name=s_Surf-1
_s_Surf-1_S4, S4
_s_Surf-1_S5, S5
_s_Surf-1_S6, S6
_s_Surf-1_S3, S3
** Constraint: Constraint-1
*Tie, name=Constraint-1, adjust=yes, type=NODE TO SURFACE
s_Surf-1, m_Surf-1
*End Assembly
*Amplitude, name=Amp-1
             0.,             0.,          2e-05,             1.,
4e-05,               0.
**
** MATERIALS
**
*Material,
*Density
 1.39,
*Elastic
 3e+09, 0.4
*Material,
*Acoustic Medium
 2.2e+09,
*Density
1000.,
**  ----------------------------------------------------------------
-----
**
** STEP: Step-1
**
*Step, name=Step-1, nlgeom=YES
*Dynamic, Explicit
, 0.02,, 1e-07
*Bulk Viscosity
0.06, 1.2
**
```

```
** BOUNDARY CONDITIONS
**
** Name: BC-1 Type: Symmetry/Antisymmetry/Encastre
*Boundary
Set-1, PINNED
** Name: BC-2 Type: Acoustic pressure
*Boundary, amplitude=Amp-1
Set-2, 8, 8, 50.
**
** OUTPUT REQUESTS
**
*Restart, write, number interval=1, time marks=NO
**
** FIELD OUTPUT: F-Output-1
**
*Output, field, variable=PRESELECT
**
** HISTORY OUTPUT: sensor
**
*Output, history, frequency=10
*Node Output, nset=Part-1-1.sensor
U1, U2, U3, UR1, UR2, UR3
**
** HISTORY OUTPUT: H-Output-1
**
*Output, history, variable=PRESELECT
*End Step
```