DETECTION OF PIPING INTERNAL DEFECT THROUGH SIMULATION USING GUIDED WAVE METHOD

By

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Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman
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DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

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Date ______________________________

APPROVAL FOR SUBMISSION

I certify that this project report entitled "**DETECTION OF PIPING INTERNAL DEFECT THROUGH SIMULATION USING GUIDED WAVE METHOD**" was prepared by **CHONG TECK SING** and submitted as partial fulfillment of the requirements for the Master of Engineering (Mechanical) at Universiti Tunku Abdul Rahman.

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ABSTRACT

This Project aims to evaluate the guided wave propagation of the hollow pipe. Due to the dispersion properties of wave propagation in the hollow pipe, the wave velocity and modes of propagation will change in certain frequency. The objective of this project identifies the wave propagation pattern in hollow pipe and modes change due to the effect of the pipe geometry change. Throughout the simulation, it has notice that the propagation modes will change if the hollow pipe have a defect, and the reflection of the guided wave mode has also been determined.

The guided wave frequency (60kHz, L (0,2)) selection will be based on dispersion curve generated by software named as GUIGUW and simulation by using ABAQUS Explicit dynamics, and the data analysis is by MATLAB

The pipe model will be based on 3inches (External Diameter) and 5mm wall thickness, the modeling illustrated in this thesis are 2m straight pipe without any defect, 2m straight pipe with cracking, and also a 2m straight pipe with wall thickness reduction. Besides that, another model will be included in this thesis is 90-degree bent pipe without any defect and also 90-degree bent pipe with a crack at the elbow. The material selection of the pipe will be steel material with a density of 7720kg/m^3 and the Poison Ratio of 0.29 with a Young modulus of 206 x 10^9 Pa.

The simulation result indicated that mode change will happen if the guided wave reacts with the crack of the pipe or erosion of the pipe, however, the mode change will be difference depending on the geometry of crack, the position of the crack and etc.

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CHAPTER 1

INTRODUCTION

1.1 Background

Piping is the system that conveys fluids from one point to another. It is important system throughout the planet. According to the statistical report given by Central Intelligence Agency, about 3,500,000km of piping transportation system had been built throughout the world, therefore the piping system is a part of world economic structure due to most of the valuable fluids is transported by piping system. (E.W. McAllister,2009).

Most of the piping system had been installed or operated for about a half-century. Therefore, it can be expected that most of the pipe in the piping system is aged. This will reduce fluid transportation efficiency due to scale generated internally or corroded due to environment issue. Besides that, some of the piping systems may have defect caused by external issues, such as a defect of the buried pipe due to soil motion, external dented due to the excessive load applied on the pipe surface. Therefore, inspection of the piping system is important, due to the defected pipe will cause fluid leakage or burst, if the piping system is transported corrosive gases or flammable liquid, it has potentially caused disaster to society and environment.

1.1 Piping Inspection

They are several inspection methods had been imposed in piping inspection, including visual inspection, where the inspection is done by naked eyes of the inspector or systematic inspection involving complicated hardware and software system (E.W. McAllister,2009).

The pig-based monitoring system is used a device called pig to perform piping inspection, the device is shown in Figure 1.1. the device usually used to pipe internal surface, and built-in pipeline monitoring system. (E.W. McAllister,2009). The leak detection method by this device is based on flow data, or pressure imbalance, once the device detects some error, it will give an alarm to notify the inspector.

Figure 1.1 Pigging Device (Contract Resources,2010)

Ultrasonic testing is also usually applied to piping inspection, where ultrasonic testing falls under Non-destructive testing, it is because the ultrasonic transducer is directly attached to the pipe wall without stopping the operation, the idea of using ultrasonic is simple by transmission and reflection, that is several types of ultrasonic testing used in pipe inspection, including guided waves testing, and phased array ultrasonic testing.

1.2 Problem Statement

Ultrasonic Guided waves testing is one of the non-destructive testing method applied on pipe inspection, the benefit by applying guided wave testing is because it can detect a long range of pipe by single excitation. However due to dispersion properties of wave propagation in the pipe, to determine the suitable frequency for pipe inspection is difficult.

1.3 Aim and Objective

The aims of this project are to simulate guided wave propagation in the pipe.

The objective of this project including following

1. Defect detection based on guided wave propagation through computer simulation
2. Wave propagation pattern and it dispersion properties.

CHAPTER2

LITERATURE REVIEW

2.1 Introduction

This chapter will introduce the structural health monitoring system, and non-destructive testing, and the linkage between structural health monitoring and non-destructive testing. Besides that, it will also introduce general physic of soundwave and the differences between soundwave and ultrasonic soundwave. Lastly, some general information of guided wave.

2.2 Structural Health Monitoring

Structural Health Monitoring is the process that involves observation of engineering structural over the time, structural health monitoring is used to confirm the (Tianwei Wang,2014). engineering structure condition The main purpose to implement structural health monitoring is to prevent disaster due to the failure of engineering structural, and secondly based on the data given in structural health monitoring experienced engineers are able to determine the maintenance period of the engineering structure based on conditions. In facts, condition based maintenance is more cost-effective compared to preventive based maintenance. (Singiresu S. Rao,2011)

Structural health monitoring system actually is same as a general measurement system. However, it is involving monitoring the engineering structural over a time. The general block diagram for structural health monitoring is defined in Figure 2.1. (John P. Bentey, 2005)

Figure 2.1 General Structural Health Monitoring (John P. Bentey,2005)

From the block diagram plotted in Figure 2.1, the external signal excitation is defined as the external load applied on the engineering structure. In facts, the external signal excitation sometime is not really needed an extra device to perform. For example, acoustic emission effect, water hammer effect, that effect will create stress wave and then propagate within the engineering structure, the propagating wave can be used to do the monitoring as well. Sensing element is the device that transforming useful physical variable such as amplitude, acceleration, pressure and so on into electrical signal, the electrical signal will be either analog signal or digital signal. (John P. Bentey,2005) The next step is signal conditioning, the signal conditioning involving convert the electrical signal recorded by the sensor into the more useful form of signal, for example, amplification of the electrical signal from millivolts to volts. (John P. Bentey,2005) The next step is signal processing where involve noise reduction recorded by the sensor, signal conversion such as analog signal to digital signal, and the correction of the signal. The final step of structural health monitoring is the data presentation, where the measuring value converted into the form that easily recognized by the observer. (John P. Bentey,2005)

That have two types of structural health monitoring system, which are passive type and active type. Passive type structural health monitoring system, it only for measurement without any action. However, in the active type structural health monitoring system, it involved feedback mechanism to notify the user the present state of the structural health, Figure 2.2 shows the active type of Structural health monitoring system (Tianwei Wang,2014).

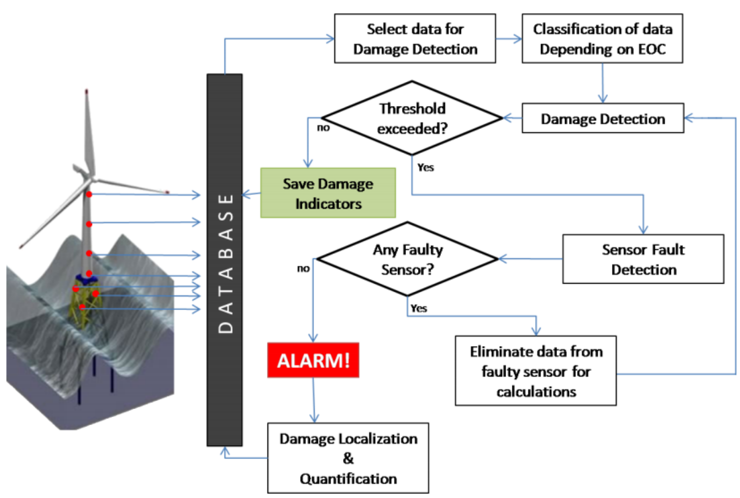


Figure 2.2 Active Type Structural Health Monitoring System

2.3 Non-Destructive Testing

The definition of Non-Destructive Testing is to determine the condition of the structure without affecting the performance. They are lots of non-destructive testing method being applied in industry, such as visual inspection, where the inspection is based on naked eyes of the observer, acoustic emission testing, where the inspection based on the “sound” produced by the engineering structure itself, bubble test, where testing leakage of the compressed air pipe, and so on.

Non-destructive testing is often implemented in structural health monitoring it is because non-destructive testing has the capability to measure the condition of the structure without affecting the structural performance. However, not all the non-destructive testing method is suitable for structural health monitoring, it is because some of the methods do not have feedback capability. (TianWei Wang, 2014)

Acoustic emission testing is the method of Non-destructive testing, it is based on “sound” generated by the material itself, the “sound” produced by the material itself is due to redistribution of stress field inside the material. To trigger acoustic emission effect within the engineering structural, external load such as pressure, force and etc. have to applied on to the engineering structure, even acoustic emission testing is widely used to detect flaw up to 1μm to 50μm, but it is not suitable applied on Structural Health Monitoring due to external load dependence.

2.4 Sound and Ultrasonic

Sounds are produced due to vibration and the vibration mean that the back and forth motion of the medium molecules, so that sound can be considered as wave (Jones/Childers, 2001). For example, the vibration of the diaphragm of the speaker will cause the air surrounded by the speaker will vibrate together, however, the air surrounded of the speaker is not traveling due to the vibration. In facts, the vibration of air surrounded of the speaker will cause vibration to entire boundary of air to vibrate as well, it is due to kinetic energy created by diaphragm transfer into air surrounded by the speaker, and then the kinetic energy in air will transfer through entire boundary, the energy transfers of air produce sound.

To transfer sound energy, it is required to transfer medium such as gas, fluid and solid, without the medium the sounds are unable to transfer from one point to another. Therefore, the energy transfer is depending on material properties of the medium. The speed of sound in air is about 343m/s in the air at 20^{o}C (Jones/Childers, 2001). however, the speed of sound is not a constant fix value, it is influenced by the medium as well. in general, the speed of sound in solid will be fastest compare to liquid and gas. It is because solid have higher density compared to the liquid and gas (Jones/Childers, 2001). For example, the soundwave velocity of steel will have about 5000m/s it is about 15 times higher compared to the soundwave velocity in air. Note that, the speed of sound is not the speed of the vibration, it is the speed of disturbance to another molecule.

Generally, the wave can be categorized into two types, which are transverse wave and longitudinal wave. Soundwave travel in the air is longitudinal wave it is because the direction of the vibration is same as the direction of energy transfer, for the transverse wave the vibration direction will be perpendicular to the direction of energy transfer (Jones/Childers, 2001). The typical example of a transverse wave is a light wave.

Human is able to listen sound frequencies from 20Hz to 20kHz, the ultrasonic wave is the frequency above 20kHz, in another hand, frequency below 20Hz is categorized as infrasound Figure 2.3 shows approximate frequency ranges corresponding to the application.

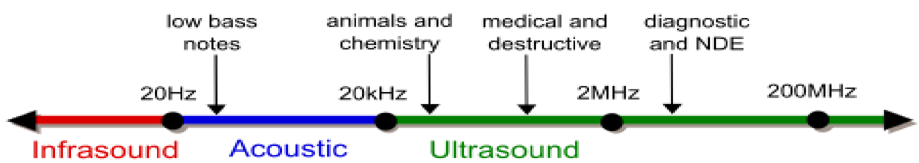


Figure 2.3 Acoustic Frequency and Application (‘Sound’,2018)

2.5 Guided Waves

Guided waves are mechanical stress wave propagating along an elongated structural. (Hegeon Kwun, Sang-Yong Kim et al., 2001), Guided waves usually propagated along an elongated structure in ultrasonic frequency (Angela Angulo, Jane Allwright et al.,2017) typically the frequency applied in guided wave testing is about 10kHz to 100kHz, however high frequency of guided wave will be applied in testing but the detection range will shorten (‘Guided Wave Testing’, 2017).

Guided waves testing become more popular in non-destructive testing it is because, guided waves testing is able to measure a long range of engineering structure in single excitation location (Peter Cawley,2002). Besides that, Guided waves also able to inspect hidden engineering structures such as insulation pipe.

Guided wave testing usually grouped into 3 type, short-range guided wave testing which is the inspection length is below 1m, for medium range usually refer to the range up to 5m, and long-range guided wave testing is up to 100m. (Peter Cawley,2002).

Although guided wave testing has the ability to inspect a long range of engineering structural, the guided wave has some shortcoming as well. Peter Cawley (2002) reported that the signal obtained by guided wave sensor is consists of a lot of noise as shown in Figure 2.4. Another shortcoming is a lot of wave modes in a single frequency, and most of the modes are dispersive (Relation between mode, Frequency and Wave Velocity) as shown in Figure 2.5

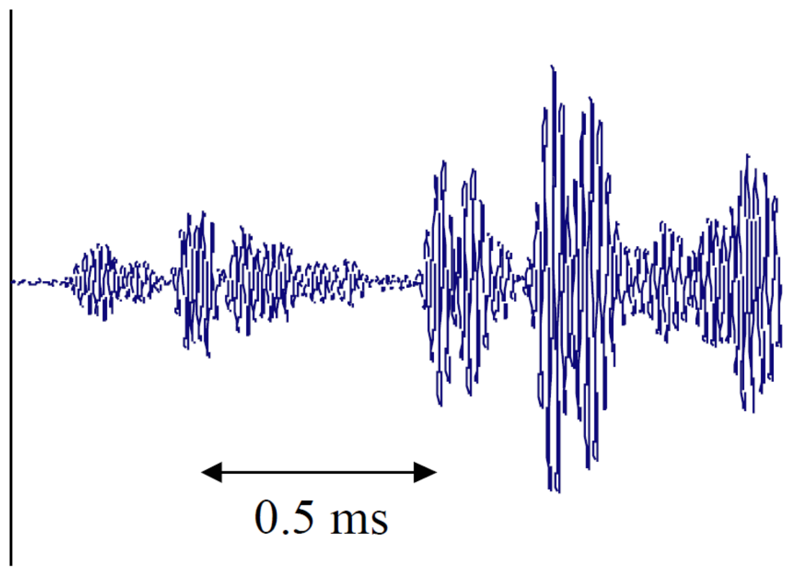


Figure 2.4 Noise Signal in Guided Wave testing (Peter Cawey,2002)

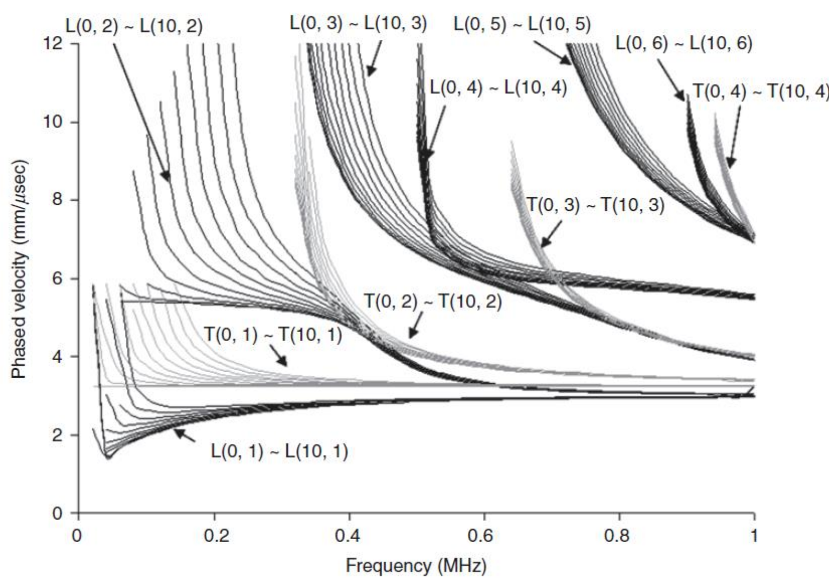


Figure 2.5 Sample Dispersion Curve for 3 inches Pipe (Rose,2014)

Zhenhua Song, et.al (2018) carrying an experiment of damage detection in large diameter pipe filled by difference fluid, it shows that the dispersion properties for vacant pipe and fluid-filled pipe is totally different, as shown in Figure 2.6, also L (0,2) is suitable mode vacant pipe inspection and L_{wp} (0,4) is suitable for water-filled pipe.

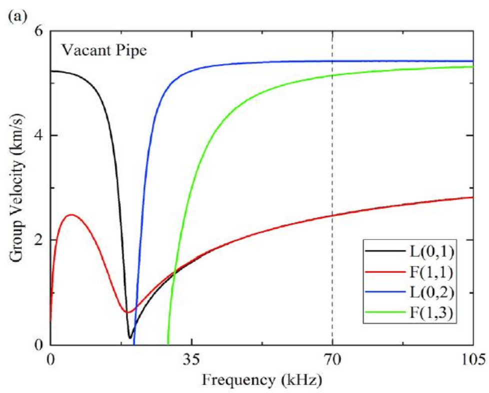


Figure 2.6(a) Dispersion Curve for Vacant pipe (88mm O.D)(Zhenhua Song et.al 2018)

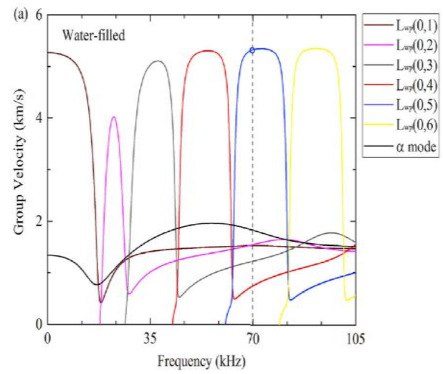


Figure 2.6(b) Dispersion Curve for Water filled Pipe (88mm O.D) (Zhenhua Song et.al 2018)

A guided wave propagating in the pipe in an axial direction involving two types of waves, which are longitudinal wave and torsional waves (Rose, 2014). Longitudinal waves travel via compressional motion in axial directions and torsional wave travel via circumferential direction. However, there are 3 types of modes which are named as longitudinal axially symmetric modes L (m, n), torsional axially symmetric mode T (m, n) and also non-axially symmetric modes F (m, n) the m and n is represented by number of mode shape across the pipe and n represents the group order mode (Rose,2014). Figure 2.7 shows the group order mode in graphical explanation.

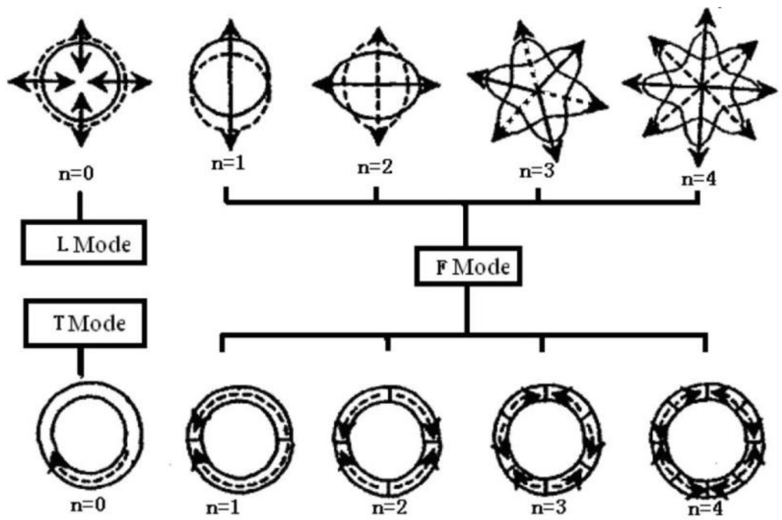


Figure 2.7 Graphical explanation of group order mode. (Tianwei Wang,2014)

When the hollow cylinder has traction-free (No external Load on the surface) boundary condition, the guided wave propagation equation is shown in equation 2.1 (Rose,2014)

$$\mu\nabla^2\vec{U} + (\lambda+\mu)\nabla\dot{\nabla}\vec{U} = \rho\left(\frac{\delta^2\vec{U}}{\delta t}\right) \quad ---2.1$$

Where μ and λ is Lame constant, ρ is the density of the elastic material, $\vec{U}$ is the displacement field in the cylindrical coordinate(Rose,2014).

2.6 Phase Velocity and Group Velocity Concept

Wave Velocity usually quantified into two terms, which are phase velocity and group velocity (TianWei Wang, 2014). Figure 2.8 Show the difference between group velocity and Phase velocity.

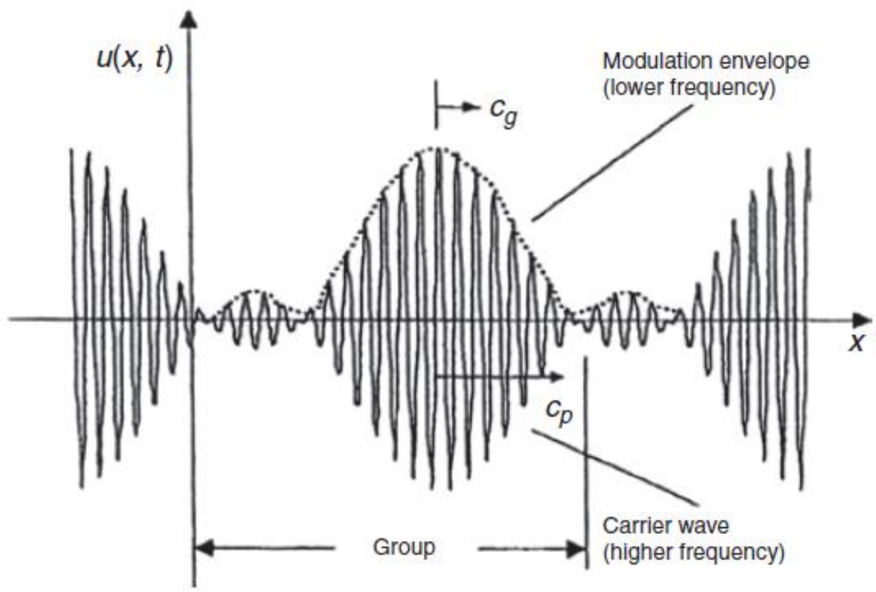


Figure 2.8 Phase Velocity and Group Velocity (Rose,2014)

Group velocity is the propagation velocity of a group of the wave which has similar propagation frequency(Rose,2014). Phase velocity is the wave velocity of the individual wave (TianWei Wang, 2014) the relationship between group velocity and phase velocity is shown in equation 2.2 (Rose,2014)

$$V_{group} = V_{phase}\left(1 - \frac{\omega}{V_{phase}}\frac{dV_{phase}}{d\omega}\right)^{-1}$$

CHAPTER 3

METHODOLOGY

3.1 Simulation Software

3.1.1 ABAQUS/CAE

The simulation was done by using ABAQUS/CAE, which is developed by Dassault Systemes. ABAQUS/CAE is the simulation software based on finite element analysis. The analysis tools in ABAQUS/CAE including following:

a. ABAQUS/Standard.
b. ABAQUS/Explicit and Implicit.
c. ABAQUS/CFD

In this Project ABAQUS/Explicit will be applied, the analysis of the problem by using ABAQUS/Explicit involving following step:

a. Preprocessing
b. Simulation
c. Post-processing

The analysis of ABAQUS/Explicit is based on central difference operator and diagonal element mass matrices.

3.1.2 GUIGUW

GUIGUW stands for Graphical User Interface for Guided Ultrasonic Wave, it is developed by Dr. Alessandro Marzani and Dr. Paolo Bocchini, the main purpose for this software is to determine the dispersion relationship of different type of engineering structures.

The dispersion properties calculation is based on Semi-Analytical Finite Element method (A. Marzani, P. Bocchini et.al)

3.2 Simulation Modeling

In this project total, 5 models will be analyzed accordingly, which including vacant straight pipe without any defect, straight pipe with crack, straight pipe with external wall thickness reduction, and 90-degree bent pipe, and 90-degree bent pipe with crack located at the elbow.

The material selection for the pipe will be steel with Density of 7720kg/m^3, Young Modulus 206 x 10^9 Pa, and Poisson Ratio 0.29.

Also, 3-inches' diameter with 5mm wall thickness pipe will be used throughout the simulation.

3.3 Pipe Parameter

As mentioned in section 3.2, the diameter of the pipe will be 3 inches(76.2mm), and the thickness of the pipe will be 5mm. the steel pipe will be selected in this simulation. The material properties are shown in Table 3.1

Description	Equation	Value
Steel Pipe Density(ρ)	-	7720kg/m^3
Young Modulus(E)	-	206x10^{9}Pa
Poisson's Ratio(ν)	-	0.29
Shear Modulus(S)	$S = \frac{E}{2(1+\nu)}$	79.84x10^{9}Pa
Bulk Modulus(B)	$B = \frac{S(E-2S)}{3S-E}$	110.33x10^{9}Pa

Table 3.1 Material Properties of the Selected Pipe.

Based on Table 3.1, longitudinal velocity(C_l) and transverse velocity(C_T) can be calculated by the following equation:

$$C_l = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

$$= \sqrt{\frac{206 \times 10^9 (1-0.29)}{7720(1+0.29)(1-2\times 0.29)}}$$

$$\therefore C_l = 5913.36 m/s$$

$$C_T = \sqrt{\frac{S}{\rho}}$$

$$C_T = \sqrt{\frac{79.84 \times 10^9}{7780}}$$

$$\therefore C_T = 3203.47 m/s$$

3.4 Dispersion Curve and Frequency Selection

As mentioned in section 3.1.2, the dispersion curve will be obtained by using software named GUIGUW, based on the result shows in GUIGUW, the dispersion curve for group velocity will be shown in Figure 3.1 and Figure 3.2

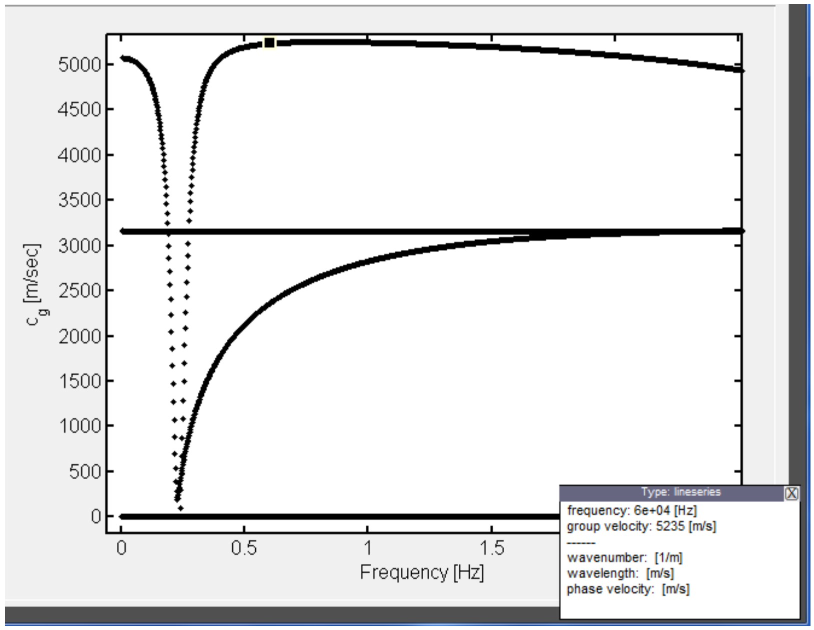


Figure 3.1 Dispersion Curve of Group Velocity for 3 Inch Pipe (Longitudinal and Torsional Mode)

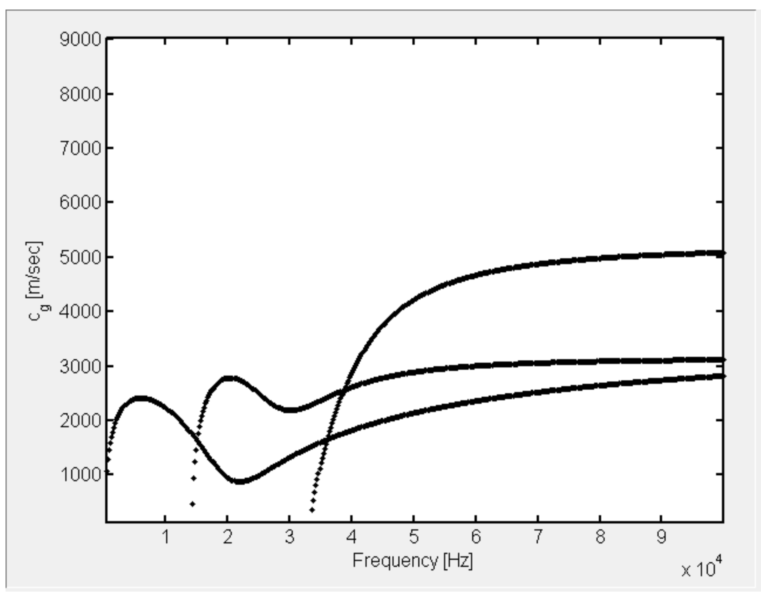


Figure 3.2 Dispersion Curve of Group Velocity for 3 Inch Pipe (Flexible Mode)

Based on the dispersion curve generated by GUIGUW, propagation frequency 60kHz and mode of L (0,2) had been selected due to it is falling in the non-dispersive regions. In this project 5 cycles hanning windows excitation signal had been applied due to 5 Hanning-windows excitation signal can limit the frequency bandwidth of the excitation, therefore reduction of unwanted reflection between wave packer (TianWei Wang, 2014). To determine hanning-windows signal, following equation 3.1,3.2 and 3.3 will be applied:

$$Y(t) = A_o \sin(\omega t + \phi) - - - 3.1$$

$$h(t) = 0.5\left[1 - \cos\left(\frac{1}{N_c}\omega t\right)\right] - - - 3.2$$

$$H(t) = Y(t) \times h(t) - - - 3.3$$

where,

$Y(t)\ is\ the\ amplitude\ of\ the\ specific\ time$

$A_o\ is\ the\ amplitude\ of\ the\ signal$

$\omega\ is\ the\ angular\ frequency\ of\ the\ wave$

$t\ is\ the\ time$

$N_c\ is\ the\ cycle\ require$

Based on above equation, the hanning-windows signal can be plotted by using MATLAB, and the result will be shown in Figure 3.3

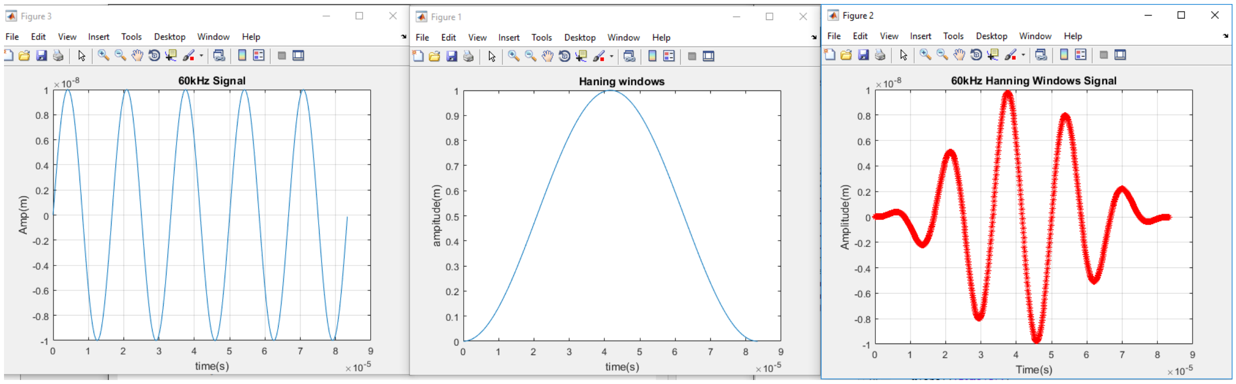


Figure 3.3 Hanning Windows Tone Burst Signal for 60kHz Excitation Signal

3.5 Element Size Selection

There are two conditions (TianWei Wang, 2014) should be properly selected before modeling, which including following:

i. Element size

To capture propagating wave, at least 10 elements per wavelength is required, based on longitudinal wave speed of steel and thickness of the pipe, to determine minimum element size will be calculated based on equation 3.4

$$f_{max} = \frac{f_{excitation}}{Thickness} - - - 3.4$$

$$f_{max} = \frac{0.06MHz}{5mm} = 0.012Hz$$

$$\lambda_{min} = \frac{C_l}{f_{max}} = \frac{5913.36ms^{-1}}{0.012Hz} = 492.78mm$$

$$\therefore L_{element} < \frac{492.78}{10} = 49.278mm$$

Therefore, the element size will be based on 4mm/element throughout all models discussed in this project.

ii. Time step of the modeling

ABAQUS Explicit analysis is based on the known value in previous time step because of the central differential method (TianWei Wang, 2014), therefore time step is very important throughout the ABAQUS Explicit analysis, to obtain accurate time step following equation, and the time step calculated over here will be used throughout the project.

$$T_{step} < \frac{L_{element}}{c_l}$$

$$T_{step} < \frac{15 \times 10^{-3} m}{5913.36 ms^{-1}} = 2.536 \times 10^{-6} s$$

Based on above calculation, and the time step value selected throughout the project will be $1 \text{x} 10^{-8}$s

CHAPTER 4

RESULT AND DISCUSSION

4.1 3 Inches Pipe without Crack

The modeling of the pipe consists of 4 sensors and 4 exciters and the location of 4 sensors and 4 exciters is offset from the edge of the pipe 2cm.

In the simulation, fixed end boundary conditions had been added to the model, it is because without fix boundary condition is unable to examine the reflection characteristic.

The dimension of the pipe is shown in Figure 4.1, where the diameter of the pipe is 3inches with 5mm thickness and 2m long. That is 4 excitation points and 4 signal points to measure the amplitude of the signal and the location of excitation points and signal point will be shown in Figure 4.2. and the signal obtained will be plotted by using MATLAB.

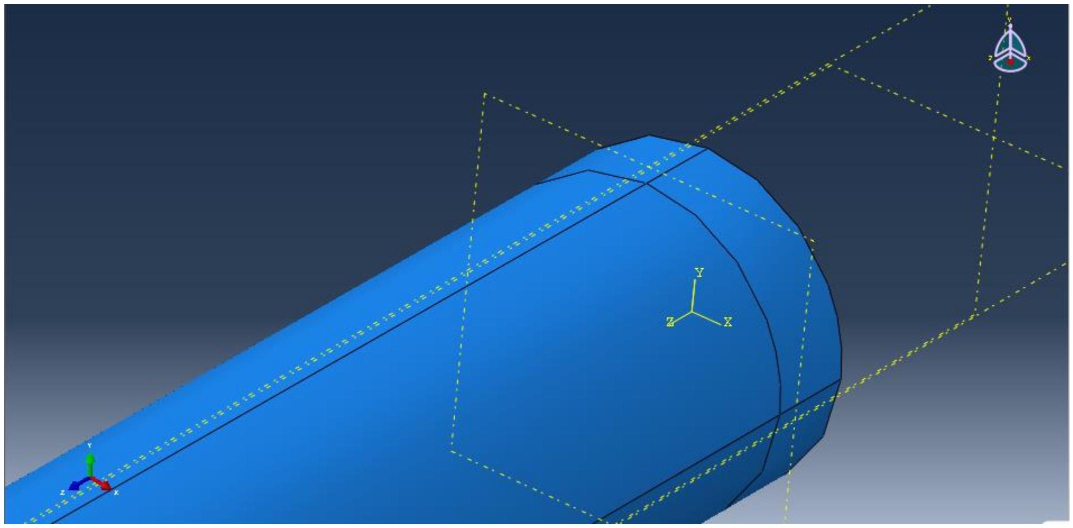


Figure 4.1 Location of E1, E2, E3, E4 (Vacant Straight Pipe)

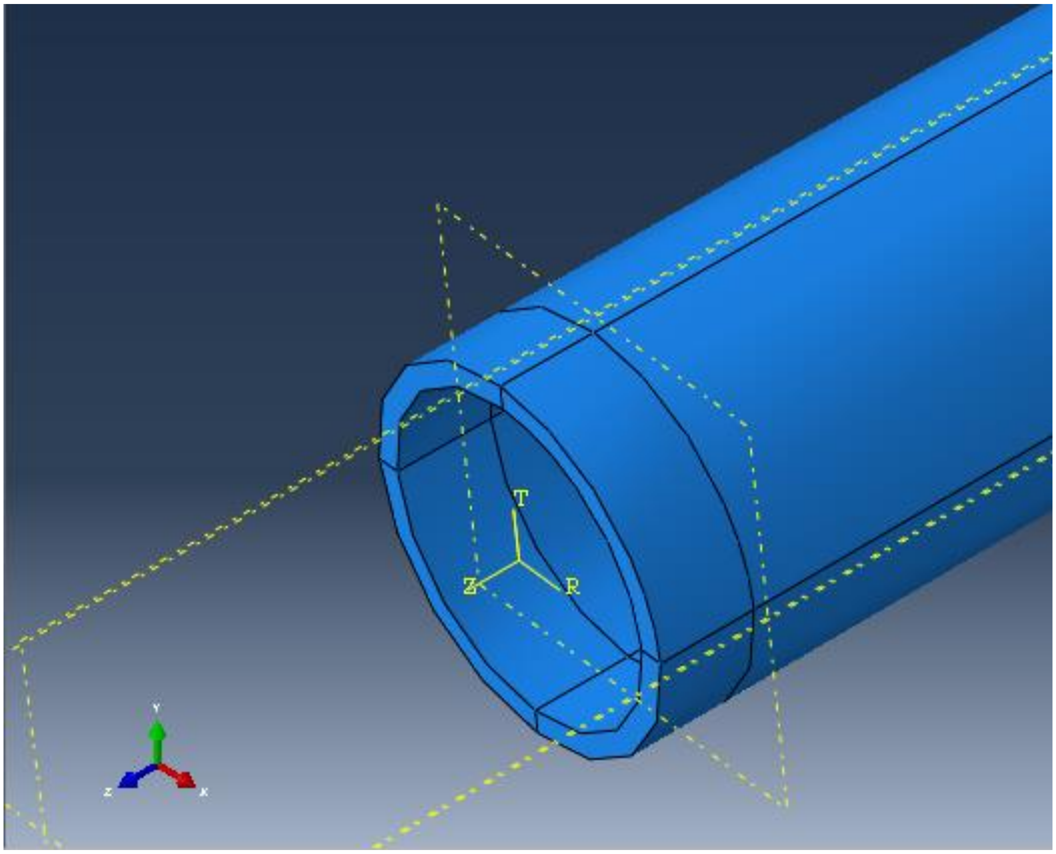


Figure 4.2 Location of S1, S2, S3, S4 (Vacant Straight Pipe)

The L (0,2) wave propagation pattern had been plotted in Figure 4.3, based on the simulation, it shows that the signal will be reflected back at end of the pipe if no disturbance in between as shows in Figure 4.4, the reflected signal will propagate back to the original point and reflected back again.

The signal data had been recorded and tabulated by ABAQUS Explicit, and the numerical data recorded by ABAQUS Explicit will be imported to MATLAB for analysis, based on the signal generated by ABAQUS Explicit, the amplitude data is plotted as shown in Figure 4.5, where black color line is group velocity and red color line is phase velocity**.**

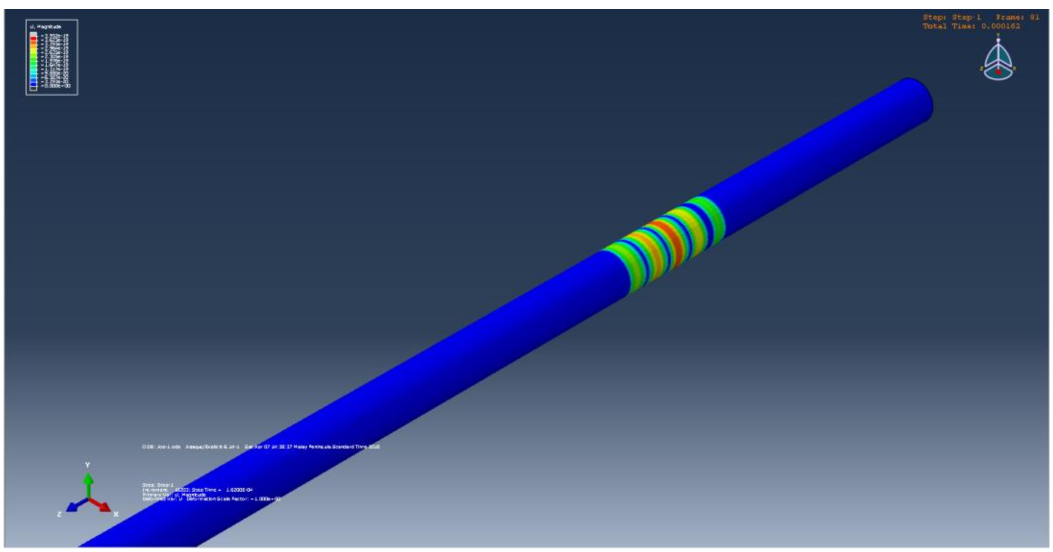
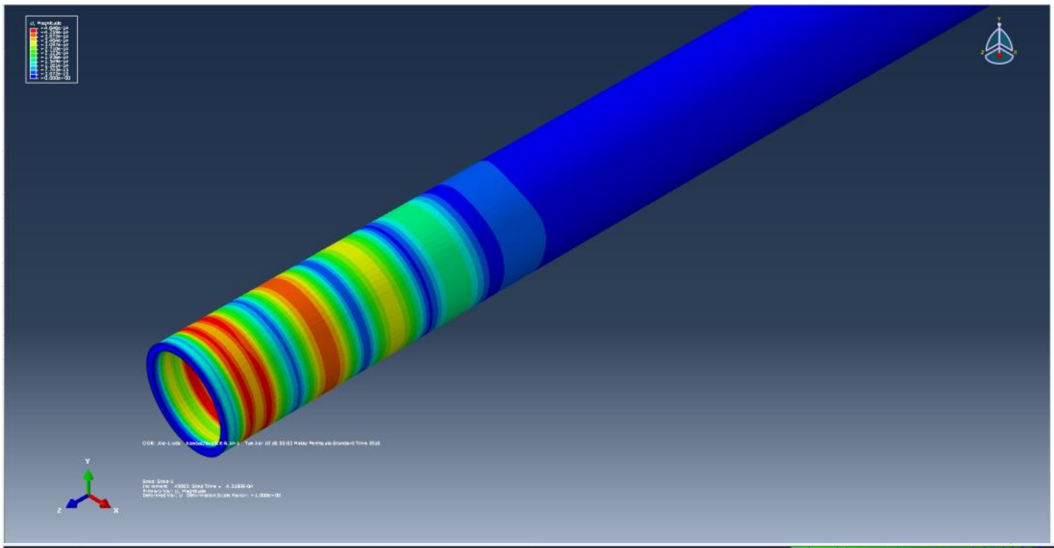


Figure 4.3 L (0,2) Mode Propagate along Vacant Pipe



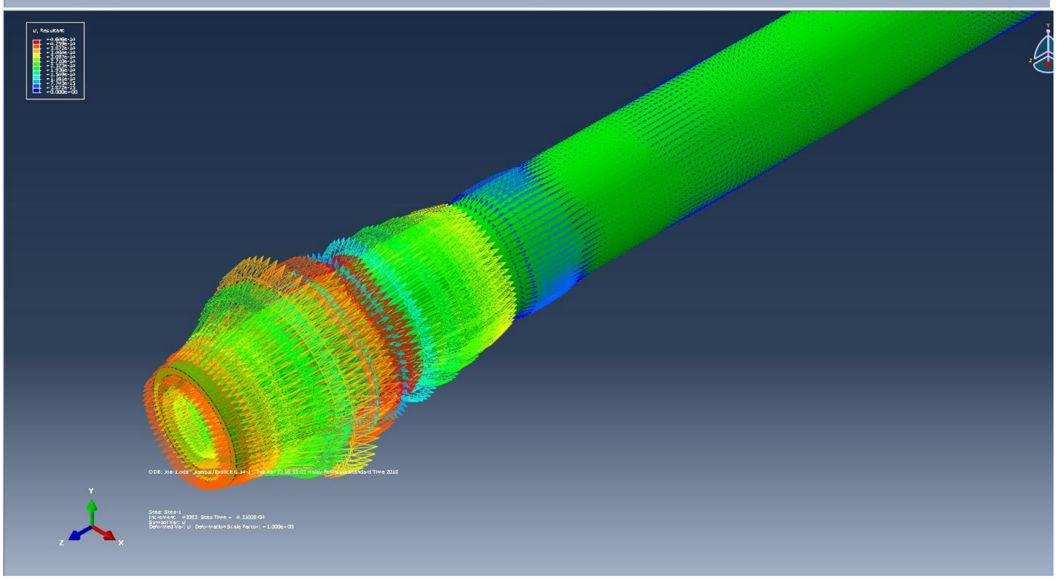


Figure4.4 L (0,2) Mode Reflection at End of the Vacant Straight Pipe

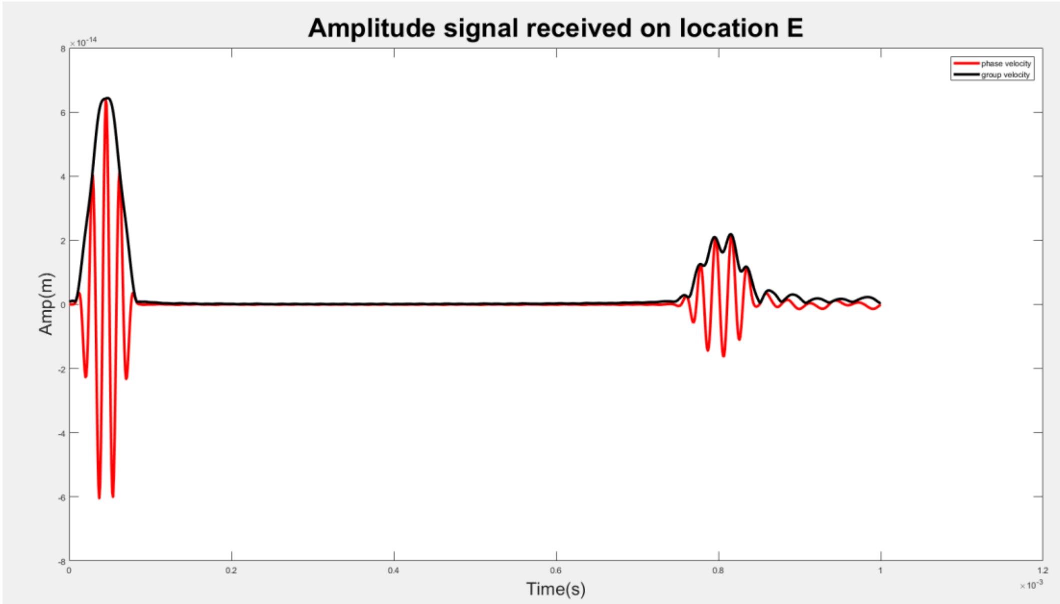


Figure 4.5 Signal Recorded at Point E1

From the recorded data, it can clearly know that it has two types of signal had been recorded at location E1, which are including excitation signal and the reflection signal. Based on the recorded time the approximate group velocity of the reflected signal can be determined by the following equation

$$v_{appx} = \frac{ds}{dt}$$

$$v_{appx} = \frac{3.96m}{0.000769s - 2 \times 10^{-5}s} = \mathbf{5287.05m/s}$$

Since the reflection signal has frequency value of 60kHz, based on the frequency and referring to the dispersion curve plotted in Figure 3.1, it shows that in 60kHz the group velocity in mode L (0,2) should be 5235m/s, but the calculated group velocity is 5287.05m/s. However, the calculated value and dispersion curve value is slightly difference, but is still can confirm that the reflected signal is L (0,2), it is because, in this frequency region, it only has 3 type of mode involved, which is L

(0,1), L (0,2), T (0,1). However, only L (0,2) can travel in 5000m/s and above in 60kHz frequency.

Based on the recorded data of E2, E3, and E4, it shows that these 3 data have the same characteristic compared to E1. Also, Data of S2, S3, S4 will have the same characteristic compared to S1, the graph is plotted in Figure 4.6 and Figure 4.7

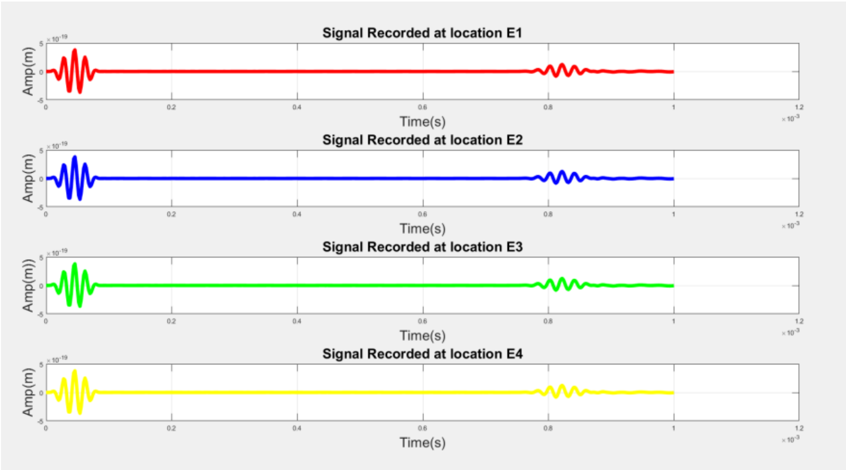


Figure 4.6 Signal Recorded at E1, E2, E3 and E4 (Without Crack)

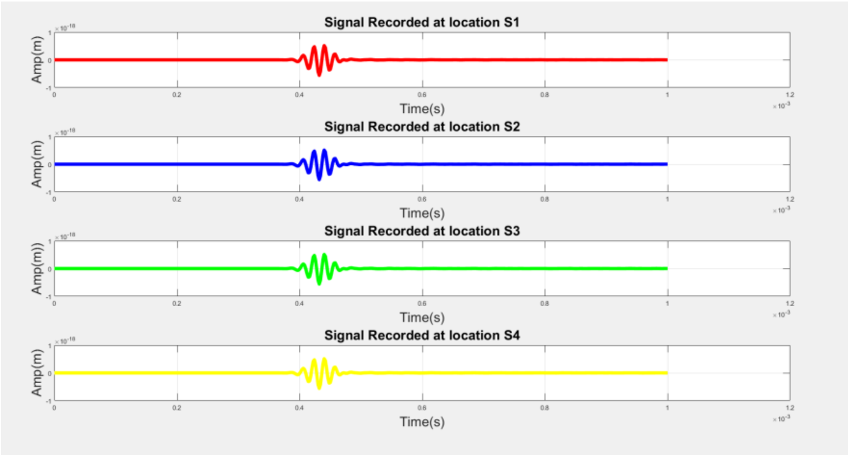


Figure 4.7 Signal Recorded at S1, S2, S3, S4 (Without Crack)

Based on the above analysis, it can be concluded that guided wave mode of L (0,2) travel along the hollow pipe without any defect, modes change will not happen. However, based on Figure 4.7 and Figure 4.6, it shows that the wave propagation amplitude will be reduced throughout the propagation process.

4.2 3 Inches Pipe with Artificial Crack

The cracked pipe is modeled as a rectangular hole, and the dimension of the rectangular hole is 40mm width and 100mm long, the detail of the location is shown in Figure 4.8(b). The pipe parameter is remaining unchanged, which is 3inches steel pipe and the correspondence thickness is 5mm, and it is also 2m long. Any other parameter such as frequency, time steps, element size is same as section 3.4. Also, the location of 4 excitation points and 4 signal points is remaining unchanged.

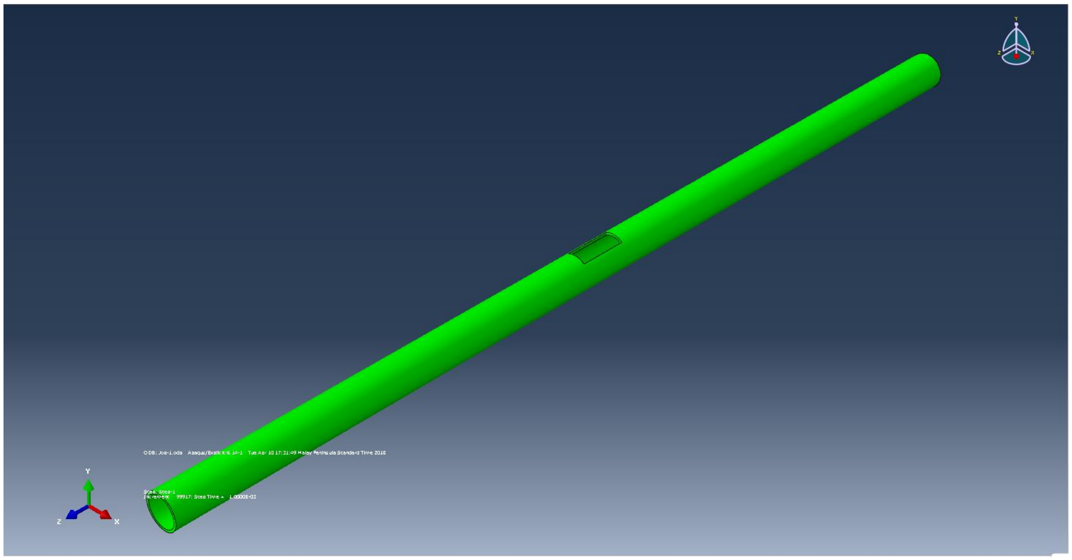


Figure 4.8 (a) Artificial cracked Straight Pipe

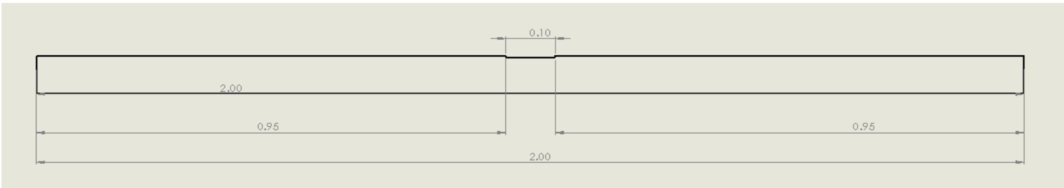


Figure 4.8 (b) Artificial Cracked Straight Pipe Dimension

The wave propagation pattern had been plotted in Figure 4.9 when the wave passes through the rectangular hole, the energy will be disrupted as shown in Figure 4.10, besides that some of the energy will be reflected as shown in Figure 4.11(a) and Figure 4.11(b).

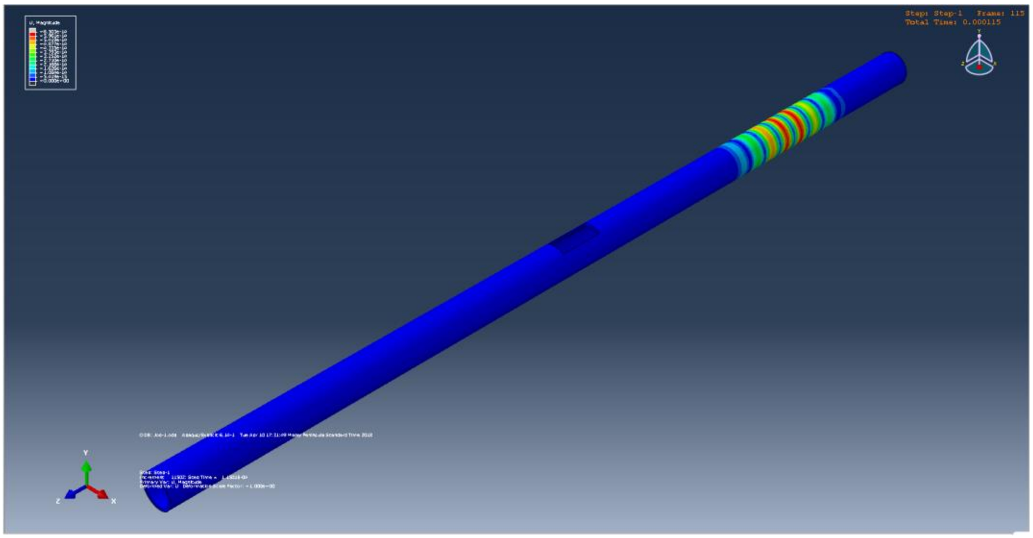


Figure 4.9 L (0,2) Mode Propagate along Artificial Cracked Pipe

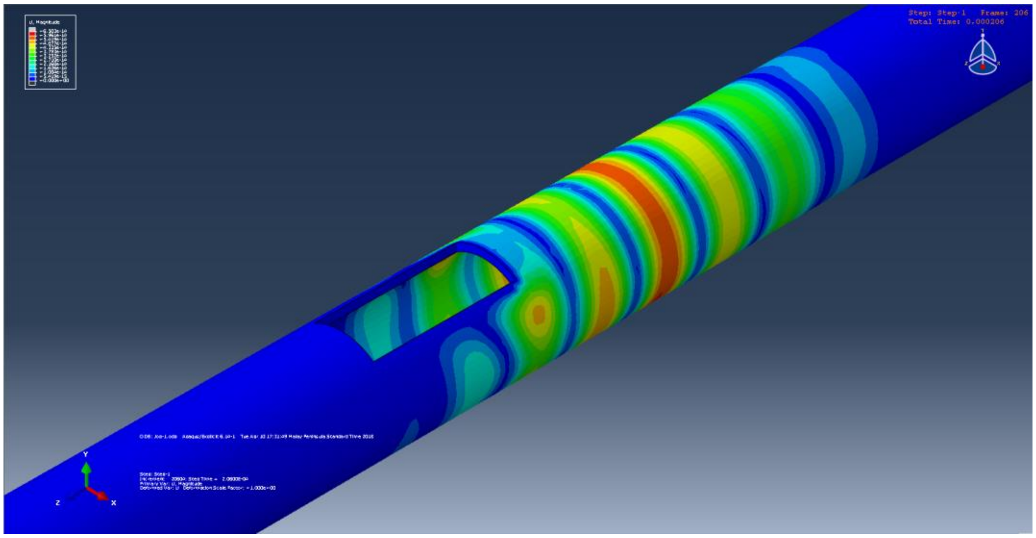


Figure 4.10 L (0,2) Signal React with the Artificial Cracked Pipe

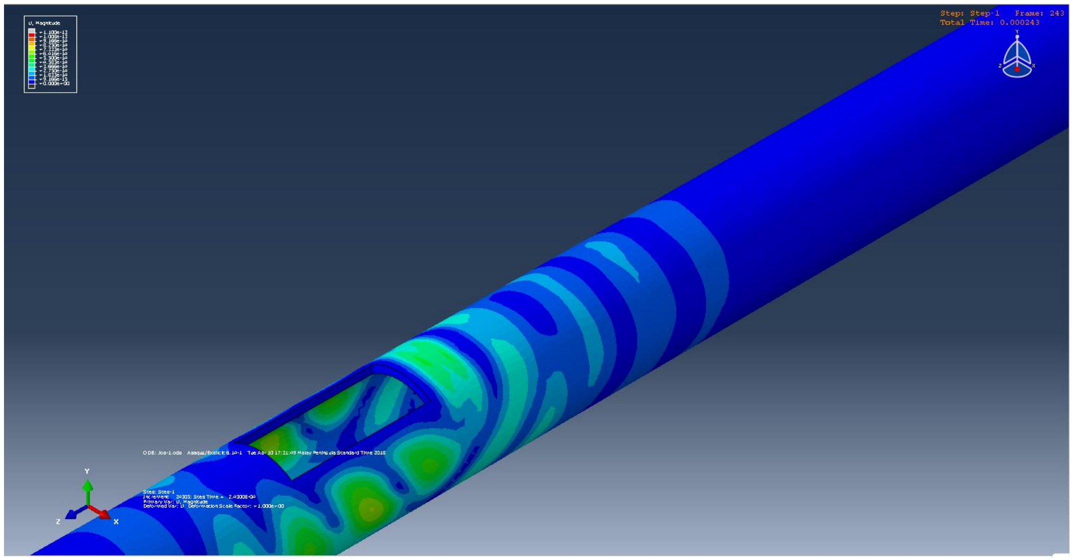


Figure 4.11 (a) L (0,2) Propagating Wave Reflection due to Artificial Crack

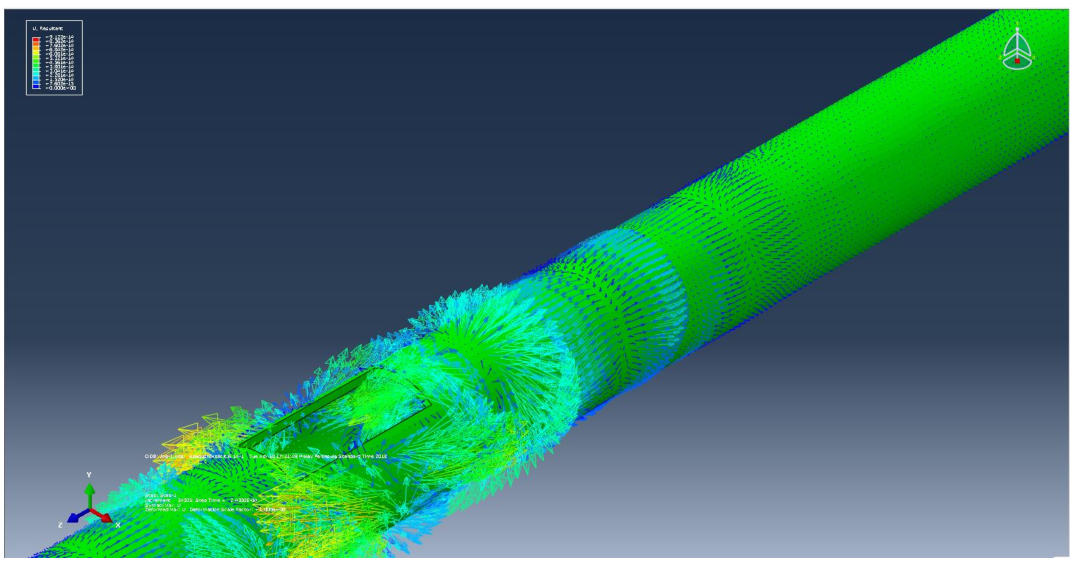


Figure 4.11(b) Vector Representation of L (0,2) Propagation Wave Reflection due to Artificial Crack

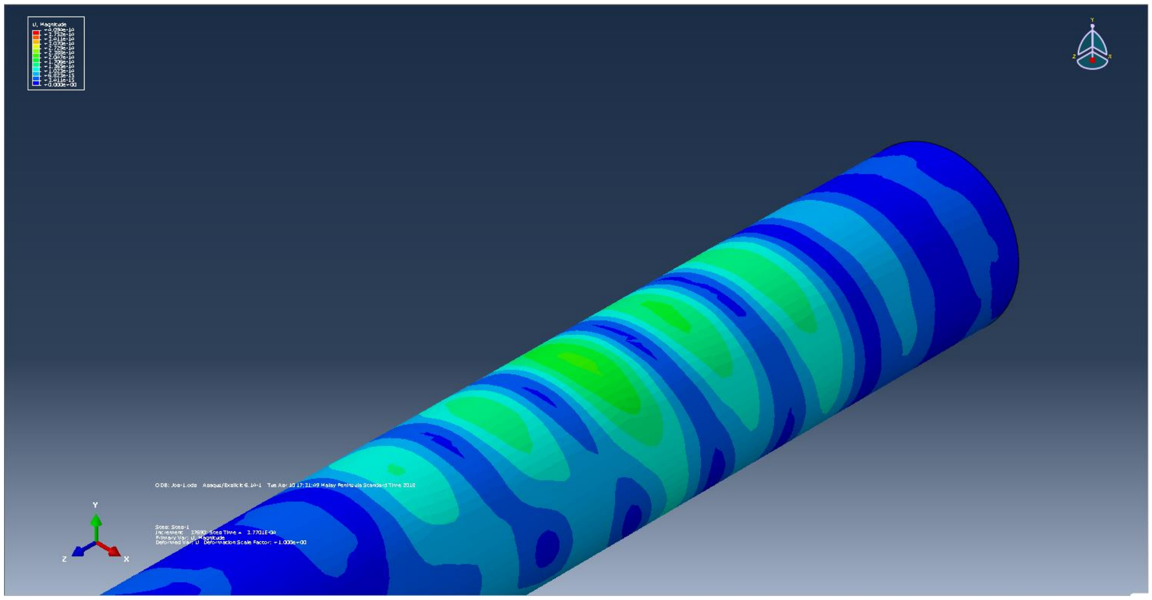


Figure 4.12 Reflection Signal Returned Back to Excitation Point

From the simulation shows in Figure 4.11(a), it clearly to notice that, the reflection and scattering is happening when the ultrasonic wave reacts with the small square hole, it can be predicting the excitation E1, E2, E3, and E4 will receive echo signal due to reflection of the ultrasonic wave, the data recorded by ABAQUS/ Explicit will be imported into MATLAB for signal analysis and the result is shown in Figure 4.13

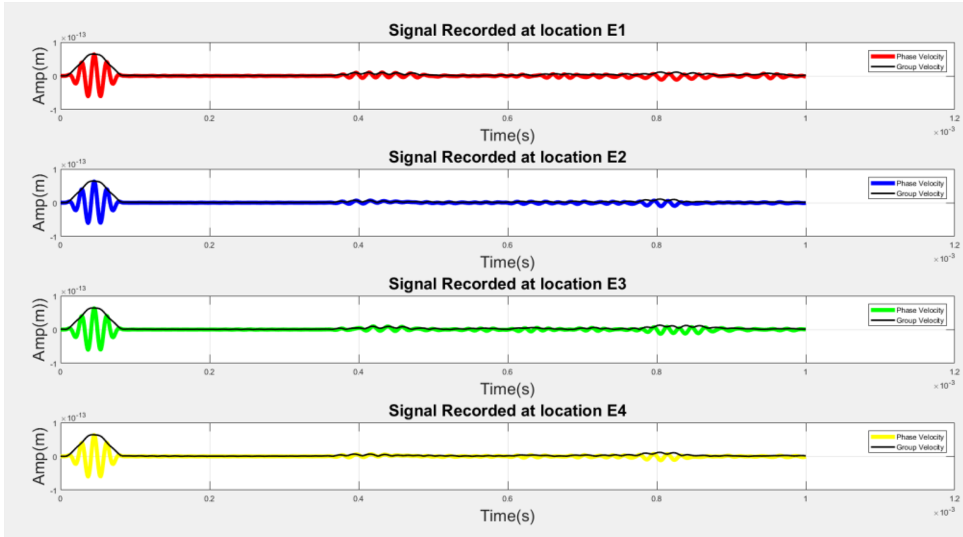


Figure 4.13 Signal recorded at location E1, E2, E3, E4 (with Crack)

Based on the graph shown in Figure 4.13, it shows that 1st echo occurs at 0.00036s, this echo is caused by the small rectangular hole, based on the time, it shows that the wave velocity is about 5222.22m/s, it is confirmed that the echo signal is L (0,2) because based on dispersion curve in 60kHz, at L (0,2) mode is 5235m/s. However, based on the analysis, the signal recorded in E1, E2, E3, and E4 have an excessive signal which is caused by interruption and other wave mode propagation.

Further analysis on another side, which are the signal recorded at S1, S2, S3, and S4, the graph is shown in Figure 4.14, based on the graph is shows that at least 4 non-dispersive wave packets in the continues signal, based on the calculation the group velocity of this 4 wave packages are, 5224.27m/s, 4429.53m/s,3897.63m/s, and 3084.11m/s, based on the fastest wave achieve to the location of S1, S2, S3, and S4, it is concluded that 1st signal recorded at location of S1, S2, S3, and S4 is L(0,2) mode.

Further comparison of S1 Signal between the defected pipe and good pipe and the result is plotted in Figure 4.15, it shows that the amplitude of the recorded is significantly reduced it is because some of the energy had been consuming due to the small rectangular hole.

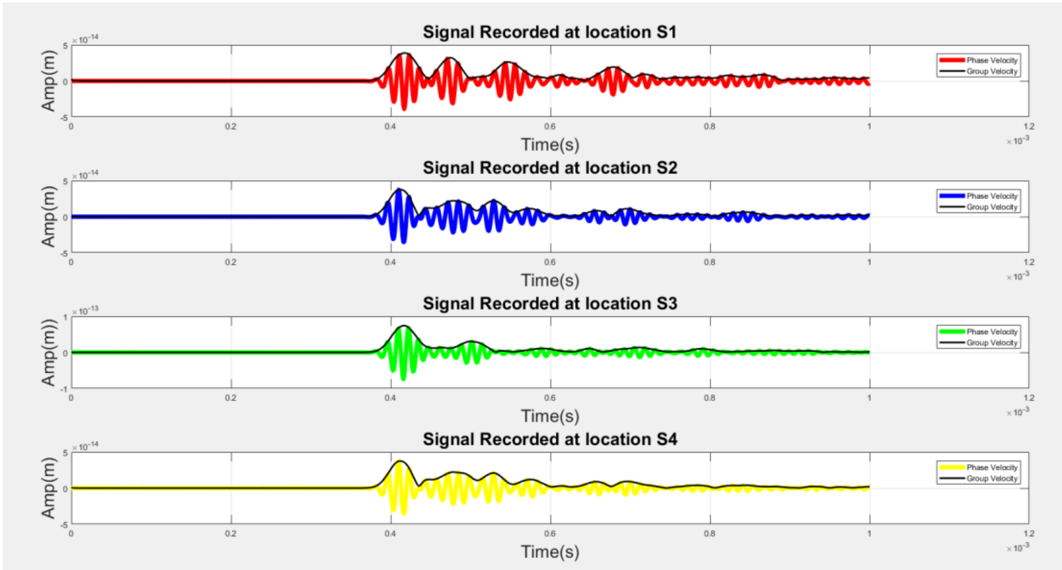


Figure 4.14 Signal Recorded at S1 S2 S3 and S4 (With Crack)

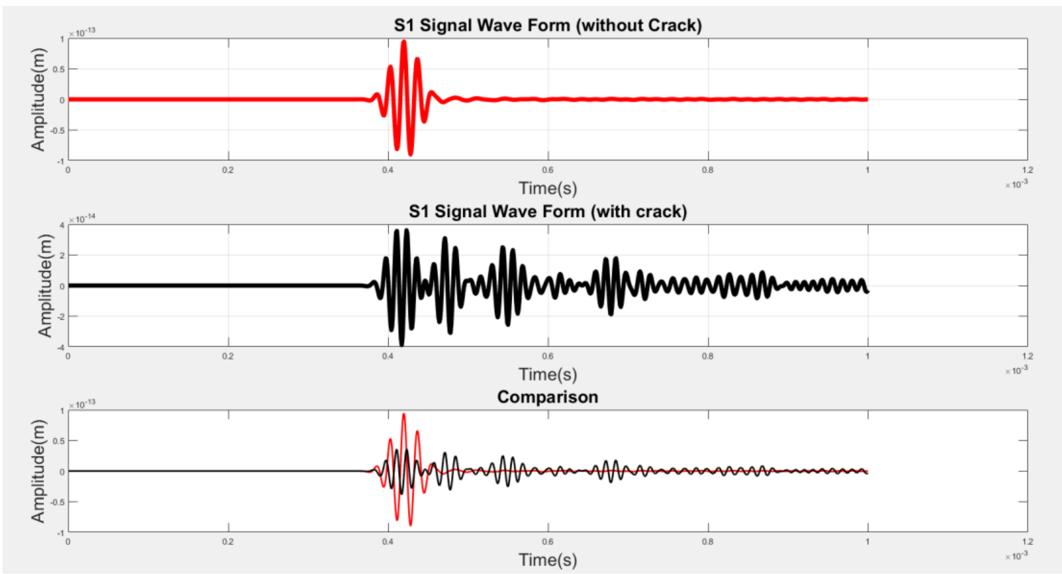


Figure 4.15 Signal Comparison between Vacant Straight Pipe without defect and Defected Pipe for S1

4.3 3 Inches Pipe with External Artificial Corrosion and Dent

The corrosion is modeled based on surface thickness reduction, the detail of the external corrosion model is shown in Figure 4.16(a) and the exact location and dimension shows in Figure 4.16(b), all the parameter of the pipe such as pipe length, pipe material, location of signal recorded point and excitation recorded point excitation signal are remaining unchanged.

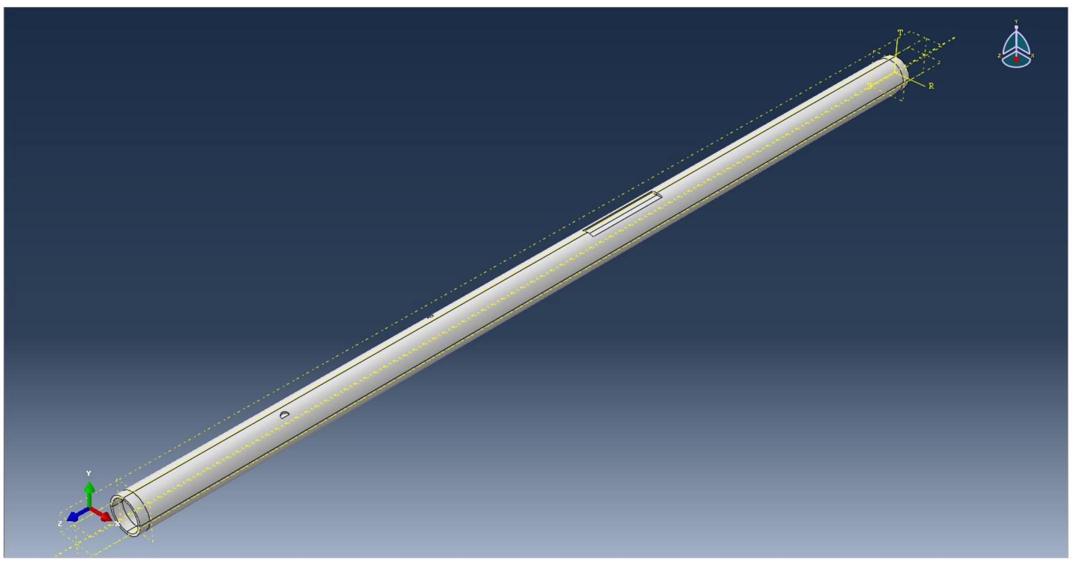


Figure 4.16(a) Artificial External Corrosion Pipe

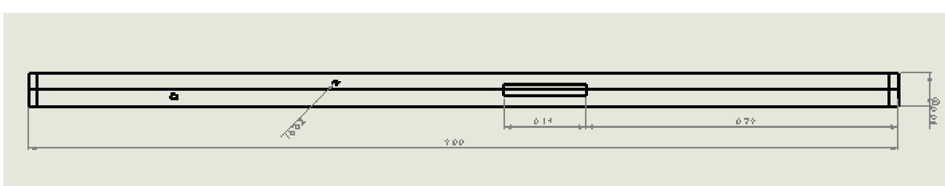


Figure 4.16(b) Artificial External Corrosion Pipe Dimension

The simulation result had been plotted in Figure 4.17, Figure 4.18. based on the simulation result, the first echo happened when the wave hit the rectangular area, which is artificial corrosion area as shown in Figure 4.19.

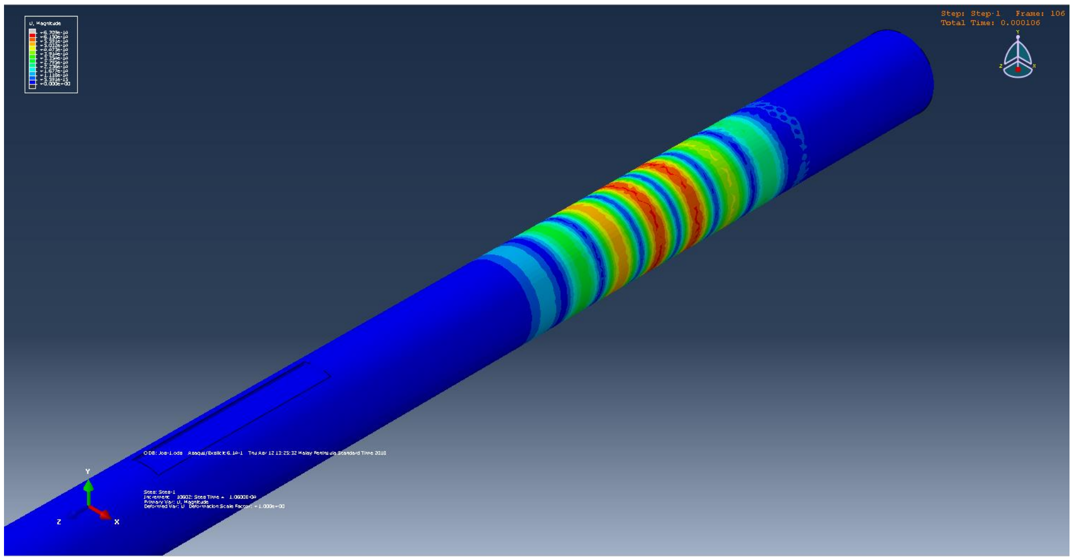


Figure 4.17 L (0,2) Mode Propagate along artificial corroded Pipe

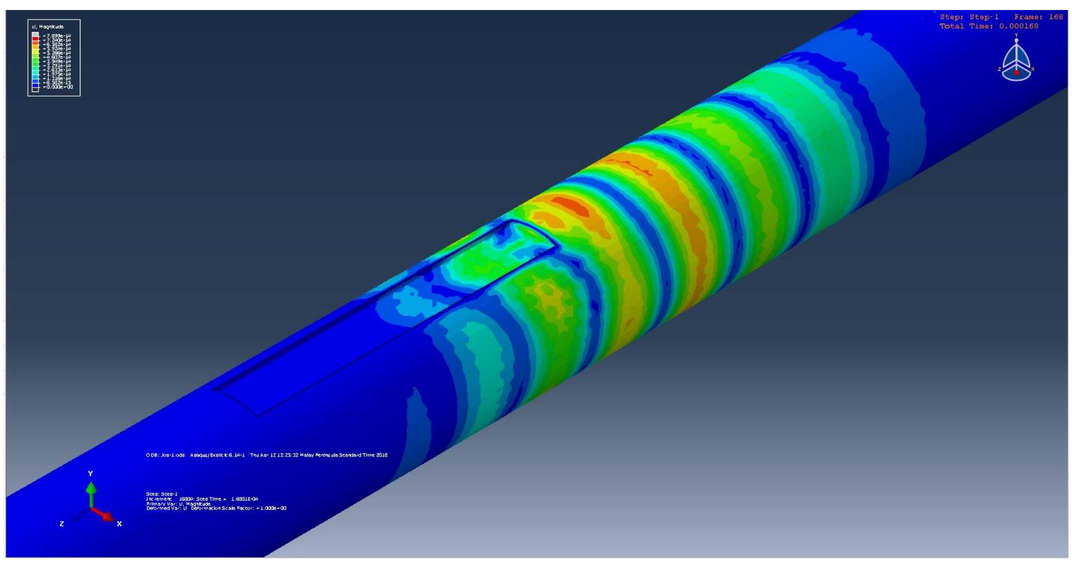


Figure 4.18 L (0,2) Signal React with the Artificial Corroded Pipe

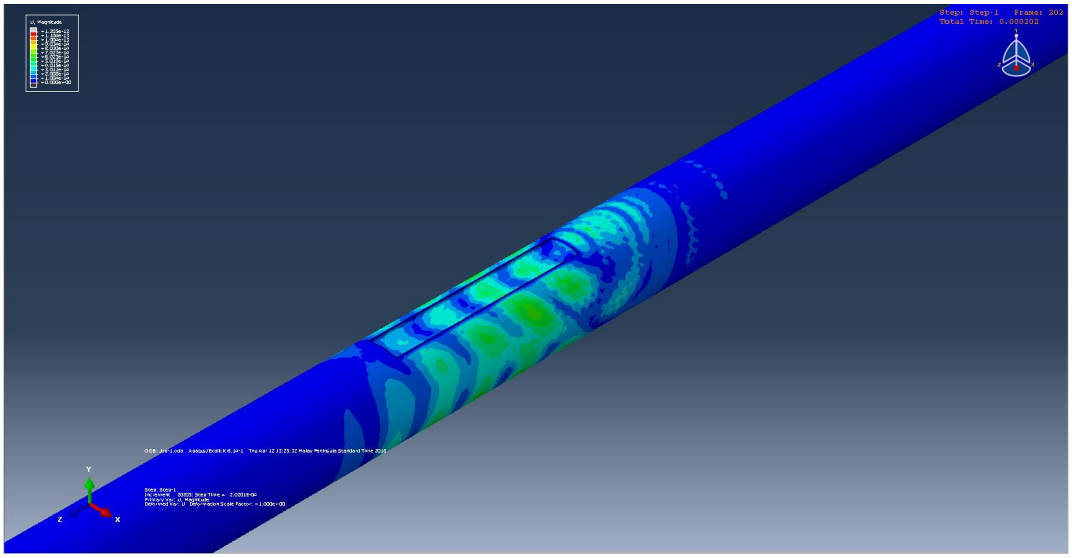


Figure 4.19L (0,2) Propagating Wave Reflection due to Artificial Corrosion

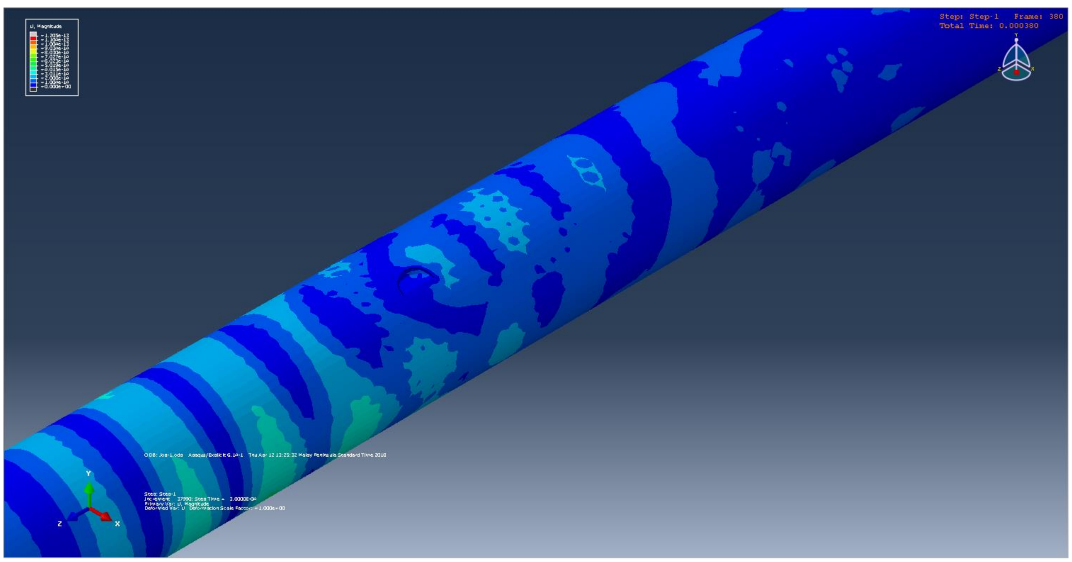


Figure 4.20 L (0,2) Propagating Wave Reflection due to Artificial Small Dent

Figure 4.20 shows the wave reaction to the artificial small dent, based on the simulation, the wave does not reflect any signal, therefore it can be predicted that no amplitude will be recorded due to this crack in E1, E2, E3, and E4.

The signal generated by ABAQUS/Explicit for E1, E2, E3, and E4 will then imported into MATLAB for further analysis, the signal recorded by ABAQUS/Explicit is then plotted in Figure 4.21.

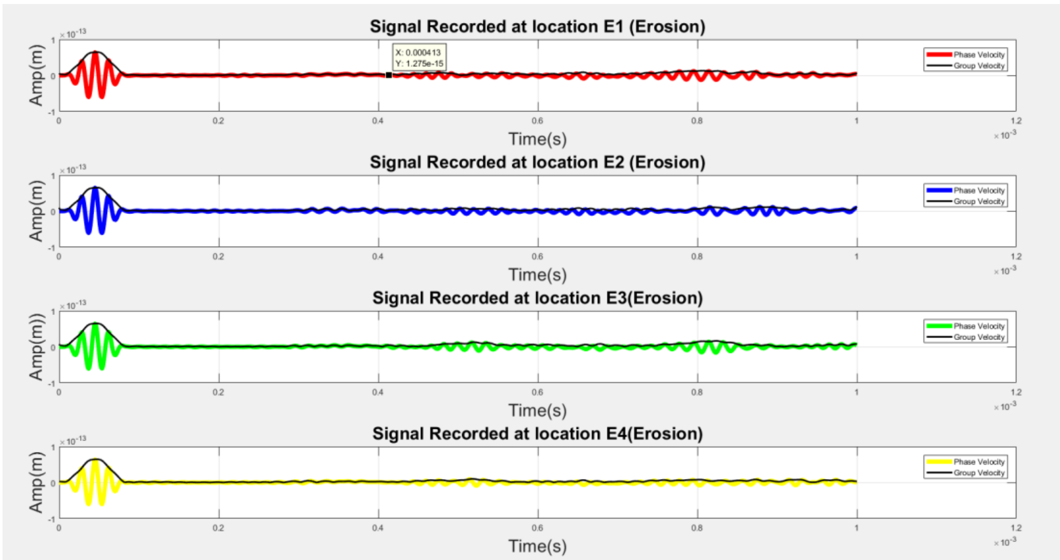


Figure 4.21 Signal Recorded at E1, E2, E3, E4 (With Artificial Corrosion and Dent)

Based on the Figure 4.21, the calculated group velocity is 1864m/s, based on the group velocity and comparing to the dispersion curve shown in Figure 4.22, the mode is changed to F (7,1)

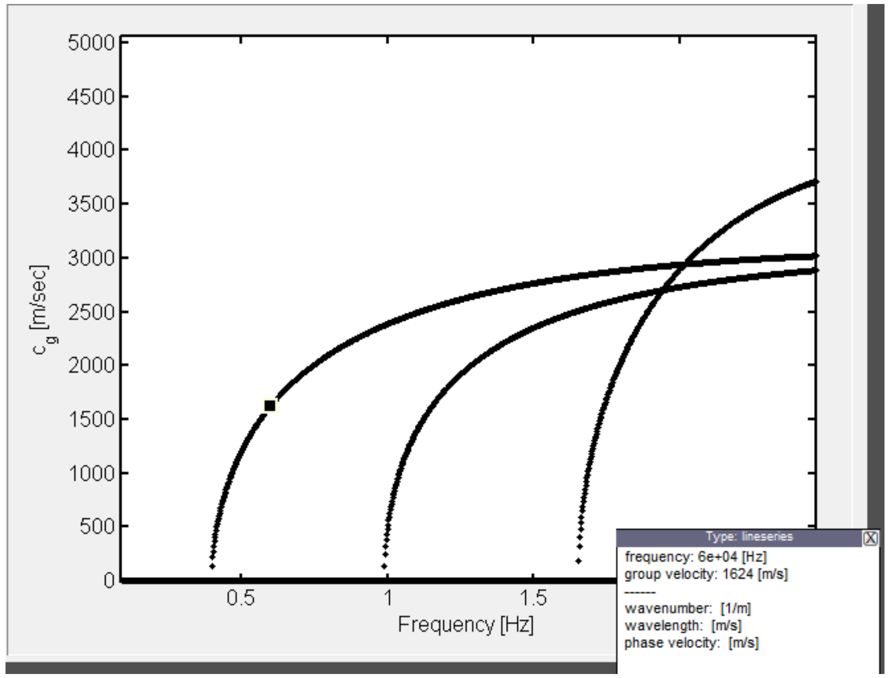


Figure 4.22 Dispersion Curve for 3 inches Pipe Flexible Mode

Further analysis will be done for S1, S2, S3, and S4 the signal is plotted in Figure 4.23. Based on Figure 4.23, it shows that S1 and S3 have an almost same pattern of the waveform, but S2 and S4 will have a different kind of waveform. It is due to the effect caused by the small dented. However, the group velocity for S1, S2, S3, and S4 is almost same and based on the time analysis is shows that the group velocity is 5265.95m/s, which is L (0,2) mode based on dispersion curve shown in Figure 3.1. Further comparison of S1, S2, S3, and S4 to the vacant straight pipe shows that the amplitude of the signal is reduced due to the artificial erosion, refer to Figure 4.24. If we compare to Figure 4.18, in previous analysis is shows that the amplitude reduction is lower compared to a cracked pipe.

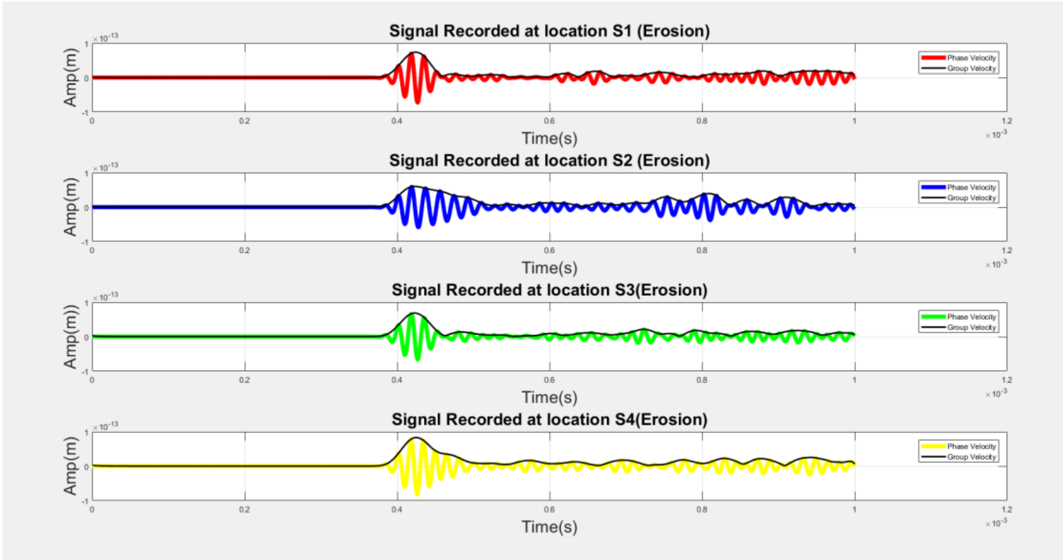


Figure 4.23 Signal Recorded at S1, S2, S3, S4 (With Artificial Corrosion and Dent)

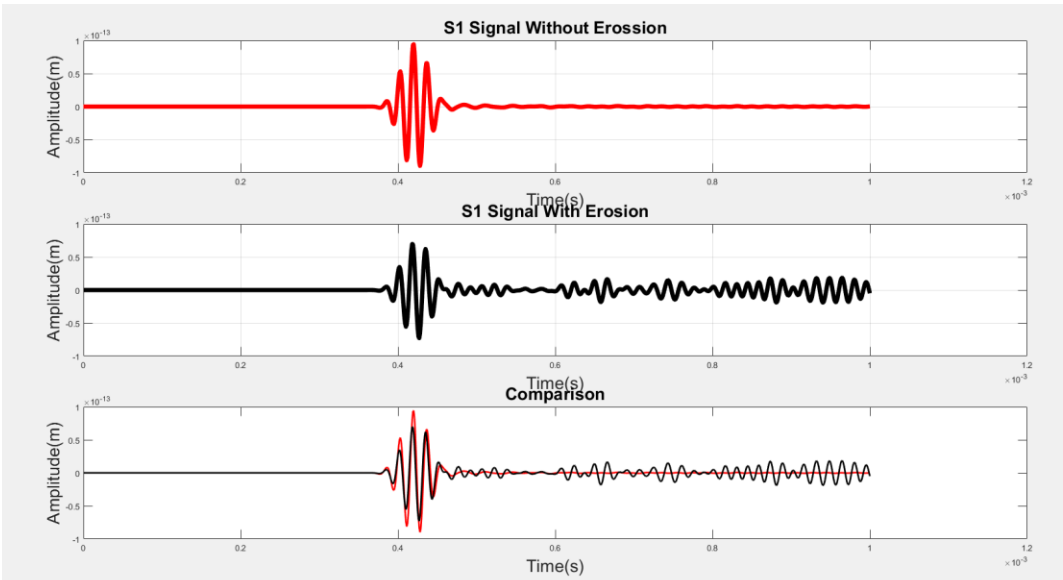


Figure 4.24 Signal Comparison between Vacant Straight Pipe and Artificial Corrosion Pipe

4.4 3 Inches Pipe with 90-degree Elbow Pipe

The elbow pipe discussed over here is 3 inches' steel pipe with wall thickness of 5mm the detail of dimension is shown in Figure 4.25. excitation location and signal measuring location are also at 2cm from pipe edge. The exact location of E1, E2, E3, E4 and corresponding of S1, S2, S3, S4 will be shown in Figure 4.26(a) and Figure 4.26(b).

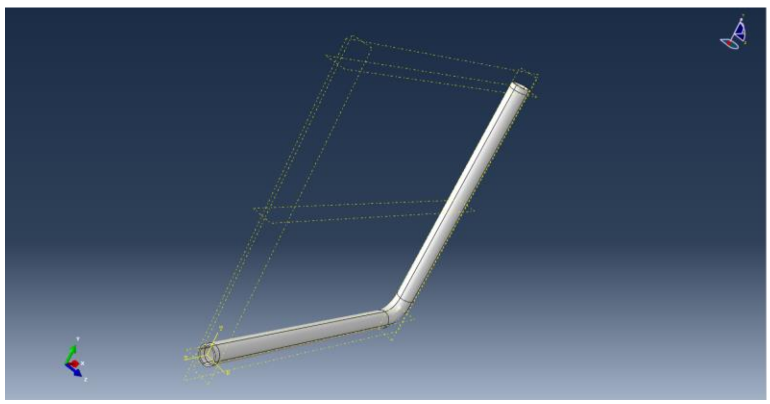


Figure 4.25(a) 90-degree Bend Pipe

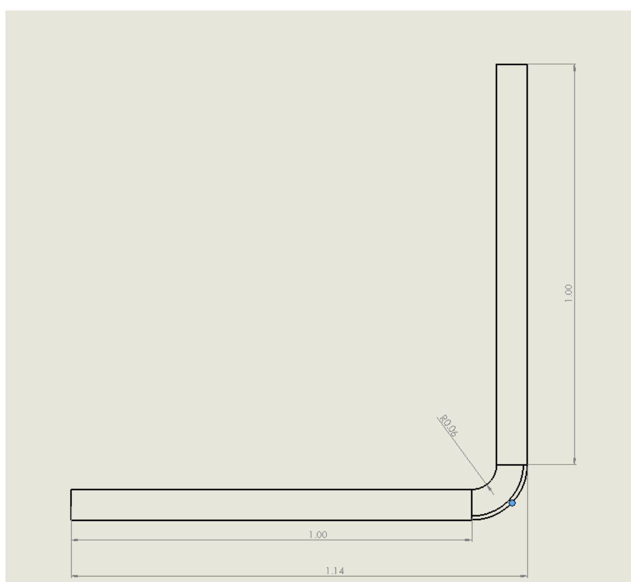


Figure 4.26(b) 90 Degree Bend Pipe Dimension

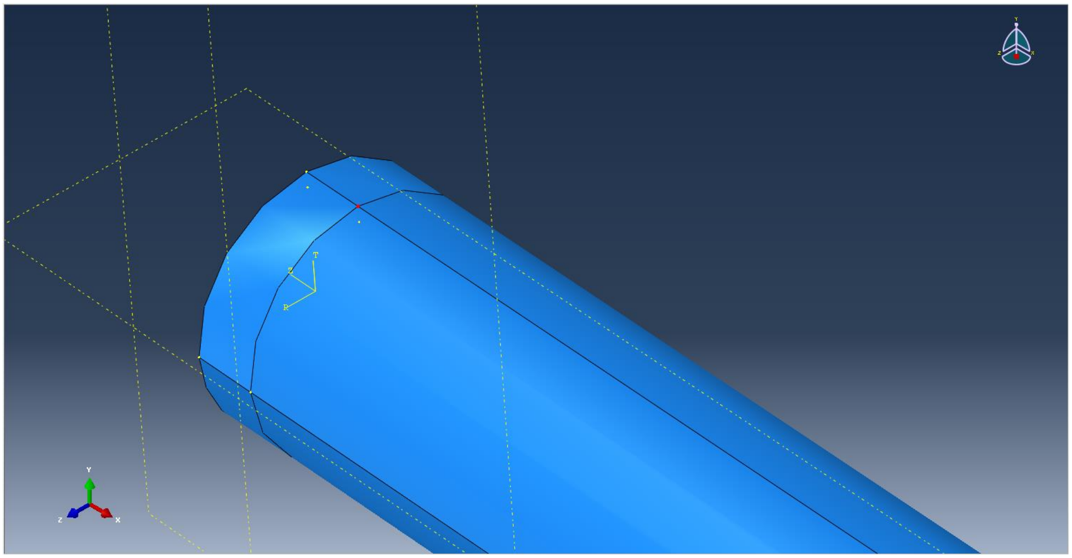


Figure 4.26(a) Location of E1, E2, E3, E4 (90 Degree Bend Pipe)

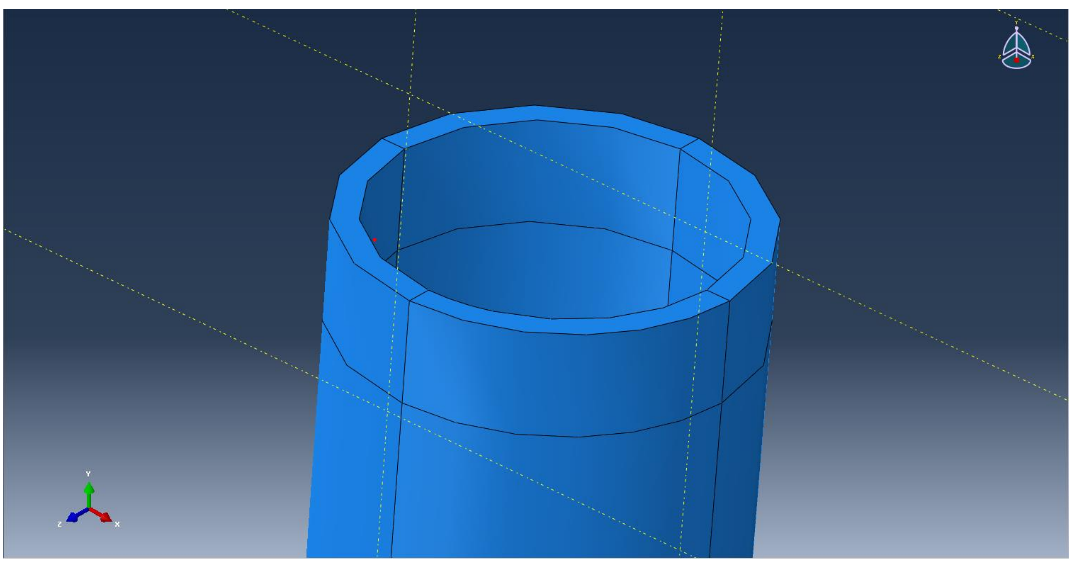


Figure 4.26(b) Location of S1, S2, S3, S4 (90 Degree Bend Pipe)

The simulation result is shown in Figure 4.27, Figure 4.28 and Figure 4.29, based on Figure 4.29, the guided wave propagation does not have any reflection even it propagates in curve pipe.

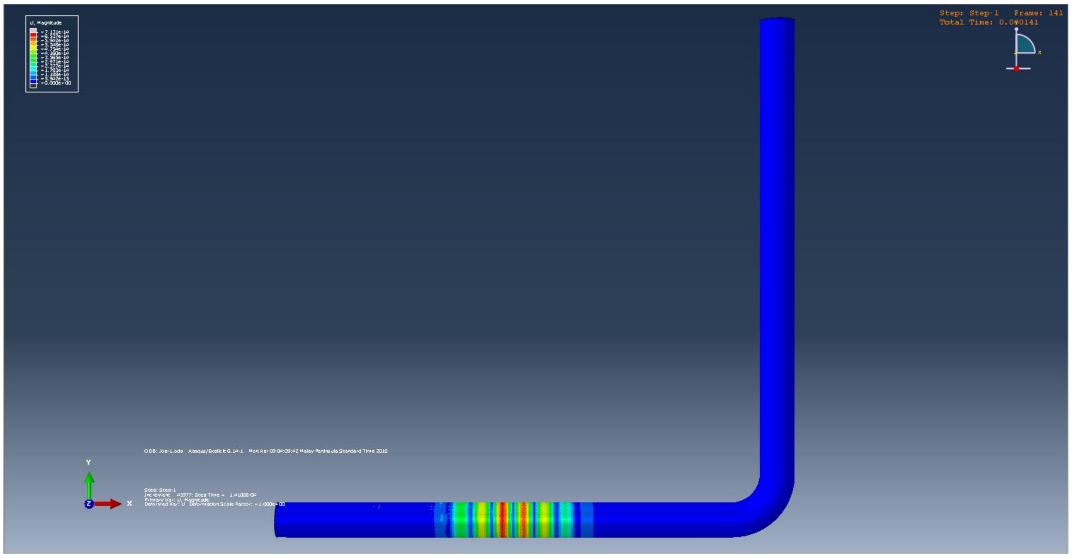


Figure 4.27 L (0,2) Signal Propagating along 90 Degree Bend Pipe

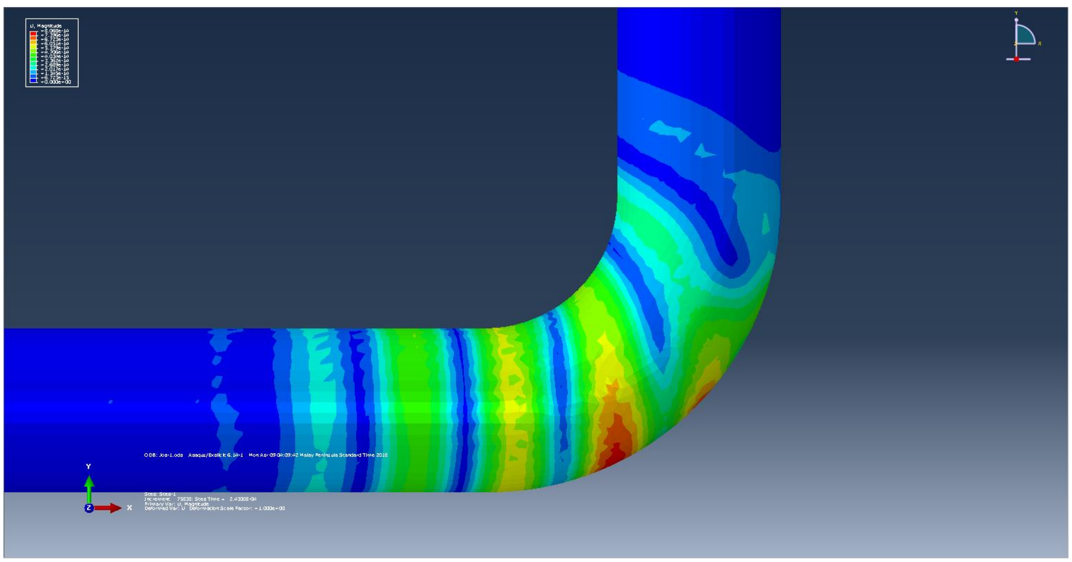


Figure 4.28 L (0,2) Signal Reaction with 90 Degree Bend Pipe at Elbow

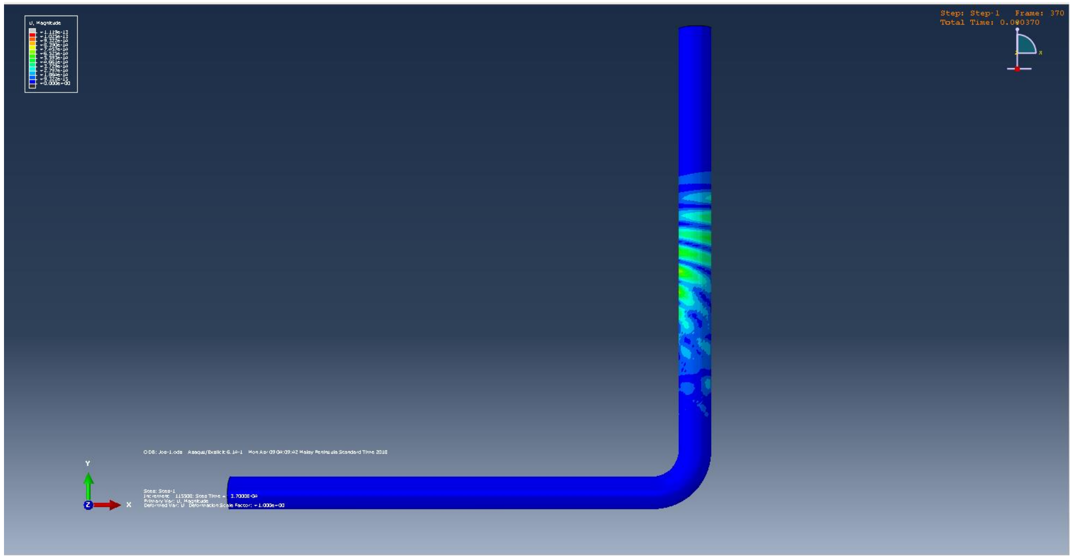


Figure 4.29 Signal Propagation Continue Propagate after a pass through Elbow

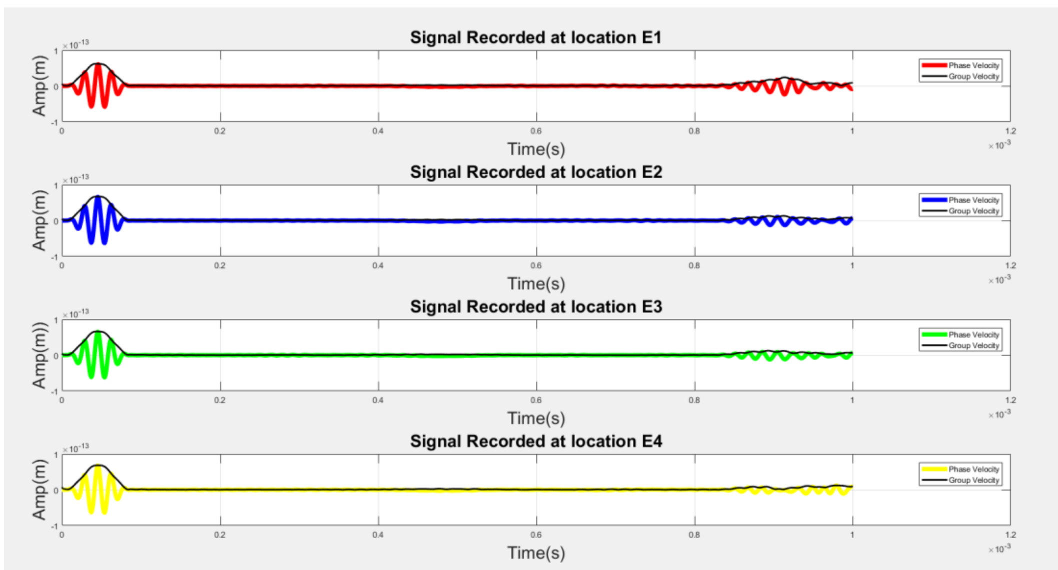


Figure 4.30 Signal Recorded at E1, E2, E3, E4(90 Degree Bend Pipe)

The data captured by ABAQUS/Explicit is then imported into MATLAB for further analysis, and the result is plotted in Figure 4.31. Based on the data recorded at E1, E2, E3, and E4, the waveform has the same pattern compared to the straight pipe without defect as discussed in section 4.1. However, the reflected amplitude is almost same but the time required to reflect back to the original position is slower compared to the straight non-defected pipe and the signal comparison is plotted in Figure 4.31.

Based on time analysis, it found out that the group velocity for 90-degree elbow pipe without defect is 2476.07m/s therefore based on dispersion curve described in 4.32, the reflection signal is not L (0,2) mode but is L (0,1) mode.

Further analysis at Signal recorded at S1, S2, S3, S4, the data is plotted in Figure 4.33. based on the data and perform time analysis is found out that the fastest group velocity is 4813.95m/s. Based on the dispersion curve, the mode of the waveform is F (1,3), the dispersion curve is plotted in Figure 4.34.

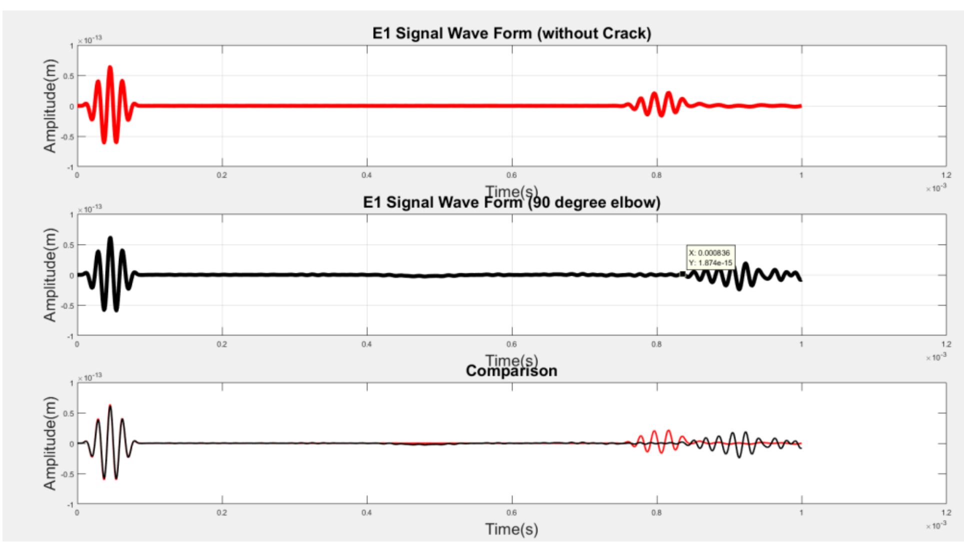


Figure 4.31 Reflection signal comparison

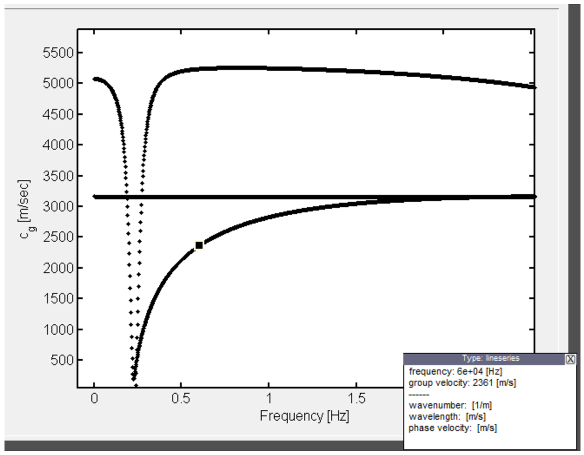


Figure 4.32 Dispersion Curve for 90 Degree Elbow Pipe (Torsional and Longitudinal)

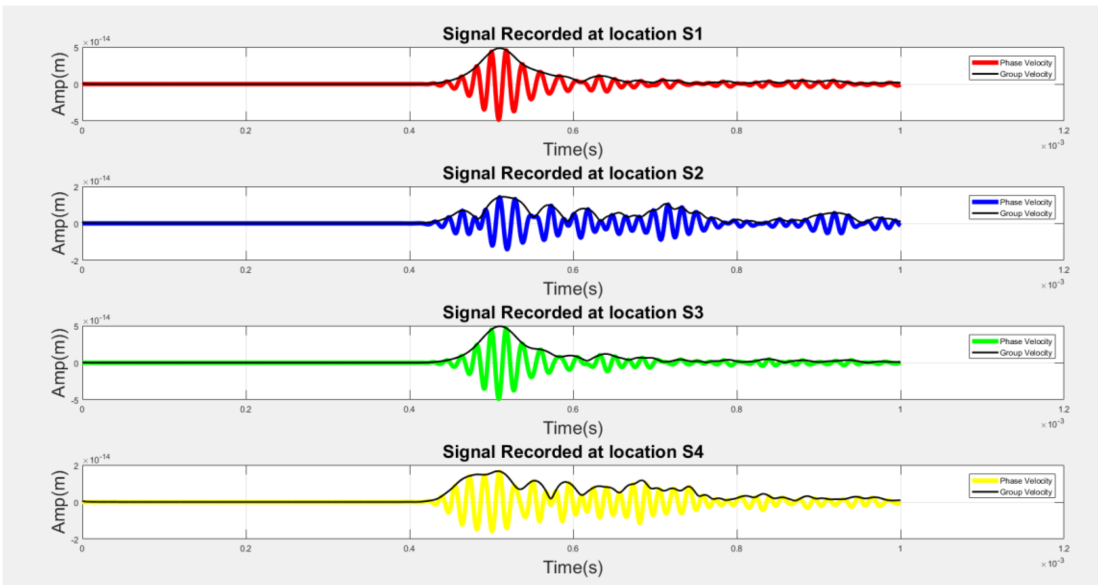


Figure 4.33 Signal Recorded at S1, S2, S3, S4 (90 Degree Bend Pipe)

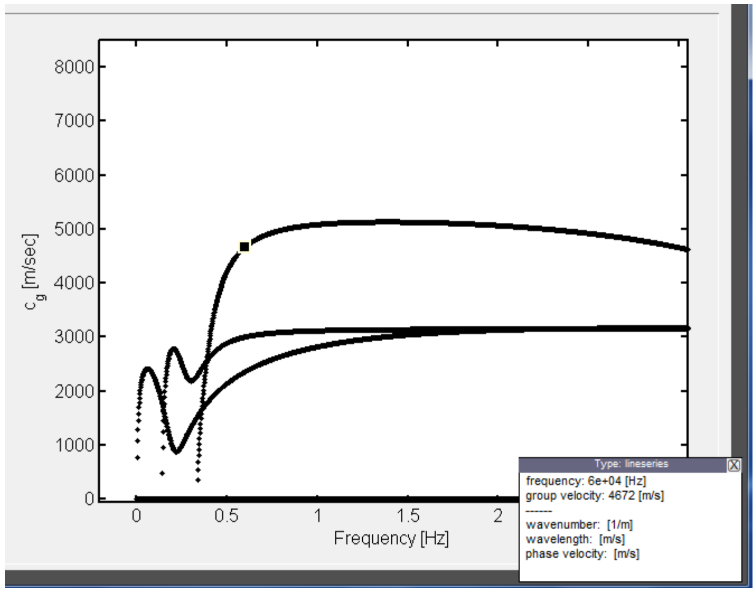


Figure 4.34 Dispersion Curve for 90 Degree Elbow Pipe (Flexible Mode)

4.5 3 Inches Pipe with 90 Degree Bend with Crack

The small crack will have uneven shape in the elbow area, the detail of drawing is shown in Figure 4.35, and all another parameter such as pipe length, thickness, material is remained unchanged, besides that the excitation point E1, E2, E3, E4 and signal recorded point S1, S2, S3, S4, remain unchanged as well.

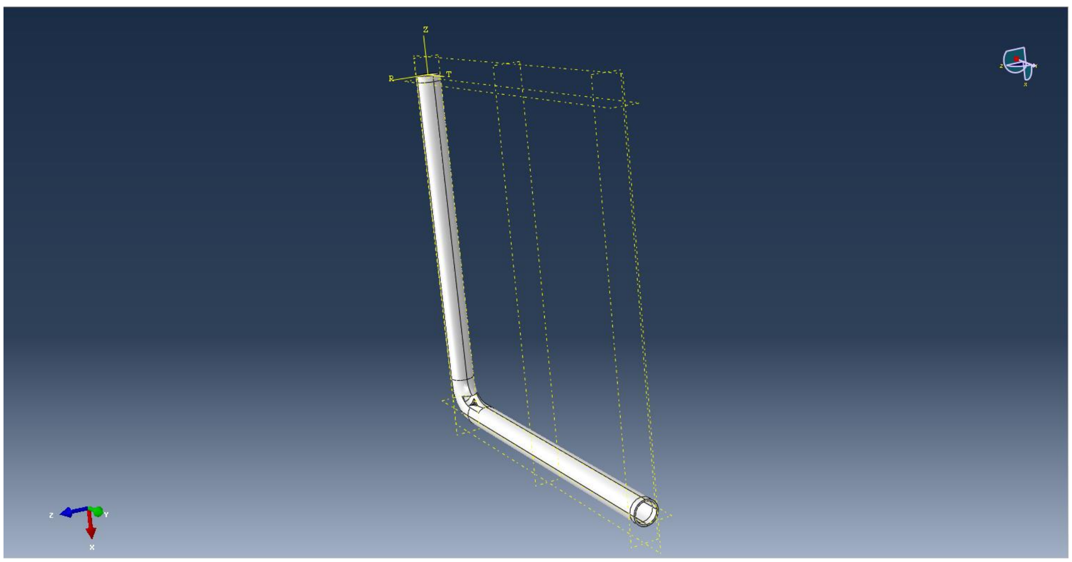


Figure 4.35 Small Crack at Elbow Area

The simulation result is plotted in Figure 4.36, Figure 4.37. it can be cleared to notice that the wave energy is shifted to the outer elbow area. However, it still has reflection signal as shown in Figure 4.37.

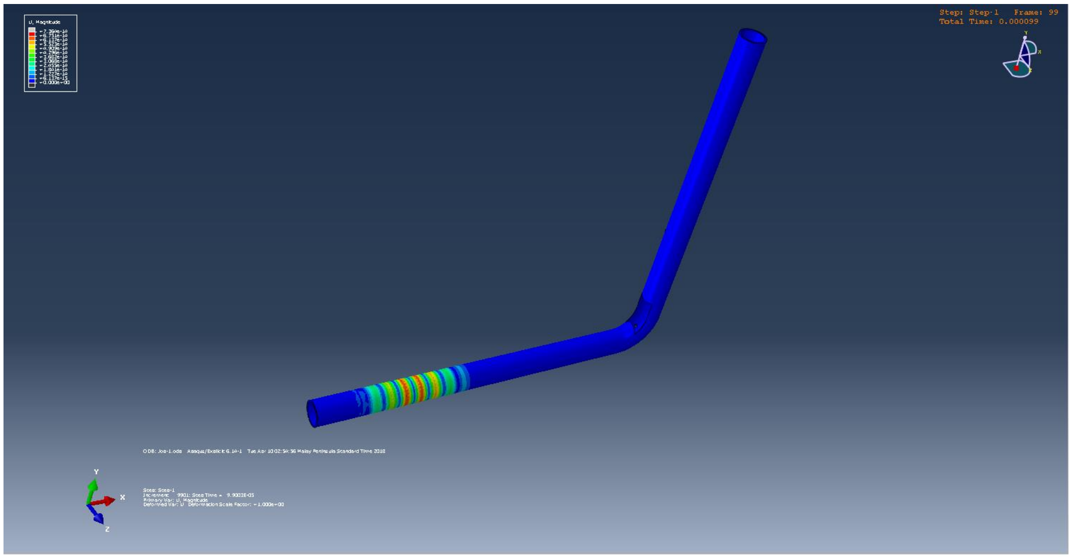


Figure 4.36 L (0,2) Mode Propagate along the Bend Pipe (With Crack)

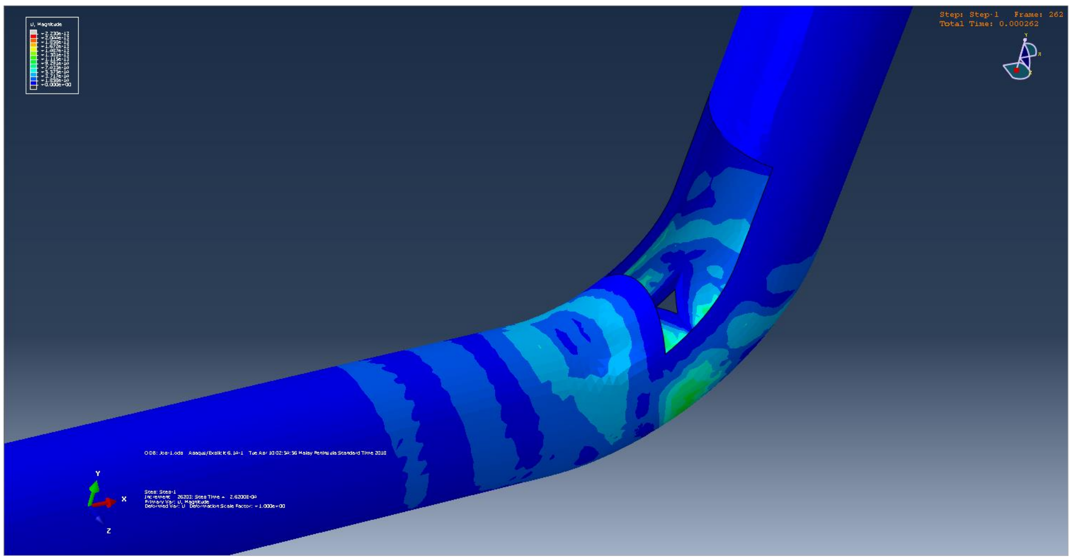


Figure 4.37 L (0,2) Signal React with Small Crack

Based on the data recorded by ABAQUS/Explicit, the detail of waveform is plotted in Figure 4.38, it can be noticed that the 1st echo signal happen on 0.000426s, based on time analysis is found out that the group velocity is 2347.42m/s, based on the dispersion curve plotted in Figure 4.39, the mode is F (1,1)

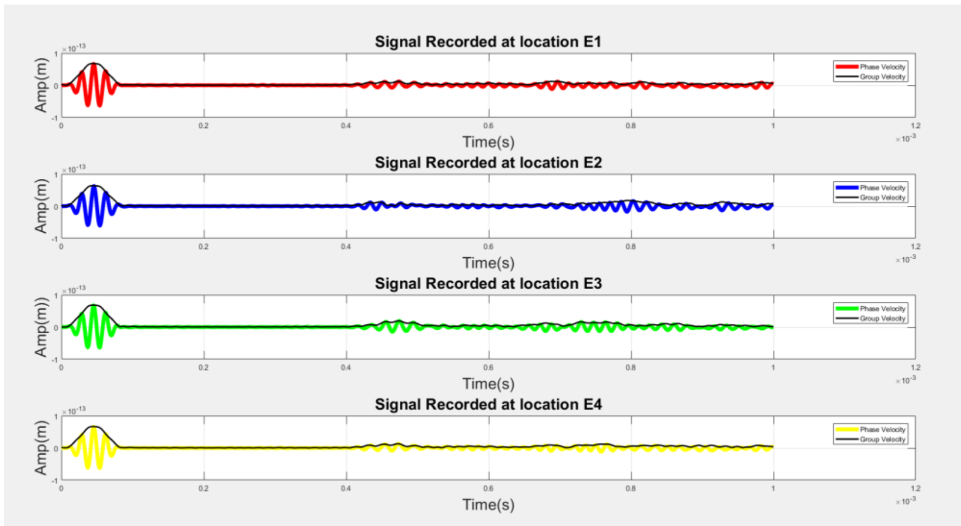


Figure4.38 Signal Recorded at E1, E2, E3, E4 (90 Degree Bend Pipe with Crack)

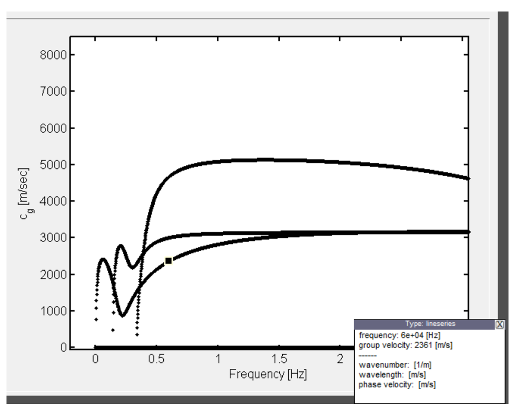


Figure 4.39 Dispersion Curve for 90 Degree Elbow Pipe (Flexible Mode)

Further analysis of Signal of S1, S2, S3, and S4 the graph is plotted under Figure 4.40. Based on the simulation it has something like wave separation at elbow area as shown in Figure 4.44. The 2nd Signal recorded is not the interference signal. Which mean that at least 2 types of mode will penetrate through the end of the pipe

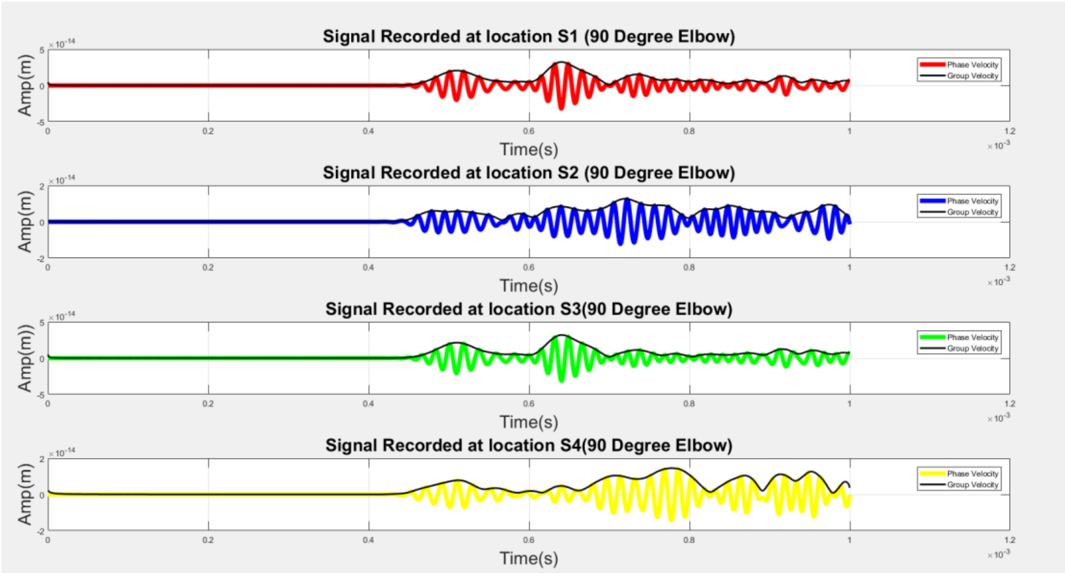


Figure 4.40 Signal Recorded at S1, S2, S3, S4(90 Degree Bend Pipe with Crack)

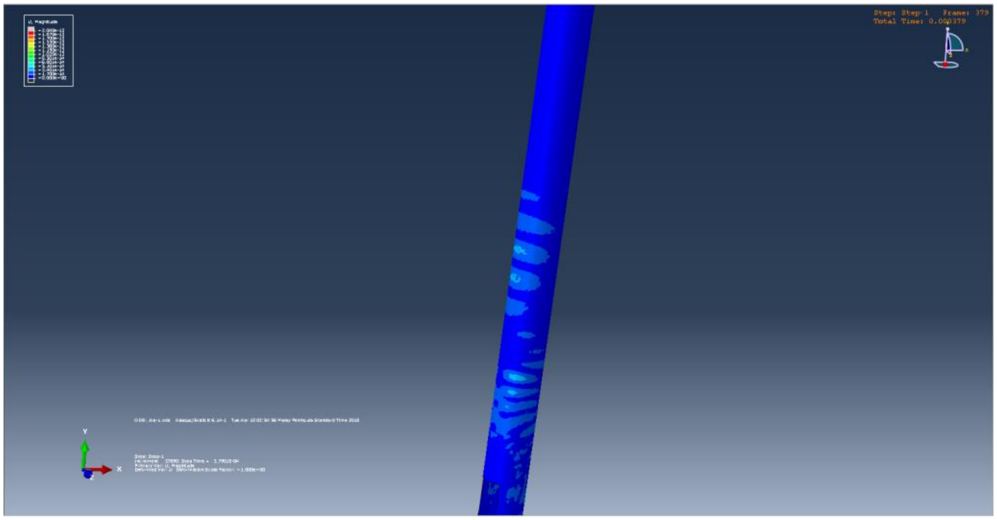


Figure 4.41 Signal Propagation Separation after Pass-Through Elbow

Based on time analysis is found out that the speed of the 1st signal is 4545.45m/s, based on the dispersion curve plotted at Figure 4.37, it is confirmed that the signal is L (0,1) and the 2nd signal with speed of 3369.98m/s, based on the dispersion curve, the 2nd signal is closed to T (0,1). Further, compare both cracked in the elbow and without cracked in elbow area the graph is plotted in Figure 4.45.

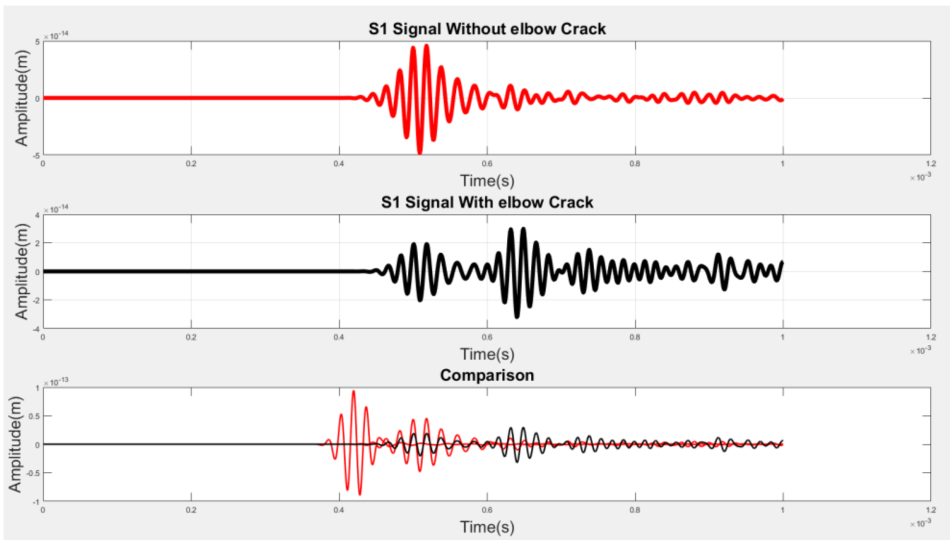


Figure 4.42 Signal Comparison between Cracked 90 Degree Bend Pipe and Without Cracked 90 Degree Bend Pipe

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As the project is all about the simulation of the effect of guided wave propagation of the pipe. Therefore, some of the actual conditions are not involving in this simulation such as noise recorded by the actual transducer, actual material properties and so on.

Throughout the simulation, it is concluded that the wave mode and wave speed will be change if that is any defect on the pipe. However, the mode change is geometry dependence, which means that the mode shape and wave velocity will change depending on which kind of defect geometric. Also, wave reaction to the crack is not only generated 1 type of mode, it is the combination of few types of mode, in difference velocity in a single frequency.

Since the project is based on L (0,2),60kHz, the sensitivity to the defect for other non-dispersive frequency or mode is unknown. it is being expected that different mode of excitation signal will generate different kind of mode propagation, wave speed and also the signal amplitude.

5.2 Recommendations

In this project, the vacant pipe is under consideration. However, to apply guided wave testing to the structural health monitoring, some of the consideration shall be taken into account. Such as the installation location of the pipe, external support of the pipe, fluid flow effect, and so on. Also in the actual piping system, it has a lot of auxiliary devices is installed on the system, such as reducing nipple, reservoir tank, branches, 45-degree elbow there for this all auxiliary device may affect the guided wave propagation properties as well. since the guided wave propagation is directly related to material of the pipe, some of the application may couple difference pipe material, this all will affect the guided wave propagation performance. To gain more accurate simulation, the real condition should take into account.

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by Teck Sing Chong

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CHAPTER 1

INTRODUCTION

1.1 Background

Piping is the system that convey fluids from one point to another. It is important system throughout the planet. According to the statistical report given by Central Intelligence Agency, about 3500000km of piping transportation system had been built throughout the world, therefore piping system is a part of world economic structure due to most of the valuable fluids is transported by piping system. (E.W. McAllister,2009).

Piping system is important systems, however, most of the piping system had been installed or operated about half century. Therefore, it can be expected that most of the pipe in the piping system is aged. Aged pipe will reduce fluid transportation efficiency due to scale generated internally, or corroded due to environment issue. Besides that, some of the piping system may have defect caused by external issue, such as, defect such as the defect of buried pipe due to soil motion, external dented due to excessive load applied on pipe surface. Therefore, inspection of piping system is important, due to the defected pipe in the end will caused fluid leakage, if the piping system is transport corrosive gases, or flammable liquid, it has potentially caused disaster to society and environment.

1.2 Piping Inspection

They are several inspection methods had been imposed in piping inspection, the more generally is visual inspection, where the inspection is done by inspector naked eyes, or systematic inspection involving complicated hardware and software system (E.W. McAllister,2009).

Pig-based monitoring system is used a device called pig to perform piping inspection, the device is shows in Figure 1.1. the device usually used to pipe internal surface, and built in pipeline monitoring system. (E.W. McAllister,2009). The leak detection method by this device is based on flow data, or pressure imbalance, once the device detects some error, it will give an alarm to notice the inspector.

Figure 1.1 Pigging Device (Contract Resources,2010)

Ultrasonic testing is also usually applied on piping inspection, where ultrasonic testing is fall under Non-destructive testing, it is because the ultrasonic transducer is direct attached on the pipe wall without stopping the operation, the ideal of using ultrasonic is simple by transmission and reflection, that is several type of ultrasonic testing used in pipe inspection, including guided waves testing, and phase array ultrasonic testing.

1.3 Problem Statement

Ultrasonic Guided waves testing is one of the non-destructive testing method applied on pipe inspection, the benefit by applying guided wave testing is because it can detect long range of pipe in single excitation location. However due, to dispersion properties of wave propagation in pipe, to determine the suitable frequency for pipe inspection is difficult.

1.4 Aim and Objective

The aims of this project is to simulate guided wave propagation in pipe.

The objective in this project including following

a. Defect detection based on guided wave propagation through computer simulation
b. Wave propagation pattern and it dispersion properties.

CHAPTER2

LITERATURE REVIEW

2.1 Introduction

This chapter will introduce the structural health monitoring system, and non-destructive testing, and the linkage between structural health monitoring and non-destructive testing. Also, it will introduce general physic of soundwave and the differences between soundwave and ultrasonic soundwave. Lastly, it will be including some general information of guided wave.

2.2 Structural Health Monitoring

Structural Health Monitoring is the process that involve observation of engineering structural over the time, structural health monitoring is used to confirm the (Tianwei Wang,2014). engineering structure condition The main purpose to implement structural health monitoring is to prevent disaster due to failure of engineering structural, and secondly based on the data given in structural health monitoring experienced engineers are able to determine the maintenance period of the engineering structure based on conditions. In facts, condition based maintenance is more cost effective compared to preventive based maintenance. (Singiresu S. Rao,2011)

Structural health monitoring system actually is same as general measurement system. However, it is involving monitoring the engineering structural over a time. The general block diagram for structural health monitoring is defined in Figure 2.1. (John P. Bentey, 2005)

Figure 2.1 General Structural Health Monitoring (John P. Bentey,2005)

From the block diagram plotted on Figure 2.1, the external signal excitation is defined as external load applied on the engineering structure. In facts, the external signal excitation sometime is not really need extra device to perform. For example, acoustic emission effect, water hammer effect, those effect will create stress wave and then propagate within the engineering structure, the propagating wave can be used to do the monitoring as well. Sensing element is the device that transforming useful physical variable such as amplitude, acceleration, pressure and so on into electrical signal, the electrical signal will be either analog signal or digital signal.

(John P. Bentey,2005) The next step is signal conditioning, the signal conditioning involving convert the electrical signal recorded by sensor into more useful form of signal, for example amplification of electrical signal from millivolts to volts. (John P. Bentey,2005) The next step is signal processing where involve noise reduction recorded by sensor, signal conversion such as analog signal to digital signal, and the correction of the signal. The final step of structural health monitoring is the data presentation, where the measuring value converted into the form that easily recognized by observer. (John P. Bentey,2005)

That have 2 types of structural health monitoring system, which including passive type and active type, for passive type structural health monitoring system, it is only do the measurement without any action. However, in active type structural health monitoring system, it will also involve feedback mechanism to notify the user the present state of the structural health, Figure 2.2 shows the active type of Structural health monitoring system (Tianwei Wang,2014).

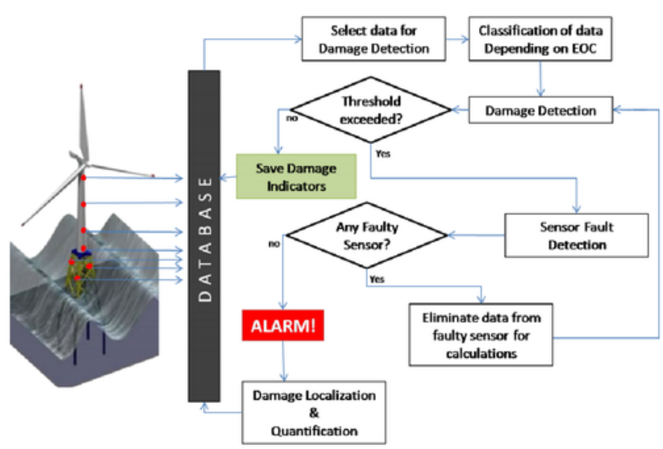


Figure 2.2 Active Type Structural Health Monitoring System

2.3 Non-Destructive Testing

The definition of Non-Destructive Testing is to determine condition of structure without affecting the performance (NDT, n.d). They are lots of Non-destructive testing method being applied in industry, such as visual inspection, where the inspection is based on naked eyes of the observer, acoustic emission testing, where the inspection based on the "sound" produced by the engineering structure itself, bubble test, where testing leakage of the compressed air pipe, and so on.

Non-Destructive Testing are often implemented in structural health monitoring it is because non-destructive testing has capability to measure the condition of the structural without affecting the structural performance. However, not all the non-destructive testing method is suitable for structural health monitoring, it is because some of the method do not have feedback capability. (TianWei Wang, 2014)

Acoustic emission testing is the method of Non-destructive testing, it is based on "sound" generated by material itself, the "sound" produced by the material itself is due to redistribution of stress field inside the material. To trigger acoustic emission effect within the engineering structural, external load such as pressure, force and etc. have to applied on to the engineering structure, even acoustic emission testing is widely used to detect flaw up to 1μm to 50μm, but it is not suitable applied on Structural Health Monitoring due to external load dependence.

2.4 Sound and Ultrasonic

Sounds are produced due to vibration and the vibration mean that the back and forth motion of the medium molecules, so that sound can be considering as wave (Jones/Childers, 2001). For example, vibration of diaphragm of the speaker will caused the air surrounded of the speaker will vibrate together, however, the air surrounded of the speaker is not travel due to the vibration. In facts, the vibration of air surrounded of the speaker will caused vibration to entire boundary of air to vibrate as well, it is due to kinetic energy created by diaphragm transfer into air surrounded of the speaker, and then the kinetic energy in air will transfer through entire boundary, the energy transfers of air produce sound.

To transfer sound energy, it is required transfer medium such as gas, fluid and solid, without the medium the sounds are unable to transfer from one point to another. Therefore, the energy transfer is depending on material properties of the medium. The speed of sound in air is about 343m/s in air at 20ºC (Jones/Childers, 2001). however, the speed of sound is not a constant fix value, it is influence by the medium as well. in general, speed of sound in solid will be fastest compare to liquid and gas. It is because solid have higher density compared to the liquid and gas (Jones/Childers, 2001). For example, the soundwave velocity of steel will have about 5000m/s it is about 15 times higher compared to the soundwave velocity in air. Note that, the speed of sound is not the speed of the vibration, it is the speed of disturbance to another molecule.

Generally, wave can be categorized into 2 types, which are transverse waves and longitudinal waves. Sound wave travel in air is longitudinal waves it is because the direction of the vibration is same as the direction of energy transfer, for transverse wave the vibration direction will be perpendicular to the direction of energy transfer (Jones/Childers, 2001). The typical example of transverse wave is light wave.

Human are able to listen sound frequencies from 20Hz to 20kHz, the ultrasonic waves are the frequencies above 20kHz, in another hand, frequencies below 20Hz is categorized as infrasound Figure 2.3 shows approximate frequency ranges corresponding to application.

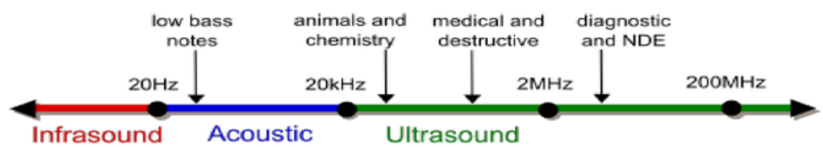


Figure 2.3 Acoustic Frequency and Application ('Sound',2018)

2.5 Guided Waves

Guided waves are mechanical stress wave propagating along an elongated structural. (Hegeon Kwun, Sang-Yong Kim et al., 2001), Guided waves usually propagated along an elongated structure in ultrasonic frequency (Angela Angulo, Jane Allwright et al.,2017) typically the frequency applied in guided wave testing is about 10kHz to 100kHz, however high frequency of guided wave will be applied in testing but the detection range will shorten (‘Guided Wave Testing’, 2018).

Guided waves testing become more popular in non-destructive testing it is because, guided waves testing is able to measure long range of engineering structure in single excitation location (Peter Cawley,2002). Besides that, Guided waves also able to inspect hidden engineering structural such as insulation pipe.

Guided wave testing usually grouped into 3 type, short range guided wave testing which is the inspection length is below 1m, for medium range usually refer to the range up to 5m, and long range guided wave testing is up to 100m. (Peter Cawley,2002).

Although guided wave testing has the ability to inspect long range of engineering structural, but guided wave has some short coming as well. Peter Cawley (2002) reported that the signal obtained by guided wave sensor is consists of a lots of noise as shows in Figure 2.4. Another short coming is a lots of wave modes in single frequency, and most of the modes is dispersive (Relation between mode, Frequency and Wave Velocity) as shows in Figure 2.5

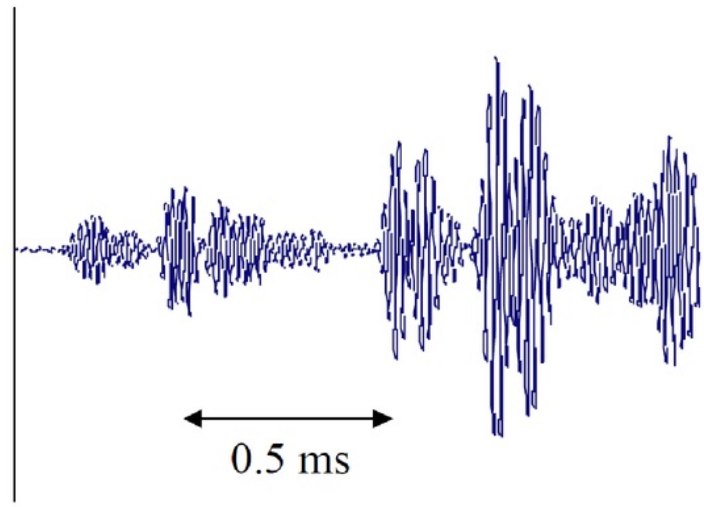


Figure 2.4 Noise Signal in Guided Wave testing (Peter Cawey,2002)

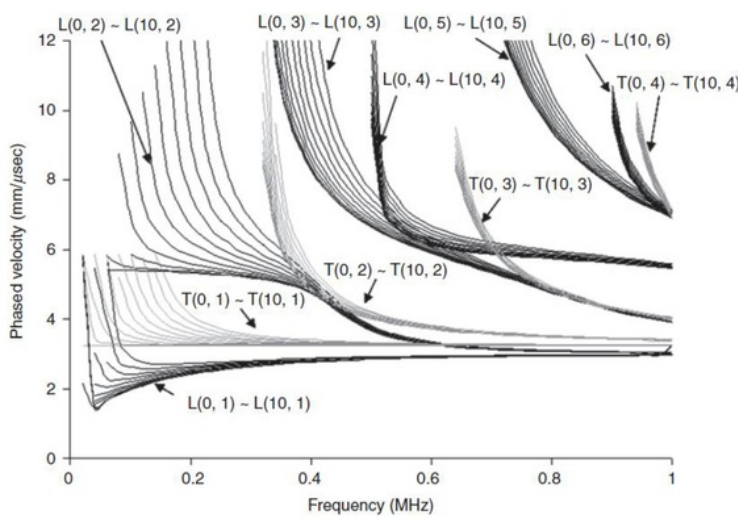


Figure 2.5 Sample Dispersion Curve for 3 inches Pipe (Rose,2014)

Zhenhua Song, et.al (2018) carrying and experiment of damage detection in large diameter pipe filled by difference fluid, it shows that the dispersion properties for vacant pipe and fluid filled pipe is totally difference, as shows in Figure 2.6, also L (0,2) is suitable mode vacant pipe inspection and L_{wp} (0,4) is suitable for water filled pipe.

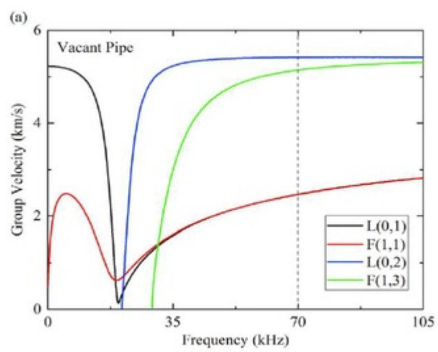


Figure 2.6(a) Dispersion Curve for Vacant pipe (88mm O.D)(Zhenhua Song et.al 2018)

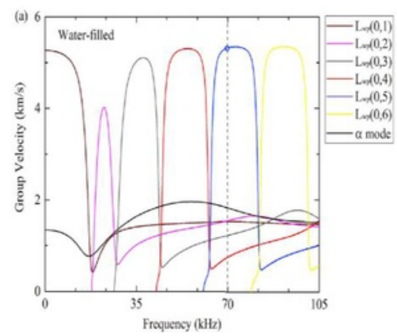


Figure 2.6(b) Dispersion Curve for Water filled Pipe (88mm O.D) (Zhenhua Song et.al 2018)

Guided wave propagating in pipe in axial direction involving 2 types of wave, which are Longitudinal wave and torsional waves (Rose,2014). Longitudinal waves travel via compressional motion in axial directions and Torsional wave travel via circumferential direction. However, there are 3 types of modes which is named as Longitudinal axially symmetric modes L (m, n), Torsional axially symmetric mode T (m, n) and also Non-axially symmetric modes F (m, n) the m and n is represent number of mode shape across the pipe and n is represent the group order mode (Rose,2014). Figure 2.7 shows the group order mode in graphical explanation.

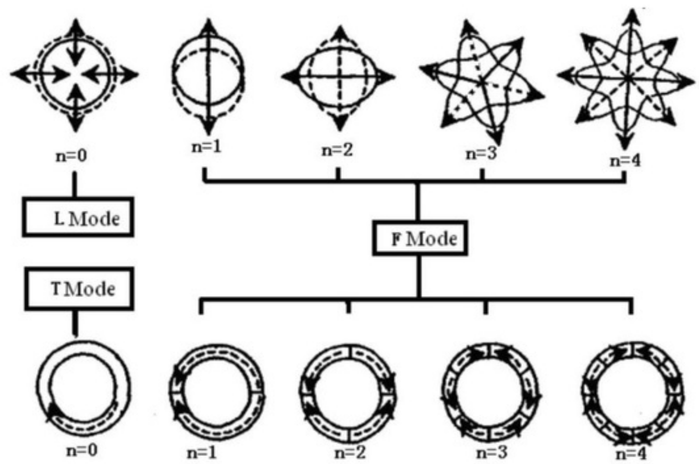


Figure 2.7 Graphical explanation of group order mode. (Tianwei Wang,2014)

When the hollow cylinder has traction-free (No external Load on surface) boundary condition, the guided wave propagation equation is shows in equation 2.1 (Rose,2014)

$$\mu\nabla^2\vec{U} + (\lambda + \mu)\nabla\dot{\nabla}\vec{U} = \rho\left(\frac{\delta^2\vec{U}}{\delta t}\right) \quad --- 2.1$$

Where μ and λ is Lame constant, ρ is density of the elastic material, $\vec{U}$ is the displacement field in cylindrical coordinate(Rose,2014).

2.6 Phase Velocity and Group Velocity Concept

Wave Velocity usually quantified into 2 terms, which are phase velocity and group velocity (TianWei Wang, 2014). Figure 2.8 Show the difference between group velocity and Phase velocity.

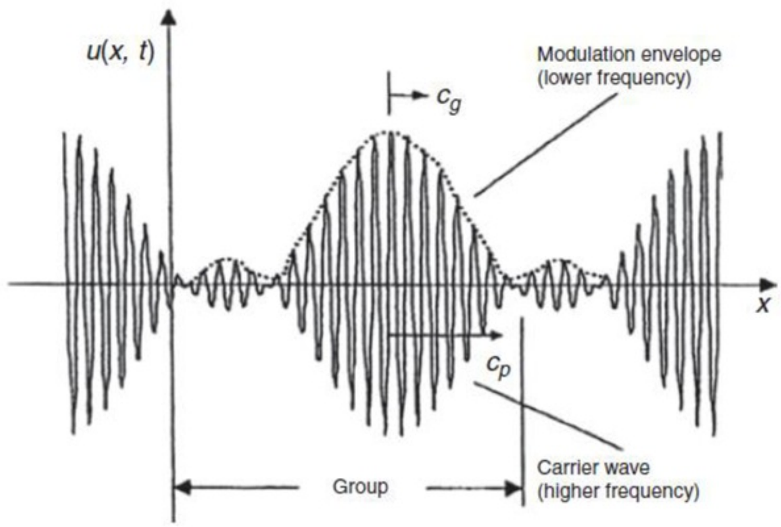


Figure 2.8 Phase Velocity and Group Velocity (Rose,2014)

Group velocity is the propagation velocity of group of wave which have similar propagation frequency(Rose,2014). Phase velocity is the wave velocity of the individual wave (TianWei Wang, 2014) the relationship between group velocity and phase velocity is shows in equation 2.2 (Rose,2014)

$$V_{group} = V_{phase}\left(1 - \frac{\omega}{V_{phase}}\frac{dV_{phase}}{d\omega}\right)^{-1}$$

CHAPTER 3

METHODOLOGY

3.1 Simulation Software

3.1.1 ABAQUS/CAE

The simulation was done by using ABAQUS/CAE, which is developed by Dassault Systemes. ABAQUS/CAE is the simulation software based on finite element analysis. The analysis tools in ABAQUS/CAE including following:

a. ABAQUS/Standard.
b. ABAQUS/Explicit and Implicit.
c. ABAQUS/CFD

In this Project ABAQUS/Explicit will be applied, the analysis of problem by using ABAQUS/Explicit involving following step:

a. Preprocessing
b. Simulation
c. Post-processing

The analysis of ABAQUS/Explicit is based on central difference operator and diagonal element mass matrices(ABAQUS,2013).

3.1.2 GUIGUW

GUIGUW stand for Graphical User Interface for Guided Ultrasonic Wave, it is developed by Dr. Alessandro Marzani and Dr. Paolo Bocchini, the main purpose for this software is to determine the dispersion relationship of difference type of engineering structural.

The dispersion properties calculation is based on Semi-Analytical Finite Element method (A. Marzani, P. Bocchini et.al)

3.2 Simulation Modeling

In this project total 5 models will be analyzing accordingly, which including vacant straight pipe without any defect, straight pipe with crack, straight pipe with external wall thickness reduction, and 90-degree bended pipe, and 90-degree bended pipe with crack located at elbow.

The material selection for the pipe will be steel with Density of 7720kg/m^3, Young Modulus 206 x 10^9 Pa, and Poisson Ratio 0.29.

Also, 3-inches' diameter with 5mm wall thickness pipe will be use throughout the simulation.

3.3 Pipe Parameter

As mentioned in section 3.2, the diameter of the pipe will be 3 inches(76.2mm), and the thickness of the pipe will be 5mm. the steel pipe will be selected in this simulation. The material properties are shows in Table 3.1

Description	Equation	Value
Steel Pipe Density(ρ)	-	7720kg/m^3
Young Modulus(E)	-	206x10^{9}Pa
Poisson's Ratio(ν)	-	0.29
Shear Modulus(S)	$S = \frac{E}{2(1+\nu)}$	79.84x10^{9}Pa
Bulk Modulus(B)	$B = \frac{S(E-2S)}{3S-E}$	110.33x10^{9}Pa

Table 3.1 Material Properties of the Selected Pipe.

Based on Table 3.1, longitudinal velocity(C_l) and transverse velocity(C_T) can be calculated by following equation:

$$C_l = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

$$= \sqrt{\frac{206 \times 10^9(1-0.29)}{7720(1+0.29)(1-2\times 0.29)}}$$

$$\therefore C_l = 5913.36m/s$$

$$C_T = \sqrt{\frac{S}{\rho}}$$

$$C_T = \sqrt{\frac{79.84 \times 10^9}{7780}}$$

$$\therefore C_T = 3203.47 m/s$$

3.4 Dispersion Curve and Frequency Selection

As mentioned in section 3.1.2, the dispersion curve will be obtained by using software named GUIGUW, based on the result shows in GUIGUW, the dispersion curve for group velocity will be shows in Figure 3.1 and Figure 3.2

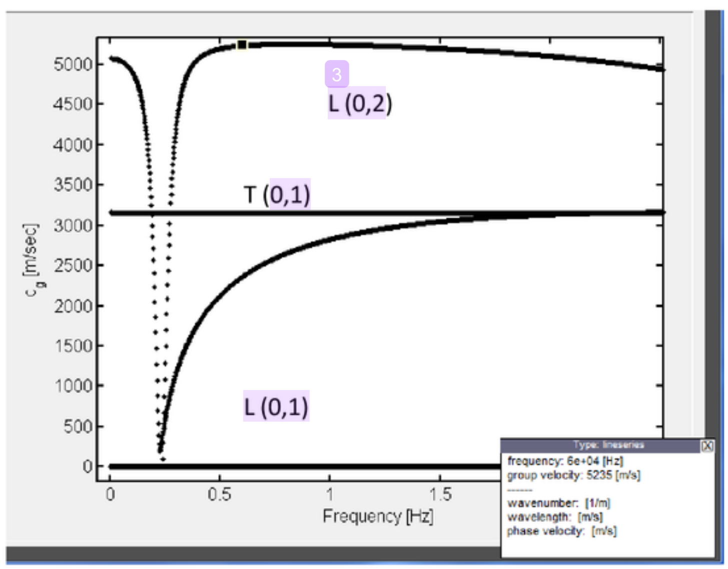


Figure 3.1 Dispersion Curve of Group Velocity for 3 Inch Pipe (Longitudinal and Torsional Mode)

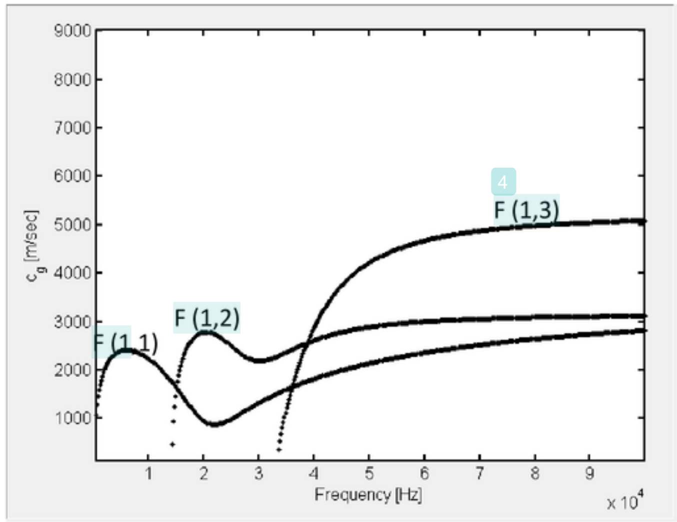


Figure 3.2 Dispersion Curve of Group Velocity for 3 Inch Pipe (Flexible Mode)

Based on the dispersion curve generated by GUIGUW, propagation frequency 60kHz and mode of L (0,2) had been selected due to it is falling in the non-dispersive regions. In this project 5 cycles Hanning Windows excitation signal had been applied due to 5 Hanning-windows excitation signal can limit the frequency bandwidth of the excitation, therefore reduction of unwanted reflection between wave packer (TianWei Wang, 2014). To determine Hanning-windows signal, following equation 3.1,3.2 and 3.3 will be applied:

$$Y(t) = A_o \sin(\omega t + \phi) - - - 3.1$$

$$h(t) = 0.5\left[1 - \cos\left(\frac{1}{N_c}\omega t\right)\right] - - - 3.2$$

$$H(t) = Y(t) \times h(t) - - - 3.3$$

where,

$Y(t)$ *is the amplitude of the specific time*

A_o *is the amplitude of the signal*

ω *is the angular frequency of the wave*

t *is the time*

N_c *is the cycle require*

Based on above equation, the Hanning-windows signal can be plotted by using MATLAB, and the result will be shows in Figure 3.3

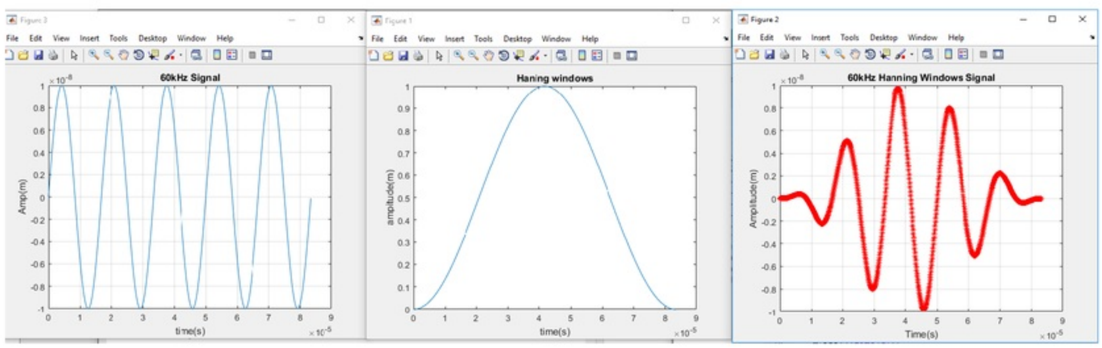


Figure 3.3 Hanning Windows Tone Burst Signal for 60kHz Excitation Signal

3.5 Element Size Selection

That are 2 conditions (TianWei Wang, 2014) should be properly selected before modeling, which including following:

i. Element size

To capture propagating wave, at least 10 elements per wavelength is required, based on longitudinal wave speed of steel and thickness of the pipe, to determine minimum element size will be calculated based on equation 3.4

$$f_{max} = \frac{f_{excitation}}{Thickness} - - - 3.4$$

$$f_{max} = \frac{0.06MHz}{5mm} = 0.012Hz$$

$$\lambda_{min} = \frac{C_l}{f_{max}} = \frac{5913.36ms^{-1}}{0.012Hz} = 492.78mm$$

$$\therefore L_{element} < \frac{492.78}{10} = 49.278mm$$

Therefore, the element size will be based on 4mm/element throughout all models discussed in this project.

ii. Time step of the modeling

ABAQUS Explicit analysis is based on known value in previous time step because of central differential method (TianWei Wang, 2014), therefore time step is very important throughout the ABAQUS Explicit analysis, to obtain accurate time step following equation, and the time step calculated over here will be used throughout the project.

$$T_{step} < \frac{L_{element}}{c_l}$$

$$T_{step} < \frac{15 \times 10^{-3} m}{5913.36 ms^{-1}} = 2.536 \times 10^{-6} s$$

Based on above calculation, and the time step value selected throughout the project will be $1 \text{x} 10^{-8}$s

CHAPTER 4

RESULT AND DISCUSSION

4.1 3 Inches Pipe without Crack

The modeling of the pipe consists of 4 sensors and 4 exciters and the location of 4 sensors and 4 exciters is offset from edge of the pipe 2cm.

In the simulation, fixed end boundary conditions had been added into the model, it is because without fix boundary condition it unable to examine the reflection characteristic.

The dimension of the pipe is shows in Figure 4.1, where the diameter of the pipe is 3inches with 5mm thickness and 2m long. That is 4 excitation points and 4 signal points to measure the amplitude of the signal and the location of excitation points and signal point will be shows in Figure 4.2. and the signal obtained will be plotted by using MATLAB.

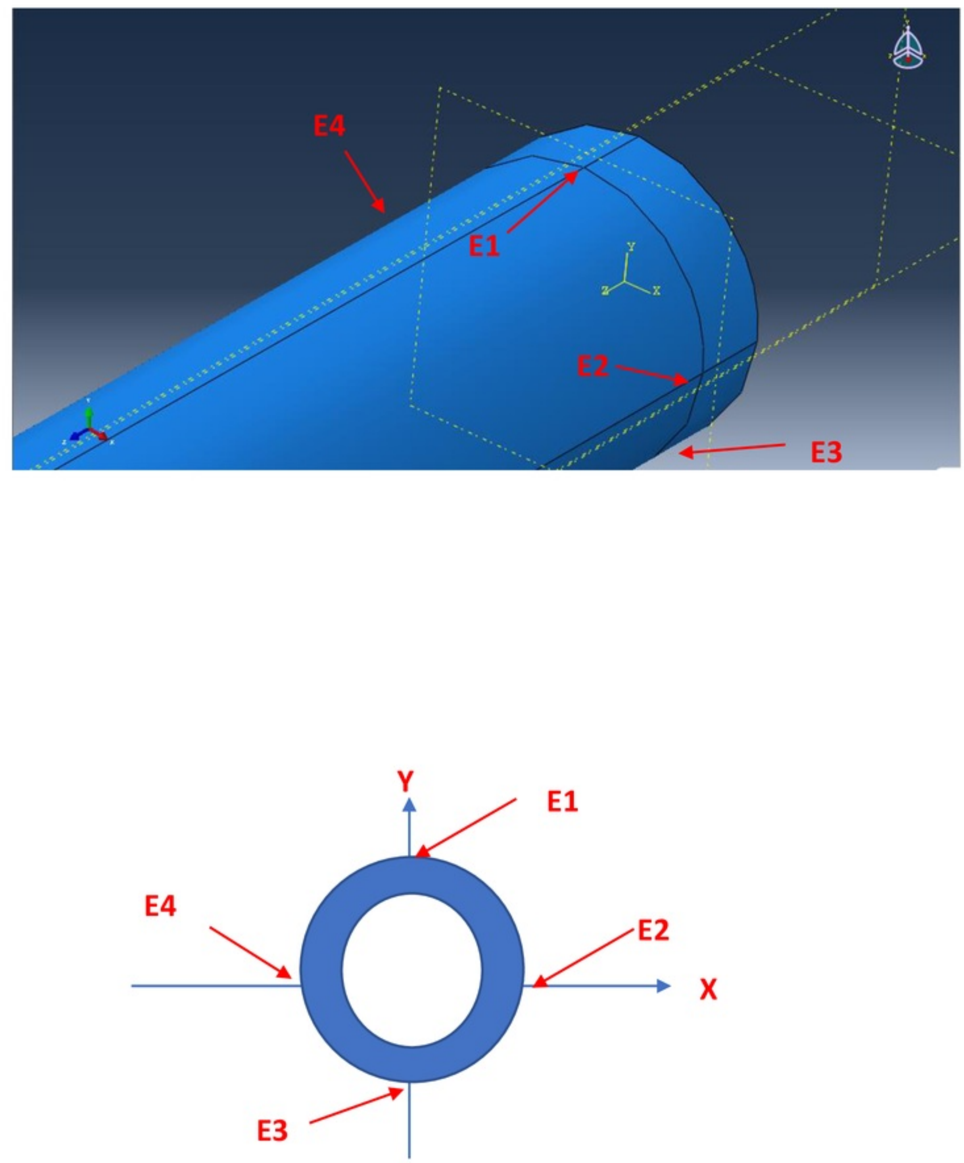
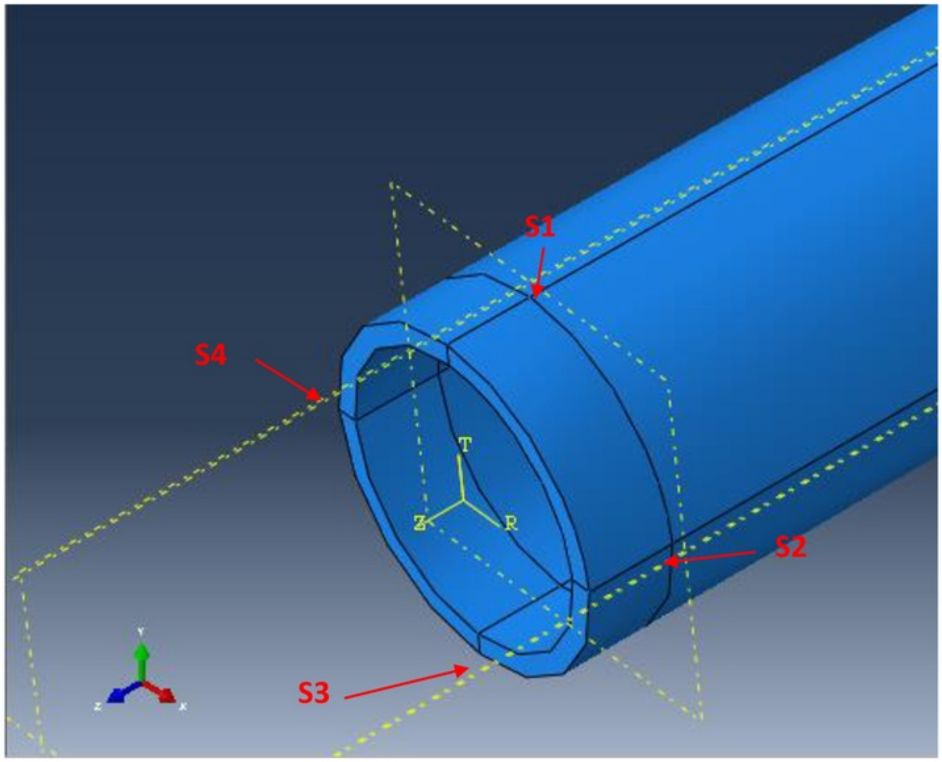


Figure 4.1 Location of E1, E2, E3, E4 (Vacant Straight Pipe)



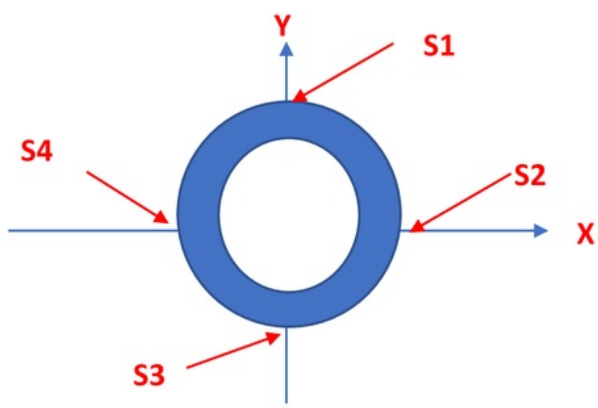


Figure 4.2 Location of S1, S2, S3, S4 (Vacant Straight Pipe)

The L (0,2) wave propagation pattern had been plotted in Figure 4.3, based on the simulation, it shows that the signal will be reflect back at end of the pipe if no disturbance in between as shows in Figure 4.4, the reflected signal will propagate back to original point and reflected back again.

The signal data had been recorded and tabulated by ABAQUS Explicit, and the numerical data recorded by ABAQUS Explicit will be imported to MATLAB for analysis, based on the signal generated by ABAQUS Explicit, the amplitude data is plotted as shows in Figure 4.5, where black color line is group velocity and red color line is phase velocity.

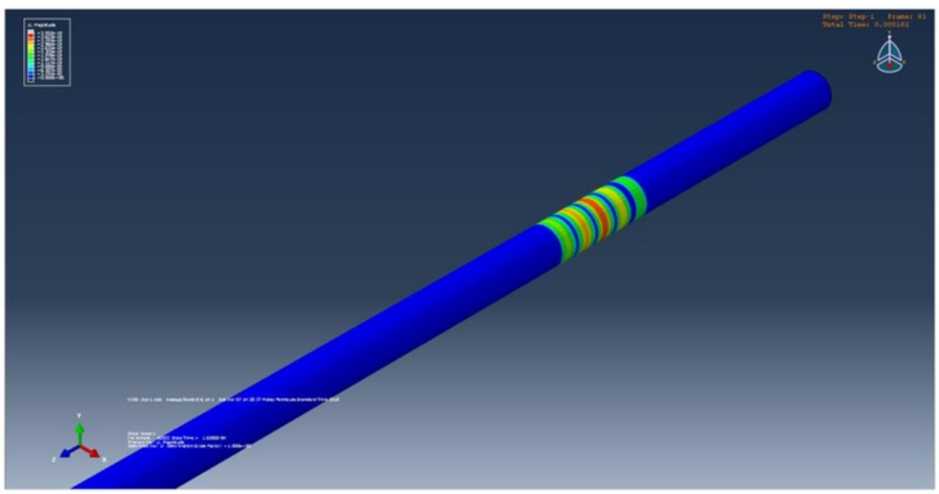


Figure 4.3 L (0,2) Mode Propagate along Vacant Pipe

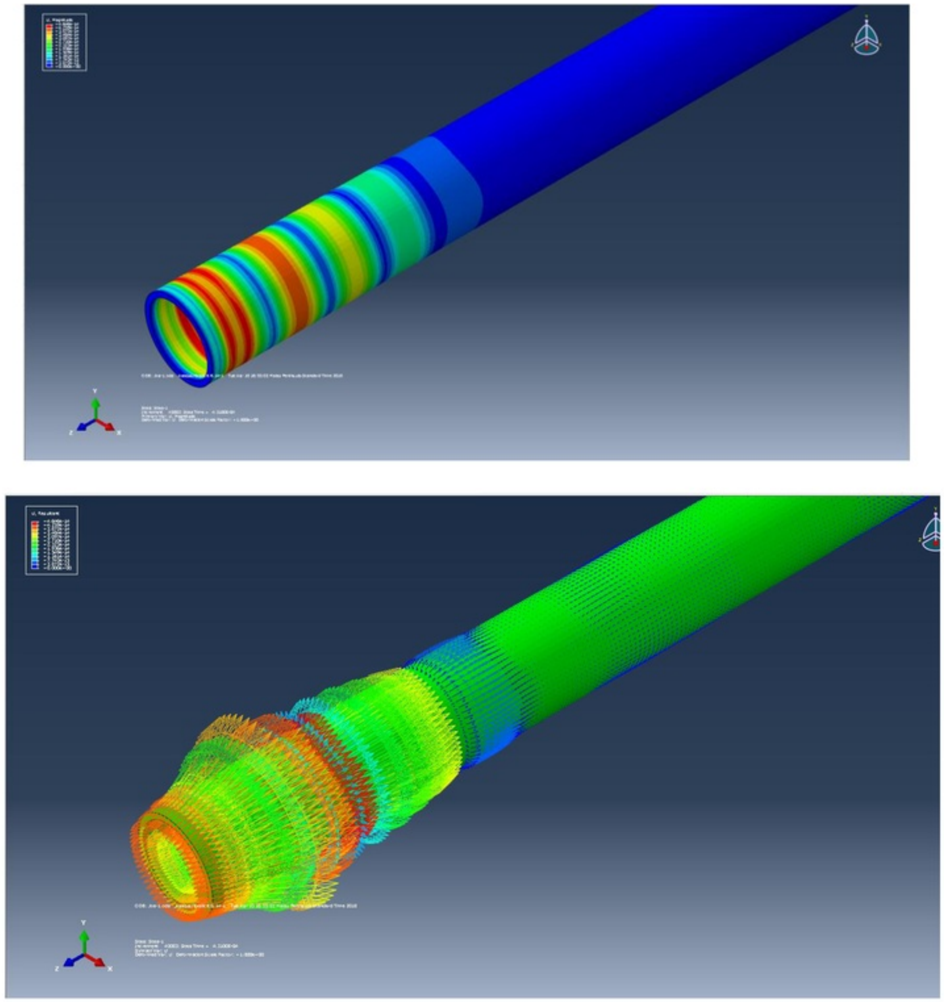


Figure4.4 L (0,2) Mode Reflection at End of the Vacant Straight Pipe

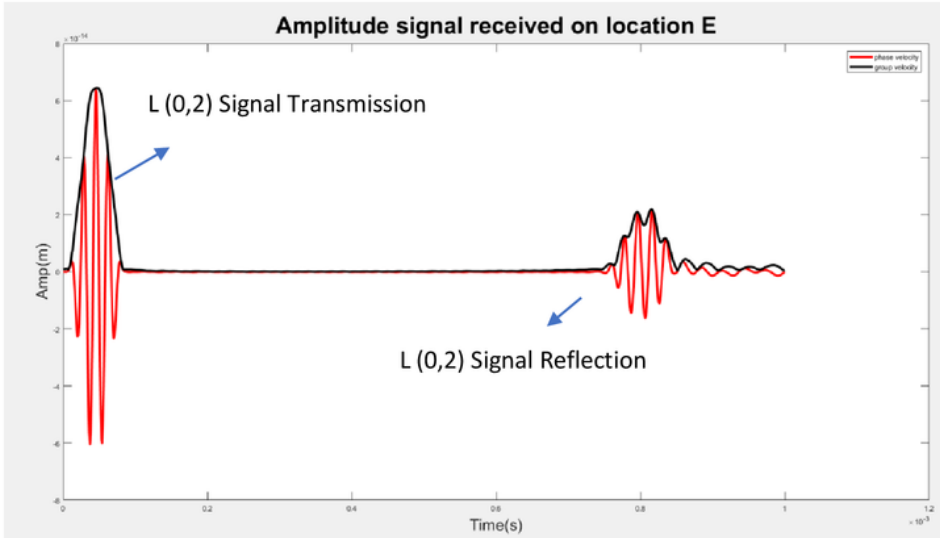


Figure 4.5 Signal Recorded at Point E1

From the recorded data, it can clearly know that that have 2 types of signal had been recorded at location E1, which are including excitation signal and reflection signal. Based on the recorded time the approximate group velocity of the reflected signal can be determine by following equation

$$v_{appx} = \frac{ds}{dt}$$

$$v_{appx} = \frac{3.96m}{0.000769s - 2 \times 10^{-5}s} = \mathbf{5287.05}\boldsymbol{m/s}$$

Since the reflection signal has frequency value of 60kHz, based on the frequency and referring to the dispersion curve plotted in Figure 3.1, it shows that in 60kHz the group velocity in mode L (0,2) should be 5235m/s, but the calculated group velocity is 5287.05m/s. However, the calculated value and dispersion curve value is slightly difference, but is still can confirmed that the reflect signal is L (0,2), it is because in this frequency region, it only has 3 type of mode involved, which is L

(0,1), L (0,2), T (0,1). However, only L (0,2) can travel in 5000m/s and above in 60kHz frequency.

Based on the recorded data of E2, E3, and E4, it shows that these 3 data have same characteristic compared to E1. Also, Data of S2, S3, S4 will have same characteristic compared to S1, the graph is plotted in Figure 4.6 and Figure 4.7

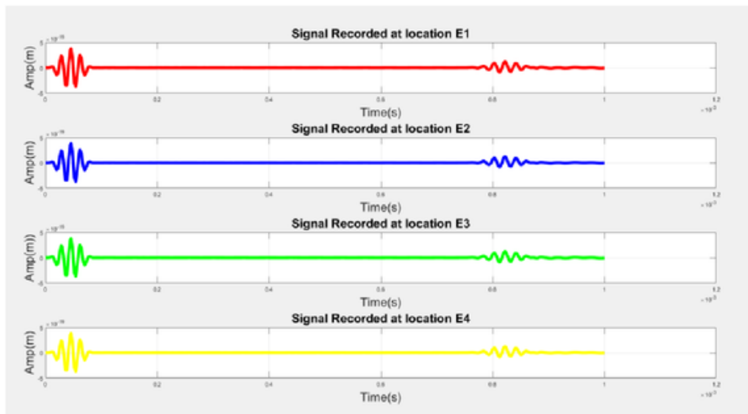


Figure 4.6 Signal Recorded at E1, E2, E3 and E4 (Without Crack)

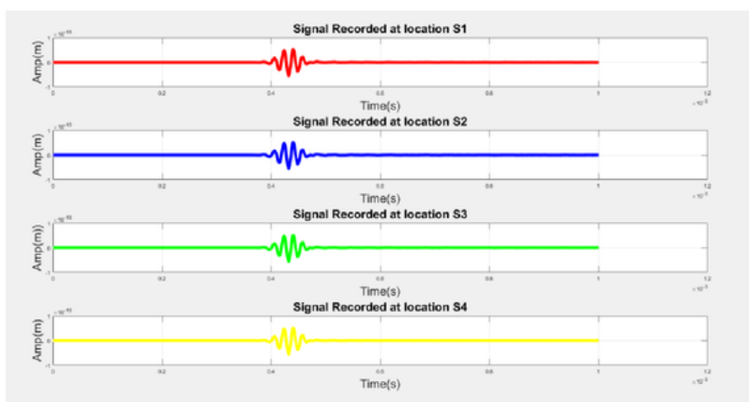


Figure 4.7 Signal Recorded at S1, S2, S3, S4 (Without Crack)

Based on the above analysis, it can be concluded that guided wave mode of L (0,2) travel along the hollow pipe without any defect, modes change will not happen. However, based on the Figure 4.7 and Figure 4.6, it shows that the wave propagation amplitude will be reduce throughout the propagation process.

4.2 3 Inches Pipe with Artificial Crack

Cracked pipe is modeled as rectangular hole, and the dimension of the rectangular hole is 40mm width and 100mm long, the detail of the location is shows in Figure 4.8(b). The pipe parameter is remaining unchanged, which is 3inches steel pipe and the correspondence thickness is 5mm, and it is also 2m long. Any other parameter such as frequency, time steps, element size is same as section 3.4. Also, the location of 4 excitation points and 4 signal points is remaining unchanged.

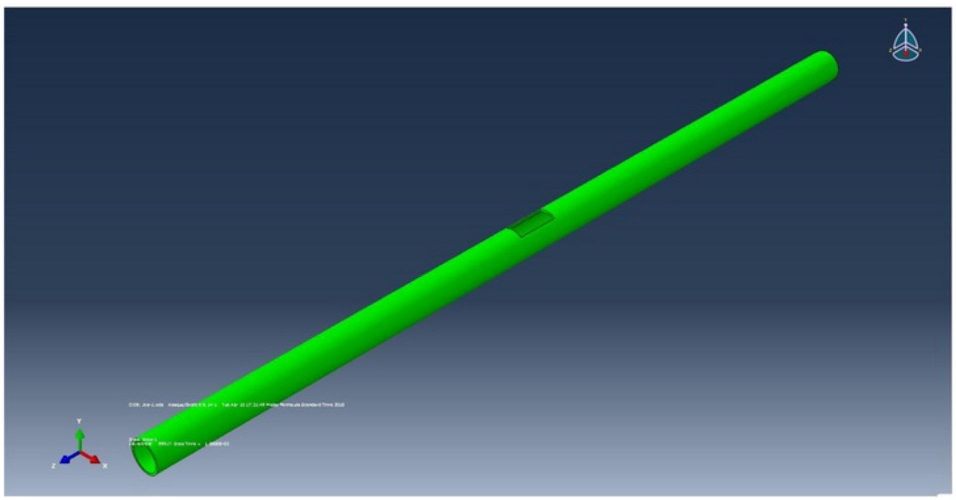


Figure 4.8 (a) Artificial cracked Straight Pipe

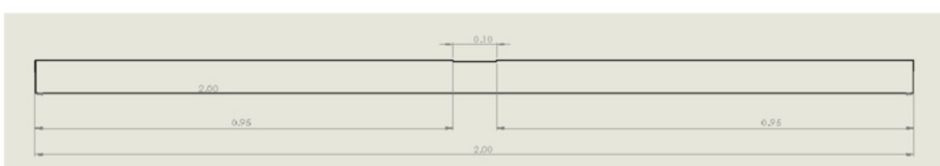


Figure 4.8 (b) Artificial Cracked Straight Pipe Dimension

The wave propagation pattern had been plotted in Figure 4.9, when the wave pass through the rectangular hole, the energy will be disrupted as shows in Figure 4.10, beside that some of the energy will be reflected as shows in Figure 4.11(a) and Figure 4.11(b).

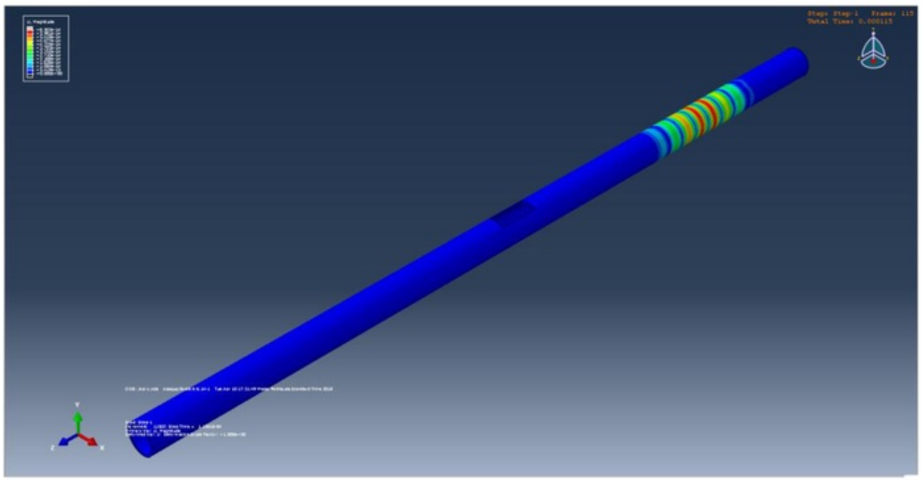


Figure 4.9 L (0,2) Mode Propagate along Artificial Cracked Pipe

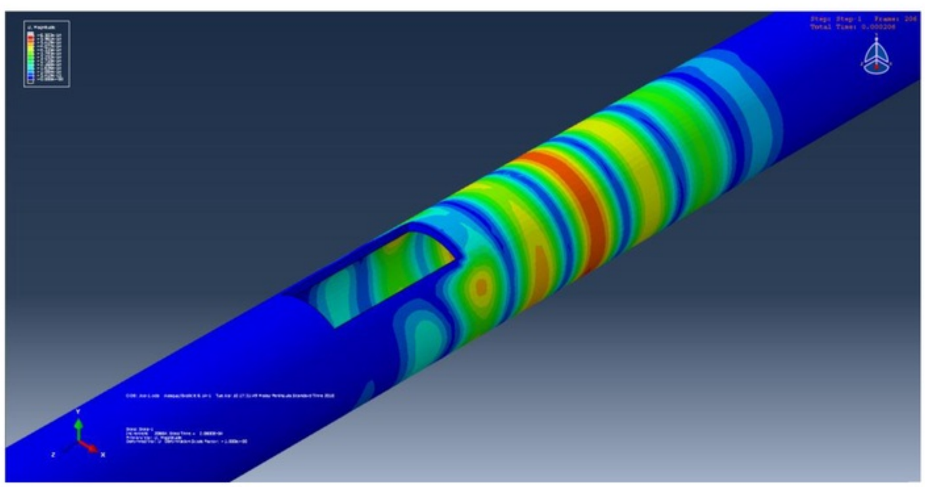


Figure 4.10 L (0,2) Signal React with the Artificial Cracked Pipe

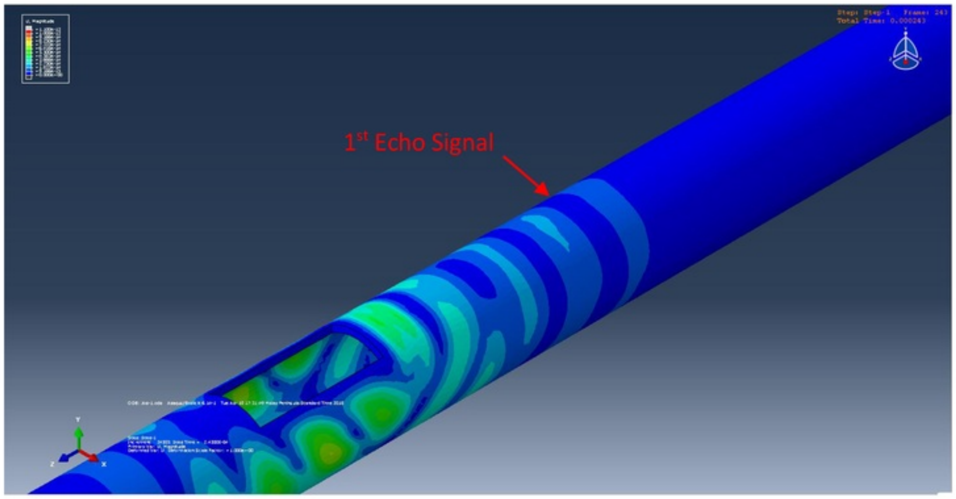


Figure 4.11 (a) L (0,2) Propagating Wave Reflection due to Artificial Crack

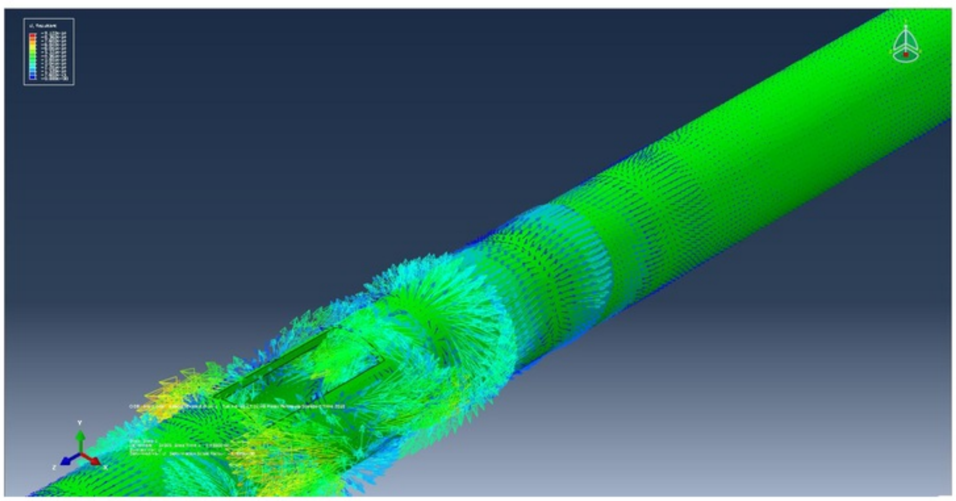


Figure 4.11(b) Vector Representation of L (0,2) Propagation Wave Reflection due to Artificial Crack

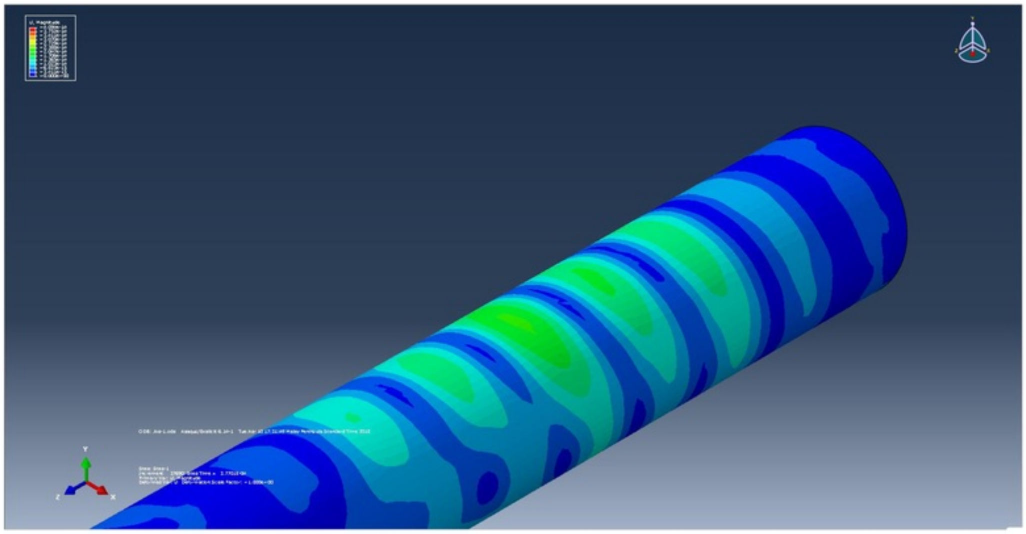


Figure 4.12 Reflection Signal Returned Back to Excitation Point

From the simulation shows in Figure 4.11(a), it clearly to notice that, the reflection and scattering is happening when the ultrasonic wave react with the small square hole, it can be predicting the excitation E1, E2, E3, and E4 will receive echo signal due to reflection of the ultrasonic wave, the data recorded by ABAQUS/ Explicit will imported into MATLAB for signal analysis and the result is shows in Figure 4.13

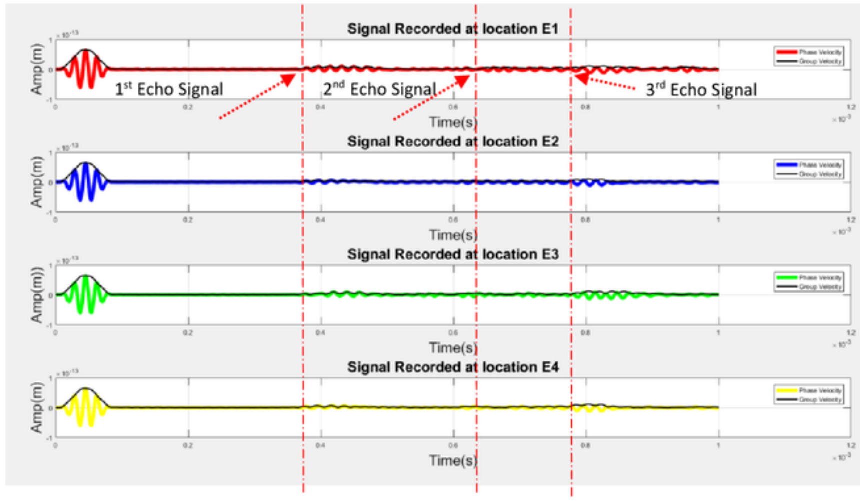


Figure 4.13 Signal recorded at location E1, E2, E3, E4 (with Crack)

Based on the graph shows in Figure 4.13, is shows that 1st echo occur at 0.00036s, this echo is caused by the small rectangular hole, based on the time, it shows that the wave velocity is about 5222.22m/s, it is confirmed that the echo signal is L (0,2) because based on dispersion curve in 60kHz, at L (0,2) mode is 5235m/s. However, based on the analysis, the signal recorded in E1, E2, E3, and E4 have excessive signal which is caused by interruption and other wave mode propagation.

Further analysis in another side, which are the signal recorded at S1, S2, S3, and S4, the graph is shows in Figure 4.14, based on the graph is shows that at least 4 non-dispersive wave packets in the continues signal, based on the calculation the group velocity of this 4 wave packages are, 5224.27m/s, 4429.53m/s,3897.63m/s, and 3084.11m/s, based on the fastest wave achieve to the location of S1, S2, S3, and S4, it is concluded that 1st signal recorded at location of S1, S2, S3, and S4 is L(0,2) mode.

Further comparison of S1 Signal between defected pipe and good pipe and the result is plotted in Figure 4.15, it shows that the amplitude of the recorded is significantly reduce it is because some of the energy had been consume due to small rectangular hole.

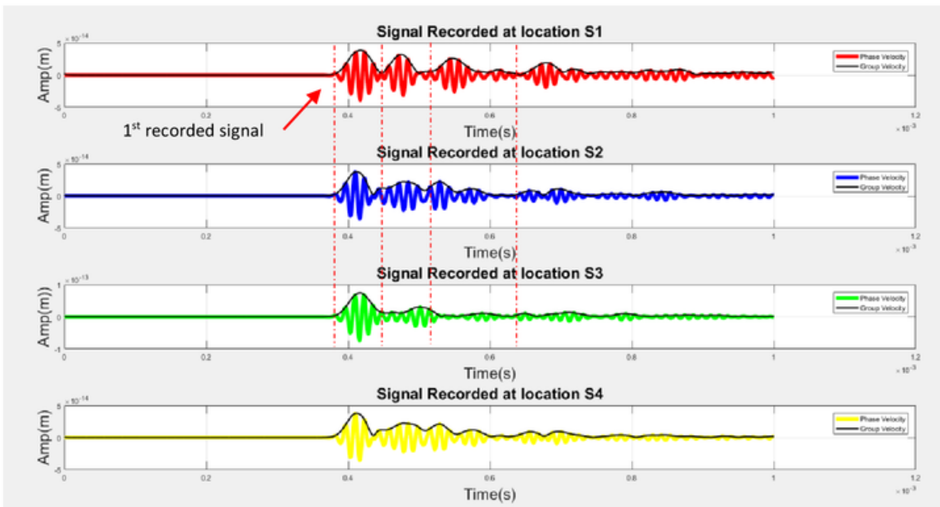


Figure 4.14 Signal Recorded at S1 S2 S3 and S4 (With Crack)

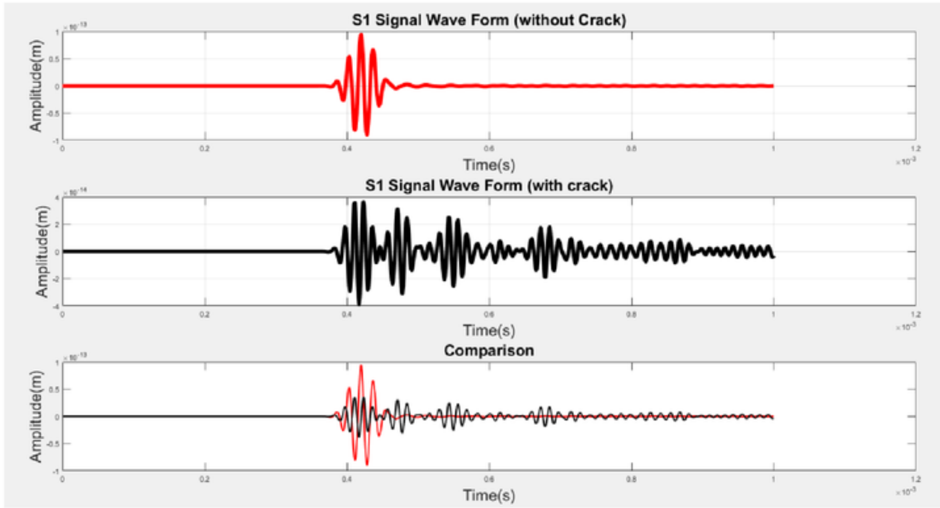


Figure 4.15 Signal Comparison between Vacant Straight Pipe without defect and Defected Pipe for S1

4.3 3 Inches Pipe with External Artificial Corrosion and Dent

The corrosion is modeled based on surface thickness reduction, the detail of the external corrosion model is shows in Figure 4.16(a) and the exact location and dimension shows in Figure 4.16(b), all the parameter of the pipe such as pipe length, pipe material, location of signal recorded point and excitation recorded point excitation signal are remaining unchanged.

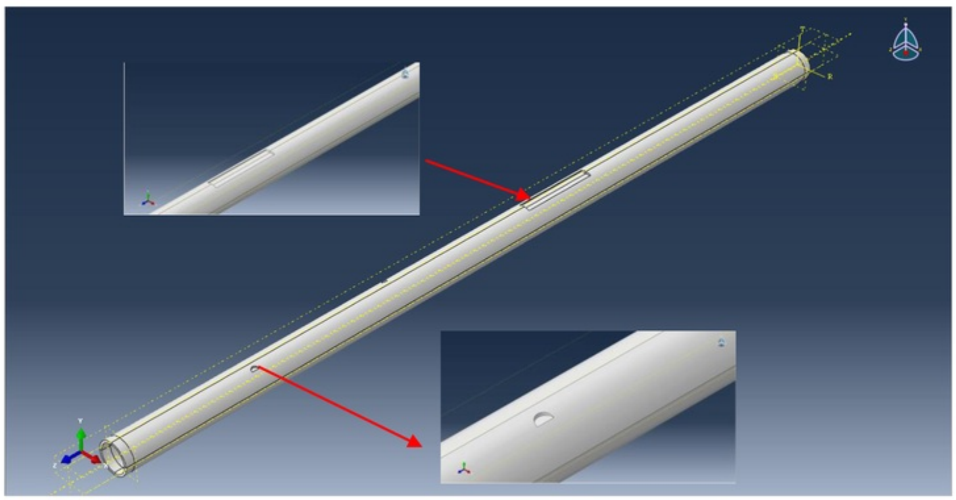


Figure 4.16(a) Artificial External Corrosion Pipe

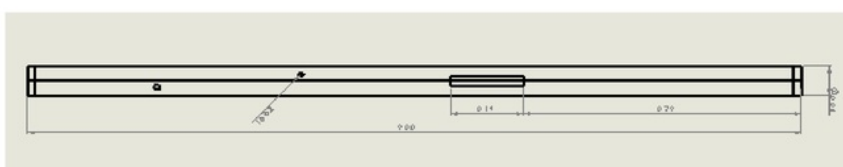


Figure 4.16(b) Artificial External Corrosion Pipe Dimension

The simulation result had been plotted on Figure 4.17, Figure 4.18. based on the simulation result, first echo happened when the wave hit to the rectangular area, which is artificial corrosion area as shows in Figure 4.19.

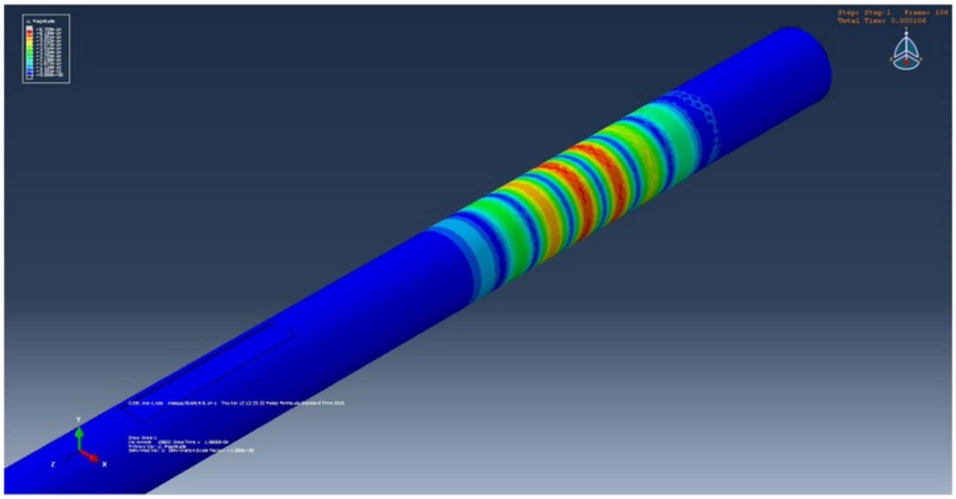


Figure 4.17 L (0,2) Mode Propagate along artificial corroded Pipe

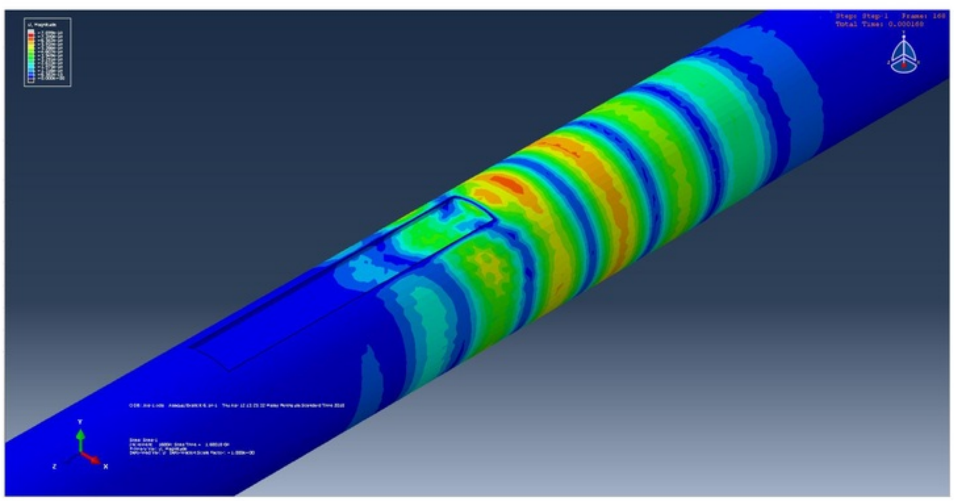


Figure 4.18 L (0,2) Signal React with the Artificial Corroded Pipe

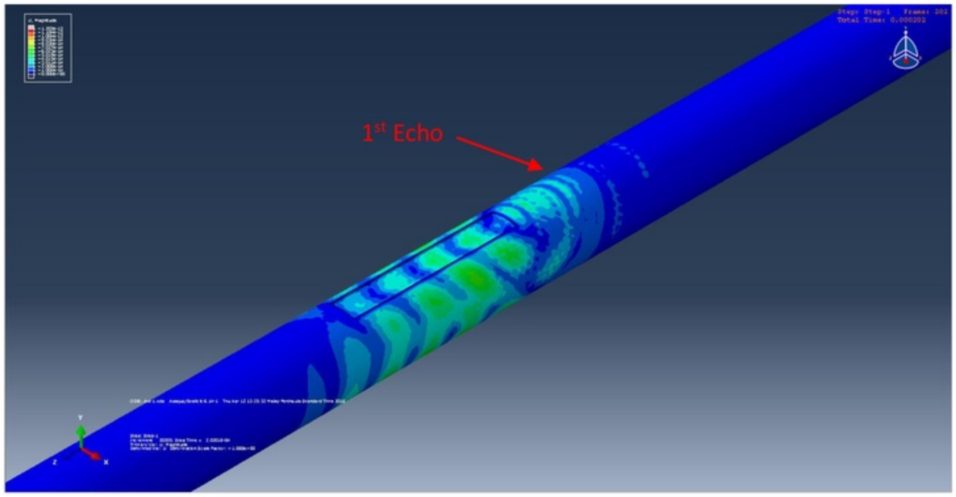


Figure 4.19L (0,2) Propagating Wave Reflection due to Artificial Corrosion

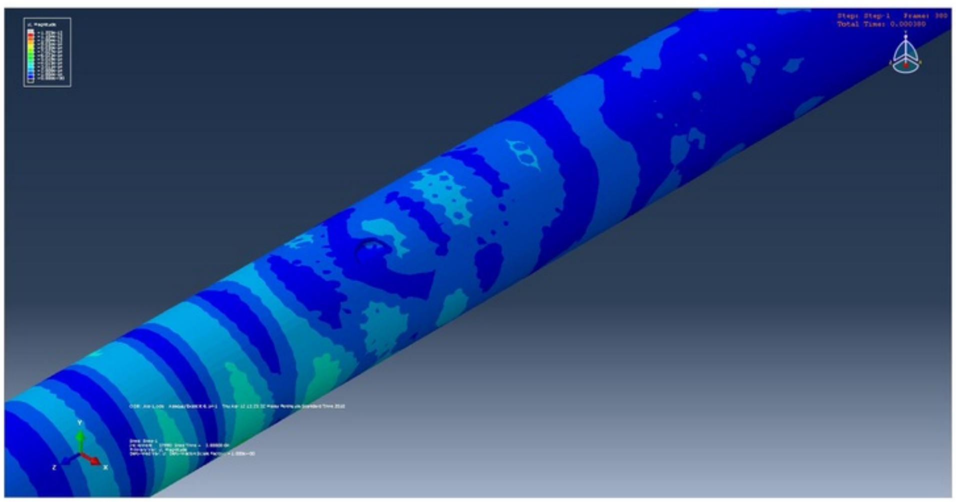


Figure 4.20 L (0,2) Propagating Wave Reflection due to Artificial Small Dent

Figure 4.20 shows the wave reaction to the artificial small dent, based on the simulation, the wave does not reflect any signal, therefore it can be predicting that no amplitude will be recorded due to this crack in E1, E2, E3, and E4.

The signal generated by ABAQUS/Explicit for E1, E2, E3 and E4 will then imported into MATLAB for further analysis, the signal recorded by ABAQUS/Explicit is then plotted in Figure 4.21.

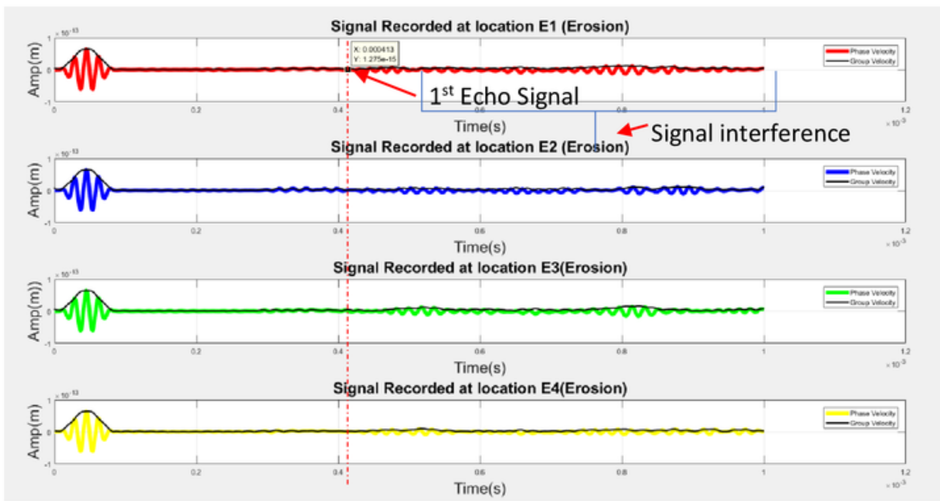


Figure 4.21 Signal Recorded at E1, E2, E3, E4 (With Artificial Corrosion and Dent)

Based on the Figure 4.21, the calculated group velocity is 1864m/s, based on the group velocity and comparing to the dispersion curve show is Figure 4.22, the mode is changed to F (7,1)

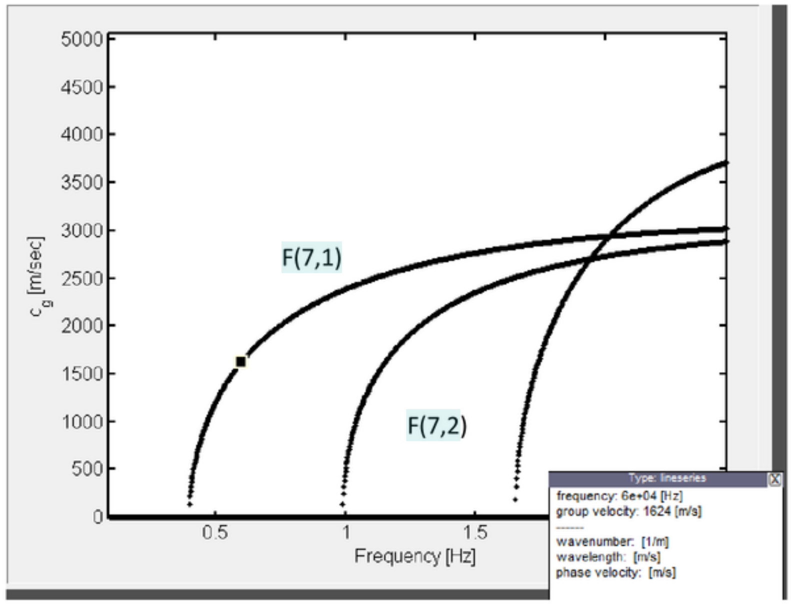


Figure 4.22 Dispersion Curve for 3 inches Pipe Flexible Mode

Further analysis will be done for S1, S2, S3, and S4 the signal is plotted in Figure 4.23. Based on Figure 4.23, it shows that S1, and S3 have almost same pattern of wave form, but S2 and S4 will have difference kind of wave form. It is due to the effect caused by the small dented. However, the group velocity for S1, S2, S3 and S4 is almost same and based on the time analysis is shows that the group velocity is 5265.95m/s, which is L (0,2) mode based on dispersion curve shows in Figure 3.1. Further comparison of S1, S2, S3, and S4 to the vacant straight pipe is shows that the amplitude of the signal is reduced due to the artificial erosion, refer to Figure 4.24. If we compare to Figure 4.18, in previous analysis is shows that the amplitude reduction is lower compared to cracked pipe.

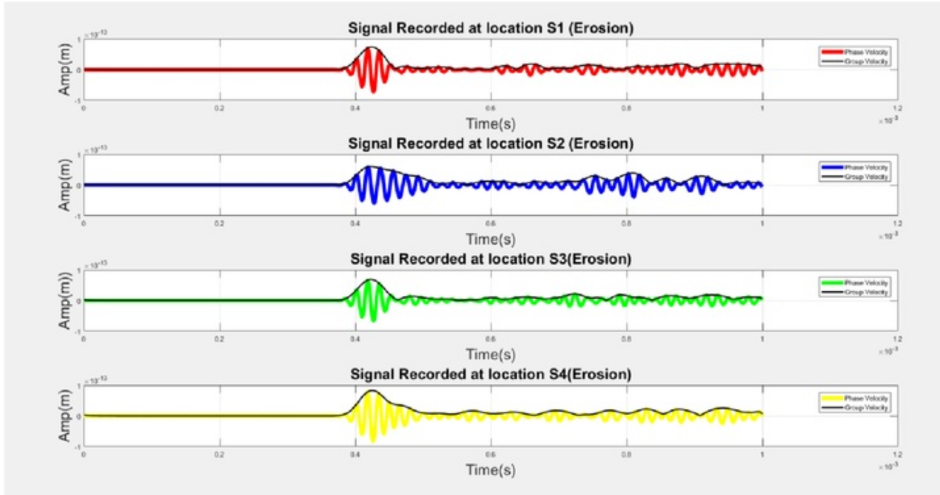


Figure 4.23 Signal Recorded at S1, S2, S3, S4 (With Artificial Corrosion and Dent)

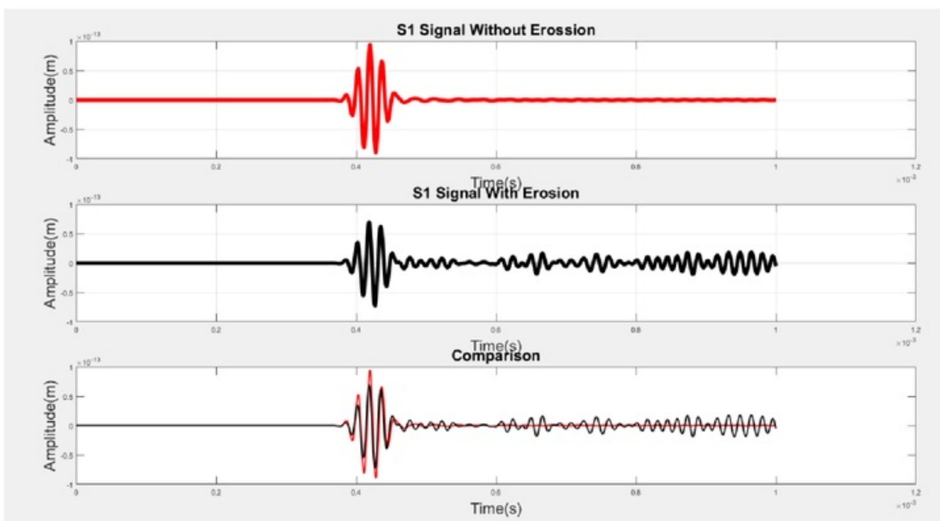


Figure 4.24 Signal Comparison between Vacant Straight Pipe and Artificial Corrosion Pipe

4.4 3 Inches Pipe with 90-degree Elbow Pipe

The elbow pipe discussed over here is 3 inches' steel pipe with wall thickness of 5mm the detail of dimension is shows in Figure 4.25. excitation location and signal measuring location is also at 2cm from pipe edge. Exact location of E1, E2, E3, E4 and corresponding of S1, S2, S3, S4 will be shows in Figure 4.26(a) and Figure 4.26(b).

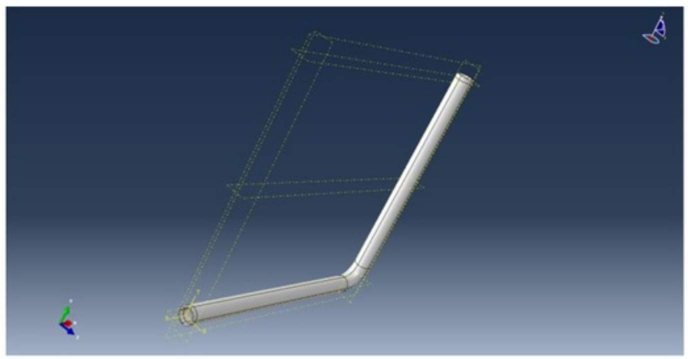


Figure 4.25(a) 90-degree Bend Pipe

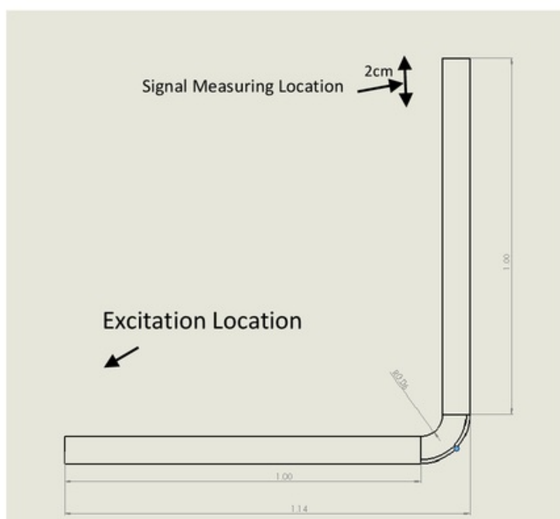


Figure 4.26(b) 90 Degree Bend Pipe Dimension

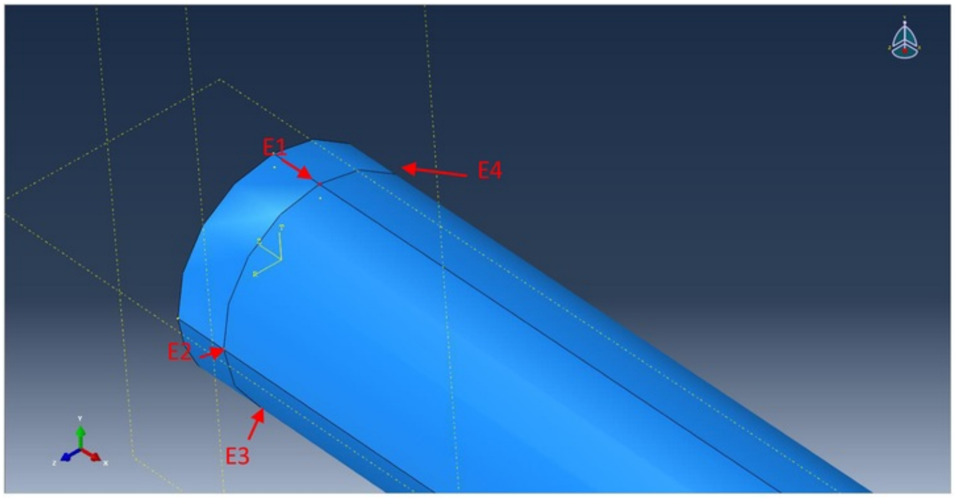


Figure 4.26(a) Location of E1, E2, E3, E4 (90 Degree Bend Pipe)

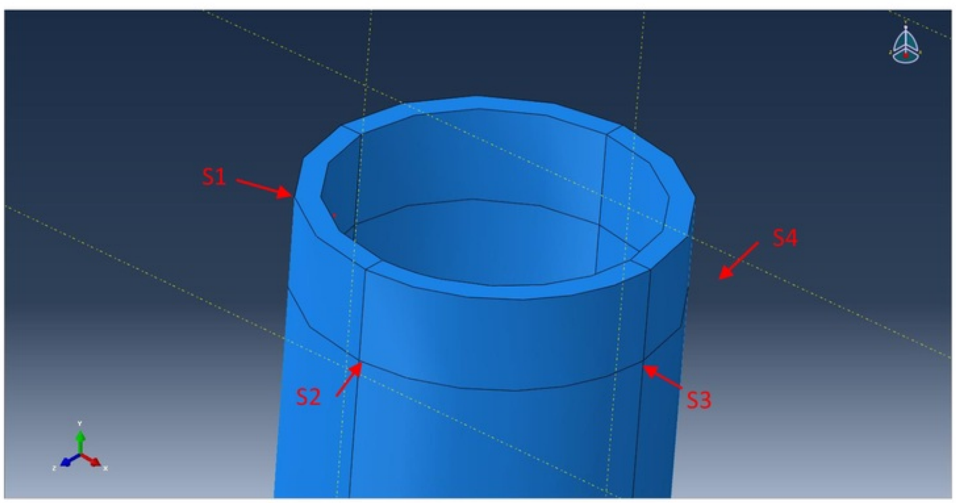


Figure 4.26(b) Location of S1, S2, S3, S4 (90 Degree Bend Pipe)

The simulation result is shows in Figure 4.27, Figure 4.28 and Figure 4.29, based on Figure 4.29, the guided wave propagation does not have any reflection even it propagates in curve pipe.

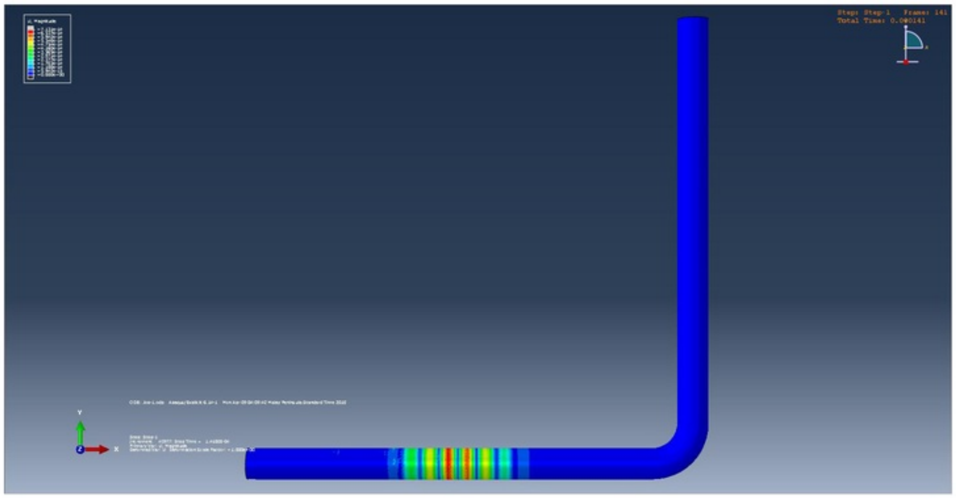


Figure 4.27 L (0,2) Signal Propagating along 90 Degree Bend Pipe

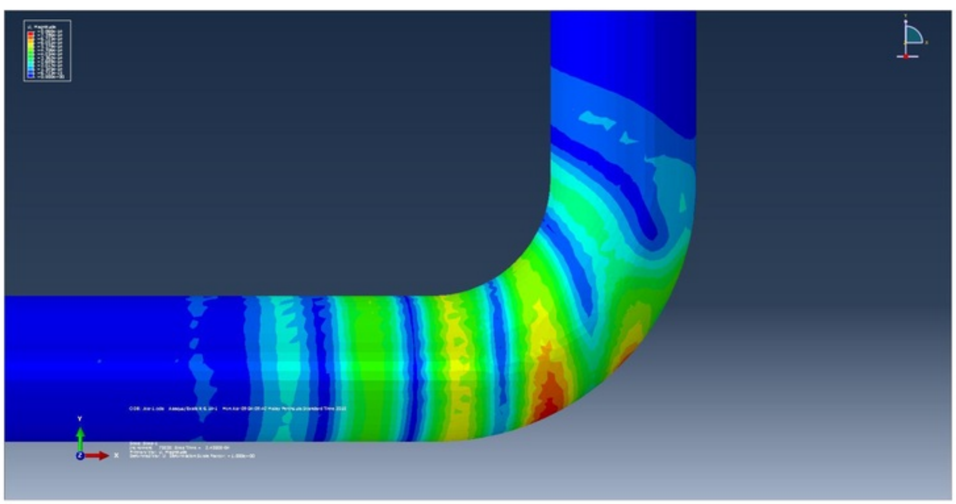


Figure 4.28 L (0,2) Signal Reaction with 90 Degree Bend Pipe at Elbow

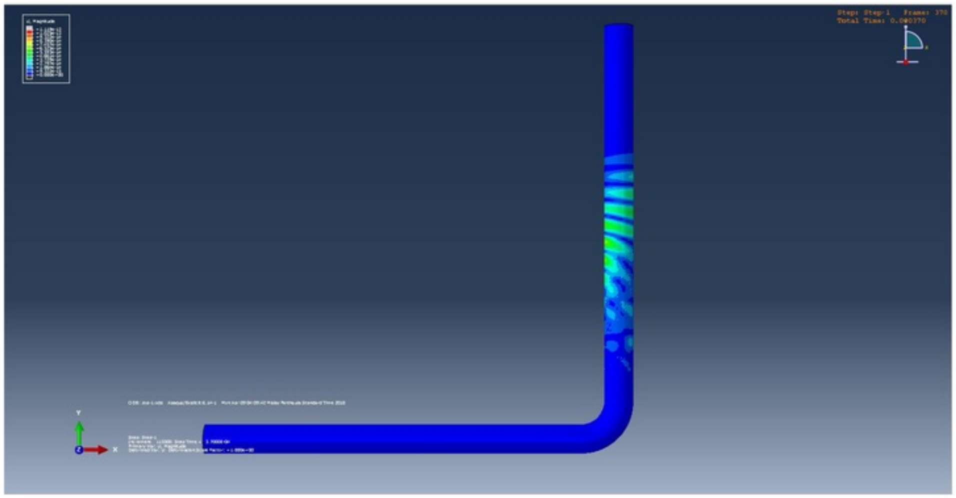


Figure 4.29 Signal Propagation Continue Propagate after pass through Elbow

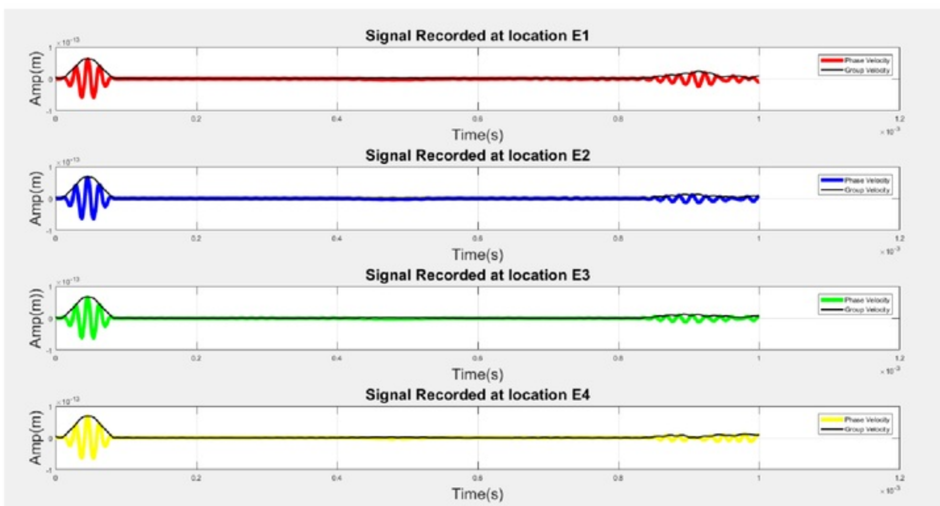


Figure 4.30 Signal Recorded at E1, E2, E3, E4(90 Degree Bend Pipe)

The data captured by ABAQUS/Explicit is then imported into MATLAB for further analysis, and the result is plotted in Figure 4.31. Based on the data recorded at E1, E2, E3, and E4, the wave form has same pattern compared to the straight pipe without defect as discussed in section 4.1. However, the reflect amplitude is almost same but the time required to reflect back to the original position is slower compared to straight non-defected pipe and the signal comparison is plotted in Figure 4.31.

Based on time analysis, it found out that the group velocity for 90-degree elbow pipe without defect is 2476.07m/s therefore based on dispersion curve described in 4.32, the reflection signal is not L (0,2) mode, but is L (0,1) mode.

Further analysis at Signal recorded at S1, S2, S3, S4, the data is plotted in Figure 4.33. based on the data and perform time analysis is found out that the fastest group velocity is 4813.95m/s. Based on the dispersion curve, the mode of the wave form is F (1,3), the dispersion curve is plotted in Figure 4.34.

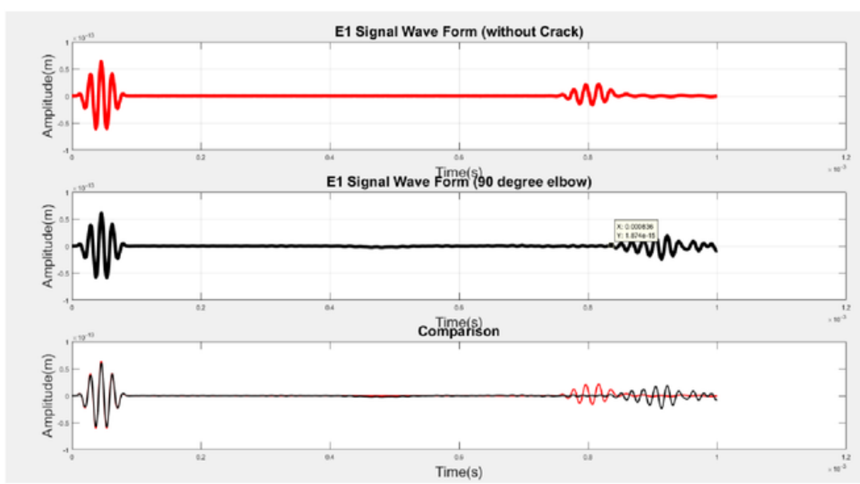


Figure 4.31 Reflection signal comparison

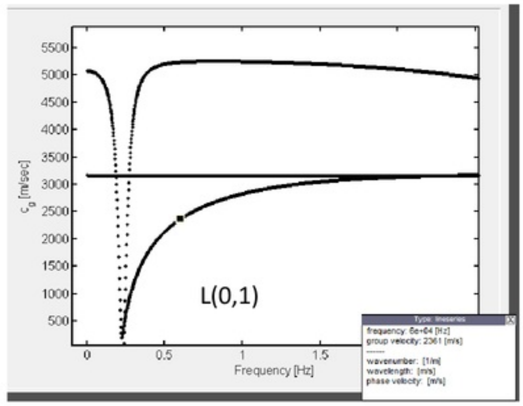


Figure 4.32 Dispersion Curve for 90 Degree Elbow Pipe (Torsional and Longitudinal)

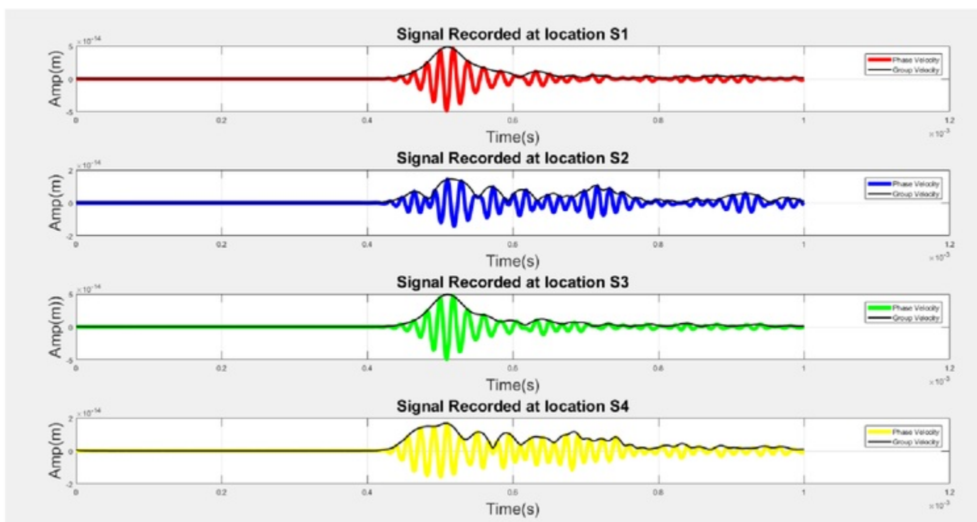


Figure 4.33 Signal Recorded at S1, S2, S3, S4 (90 Degree Bend Pipe)

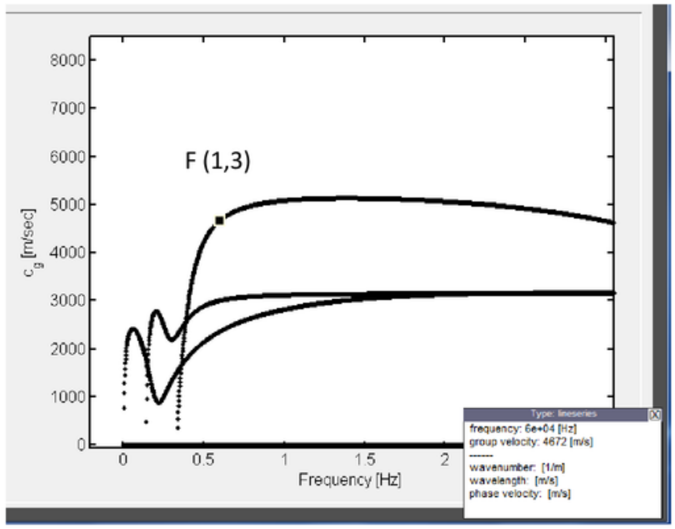


Figure 4.34 Dispersion Curve for 90 Degree Elbow Pipe (Flexible Mode)

4.5 3 Inches Pipe with 90 Degree Bend with Crack

The small crack will have uneven shape in the elbow area, the detail of drawing is shows in Figure 4.35, and all other parameter such as pipe length, thickness, material is remained unchanged, beside that the excitation point E1, E2, E3, E4 and signal recorded point S1, S2, S3, S4, remain unchanged as well.

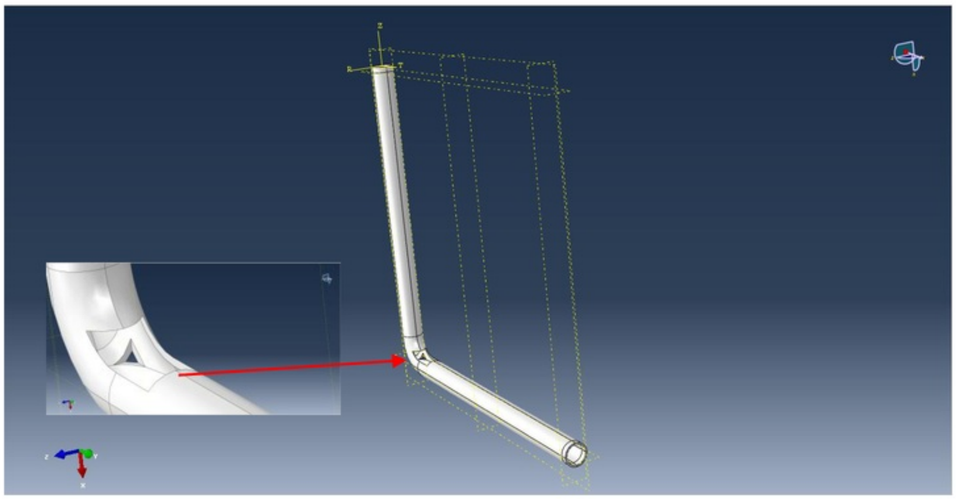


Figure 4.35 Small Crack at Elbow Area

The simulation result is plotted under Figure 4.36, Figure 4.37. it can be clearly to notice that the wave energy is shifted to outer elbow area. However, it still has reflection signal as shows in Figure 4.37.

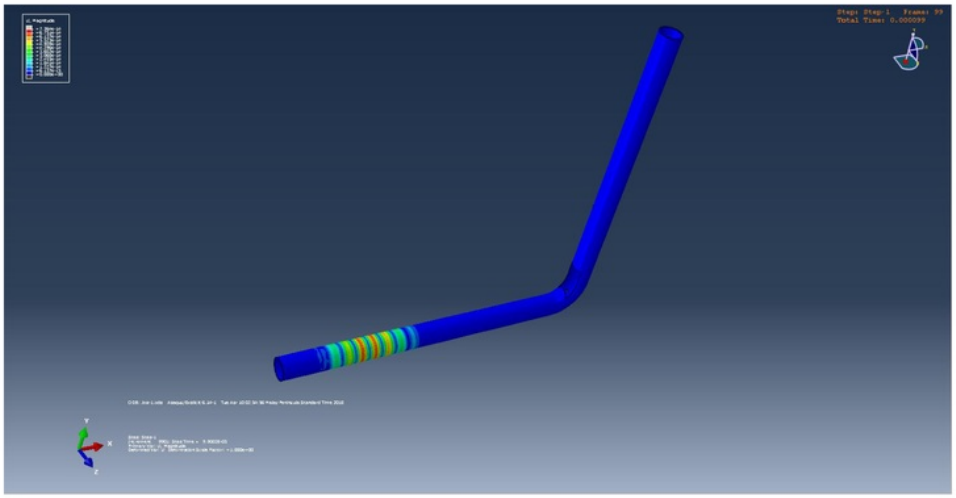


Figure 4.36 L (0,2) Mode Propagate along the Bend Pipe (With Crack)

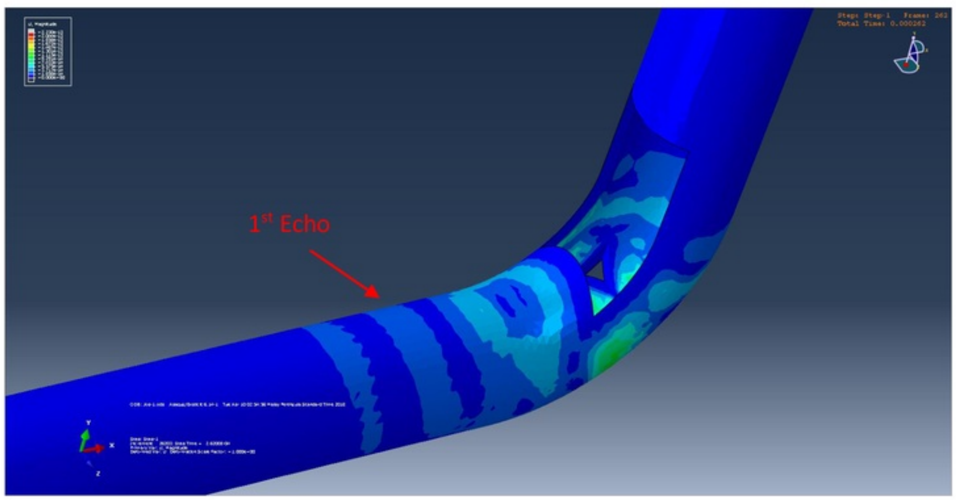


Figure 4.37 L (0,2) Signal React with Small Crack

Based on the data recorded by ABAQUS/Explicit, the detail of wave form is plotted in Figure 4.38, it can be notice that the 1st echo signal happen on 0.000426s, based on time analysis is found out that the group velocity is 2347.42m/s, based on the dispersion curve plotted in Figure 4.39, the mode is F (1,1)

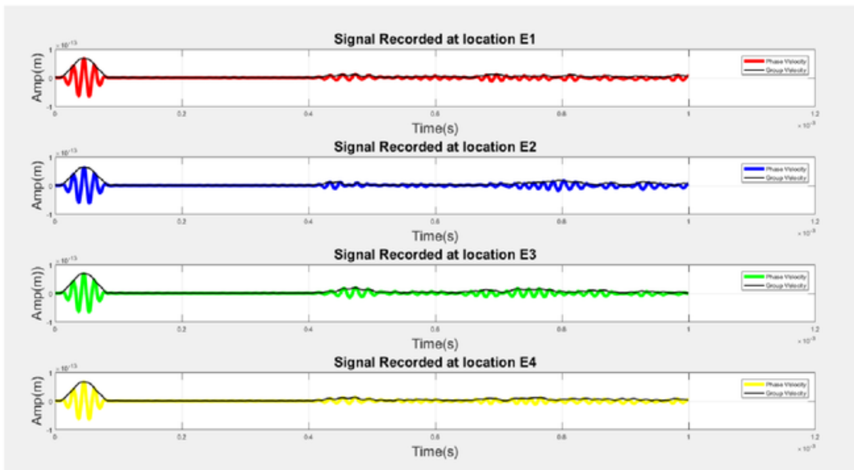


Figure4.38 Signal Recorded at E1, E2, E3, E4 (90 Degree Bend Pipe with Crack)

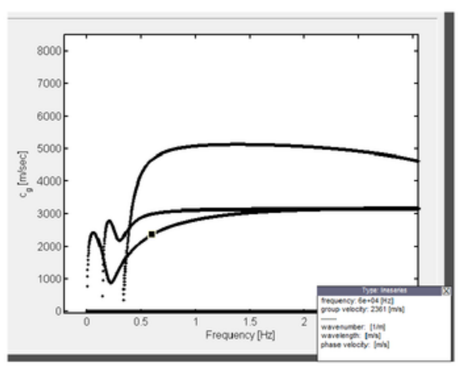


Figure 4.39 Dispersion Curve for 90 Degree Elbow Pipe (Flexible Mode)

Further analysis of Signal of S1, S2, S3, and S4 the graph is plotted under Figure 4.40. Based on the simulation it has something like wave separation at elbow area as show in Figure 4.44. The 2nd Signal recorded is not the interference signal. Which mean that at least 2 types of mode will be penetrate through end of the pipe

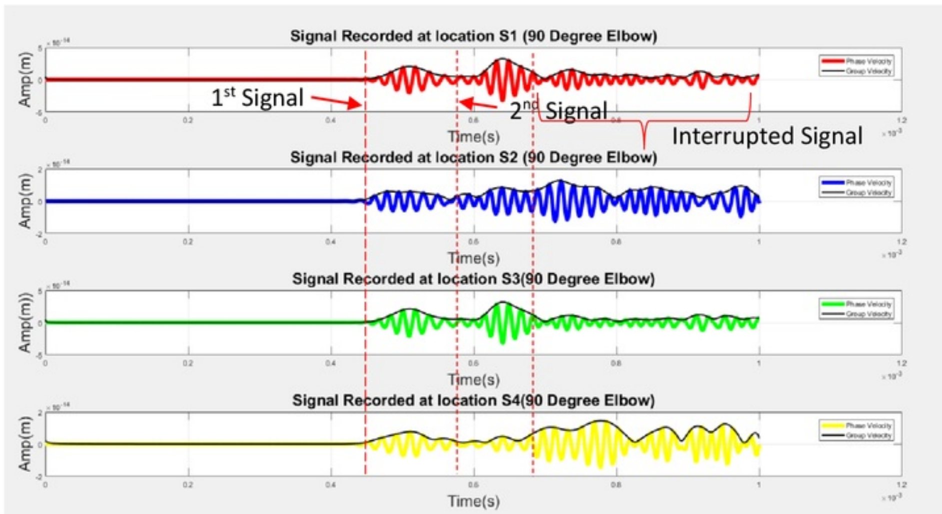


Figure 4.40 Signal Recorded at S1, S2, S3, S4(90 Degree Bend Pipe with Crack)

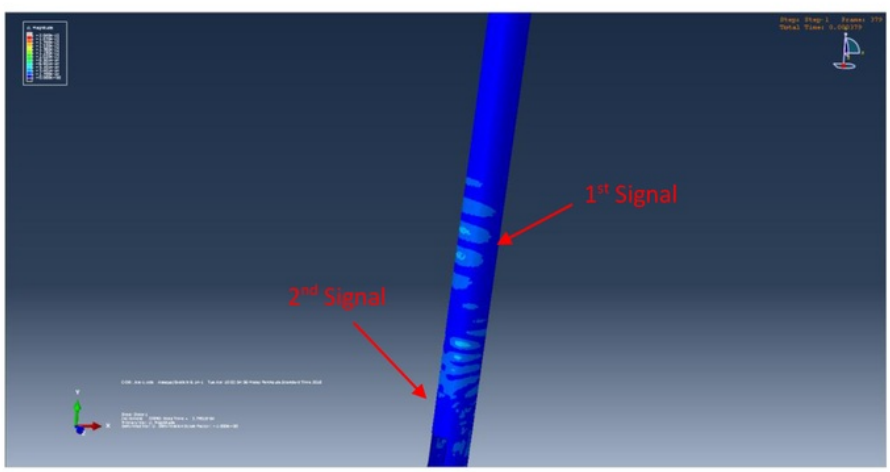


Figure 4.41 Signal Propagation Separation after Pass Through Elbow

Based on time analysis is found out that the speed of the 1st signal is 4545.45m/s, based on the dispersion curve plotted at Figure 4.37, it is confirmed that the signal is L (0,1) and the 2nd signal with speed of 3369.98m/s, based on the dispersion curve, the 2nd signal is closed to T (0,1). Further compare both cracked in elbow and without cracked in elbow area the graph is plotted in Figure 4.45.

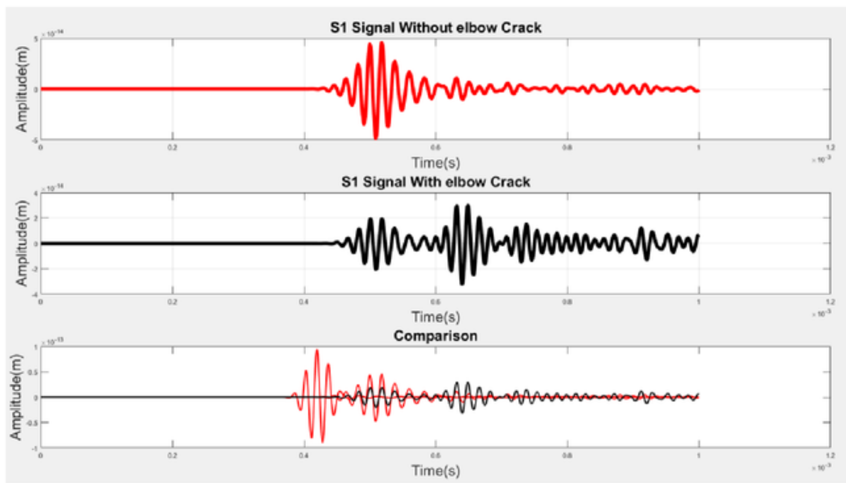


Figure 4.42 Signal Comparison between Cracked 90 Degree Bend Pipe and Without Cracked 90 Degree Bend Pipe

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As the project is all about the simulation of the effect of guided wave propagation of the pipe. Therefore, some of the actual condition is not involving in this simulation such as noise recorded by actual transducer, actual material properties and so on.

Throughout the simulation, it is concluded that the wave mode and wave speed will be change if that is any defect on the pipe. However, the mode change is geometry dependence, which mean that the mode shape and wave velocity will be change depending on which kind of defect geometric. Also, wave reaction to the crack is not only generate 1 type of mode, it is the combination between few type of mode, in difference velocity in a single frequency.

Since the project is based on L (0,2),60kHz, the sensitivity to the defect for other non-dispersive frequency or mode is unknown. it is being expected that difference mode of excitation signal will generate difference kind of mode propagation, wave speed and also the signal amplitude.

5.2 Recommendations

In this project, vacant pipe is under consideration. However, to apply guided wave testing to the structural health monitoring, some of the consideration shall be taken into account. Such as, the installation location of the pipe, external support of the pipe, fluid flow effect, and so on. Also in actual piping system, it has a lots of auxiliary device is installed on the system, such as reducing nipple, reservoir tank, branches, 45-degree elbow there for this all auxiliary device may affect the guided wave propagation properties as well. since the guided wave propagation is direct related to material of the pipe, some of the application may couple difference pipe material, this all will affect the guided wave propagation performance. To gain more accurate simulation, real condition should take into account.

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