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SIGNED: Milos Vasiljevic

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This thesis has been approved on the date shown below:

______________________________  12/3/2007
Tribikram Kundu
Professor of Civil Engineering
I would like to express my gratitude to Professor Dr. Tribikram Kundu for believing in me from the day we met. Few students can say that research performed and classes taken towards the degree were a pleasure first and duty second and my sole thanks goes to Dr. Kundu for making such a statement possible on my behalf. I am also grateful to Professor Dr. George Frantziskonis and Professor Dr. Hamid Saadatmanesh for their support and reviewing of my Masters thesis.

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ABSTRACT

This research covers modeling of Electro Magnetic Acoustic Transducers (EMATs) and their application in excitation and detection of longitudinal guided Lamb wave modes for evaluation of flaws in cylindrical pipes. The combination of the configuration of transducers and the frequency of the input current is essential for successful excitation of desired guided wave modes and for proper interpretation of the results. In this study EMATs were successfully constructed and longitudinal modes L(0,1) and L(0,2) were excited in the pipe. From the recorded signals the level of simulated damage in pipes could be assessed. It is also possible to theoretically predict the location of the pipe flaws. Theoretical predictions are matched with experimental results. Dents and holes in pipes are detected by appropriate signal processing of received L(0,1) and L(0,2) modes.
CHAPTER 1: INTRODUCTION

1.1 GENERAL

Non-Destructive Testing (NDT) has evolved into an important subcategory in the civil engineering industry due to the ever increasing demand for rehabilitation of the aging infrastructure in the United States and the rest of the world. Ultrasonic Testing is the part of NDT that employs high frequency ultrasound waves for health assessment of structures that includes flaw detection and material characterization. For example, honeycombing in a concrete beam or column can be detected by measuring the velocity of the ultrasound propagating through the tested material.

In this study, ultrasonic waves are used to detect pipe wall defects from which the overall integrity of pipes can be evaluated. For this purpose the propagating waves are analyzed in time and frequency domains. Existing defects can be detected by studying the time history of the propagating ultrasound, as a flaw in the material becomes a barrier that reflects part of the energy of the wave. The amplitude of the propagating wave is also affected by an increase in the size and number of defects throughout the life of the structure. Both aspects are important in the non-destructive assessment of the degree of deterioration and prediction of the remaining life of the structure. Oil, chemical and nuclear industries are all dependant on continuous monitoring and maintenance of
pipelines for proper functionality of their infrastructure. A pipe leak could lead to a loss of productivity, a factory shutdown or to an environmental disaster inflicting non-repairable damage to the surrounding eco-system. Since there can be thousands of miles of pipes in a plant under maintenance, the evaluation of the current condition should be a simple process that requires a minimum amount of time to prepare the test specimen and to perform the actual testing. Electro Magnetic Acoustic Transducers (EMATs) are devices that can generate and detect ultrasonic waves in metals. An EMAT consists of a permanent magnet (or electromagnet) to introduce a static field and a coil to induce a dynamic current in the surface skin. Generation and detection of ultrasound are provided by coupling between the electromagnetic fields and the elastic field in the surface skin. It transfers the electromagnetic energy to the mechanical energy and vice versa through a thin air gap. The wave source is then established within the material to be inspected. EMAT’s geometry can be designed to measure the desired mode of elastic waves on the basis of the coupling mechanisms, the Lorentz force and the magnetostrictive force (Hirao and Ogi, 2003). The fact that EMATs are not in contact with the testing specimen and that there is no need for a coupling solid, fluid, or gel between the two is the main advantage of EMATs compared to piezoelectric transducers (PZTs) which are the most widely used alternative method for ultrasonic testing of materials. EMATs in general do not need specimen preparation for testing which in some cases might not be possible. Also, in order to generate acoustic waves, PZTs need to create a bond through the coupling fluid (or gel or solid) with the test specimen. The elastic waves that are generated, propagate not only through the specimen but also through the coupling
medium and the transducers, and noise and echoes are generated from the natural vibration of the transducers; They interfere with the accurate interpretation of the signal and calculation of the time-of-flight measurements. In spite of these shortcomings, Piezoelectric Transducers are often used because those are capable of generating stronger signals. The low strength of the EMAT generated signal is its main disadvantage.

1.2 PROBLEM STATEMENT

The focus of this study is to create the hardware and software for ultrasonic testing of pipes with EMATs. Pipes with the same cross-section and different lengths and types of defects were tested in the process. Collected data was analyzed in time and frequency domains for determination of the location and size of the defects.

Time history analysis, which is also called transient data analysis, gives information on the location of a defect in a pipe. Nevertheless, it might not be very sensitive to the size of defects; besides, the signal may be too noisy to differentiate small defects from the echoes reflecting from the ends of the pipe which overlap with the signal generated by the defect. In order to further analyze the transient data, Fourier transformation is performed to generate the frequency spectrum of the signal. The sound waves propagate through a pipe comparatively easily at certain frequencies and multiple peaks in the frequency domain plot are observed. These peaks will be shown to be very sensitive to defect size. Analysis of this data gives more precise information on defects, or in general terms, the overall condition of the test specimen. For example, the
amplitude of certain peaks will be shown to change monotonically as the size of a defect changes. However, from the frequency domain it is impossible to determine the exact location of the defect, but the overall condition can be assessed more precisely in comparison to the transient data analysis. Therefore, the signals in time domain and frequency domain are complementary to each other for the assessment of a pipe’s condition – one analysis is good for predicting the defect location while the other analysis is better for the size prediction.

1.3 SCOPE

In the course of the study, two Electromagnetic Acoustic Transducers were modeled for optimum performance and fabricated. To complete the hardware, a proper function generator and pre-amplifier were selected. The available software was modified in order to work with the new hardware (EMATs) and new software was developed for the data analysis. Time and frequency domain signals were analyzed in its entirety and peak by peak analysis of the data was also performed.
CHAPTER 2: LITERATURE REVIEW

The theory behind developing and the practice of using Electro-Magnetic Acoustic Transducers has been discussed in several articles. The general review of EMAT theory and applications has been given by Alers and Burns (1987), Dobbs (1976), Frost (1979), Maxfield et al. (1987), and Thompson (1990); Alers et al. (1990) address how EMATs are used in nondestructive testing (NDT).

In relations to the scope of this study, certain accomplishments were previously achieved by the group working under Dr. Tribikram Kundu at the University of Arizona. The efforts made by W.B. Na (Na and Kundu, 2002a) proved successful in using a PZT as a transmitter and an EMAT as a receiver for testing of interface between pipes and concrete, but showed limited success in testing EMAT – EMAT systems. More successful was testing for delaminations of concrete filled steel pipes where EMATs were used both as transmitters and receivers for time history analysis only (Na and Kundu, 2002b). This research was the first attempt to actually model and manufacture the sensors. Once completed, they were successful in experiments where EMATs were used as transmitters and receivers. The data collected was then successfully analyzed both in time and frequency domains, and thus advanced the knowledge of EMAT based pipe inspection technology.

The background knowledge of the theory of elasticity and wave propagation is necessary to fully understand the experiments and properly interpret the results. Basic
theory of guided waves and their applications to nondestructive evaluation can be found in the works of Achenbach and Keshava (1967); Achenbach (1973); Guyott and Cawley (1988); Lowe (1997); Lowe et al. (2000); Chimenti and Nayfeh (1985, 1989); Nayfeh (1995); Shah and Datta (1982); Datta et al. (1991); Mal (1988); Mal et al. (1991); Nagy and Kent (1995); Nagy et al. (1994); Rokhlin and Wang (1988); Rose (1999); Rose and Soley (2000), Kundu (2004). The following chapter gives the theory of guided wave propagation in hollow cylinders.
CHAPTER 3: THEORETICAL BACKGROUND

3.1 GENERAL

An elastic wave that propagates through a waveguide is called a guided wave. A waveguide is a structure with boundaries that help elastic waves to propagate from one point to another (Kundu, 2004). In this research, the waveguide is a cylindrical hollow rod (pipe), and the guided waves of interest are propagating in the axial direction of the pipe through the annular cross-section which on the $x-y$ plane, as shown in Figure 1. Waves propagating in this manner are called cylindrical guided waves. Cylindrical guided waves are also sometimes called Lamb waves in pipes. The inner radius of the pipe is $a$ with the outer radius $b$. Since the pipes tested were all hanging freely in the air (supported at the ends by threads or Styrofoam holders), it is assumed that both the inner and outer surfaces are stress-free, i.e.

$$
\sigma_{rr} = 0, \quad \sigma_{r\theta} = 0, \quad \sigma_{\theta\theta} = 0, \quad \text{at } r = a, b
$$

(3.1)

EMATs used in this study emit acoustic waves in the axial direction of the pipe and the EMAT design is such that it only emits longitudinal waves and no shear or torsional waves along the length of the pipe. These Longitudinal waves therefore have
the displacement components in the radial and axial directions, but none in the azimuthal or $\theta$-direction. They are also axisymmetric, and therefore $\theta$-independent.
Figure 1: cylindrical waveguide with the cylindrical coordinate system (rθz). (Kundu, 2004)
The displacement equations of motion are written here in a cylindrical coordinate system (Alchenbach, 1973, p.236; Kundu, 2004). Their expressions are:

\[
\nabla^2 u_r - \frac{u_r}{r^2} - \frac{2}{r^2} \frac{\partial u_\theta}{\partial \theta} + \frac{1}{1-2\nu} \frac{\partial^2 \Delta}{\partial \theta^2} = \frac{1}{c_s^2} \frac{\partial^2 u_r}{\partial t^2}
\]

(3.2)

\[
\nabla^2 u_\theta + \frac{2}{r^2} \frac{\partial u_r}{\partial \theta} - 1 - 2\nu \frac{\partial \Delta}{\partial \theta} = \frac{1}{c_s^2} \frac{\partial^2 u_\theta}{\partial t^2}
\]

(3.3)

\[
\nabla^2 u_z + \frac{1}{1-2\nu} \frac{\partial \Delta}{\partial z} = \frac{1}{c_s^2} \frac{\partial^2 u_z}{\partial t^2}
\]

(3.4)

where \(\nabla^2\) is the Laplacian operator

\[
\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \theta^2} + \frac{\partial^2}{\partial z^2}
\]

(3.5)

and the symbol \(\Delta\) represents the dilation

\[
\Delta = \frac{\partial u_r}{\partial r} + \frac{1}{r} \left( \frac{\partial u_\theta}{\partial \theta} + u_r \right) + \frac{\partial u_z}{\partial z}
\]

(3.6)

The corresponding stresses are given in terms of the displacements (Achenbach, 1973, pp. 75)
From Stokes-Helmholtz decomposition it follows that the displacement vector can be written in terms of a scalar and a vector potential function \( \varphi \) and \( \psi = (\psi_r, \psi_\theta, \psi_z)^T \):

\[
\begin{align*}
\sigma_{rr} &= \lambda \left( \frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} + \frac{\partial \psi_z}{\partial z} \right) + 2\mu \frac{\partial u_r}{\partial r} \\
\sigma_{r\theta} &= \lambda \left( \frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} + \frac{\partial \psi_z}{\partial z} \right) + 2\mu \frac{\partial \psi_r}{\partial \theta} \\
\sigma_{rz} &= \lambda \left( \frac{\partial u_r}{\partial r} + \frac{u_r}{r} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} + \frac{\partial \psi_z}{\partial z} \right) + 2\mu \frac{\partial \psi_z}{\partial z} \\
\sigma_{r\theta} &= \mu \left( \frac{\partial \psi_r}{\partial r} - \frac{u_r}{r} + \frac{1}{r} \frac{\partial \psi_r}{\partial \theta} \right) \\
\sigma_{\theta\theta} &= \mu \left( \frac{\partial \psi_r}{\partial r} + \frac{\partial \psi_r}{\partial \theta} \right) \\
\sigma_{z\theta} &= \mu \left( \frac{\partial \psi_r}{\partial r} + \frac{\partial \psi_z}{\partial r} \right) \\
\sigma_{zz} &= \mu \left( \frac{\partial \psi_r}{\partial r} + \frac{\partial \psi_z}{\partial z} \right)
\end{align*}
\]
Through direct substitution, displacement equations of motion (3.2) through (3.4) are identically satisfied when the potentials satisfy the following equations:

\[ u_\theta = \frac{1}{r} \frac{\partial \phi}{\partial \theta} + \frac{\partial \psi_r}{\partial z} - \frac{\partial \psi_z}{\partial r} \]  

(3.14)

\[ u_z = \frac{\partial \phi}{\partial z} + \frac{1}{r} \left( \frac{\partial (r \psi_r)}{\partial r} \right) - \frac{1}{r} \frac{\partial \psi_z}{\partial \theta} \]  

(3.15)

Equations (3.13) through (3.15) can be substituted into equations (3.7) through (3.12) to give the stresses in terms of the displacement potentials:

\[ \sigma_{rr} = \lambda \nabla^2 \phi + 2 \mu \left( \frac{\partial^2 \phi}{\partial \theta^2} + \frac{\partial^2 \psi_r}{\partial z^2} - \frac{1}{r^2} \frac{\partial \psi_z}{\partial \theta} + \frac{\partial^2 \psi_z}{\partial r^2} \right) \]  

(3.18)
\[
\sigma_{\theta\theta} = \lambda \nabla^2 \phi + 2\mu \left( \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta^2} + \frac{1}{r} \frac{\partial^2 \phi}{\partial \theta \partial z} - \frac{1}{r^2} \frac{\partial \phi}{\partial z} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial r^2} - \frac{1}{r^2} \frac{\partial^2 \phi}{\partial r \partial \theta} \right)
\]

(3.19)

\[
\sigma_{\theta z} = \lambda \nabla^2 \phi + 2\mu \left( \frac{\partial^2 \phi}{\partial z^2} + \frac{1}{r} \frac{\partial^2 \phi}{\partial \theta \partial z} - \frac{1}{r^2} \frac{\partial \phi}{\partial z} + \frac{\partial^2 \phi}{\partial \theta \partial \theta} \right)
\]

(3.20)

\[
\sigma_{r\theta} = 2\mu \left( \frac{2 \partial \phi}{r^2 \partial \theta} - \frac{2}{r} \frac{\partial \phi}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta^2} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial \theta \partial z} + \frac{1}{r^2} \frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r^2} \frac{\partial \phi}{\partial r} - \frac{\partial^2 \phi}{\partial r \partial \theta} \right)
\]

(3.21)

\[
\sigma_{zz} = 2\mu \left( \frac{\partial^2 \psi}{\partial z^2} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta^2} + \frac{2}{r^2} \frac{\partial^2 \psi}{\partial \theta \partial z} - \frac{1}{r^2} \frac{\partial \psi}{\partial z} + \frac{\partial^2 \psi}{\partial \theta \partial \theta} + \frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r^2} \frac{\partial \psi}{\partial r} - \frac{\partial^2 \psi}{\partial r \partial \theta} \right)
\]

(3.22)

\[
\sigma_{rz} = \mu \left( -\frac{1}{r^2} \psi \frac{\partial^2 \psi}{\partial z^2} + \frac{1}{r^2} \frac{\partial \psi}{\partial z} + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta \partial z} + \frac{1}{r^2} \frac{\partial \psi}{\partial \theta} + 2 \frac{\partial^2 \psi}{\partial r \partial \theta} - \frac{1}{r^2} \frac{\partial \psi}{\partial r} + \frac{\partial^2 \psi}{\partial r \partial \theta} \right)
\]

(3.23)
3.1.2 PROPAGATION IN THE AXIAL DIRECTION

EMATs used in this study emit sound waves in the axial direction of the pipe. Time-harmonic waves in hollow circular cylinders that propagate in the axial direction have the following displacement potentials (Achenbach, 1973, p. 240; Kundu 2004)

\[ \phi = \phi(r) \cos(m \theta + \phi_0) \exp[(k_z - \omega t)] \]  
(3.24)

\[ \psi_r = \psi_r(r) \sin(m \theta + \phi_0) \exp[(k_z - \omega t)] \]  
(3.25)

\[ \psi_\theta = \psi_\theta(r) \cos(m \theta + \phi_0) \exp[(k_z - \omega t)] \]  
(3.26)

\[ \psi_\phi = \psi_\phi(r) \sin(m \theta + \phi_0) \exp[(k_z - \omega t)] \]  
(3.27)

where \( \phi_0 \) is an arbitrary constant with \( m \) being able to have values of either zero or integers, since the functions must be periodic in the circumferential direction for waves propagating in the axial direction.

The three displacement components are related to four scalar potential functions, the scalar potential and the three components of the vector potential. Additionally, for
axial waves propagating in the cylindrical medium it is more convenient to require also that:

\[
\psi_z(\rho) - \psi_r(\rho)
\]

(3.28)

Equations (3.16) through (3.19) are then rearranged by substituting equations (3.24) through (3.27) into them, in order to get the following differential equations:

\[
\frac{d^2 \psi_z}{d\rho^2} + \frac{1}{\rho} \frac{d \psi_z}{d\rho} + \frac{\rho^2}{\rho^2} \psi_z - \frac{m^2}{\rho^2} \psi_z = 0
\]

(3.29)

\[
\frac{d^2 \psi_z}{d\rho^2} + \frac{1}{\rho} \frac{d \psi_z}{d\rho} + \frac{\rho^2}{\rho^2} \psi_z - \frac{m^2}{\rho^2} \psi_z = 0
\]

(3.30)

\[
\frac{d^2 \psi_z}{d\rho^2} + \frac{1}{\rho} \frac{d \psi_z}{d\rho} + \frac{\rho^2}{\rho^2} \psi_z - \frac{m^2}{\rho^2} \psi_z = 0
\]

(3.31)

where

\[
\rho = \sqrt{\frac{\omega^2}{c_z^2} - \frac{\omega^2}{c_z^2}} = k_z \sqrt{\frac{\omega^2}{c_z^2} - 1}, \quad q = \sqrt{\frac{\omega^2}{c_z^2} - \frac{\omega^2}{c_z^2}} = k_z \sqrt{\frac{\omega^2}{c_z^2} - 1}
\]

(3.32)

and \(c_z = \frac{\omega}{|k_z|}\) is the phase velocity of waves propagating in the axial direction.
Equations (3.29) through (3.31) are Bessel equations. Their solutions are the Bessel functions of the first and second kinds of order \( m \) for \( \Phi(r) \) and \( \Phi'(r) \), and order \( m + 1 \) for \( \psi_{r}(r) \).

\[
\Phi(r) = A_{1}J_{m}(qr) + A_{2}Y_{m}(qr)
\]

(3.33)

\[
\psi_{r} = B_{1}J_{m+1}(qr) + B_{2}Y_{m+1}(qr)
\]

(3.34)

\[
\psi_{z} = C_{1}J_{m}(qr) + C_{2}Y_{m}(qr)
\]

(3.35)

The constants \( A_{n} \), \( B_{n} \), and \( C_{n} \) are to be determined by the boundary conditions of the given problem.

Substituting equations (3.26) through (3.29) into equations (3.13) through (3.15) gives the corresponding displacements

\[
u_{r} = u_{1}(r)\cos(m\theta + \phi_{0})\exp(ik_{2}z)
\]

(3.36)

\[
u_{\theta} = u_{2}(r)\sin(m\theta + \phi_{0})\exp(ik_{2}z)
\]

(3.37)

\[
u_{z} = u_{2}(r)\cos(m\theta + \phi_{0})\exp(ik_{2}z)
\]

(3.38)
where

\[ \psi_1(\theta) = \hat{\Phi}_{s} + \frac{m}{p} \hat{\Psi}_s + i k_2 \hat{\Psi}_r \]  
(3.39)

\[ \psi_2(\theta) = \frac{m}{p} \hat{\Phi} + i k_2 \hat{\Phi}_r - \hat{\Psi}_s \]  
(3.40)

\[ \psi_3 = i k_2 \hat{\Phi} - \frac{m + 1}{p} \hat{\Psi}_r - \hat{\Psi}_s \]  
(3.41)

The stress components are then obtained by substituting equation (3.26) through (3.29) into equations (3.20), (3.23) and (3.25), respectively,

\[ \sigma_{rr} = \mu \sigma_{11} \theta \cos(m \theta + \theta_0) \exp(i k_2 z) \]  
(3.42)

\[ \sigma_{\theta \theta} = \mu \sigma_{22} \theta \sin(m \theta + \theta_0) \exp(i k_2 z) \]  
(3.43)

\[ \sigma_{z z} = \mu \sigma_{33} \theta \cos(m \theta + \theta_0) \exp(i k_2 z) \]  
(3.44)
where

\[
\sigma_{1x}(r) = \left(\frac{2m^2}{r^2} - (\frac{\rho \gamma}{k}) \right) \phi + \frac{2}{r} \phi' + 2ik_{x} \psi_{r} - \frac{2m}{r^2} \psi_{r} + \frac{2m}{r} \psi_{r}'
\]

(3.45)

\[
\sigma_{1x}(r) = \frac{2m}{r^2} (\phi - r \phi') - \frac{ik(1 + m)}{r} \psi_{r} + \left[\frac{\rho \gamma}{k} - \frac{2m^2}{r^2}\right] \psi_{r} + ik_{x} \psi_{r}' + \frac{2m}{r} \psi_{r}'
\]

(3.46)

\[
\sigma_{1y}(r) = \left(\frac{\rho \gamma}{k^2} - \frac{m(m + 1)}{r^2}\right) \psi_{r} - \frac{m}{r} \psi_{r}' + 2ik_{x} \phi' + ik_{x} \frac{m}{r} \psi_{r}
\]

(3.47)

### 3.1.3 AXIAL WAVES IN A HOLLOW CYLINDER

For a hollow cylinder used in this study, as shown in Figure 1 we have the stress boundary conditions given in equation (3.1). The displacement components are given by equations (3.38) through (3.40), and the corresponding stresses can be calculated from equations (3.44) through (3.46):

\[
\begin{bmatrix} \sigma_{rr} & \sigma_{rz} & \sigma_{r\theta} \end{bmatrix} = \mu \left[ \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{12} & 0 \\ 0 & 0 & d_{22} \end{bmatrix} \right] \begin{bmatrix} \sigma_{rr} & \sigma_{rz} & \sigma_{r\theta} \end{bmatrix}
\]

(3.48)

where \( A = [A_{e}, B_{e}, C_{e}, A_{c}, B_{c}, C_{c}] \) and the elements \( d_{ij}(m, r) \) for waves in the longitudinal direction are as follows:
\[ a_{11}^m (n, r) = \frac{2m(n-1)}{r^2} + k_x^2 - q^2 \] \[ a_{11}^m (n, r) + \frac{2n}{r} Z_{m+1} (qr) \] (3.49)

\[ a_{21}^m (n, r) = 2k_x \left[ q Z_m (qr) - \frac{m+1}{n} Z_{m+1} (qr) \right] \] (3.50)

\[ a_{12}^m (n, r) = 2m \left[ \frac{m-1}{n} Z_m (qr) - \frac{q}{n} Z_{m+1} (qr) \right] \] (3.51)

\[ a_{22}^m (n, r) = 2k_x \left[ m Z_m (qr) - q Z_{m+1} (qr) \right] \] (3.52)

\[ a_{13}^m (n, r) = -\frac{2m}{n} Z_m (qr) + (q^2 + k_x^2) Z_{m+1} (qr) \] (3.53)

\[ a_{33}^m (n, r) = -\frac{ik_x m}{n} Z_m (qr) \] (3.54)

\[ a_{31}^m (n, r) = -2m \left[ \frac{m-1}{n} Z_m (qr) - \frac{q^2}{n} Z_{m+1} (qr) \right] \] (3.55)

\[ a_{32}^m (n, r) = ik_x \left[ q Z_m (qr) - \frac{2m+1}{n} Z_{m+1} (qr) \right] \] (3.56)
where $\mathcal{Z}_m(\cdot \cdot \cdot)$ can be either Bessel function of the first kind, $J_m(\cdot \cdot \cdot)$, or the second kind, $Y_m(\cdot \cdot \cdot)$. The superscript $z$ in $\mathcal{Z}_m(z \cdot \cdot \cdot)$ is to indicate which Bessel function to use.

For a hollow cylinder with traction-free surfaces at $\eta = a \hat{\eta}$ we have the following eigenvalue problem:

\begin{equation}
\mathcal{Z}_m(z \cdot \cdot \cdot) = [q^2 - \frac{2m \zeta_m - 1}{r^2}]z_m(\eta r) + \frac{2q}{r}z_{m+1}(\eta r) = 0
\end{equation}

(3.57)

By setting the determinant to zero, we obtain the dispersion equation for waves propagating in the axial direction of a hollow cylinder of inner radius $a$ and outer radius $b$.

Longitudinal waves that we are interested in this study have the displacement components in the radial and axial direction, but none in the $\theta$ -direction. They are also axisymmetric, and therefore $\theta$ -independent as well. These conditions are met by setting $\zeta_{a} = \zeta_{b} = 0$ and $\xi_{a} = 0$ in the general solution of equation (3.58). Thus we obtain:

\begin{equation}
\mathcal{Z}_m(z \cdot \cdot \cdot) = [q^2 - \frac{2m \zeta_m - 1}{r^2}]z_m(\eta r) + \frac{2q}{r}z_{m+1}(\eta r) = 0
\end{equation}

(3.59)
By setting the determinant to be equal to zero we obtain the dispersion equation for longitudinal waves propagating in the axial direction of a hollow cylinder of inner radius $a$ and outer radius $b$.

### 3.2 Dispersion Curves

Variation of the wave velocity as a function of the frequency is known as the dispersion curve (Kundu, 2004). In order to obtain these curves, the dispersion equations must be solved. This equation is solved using the software “Disperse”. For this software the parameters that need to be set by the user are the material properties, boundary conditions and the dimensions of the cross-section of the specimen. Dispersion curves for Phase and Group Velocities of the pipes used in this study are shown in Figures 2a and 2b.
Figure 2a: Phase Velocity Dispersion Curves For the Steel Pipe
Figure 2b: Group Velocity Dispersion Curves For the Steel Pipe
CHAPTER 4: ELECTROMAGNETIC ACOUSTIC TRANSUCER MODELLING

4.1 ELECTROMAGNETIC ACOUSTIC TRANSUCER

Electromagnetic Acoustic Transducers are used in the Non-Destructive Evaluation field due to their capability to generate and detect ultrasonic waves in an electrically conducting sample without the need of any mechanical contact or coupling media. This is useful since it makes it possible to perform tests without the surface preparation and EMATs can be moved in the axial direction of the specimen for performing differential measurements or taking data at different points along the specimen surface.

EMATs can be constructed to be more sensitive to either in-plane vibration that generates shear waves, or out of plane vibration, which is more responsive to longitudinal waves. The difference depends on the orientation of the magnetic field, which has to be perpendicular to the vibrating direction. In-plane EMATs have the magnetic field perpendicular to the surface of the sample and out-of-plane EMATs have the magnetic field parallel to it.

The basic parts of an Electromagnetic Acoustic Transducer are an insulated copper wire wound into a solenoid coil, permanent magnet and an iron casing. This
EMAT is placed close to the metal surface. A pulse of radio frequency (RF) current (at the frequency of the ultrasonic wave one wishes to generate) is passed through the coil. Maxwell’s equations (Jackson, 1962) tell us that this coil current generates a mirror image current in the metal surface, called eddy current, \( \mathbf{j} \). The magnetic field produced by the permanent magnet, \( \mathbf{B}_0 \), covers the entire area over which eddy currents are generated. The magnetic Lorentz force, \( \mathbf{f} \), on these eddy currents is transferred to the atomic lattice in the metal. It is the Lorentz force on the eddy currents that generates the elastic wave (Kundu, 2004). This body force is then given by

\[
\mathbf{f} = \mathbf{j} \times \mathbf{B}_0
\]

(4.1)

For an out-of-plane EMAT (Figure 3) the Lorentz force generates longitudinal waves in the axial direction. Hence, the amplitude of those waves is directly proportional to the magnetic field and the driving current of the EMAT. Increasing \( \mathbf{B}_0 \) will therefore increase the amplitude of the signal which is an important aspect in the design of EMATs, and one of the goals of this research.

### 4.1.1 Modeling the EMAT

The electromagnetic field simulation program, “Maxwell 2D” was used to model the optimal magnetic configuration for the EMAT. The program was used to create a two dimensional model of the spatial distribution of the magnetic flux which is done using a
finite element analysis model. The software automatically creates the required finite element mesh and only a limited number of parameters have to be specified for solving the 2D electromagnetic problem.

The model of the EMAT is drawn on a two dimensional plane which is intended for axisymmetric models. A typical drawing plane of the designed EMAT can be seen in Figure 3, where the cross-section is rotated about the axis of symmetry (z-axis) in order to calculate the field distribution.

Two shapes were considered for the EMAT design. The shape in Figure 3, which is the final shape used in the experiments, as well as the conventional EMAT design which uses only flat circular ferromagnetic discs. The conical shape of the disks of the EMAT in Figure 3 increases the magnetic induction in the location of the coil. The direct comparison between the two designs is shown in Figure 4. The magnetic induction distribution of the final design is shown in Figure 5 and the Flux line distribution is shown in Figure 6.
Figure 3: Electromagnetic Acoustic Transducer. Note that this is a cross-section and that the EMAT goes around the pipe.
Figure 4: EMAT Design Comparison
Figure 5: Magnetic Field Distribution of the Final EMAT Design
Figure 6: Flux Lines Distribution of the Final EMAT Model
CHAPTER 5: EXPERIMENTAL SETUP

Three different steel pipes of the same cross-section but different lengths were inspected. The outer and inner diameters of the pipes are 21.4 mm and 16.4 mm, respectively. The defects created are 1) a dent along the circumference of the pipe on a 6000 mm long pipe and 2) holes of varying diameter from 1 mm to 5 mm on a 1200 mm long pipe. A dent is a localized depression or deformation in the pipe’s cylindrical geometry resulting from an applied force (Na and Kundu, 2002). The holes in the pipes were manufactured by a drill of varying drill bit, from 1 mm to 5 mm. During the experiment, a pipe was first tested in its perfect condition (no hole). The same setup was then maintained while the 1 mm hole was drilled in the same pipe and then expanded to the size of 5 mm, while during that process, differential measurements of transient and $W(t)$ functions were taken. The process of expansion of the hole in the pipe resembles the real life problem of the Leak-Before-Break phenomenon, where a surface crack grows in a stable manner through the wall of the pipe, breaks through the wall (causing a leak) and expands until it causes a catastrophic failure (Takahahi, 2002).

Figure 7 shows the pipes used in the experiment. Pipes are numbered from (a) to (c) and they will be referred in that nomenclature through the rest of the document. Note that there are two defect-free pipes of different lengths: 6000 mm and 1200 mm matching the lengths of the pipes with defects.
Electromagnetic Acoustic Transducers (EMATs) as shown in Figure 3 were used to generate and receive the signal. EMATs were mounted on brass holders that helped position the EMATs perpendicular to the pipes with a spacing of approximately 1 mm between the pipe and the EMAT. This position was fine tuned by the small plastic screws in the brass holders (which were also the only points of contact between the entire EMAT system and the pipes). Digital oscilloscope TiePie Handyscope HS3 was used to generate chirp signals of varying frequencies (depending on the experiment performed) controlled through the LabView program written for that particular application. The signal sent through the transmitting EMAT propagated through the pipe and was received by the receiving EMAT. It was then amplified by the Princeton Applied Research 113 Low Noise Preamplifier, digitized by the same Handyscope HS3 unit that was used to generate the signal, and displayed on the computer in the same LabView program as a function of time, as well as a function of frequency. The signal strength for both time history and frequency spectrum was displayed in Volts. The variation of time vs. signal strength is called time history or transient curve, and the variation of frequency vs. signal amplitude is called the \( f(t) \) curve. During the raw data collection, every time step was averaged by the program for at least 1024 times before being recorded to give a consistent value. Then it was analyzed in the new LabView program created for data analysis and capable of setting the frequency window as well as time window for the data analysis. Figure 8 shows the EMAT assembly and Figure 9 shows the experimental setup. In Figure 9, dimensions (a), (b), (c), (d) and (e) are dependent on the experiment performed, and the type of defect.
Figure 7: Steel pipe specimen - (a) defect free; (b) dent; (c) hole. All pipes have the same inner and outer radius.
Figure 8: EMAT assembly
Figure 9: Testing Schematic. Dimensions (a), (b), (c), (d) and (e) are dependent on the experiment performed.
5.1 EXPERIMENTAL RESULTS

5.1.1 Pipe with a Dent - Experimental Results

Figures 8 and Figure 9 show the experimental setup for a pipe with a dent. EMAT to EMAT distance (dimension “b” in Figure 9) is 2550 mm, EMAT to defect distance (dimension “d” in Figure 9) is 250 mm and the distance between the defect to the end of the pipe (dimension “c” in Figure 9) is 1460 mm. A dent is a localized depression or deformation in the pipe’s cylindrical geometry resulting from an applied force (Na, Kundu, 2002c). It is 1 mm deep and 0.5 mm wide as shown in Figure 7b. A chirp signal with a frequency range of 100 to 150 kHz is sent to the transmitting EMAT. PAR 113 pre-amplifier has a built in high-pass and low-pass filters of 1 kHz and 300 kHz, respectively. It magnifies the signal from the receiving EMAT ten thousand times. Excitation signal, as well as the pre-amplifier settings will stay the same for all experiments. Figure 10 shows the transient recording for the pipe with and without the defect. The first prominent peak is due to the crosstalk between output and input channels. Marked out are also Regions (1), (2), (3) and (4). Figure 11 shows the \( V(t) \) curve for the entire recorded signal length. Figures 12 through 15 show the \( V(t) \) curves for Regions (1) through (4), respectively.
5.1.2 Pipe with a Dent - Analysis

Wave modes for Regions (1) and (2) in Figure 10 can be identified from the group velocity dispersion curves which are obtained and shown in Figure 2. For drawing of dispersion curves material properties and the cross-section of the specimen must be known. As previously stated, pipes are made of steel, they can be assumed to be in vacuum (ignoring the effect of air coupling), and their inner and outer diameters are 15.4 mm and 21.4 mm, respectively. The density of steel is 7.932 kg/m$^3$ and the corresponding longitudinal wave speed is 5.96 km/s (Kundu, 2004). The group velocity of a longitudinal propagating wave is

$$c_g(f) = \frac{s}{t}$$

(4.2)

where group velocity $c_g$ is a function of frequency, $s$ is the distance traveled and $t$ is the time. Region (1) in Figure 10 is where the first peak is detected. The first detected major peak is the wave traveling the direct path between the transmitting and receiving EMATs. The time this signal takes to travel the distance of 2550 mm is 5.24 ms (from Figure 10 distance between the crosstalk and region 1) which gives the group velocity of 4.9 km/s. From Figure 12, the dominant frequency at which this wave packet is
propagating is 130 kHz. Plotting these two values on the group velocity dispersion graph one can identify this wave mode as the longitudinal L(0,2) mode, see Figure 2.

The peak in Region (2) of Figure 10 shows up only for the pipe with the defect. One can then conclude that this is the reflected signal from the defect. If one examines the travel time between the largest peak in Region (1) and the largest peak in Region (2), one can say that it is the time taken by the propagating wave to travel from the receiving EMAT to the defect and back. Earlier, it was determined that the wave traveling from the EMAT to the transducer is L(0,2) mode. When that wave is reflected by the defect then mode conversion can occur and L(0,2) mode can become the fundamental L(0,1) mode. One can verify this by calculating theoretically the time a signal should take that experiences mode conversion to travel the distance of 500 mm and compare it to the experimental measurements.

Receiving EMAT to defect distance is 250 mm. Group Velocity of L(0,2) mode at 130 kHz is \(4.9 \frac{\text{m}}{\text{m s}}\) and for L(0,1) mode at 110 kHz (see Figure 8) it is \(1.8 \frac{\text{m}}{\text{m s}}\).

Therefore, the total time the wave should take to travel from the EMAT to defect and back is:

\[
\frac{0.25\text{m}}{4.9\frac{\text{m}}{\text{m s}}} + \frac{0.25\text{m}}{1.8\frac{\text{m}}{\text{m s}}} - 0.000051 + 0.000138 - 0.000189 s
\]

(4.3)

From Figure 10, the time is measured to be \(0.000189 s\), that gives a perfect match between the two values. Since only modes L(0,1) and L(0,2) are propagating at
this frequency range, it is safe to say that the experimental setup confirms the theoretical prediction. This problem can be then reversed to calculate the distance of the defect from the EMAT, thus one can solve the practical challenge of detecting the location of defects in pipes.

Regions (3) and (4) show what can occur when using EMATs for ultrasonic testing. The signals traveling with different group velocities can overlap. In Region (3) of the transient data, reflections from the ends of the pipe and the reflections of different modes from the defect overlap. In the region of the overlap it becomes impossible to differentiate individual signals, but the overall condition of a pipe can be determined from the curves. Figure 14 shows how the amplitude of the signal increases due to presence of a defect.

The curve of Region (4) in Figure 10 is shown in Figure 15. This figure describes the behavior of the waves propagating in the pipes with or without a defect after a long time. Mode conversion described earlier while dismissing the peaks of Region (2) becomes very prominent in Figure 15. The defect in the pipe generates the additional L(0,1) mode that travels with 110 kHz frequency, while the waves in the pipe without a defect travel at a dominant frequency of 130 kHz. The pipe without a defect also experiences some mode conversion at the ends of the pipe, but this is not as prominent as the mode conversion due to the defect.

Mode conversion that occurs at the defect region also explains the shape of the curve of the entire time history of the signal that is shown in Figure 11. There is a
noticeable shift in the peak amplitude from 130 kHz (for the pipe without a defect) to 110 kHz. From the dispersion graph in Figure 2, one can see that at 135 kHz both L(0,1) and L(0,2) modes exist and the two wave packets travel at two different group velocities. At 110 kHz, the graph for L(0,2) mode has a very steep slope, meaning high dispersion and wave packets traveling through the pipe are separated and travel at many different group velocities, whereas L(0,1) mode shows relatively low dispersion. Looking back to Figure 11, one can see that both defect free and defective pipe have peaks at 110 and 130 kHz, but for the pipe with the defect, the amplitude of the signal is significantly larger at 110 kHz and vice versa.
Figure 10: Transient Data for the Dented Pipe Experiment
Figure 11: V(f) curve for the complete Transient Signal
Figure 12: $V(f)$ domain for Region (1) from Figure 10
Figure 13: $V(f)$ domain for Region (2) from Figure 10
Figure 14: $V(f)$ domain for Region (3) from Figure 10
Figure 15: $V(f)$ domain for Region (4) from Figure 10
5.1.3 Pipe with Drilled Holes - Experimental Results

Figure 9 shows the experimental setup for a pipe with drilled holes. EMAT to EMAT distance (dimension “b” in Figure 9) is 270 mm, EMAT to defect distance (dimension “d” in Figure 9) is 100 mm and distance of the defect from the end of the pipe (dimension “c” in Figure 9) is 450 mm. A chirp signal was sent through the pipe with and without a defect with a frequency range of 100 to 150 kHz. The same experiment was then repeated with a chirp signal in the range of 40 to 50 kHz.

In the 100-150 kHz range, Figures 16 through 19 show the recorded time history for the pipe without a defect and with 1 mm through 5 mm diameter hole. As in the previous study, separate regions of interest are analyzed. In Figures 20 through 28 Frequency spectra are given for regions (0) through (8). Due to the proximity of the EMAT to EMAT distance as well as the EMAT to defect distance, the signal caused by the direct path of the wave traveling from the transmitting EMAT to receiving EMAT as well as the distance traveled to and from the defect is contained in Region (0), which is also affected by the crosstalk between transmitting and receiving channels of the HandyScope unit. This can be shown from the group velocity calculations and dispersion curves. In particular, distance from EMAT to EMAT (270 mm) divided by the group velocity of the L(0,2) mode which is for a frequency of 130 kHz determined to be \( \frac{4.9}{s} \) would give the time of 0.0000574 s, which is near the middle of Region (0). In the same
manner it can be calculated that the reflection from the defect (if mode conversion from L(0,2) to L(0,1) occurs) would be at .00014 seconds which is also within Region (0).

For the experiment performed with a signal in the 40-50 kHz range, only L(0,1) mode is present. From Figure 2 one can determine that L(0,2) mode does not exist at frequencies below 95 kHz. As a result, the time domain now has five distinct regions (Figures 29-32) instead of eight. In Figures 33 through 37 Frequency spectra are given for regions (0) through (4).

5.1.4 Pipe with Drilled Holes - Analysis

It can be seen for both frequency ranges (100-150 kHz and 40-50 kHz) that the peaks of the highest frequency of the analyzed regions monotonically increase or decrease as the hole diameter is increased. The magnitude of the signal is found to be increasing when the peak analyzed is influenced mostly by the reflected waves from the defect and it decreases when the peak analyzed is due to the waves reflected from the end of the pipe. This decrease occurs because some energy is lost due to scattering as the signal travels through the defect. In the case where both wave modes are present (100-150 kHz) waves traveling at both group velocities corresponding to L(0,1) and L(0,2) modes affect the signal. All these parameters and factors working simultaneously create uncertainty in determining the path of the traveling wave which makes it very difficult to predict the size and location of the defect. However, the defect size can be determined
from the frequency domain analysis with excellent consistency as shown in the figures.

The ability to detect the growth of a defect in a pipe is a very important feature as it can help identify active cracks and prevent catastrophic failure.
Figure 16: Transient Data for a pipe without a defect (100-150 kHz signal). Individual regions are numbered and separately analyzed.
Figure 17: Transient Data for a pipe with a 1 mm diameter hole (100-150 kHz signal). Individual regions are numbered and separately analyzed.
Figure 18: Transient Data for a pipe with a 3 mm diameter hole (100-150 kHz signal). Individual regions are numbered and separately analyzed.
Figure 19: Transient Data for a pipe with a 5 mm diameter hole (100-150 kHz signal). Individual regions are numbered and separately analyzed.
Figure 20: Frequency Domain (plot) of Region (0) in Figures 16-19
Figure 21: Frequency Domain (V(f) plot) of Region (1) in Figures 16-19
Figure 22: Frequency Domain (V(f) plot) of Region (2) in Figures 16-19
Figure 23: Frequency Domain (V(f) plot) of Region (3) in Figures 16-19
Figure 24: Frequency Domain (V(f) plot) of Region (4) in Figures 16-19
Figure 25: Frequency Domain (V(f) plot) of Region (5) in Figures 16-19
Figure 26: Frequency Domain (V(f) plot) of Region (6) in Figures 16-19
Figure 27: Frequency Domain (V(f) plot) of Region (7) in Figures 16 - 19
Figure 28: Frequency Domain (V(f) plot) of Region (8) in Figures 16 - 19
Figure 29: Transient Data for a pipe without a defect (40-50 kHz signal). Individual regions are numbered and separately analyzed.
Figure 30: Transient Data for a pipe with a 1 mm diameter hole (40-50 kHz signal). Individual regions are numbered and separately analyzed.
Figure 31: Transient Data for a pipe with a 3 mm diameter hole (40-50 kHz signal). Individual regions are numbered and separately analyzed.
Figure 32: Transient Data for a pipe with a 5 mm diameter hole (40-50 kHz signal). Individual regions are numbered and separately analyzed.
Figure 33: Frequency Domain (V(f) plot) of Region (0) in Figures 29-32
Figure 34: Frequency Domain (V(f) plot) of Region (1) in Figures 29-32
Figure 35: Frequency Domain (V(f) plot) of Region (2) in Figures 29-32
Figure 36: Frequency Domain (V(f) plot) of Region (3) in Figures 29-32
Figure 37: Frequency Domain (V(f) plot) of Region (4) in Figures 29-32
CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY

Electromagnetic Acoustic Transducers (EMATs) were fabricated and used to generate the time history and frequency domain graphs for pipes with different types of defect. The EMAT’s design was changed from the traditional out-of-plane EMAT design to increase the magnetic field at the location of the coil and consequently increase the amplitude of the generated signal.

In the experiment on the pipe with a dent, the analysis of the time history domain showed that it is possible to predict the location of the defect, when the defect is positioned at a favorable position where its signal does not overlap with the rest of the signals traveling through the pipe. The change in the amplitude and position of peaks in the frequency domain show the sensitivity of the curve to defects and mode conversion that may occur due to defects in a pipe.

In the experiment on the pipe in which different diameter holes were drilled, it was not possible to determine the exact location of the defect in the time-history domain due to overlapping of the signals from the hole, different modes traveling through the pipe and the echo from the ends of the pipes. The frequency domain amplitude is shown to be sensitive to the defect size; the amplitude monotonically increases or decreases with the increase in hole diameter from 1 to 5 mm.
The two experiments show that the time history domain is favorable in determining the location of the defect, but it is often difficult to render meaningful data due to overlapping signals. The frequency domain is proven to be very sensitive to defect size, and consequently the overall condition of the pipe. However, from the frequency domain data it is impossible to determine the exact location of the defect. Therefore, the domain and frequency domain analyses are complementary to each other for the assessment of a pipe’s condition.

6.2 CONCLUSIONS AND FUTURE WORK

The signals of the propagating wave modes have been shown to be strongly affected by the presence of defects in pipes and the defect size. Stronger new modes can be generated due to mode conversion that may occur due to presence of defects. In this study the analysis was performed for pipes hanging freely in the air by two wires. This work can be extended to pipes embedded in soil, in water, or under pressure. Broadening the application of the EMATs in such a way would make them a very useful tool for non-destructive testing of pipelines.
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