Health monitoring of cylindrical structures using MFC transducers

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**HEALTH MONITORING OF CYLINDRICAL
STRUCTURES USING MFC TRANSDUCERS**

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HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

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ABSTRACT

Wave propagation techniques are widely used in structural health monitoring (SHM) because of their easily recognizable and controllable characteristics. Using wave propagation in SHM, controllable ultrasonic stress waves activated in the structures that be distorted if there exist discontinuities like cracks, delaminations, and corrosions. The received signals are analyzed, and the discontinuities can be identified. In cylindrical structures such as pipelines, cracks are more likely to occur along the longitudinal (axial) direction, and they can be fatal to the serviceability of the structures. Unfortunately, the conventional ultrasonic crack detection methods which use longitudinal waves are not very sensitive to this type of cracks.

The purpose of this research work is to find an appropriate SHM method for cylindrical structures by using surface attached piezoelectric macro-fiber composite (MFC) to generate guided wave in cylindrical structures. MFC transducers oriented at 45° against the neutral axis of the specimen are used as both actuator and sensor to generate longitudinal and torsional waves and to pick up the signals, respectively.

Firstly, MFC generated torsional wave pack is used for the axially oriented crack growth monitoring of cylindrical structures. Numerical simulations are performed using ANSYS and nodal release method is used to model the progress of crack growth. Experimental studies are conducted to verify the simulation results. Root mean square deviation (RMSD) method is proposed to capture the slight amplitude changes between the signals collected from the specimen with different crack sizes. Both the numerical results and the experimental data suggest that the axial-direction crack propagation in cylindrical structures can be well monitored using this wave propagation approach.

The proposed SHM system then extended with an additional piece of MFC transducer. The new system is not only able to pick up the axial crack growth but also able to identify the axial crack position in the cylindrical structure. The crack position is determined by the time of flight of the wave pack, while the crack propagation is monitored by measuring the variation in the crack induced disturbances, namely, the RMSD crack index. Both numerical simulations and experimental tests on aluminum pipes have been carried out for verification. The results demonstrated that the crack

ABSTRACT

position can be identified, and its growth can be well monitored with the proposed approach.

Based on the same principle and experiment setup, the detection of crack size and orientation in the cylindrical structure are studied. First, a crack of finite size is induced in a laboratory specimen. Later, the size is gradually increased along various orientations. The effects of the crack size and transmitted waves, captured by the sensor, are correlated with the RMSD values of the torsional wave packs and the longitudinal wave packs. The results show that both size and orientation of the crack can be evaluated based on the proposed method. The system developed in this thesis is easy to setup, cost efficient and able to achieve automatic continuous online monitoring with good results.

Key Words: Torsional Wave, MFC, Structural Health Monitoring, Cylindrical Structures, RMSD Crack Index

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LIST OF SYMBOLS

$\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$	Barium Titanate and Lead Zirconate Titanates
D	electric displacement vector
S	strain vector
E	applied electric field vector
T	stress vector
ε_{ik}^T	dielectric permittivity
d_{ip}^d and d_{kp}^c	piezoelectric strain coefficients
s_{pq}^E	elastic compliance
d_{kp}^c	piezoelectric coefficient
K_A	static stiffness of the PZT
Y_p	Elastic modulus of the piezoelectric actuator
$H(t)$	Hanning window function
$\text{RMSD}_p^i(t)$	RMSD crack index
R_T and R_L	RMSD value
K_{TA}	Slope of crack index of axial direction cracks calculated from torsional wave pack

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1 INTRODUCTION

1.1 Background

Pipes and cylindrical structures are widely used in the oil, chemical, and nuclear power generation industries. According to pipeline and gas journal 2013 worldwide construction report (Tubb 2013), there are nearly 800,000 kilometers (km) of pipelines in service in the petroleum industry across the U.S. in 2012. By the end of 2012, 188,031 km of pipelines is planned or being constructed all around the world. The integrities of such structures are important because once the failure occurs, not only massive economic losses are caused but also irreversible disaster is brought into the environment and human beings nearby. If structures are being monitored appropriately, defects can be found at the incipient stage. If the structures are fittingly maintained, catastrophic failure can thus be prevented, and their service life can be prolonged. Therefore, structural health monitoring (SHM) of such cylindrical and tubular structures has become one of the most challenging research topics in recent decades.

SHM of cylindrical structures is much more complicated as compared with SHM of plate-like structures due to the complex geometric and boundary conditions of hollow cylinders. One of the most commonly used SHM methods for the pipeline is the ‘PIG’ method. The ‘smart pig’ sent inside the pipeline travels through the tube to perform the inspection. Defects in such a pipeline can be well located by PIG method. However, the service of the host system needs to be shut down to launch the ‘smart pig’. Rather than ‘PIG’ method, other conventional nondestructive testing/evaluation (NDT/E) methods

like X-ray and ultrasonic inspection follow a point by point standard beam inspection procedure. They can also locate precisely the exact position of various kinds of defects on tubular structures. However, such methods usually have limitations on the sensing range and equipment mobility. Either the rough locations of the defects need to be pre-determined before examination or the testing equipment is difficult to move from a place to another. Additionally, most of the time, experienced labor workers are required to fulfill the inspections, which is not cost effective, especially when the structure being inspected is large in scale. Furthermore, when some tubular structures are exposed to extreme working conditions where human beings have limited access, it is almost impossible to perform the examinations. On the other hand, active monitoring has become more and more popular with the development of transducer technologies. The actuators are placed on the structures to send out activating signal, and the sensors receive the response from the host structures. If defects are introduced to the structures, their information is included in the response, and the signal will be captured and further analyzed. This research adopted the active monitoring concept to develop the proposed SHM system. One of the advantages of active monitoring methods is that with a properly designed control system, it can achieve automatic on-line monitoring without the presence of operators, which offers the possibility of remote on-line monitoring.

When structures are exposed to extreme conditions, maintenance of the structures is highly expensive in cost. If the crack in such structures is not so critical to the service life of the host structure, the maintenance is unnecessary. However, compared with the presence of the crack, other information like crack size and orientation has not received enough attention. A better understanding of the crack characteristics like crack dimension and direction will help in planning an economical maintenance program for the structures. In this research, the crack growth and orientation monitoring will be discussed.

Ultrasonic guided waves which can propagate long distance with little attenuation are commonly used in active SHM (Ditri and Rose 1992, Alleyne et al. 1993, Feroz and Oyadiji 1996). Different transducers have been developed to generate guided waves in structures (Ditri and Rose 1993, Giurgiutiu et al. 2004, Li and Rose 2006, Kannan et al. 2007). Compared with waves propagating in plate-like structures, waves propagating in cylindrical structures have more wave modes existing at the same time, and hence, the

wave structures are more complicated. Wave mode extraction and identification are required if particular wave mode is to be used in the analysis. In cylindrical structures, longitudinal wave mode travels faster than circumferential wave modes, so it is usually adopted to avoid wave modes overlapping. However, when cylindrical structures are used to transport oil, gas and chemicals the inner pressure of the pipe will cause the crack more likely to happen along the axial direction than the circumferential direction. Since the particle motion direction of longitudinal wave mode is parallel to the crack direction, the longitudinal wave is not sensitive to this type of crack. Hence, in this research, the torsional wave has been used to perform the SHM works.

One of the biggest challenges in active SHM of continuous cylindrical structures comes from the testing system. Usually, the testing equipment is focusing on the local integrity of the structure, and the whole system is too complicated to be used in the SHM of structures that cover a large area. For example, the ring type transducers are usually placed at the certain part of the pipe to inspect its adjacent area. Once the inspection is completed, the transducers need to be shifted to the next target area. The mobility of the experiment setup significantly limited the application of this type of transducer where a straightforward and easy-to-use experiment setup should be developed for the SHM of continuous cylindrical structures. The piezoelectric material is one of the most innovative materials that have been invented in recent decades. Since its strain can be controlled by the input voltage, it has been widely used in ultrasonic inspections. The Lead Zirconate Titanate (PZT) patches and macro-fiber composite (MFC) patches are two types of most commonly used transducers. PZT patch is small, light, easy to be bonded on the surface of the structures, however, too brittle to be applied on the curved surface. On the other hand, MFC consists of rectangular piezoceramic rods sandwiched between layers of adhesive and electroded polyimide film. Because of its exceptional flexible property, MFC could be bonded onto any slick curved surface, especially on the cylindrical shell or tubular structures. So MFC transducers are used as both actuator and sensors in this research.

1.2 Scope and Objectives

Base on the background stated in the previous section, it can summarize that ultrasonic guided wave inspection method is suitable for long range inspection but the commonly

used ring type transducers (Ditri and Rose 1993, Kannan et al. 2007) are either lacking in mobility, or the experiment setup is too complicated to be widely used. The circumferential crack and drilled holes can be well detected and located, but the information on axial crack or crack with any orientation and dimension have not been clearly studied. The primary objective of this research is to investigate the feasibility and methodology of using MFC transducers to generate guided waves for continuous tubular structure damage diagnosis. Since many researchers have published numerous studies on how to detect the circumferential crack or drilled holes, to fulfill this objective of damage diagnosis, the following works are discussed in this research:

1. Using MFC as transducers, generate longitudinal wave pack and torsional wave pack on the cylindrical structure for axial crack detection. Analyze the output signal to find a suitable method to detect and monitor the axial crack growth in cylindrical structure.
2. Locate the axial position of the axial crack; combined with the previous task, establish a close-loop in-situ online SHM system for the axial crack location identification and crack growth monitoring.
3. Expand the system to be able to justify the orientation and dimension of a crack with arbitrary direction and dimension in the cylindrical structures from the received signals.

1.3 Originality and Contributions

Due to the complexity of the geometric shape of hollow cylinders, the author first tried to use oriented MFC patches attached on pipe surface to generate guided torsional wave for SHM of cylindrical structures. Compared with other ring type actuators that had been employed in SHM of cylindrical structures, this proposed transducer is cost efficient, easy to setup and the results are acceptable.

Most of the research topics published on cylindrical structures SHM are focused on the detection of circumferential notches or drilled holes. Due to the existence of hoop stress, the cracks on hollow cylinders are likely to happen along the axial direction. The author then studied the axial crack growth monitoring of cylindrical structures. Furthermore, the author developed the monitoring system to be able to locate the axial crack position and identify its dimension. Based on the proposed SHM system and crack index for

cylindrical structures, the author developed a method that can detect not only the dimension but also the orientation of arbitrary line type crack on cylindrical structures.

1.4 Layout of Thesis

The thesis consists of six chapters and an appendix, where the first chapter introduces the background, objective, and originalities of this research.

In Chapter 2, the in-depth literature review on the concept of smart structures and system as well as commonly used smart materials are presented. Some conventional non-destructive testing techniques for both plate and cylindrical structures SHM are also presented. Different transducers especially piezoelectric transducers and their characteristics and applications are reviewed and listed.

Chapter 3 analyzes the wave mode particle motion and their interaction with axial direction line type crack on cylindrical structures. Base on the analysis, an axial crack monitoring system for the cylindrical structure is proposed. The crack dimension change is correlated with the overall shape change of the signal via the Root Mean Square Deviation (RMSD). The RMSD value calculated from the targeting wave pack can be used as the crack index which indicates the axially oriented crack dimension change.

In Chapter 4, the SHM system is extended by adding one additional piece of the transducer. Pulse-echo method and RMSD crack index are used together to identify the position and dimension of the axial crack in cylindrical structures.

In Chapter 5, the application of RMSD crack index is extended from axially oriented crack to arbitrarily oriented line type crack. With RMSD crack indices calculated from axial crack and circumferential crack, the dimension and the orientation of arbitrary line type crack can be identified.

The concluding remarks of this research and recommendations for future works are presented in Chapter 6, followed by the list of references that cited in the thesis.

In Appendix I, selected publications from the author are listed.

In Appendix II and Appendix III, selected MATLAB codes and ANSYS input files used in this study are listed.

2 LITERATURE REVIEW

2.1 Smart Materials and Systems

Smart materials, due to their characteristics that one or more of their properties can be significantly changed in a controlled fashion by external stimulation such as stress, temperature, moisture, pH, electric or magnetic fields, have been extensively used in the areas of control and damage diagnoses of aerospace, mechanical and civil structures. In recent 30 years, tremendous research efforts have been dedicated to this promising new field, and it has brought huge development in the technologies associated with smart material and their applications. One of the most interesting topics that have emerged is smart system/structures.

2.1.1 Concept of Smart Structural Systems

In the ARO Workshop organized by the US Army Research Office, smart system/structure was firstly defined as “a system or material which has built-in or intrinsic sensor(s), actuator(s), and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short and appropriate time, and reverting to its original state as soon as the stimulus is removed.” (Ahmad 1988).

Explicated in a broader sense, the definition of smart systems/structures encompasses a group of structures and systems that are capable of sensing their environment changes by receiving the relevant responses, and taking the necessary actions. These features can be realized by embedding or bonding actuators and sensors to the structures. The control of the actuators and the feedback from the sensors should be properly integrated;

and because of the unique properties of various smart materials, they are usually used as sensors or actuators.

The engineering structures can only be called ‘smart’ when they meet such criteria: functionality, reliability, durability, affordability, safety and cost effectiveness. Until now, not too many systems can be qualified as real ‘smart’ structures. Even some of them met functionality criteria, the reliability, sensitivity of such systems are still pending. There have been plenty of rooms for such structures/systems to be improved, which also stimulates researchers’ further investigation in the fundamental areas of this field.

2.1.2 Smart Materials

In 1988, smart materials were firstly defined as “materials which possess the ability to change their physical properties in a specific manner in response to specific stimulus input.” (Rogers et al. 1988). Under different conditions like temperature, poling direction, electric field, magnetic field and so on, the smart materials have the abilities to change their properties like damping, viscosity, shape and stiffness and so on in response. Because of these unique characters, the smart materials are commonly used as transducers in structures/systems to make the structures/systems ‘smart’. There are many kinds of smart materials like fibre optics (Rogers et al. 1988, Ng et al. 1998, Tjin et al. 2001, Storoy et al. 1997, Yamakawa et al. 1999, Brownjohn et al. 2003), shape-memory alloy (Reddy and Barbosa 2000, Littlefield 2000), Electro-Rheological (ER) fluid (Stanway et al. 1996, Neumann 1996) and many others.

2.2 Piezoelectric Materials

Piezoelectric materials exhibit significant material deformation in response to an applied electric field and produce a dielectric polarization when subjected to mechanical strain. They have been successfully implemented in many different applications such as distributed vibration sensors (Choi and Chang 1996, Kawiecki 1998) strain actuators (Sirohi and Chopra 2000a) and sensors (Sirohi and Chopra 2000b), receptors of stress waves (Giurgiutiu et al. 2000, Boller 2002), and pressure transducers (Kuoni et al. 2003).

2.2.1 Piezoelectricity

The phenomenon of piezoelectricity was firstly found in a kind of crystalline minerals by Pierre and Paul-Jacques Curie in one of their experiment in 1880. The crystals became electrically polarized when subjected to a mechanical force. Moreover, the voltages generated by tension and compression are of opposite polarity and in proportion to the applied force. Contrary to this phenomenon, the crystals exhibit significant deformation when exposed to an electric field. The trend of the deformation agreed with the polarity of the field and the amount of the deformation also in proportion to the strength of the field. This phenomenon was labelled as the piezoelectric effect and the inverse piezoelectric effect, respectively.

Piezoelectricity can be found in several crystalline materials including natural crystals of Quartz, Rochelle salt and Tourmaline and manufactured ceramics. Piezoelectric ceramics, because of their unit cells' specific composition, shape, and dimension can be tailored to meet the requirement of employing the piezoelectric effect and the inverse piezoelectric effect. The most commonly available type of piezoelectric ceramics is Barium Titanate and Lead Zirconate Titanates $[\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3]$, as known as PZT.

PZT crystallites, at temperatures above a critical value, the Curie temperature, take on a simple cubic symmetry with no dipole moment (Figure 2-1a); while at temperatures below the Curie point, exhibit tetragonal or rhombohedral symmetry and a dipole moment (Figure 2-1b).

Figure 2-1 Crystal structures of a traditional piezoelectric ceramics when (a) temperature above Curie point and (b) temperature below Curie point

The process of converting a crystal material into piezoelectric material permanently is called poling, as shown in Figure 2-2. When an intense electric field ($>2000\text{V/mm}$) is applied to the piezoelectric materials, the material expands along the axis of the field and contracts perpendicular to that axis. After the field is removed, most of the dipoles are locked, and the electric dipoles stay roughly, but not completely in alignment. The material now has a permanent and remnant polarization.

Figure 2-2 Electric dipoles in piezoelectric materials (a) before, (b) during and (c) after poling

2.2.2 Piezoelectric Constitutive Relations

For PZT material, the reference axes are as shown in Figure 2-3 where the direction of polarization (axis Z) is established during the poling process by a strong electrical field applied between two electrodes. For actuators, the piezoelectric properties of PZT along the poling axis are the most important.

Figure 2-3 Definition of axes

Under small field considerations, the general constitutive equations for a piezoelectric material can be written as (IEEE-Standard 1988)

$$\mathbf{D}_i = \varepsilon_{ik}^T \mathbf{E}_k + d_{ip}^d \mathbf{T}_q \quad (\text{Eq.2-1})$$

$$\mathbf{S}_p = d_{kp}^c \mathbf{E}_k + s_{pq}^E \mathbf{T}_q \quad (\text{Eq.2-2})$$

In compressed matrix notation, the above equations can be expressed in the form of

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{S} \end{pmatrix} = \begin{bmatrix} \boldsymbol{\varepsilon}^T & \mathbf{d}^d \\ \mathbf{d}^c & \mathbf{s}^E \end{bmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{T} \end{pmatrix} \quad (\text{Eq.2-3})$$

Where $\mathbf{D}$ is the electric displacement vector (C/m^2); $\mathbf{S}$ is the strain vector; $\mathbf{E}$ is the applied electric field vector (V/m^2), and $\mathbf{T}$ is the stress vector (N/m^2). The piezoelectric constants are the dielectric permittivity, ε_{ik}^T (Farad/m), the piezoelectric strain coefficients, d_{ip}^d and d_{kp}^c (C/m or m/V), and the elastic compliance, s_{pq}^E (m^2/N). The piezoelectric coefficient d_{kp}^c defines the stress per unit field at constant stress, while d_{ip}^d defines electric displacement per unit stress at constant electric field. The subscripts ‘ c ’ and ‘ d ’ indicate the direct and converse piezoelectric effects respectively, while the superscripts ‘ T ’ and ‘ E ’ indicate that the quantity is measured at constant stress and constant electric field respectively (Sirohi and Chopra 2000b).

Figure 2-4 Material directions of a piezoelectric element

For a piece of piezoelectric material, as shown in Figure 2-4, the poling direction is usually in the direction of the thickness, denoted as the 3rd axis. With the 1st axis and the 2nd axis in the plane of the sheet, the d_{kp}^c matrix can be written in the expanded form as

$$\mathbf{d}^c = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (\text{Eq.2-4})$$

$$\mathbf{d}^d = (\mathbf{d}^c)^T \quad (\text{Eq.2-5})$$

where d_{31} , d_{32} and d_{33} are related to the normal strain in the 1, 2, and 3 directions, respectively, to a field along the poling direction, 3. The coefficients d_{15} and d_{24} relate to the shear strain in the 1-3 plane and 2-3 plane and under the field E_1 and E_2 , respectively. It is impossible to obtain shear strain in the 1-2 plane purely by application of an electric field.

The compliance matrix is in the form of

$$\mathbf{S}^E = \begin{bmatrix} S_{11}^E & S_{12}^E & S_{13}^E & 0 & 0 & 0 \\ S_{21}^E & S_{22}^E & S_{23}^E & 0 & 0 & 0 \\ S_{31}^E & S_{32}^E & S_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66}^E \end{bmatrix} \quad (\text{Eq.2-6})$$

Moreover, the permittivity matrix is

$$\boldsymbol{\epsilon}^T = \begin{bmatrix} \epsilon_{11}^T & 0 & 0 \\ 0 & \epsilon_{22}^T & 0 \\ 0 & 0 & \epsilon_{33}^T \end{bmatrix} \quad (\text{Eq.2-7})$$

The stress vector is defined in the form of

$$\mathbf{T} = (T_{11} \quad T_{22} \quad T_{33} \quad T_{23} \quad T_{31} \quad T_{12})^T \quad (\text{Eq.2-8})$$

where the last three terms are the shear stress components, and the subscripts indicate the direction of axes.

The strain vector can be written in the form of

$$\mathbf{S} = (S_{11} \quad S_{22} \quad S_{33} \quad S_{23} \quad S_{31} \quad S_{12})^T \quad (\text{Eq.2-9})$$

The electric displacement vector can be written as

$$\mathbf{D} = \begin{pmatrix} D_1 \\ D_2 \\ D_3 \end{pmatrix} = \begin{pmatrix} D_{11} \\ D_{22} \\ D_{33} \end{pmatrix} \quad (\text{Eq.2-10})$$

Moreover, the electric field vector is

$$\mathbf{E} = \begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} = \begin{pmatrix} E_{11} \\ E_{22} \\ E_{33} \end{pmatrix} \quad (\text{Eq.2-11})$$

Eq.2-1 is commonly termed as the sensor equation, and Eq.2-2 is termed as the actuator equation. Actuator applications are based on the converse piezoelectric effect and for sensor applications, the direct piezoelectric effect. Therefore, when the transducer is bonded to a structure and subjected to an electric field, a strain field is induced. Conversely, when the transducer is exposed to a stress field, an electric charge is generated in response. The uniqueness of the piezoelectric material is that the material can perform both as an actuator and a sensor. The behaviours of the piezoelectric sheet as actuators as well as sensors are systematically reviewed by Sirohi and Chopra (Sirohi and Chopra 2000a, Sirohi and Chopra 2000b).

2.2.3 Piezoelectric Sensors and Actuators

Piezoelectric sensors have been successfully used in many aspects. Qiu and Tani (Qiu and Tani 1995) have used polyvinylidene difluoride (PVDF) as both actuators and sensors in controllable structural systems. PZT sensors have also been used for wave propagation studies (Feroz and Oyadiji 1996). Active vibration control of a laminated composite plate with PZT actuators and sensors has been studied by Raja et al. (Raja et al. 2004). Piezoelectric sensors were also used to demonstrate a thermomechanical writing system and a piezoelectric readback system for a low-power scanning-probe-microscopy data-storage system (Lee et al. 2004).

In the case of a sensor, where the applied external electric field is zero, Eq.2-3 becomes

$$\begin{pmatrix} \mathbf{D}_1 \\ \mathbf{D}_2 \\ \mathbf{D}_3 \end{pmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{23} \\ T_{31} \\ T_{12} \end{pmatrix} \quad (\text{Eq.2-12})$$

Eq.2-12 summarizes the principle of operation of piezoelectric sensors. A stress field causes an electric displacement to be generated as a result of the direct piezoelectric effect.

The electric displacement $\mathbf{D}$ is related to the generated charge by the relation

$$q = \iint [\mathbf{D}_1 \quad \mathbf{D}_2 \quad \mathbf{D}_3] \begin{bmatrix} dA_1 \\ dA_2 \\ dA_3 \end{bmatrix} \quad (\text{Eq.2-13})$$

where dA_1 , dA_2 and dA_3 are the components of the electrode area in the 2-3, 1-3, and 1-2 planes respectively.

The charge q and the voltage generated across the sensor electrodes V_c are related to the capacitance of the sensor, C_p as

$$V_c = q/C_p \quad (\text{Eq.2-14})$$

The sensors used in this research are all in the form of sheets with two faces coated with thin electrode layers. The first and second axes of the piezoelectric material are in the plane of the sheet. In the case of a uniaxial stress field, the correlation between strain and developed charges is simple due to the mechanical structure of PZT sheet.

It has been found that the performance of piezoelectric sensors is of superiority with much less signal conditioning required, especially in applications involving low strain levels and high noise levels. The output of the sensors needs no temperature correction over a moderate range of operating temperatures despite the fact that the piezoelectric coefficients are temperature dependent (Sirohi and Chopra 2000b). It is also possible to accurately calibrate these sensors.

Crawley and De Luis (Crawley and De Luis 1987) studied the model of piezoelectric actuators as elements of intelligent structures both analytically and experimentally. The static as well as dynamic analytic models were derived for the segmented piezoelectric actuators that either bonded to an elastic substrate or embedded in a laminated composite. These models established a quantitative relation between the response of the structural member and the voltage applied to the piezoelectric.

Sirohi and Chopra (Sirohi and Chopra 2000a) investigated the fundamental behaviour of PZT sheet actuators under different types of excitation and mechanical loadings. In their study, the magnitudes and phases of the free strain response of the actuator under different excitation voltages and frequencies were measured and a phenomenological model to predict this behaviour was developed and validated. For an actuator of length a_p , width b_p and thickness h_p , and with an elastic modulus Y_{11}^E , the force exerted is given by

$$F = K_A a_p (\varepsilon_{mech} - \varepsilon_0) \quad (\text{Eq.2-15})$$

where K_A is the static stiffness of the PZT, given by $Y_{11}^E b_p h_p / a_p$; ε_0 is the free strain which is defined as $d_{31} V / h_p$; ε_{mech} is the mechanical strain of the structure at the actuator location; and V is the electric voltage applied to the PZT.

Figure 2-5 PZT actuator with bonded structure

According to Preumont's (Preumont 2002) study, for a laminar piezoelectric actuator of constant width b_p , as shown in Figure 2-5, the effect of the distributed actuator is equivalent to adding a concentrated moment M_p at the boundary of the actuator. The expression for the concentrated moment M_p is given in the form of

$$M_p = -Y_p d_{31} V b_p \frac{h+h_p}{2} \quad (\text{Eq.2-16})$$

where Y_p is the Elastic modulus of the piezoelectric actuator; V is the voltage added onto the electrode; h and h_p are the thickness of host structure and piezo layer, respectively.

As discussed above, the application of sensors is based on the piezoelectric effect, and the actuator application is based on the converse piezoelectric effect. A piezoelectric transducer utilizes both the effects to serve as both actuator and sensor. Based on the coupled electrical and mechanical properties of a PZT transducer, EMI method was introduced for SHM.

2.2.4 Macro-Fiber Composites (MFC)

MFC actuator was developed at the NASA Langley Research Center (Wilkie et al. 2000). The MFC transducer consists of active piezoceramic fibers aligned in a unidirectional manner, interdigitated electrodes, and an adhesive polymer matrix as shown in Figure 2-6.

Figure 2-6 Structure of a Macro-Fiber Composite transducer

The MFC has rectangular fibres which greatly affects the manufacturing process and the performance (Wilkie et al. 2000). The fibres of the MFC have a rectangular cross section due to the method used to form the fibres. MFC is extremely flexible, durable and has the advantage of higher electromechanical coupling coefficients due to the interdigitated electrodes. MFC has found many applications in actuation, vibration control, structural health monitoring and energy harvesting in recent years (Park and Kim 2004, Sodano et al. 2004, Schönecker et al. 2006, Ro et al. 2007, Tang and Yang 2012, Wu et al. 2012).

MFC has been manufactured in d_{31} and d_{33} (also called d_{11}) types, where d_{31} and d_{33} are related to the normal strain in the 1, 3 directions. For the d_{33} type, the electrical potential flow in the length of the MFC instead of the thickness of the MFC. The MFC- d_{33} is a good sensor and very strong actuator. High flexibility and maximum operational voltage of 1500 volts DC and 500 volts AC make it very strong actuator. Despite all the improvement in MFC, MFC is less sensitive as compared to PZT for SHM for the same level of applied electrical fields.

Figure 2-7 (a) Typical piezoelectric effect and (b) d_{31} and d_{33} type MFC in-plane electric field and displacement

For many smart materials, the strain actuation characteristics under unloaded operating conditions and at low frequencies are typically the easiest to obtain. These free-strain actuation measurements, combined with some knowledge of the actuator elastic properties, are often the best general indicator of overall actuator effectiveness. As shown in Figure 2-8 (W. Wilkie et al. 2002), compared with a typical through-plane poled piezo-ceramic actuator device, the maximum free strain performance for an MFC is considerably larger.

In addition to high strain and stress actuation ability, high endurance under various electrical and mechanical cycling conditions is also necessary for a practical active structure. An example of typical room-temperature electrical endurance trends of MFC devices operating under free strain conditions is shown in Figure 2-10 (W. Wilkie et al. 2002).

Figure 2-8 Comparison of MFC and typical PZT longitudinal (fibre-direction) free-strain actuation behavior (W. Wilkie et al. 2002)

Figure 2-9 Normalized room temperature free-strain amplitude trend of MFC actuator under repeated cycling (1500V peak to peak, +300V bias, 500 Hz). (W. Wilkie et al. 2002)

Based on its manufacturing process and physical characteristic, MFC has such benefits and applications as listed in Table 2-1.

Table 2-1 Benefits and application of Macro-fiber Composites

Benefits of MFC	Applications of MFC
Flexible and durable	vibration and noise control
Increased strain actuator efficiency	dynamic structural morphing
Directional actuation/sensing	structural health monitoring
Damage tolerant	strain gauges
Different piezo ceramic materials available	loudspeaker applications
Conforms to surfaces	energy harvesting
Readily embeddable	
Environmentally sealed package	
Demonstrated performance	
Available as elongator (d33 mode) and contractor (d31 mode)	

2.3 Structural Health Monitoring

2.3.1 Introduction

Structural Health Monitoring (SHM) can be interpreted as the activities of monitoring the healthy condition of engineering structure. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real-time, reliable information regarding the integrity of the structure. One of the most core content in SHM is damage detection which involves four distinct objectives (Farrar and Jauregui 1998):

- 1.) Proof the existence of damage.

- 2.) Locate the position of the damage.
- 3.) Evaluate the severity of the damage.
- 4.) Predict the remaining service life of the structure.

Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The first three steps are usually called damage diagnosis, and the last step is a new field which called damage prognosis.

There are many approaches to achieving SHM or damaged detection in structures. The basic principle is that the damages can be related to the changes of these measured parameters. From the differences between data acquisition, most of the methods can be divided into two categories, passive, and active SHM. Passive SHM methods directly take the measurement of the dynamic responses of structure and inferring the state of structural health from these parameters, where active SHM methods focus on directly assessing the state of structural health by trying to detect the presence and extent of structural damage (Giurgiutiu 2007).

2.3.2 Passive Structural Health Monitoring

Passive SHM chooses kinematic quantities typically measured in vibration testing for monitoring. Those physical quantities like strain, displacement and accelerations are relevant and sensitive to the structural properties. From the changes of measured physical parameters, the healthy condition of the structures is evaluated.

Maaskant et al. (Maaskant et al. 1997) attached FBG sensors on the steel and carbon-fiber reinforced girder which embedded in a road bridge. The sensors network can pick up the maximum strain and the deformation of the bridge. Also, the FBG sensors stood under moisture condition where the traditional strain gauges were failed. Wang et al. (Wang et al. 2001) used FBG sensors to measure the bending, torsion, shear force and compression force on a ship hull. The maximum global bending moment that worked on the ship hull was calculated from the acquired data. Satpathi et al. (Satpathi et al. 1999) used PVDF as strain gauges to set up a low-cost SHM system for infrastructure monitoring. The PVDF transducers were cut into small pieces, and the whole system is driven by low power. The test results showed that the proposed system served its purpose quite well.

Displacement also can be used as an indicator of the healthy condition of structures. If the movement of the structure is too large compared with normal displacement, the structures can be considered overstressed. Çelebi (Çelebi 2000) proposed to use global positioning system(GPS) for long-period structures health monitoring. GPS can capture displacement with an accuracy of 2cm. Even though the device can precisely pick up the movement of the structures, this method is not able to assess the existence and position of the damage on the structures.

Accelerometers can measure the dynamic response of structures that is often used as transducers to perform SHM. Fugate et al. (Fugate et al. 2001) using a statistical method to analysis the results from accelerometers for vibration-based SHM problem. An autoregressive (AR) model is fit to the undamaged results where the residual is used to quantify the future damage. The experiment setup successfully indicated the damages on the bridge beam. However, the results might be interference by the surrounding environment.

2.3.3 Active Structural Health Monitoring

The essence of SHM technology is to develop autonomous systems for continuous monitoring, inspection, and damage detection of structures with minimum labour involvement (Chang 1997). Such a technology of an onboard system will involve sensors and actuators attached to the structures to monitor the structural health. The success of monitoring practice depends on the ability to identify and relate changes in sensor measurements with physical changes of the structures.

Active structural health monitoring focused on delivering a one stop solution to SHM. Compared with passive SHM, which only focuses on monitoring the evolution of the structure, active SHM integrated the structure with both sensors and actuators. In active SHM system, the embedded/integrated actuator sends out controllable periodic excitation to the host structure where the sensor monitors the response of the host structure. The healthy condition of the host structure is then inferred from the analysis of the signals captured by the sensor. Because both actuator and sensor are needed to perform active SHM, smart materials with both actuation and sensing characteristics such as piezoelectric material, magnetostrictive material, shape alloys, etc. are favorable in this application.

2.3.3.1 Electro-Mechanical Impedance (EMI) Method

Mechanical impedance is a measure of how much a structure resists motion when subjected to a given force. It relates forces with velocities acting on a mechanical system. Piezoelectric transducer can convert mechanical stress into an electrical signal and vice versa, a mechanical strain is a product when an applied electric field charges the transducer. The piezoelectricity character of such transducers related the mechanical impedance of a structure to the electrical impedance of the piezoelectric transducer bonded to the structure where any physical change of the structure leads to the electrical impedance change of the transducer. This SHM method is so-called electromechanical impedance (EMI) method. Sun et al. (Sun et al. 2005a) initiated the application of EMI method for SHM. They presented the first proof-of-concept and application of the EMI method in the detection and localization of structural damage, for a three-bay aluminium truss. The surface bonded PZT generates dynamic force on the structure and senses the feedback from the structure. Any variation in the mechanical impedance by damages or flaws in structure will change the electrical admittance of PZT. Thus, the healthy condition of the structure can be identified.

While the EMI model provides the EM admittance signatures of the PZT transducers, the noticeable effects of structural damages on the PZT EM admittance signatures are the lateral and vertical shifting of the baseline signatures (Sun et al. 1995), which are the main damage indicators. Statistical techniques have been employed to associate the damage with the changes in the admittance signatures, such as the root mean square deviation (RMSD) (Giurgiutiu and Rogers 1998) and the relative deviation (RD) (Sun et al. 1995). Bhalla et al. (Bhalla et al. 2001) performed a comparative study of these statistical indices and found that the RMSD is the most robust and representative index for assessing damage progression. Therefore, the sensitivity of the RMSD index to structural damage deserves further investigation. Park et al. (Park et al. 2003a, Park et al. 2003b) systemically reviewed the applications of EMI method for SHM.

2.3.3.2 Wave Propagation Method

Even though the EMI method can precisely identify the existence of defects in the structure, the exactly crack position of the defect still cannot be located by only EMI method. Besides, EMI method is limited by the sensing region of only a few meters.

Ultrasonic guided waves are kind of stress wave that propagate in a structure where its propagation can be guided by the boundary of the structure. Owing to their unique potential for long-range, in-plane propagation, this wave-based techniques offer appealing ability to inspect a wide area of structures. So far, several wave-based SHM techniques have been developed and investigated for detecting damages in various engineering structures. These methods measure the reflections and transmissions of waves using a single patch or arrays of sensors and actuators.

Waves can reflect or scattered from obstacles on their propagation path. Two of the methods are commonly used in wave propagation based SHM. Pulse-echo method is focusing on detecting the additional wave pack that reflected from the defects on the wave propagation path, and transmission method is focusing on differentiating the changes that damage added on the passed-by signals. Piezoelectric materials demonstrated both good actuating and sensing ability hence they are usually used as transducers in wave propagation applications. The time of flight of additional wave pack reflected from defects has shown a good estimation of damage location in beam structures (Díaz Valdés and Soutis 2000), aircraft wings (Giurgiutiu et al. 2004) and composite plate-like structures (Wang and Yuan 2005). Quantification of damages is also one of the critical problems in wave-based SHM. From the measured time history data of the propagating waves which are generated and received by PZT transducers, various types of damages, i.e., delamination, saw cut, and impact damage was successfully evaluated in carbon-epoxy-laminated composite beam specimens (Lestari and Qiao 2005). Based on longitudinal wave propagation theory associated with PZT impedance measurement, quantitative techniques for assessment of the structural damage conditions (e.g. size, form, and severity) in beam structures were developed (Su et al. 2003).

2.3.3.2.1 Lamb Wave NDT Applications

Many other researchers were also involved in the study of Lamb waves, including practical applications. Among them, Alleyne et al. (Alleyne et al. 1993) carried out a study of the use of Lamb waves in nondestructive testing and developed a technique which can assist the interpretation of the compound signals which were produced by mode conversion and dispersion. Alleyne and Cawley (Alleyne and Cawley 1992) also studied the interaction of Lamb waves with defects to assess the sensitivity of different

Lamb wave modes in various frequency-thickness regions and then determine the best testing regime for a particular type of defect. Ditri and Rose (Ditri and Rose 1992) used S-parameter formalism to study the phenomenon of scattering of Lamb waves from a circumferential crack in an isotropic hollow cylinder. Similarly, McKeon and Hinders (McKeon and Hinders 1999) explored the higher order plate theory to derive analytical solutions for the scattering of the lowest order symmetric Lamb waves from a circular inclusion in plate-like structures. The results were used to explain the scattering effects found in Lamb wave tomography. Alleyne et al. (Alleyne et al. 1998) also studied the reflection of $L(0,2)$ mode Lamb wave from notches in pipe-like structures and the relationship between reflection ratio and the depth of the notch. The pulse-echo method was adopted in his research.

Malyarenko and Hinders (Malyarenko and Hinders 2001) described the application of Lamb wave tomography for mapping the flaws in multi-layer aircraft materials. A circular array of spaced transducers was set up for the reconstruction of tomography, which was used to judge the health states of aircraft structures. The study was aimed at scanning a large area quickly and automatically. Although that technique cannot be applied to tube-like structures, it is still an important step in the application of Lamb wave technologies in the aerospace industry.

Halabe and Franklin (Halabe and Franklin 2001) tried to detect fatigue cracks in metallic members using the statistical properties of guided waves in the frequency domain. The Rayleigh waves were produced, and several types of crack-like defects (for example, micro fatigue and macro fatigue) were tested using five-cycle sine pulse excitation with 2.25 MHz of the central frequency. The study illustrates the sensitivity of Rayleigh waves to surface flaws, but location and classification were not studied in their research. Jung et al. (Jung Y et al. 2001) detected discontinuities in concrete structures using Lamb waves and frequency domain analysis.

2.3.3.2.2 Time-Frequency and Spectrum Analysis of Lamb Wave

Time-frequency analysis methods are essential for characterizing acoustic waves. Niethammer et al. (Niethammer et al. 2001) compared four methods of time-frequency representations of Lamb waves. The reassigned spectrogram from short-time Fourier Transform (STFT), the reassigned scalogram from wavelet transform (WT), Wigner-

WVD) and Hilbert transform were used to represent multi-mode Lamb waves. The advantages and shortcomings were discussed. The results showed that spectrogram and smoothed WVD gave the best time-frequency distribution for wide-band Lamb waves.

Valle and Littles (Valle and Littles Jr 2002) studied flaw localization with reassigned spectrogram of detected Lamb modes using a modified signal processing technique. The spectrogram was generated by STFT, and the image change due to the flaw reflection was used to locate notch-type defects. Only one type of flaw was studied, and the accuracy of the detection depended heavily on the signal quality; a high level of noise was a big challenge in the performance of this algorithm. Although the scope of this research is limited, it embodied some good ideas such as using non-contact methods to generate guided waves and utilizing advanced signal processing techniques to explore the hidden information. Similarly, in the work of Clezio et al. (Le Clézio et al. 2002), the interaction between cracks and the first symmetric Lamb mode S_0 in an aluminium plate placed in a vacuum were demonstrated using both experiments and finite element simulations. The work illustrates a nonlinear relationship between crack thickness, and reflection and transmission coefficients. Another type of flaw, a hole in an aluminium plate, was studied by Fromme and Sayir (Fromme and Sayir 2002). The active Lamb wave was selectively excited to have an antisymmetrical mode using piezoelectric transducers, and it is currently a very popular method for Lamb wave activation. The scattering coefficient was calculated using Mindlin's theory and a classical plate theory.

2.3.3.3 Wave Propagation Method Using Piezoelectric Materials

One of the breakthroughs in SHM research using Lamb waves was the implementation of the emitter and/or receiver of waves by using PZT transducers (Grondel et al. 2002, Kessler et al. 2002). Their contribution lies in demonstrating the potential of the selective Lamb-mode technique for in-service SHM. The PZT-generated Lamb waves have been widely studied and successfully applied for detecting and localizing the damages in isotropic plate structures (Tua et al. 2004, Wait et al. 2004, Mustapha et al. 2007). Lamb waves generated by PZT transducers have also been demonstrated feasible for damage detection in composite laminates (Lin and Yuan 2001, Su et al. 2003, Kim et al. 2005). Among all the researchers, Giurgiutiu and his group did much work on

PZT based wave propagation methods for SHM. They investigated the actuating abilities due to different types of piezo-actuators (Giurgiutiu et al. 2000); developed an embedded sensing system (Giurgiutiu et al. 2002); and designed a PZT based radar called Embedded-Ultrasonics Structural Radar (EUSR) with its corresponding software (Giurgiutiu and Bao 2004). In recent years, Xu and Giurgiutiu (Xu and Giurgiutiu 2007) and Santoni et al. (Santoni et al. 2007) used time reversal method to carry out Lamb wave inspection for SHM. Compared with traditional NDT techniques, this is a baseline free method, which is no need to record the baseline signature of the host structures. Hence, this is more convenient and greatly improved the efficiency. Due to the complex characteristics of Lamb waves, single mode tuning technique has been researched.

In addition to plates, SHM on shell structures such as large pipes are also of practical interest. The shell structure is very similar to that of a plate regarding the propagation of guided waves within the structures. A comprehensive procedure to locate and trace the cracks in a homogenous pipe based on time-of-flight analysis of Lamb waves generated and received by PZT transducers was presented by Tua et al. (Tua et al. 2004). The effect of large deformation on wave propagation in piezoelectric cylindrically laminated shells was systematically detected by Dong and Wang (Dong and Wang 2007).

The wave-based SHM technique has also been used for damage detection in other structures. By using a PZT active sensor, the spectral element method based on wave propagation approach was used for quantitative health monitoring of bolted joints (Ritdumrongkul et al. 2004). The research has successfully demonstrated the feasibility and reliability of wave-based SHM for damage detection. However, this method has limitations on application to real complex structures such as buildings, bridges, and other infrastructures. It is also difficult to be used in anisotropic material structures.

2.3.3.4 Piezoelectric material Generated Guided Waves

When the PZT transducers are bonded to the surface of the host structure and actuated by the electrical voltage, surface waves are generated. There are several commonly adopted methods for Lamb wave generation as discussed by Viktorov (Viktorov 1970). These methods are illustrated in Figure 2-10.

Figure 2-10 Methods of Lamb wave generation

In Figure 2-10(a), the PZT patch is directly bonded onto the specimen. When an electric field is applied to the electrode of the PZT, Lamb waves are generated. The generated Lamb wave would propagate in opposite directions. Based on the input frequency, all possible transportation modes will be actuated. This type of setup is simplest, but its disadvantage is that the generated Lamb waves are rather complicated, especially in the high-frequency range. This kind of transducer setup will be used in this research to simplify the instrument configuration. The complexity of generated Lamb due to high frequency will be lowered by careful selection of actuating signal. Also, mode separation technique will be used in this research to interpret the received signature.

Another Lamb wave excitation method is illustrated in Figure 2-10(b), where a piece of piezo-transducer (X-cut) is placed on a sheet of metal plate with corrugated, comb-shaped profile on one side. The slot width of the comb profile is λ_d , which determines the wavelength of the guided acoustics generated by this structure. The Lamb wavelength will be $\lambda = 2\lambda_d$. A significant advantage of this method is that the wavelength is selectively decided by the slot width, and thus it is easy to determine the resonant input frequency from the dispersion curves. The dispersion curve is the numerical solution of Lamb wave propagation along a plate or a cylindrical shell. With the help of dispersion curves, Lamb waves can be effectively activated in almost any elastic

material. This method has great potential for high-frequency Lamb wave implementation in long tubes such as oil pipes.

The third method called wedge technique is illustrated in Figure 2-10(c). A wedge block, usually made of plastic, is bonded to the surface of the test specimen. When a voltage is applied to the electrode of the PZT, the longitudinal wave is generated in the wedge block. The wedge block will then convert the longitudinal wave into Lamb wave in the specimen. A modified method is to use a Y-cut piezoelectric plate to generate transverse waves in the wedge block. Different Lamb mode signals may be activated by the adjustment of the wedge angle. As the most widely used method, wedge block method has been extensively explored for the study of ultrasonic testing. The advantage of this approach is the flexibility in the selective generation of Lamb waves at a given frequency. However, it is not as efficient as the comb structure discussed earlier, and its setup is not suitable for monitoring tubes due to the limited available space; hence it is not considered in this research.

2.3.3.5 Baseline free SHM method

Conceptually, there are two ways to use guided wave to carry out SHM (Lieske and Boller, 2012). The most commonly used way is to collect the signal from undamaged structure and compare it with the signal from ‘potentially’ damaged structure and using signal processing techniques to quantify the damage. The historical signal used as baseline signature and the quality of the baseline signature usually has great effect on the quality of SHM results. The second way is using other signal processing techniques, like time reversed method to process the signal and get the crack information. In such SHM method baseline signal is not necessary to get the conclusion. Qiu (Qiu.et.al ,2014) proposed a phase synthesis based time reversal focusing method to carry out SHM for aircraft composite structures. The system does not rely on the transfer function and the experiment results show the proposed method successfully monitored the presence of the crack on the composite structures. Sohn Hoon and his team (P Liu, H Sohn and B Park, 2015; P Liu et. al, 2014) focused on the detection of nonlinear behaviors changes in structure when damages occur. The nonlinear features of structure are more sensitive to the damage than their linear counterparts. They use laser based nonlinear wave modulation spectroscopy to generate and to measures the ultrasonic wave propagates in

the plate like media. Both baseline free methods successfully demonstrate their application in the SHM of plate like structures. However, for structures with more complicated wave modes like tubular structures, such baseline free method is hard to be carried out due to the complexity of wave propagate in cylindrical structures.

2.3.3.6 SHM of Fatigue Type of Crack

Fracture type of crack causes discontinuity in wave propagation media hence the disturbance of waves that propagate in the media can be detected and correlated with the change of damage. Unlike fracture type of crack there is fatigue type of crack that is generated due to the high stress concentration at connection point or at where geometry discontinuity occurs. Cho and Lissenden (2012) focused on using PZT to generate ultrasonic waves to detect crack initiated around the air craft fastener holes. The guided wave will have interaction with the fastener holes and if there is fatigue crack exists, the response can be detected by using pitch-catch method. Masserey and Formme (2013) used standard Rayleigh wedge transducer to generate ultrasonic wave and used a non-contact laser interferometer to detect the fatigue type of crack around the fastener holes. Chan et. al (2015) further developed the concept and used this method to detect the fatigue cracks in multi-layer model aerospace structures. However, unlike the fracture type of crack can be happened at any location on the host structure, the fatigue type of crack is usually happened at a given location where high stress concentration will occur. If the location of the fatigue type of crack is unknown, to perform SHM of such type of crack is very difficult.

2.3.3.7 PZT Sensing Region

To ensure high sensitivity to incipient structural damage, the elastic wave should be generated by PZT actuators at high frequencies, typically hundreds of kHz, so that the wavelength of the resulting stress waves is shorter than the typical size of the defects to be detected (Giurgiutiu and Rogers 1998). The high-frequency excitation provided by PZT actuators ensures the detection of minor changes in the monitored structure, but it also limits the sensing area to a region close to the PZT source. That is because the PZT transducer vibrating at high frequencies excites the ultrasonic-mode-vibration of the structure, which is essentially local in nature. Besides, damping is much more significant at high frequencies, which leads to wave localization.

Based on the wave propagation approach, Esteban et al. (Esteban et al. 1996) made effort to identify various factors that affect the PZT sensing region, including mass loading effect, discontinuities in cross section, multi-member junctions, bolts in structures and energy-absorbent inter-layers. At such high frequencies, exact quantifications of energy dissipation were proven tough and hence the sensing zone could not be exactly determined, though it was found that the sensing region of PZT transducers depends on the material of the host structure, its geometry, the frequency of excitation and the presence of structural discontinuities. Thus, no exact quantitative results were obtained.

Some experiments on several engineering structures including a composite reinforced concrete wall, a 1/4-scale steel bridge section, and a civil pipe joint were carried out by Park et al. (Park et al. 2000). As a result, they claimed that the sensing area of a single PZT transducer could vary anywhere from 0.4 m, on composite reinforced concrete structures, to 2 m on simple metal beams. Later, based on experimental data from a large number of case studies, Naidu (Naidu 2004) also reported the sensing region of a PZT transducer to be greater than 1 m in thin aluminium beams. However, all these conclusions were drawn from the experimental tests. Neither theoretical nor numerical model to identify the sensing region of PZT transducers has been built.

Due to significant energy dissipation in complex structures, a large number of PZT transducers may assist to enlarge the sensing region and enhance the validity (Boller 2002). The amount of PZT patches required in monitoring a structure will be significantly reduced if the PZT patches are wisely located. Bhalla and Soh (Bhalla and Kiong Soh 2003) suggested that PZT patches should be placed in a critical location such as those susceptible to shear crack and bending failure. These conclusions are of paramount significance in practical application. However, they are just based on the researchers and engineers' experience. Hu (Yuhang 2007) established the relationship between the input voltage of actuator and the output voltage of sensors for an aluminium beam. It is revealed that the ratio $V_{sensor}/V_{actuator}$ is not only related to the distance between the sensor and the actuators but also related to the material properties, the dimension of PZT patches and thickness of the host structures. However, the sensing range of MFC for a pipe like structures is still unknown.

This chapter has introduced the concept of smart materials and structures and presented a detailed review of PZT application in SHM with particular emphasis on the wave propagation method. Over the last two decades, several prominent research groups in the world have built a solid foundation for the application of PZT transducers in SHM in various areas, including aerospace, aeronautics, mechanical, civil engineering and even biomedical industries. As the technology continues to advance and refines itself, PZT transducers will find bright future in more applications.

Based on previous research work done by other researchers, we found that it was more complicated to do SHM inspection for cylindrical shells than for plate-like structures. Due to the brittleness of PZT transducer, it is tough to bond them on the pipe like structure especially when the curvature of the structure is significant. Such a pipe like structure inspection has to be carried out using other smart material like magnetic tape or ultrasonic transducers. The author prefers to use the easy bending character of MFC to conduct pipe SHM, which is the aim and objective of this research.

2.4 Structural Health Monitoring of Cylindrical Structures

2.4.1 Guided Wave Method for Cylindrical Structures SHM

Gazis (Gazis 1959a, Gazis 1959b) published the analytical foundations for the investigation of harmonic waves in an infinite hollow circular cylinder. The following research on waves propagate in tubular structures are based on his analysis. Harari (Harari 1977) studied the wave propagated in cylindrical shells with finite regions of structural discontinuity. The stiffener inside the tube plays a major role in scattering the impinging wave. With careful choosing and locating of the stiffeners, the unwanted sound transmission was impeded. Silk and Bainton (Silk and Bainton 1979) compared the wave propagate in a tube with Lamb wave in a flat plate. The results show that both the wave propagated in the tube and plate have similar characteristics; the simplest modes could be actuated easily. The interaction of both $L(0,1)$ and $L(0,2)$ wave modes with artificial cracks has been investigated. Ditri and Rose (Ditri and Rose 1992) studied the excitation of guided waves in cylindrical shells. With the help of mode expansion technique, based on Gazis's solution, they derived the general solution for this problem. Due to the differences of amplitudes, any guided wave modes could be

generated by prescribed surface traction. Zhang et al. (Zhang et al. 2001) pointed out that with wave propagation methods, vibration analysis of thin cylindrical shells turns out to be much more convenient, efficient and accurate. Using this approach, complex boundary conditions, and fluid-loaded cases could be investigated. Li and Rose (Li and Rose 2001) extended their earlier research on non-axisymmetric guided wave excitation and propagation in hollow cylinders. Using normal mode expansion (NME) technique, they applied the expression of guided wave excitation to both the axisymmetric and flexural longitudinal modes. Then guided waves were used to locate both the distance and circumferential location based on the utilization of the angular profile. Na et al. (Na et al. 2001) investigated the cylindrical guided waves response with the clay-steel pile interface. They found that some non-axisymmetric modes had excellent sensitivity to the interface defects and with low attenuation. Barshinger et al. (Barshinger et al. 2002) reviewed the history of guided waves inspection techniques for pipes. They argued each technique's benefits and shortcomings and pointed out the future direction in this research area. Sun et al. (Sun et al. 2005b) first presented the concept of guided wave mode categories. They emphasized on flexural-torsional wave mode theory, excitation parameters, and tuning process, followed by experiment verifications. Kannan et al. (Kannan et al. 2007) designed a cheap and low energy consuming experiment set for generating torsional waves. They used video magnetic tapes as actuators to successfully generate torsional wave mode $T(0,1)$ for crack detection. They also pointed out that low power level actuation has its limitation. When performing long range detection or on specimens in contact with oil or fluids, the actuating power level should be increased. Electromagnetic acoustic transducer (EMAT) is the other commonly used transducers to generate torsional wave in cylindrical structures. The EMAT transducers also can be separated as magnetostrictive EMAT and Lorentz force EMAT. Kim et al. (2005, 2013) uses circumferential phased magnetostrictive patch transducer (PMPT) array focus shear- horizontal waves in tubular structures. Based on 3-D FEM, Wang et al. (2015) investigate the efficiency to generate torsional wave in cylindrical structures. Compared with experiment verification, both the passing signal amplitude and the response from crack are increased by 29% compared with the results before optimization. However, those above mentioned techniques and methods are not suitable to be applied for

continuous SHM of cylindrical structures, either due to the complexity of the installation or the limits of their application. Hence, they are not suitable for this study.

2.4.2 Other Commonly Used Techniques for Cylindrical Structures Inspection and Detection

Other than guided wave SHM techniques, there are also many other commonly used inspection and monitoring techniques for cylindrical structures.

One of the most commonly used technique for pipeline integrity check is called in-line inspection technology or pig method. Smart Pig, a robotic device that integrated with sensors, data acquisition module that can travel inside pipeline is used for the damage detection whenever pipeline is damaged (Jim L Cordell, 1995). Many damage detection methods have been integrated with Smart Pig, like eddy current (Stankoff, 1978), magnetic flux leakage (Nestleroth J.B. and T.A. Bubenik, 1999), ultrasonic testing (Okamoto et. al, 1999), Electromagnetic Acoustic Transducer (EMAT) (Hirao, Masahiko, and Hirotsugu Ogi. 1999), etc to form different types of in-line inspection (INI) tools. One of the disadvantage of using “smart pig” is it requires the system to shut down in order to launch the pig. The damage cannot be well detected and monitored when it is still under developing using “pig” based method. All the techniques that integrated in the pig can also be used for local pipeline damage detection. The advantage of those local detection methods is they can set up the testing equipment outside the pipeline without shutdown the whole system. However, the inspection is usually time consuming, tedious, and cost in-effective.

Real-time monitoring or on-line monitoring is a trend in 21st century for continuous pipeline inspection. Real-time monitoring can monitor the target object from time to time. It can detect and report the damage right after the damage occurred. With real-time monitoring the damage can be identified/repared at it early stage which prevent huge lost to the client. British Gas first used the pipe wall as an acoustic signal carrier with a detector on the pipe wall to detect contact, product loss and encroachment (Leis, B. 2003). The sound is conducted in the gas stream; the sensors are placed on the outside wall of the pipe. However, the sensitivity is reduced when potentially damaging contact such as boring tools and drills happened, which do not have impact characteristics. The whole system is also very sensitive to the environmental noise level.

However, the on-line monitoring of the healthy condition of continuous pipeline is yet to be developed.

2.5 Summary

In this chapter, a literature review of some of the conventional NDT/E techniques used in traditional structures as well as cylindrical structures SHM is presented. Different transducers especially piezoelectric transducers and their characteristics are also presented.

3 AXIAL CRACK GROWTH MONITORING OF CYLINDRICAL STRUCTURE

3.1 Introduction

Pipelines and tubular structures are extensively used in many energy-related industries like nuclear industry and onshore/offshore oil and gas industries. Because of its hollow shape geometry character, tubular structures are widely used in the transportation of liquid, gas as well as chemical materials. Sometimes those tubular structures are exposed to the extreme condition like ultra-deep water, extremely cold/hot areas, or regions with high-level radiation. In such a case, once the tubular structures are damaged, the whole system needs to be shut down for repair work, and irreversible damage may bring to the surrounded eco-system. Those catastrophe disasters may lead to losing both economically and environmentally. To reduce the possibility of such critical damage happened on the tubular structure, the structural health monitoring of tubular structures is needed.

Normal damage detections for tubular structures are usually in a passive way. Once damage occurs, the system is shut down from operation to perform a damage detection. Generally, the detection method is involved with manpower, and it is very time-consuming. Those shortcomings of such detection methods lead to a huge loss on operation costs. If there is a self-powered closed-loop monitoring system that can achieve following functions: 1.) automatically trigger the actuation; 2.) send out the detection signals; 3.) receive the feedback signal; 4.) analyze the signal and interpret; 5.)

find the healthy condition of the host structure if there is any damage to the host structure; 6.) identify the damage type and position, etc, the repair work will be much more efficient and the cost can be significantly reduced. This chapter is trying to establish a simplified monitoring system that can achieve actuation and reception of the signal, the information contained in the signal is analyzed and interpreted into useful information about the healthy condition of tested pipes.

As mentioned in Chapter 2, compared with waves propagating in a plate, where only symmetric and antisymmetric modes exist, guided waves propagating in cylindrical structures are more complicated. Ghosh (Ghosh 1923) first gave the mathematical solution of axisymmetric longitudinal wave modes propagating in a hollow cylinder. Gazis (Gazis 1959a, Gazis 1959b) provided the analytical solution of all the wave modes propagating through an infinite long traction free hollow cylinder. There are two basic types of guided waves exist in cylindrical structures, the axisymmetric waves and non-axisymmetric waves. At each section that perpendicular to the axis of the pipe, all the particles' movement are symmetric to the tube axis. The axisymmetric waves also can be categorized into two types: $T(0,n)$ and $L(0,n)$. The non-axisymmetric waves, on the other hand, are waves that on any section that perpendicular to the pipe axis, the particles' movement are non-axisymmetric to the pipe axis. The non-axisymmetric waves are represented by $F(m,n)$. In the bracket, there are two numbers. The number m and n stand for the circumferential order and family order of each wave mode, respectively. For axisymmetric waves, since all the particles on the circumference are having the same movement, so the circumferential order is '0', only family number n exists. For non-axisymmetric wave modes, there are not only infinite numbers of wave families n , but also infinite wave modes with different circumferential order m . Ditri and Rose (Ditri and Rose 1992) found that the double infinite numbers of wave modes based on Gazis's work are all normal to each other, and they developed a normal mode expansion (NME) method to calculate the amplitude profile from the orthogonality of each wave modes. Their analytical works were verified by Li and Rose (Li and Rose 2001) in their numerical simulation of waves propagating in a partially loaded cylinder.

3.1.1 Axisymmetric and Non-axisymmetric Waves in tubular structures

The speeds of guided waves in cylindrical structures are determined not only by the material properties but also by the wall thickness of the host structure as well as the actuation frequency. The dispersion effects and the double infinite wave modes made the wave structures even more complicated. There are no analytical solutions for wave propagation in tubular structures. However, base on the existing equations by Gazis[1958] products of frequency and thickness can be obtained by the numerical method. If the thickness of the testing specimen and all other parameters are defined, the dispersion curve of phase velocity and group velocity of each wave mode against the frequency can be plotted.

Figure 3-1 and Figure 3-2 showed the phase speed and group speed dispersion curves for an aluminium pipe with 102 mm diameter and 3 mm wall thickness are obtained using Matlab code that attached in Appendix II.

Figure 3-1 Phase speed dispersion curve of aluminium pipe (Ø102mm×3mm WT)

Figure 3-2 Group speed dispersion curve of aluminium pipe (Ø102mm×3mm WT)

Figure 3-1 and Figure 3-2 listed the first 10 orders of flexural wave that corresponding to axisymmetric wave modes $L(0,1)$, $T(0,1)$ and $L(0,2)$. The red lines in both Figure 3-1 and Figure 3-2 represent the axisymmetric wave mode $T(0,1)$, which is a non-dispersion wave with fixed wave speed. The two blue lines denote the other two axisymmetric wave modes in the given frequency range: the first order longitudinal wave mode $L(0,1)$ and the second order longitudinal wave mode $L(0,2)$. The three types of axisymmetric wave are the most fundamental and common waves existing in cylindrical structures. The following number in the bracelet represents the family number of either torsional waves or longitudinal waves. There is no 2nd order torsional waves or 3rd order longitudinal waves showed in Figure 3-1 and Figure 3-2. This is because with given targeting frequency range (0-400 kHz) and testing material (aluminium pipe $\varnothing 102\text{mm} \times 3\text{mm WT}$), the cut-off frequency of those high order axisymmetric waves is greater than the upper limit of the given frequency range, which is 400 kHz, those wave modes cannot be activated. Those green color lines represent flexural wave modes $F(m,n)$. Those flexural wave modes are non-axisymmetric wave modes. At any given cross section that perpendicular to the axis of the pipe, non-axisymmetric wave modes do not share same displacement value on the circumference. Table 3-1 listed the group speed of axisymmetric wave modes and non-axisymmetric wave modes. Take $L(0,2)$ and $F(m,3)$ for example, at 100 kHz, $L(0,2)$'s group speed is 5412 m/s and $F(5,3)$'s group speed is 2438 m/s. The difference is almost 3000m/s. However, at 250 kHz, $L(0,2)$'s group speed is 5282 m/s and $F(5,3)$'s group speed is 4990 m/s. The difference is almost 292m/s. This phenomenon can be explained as: with the same wave family number n , flexural waves $F(m,n)$ ($m = 1 \dots n$) share similar wave speed as their corresponding axisymmetric wave mode when the frequency is going towards the higher end.

Table 3-1 lists the group speed of an aluminium pipe with 103mm diameter and 3mm wall thickness; the actuation frequency is 100 kHz, 150 kHz, and 250 kHz, respectively. The blank slots mean these wave modes cannot be activated since the actuation frequency is below cut-off frequency. The wave structures of each flexural wave modes can be calculated based on the governing equation (Rose 1999). Figure 3-3 shows the first three order of waves with the same family number but different circumferential order. When circumferential order m is small, the wave structures of flexural waves are quite similar to the wave structures of the corresponding axisymmetric wave modes. However, when the circumferential order goes up, wave structure and amplitude will become more and more complex, and it will increase the difficulty of interpretation of output signals. Since axisymmetric waves have the same value at anywhere on the circumference of the pipe, the axisymmetric waves usually compose the main structure of the output signal, and they are easier to be detected and identified.

Figure 3-3 Circumferential order of flexural waves ($m = 0 \sim 3$)

Table 3-1 Group speed of different wave modes at 100 kHz, 150 kHz, and 250 kHz actuation (m/s)

Wave Mode	100 kHz	150 kHz	250 kHz
L(0,1)	2570	2869	3109
F(1,1)	2567	2867	3108
F(2,1)	2559	2861	3105
F(3,1)	2545	2851	3100
F(4,1)	2526	2837	3092
F(5,1)	2500	2819	3082
F(6,1)	2468	2797	3070
F(7,1)	2429	2770	3056
F(8,1)	2381	2738	3040
F(9,1)	2326	2702	3021
F(10,1)	2261	2661	3000
T(0,1)	3149	3149	3149
F(1,2)	3131	3142	314
F(2,2)	3076	3120	3140
F(3,2)	2984	3084	3128
F(4,2)	2855	3033	3111
F(5,2)	2685	2966	3090
F(6,2)	2470	2883	3064
F(7,2)	2196	2783	3032
F(8,2)	1834	2664	2996
F(9,2)	1296	2524	2954
F(10,2)	-	2358	2907
L(0,2)	5412	5389	5282
F(1,3)	5324	5353	5271

Wave Mode	100 kHz	150 kHz	250 kHz
F(2,3)	5052	5246	5236
F(3,3)	4561	5061	5179
F(4,3)	3770	4789	5097
F(5,3)	2438	4416	4990
F(6,3)	-	3914	4855
F(7,3)	-	3226	4692
F(8,3)	-	-	4496
F(9,3)	-	-	4263
F(10,3)	-	-	3987

3.1.2 Conventional Damage Detection for Tubular Structures

Conventional damage detection is usually on a pulse-echo basis (Ditri and Rose 1992, Ditri and Rose 1993, Li and Rose 2001, Demma et al. 2003, Sun et al. 2003, Sun et al. 2005b, Kannan et al. 2007, Rose et al. 2009). The actuators are usually needed to cover the pipe circumference fully, or actuators need to be symmetrically distributed around the circumference of the pipe so as to generate the axisymmetric target wave mode. Otherwise, flexural wave modes will disturb the axisymmetric wave modes and will interfere the reading.

Another shortage of traditional damage detection method for tubular structures is the actuators are usually placed at one free end of host structure to eliminate the boundary reflections which will also disturb the reading. Such arrangement limited the application to be used on continuous pipelines, and almost impossible to be integrated into a system to achieve automatical damage detection.

3.1.3 Crack Types on Cylindrical Structures

Circumferential direction cracks are sensitive to most of the waves that propagate in cylindrical structures since the crack orientation is perpendicular to the wave propagation direction. As shown in Figure 3-3, no matter for which type of waves,

axisymmetric wave modes or non-axisymmetric wave modes, continuous circumference is one of the necessary boundary conditions to ensure the wave propagate smoothly. When such continuity is broken, disturbance at the discontinuity will happen and affect the output. The larger the discontinuity is, the greater disturbed output signal it can be expected. However, cracks in pressure vessels and pipelines are most likely to occur along its axial direction instead of the circumferential direction because of the higher hoop stress. Since the particle motion direction of longitudinal wave modes $L(0,n)$ is parallel to the wave propagation direction, the sensitivity of $L(0,n)$ is significantly reduced for the axial direction crack. Compared to the longitudinal wave, torsional wave's particle motions are perpendicular to the wave propagation direction. The propagation of torsional wave pack is disturbed and interrupted by the axial direction crack. The disturbances in torsional wave pack are picked up by the sensors. Crack size growth monitoring is thus achieved through the analysis of the changes of torsional wave pack due to cracks, which is the basis of this chapter.

3.2 Method of Study

The aim of this section is to develop an axial crack detection and monitoring scheme for the cylindrical structure using torsional wave. Unlike longitudinal wave, whose particle motion is parallel to the axial crack orientation, torsional wave's particle motion is perpendicular to the axial crack. So torsional wave is expected to be easily affected by axial direction crack on cylindrical structures.

Conventional damage detection method for tubular structures usually required the actuators to cover the circumference of the pipe entirely to generate guided waves, the advantage of such arrangement is with actuators covered most of the circumference, the axisymmetric wave is easily generated. However, such arrangement also has shortages. The conventional testing method usually requires the actuators and sensors be placed at one end of the pipe. The reason to do so is that such arrangement can avoid the reflection from one free end, so the echo signal from crack and echo signal from another open end will be identified based on pulse-echo method. The position of crack can also be located. However, such arrangement also required the testing structure must have an open end, and this is not achievable for monitoring of continuous cylindrical structures. Furthermore, such arrangement usually has relatively complicated setup to drive the

probes to generate guided waves and retrieve data from the testing specimen. Such experiment system is not easy to be moved or relocated due to the complicated setup which also limited its industrial application. To overcome the shortages of conventional damage detection method for cylindrical structures, MFC is proposed to be used as actuators and sensors. The highly flexible character of MFC made it easy to be curved to suit the surface of the cylindrical pipe. The high actuation ability of MFC is used to generate and collect surface waves in cylindrical structure. Unlike the conventional actuation method, MFC actuator will not need to cover the whole circumference of the pipe to generate/collect waves, the primary interest of the method used in this chapter is to extract the useful information from the acquired signal which contained both axisymmetric wave modes and non-axisymmetric wave mode. Additionally to the benefits mentioned earlier, in the method used in this chapter the actuator and sensor are placed at both sides of the crack. This setup is used to monitor the occurrence of the longitudinal crack and the growth of the longitudinal crack. The crack position detection is not included in this chapter. The experiment setup used in this chapter can be further developed and expanded for more applications like crack position identification and crack orientation identification which will be discussed in Chapter 4 and Chapter 5, respectively.

3.3 Numerical Simulation

3.3.1 Numerical Model of Specimen

To investigate the feasibility of axial crack detection and monitoring using torsional wave, the FE simulation of guided wave propagation in a 1.2m long aluminium pipe with 102mm diameter and 3mm wall thickness is performed using ANSYS, an FE analysis software.

To simulate guided wave propagated in cylindrical structures, the numerical model must be set up in ANSYS. ANSYS is a very powerful multi-physics analytical software. It can solve both time domain and frequency domain problem.

The reason of using MFC in this experiment setup is when MFC is being actuated, due to the bond between MFC and the host structure, the deformation of MFC will be transferred to the surface of host structure to activate surface wave on host structure.

When the surface wave is propagated to the sensor, the displacement of host structure also can be collected via the change of output signal of sensors. Assume that the displacement is linearly proportional to the output signal of MFC, the non-dimensional displacement of a surface particle on host structure shall have the same output as the non-dimensional output of MFC. To simplify the simulation, the coupling of piezoelectric effect of MFC is not included in the simulation. Investigating the wave propagation problem in cylindrical structures is equal to find out the particle motion at a given point (sensor or actuator position).

The most accurate method to simulate particle displacement in FEM is to use solid element. The benefit of using solid element are:

- Through thickness property is well addressed;
- Results are more accurate compared with using shell element.

However, solid element also has its drawback:

Using solid element for wave propagation problem is very time-consuming. To successfully simulate the through thickness character, at least three layers of solid elements are required. For instance, taking the 103 mm diameter X 3mm thickness aluminium pipe as an example, the through thickness direction requires at least three layers of elements. This requirement leads to the smallest element dimension is 1mm. To ensure the simulation accuracy, the recommended ratio between the longest edge of the element to the shortest edge of the element shall be less than 2. Consider the circumference length and the longitudinal length, the total element number in this numerical model is huge. Consider using the most commonly used solid element SOLID185, a 20-node element, to simulate the time-domain response of wave propagation in cylindrical structures is almost impossible.

Compared with a solid element, the most commonly used shell element is SHELL63, an 8-node shell element. Since there is only one layer of the element, the through thickness properties are predictable and easy to be simulated. Due to the reduction of both total element number and node number in each element, the time for a simulation using shell element is greatly boosted compared with the time for a simulation using solid element.

Table 3-2 compared the difference between typical solid element and shell element. Because each node has 6 degrees of freedom and it also contains more multi-physical

parameters, the total number of the equation to be solved in the solid element is much greater than the total number of the equation to be solved in shell element.

Table 3-2 Comparison between typical shell element and solid element in ANSYS

Element Type	Shell 63	Solid 186
No. of Node per element	8	20
No. of layers along thickness	1	3
No. of element along circumference	120	160
No. of element along longitudinal	480	1200
Total number of node	57.6×10^3	11.52×10^6
Simulated time duration	300ms	300ms
Simulation time	Around 5 minutes	More than 24 hours

The penetrated axial direction crack at the centre of the pipe is modelled using nodal release method, as shown in Figure 3-4. Node release method is a commonly used FE method in crack propagation simulation. In an intact model, all nodes are connected to the adjacent nodes. All the values of the parameters of this node are calculated based on the nodes surrounding it. This node's values will also be used to calculate the value of its adjacent nodes. If this node is broke into two nodes at the same position but they are not connected to each other, the values propagated to one node but cannot pass to the other node, discontinuity occurred. Such discontinuity is considered to be a 'crack.' If more nodes on the line are broke into pairs, the 'crack' is considered growing. In ANSYS model, two half shells are created in working space. The two half shells share the same edges along the longitudinal direction. After meshing the shells, all nodes on the shared edges can be grouped into pairs. Merge the nodes that share the same coordinate in working space will create an undamaged cylinder. As shown in Figure 3-4, at the centre of one shared edge of the two half shells, 7 group of nodes are highlighted. Those nodes are selected to simulate the longitudinal direction crack propagation. When simulating the undamaged case, all the seven sets of nodes are merged as all the pairs of nodes on the shared edges. Once the crack is generated, the DOF of node set 1 is

unmerged. As the crack is gradually growing, more sets of nodes are unmerged. The merged pairs of nodes are released to prevent physical measurements transfer between elements.

The fixed boundary condition is applied at one end of the pipe to prevent rigid body movement.

Figure 3-4 FE model of aluminium pipe with crack propagation (using nodal release method)

3.3.2 Actuators and Sensors Modelling

Unlike in the pulse-echo method, the crack existence is identified from additional wave pack reflected from the crack. In the proposed method, the transducers are placed at both sides of the crack. The presence of the crack is identified based on the analysis of the change of the first pass-by wave packs.

The wave propagation paths and transducer distribution are depicted in Figure 3-5. As shown in Figure 3-5, the actuator to sensor distance of 550 mm is used. All wave packs will start from the actuator and propagate along the pipe; the wave pack will pass-by the crack and finally reached the sensor position. Based on the group dispersion speed differences(taking 100 kHz actuation as an example), the predicted arrival time of each wave pack is listed in Table 3-3, only the first three circumferential orders of flexural waves modes are listed.

Table 3-3 Predicted wave pack travelling time-based on group speed dispersion curve (only the first three circumferential order are considered $n=0\sim3$)

Wave Mode	Path 1 (μs)	Path 2 (μs)	Path 3 (μs)
L(0,1)	214.0	470.8	463.0
F(1,1)	214.3	471.4	463.6
F(2,1)	214.9	472.8	465.0
F(3,1)	216.1	475.4	467.6
T(0,1)	174.7	384.2	377.9
F(1,2)	175.7	386.5	380.1
F(2,2)	178.8	393.4	386.9
F(3,2)	184.3	405.5	398.8
L(0,2)	101.6	223.6	219.9
F(1,3)	103.3	227.3	233.5
F(2,3)	108.9	239.5	235.6
F(3,3)	120.6	265.3	260.9

Figure 3-5 (a) Wave propagation paths; (b) Simplification of full actuation; (c) Simplification of partial actuation; (d) actual MFC transducers on pipe

The model of transducers is simplified in the numerical model. The piezoelectric characteristic of MFC is not considered in the simulation. In the proposed setup, MFC is 45° oriented against the pipe central axis, as both actuator and sensor. This arrangement is because the deformation of MFC along its long axis can be projected into two directions, pipe axial direction and pipe circumferential direction. The axial direction actuation will generate longitudinal wave packs; the circumferential direction actuation will generate torsional wave packs.

Two types of simulation are considered in the simulation, full actuation and partial actuation. Full actuation condition considered the actuator covered the entire circumference of tubular structure, axial and circumferential force conditions are applied to all the nodes on the circumference at actuator position as shown in Figure 3-5(b), where only the axisymmetric wave modes $T(0,n)$ and $L(0,n)$ are activated. Such arrangement is the ideal case where only axisymmetric wave modes are activated which is not feasible to achieve when using MFC as actuators. According to the proposed experimental setup, where MFC can only cover partial of the circumference of the pipe, the axial and circumferential force boundary conditions are also covered the only partial of the circumference, as showed in Figure 3-5 (c). In actual condition, MFC covers an area which has both longitudinal dimension and circumferential dimension. Due to simplification, the numerical simulation of partial actuation condition only consider the nodes at actuator position on the circumference are being activated. Since partial actuation condition only activates part of the circumference, the flexural wave modes are activated.

3.3.3 Actuation Signal

5-cycles Hanning windowed sinusoidal wave tone burst was used as the actuation signal. The Hanning window function is expressed in Eq. 3-1. If the 5-cycles sinusoidal tone burst has a frequency f , then the T_H equals to the number of counts times the period of this burst.

$$H(t) = \frac{1}{2} \left[1 - \cos \left(\frac{2\pi t}{T_H} \right) \right] \quad \text{Eq. 3-1}$$

The 5-cycles Hanning windowed sine wave is compared with normal 5-cycles sine wave burst in Figure 3-6, both signals are being actuated at 100 kHz frequency.

Figure 3-6 Comparison of actuation signals: Hanning windowed sine wave, and original sine wave burst at 100 kHz actuation frequency

Compared with normal 5-cycles sine wave burst, the Hanning windowed sine wave burst have a 'centred' middle peak. This feature of signal make the post-processing of output signal easier: the targeting wave pack is easy to be located when it has a centred peak.

Another reason of using Hanning window to filter the original sine wave tone burst is to get a relatively purified actuation signal with concentrated frequency bandwidth. Figure 3-7 compares the Fast Fourier Transform (FFT) of the two actuation signals: Hanning windowed 5-cycles sine wave and normal 5-cycles sine wave tone burst. Fourier analysis converts the signal from time domain to frequency domain to demonstrate its frequency character. From Figure 3-7, it can be found that when being activated at 100 kHz, the normal 5-cycles sine wave tone burst has more frequency components in the frequency domain. Since guided waves have dispersion character, the wave packs will become dispersed during propagation. More frequency components will generate more waves at different propagation speed, which will greatly interfere the main wave pack and cause trouble to the interpretation of output signal. After filtering by Hanning window, the sine wave burst has concentrated frequency bandwidth in the frequency domain which reduced the complexity of dispersion behaviour and extrusive centre peak in the time domain.

Figure 3-7 Fast Fourier Transform of Hanning windowed sine wave and normal sine wave tone burst

3.3.4 Actuation Frequency

100 kHz frequency has been chosen as actuation frequency. This specific actuation frequency 100 kHz is chosen based on several facts.

➤ Towards the high-frequency end:

(1) The element size.

To ensure the element can capture the accurate response of specimen, the element size is suggested to be around $1/10^{\text{th}}$ of the wavelength. The higher the actuation frequency is used, the narrower the wave pack will be and the less interference will happen between wave packs. However, on the other hand, the higher the actuation frequency it is, the shorter the wavelength will be, and the denser mesh will be required to secure the simulation accuracy which will double reduce the efficiency of the simulation.

(2) The experiment equipment limitation

Even though regardless of simulation time, a numerical simulation can achieve higher actuation frequency as possible. However, in practise, the actuation frequency also depends on the limit of experiment equipment. The arbitrary function generator usually has a bandwidth limitation. The signal amplifier which is connected to the function generator also has bandwidth limitation. Most of the time, when the actuation signal is beyond the upper limit of the equipment, the equipment capacity is greatly dropped. The amplified signal quality will greatly drop and the noise-to-signal ratio will increase. Those facts will lead to the inaccuracy of the interpretation of the experimental data. Equipment limitation usually limits the actuation frequency within 200 kHz.

➤ Towards the low frequency end:

A lower frequency will take more time to generate the signal. Take five cycles Hanning windowed sine wave at 60 kHz for example; it will take $83 \mu\text{s}$ (10^{-6} second) to complete the generation of the signal. Assume the Actuator-to-Sensor distance is 0.55m; at 60kHz, as per the group speed dispersion curve, both torsional wave speed and longitudinal wave speed are quite similar to the corresponding wave speed at 100 kHz actuation frequency. Assume that the wave speeds differences can be neglected, then all wave packs will arrive at the

same position as compared with 100 kHz actuation signal used case. Figure 3-8 shows the wave shape of sensor output at 100 kHz. In Figure 3-8, the torsional wave pack is separated with longitudinal wave pack. If the actuation signal is changing from 100 kHz actuation frequency to 60 kHz actuation frequency, each wave pack will increase 60% of its original width. Then the torsional wave pack will be overlapped with longitudinal wave pack. Hence for this particular testing specimen, 100 kHz auction frequency is better than 60 kHz auction frequency. However, 60 kHz actuation frequency is also suitable for the experiment if the testing specimen have a longer actuator to sensor distance to separate the torsional wave pack and longitudinal wave pack.

Take all the three aspects into consideration, 100 kHz actuation frequency is chosen to make sure all points are well addressed. Unless noted otherwise, all actuation frequency used in this dissertation is fixed at 100 kHz.

To be noted, the selection of actuation frequency relies on trial and error. There is no fixed frequency for the testing, as long as the actuator successfully activates the target wave modes and the sensor is acquiring useful information that can be used for crack identification, the actuation signal frequency is suitable to be employed.

3.3.5 Full Actuation Simulation of Guided-Wave Propagating in Tubular Structure

Purely full actuation of guided waves in the cylindrical structure is only achievable in numerical simulation. When actuators have fully covered the circumference of the tubular and worked simultaneously, only the axisymmetric wave modes are activated.

Extract the output of the node at the sensor location, the simulation results of full actuation case of the undamaged specimen and damaged specimen (with 40mm axial oriented crack) are plotted in Figure 3-8. Output results amplitude are normalized against the magnitude of the actuation signal to give a better demonstration. Assume the actuation signal have unit amplitude, the output signal amplitude is non-dimensional after divided by the maximum actuation signal. Below points can be found in Figure 3-8:

- Outputs from both undamaged case and damaged case have three significant wave packs.
- There is no significant time of flight (TOF) difference between the two outputs.

- Compared with the undamaged case, the first wave pack of damaged case has amplitude changed barely; the second wave pack of damaged case has obvious amplitude change compared with the amplitude change of the first wave pack. The magnitude of the third wave pack also doesn't change much.
- The first and third wave packs from damaged case matched the wave packs from undamaged case quite well. The second wave pack from damaged case appears 'wider' compared with wave pack from the undamaged case. The difference comes from the crack.

The wave speeds of first two wave packs are calculated from the TOF of the wave pack (center-to-center) and the actuator-to-sensor distance. Compared with the wave speed listed in Table 3-1, the calculated wave pack speeds of the first and second wave packs are well matched with group speeds of symmetric wave modes $L(0,2)$ and $T(0,1)$, respectively. The maximum deviation from the theoretical result is around 3%. The calculation results are listed in Table 3-4.

From Figure 3-8, it can be concluded that the axially oriented crack has a greater impact on passed-by torsional wave mode, but it has barely effect on longitudinal wave mode.

Table 3-4 Simulation results wave packs group speed calculation

Wave pack	C-to-C TOF(mS)	A-to-S Distance (mm)	Calculated Group Speed (m/s)	Theoretical Group Speed (m/s)	Difference
1 st	104	550	5288.5	5412	2.29%
2 nd	180	550	3055.6	3149	2.97%

Figure 3-8 Comparison of full actuation outputs from undamaged case and damaged case

Even though the existence of the axially oriented crack changes the torsional wave pack's amplitude and overall wave shape, the changes of the signal are tiny, and they are hard to trace in a quantitative way. Numerical simulations of the damaged case start from 2.5mm crack (Release one node) until crack size reached 42.5mm (release 17 nodes). The pitch-catch method is one of the commonly used ways to trace the change of signal amplitude. However, it cannot produce a recognizable pattern between the peak value changes of each wave pack and the growing crack size. In Figure 3-8, the two 'expected' maximum changes of torsional wave pack amplitude are marked as point A and point B, which are the maximum and minimum amplitude of the targeting wave pack. Figure 3-9 plots the absolute values of both point A and point B. Each data point represents either point A or Point B amplitude from corresponding simulation results. As it can be found in Figure 3-9, there is no clear pattern can be found when crack size is growing larger and larger. No firm conclusion can be drawn from the result of pitch-catch method. Even though the results from point B demonstrated a 'trend' of growing pattern along with the growing crack, the absolute normalized amplitude change is less than 10^{-6} of the absolute peak amplitude. This value of change is too weak to be used as an indicator of crack changes. Other more efficient and easy to recognized method shall be used to reflect the crack size growth.

Figure 3-9 Absolute amplitude change of Point A and Point B from numerical simulation of undamaged and damaged cases

3.3.5.1 Root Mean Square Deviation Crack Index

Root mean square deviation (RMSD), which is defined as

$$RMSD = \sqrt{\frac{\sum_{i=1}^n (x_i - x_0)^2}{\sum_{i=1}^n x_0^2}} \times 100 \quad \text{Eq. 3-2}$$

is a commonly used method to evaluate the difference between a new set signal and the original signal. Assume that there is axially oriented crack exists on the tubular structure. Due to wave mode particle motion direction, the crack is sensitive to torsional wave pack and it is not sensitive to longitudinal wave pack. It could be expected that the torsional wave pack will be more distorted if the wave pack passed the crack. Meanwhile, longitudinal wave pack will not be affected as much as torsional wave pack. If the actuation wave pack length is known, based on the wave mode group speed dispersion curve, the targeted longitudinal wave pack, and torsional wave pack can be identified. RMSD method is used to measure how much difference between the signals collected from cracked specimen and the original signals. As the crack growth, the torsional wave pack will be distorted more and more, and the change of wave pack will be reflected on the RMSD value change, and the longitudinal wave will remain the original shape where the RMSD value changes are quite small.

A modified equation based on Eq. 3-2 is used here to evaluate the total change of the targeting wave pack as

$$RMSD_p^i(t) = \sqrt{\frac{\sum_{t_0}^{t_0+t_a} [x_i(t) - x_0(t)]^2}{\sum_{t_0}^{t_0+t_a} x_0^2(t)}} \times 100 \quad \text{Eq.3-3}$$

where t_0 is the starting point of the time interval and t_a is the actuation signal length. From t_0 to t_a defines the time window to calculate the deviation. Take 100 kHz actuation for example; the actuation signal is a 5-cycles Hanning windowed sine wave tone burst. The duration of this actuation signal is 50ms. So a 50ms long time window will be used to select targeting signal that is used to calculate the deviation. Assume there is no dispersion happened after the wave pack travelled for a certain while, the wave pack shape is unchanged. However, if there are discontinuous on the wave propagation path, the signal will be disturbed. Both crack tips will be functioned as a new wave source. The wave interferes at crack tips. The original wave pack, as well as the two wave packs from both end of crack tips, will travel together, and the output signal for the crack case

will be different from the undamaged case. The $RMSD_p^i(t)$ value calculates the disturbance on wave pack p that starts at t_0 with duration of t_a . The superscript i represents the data $x_i(t)$ comes from the i th experiment(with $i \times 2.5$ mm crack size). The value $RMSD_p^i(t)$ is used to quantify the disturbance caused by the axial oriented crack and to establish the relationship between crack size and the output signals. Figure 3-10 demonstrated the 50ms long time window to calculate the RMSD value of 2nd order longitudinal wave pack L(0,2) and the RMSD value of 1st order torsional wave pack T(0,1) in blue and red dash line windows, respectively. In Figure 3-10, only damaged case with 40mm axial oriented crack is compared with undamaged case. Take all the RMSD value calculated from simulation case 1 to case 17 and plot them against the crack size growth in Figure 3-11.

Figure 3-10 Time window for second order longitudinal wave pack L(0,2) and first order torsional wave pack T(0,1)

Figure 3-11 RMSD crack index from full actuation simulation longitudinal wave pack and torsional wave pack

As shown in Figure 3-11, the RMSD values from both second order longitudinal wave pack and first order torsional wave pack demonstrate a linear growth relationship against the axial direction crack growth with R^2 almost equal to 1. R^2 is an indicator of the quality of linear regression. The closer between R^2 and 1, the better the linear regression quality it is, which means the data are better fitted on a line.

Since in longitudinal wave mode, all the particles vibrate along the axis of tubular, the axial direction crack will not have a significant effect on the particle motions of longitudinal wave packs. Compared with longitudinal wave packs, in torsional wave packs, the particle vibrate in the circumferential direction. The axially oriented crack caused discontinuity on the propagation paths of torsional wave pack. Hence, even though both wave packs showed a linear relationship between the RMSD value and the growing crack size, the RMSD values calculated from torsional wave pack demonstrates a steeper slope compared with the RMSD value calculated from longitudinal wave pack. This result indicates that the torsional wave pack is more sensitive than longitudinal wave pack on axially oriented crack, which is exactly as we have mentioned in the previous section.

3.3.6 Partial Actuation Simulation

Full simulation condition can only be achieved in numerical simulation. In actual application, due to the limitation of the actuator, only part of the tubular circumference can be driven. Partial actuation will lead to the generation of flexural wave modes $F(m,n)$, which will have dispersion effect during wave propagation. The wave dispersion effect will interfere the interpretation of output signal, which is not good for the RMSD crack index.

To compare the simulation results with experiment results, partial actuation cases are also studied in numerical simulation.

In partial actuation numerical simulation, only part of the nodes on the circumference at actuator positions have been activated. Consider the MFC functional area and it is 45 degree oriented on the pipe, around 40 degrees of the circumference is activated as shown in Figure 3-5. Since only partial of the circumference is activated, the flexural wave modes are activated together with the axisymmetric wave modes, as illustrated in Figure 3-12.

Figure 3-12 Comparison of partial actuation simulation results between damaged and undamaged cases

Figure 3-12 compared the output from partial actuation undamaged case and damaged case. In the damaged case simulation, the 40mm axial oriented crack case is used. The reason to compare the 40mm cracked case with the undamaged case is to demonstrate the maximum output signal difference between undamaged and damaged cases. Similar to the finding from full actuation simulation output, even though the damaged case has a very long axial direction crack already, from Figure 3-12 it is also impossible to get the signal amplitude change via pitch-catch method. Take the torsional wave pack for instance; the five cycles tone burst have several peak amplitudes and some of the peak value increases; some of them decreases; the rests are hard to tell whether they are increased or decreased from the undamaged signal base.

The more the actuator covers the circumference of the pipe, the more dominant the axisymmetric wave modes will be in the whole wave pack (Ditri and Rose 1992, Li and Rose 2001). Figure 3-13 compares output signals from both full actuation and partial actuation damaged case with 40mm crack. The induced flexural wave modes not only changed the amplitude of wave packs but also changed the overall wave pack shape. In full actuation case, two clearly separated wave packs belong to longitudinal wave mode $L(0, 2)$ and torsional wave mode $T(0,1)$, respectively. When flexural wave modes are activated in partial actuation case, more wave packs are filled in between longitudinal wave pack and torsional wave pack. These additional wave packs are flexural wave packs.

To better demonstrate the overall wave shape change, Figure 3-14 compares the envelope of the two output signals from full actuation and partial actuation. Compared both output signals from full actuation and partial actuation case, below findings are highlighted.

- Compared with full actuation, each wave pack demonstrated dispersion effect. The overall wave shape of partial actuation case is ‘wider’ compared with full actuation case.
- Flexural wave packs travel at similar but slower group speed compared with their corresponding axisymmetric wave packs. The existence of flexural wave packs will interfere the effect of axially oriented crack on torsional waves. In partial actuation case, between longitudinal wave pack $L(0,2)$ and torsional wave pack $T(0,1)$, there is one new wave pack from flexural wave modes $F(m,n)$.

Figure 3-13 Comparison of simulation results of full actuation and partial actuation of 40mm cracked case

Figure 3-14 Comparison of envelope of simulation results of full actuation and partial actuation of 40mm cracked case

- Flexural wave modes are also affected by the axially oriented crack, but due to the particle movement direction of flexural wave mode is neither parallel to the circumferential direction nor parallel to the longitudinal direction, the sensitivity of flexural wave modes on axially oriented crack is expected to be in between the sensitivity of torsional wave and sensitivity of longitudinal wave on the same type of crack.

With the presences of flexural wave mode $F(m,n)$, the output signal from partial actuation is more complicated compared with full actuation output.

Taking all the partial actuation results into Eq. 3-3, an RMSD crack index for partial actuation simulation results are plotted in Figure 3-15. Similar to Figure 3-11, Figure 3-15 shows the RMSD crack index calculated from the partial actuation simulation result of two wave packs, torsional and longitudinal wave pack. Unlike full actuation simulation results, in the RMSD crack index calculation, there is not only axisymmetric wave modes but also non-axisymmetric wave modes. However, still, with the presence of flexural wave modes in the computation of RMSD crack index, the effect of axial direction crack is still more severe on torsional wave pack than that on longitudinal wave pack. In partial actuation simulation, the torsional wave pack contains the components of axisymmetric wave modes $T(0,1)$ as well as its corresponding non-axisymmetric flexural wave modes $F(m,2)$; the first longitudinal wave pack contains the component of axisymmetric wave modes $L(0,2)$ and its corresponding non-axisymmetric flexural wave modes $F(m,3)$. The presence of flexural wave modes lowered down the R^2 value of the linear regression, which means the flexural wave modes reduced the sensitivity of using torsional wave pack to monitor the axially oriented crack growth.

Figure 3-15 RMSD crack index from partial actuation simulation longitudinal wave pack and torsional wave pack

Figure 3-16 compares the RMSD crack index calculated from both full and partial actuation. In the case of partial actuation, the ‘torsional’ wave pack also includes the flexural wave modes $F(m,2)$. Since the wave structures of flexural waves are only partially affected by the axially oriented crack, when RMSD crack growth index is calculated, the present of flexural waves $F(m,2)$ reduce the sensitivity of crack growth index as compared with the case of full actuation where only torsional wave, $T(0,1)$, is included. Similarly, the partial actuation caused “longitudinal” wave pack also includes the flexural wave modes $F(m,3)$ with is more sensitive to the axial crack than the $L(0,2)$. Therefore, the calculated RMSD crack growth index is better than for the case of full actuation where only $L(0,2)$ is included.

The foundation of this study is to use MFC generate axisymmetric wave modes (torsional wave and longitudinal wave modes) in tubular structures to monitor the structural healthy condition. In this section, partial actuation case is studied. Figure 3-13, Figure 3-14 and Figure3-16 compare the full actuation results with the partial actuation results. The comparison results show that when partial actuation method is used, more flexural wave modes are activated. As explained in the previous section, when tubular structure is fully activated, only axisymmetric wave modes can be activated. In partial activation modes, flexural wave modes are also activated. In Figure 3-16, both crack indexes generated using full actuation results and partial actuation results are compared. Compared with full actuation torsional wave result and partial actuation torsional wave result, the slope of the two curves is slightly different, where the data from full actuation case is more sensitive to the crack growth than the data from partial actuation case. This result reveals that when partial actuation case is used, the flexural wave modes $F(m,n)$ activated will interference with their corresponding axisymmetric wave modes $T(0,n)$ and $L(0,n)$, hence reduced the sensitivity of the crack index.

Since the aim of this study is to use the axisymmetric for crack identification, monitoring, and prediction, axisymmetric wave modes are the wave modes that are functional. Hence to better represent the effectiveness of the proposed method, only full actuation simulation results are used in following Chapters. However, to better compare the experimental data and simulation results, more digital signal processing techniques are required to extract the axisymmetric wave modes from the experimental data which will be included in future studies.

Figure 3-16 Comparison of RMSD crack index between full actuation and partial actuation simulation results

3.4 Experiment Verification

3.4.1 Experimental Setup

The experimental test is carried out on an AI 6061 T6 aluminium alloy tube with material properties and dimensions as listed in Table 3-5.

Table 3-5 Material properties, dimensions of specimen and MFC

Material	Aluminum Alloy 6061 T6
Density	2700 kg/m ³
Young's modulus	68.9 GPa
Length	1200 mm
Inner Diameter	48 mm
Outer Diameter	51 mm
Wall thickness	3 mm
MFC position 1(Actuator)	320mm from left end
MFC position 2 (Sensor)	870mm from left end
MFC type	M-4010-P1
MFC functional area	40mm by 10mm

The aluminium pipe is freely placed on the table and supported by soft foam so as to absorb any unnecessary vibration. There is no need to fix the pipe to prevent rigid body movement. That is because that the compared with the overall movement of pipe, the guided wave are particle motion that the two kinds of movements are not in the same or similar level. These two types of movement will not interfere each other.

In the numerical simulation, hairline type of full penetrated crack is simulated. However, in the experimental study due to the limitation of processing tools, penetrated crack is pre-initiated at the centre of the pipe with an initial length of 15mm along the axial direction and width 5mm along the circumferential direction. That is because a 5mm diameter cutter is used to generate and enlarge the axially oriented crack by using a milling machine. Unlike crack tips in numerical simulation, which is a single node, the crack tips in the experiment are rounded to prevent stress concentration as well as wave scattering. The axial dimension of the crack is started at 15mm, and it increases 2.5mm each time until it reaches 40mm. Since crack is pre-initiated, the first set of data from 15mm cracked specimen is collected as baseline signature. All future signals are

compared with the baseline signature, and they are used to generate the RMSD crack index.

The conventional PZT transducers have the weakness of being too brittle to be attached to the nonplanar surface. Hence, flexible MFC transducer is used as both actuator and sensor in this study. Compared with a typical through-plane poled PZT actuator, the maximum free strain performance of MFC is considerably larger and is also very durable under various electrical and mechanical cyclic loading conditions (W. Wilkie et al. 2002). Because of its manufacturing process and its structure, MFC shows different electromechanical characteristic along its long and short edges. For simplicity, only the dominant strain along its long edge is used in this experiment. MFC transducers M-4010-P1 with functional area 40 mm by 10 mm are bonded on the surface of the pipe, 45° oriented against the pipe central axis, as both actuator and sensor as shown in Figure 3-5(d) and Figure 3-17.

The experimental setup consists of a Tabor Electric ww5601 arbitrary function generator, a TREK PZD350A high power amplifier and a National Instruments integrated data acquisition (DAQ) system as shown in Figure 3-17. The 1-volt peak-to-peak actuation signal from function generator is 100 times amplified before it is applied to the MFC actuator. The MFC sensor is directly connected to the DAQ device to receive the output signal. One additional cable from the function generator is connected to the DAQ device to synchronize the actuation and DAQ process.

There is background white noise from alternating current (AC) which will contribute to the deviation of the output signal. To eliminate such background white noise, 32-times cycle averaging is used to reduce the influence of random noise. This function allowed the DAQ device to collect 32 times data and stored temporarily in memory. Then the average of the 32 times signal will be written to the output data file. The function generator is setup to repeat the actuation signal every second. The 1-second interval between two actuations is to make sure the guided waves generated from the previous actuation is completely gone and newly generated guided wave will not be interfered by last time generated waves.

As mentioned in Section 3.3.4, the actuation frequency cannot be neither too high nor too low. When driven by signals with actuation frequency above 250 kHz, the actuation ability of MFC is greatly depressed and the signal to noise ratio (SNR) is too low. On

the other hand, under actuation frequency lower than 50 kHz, the wave packs are overlapped with each other which increase the difficulty in extracting target wave pack from the overall wave structure. Thus, only the actuation frequency of between 50 kHz to 250 kHz is used in this research. To demonstrate the experiment results and compared them with numerical simulation results, 100 kHz actuation frequency is selected.

Figure 3-17 Experiment equipment setup

3.4.2 Signal Processing

Due to the limitation of DAQ device, the background AC noise cannot be fully removed by just using the signal averaging technique. The original experimental results are further processed before they can be utilized for calculating the RMSD crack growth index.

The background AC noise has a fixed frequency of 50 Hz. So one full cycle of background AC takes 0.02s. If guided wave is being activated at 1 kHz actuation frequency, 5-cycle Hanning windowed sine wave tone burst takes 0.005S which is 1/4th of the AC period. Figure 3-18 demonstrates how the AC background noise affects the output signal. To remove the AC background noise, the exactly AC noise equation must be found. It is known that the AC has fixed the period of $T=0.02s$, and the amplitude of AC keep oscillating about the zero axes. Assume that the AC have below expression

$$f(t) = a * \sin \left[\frac{2\pi(t-b)}{T} \right] + c \quad \text{Eq. 3-4}$$

with $T = 0.02$ and $c = 0$, the sinusoidal curve $f(t)$ for the background AC noise in the experimental result is fitted by MATLAB curve fitting toolbox. Once a and b are acquired, the AC background noise can be totally removed from the experiment results.

Figure 3-20 demonstrated the original experimental result and modified experimental result using the method mentioned above as well as the fitted sine curve.

Figure 3-18 Effect of AC background noise

Figure 3-19 Remove of AC background noise from experimental result

3.4.3 Experimental Results

Since the aluminium pipe is pre-initiated with a 15mm long axial oriented crack, the output signal collected from 15mm cracked specimen is being used as baseline structure to calculate the RMSD crack index.

To compare the overall wave shape difference between full actuation numerical simulation result, partial actuation numerical simulation result and experimental result, normalization method is used to process the signals. Since RMSD method is to calculate the deviation of two relevant data series, the normalization will not change the RMSD crack index.

Figure 3-20 compares the three types of output signals mentioned above: full actuation simulation result, partial actuation simulation result, and experimental result. In Figure 3-20. Compared with the full actuation simulation result, which only has axisymmetric wave modes, both the partial actuation simulation result and the experimental results include the non-axisymmetric flexural wave modes. The slight differences between the partial actuation simulation result and experimental result are:

- 1) Some part of the amplitude of experimental results is greater than the partial actuation simulation results;
- 2) At some part of the signal, the phase angle of these two signals cannot match.

These differences are caused by the simplification of actuator used during simulation. As shown in Figure 3-5, in partial actuation simulation, all the force boundary conditions have been applied on the circumference at the actuator's centre position and the output is also from a single node. On the other hand, in the experiment, the actuator covers a particular area of the specimen where the output from the sensor is an average of the total output of the MFC functional area. The simplified transducers used in the simulation made the simulation results look 'slimmer' than the experimental results, as shown in Figure 3-20.

Figure 3-20 Numerical simulation result compared with experimental result @ 100 kHz actuation

In both the partial actuation simulation result and the experimental result, the non-dispersed torsional wave pack $T(0,1)$ which is used to calculate the RMSD crack growth index for axially oriented crack are mixed with the flexural wave modes; thus hard to extract only $T(0,1)$ wave pack. However, just as shown in Figure 3-16, even when flexural wave modes are included in the targeting wave pack, the RMSD crack index for axially oriented crack is still valid, just not as sensitive as using only pure torsional wave pack. Taking the output from 15mm cracked case as baseline signature, the RMSD crack growth index for axially oriented crack from the experimental results is calculated and compared with those from the full actuation and partial simulation in Figure 3-21.

Comparing the three RMSD crack growth indices obtained from the full actuation simulation, partial actuation simulation and experimental result in Figure 3-21, the crack growth index from numerical simulations suggests a very clear linear trend. In contrast, the RMSD from the experimental result is slightly scattered. However, an approximately linear relationship between the RMSD index and the crack size can still be observed. There are several causes for the differences between these crack growth indices:

- 1) The simplified actuator and sensor are modelling in numerical simulation.

In the numerical simulation, both actuating and sensing behaviour are simplified. For activating, loading boundary conditions are added directly to the nodes located at the actuator position on the circumference of tubular; for sensing, the output from the node at sensor position on the circumference of tubular is used as the output result. In both actuating and sensing case, the longitudinal direction dimension of transducers is neglected. However, in the experiment, the activating and sensing are achieved by using MFC. The MFC functional area covers not only the circumference of the pipe but also the certain longitudinal range of pipe, which will trigger more ‘dispersed’ flexural wave modes that will interfere the RMSD crack index reading.

- 2) Simplified crack modelling in numerical simulation.

The crack model in numerical simulation is simplified as a pure hairline type of crack with two shape crack tips. Circumferential direction dimension of crack is not considered in the numerical simulation. However, in the experiment, the

minimum crack size can be achieved limited by the lab tools. The circumferential direction dimension of crack is unneglectable. Reflection and scattering will cause more dispersion behavior of flexural wave modes.

3) The bonding quality between MFC transducers to host structure.

The MFC transducers are connected to the host structure via super glue. The bonding quality between MFC and the host structure will affect the testing result very much. The actuation signal is transferred from MFC to host structure via the epoxy layer at actuator position; the guided wave is also converted back to electric signal via the bond between host structure and sensor.

4) Limitation of testing equipment

In the experimental test, the restriction of testing equipment will also contribute to the quality of the signal collected. The noises from the laboratory background and power supply need to be removed as much as possible which also lowered the sensitivity of the proposed crack growth index.

5) The quality of testing results.

Last but not the least, the quality of the testing results is also important to the final results. As shown in Figure 3-21, RMSD crack growth index from the experimental result is more scattered compared with those from the numerical simulation. Especially, at crack size 30mm and crack size 37.5mm, the deviation looks much greater compared with other testing results. It can be expected that the signal collected in such cases are 'low quality' signals. Since the crack on the specimen is not reversible, to eliminate the effect of such 'low quality' signal, it is suggested that for each case, at least three times output signals shall be collected. If one of the signal quality is not good, the other two can be used to replace the 'bad' signal that will deviate the final results.

Figure 3-21 Comparison of RMSD crack growth index between full actuation, partial actuation, and experimental result

3.4.4 Experiment Result and Discussion

Both numerical simulation and experimental results verified that using the above calculated axial direction crack growth indices, the axially oriented crack growth can be well monitored. From the numerical simulation results, it is easy to infer that if the signal from the undamaged specimen is collected, this proposed method is capable of detecting the crack at the incipient stage. From experimental results, it can be concluded that if signals are collected at any given crack length, the crack propagation and failure early warning can be achieved based on the RMSD crack growth index.

For the practical and economic reason, not all cracks on tubular structures are required to be repaired when they are found. Only when the existing crack has extended/accumulated to a critical level, the repair works it worth to be executed. Using the proposed method in this chapter can help make the repair work more reasonable and cost effective because a critical value of crack size can be pre-set in the crack growth index. When the crack size matches the critical value, the crack must be repaired.

The background AC noise is harmful to the accuracy of the simulation. Isolated DAQ device is suggested to be used in the data acquisition process. Otherwise, manual curve fitting is needed to eliminate the background noise.

Since MFC transducers are used as both the actuator and sensor in this research and they are placed on both side of the crack, a prototype of close-loop self-actuating and sensing system for axial direction crack detection in continuous cylindrical structures is proposed, as depicted in Figure 3-22. This system contains some transducers. For each region, two pieces of transducer work together to monitor the health condition of this region. For instance, region one monitoring will be performed by transducer 1 and 2. In this sub-system, transducer one will be utilized as actuator and transducer two will be utilized as a sensor. Once data has been collected, the system will switch scanning from region 1 to region 2. In region 2, transducer two will be used as an actuator and the next transducer will be utilized as a sensor. The system will control the area to be scanned, and it will automatically switch the function of the transducers in the area as actuator and sensor accordingly, and so forth so that the continuous pipe can be monitored.

Figure 3-22 Prototype of a close-loop self-actuating and sensing axial direction crack monitoring system for continuous cylindrical structures

3.5 Summary and Conclusion

This chapter presents a new proposed method that use torsional wave to measure and monitor the propagation of axial direction crack in cylindrical structures. MFC is used as both actuator and sensor because of its flexible character and strong actuating/sensing capacity. MFC transducers are first applied to generate torsional wave for detecting and monitoring axial direction crack growth in tubular structures. The actuator is driven by pre-adjusted signals to produce target guided wave modes for inspection. The sensor picks up the stress waves propagating in the pipe and returns the electrical signals. With the help of digital signal processing (DSP) techniques, the damage information is extracted from the changes of the sensor's output. Both numerical and experimental verifications have been conducted to demonstrate the effectiveness of this proposed method. Based on the proposed method, a prototype of close-loop self-actuating and sensing system for continuous cylindrical structures is proposed.

The results from the numerical simulation and experimental verification show that the axial-direction crack propagation can be well monitored. The RMSD values of torsional wave pack from a numerical simulation with different crack sizes give a linear trend against the crack size increment. However, the numerical results do not match the experimental results well. The difference is because the sensor and the actuator are simplified in the numerical simulation, and the crack is also simplified using node release method in which the crack width is not considered. Base on the analysis of both numerical and experimental results, a linear relationship can be established between the RMSD value of torsional wave pack and the axial direction crack size.

For the monitoring of continuous cylindrical structures, an integrated intelligent SHM system is needed. The integration of crack orientation detection, crack location identification, crack growth monitoring and optimized transducers distribution will be discussed in following chapters.

4 STRUCTURAL HEALTH MONITORING SYSTEM FOR AXIAL CRACK ON CYLINDRICAL STRUCTURE

4.1 Introduction

In Chapter 3, a new proposed method that use torsional wave to measure and monitor the propagation of axial direction crack in cylindrical structures has been proposed. Based on the proposed method a close-loop self-actuating and sensing axial direction crack monitoring system for continuous cylindrical structures has been proposed. With the proposed monitoring system, the growth of axial direction crack can be well monitored.

However, the proposed monitoring system has its limitation. Most of the time, the repair work of damaged structure will require two fundamental information, 'how severe the damage is' - whether it can be repaired or not; and 'where the damage location is.' The proposed monitoring system solved the first problem, the next problem of 'where the damage location is' will be discussed in this chapter.

4.2 Method of Study

The aim of this section is to expand the method and SHM system developed in Chapter 3. The existing system developed in Chapter 3 can monitor the axially oriented crack

growth with RMSD crack index. Both numerical and experimental results reveal that the axially oriented crack can be well monitored using the proposed method. The system is also able to be expanded to suit continuous tubular structure monitoring due to its MFC transducer distribution scheme. This chapter is trying to use the same transducer distribution scheme. With the involvement of more transducers in the system, both axial oriented crack growth and position identification can be achieved.

The basis of Chapter 3 is to use MFC generated guided wave in cylindrical structure to detect the axial direction crack. Because the particle movement direction of one of the axisymmetric wave modes, torsional wave, is perpendicular to the crack orientation, when the propagating torsional wave pack passes the crack, the wave pack shape and amplitude are affected by the crack. On the other hand, another type of axisymmetric wave mode, longitudinal wave, the particle movement direction is parallel to the crack orientation. When longitudinal wave pack passed the crack, the wave pack shape and amplitude are less affected by the crack. So the sensor output of each type of wave pack will change accordingly. However, since the actuator to sensor distance is fixed, the TOF of each wave pack is unchanged. The proposed RMSD crack index is used to quantify the signal changes and to correlate the signal change of torsional wave pack with the change of axially oriented crack dimension. However, this proposed method is not able to catch the crack location on the pipe. The crack may be located in the centre of the tube; it also may be located close to either the actuator or the sensor. Since guided wave propagates in cylindrical structures can only propagate along the axis, the distance of wave pack that travelled is proportional to the TOF of that wave pack. Hence, the presence of the crack can be detected based on pulse-echo method, theoretically. Pulse-echo method is a commonly used method to identify the damage location in SHM. To use the pulse-echo method in an SHM system requires the actuator to send out one pulse type signal. It also requires the sensor to pick up the signal reflected from any discontinuity on the wave propagation path. If the defect on the structure is big enough, the reflected signal can be identified via data processing techniques. The signal sent by the actuator is called 'pulse', and the signal reflected from discontinuity and received by the sensor is called 'echo.' To use the pulse-echo method, the sensor needs to be placed on the same side of crack as the actuator so it can get the 'echo' reflected from the crack.

Base on the system developed in Chapter 3, a new regime with one additional sensor is proposed in this chapter.

Figure 4-1 Place of transducers

The placement of transducers for the proposed SHM system to be used in Chapter 4 is plotted in Figure 4-1. In the real continuous piping system, there are only a few terminations. In between two terminations, there is super long continuous tubular structure. To perform the SHM of such long continuous pipe, the free end can be assumed at the infinite far position. Hence, if the pulse-echo method is used in SHM of such piping system, no additional wave pack reflected from the free end. Unlike the 1200mm long testing specimen used in Chapter 3, the testing specimen employed in this section is extended to 2400mm in length. The actuator to sensor path one distance is 550mm and the actuator to sensor path two distance is 700 mm. In path 1, an actuator (A) and sensor are placed at both sides of the crack. The sensor 1(s1) is used to pick up the torsional wave amplitude and shape changes. In path 2, actuator and sensor are placed on the same side of the crack. The sensor 2 (s2) is used to pick up the reflected torsional wave pack to identify the crack position. The proposed SHM system for an axially oriented crack in cylindrical structures will be verified both numerically and experimentally in the following part of this chapter.

4.3 Numerical Simulation of SHM of Axial Cracks Using Torsional Wave

Similar to the numerical model in Chapter 3, only penetration crack is considered in this research, a 2.4 m (length) x 102 mm (diameter) x 3 mm (wall thickness) aluminium pipe is modelled in the FE software ANSYS using shell 63 elements as shown in Figure 4-2.

Figure 4-2 Numerical model of 2.4m long pipe in ANSYS

The growth of penetrated crack at the centre of the pipe is simulated via nodal release method which has been commonly used in FE analysis of fracture mechanics. As shown in Chapter 3, both full actuation case and partial actuation case results can be used to generate the RMSD crack index. For simplicity, only full actuation case is considered in this chapter. This fully covered ring-shaped actuator generates only the axisymmetric wave modes. Force along the axial direction is uniformly distributed on the pipe circumference to produce the longitudinal wave modes, and torque is applied to generate the torsional wave modes.

For the purpose of crack growth monitoring, S1 and wave propagation path one are used. Because the A-to-S1 distance is fixed, for a fixed actuation frequency, the TOF of a torsional wave pack is also a constant. Since axial crack will disturb the propagation of the torsional wave pack, when the crack size increases, larger disturbances on the torsional wave pack is expected. For the purpose of crack position identification, S2 and wave propagation path two are used. Additional torsional wave pack reflected from the crack is expected, and the TOF of the extra wave pack is used to locate the crack position.

Same as the actuation signal used in Chapter 3, five cycles Hanning windowed sine wave burst, which is one of the most commonly used signals in guided wave testing, is adopted in this chapter as actuation signal.

4.3.1 Numerical Simulation of Axial Crack Growth Monitoring

The output from sensor S1 is used to monitor the growth of the axial crack. As mentioned in the previous section, if the axial direction crack exists in the wave propagation path, its disturbance on the torsional wave pack will be greater than that on the longitudinal wave pack. The only difference between the testing specimen in Chapter 4 and Chapter 3 is the specimen length; the phase speed and group speed of all wave modes that used in Chapter 4 are the same as those used in Chapter 3. Since the A-to-S1 distance is fixed at 55cm, the wave speed is obtained from the dispersion curve of group speed in Figure 3-2, and the TOF of each wave pack can be calculated.

Simulation results of the output of S1 at 100 kHz actuation frequency are plotted in Figure 4-3. Based on the group speed of L(0,2) and T(0,1), which are 5412 m/s and 3149 m/s respectively, the TOFs of the longitudinal wave pack and the torsional wave

pack are calculated to be $101.6 \mu\text{s}$ and $174.7 \mu\text{s}$, respectively. The TOFs of both wave modes are the same as the numerical results measured from Figure 4-3. Comparing the signal of the undamaged specimen with that of the cracked specimen; the differences are difficult to track by naked eyes. Thus, to quantify the crack-caused disturbance on the torsional wave pack, the RMSD method is used to evaluate the differences between the signal of the undamaged and the cracked specimens.

Figure 4-3 Comparison of normalized numerical simulation results: output of sensor S1 from undamaged and cracked specimens

Figure 4-4 RMSD crack indices from the output of sensor S1 to monitor the axial direction crack growth (numerical simulation).

Take all the numerical simulation output into Eq. 3-3, the RMSD crack index of torsional wave pack and longitudinal wave pack are compared in Figure 4-4. Just as expected, torsional wave pack is more sensitive to the crack growth than the longitudinal wave pack. The linear fit of these RMSD values suggests that the RMSD value varies linearly with the axial crack length. Hence, it can be conveniently used to monitor the growth of the axial crack.

4.3.2 Numerical Simulation of Axial Crack Position Identification

The output from sensor S2 is used to identify the position of the axial crack. Results of the undamaged specimen and the specimen with 25mm axial direction crack are compared in Figure 4-5. Besides the wave pack directly from the actuator to sensor S2, two additional wave packs are found, which are the longitudinal wave mode L(0,2) and the torsional wave mode T(0,1). Just as expected, the torsional wave pack is more sensitive to the axial crack, and the reflected wave pack is hence larger. As the TOF of the torsional wave pack can be measured from the graph, and the group speed of the torsional wave is obtained from the group speed dispersion curve in Figure 3-2, the position of the crack is thus located. If the distance from actuator to crack position is denoted by X , it can be calculated by

$$X = (TOF_{\Delta T} \times V_T - S_{A \text{ to } S2})/2 \quad \text{Eq.4-1}$$

where $TOF_{\Delta T}$ is the TOF of the additional torsional wave pack reflected from the defect; V_T is the group speed of the first order torsional wave mode; and $S_{A \text{ to } S2}$ is the A-to-S2 distance. Substitute the additional torsional wave pack TOF of 225 μ s into Eq.4-1, the estimated crack position is 27.90cm away from the actuator, which is very close to the exact crack position of 27.5cm from the actuator.

The longitudinal wave pack has also been used to calculate the axial crack position. However, the reflected longitudinal wave mode from the axial crack is relatively small. As shown in Figure 4-6, even when the output results have been zoom-in five times than its original size as plotted in Figure 4-5, it is still tough to identify the centre and the beginning of the longitudinal wave pack. It leads to an inaccurate reading of longitudinal wave pack TOF which gives an inaccurate result as compared with the result calculated from the torsional wave pack. The calculated crack positions from the longitudinal wave pack and the torsional wave pack are compared with the actual crack

position in Table 4-1 and Table 4-2, respectively. As listed in Table 4-2, using reflected longitudinal wave pack to calculate the TOF of additional wave pack reflected from axial direction crack end up with a much greater error.

Table 4-1 Exact axial crack position (calculated based on group speed from dispersion curve)

Wave Pack	TOF _p (μs)	V _p (m/s)	S _{A to S} (m)	Calculated crack position X (m)	Actual crack position (m)	Error (%)
L(0,2)	129.3	5412	0.15	0.275	0.275	0
T(0,1)	222.9	3149	0.15	0.275	0.275	0

Table 4-2 Numerical simulation axial crack position

Wave Pack	TOF _p (μs)	V _p (m/s)	S _{A to S} (m)	Calculated crack position X (m)	Actual crack position (m)	Error (%)
L(0,2)	150	5412	0.15	0.331	0.275	20.3
T(0,1)	225	3149	0.15	0.279	0.275	1.55

Figure 4-5 Axial crack position identification from the output of sensor S2 (numerical simulation)

Figure 4-6 5-times zoom-in numerical simulation results

4.4 Experimental Study of SHM of Axial Crack Using Torsional Wave

In the numerical simulation, the specimen is considered to be fully covered by the ring-shaped actuator by which only the axisymmetric wave modes can be activated. Since in the experimental study, the MFC patches can only cover part of the circumference, the flexural wave modes are the concomitance of the axisymmetric wave modes.

4.4.1 Experiment Setup

An aluminum pipe with 2.4m in length, 102mm in outer diameter and 3mm in wall thickness is used in the experimental study. The aluminum pipe is supported by four stands at the bottom. Three MFC transducers are bonded to the surface of the tube, 45° oriented to the axial direction, as shown in Figure 4-7.

Figure 4-7 Experimental setups for torsional wave SHM of pipe using MFC transducers

The experimental setup consists of a Tabor Electric ww1701 arbitrary function generator, a Terk PZD350A high power amplifier, a YOKOGAWA DL1740 Oscilloscope and a National Instruments (NI) integrated digital signal acquisition (DAQ) system. The MFC actuator is driven by amplified 100V peak-to-peak actuation signals. The sensors are connected to the NI multi-channel switching box to receive the signal simultaneously. An additional cable from the function generator is connected to the DAQ device to synchronize the data acquisition process.

A penetrated crack is initiated at the centre of the pipe with an initial length of 3mm and a constant width of 3mm. The crack length is increased at 2mm increment until it reached 49mm which is almost the radius of the pipe. At each crack size, experimental data within target frequency bandwidth (60 kHz – 200 kHz) are collected. To eliminate the influence of background noise, 16-times cycle averaging method is used. At low actuation frequency, the actuation signal will take a longer time to be generated. Hence, low actuation frequency is equal to ‘wider’ wave pack. To prevent wave packs overlapping with each other, longer A-to-S distance is needed. At high actuation frequency, the actuating and sensing capability of MFC is greatly reduced which lowers

the accuracy of the SHM results. The lower and upper limit of the frequency bandwidth is thus set at 60 kHz – 200 kHz according to the dimension of the specimen and the actuating capability of MFC, respectively. As the DAQ device does not have any power isolation function, the AC background noise needs to be removed from the original data. Following the method discussed in section 3.4.2 and Eq.3-4, most the AC background noise can be eliminated from the data collected by sensors.

4.4.2 Experiment on Axial Crack Size Growth Monitoring

Experimental results of sensor S1 from the undamaged specimen and the specimen with 50mm crack are compared in Figure 4-8.

Figure 4-8 Comparison of experimental results: output of sensor S1 from undamaged and cracked specimens.

Apparently, they are different from the numerical simulation results under the same actuation frequency of 100 kHz (as shown in Figure 4-3) because the experimental data are complex due to the existence of flexural waves, which are too complicated to be separated. However, as the A-to-S1 distance and the group speed of each wave mode are known, the TOF of each wave mode under 100 kHz actuation frequency can be calculated. The torsional wave pack $T(0,1)$ and longitudinal wave pack $L(0,2)$ are then identified and marked in Figure 4-8. Just as expected, the longitudinal wave pack is not sensitive to the axial crack growth. Compared with the torsional wave pack, the crack caused change on the longitudinal wave pack is relatively small. The experimental RMSD crack indices from the torsional wave and the longitudinal wave are calculated based on Eq.3-3 and plotted in Figure 4-9.

Figure 4-9 RMSD crack indices from output of sensor S1 to monitor the axial direction crack growth (experimental results)

Compared with the RMSD crack indices from numerical simulation, the RMSD crack indices from the experimental data are more disordered. However, they still suggest a linear pattern between output signatures changes and crack growth. Compared with the experimental results listed in Chapter 3, the experimental data in Chapter 4 is using undamaged specimen as reference baseline signature. Figure 5-9 illustrates again that the torsional wave pack is more sensitive to axial crack growth than the longitudinal wave pack.

To reduce scattering of the experimental results, the possible improvements can be:

- 1) Proper selection of baseline signature

All the experimental data are compared to the baseline signature to compute the RMSD crack indices. A good baseline signature from the undamaged specimen is critical to ensure accuracy. Since the DAQ are automatically performed, it is suggested to have multiple and stable baseline signatures that could be used for the calculation of RMSD method.

- 2) Stable experiment environment, setup and boundary conditions.

The data should be collected under similar circumstances. Especially when the baseline signature is collected, the following data should be collected under the same environment and boundary condition to limit any uncertainties which may cause the change of signals. In the experiment, because the crack is created and expanded on a milling machine, the transducers are disconnected and reconnected every time the crack is enlarged, which increased the uncertainty of the change of the signal.

- 3) Pre-process of signals to remove the background noise

RMSD method highly depends on the quality of signals. The changes of wave pack can come from defects, change of boundary conditions as well as background noises. When background noise is not removed from the signals, it will lead to a higher RMSD value.

- 4) Dimension of the crack

In the experiment, an axial crack with 3mm width is adopted whereas in the numerical simulation an ideal axial crack with zero width is considered. The circumferential dimension of the crack also contributed to the change of RMSD value.

5) Dimension of MFC

In the numerical study, a ring-shaped actuator is simulated. The actuation only worked at a single axial position of the pipe. The sensor output is also from a single point. In the experiment, MFC transducer covered certain area to actuate, and the sensor output is also the average result of the covered area, which increased the difficulty of interpreting the signatures.

Compared with the RMSD crack indices from the torsional wave pack, the RMSD crack indices from the longitudinal wave pack showed a more scattered pattern. This phenomenon is because the disturbance of axial crack on the longitudinal wave pack is very tiny, so the RMSD value is easily affected by any noise or change in boundary condition

4.4.3 Experiment of Axial Crack Position Identification

The numerical simulation used a simplified ring-shaped actuator which can only generate axisymmetric wave modes. However, in the experiment under partial actuation condition, the flexural wave modes are also included in the output signatures. The experimental results of sensor S2 from the undamaged specimen, the specimen with 3mm crack, and the specimen with 8mm crack have been compared in Figure 4-10.

Figure 4-10 Comparison of experimental results: output of sensor S2 from undamaged and cracked specimens

Unlike the numerical simulation results are shown in Figure 4-5, the experimental output signature of sensor S2 is rather complicated. As shown in Figure 4-10, the additional signal reflected from the axial crack is buried inside the flexural wave modes following behind (color shade zone). To use Eq.4-1 to calculate the crack position, the additional reflected torsional wave pack needs to be identified before the TOF of the wave pack can be obtained.

4.4.3.1 Mode Separation

Since there is no crack existing in between the actuator and sensor S2, the direct-passed wave packs measured by S2 from the cracked and undamaged specimen are the same regarding amplitude and phase if the actuations are the same. Using the signature from the undamaged specimen as a reference, the signals from the cracked specimen are subtracted from the baseline signature and the residual signals are then assumed to be the crack affected signals. Figure 4-11 compares three residual signals: (1) the ‘undamaged’ signal is the residual of two different baseline signatures of the undamaged specimen; (2) the ‘3mm crack’ signal is the residual of subtracting a signal of undamaged specimen from the signal of the specimen with 3mm crack; and (3) the ‘8mm crack’ signal is similarly obtained as the ‘3mm crack’ signal. The ‘undamaged’ residual is considered as noise whose amplitude is covered by the shadowed area. Any residual wave pack, whose peak amplitude is less than the ‘undamaged’ level or the noise level, is considered nil and the structures are considered healthy. Once the crack is initiated, as shown in Figure 4-11, additional reflected wave pack from the axial crack, which exceeds the noise level, can be detected. As compared with the ‘3mm crack’ residual, the ‘8mm crack’ residual includes a larger torsional wave pack regarding both amplitude and wave pack width, while the included longitudinal wave pack remains almost the same as that in the ‘3mm crack’ residual. This phenomenon is because when the axial crack size is growing, its axial dimension increases but its circumferential dimension remains constant. Thus, the longitudinal wave pack is less affected than the torsional wave pack.

Figure 4-11 Comparison of residual signals from undamaged, 3mm cracked and 8mm cracked specimen after wave modes extraction.

4.4.3.2 Crack Position Identification

After the mode separation process, additional reflected wave pack from the axial crack can be identified on the residual signal graph. The TOF of the extra wave pack is marked in Figure 4-11. The actual position of the crack is 27.5cm from the center of the actuator, and the center-to-center (C-to-C) distance of A-to-S2 is 70cm. Using the 100 kHz group speed of torsional wave from the dispersion curve shown in Figure 3-2, the exact TOF of torsional wave pack is calculated. Table 4-2 and Table 4-3 listed the axial crack position calculated from the numerical simulation results and the experiment results, respectively. As shown in Table 4-2, numerical simulation with only axisymmetric wave modes gives the very precise location of the crack. However, when flexural wave modes are included in the experimental results, the accuracy of the results is reduced as shown in Table 4-3.

Table 4-3 Experimental axial crack position

Data from	Wave pack used	TOF _p (μs)	V _p (m/s)	S _{A to S} (m)	Calculated crack position X (m)	Actual crack position(m)	Error (%)
3mm	T(0,1)	192	3149	0.15	0.227	0.275	17
5mm	T(0,1)	197	3149	0.15	0.235	0.275	14.5
10mm	T(0,1)	206	3149	0.15	0.249	0.275	9.4
15mm	T(0,1)	206	3149	0.15	0.249	0.275	9.4
M3mm	T(0,1)	192	3149	0.15	0.227	0.26	12.7
M5mm	T(0,1)	197	3149	0.15	0.235	0.26	9.6
M10mm	T(0,1)	206	3149	0.15	0.249	0.26	4.2
M15mm	T(0,1)	206	3149	0.15	0.249	0.26	4.2

Figure 4-12 Modified wave propagation path length

The low accuracy of the position identification is also due to the distance of actuator to crack used in Eq.4-1. In the numerical simulation, the transducers have exact axial positions, but in the experiment, the transducers cover parts of the pipe in the axial direction, which increases the complexity of the output signals. As shown in Figure 4-12, taking the transducer's dimension into consideration, the actuator to crack distance is changed from 27.5cm to 26cm. The corrected results, using the new value in Eq.4-1, are also listed in Table 4-3. Apparently, their accuracy improved greatly. It is also found from Table 4-3 that, as the crack size increases, the accuracy of the crack position identification also increases. This phenomenon is because when the crack size is small, the wave pack reflected from the crack is also small in amplitude and it is hard to determine the center of the wave pack, which reduced the accuracy. As the crack size increases, the reflected wave pack amplitude also increases due to the larger disturbance and the wave pack is thus easier to measure.

4.4.4 Sensitivity range of the MFC transducers

Each type of transducers has its own sensing range. If the transducers are located out of its recommended sensing range either the results is unreliable or there is no results at all.

In this study, no MFC transducer sensitivity study is covered. The actuator to sensor distance is fixed because of following reasons:

1. Input energy.

The input energy is critical to MFC type of transducers. There is a suggested working voltage for MFC transducers from the manufacture. For P1 type MFC the maximum working voltage is from -500V to +1500V. The higher driving voltage is used, the larger response we can expect. However, at the same time, at a higher driving voltage, the signal is easy to be distorted after amplification. To be noted the original actuation signal is generated from the digital function generator and enlarged by the signal amplifier. The amplified driving signal will be then applied to the MFC actuators. Most of the time, there is a limitation on the signal amplifier where the actuation frequency and output voltage both have an upper bound. The amplifier used in the experiment setup TREK 350A. The specs mentioned that the amplifier is good for $\pm 350V$ AC and up to 250kHz signal. Even though we wanted to carry out experiment study on the sensitivity of the input signal, we were limited by the equipment setup. Our amplifier cannot drive the MFC to its full capacity hence we can only amplify the signal to the current voltage level where the driven signal still maintains the wave shape we want. If higher actuation voltage or frequency is used, the amplified actuation signal can no longer maintain the designed wave shape; more disturbance will be included in the output signals. We also carry out an experiment with actuation frequency at 300kHz. The results showed that the amplifier greatly distorts the signal, and no recognized pattern can be used for the crack growth monitoring process.

2. Testing Specimen.

In this study, there are two types of testing specimens used: the 1.2m length specimen and the 2.4m length specimen. The 1.2m length specimen is initially used to perform the longitudinal crack growth monitoring task that described in Chapter 3. Then, 2.4m specimens are used to detect both the location and crack growth that described in Chapter 4. The reason not to use 1.2m specimen in Chapter 4 experiment study is to eliminate the wave reflection from specimen open end which is not occurred in continuous pipeline structures. Because of the space limitation of laboratory and the milling machine that initiate the crack on the specimen, 2.4m length specimen is the maximum length that can be tested in current experiment setup. In this study, torsional

wave pack is the priority target wave pack since it is not dispersive during propagation. Hence it is good to be used for range sensitivity test. However, due to the low travel speed of the torsional wave, it is easy to be interference by other faster wave modes that reflected from free boundaries. Hence, it is not practical to carry out experiment study on the sensitivity range of MFC transducers.

3. Wave attenuation

There is wave attenuation during propagation. The wave attenuation is because of the energy is absorbed or dispersed during propagation. There are so many uncertainties that will cause the attenuation. The attenuation may be because of the host material properties, the pressure, the temperature, the content the host structure is carrying, the boundary conditions, etc.

4.5 Summary and Conclusion

This chapter presents a close-loop self-sensing and monitoring system for an axial crack in cylindrical structures. Different from Chapter 3, this chapter developed the SHM system that is capable of detecting both axial oriented crack's dimension and position. Since the particle motion direction of torsional wave modes is perpendicular to the orientation of axial cracks, torsional wave pack is more sensitive to axial crack. In this system, MFC is placed 45 degrees clockwise oriented against the axis of the cylinder to generate torsional wave packs. The MFC transducer at the center works as the actuator; the other two MFC transducers operate as sensors to detect the axial position of the crack and to monitor the crack size growth, respectively. Five-cycle Hanning windowed sine wave tone burst was used to activate guided waves in the cylindrical structures. With the help of its concentrated wave pack center, the accuracy of locating the crack position is improved; and with its narrowed bandwidth, the dispersion effect of wave modes is limited. To monitor the crack growth, RMSD method is adopted to correlate the crack growth to the total waveform changes, where a linear pattern between the RMSD index and the crack size is observed. TOF based method is adopted to find the axial position of the crack in the cylindrical structures. To eliminate the effect of flexural waves, the residual signal whereby the signal of the undamaged specimen is subtracted from the signal of cracked specimen is used.

Both numerical simulation and experimental investigation are conducted. The results show that both the axial position and crack size growth of the axial crack can be well located/monitored using this close-loop sensing system. In the experimental investigation, the existence of flexural waves, changes of boundary conditions, errors in data processing procedure, etc., all contributed to the reduced accuracy of the results as compared with the numerical simulation. Nevertheless, the experimental data still show promise in the SHM of axial crack in cylindrical structures.

For the monitoring of continuous cylindrical structures, an integrated intelligent SHM system can be further developed based on the proposed close-loop self-sensing system. To further develop the SHM system to achieve continuous cylindrical structures monitoring, optimized placement of transducers and artificial intelligence to integrate automatic data acquisition with data processing and result analysis are needed. Furthermore expansion of this ‘smart’ system is discussed in Chapter 5.

5 THE IDENTIFICATION OF CRACK ORIENTATION AND DIMENSION ON CYLINDRICAL STRUCTURE

5.1 Introduction

In cylindrical structures, there are many types of guided waves. The most commonly discussed are the two fundamental axisymmetric waves: torsional waves and longitudinal waves. There are also many complicated non-axisymmetric wave modes existing, like flexural wave modes. Usually at certain actuation frequency range (below 200 kHz), only limited wave modes can be dominated in the overall wave shape and show their characters during propagation. Because the particle movement direction of torsional wave modes are perpendicular to the axis, and the particle movement direction of longitudinal wave modes are parallel to the axis of the cylindrical structure, when the crack on the structure is axial oriented, the torsional wave packs are more easily affected by the crack than the longitudinal wave packs. Due to MFC's ease to bend and ease to be driven characters, MFC is used as transducers to activate and receive signals. In Chapter 3, a new axial oriented crack growth monitoring system is proposed based on MFC generated torsional waves. The close-loop system can pick up the axially oriented crack growth on a cylindrical structure. RMSD crack index is proposed to be used to quantify the signal change and correlated the change with the crack size change.

Chapter 4 proposed an expanded system based on the system developed in Chapter 3. With one additional sensor placed next to the actuator, the new regime can pick up both the axially oriented crack growth and its location. The increase of crack will be monitored based on RMSD crack index, and the location of the crack will be estimated based on the pulse-echo method.

All the works described in Chapter 3 and Chapter 4 are focused on axially oriented crack only. The reason is that the torsional wave is sensitive to the change of axially oriented crack. The high sensitivity of torsional wave on axially oriented crack comes from the particle motion direction is perpendicular to the crack orientation. On the other hand, the longitudinal wave is also sensitive to circumferential direction crack. These two types of crack are most commonly occurred cracks on the cylindrical structure. This chapter is focusing on developing a system that can be used for crack size and orientation identification of line type crack on cylindrical structures.

5.2 Method of Study

The governing equation of wave propagation in hollow cylinders is first given by Gazis (Gazis 1959a, Gazis 1959b). The wave propagating in cylindrical structures can be grouped into axisymmetric wave modes and non-axisymmetric wave modes based on their particle motion (PM) directions. As shown in Figure 5-1, there are two types of axisymmetric wave modes, namely longitudinal wave modes and torsional wave modes. The PM of a longitudinal wave is parallel to the axis of the hollow cylinder, and only the axial displacement (u_z) is included. On the other hand, the PM of the torsional wave is perpendicular to the axis, where only the circumferential displacement (u_θ) is included.

Figure 5-1 axisymmetric wave modes in cylindrical structures: torsional wave (T) and longitudinal wave (L)

If a discontinuity exists on the wave propagating path, the waveform will be distorted after it transmits through. In this chapter, an actuator (A) and a sensor (S) are placed at both sides of the crack. According to the PMs of the torsional wave pack and the longitudinal wave pack, when an axial crack is in the wave propagating path, the torsional wave pack will be more distorted after it transmits through the crack than the longitudinal wave pack, as shown in Figure 5-2(a). When a circumferential crack is in the wave propagating path, both the torsional wave pack and the longitudinal wave pack are equally affected, as shown in Figure 5-2(b). The distortions of the wave packs can be quantified by RMSD values calculated from Eq. 3-3.

Figure 5-2 Torsional and longitudinal wave modes transmitted through (a) axial crack and (b) circumferential crack

In this chapter, these different behaviors and RMSD values for the various wave packs (torsional and longitudinal) transmitted through the different cracks (axial and circumferential) are used to determine the crack size and orientation.

To be noticed that Chapter 3 is the initial experiment proposal with the original experiment setup: the transducers are placed on both side of the crack, one as an actuator and the other as a sensor. The purpose is to monitor the crack growth use the first torsional wave pack that generated by the actuator. The sensor will catch the signal that affected by the crack and the proposed method will identify the changes in the targeting wave pack and correlated the crack changes with the signal changes. As per the conclusion of Chapter 3, this experiment setup successfully monitored the development of longitudinal direction crack.

In Chapter 3, the axially oriented crack growth is successfully monitored. Based on the results in Chapter 3, Chapter 4 is aimed to identify the crack location on the specimen at the same time of monitoring the crack growth. Longer specimen is used in the experiment. Pulse-echo method is used to detect the crack location. The longer specimen will increase the wave propagation path and it will not only be beneficial to the separation of different wave packs but also more close to the actual condition of “continuous” pipeline. To be noted that in lab testing environment, it is extremely hard to carry out an experiment on continuous pipelines health monitoring. Hence, the longer specimen will be helpful on separating (eliminating) the wave pack reflected from the open end. Compared with testing specimen used in Chapter 3, the crack is still placed at the center of the specimen. The actuator to sensor distance is almost the same. The only difference between the specimens used in these two chapters is the length of the specimen before the actuator (left) and after the sensor (right). Since longitudinal wave pack travels faster than the torsional wave pack, the aim of such setup is to ensure the torsional wave pack for crack growth monitoring and crack position identification is not overlapped with the longitudinal wave pack reflected from the open end. Based on the experiment setup, the wave propagation path has been increased which will contribute to the separation of targeting wave packs. In actual continuous pipelines, there is no such open “termination” under operation condition. Hence there is no reflection from discontinuity other than reflections from the crack. Using a longer specimen make the experiment more close to the actual condition (without reflection from open end).

Since the longitudinal oriented crack growth and crack location identification have been proved to be able to monitor by proposed method, chapter 5 is focusing on detection of crack with any orientation and dimension. More specimens with different crack orientations were tested. The lathering machine is used to initiate crack on the specimen and then enlarge it. Whenever crack is required to be enlarged, cables had to be disconnected from the testing specimen and the specimen needs to be taken to the machine for machinery. Since more specimens are required to be tested, if the long specimen is used, it would greatly increase the duration and the effort on the machinery part. Based on the experiment design concept, the first torsional wave pack, and the first longitudinal wave pack is what we required. Even though there might be some other wave packs reflected from the open end due to shortened wave propagation path from shortened specimen, it is still effective when using the targeted wave packs for crack orientation and size monitoring.

5.3 RMSD Crack Index

The effects of various cracks on the different wave packs, which are described in the last section, are quantitatively analyzed through both numerical simulation and experimental test. A T6061 aluminium pipe with a length of 1200 mm, the inner radius of 48 mm, and the wall thickness of 3 mm is used for this test. The MFC patches are attached at 45-degree orientation about the centroid axis of the pipe. As shown in Figure 5-3, the transducers are placed 300 mm from the free end of the specimen. The actuator to sensor (A-to-S) distance is 600 mm and the actuator to crack (A-to-C) distance is 200 mm. In the application, only the first few wave packs are considered, i.e., the wave packs directly from the actuator to the sensor. Such transducers distribution avoids wave packs reflected from free end (arrive later) overlapped with the target wave packs (arrive earlier).

Figure 5-3 Placement of transducers and location of cracks

The Hanning windowed sine wave tone burst has ‘narrow’ bandwidth which limits the dispersion effect in experiments and the centred peak helps in locating the wave packs precisely. The actuation frequency will greatly affect the output signal so it should be chosen carefully. In the numerical simulation, higher actuation frequency means more time steps resulting in denser meshes and longer simulation times. In the experiment, when a low frequency is adopted, the incident wave packs will easily be overlapped by the reflected wave packs from the boundary. In the same way, when high frequency is adopted, the actuation/sensing ability of MFC patches is dramatically dropped and the signal to noise ratio will be too small to use. Hence, based on trial and error, an actuation frequency ranging from 60 kHz to 200 kHz is recommended. Take the computing time in the numerical simulation into consideration, in this research, an actuation frequency of 100 kHz is used.

5.3.1 Numerical Simulation of RMSD Method Based Crack Identification

The simulation is performed using SHELL63 element in ANSYS. Ring type actuation is adopted to activate axisymmetric wave modes in the finite element analysis (FEA). Forces in both axial and circumferential directions are applied to every node on the circumference of the pipe at the actuator position. The induced crack on the pipe is modeled using nodal release method which is commonly employed in FEA of fracture mechanics. The growth of crack is simulated by releasing more nodes on the shared boundaries of two pieces of adjacent structures. At one end of the pipe, fixed boundary condition is applied to prevent rigid body movement.

Figure 5-4 compares the normalized output from an undamaged specimen with outputs from two cracked specimens which are 46 mm circumferential crack and 45mm axial crack, respectively. In the three cases, the actuator to sensor distance is unchanged; the wave propagation paths are the same. All wave modes speed can be calculated from the frequency governing equations (Gazis 1959a, Gazis 1959b) as listed in Table 5-1. The time of flight of the second ordered longitudinal wave $L(0,2)$ and first order torsional wave $T(0,1)$ are approximately 110 μs and 190 μs , respectively. The group speed of $L(0,2)$ and $T(0,1)$ that transmitted in this aluminum pipe under 100 kHz actuation is calculated from the frequency governing equations as listed in Table 5-1.

Table 5-1 Time of flight of wave packs.

Wave mode	Group speed(m/s)	A-to-S distance(m)	TOF(μ s)
L(0,2)	5412	0.6	110.8
T(0,1)	3149	0.6	190.5

Figure 5-4 Comparison of outputs from undamaged, 45mm axially cracked, and 48mm circumferentially cracked specimens

Figure 5-5 Extracted upper envelope of signals in Figure 5-4

As compared with the ideal TOF listed in Table 5-1, the TOF of both torsional and longitudinal wave packs obtained from Figure 5-4 are almost identical. As observed from Figure 5-4, the wave patterns of the results from the three sets of data are quite similar. Figure 5-5 extracted the upper envelope of the signals from Figure 5-4. The extracted envelope clearly showed that axial crack has only a slight effect on the longitudinal wave pack but has much effect on the torsional wave pack. Substituting the numerical simulation results into Eq.3-3, the four RMSD crack indices calculated from longitudinal and torsional wave packs transmitted through the circumferential and axial cracks are obtained and plotted in Figure 5-6.

Figure 5-6 RMSD crack indices of both circumferential crack and axial crack (based on numerical simulation)

According to Figure 5-6, the certain pattern can be recognized between the RMSD values and the crack sizes. A linear relationship is the simplest and the most convenient way to correlate the RMSD values to the crack sizes. Linear regression is conducted using MATLAB, and the slopes are thus obtained. The effectiveness of the linear regression has been checked by the coefficient of determination (COD) or R^2 values. The closer R^2 is to 1, the better the linear regression. Table 5-2 compared the COD value of the four linear regressions, which clearly shows that the axial crack has only limited effect on the longitudinal wave but many effects on the torsional wave.

Table 5-2 Parameter of linear regression.

Wave mode	Crack orientation	Slope	COD(R^2)
Longitudinal	Axial	0.0011	0.995
Torsional	Axial	0.0083	0.990
Longitudinal	Circumferential	0.0077	0.993
Torsional	Circumferential	0.0088	0.996

The slope difference is because the PM of longitudinal wave is not disturbed by the presence of axial crack but as the PM of torsional wave is perpendicular to the axial crack, it is greatly affected, as shown in Table 5-1. Comparing to axial crack, the presence of circumferential crack caused discontinuity on the wave propagating path of both longitudinal and torsional waves, so it affected both the wave packs.

5.3.2 Experiment Verification of RMSD Method Based Crack Identification

Figure 5-7 Experimental setup

Experiments on the effects of circumferential and axial cracks on the torsional and longitudinal waves are also conducted for verification of numerical results. The experimental setup consisted of a.) Tabor Electric ww1701 arbitrary function generator, b.) Terk PZD350A high power amplifier and c.) National Instruments (NI) integrated digital signal acquisition (DAQ) system. The MFC actuator is driven by amplified 100V peak-to-peak actuation signals. The sensor is connected to the NI multi-channel switching box to receive the signal simultaneously. An additional cable from the function generator is connected to the DAQ device to synchronize the data acquisition process. The NI multi-channel switching box enabled the expansion of the experimental setup for continuous monitoring of cylindrical structures. The experimental specimens (hollow cylinder) are mounted on a rotatable table to control the crack orientation. The crack is initiated by a 3mm cutter. The crack length is increased 5mm each time until it reached 48mm which is almost the radius of the pipe. To eliminate the influence of background noise, 16-times cycle signal averaging process is used.

Figure 5-8 Comparison of initial experimental result and modified experimental result

As the DAQ device lacks a power isolation module, the AC background noise is also included in the received signals. However, as the frequency (50 Hz) and the neutral position (0 V) of the AC noised are known, this AC noise can be removed by curve fitting. The modified signal is compared with the original signal and the fitted AC noise in Figure 5-8. Comparing with the numerical simulation result, which has only the axisymmetric wave modes (L and T), the experimental data included the flexural wave modes, and thus, the dispersion effect is much greater. Figure 5-8 shows that even though the non-axisymmetric wave modes greatly messed up the axisymmetric wave modes, the L(0,2) and T(0,1) wave packs are still recognizable based on the TOF.

Figure 5-9 RMSD crack indices of both circumferential crack and axial crack(based on experimental result)

Substituting the experimental results into Eq.3-3, the four RMSD crack indices of experimental results are calculated and plotted in Figure 5-9. Because of the existence of flexural wave modes, the slope and sensitivity of the crack indices are slightly different from the numerical simulation.

The RMSD crack indices obtained from numerical simulation and experimental results are shown the following features:

- 1.) Axial crack has little influence on transmitted longitudinal wave packs but has a significant effect on transmitted torsional wave pack.
- 2.) Circumferential crack has a significant effect on both transmitted longitudinal and torsional wave packs.

5.4 Identification of Crack Size and Orientation

Different cracks on the wave propagation path will have different consequences for the transmitted wave packs. As shown in Figure 5-2, axial crack only causes a discontinuity in torsional wave-particle motions but has little effect on longitudinal waves. Circumferential crack causes a discontinuity in both torsional and longitudinal wave-particle motions. Thus, both wave packs are greatly affected. The RMSD crack indices connected the crack size growth with the RMSD value change. If crack orientation is initiated on the pipe in between the circumferential and axial directions, the RMSD crack indices can also be obtained from the circumferential and axial crack indices. Both the crack size and orientation can be achieved from the RMSD value of the wave target packs.

5.4.1 Crack Index for Crack with Any Orientation

Based on RMSD Crack Indices obtained from both axial and circumferential cracks, the effects when the torsional and longitudinal wave passes through an axial crack (with length l) and an additional part related to both length l and orientation θ . This extra part came from (1) the difference in the effects when a wave pack passes through an axial crack and a circumferential crack ($K_{TA}-K_{TC}$ or $K_{LA}-K_{LC}$) and (2) the difference in the geometry of a slant crack from an axial crack, that is, the slant crack has a circumferential component $l \cdot \sin \theta$. The RMSD crack index of a slant crack with length l and orientation θ can thus be calculated as

$$\begin{Bmatrix} R_T \\ R_L \end{Bmatrix} = \begin{bmatrix} K_{TA} & K_{TA} - K_{TC} \\ K_{LA} & K_{LA} - K_{LC} \end{bmatrix} \begin{Bmatrix} l \\ l \cdot \sin\theta \end{Bmatrix} \quad \text{Eq.5-1}$$

where R represents the RMSD value; K is the slope of the RMSD crack index determined in the previous section. The subscript C and A represent the circumferential and axial cracks, respectively; the subscript T and L represent the RMSD value calculated from the torsional and longitudinal wave packs, respectively; and l and θ are the length and orientation of the slant crack, respectively. It can be verified from Eq. 5-1 that for axial crack ($\theta = 0^\circ$), $R_T = K_{TA}l$ and $R_L = K_{LA}l$; and for circumferential crack, ($\theta = 90^\circ$), $R_T = K_{TC}l$ and $R_L = K_{LC}l$. These RMSD values are consistent with the results in the previous section. Using Eq. 5-1, the crack dimension l and crack orientation θ can be derived from the two RMSD values from longitudinal and torsional waves, respectively, R_L and R_T , as

$$\begin{Bmatrix} \theta \\ l \end{Bmatrix} = \begin{Bmatrix} \arcsin\left(\frac{R_L K_{TA} - R_T K_{LA}}{R_T(K_{LC} - K_{LA}) - R_L(K_{TC} - K_{TA})}\right) \\ \frac{R_T(K_{LC} - K_{LA}) - R_L(K_{TC} - K_{TA})}{K_{TA}(K_{LC} - K_{LA}) - K_{LA}(K_{TC} - K_{TA})} \end{Bmatrix} \quad \text{Eq.5-2}$$

Numerical simulations of different crack orientations have been performed. For any given crack orientation θ , two RMSD crack indices can be calculated from the simulation results. For example, by considering 75 degrees as constant, the length of the crack is obtained using Eq.5-1. Figure 5-10 compares the estimated crack sizes with the real crack sizes in the simulation. The horizontal axis is the numerical simulated (Real) crack size. The vertical axis is the estimated crack size. The diagonal of the plotting area is the reference line to gauge the estimation. The closer the data points are to the diagonal, the better the estimation. As shown in Figure 5-10, the estimated values from Eq.5-2 fit the real crack dimension quite well.

Figure 5-10 Comparison of estimated crack size and actual crack size from the T and L wave pack RMSD crack indices of the specimen with 75° oriented crack.

5.4.2 Experimental Verification of Crack Index for Crack with Any Orientation

As shown in Figure 5-11, four specimens with crack oriented at 30, 45, 60 and 75 degrees have been tested to verify the proposed crack diagnostic identification method.

Figure 5-11 Specimens for crack size and orientation identification

Figure 5-12 and Figure 5-13 compare the experimental results with the fixed crack orientation and the fixed crack size, respectively. When crack orientation is fixed at 45 degrees, the estimated crack length is compared with the real crack size in Figure 5-12. As observed from the graph, both longitudinal and torsional wave packs demonstrated the ability to monitor the crack growth when the crack angle is fixed. Compared with numerical simulation, the experimental results are “scattered” because of the presences of flexural wave modes. When the crack dimension is fixed, Figure 5-13 compares the estimated crack orientation with the real crack orientation. When crack size is fixed at 38mm, the calculated crack orientations vary around the actual crack orientations.

Figure 5-12 Comparison of estimated crack size and real size of the torsional wave pack RMSD crack indices of specimen with 45 degrees oriented crack

Figure 5-13 Comparison of estimated crack orientation and actual crack orientation from RMSD crack indices of specimen with fixed crack size 38mm

5.4.3 Analysis of results

Both numerical simulation results and experimental results verified that the proposed method is capable of detecting the orientation and dimension of existing line crack on cylindrical structures. However, some of the facts need to be noted:

1.) The numerical simulation results show better linear pattern than the experimental data.

This statement is because only full actuation is considered in the numerical simulation and under such actuation, only axisymmetric wave modes are generated. However, in the experiment, the MFC patches can only cover part of the circumference of the pipe where flexural wave modes are also generated. The existence of flexural wave modes lowered the sensibility of axisymmetric wave modes which increased the uncertainty of the RMSD value calculated from the wave packs.

2.) The uncertainty of experimental results came from several aspects:

Both the actuator and the sensor are not only covering part of the circumference of the pipe but also covering part of the pipe in the axial direction, which increased both the difficulty of identification and the dispersion effect of wave packs.

The results of the experiment are highly sensitive to the quality of the signals especially the quality of the baseline signals. It is suggested that the baseline signature should be collected multiple times to ensure the repeatability and stability of the experiment.

3.) Both length and orientation are needed to identify the damage information. When one parameter is known, the results calculated from Eq.5-2 are quite close to the real cases as demonstrated in Figure 5-10, Figure 5-12 and Figure 5-13. However, when both length and orientation of the crack are unknown, more uncertainties arise in the calculated results. The calculated crack length and direction from the numerical simulation results and experimental results are listed in and Table 5-4, respectively.

Table 5-3 Estimated crack orientation(θ) and crack length(l) from numerical simulation

RMSD-T	RMSD-L	Est. θ (deg)	Real θ (deg)	Est. l (mm)	Real l (mm)
0.231496	0.036424	1.81	0	27.8	30
0.365512	0.046202	-0.45	0	44.1	42.5
0.105696	0.053883	29.6	30	12.4	10.68
0.347522	0.190652	33.1	30	40.5	37.38
0.107358	0.067986	41.4	45	12.4	11.34
0.186726	0.140115	55.5	45	21.4	26.46
0.057541	0.045059	60.4	60	6.59	6.16
0.101622	0.081668	64.0	60	11.6	9.24
0.22382	0.191091	75.9	75	25.5	24.876
0.424262	0.359751	74.0	75	48.3	49.752
0.340728	0.296327	82.9	90	38.7	37.38
0.369544	0.319427	80.0	90	42.0	40.05

Table 5-4 Estimated crack orientation (θ) and crack length(l) from experimental results

RMSD-T	RMSD-L	Est. θ (deg)	Real θ (deg)	Est. l (mm)	Actual l (mm)
0.306251	0.051177	0.62	0	26.5	28
0.429529	0.076313	2.58	0	37.5	38
0.073626	0.026877	34.1	30	7.5	8
0.188545	0.072998	37.7	30	19.6	23
0.308997	0.131475	44.1	45	33.0	33
0.542132	0.21497	39.2	45	56.6	48
0.213851	0.093079	45.8	60	23.0	18
0.337299	0.172343	60.3	60	38.2	38
0.226077	0.130805	82.7	75	26.8	18
0.376882	0.184674	55.9	75	42.1	43
0.339626	0.200213	90.6	90	40.6	38
0.33336	0.195805	90.5	90	39.8	43

This RMSD crack index method can roughly provide the crack growth trend and detect its orientation. When simulation model is improved, and advanced signal processing and mode extraction techniques are adopted in the experiment, more accurate results can be expected.

5.5 Summary and Conclusion

This chapter presents an RMSD crack index method to identify the crack orientation and dimension on cylindrical structures. Because of the PM direction of the torsional wave modes and longitudinal wave modes, the axial crack only has a significant effect on the transmitted torsional waves, while the circumferential crack affected both transmitted torsional and longitudinal waves. The RMSD crack index method has been shown to be able to correlate the RMSD value change of the transmitted wave packs with the crack growth.

Simplified numerical simulation and experiments have been conducted to verify the proposed method. The results show that when one parameter is known, the accuracy of the equations is higher than the case when both parameters are unknown. When both parameters are unknown, the accuracy of the proposed method is affected. The improvement of precision may be achieved through the enhancement of the numerical model or the use of advanced mode extraction technique and an advanced signal processing technique to remove the effect of flexural waves and noises.

6 CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

This research explored the possibility of using MFC transducers to set up a close-loop in-situ online SHM system for cylindrical structures. The major contribution of this research are: 1) use oriented MFC patches to generate torsional wave for axial crack monitoring of cylindrical structures because of its flexible character and strong actuating/sensing capacity; 2) use torsional wave RMSD crack index for axial crack growth monitoring of cylindrical structures; and 3) expand its application to estimate arbitrary crack dimension and orientation in cylindrical structures.

This study presents a new proposed method that use axisymmetric wave modes for cylindrical structure SHM.

Firstly, MFC transducers are applied to generate torsional wave for detecting and monitoring axial direction crack growth in tubular structures. The actuator is driven by pre-adjusted signals to generate target waveguides for inspection. The sensor picks up the stress waves propagating in the pipe and returns the electrical signals. With the help of digital signal processing (DSP) techniques, the damage information is extracted from the changes of the sensor's output. Both numerical and experimental verifications have been conducted to demonstrate the effectiveness of this method. The results from the numerical simulation and experimental verification show that the axial-direction crack propagation can be well monitored. The RMSD values of torsional wave pack from a numerical simulation with different crack sizes give a linear trend against the crack size

increment. Based on the analysis of both numerical and experimental results, a linear relationship can be established between the RMSD value of torsional wave pack and the axial direction crack size.

Secondly, the SHM system is developed to pick up not only axial crack growth but also axial crack position. Three pieces of MFC transducers are used in the new regime. The MFC transducer at the center works as the actuator; the other two MFC transducers operate as sensors to detect the axial position of the crack and to monitor the crack size growth, respectively. RMSD crack index is used to monitor the axial crack growth, and TOF-based method is adopted to find the axial position of the crack in cylindrical structures. To eliminate the effect of flexural waves, the residual signal whereby the signal of the undamaged specimen is subtracted from the signal of cracked specimen is used. Both numerical simulation and experimental investigation are conducted to verify the proposed method. The results show that both the axial position and crack size growth of the axial crack can be well located/monitored using this sensing system. In the experimental investigation, the existence of flexural waves, changes of boundary conditions, errors in data processing procedure, etc., all contributed to the reduced accuracy of the results as compared with the numerical simulation. Nevertheless, the experimental data still show promise in the SHM of axial crack in cylindrical structures. Finally, based on the RMSD crack index method, an SHM system to identify the crack orientation and dimension in cylindrical structures are developed. Because of the PM direction of the T-wave modes and L-wave modes, the axial crack only has a significant effect on the transmitted T waves, while the circumferential crack affected both the transmitted T and L waves. The RMSD crack index method has been shown to be able to correlate the RMSD value change of the transmitted wave packs with the crack growth. Both numerical simulation and experiments have been conducted to verify the proposed method. The results show that when one parameter is known, the accuracy of the equations is higher than the case when both parameters are unknown. When both parameters are unknown, the accuracy of the proposed method is affected. The improvement of precision may be achieved through the enhancement of the numerical model or the use of advanced mode extraction technique and an advanced signal processing technique to remove the effect of flexural waves and noises.

From the study performed in this research, we can conclude that using MFC transducers to carry out SHM for the cylindrical structure is efficient and effective.

6.2 Limitation and Future Works

Compared with other SHM system for cylindrical structures, the system proposed in this research is compact, easy to setup and with great mobility. It can be moved to anywhere that the specimen is required to be monitored. It also has the potential to have more industry applications in the future if below points are addressed.

1. To further develop the proposed system to a close-loop in-situ on-line monitoring, smart-integrated system.

Figure 6-1 Proposed SHM system for continuous cylindrical structures

Current experiment setup proposed a prototype for the SHM of cylindrical system. As shown in Figure 6-1, the proposed SHM system can be used for continuous cylindrical structure monitoring. When crack occurred in region R_1 , the MFC transducers T_1 , T_2 and T_3 will work together as a group. In this group, T_1 works as a sensor to pick up additional wave pack reflected from the crack. T_2 works as an actuator and T_3 works as another sensor to collect data to be used for RMSD crack index calculation. Meanwhile, the system will automatically switch from scanning region R_1 to R_2 . In region R_2 , transducers T_2 , T_3 and T_4 will work together as a group where T_3 as actuator and T_2 and T_4 as sensors. The automatic scanning algorithm can be achieved and controlled by the control unit which can be pre-programmed. This proposed system has below benefits:

- In-situ monitoring: multiple pieces of transducers are used in the system, and each of them can monitor its adjacent area;

- On-line monitoring: real-time monitoring can be achieved since real-time feedback can be acquired and analysed right away;
- Close-loop monitoring: the system can perform SHM by its own, both actuating, sensing and data processing can be processed by the programmable control unit.

Due to the limitation of equipment and testing specimen, the proposed SHM system for continuous cylindrical structures is not tested and verified. Implementation work of the SHM system can be expected in the future.

2. To develop automatic data analysis module

The current data processing procedure requires noise cancellation, RMSD crack index calculation, curve fitting and other digital signal process techniques if future information of signal is required. Automatic data analysis module is necessary for the close-loop monitoring system. The collected data can be automatically processed by the developed digital signal processing unit. The background noise can be removed from the signal, and the RMSD crack index as well as the crack location information can be automatically extracted by the control unit. The development of automatic data analysis module can also be expected in the author's future research plan.

3. More DSP techniques for high resolution crack identification for fatigue type of cracks

The current experiment study is focusing on the detection of crack induced wave shape changes on cylindrical structures. With the currently adopted DSP techniques, fracture types of crack can be well detected and monitored. However, for fatigue type of crack, the proposed method is not as efficient as it works for fracture types of crack. To successfully detect and monitor the fatigue type of crack on cylindrical structures, improved DSP techniques are required to remove the noise from the signal collected and to extract the useful information from the output signals.

4. Self-powered actuation and signal transmission

Sometimes, an on-line SHM system requires the transducers to be exposed in the environment that is not accessible to human beings. When the transducer is far from the control system, it is not practical to use wire to connect all the transducers, especially when MFC transducers need to be driven by high voltages. It is suggested to use or to develop a self-powered transducer with wireless signal transmission function.

5. Bondline effect in numerical simulation

The bondline effect is important in numerical simulation as it will change the output signal very much. In this study, the bondline of MFC is simplified to a ring type circle where all nodes on the circle are functioned as actuators. In the experiment, the MFC transferred the deformation to the epoxy and the epoxy transferred the deformation to the hosting structure to generate guided waves. Vice versa, similar reversed process happened at the sensor place. To achieve more accurate SHM results, the simulation of bondline effect of MFC is necessary

6. The influence of environmental effects like temperature and pressure on the guided wave propagation.

The proposed experiment setup had been verified both experimentally and numerically. The verification results had shown its effectiveness to serve the original purpose on laboratory prepared testing specimen. However, guide wave in tubular structures are easy to be affected when the environmental condition is changed. For instance, when the testing temperature is changed, the output signal will also be changed (Codrut, 2014). Since continuous cylindrical structures are often used to transport high temperature and high pressurized crude oil, it is worth to carry out parametric study on the effectiveness of proposed testing method. To carry out SHM of cylindrical structures with high temperature, high pressure fluid in-side, collaboration with industry partner to carry out on-site SHM experiment on continuous cylindrical structure is suggested for future works.

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APPENDIX I LIST OF AUTHOR'S PUBLICATIONS

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APPENDIX II SELECTED MATLAB CODES

1. Matlab code to calculate the slope of the RMSD Value

```
% This is the program for calculating the slope of the RMSD value
% Written by Cui Lin
% Date 2012-06-26
% Version 0.1
% Parameter description
% m is the number of sets of simulation(node release from 0 to 9)
% n is the number of sets of experiment(crack oriented from 90 to 0).
% k is the number of time steps occupied by actuation signal in experiment
% or simulation
% l is the window length( the number of time increment in window)

clc;
clear;
m = 8000;
n = 12;
a0 = 2;
RMSD = zeros(n,m);
crack_length = zeros(n,m);
slope = zeros(n,1);
func=inline('a*x','a','x');

for i = 1:n
    slope(i,1) = nlinfit(crack_length(i,:),RMSD(i,:),func,a0);
end

clc;
clear;
m = 300;
n = 15;
undamaged_data = zeros(m,1); %need to load from data
damaged_data = zeros(m,n); %need to load from data
input = [undamaged_data,damaged_data]; %need to load from data
RMSD= zeros(6,n+1);
l = 50;
data_square = zeros(m,n+1);
temp_rmsd_value = zeros(m-l,n+1);
rmsd_value = zeros(m-l,n+1);

% calculate the undamaged square
data_square(:,1) = input(:,1).^2;
% calculate the RMSD square
for j = 1:n
    for i = 1:m
        data_square(i,j+1) = (input(i,j+1)- input(i,1)).^2;
    end
end

for i = 1:(m-l)
    for index = 1:l
        temp_rmsd_value(i,1) = temp_rmsd_value(i,1)+ data_square(i+index-1,1);
    end
    for j = 1:n
        for index = 1:l
            temp_rmsd_value(i,j+1) = temp_rmsd_value(i,j+1)+ data_square(i+index-1,j+1);
        end
    end
end

rmsd_value(i,j+1) = sqrt(temp_rmsd_value(i,j+1)/temp_rmsd_value(i,1));
end
end
```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

RMSD(1,:) = rmsd_value(111,:);
RMSD(2,:) = rmsd_value(191,:);

RMSD(3,:) = rmsd_value(110,:);
RMSD(4,:) = rmsd_value(190,:);

RMSD(5,:) = rmsd_value(115,:);
RMSD(6,:) = rmsd_value(198,:);

```

2. Matlab code to generate dispersion curves for phase speed and group speed

```

% PCDISP Generates dispersion curves for rods & tubes
%
% Last update: 19-1-2011

clear,clc

% ***** USER INPUT DATA *****
% Parameters of the pipe (iron)
c0 = 5040; % bar speed (m/s)
nu = .29; % Poisson's ratio
%rho = 7900; % density (kg/m^3)
a = 3.5e-3; % internal radius (m)
b = 4e-3; % external radius (m)

% Vector with the circumferential orders to be plotted
% The convention is n = -1 for torsional, n = 0 for
% longitudinal, and n >= 1 for flexural
% ex: nvect = [-1 0 1] for T(0,m), L(0,m) and F(1,m)
nvect = -1:8;

% Frequency range for the computation
fmin = 0; % minimum frequency (Hz)
fmax = 1000e3; % maximum frequency (Hz)
fstep = 10e3; % frequency step (Hz)
ftol = 1e-3; % tolerance (for cutoff frequencies) (Hz)
% default = 1 mHz is a good value

% Phase speed range for the computation
cmax = 12000; % maximum phase speed (m/s)
ctol = 1e-3; % tolerance (m/s)
% default = 1 mm/s is a good value

% Axes limits for the phase and group speeds plots (m/s)
cmin_phase = 0;
cmax_phase = 8000;
cmin_group = 0;
cmax_group = 6000;

% Flags for display of phase and group speeds
display_phase = 1;
display_group = 1;
display_progress = 1; % small cursor
display_speeds = 0; % show the volumetric, rotational & Rayleigh speeds
display_modenames = 1; % displays mode names in the graph (at the end)

% ***** END OF USER INPUT DATA *****

clc
disp('PCdisp running')
disp(' ')

tic

gamma = a/b; % gamma = internal/external radii ratio
Nn = length(nvect);

% Scale factors between real and normalized quantities
% sc = (real)/(normalized)
sc_freq = c0/(2*pi*b); % frequency (adim -> Hz)

```

Appendix II Selected Matlab Codes

```

sc_speed = c0;          % speed (adim -> m/s)

% Computes the normalized velocities
[cvolum,crotat,cthinplate,crayleigh]=pcspeeds(nu);

% Creates a color array, in RGB format
% T(0,m) -> red   L(0,m) -> blue   F(1,m) -> green
% F(n,m) -> shades of green
colorvect = [1 0 0; 0 0 1; 0 1 0; .4 .9 0; .3 .8 0; 0.2 .7 0; 0.1 .6 0; 0 .5 0; 0 .4 0; 0 .3 0; 0 .2 0; 0 .1 0];

% Cutoff frequencies arrays
% (cmax) -> upper cutoff freq (cph = cmax)
% (cinf) -> true cutoff freq (cph = inf)
% length(fcutoff_cinf)>=length(fcutoff_cmax)
Nmvect_cmax = zeros(Nn,1);
Nmvect_cinf = zeros(Nn,1);
fcutoff_cmax = []; % upper cutoff frequencies (cph = cmax)
fcutoff_cinf = []; % true cutoff frequencies (cph = inf)

% Find number of branches, compute cutoff frequencies
disp('Computing cutoff frequencies...')
disp(' ')
for indn=1:Nn,
    % Upper axis cutoff frequencies
    fcutoff_dummy=pcsolvefreqqcf(cmax/sc_speed,fmax/sc_freq,ftol/sc_freq,nvect(indn),nu,gamma);
    Nmvect_cmax(indn) = length(fcutoff_dummy);
    fcutoff_cmax(indn,1:length(fcutoff_dummy))=sc_freq*fcutoff_dummy;
    % True (cph=inf) cutoff frequencies
    fcutoff_dummy=pcsolvefreqqcf(inf,fmax/sc_freq,ftol/sc_freq,nvect(indn),nu,gamma);
    Nmvect_cinf(indn) = length(fcutoff_dummy);
    fcutoff_cinf(indn,1:length(fcutoff_dummy))=sc_freq*fcutoff_dummy;
    if(nvect(indn)==-1),
        disp('---')
        for indm=1:Nmvect_cmax(indn),
            disp(sprintf('T(0,%g): cutoff = %g kHz',indm,fcutoff_cmax(indn,indm)/1e3))
        end
    end
    if(nvect(indn)==0),
        disp('---')
        for indm=1:Nmvect_cmax(indn),
            disp(sprintf('L(0,%g): cutoff = %g kHz',indm,fcutoff_cmax(indn,indm)/1e3))
        end
    end
    if(nvect(indn)>0),
        disp('---')
        for indm=1:Nmvect_cmax(indn),
            disp(sprintf('F(%g,%g): cutoff = %g kHz',nvect(indn),indm,fcutoff_cmax(indn,indm)/1e3))
        end
    end
end
% Total number of branches that will be plotted
Nbranches = sum(Nmvect_cmax);
disp(' ')
disp(sprintf('%g branches will be plotted',Nbranches))

% Creates an "interlaced" array of frequencies, including the
% cutoff frequencies + a little offset
fvect=[pcmkfreqvect(fmin,fmax,fstep) unique(fcutoff_cmax(:))'+fstep/25];
Nf = length(fvect);

% This array will contain the phase speeds
% cph = -1 if that frequency is below cutoff for that given mode & branch
cpharray = -ones(Nn,max(Nmvect_cmax),Nf);

% ***** MAIN LOOP (here we go!) *****

disp(' ')
for indf=1:Nf,
    f = fvect(indf);
    disp(sprintf('Computing roots for frequency f = %g kHz (%g%% done)',f/1e3,round(indf/Nf*100)))

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

for indn = 1:Nn,
    n = nvect(indn);
    disp('---')
    disp(sprintf('n = %g',n))

    % Find number of roots to be computed
    Nrootscomputed=length(find(f>fcutoff_cmax(indn,1:Nmvect_cmax(indn))));

    if (Nrootscomputed>0),
        cph_tmp = sc_speed*pcsolvefreqqfc(f/sc_freq,cmax/sc_speed,...
            ctol/sc_speed,n,nu,gamma,Nrootscomputed);
        disp(sprintf('Found %g of %g roots',length(cph_tmp),Nrootscomputed))
        % Update the roots array
        if (length(cph_tmp)>0),
            cpharray(indn,1:length(cph_tmp),indf) = cph_tmp';
        end
    else,
        disp(sprintf('No roots found for n = %g and f = %g kHz',n,f/1e3))
    end
end

% Let's do the plots
if (display_phase==1),
    figure(1),clf
    axis([fmin/1e3 fmax/1e3 cmin_phase cmax_phase])
    xlabel('Frequency (kHz)')
    ylabel('Phase speed (m/s)')
    title('Dispersion curves (phase speed)')
    set(gca,'Box','on')
    %grid on
    hold on
end
if (display_group==1),
    figure(2),clf
    axis([fmin/1e3 fmax/1e3 cmin_group cmax_group])
    xlabel('Frequency (kHz)')
    ylabel('Group speed (m/s)')
    title('Dispersion curves (group speed)')
    set(gca,'Box','on')
    %grid on
    hold on
end

% First we sort the arrays in ascending frequency order
[fvectsort,sortind] = sort(fvect(1:indf));
cpharraysort = cpharray(:,sortind);
% Update the plots
for indn=1:Nn,
    for indm=1:Nmvect_cmax(indn),
        indplot=find(squeeze(cpharraysort(indn,indm,:))~= -1);
        fplotvect=fvectsort(indplot);
        cphplotvect=squeeze(cpharraysort(indn,indm,indplot));

        % Update phase speed plot
        if (length(fplotvect)>0 & display_phase==1),
            figure(1),plot(fplotvect/1e3,cphplotvect,'Color',colorvect(nvect(indn)+2,:))
        end
        fgplotvect=[];
        cgplotvect=[];
        for indfg=2:length(fplotvect),
            fgplotvect(indfg-1)=(fplotvect(indfg-1)+fplotvect(indfg))/2;
            cgplotvect(indfg-1)=(cphplotvect(indfg-1)+cphplotvect(indfg))^2*...
                (fplotvect(indfg)-fplotvect(indfg-1))/4/...
                (cphplotvect(indfg-1)*fplotvect(indfg)-cphplotvect(indfg)*fplotvect(indfg-1));
        end
        % Update group speed plot
        if (length(fgplotvect)>0 & display_group==1),
            figure(2),plot(fgplotvect/1e3,cgplotvect,'Color',colorvect(nvect(indn)+2,:))
        end
        % Place tags with the mode names
        if (display_modenames==1 & indf==Nf & display_phase==1),
            figure(1),

```

Appendix II Selected Matlab Codes

```

indtag=ceil(rand*length(fplotvect));
text(fplotvect(indtag)/1e3,cphplotvect(indtag),pcmodename(nvect(indn),indm),...
'Color',colorvect(nvect(indn)+2,:));
end
if (display_modenames==1 & indf==Nf & display_group==1),
figure(2),
indtag=ceil(rand*length(fgplotvect));
text(fgplotvect(indtag)/1e3,cgplotvect(indtag),pcmodename(nvect(indn),indm),...
'Color',colorvect(nvect(indn)+2,:));
end
end % loop over m
end % loop over n

if (display_speeds==1 & display_phase==1),
figure(1),
plot([0 fmax]/1e3,cvolum*sc_speed*ones(1,2),'k--')
plot([0 fmax]/1e3,crotat*sc_speed*ones(1,2),'k--')
plot([0 fmax]/1e3,crayleigh*sc_speed*ones(1,2),'k--')
end

if (display_speeds==1 & display_group==1),
figure(2),
plot([0 fmax]/1e3,cvolum*sc_speed*ones(1,2),'k--')
plot([0 fmax]/1e3,crotat*sc_speed*ones(1,2),'k--')
plot([0 fmax]/1e3,crayleigh*sc_speed*ones(1,2),'k--')
end

if(display_progress==1 & display_phase==1 & indf<Nf),
figure(1),plot(f/1e3,cmin_phase,'k^')
end

if(display_progress==1 & display_group==1 & indf<Nf),
figure(2),plot(f/1e3,cmin_group,'k^')
end

drawnow
disp('*****')

drawnow
end % End of frequency loop

fvect = fvectsort;
cpharray = cpharraysort;

toc

```


APPENDIX III SELECTED ANSYS INPUT FILES

1. Undamaged specimen (100 kHz actuation)

```

/filename,20110724-1
!Start new log, error, lock, and page files
/TITLE, shell 100K full actuation NRM undamaged

!Numbers of substeps allowed
FINISH
/PREP7
!-----!
!Geometry Dimensions
!-----!
!Aluminium Pipe
*SET,pipeL , 1.2
*SET,pipeT , 0.003
*SET,pipeR , 0.0495
*SET,INNRAD , 0.048
*SET,OUTRAD , 0.051

*SET,PL,1.2      !m      Length (height) of the pipe
*SET,Ri,0.048    !m      Inner radius of the pipe
*SET,Ro,0.051    !m      Outer radius of the pipe
*SET,RM,0.0495   !m      Mid-layer radius of the pipe
*SET,PT,0.003    !m      pipe thickness
*SET,ML,0.04     !m      lenth of the MFC functional area
*SET,MW,0.01     !m      width of the MFC functional area
*SET,MT,0.00025  !m      thickness of MFC functional area
*SET,Ra,45       !degree  deg angle of the MFC sticking on the outer surface of the pipe
*SET,RA,Ra*acos(-1)/180 !convert the angle from deg to rad
*SET,POFFS1,0.32 !m      location of the Actuator MFC sticking on the pipe from the left end.
*SET,POFFS2,0.9-(ML+MW)*sin(RA) !m      location of the Sensor MFC sticking on the pipe from the left end.
*SET,POFFS3,0.6  !m      crack starting position
*SET,POFFS4,0.87 !m      location of the Sensor
!Piezo and Expoy Offset from the free end of the tube
*SET,OffsetX , 0.20
! - Element type
!
ET,1,shell63      !Aluminum shell Element
!
! - Material properties
!
MP,DENS,1,2715    !Aluminum density, kg/m^3
MP,EX,1,68e9      !Aluminum Young's modulus, N/m^2
MP,PRXY,1,0.33    !Aluminum Poisson's ratio
R,1,pipeT,pipeT,pipeT,pipeT, , , !Real constant of shell element, thickness at point i,j,k,l
RMORE, , , ,
RMORE
RMORE, ,
!-----!
!FEM Domain Geometries
!-----!
K,1,0,0,0
K,2,0,0,pipeL
!create circle at center 1, radius pipeR
Circle,1,pipeR,,,180
lcomb,1,2,0
LSYMM,Y,1
L,1,2
!Drag arc line 1,2,along straght line 3 to create area 1,2
ADrag,1,,,,,3
ADrag,2,,,,,3
!delete line 3
LDELE, 3
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,2
ASEL,S, , ,P51X

```

Appendix III Selected ANSYS INPUT FILES

```

AAtt, 1,1,1,
FLST,5,4,4,ORDE,4
FITEM,5,5
FITEM,5,-6
FITEM,5,8
FITEM,5,-9
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,480,,,,,1
!*
FLST,5,4,4,ORDE,4
FITEM,5,1
FITEM,5,-2
FITEM,5,4
FITEM,5,7
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,60,,,,,1
!*
MSHAPE,0,2D
MSHKEY,1
!*
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL,,,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
Nummrg,node,1e-4
nummrg,kp
allsel,all
csys,1
Nrotat,all
EQSLV,SPARSE      !Use Sparse matrix solver
DMPRAT,0.00       !Define 2% damping ratio
ANTYPE,TRANS      !Perform Transient Analysis
!*
TRNOPT,FULL
LUMPM,0
!*
NSUBST,300,0,0
OUTRES,ERASE
OUTRES,NSOL,1
OUTRES,EPEL,1
TIME,0.0003
FINISH
/SOLU
*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'moment'
*SET,_FNCCSYS,0
! /INPUT,100K moment.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation: 1.5*0.5*(1-cos(2*{PI}*{TIME}/5/10^-5))*sin(2*{PI}*10^5*
! {TIME})
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1.5, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0

```

Appendix III Selected ANSYS INPUT FILES

```

*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation:  $1.5*0.5*(1-\cos(2*\{PI\}*\{TIME\}/5/10^5))*\sin(2*\{PI\}*10^5*$ 
! {TIME})
!
! Begin of equation:  $0*\{TIME\}$ 
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0, 99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation:  $0*\{TIME\}$ 
!->

*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'force'
*SET,_FNCCSYS,0
! /INPUT,100KHz.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,,_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1000, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
!

```

Appendix III Selected ANSYS INPUT FILES

```

! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0, 99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!->

```

```

nset,s,loc,z,poffs1-1e-8,poffs1+1e-8

```

```

f,all,FY,%FORCE%
f,all,FZ,%FORCE%
f,all,MY,%MOMENT%
f,all,MZ,%MOMENT%
alls,all
nset,s,loc,z,PL-1e-8,PL+1e-8
d,all,ux,0
d,all,uy,0
d,all,uz,0
d,all,ROTX,0
D,all,ROTY,0
D,all,ROTZ,0
alls,all

```

```

finish
/solu
solve

```

```

finish
/solu
solve

```

```

SAVE, 20110724-1,db

```

2. Specimen with Longitudinal crack (100 kHz actuation)

```

/filename,20110725-5
!Start new log, error, lock, and page files
/TITLE, shell 100K full actuation NRM release 9 nodes cracked

!Numbers of substeps allowed
FINISH
/PREP7
!-----!
!Geometry Dimensions      !
!-----!
!Aluminium Pipe
*SET,pipeL, 1.2
*SET,pipeT, 0.003
*SET,pipeR, 0.0495
*SET,INNRAD, 0.048
*SET,OUTRAD, 0.051

*SET,PL,1.2      !m    Length (height) of the pipe
*SET,Ri,0.048    !m    Inner radius of the pipe
*SET,Ro,0.051    !m    Outer radius of the pipe
*SET,RM,0.0495   !m    Mid-layer radius of the pipe
*SET,PT,0.003    !m    pipe thickness
*SET,ML,0.04     !m    lenth of the MFC functional area
*SET,MW,0.01     !m    width of the MFC functional area
*SET,MT,0.00025  !m    thickness of MFC functional area
*SET,Ra,45       !degree deg angle of the MFC sticking on the outer surface of the pipe
*SET,RA,Ra*acos(-1)/180 !convert the angle from deg to rad
*SET,POFFS1,0.32 !m    location of the Actuator MFC sticking on the pipe from the left end.
*SET,POFFS2,0.9-(ML+MW)*sin(RA) !m    location of the Sensor MFC sticking on the pipe from the left end.
*SET,POFFS3,0.6  !m    crack starting position
*SET,POFFS4,0.87 !m    location of the Sensor
!Piezo and Expoy Offset from the free end of the tube
*SET,OffsetX, 0.20
! - Element type
!
ET,1,shell63      !Aluminum shell Element
!
! - Material properties
!
MP,DENS,1,2715    !Aluminum density, kg/m^3
MP,EX,1,68e9      !Aluminum Young's modulus, N/m^2
MP,PRXY,1,0.33    !Aluminum Poisson's ratio
R,1,pipeT,pipeT,pipeT,pipeT, , , !Real constant of shell element, thickness at point i,j,k,l
RMORE, , , ,
RMORE
RMORE, ,
!-----!
!FEM Domain Geometries      !
!-----!
K,1,0,0,0
K,2,0,0,pipeL
!create circle at center 1, radius pipeR
Circle,1,pipeR,,,180
lcomb,1,2,0
LSYMM,Y,1
L,1,2
!Drag arc line 1,2,along straght line 3 to create area 1,2
ADRAG,1,,,,,3
ADRAG,2,,,,,3
!delete line 3
LDELE, 3
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,2
ASEL,S, , ,P51X
AAtt, 1,1,1,
FLST,5,4,4,ORDE,4

```

Appendix III Selected ANSYS INPUT FILES

```

FITEM,5,5
FITEM,5,-6
FITEM,5,8
FITEM,5,-9
CM,_Y,LINE
LSEL,, , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,, ,480, , , ,1
!*
FLST,5,4,4,ORDE,4
FITEM,5,1
FITEM,5,-2
FITEM,5,4
FITEM,5,7
CM,_Y,LINE
LSEL,, , ,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,, ,60, , , ,1
!*
MSHAPE,0,2D
MSHKEY,1
!*
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,-2
CM,_Y,AREA
ASEL,, , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*

NSEL,S,LOC,X,-pipeR-1e-10,-pipeR+1e-10,
NUMMRG,NODE,
NSEL,S,LOC,X,pipeR-1e-10,pipeR+1e-10,
NSEL,R,LOC,Z,0,PIPEL/2-0.013
NUMMRG,NODE,
NSEL,S,LOC,X,pipeR-1e-10,pipeR+1e-10,
NSEL,R,LOC,Z,PIPEL/2+0.013,PIPEL
NUMMRG,NODE,

allsel,all
csys,1
Nrotat,all
EQSLV,SPARSE      !Use Sparse matrix solver
DMPRAT,0.00       !Define 2% damping ratio
ANTYPE,TRANS      !Perform Transient Analysis
!*
TRNOPT,FULL
LUMPM,0
!*
NSUBST,300,0,0
OUTRES,ERASE
OUTRES,NSOL,1
OUTRES,EPEL,1
TIME,0.0003
FINISH
/SOLU
*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS

```


HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,_FNCNAME,'moment'
*SET,_FNCCSYS,0
!/INPUT,100K moment.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation: 1.5*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1.5, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0

```

Appendix III Selected ANSYS INPUT FILES

```

*SET,%_FNCNAME%(0,19,2),0.0,-2,0,1,0,0,-1
*SET,%_FNCNAME%(0,20,2),0.0,-4,0,1,-2,2,-1
*SET,%_FNCNAME%(0,21,2),0.0,-1,0,1,-3,3,-4
*SET,%_FNCNAME%(0,22,2),0.0,-2,0,2,0,0,0
*SET,%_FNCNAME%(0,23,2),0.0,-3,0,3.14159265358979310,0,0,-2
*SET,%_FNCNAME%(0,24,2),0.0,-4,0,1,-2,3,-3
*SET,%_FNCNAME%(0,25,2),0.0,-2,0,10,0,0,0
*SET,%_FNCNAME%(0,26,2),0.0,-3,0,5,0,0,-2
*SET,%_FNCNAME%(0,27,2),0.0,-5,0,1,-2,17,-3
*SET,%_FNCNAME%(0,28,2),0.0,-2,0,1,-4,3,-5
*SET,%_FNCNAME%(0,29,2),0.0,-3,0,1,-2,3,1
*SET,%_FNCNAME%(0,30,2),0.0,-2,9,1,-3,0,0
*SET,%_FNCNAME%(0,31,2),0.0,-3,0,1,-1,3,-2
*SET,%_FNCNAME%(0,32,2),0.0,99,0,1,-3,0,0
! End of equation: 1.5*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3),0.001,-999
*SET,%_FNCNAME%(2,0,3),0.0
*SET,%_FNCNAME%(3,0,3),0.0
*SET,%_FNCNAME%(4,0,3),0.0
*SET,%_FNCNAME%(5,0,3),0.0
*SET,%_FNCNAME%(6,0,3),0.0
*SET,%_FNCNAME%(0,1,3),1.0,-1,0,0,0,0,1
*SET,%_FNCNAME%(0,2,3),0.0,-2,0,1,-1,3,1
*SET,%_FNCNAME%(0,3,3),0,99,0,1,-2,0,0
*SET,%_FNCNAME%(0,4,3),0
*SET,%_FNCNAME%(0,5,3),0
*SET,%_FNCNAME%(0,6,3),0
*SET,%_FNCNAME%(0,7,3),0
*SET,%_FNCNAME%(0,8,3),0
*SET,%_FNCNAME%(0,9,3),0
*SET,%_FNCNAME%(0,10,3),0
*SET,%_FNCNAME%(0,11,3),0
*SET,%_FNCNAME%(0,12,3),0
*SET,%_FNCNAME%(0,13,3),0
*SET,%_FNCNAME%(0,14,3),0
*SET,%_FNCNAME%(0,15,3),0
*SET,%_FNCNAME%(0,16,3),0
*SET,%_FNCNAME%(0,17,3),0
*SET,%_FNCNAME%(0,18,3),0
*SET,%_FNCNAME%(0,19,3),0
*SET,%_FNCNAME%(0,20,3),0
*SET,%_FNCNAME%(0,21,3),0
*SET,%_FNCNAME%(0,22,3),0
*SET,%_FNCNAME%(0,23,3),0
*SET,%_FNCNAME%(0,24,3),0
*SET,%_FNCNAME%(0,25,3),0
*SET,%_FNCNAME%(0,26,3),0
*SET,%_FNCNAME%(0,27,3),0
*SET,%_FNCNAME%(0,28,3),0
*SET,%_FNCNAME%(0,29,3),0
*SET,%_FNCNAME%(0,30,3),0
*SET,%_FNCNAME%(0,31,3),0
*SET,%_FNCNAME%(0,32,3),0
! End of equation: 0*{TIME}
!->

*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'force'
*SET,_FNCCSYS,0
!/INPUT,100KHz.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,,_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1),0.0,-999
*SET,%_FNCNAME%(2,0,1),0.0
*SET,%_FNCNAME%(3,0,1),0.0
*SET,%_FNCNAME%(4,0,1),0.0

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(5,0,1), 0,0
*SET,%_FNCNAME%(6,0,1), 0,0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0,0
*SET,%_FNCNAME%(3,0,2), 0,0
*SET,%_FNCNAME%(4,0,2), 0,0
*SET,%_FNCNAME%(5,0,2), 0,0
*SET,%_FNCNAME%(6,0,2), 0,0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1000, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5

```

Appendix III Selected ANSYS INPUT FILES

```

*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0, 99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!!-->
nset,s,loc,z,poffs1-1e-8,poffs1+1e-8
f,all,FY,%FORCE%
f,all,FZ,%FORCE%
f,all,MY,%MOMENT%
f,all,MZ,%MOMENT%
alls,all
nset,s,loc,z,PL-1e-8,PL+1e-8
d,all,ux,0
d,all,uy,0
d,all,uz,0
d,all,ROTX,0
D,all,ROTY,0
D,all,ROTZ,0
alls,all

finish
/solu
solve

finish
/solu
solve

SAVE, 20110725-5,db

```

3. Specimen with Circumferential Crack (100 kHz actuation)

```

/FILNAME, 20120929-1, 1
!Start new log, error, lock, and page file
/TITLE, 1 node released circumferentially Full actuation 100K 1.2m pipe
!/CONFIG,NRES,10000
!Numbers of substeps allowed
FINISH
/PREP7
!-----!
!Geometry Dimensions      !
!-----!
!Aluminium Pipe
*SET,pipeL, 1.2
*SET,pipeT, 0.003
*SET,pipeR, 0.0495
*SET,INNRAD, 0.048
*SET,OUTRAD, 0.051
!Piezo and Expoy Offset from the free end of the tube
*SET,OffsetX1, 0.3
*SET,OffsetX2, 0.9
! - Element type
!
ET,1,shell63      !Aluminum shell Element
!
! - Material properties
!
MP,DENS,1,2700      !Aluminum density, kg/m^3
MP,EX,1,68.9e9      !Aluminum Young's modulus, N/m^2
MP,PRXY,1,0.33      !Aluminum Poisson's ratio
R,1,pipeT,pipeT,pipeT,pipeT,, !Real constant of shell element, thickness at point i,j,k,l
RMORE,, , ,
RMORE
RMORE, ,
!-----!
!FEM Domain Geometries      !
!-----!
K,1,0,0,0
K,2,0,0,pipeL
!create circle at center 1, radius pipeR
Circle,1,pipeR,,,180
lcomb,1,2,0
LSYMM,Y,1
L,1,2
!Drag arc line 1,2,along straght line 3 to create area 1,2
ADRAG,1,,,,,3
ADRAG,2,,,,,3
!delete line 3
LDELE, 3
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,2
ASEL,S, , ,P51X
AAtt, 1,1,1,
FLST,2,2,5,ORDE,2
FITEM,2,1
FITEM,2,2
AGLUE,P51X
wpcsys,-1,0
WPCSYS,-1,1
WPAVE,,,OffsetX1
ASBW,all
wpcsys,-1,0
WPCSYS,-1,1
WPAVE,,,OffsetX2
ASBW,all

wpcsys,-1,0
WPCSYS,-1,1

```

Appendix III Selected ANSYS INPUT FILES

```

WPOFFS,0,0,0.5

ASBW,all, SEPO, delete
wpcsys,-1,0
WPCSYS,-1,1

FLST,5,12,4,ORDE,10
FITEM,5,1
FITEM,5,3
FITEM,5,-4
FITEM,5,8
FITEM,5,-10
FITEM,5,13
FITEM,5,16
FITEM,5,-18
FITEM,5,21
FITEM,5,-22
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,60,,,,,1
!*
FLST,5,4,4,ORDE,3
FITEM,5,2
FITEM,5,5
FITEM,5,-7
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,120,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,19
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,160,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,11
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,80,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,12
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,80,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,20
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,160,,,,,1
!*
MSHAPE,0,2D

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

MSHKEY,0
!*
FLST,5,4,5,ORDE,4
FITEM,5,1
FITEM,5,-2
FITEM,5,4
FITEM,5,8
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
CM,_Y,AREA
ASEL, , , , 9
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
CM,_Y,AREA
ASEL, , , , 10
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
FLST,5,2,5,ORDE,2
FITEM,5,5
FITEM,5,-6
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
allsel,all
csys,1
*AFUN,DEG
NSSEL,S,LOC,Y,-269,89
Nummrg,all

allsel,all

csys,1
Nrotat,all
EQLV,SPARSE      !Use Sparse matrix solver
DMPRAT,0.00      !Define 2% damping ratio

```

Appendix III Selected ANSYS INPUT FILES

```

ANTYPE,TRANS      !Perform Transient Analysis
!*
TRNOPT,FULL
LUMPM,0
!*
NSUBST,300,0,0
OUTRES,ERASE
OUTRES,NSOL,1
TIME,0.0003
FINISH
/SOLU
*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'moment'
*SET,_FNCCSYS,0
! /INPUT,100K moment.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation:  $1.5*0.5*(1-\cos(2*\{PI\}*\{TIME\}/5/10^5))*\sin(2*\{PI\}*10^5*\{TIME\})$ 
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1.5, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0

```


HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1.5*0.5*(1-cos(2*{PI}*{TIME}/5/10^-5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0.99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!-->

```

Appendix III Selected ANSYS INPUT FILES

```

*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'force'
*SET,_FNCCSYS,0
! /INPUT,100KHz.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation:  $1000*0.5*(1-\cos(2*\{PI\}*\{TIME\}/5/10^5))*\sin(2*\{PI\}*10^5*\{TIME\})$ 
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1000, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^-5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0, 99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!-->

nset,s,loc,z,0.3-0.0001,0.3+0.0001
f,all,MY,%moment%
f,all,MZ,%moment%
f,all,FY,%force%
f,all,FZ,%force%
nset,s,loc,z,1.2
d,all,all,0

```

Appendix III Selected ANSYS INPUT FILES

```
allsel,all
finish
/solu
solve

SAVE, 20120929-1,db
finish

/POST26
FILE,'20120929-1','rst',''
/UI,COLL,1
NUMVAR,200
SOLU,191,NCMIT
STORE,MERGE
FILLDATA,191,,,1,1
REALVAR,191,191
!*
NSOL,2,331,U,Y,UY_331
STORE,MERGE
!*
NSOL,3,331,U,Z,UZ_331
STORE,MERGE
!*

! XVAR,1
! PLVAR,2,3,

! Save time history variables to file 20120929-1-90.csv
*CREATE,scratch,gui
*DEL,_P26_EXPORT
*DIM,_P26_EXPORT,TABLE,300,2
VGET,_P26_EXPORT(1,0),1
VGET,_P26_EXPORT(1,1),2
VGET,_P26_EXPORT(1,2),3

/OUTPUT,'20120929-1-90','csv',''
*VWRITE,TIME,'UY_331','UZ_331'
%C, %C, %C
*VWRITE,_P26_EXPORT(1,0),_P26_EXPORT(1,1),_P26_EXPORT(1,2)
%G, %G, %G
/OUTPUT,TERM
*END
/INPUT,scratch,gui
! End of time history save
```

4. Specimen with 30 degree oriented crack (100 kHz actuation)

```

/FILNAME, 20121003-3, 1
!Start new log, error, lock, and page file
/TITLE, 3 nodes release 30 degree Full actuation 100K 1.2m pipe
!/CONFIG,NRES,10000
!Numbers of substeps allowed
FINISH
/PREP7
!-----!
!Geometry Dimensions      !
!-----!
!Aluminium Pipe
*SET,pipeL, 1.2
*SET,pipeT, 0.003
*SET,pipeR, 0.0495
*SET,INNRAD, 0.048
*SET,OUTRAD, 0.051
!Piezo and Expoy Offset from the free end of the tube
*SET,OffsetX1, 0.3
*SET,OffsetX2, 0.9
! - Element type
!
ET,1,shell63      !Aluminum shell Element
!
! - Material properties
!
MP,DENS,1,2700      !Aluminum density, kg/m^3
MP,EX,1,68.9e9      !Aluminum Young's modulus, N/m^2
MP,PRXY,1,0.33      !Aluminum Poisson's ratio
R,1,pipeT,pipeT,pipeT,pipeT,, !Real constant of shell element, thickness at point i,j,k,l
RMORE,, , ,
RMORE
RMORE, ,
!-----!
!FEM Domain Geometries      !
!-----!
K,1,0,0,0
K,2,0,0,pipeL
!create circle at center 1, radius pipeR
Circle,1,pipeR,,,180
lcomb,1,2,0
LSYMM,Y,1
L,1,2
!Drag arc line 1,2,along straght line 3 to create area 1,2
ADRAG,1,,,,,3
ADRAG,2,,,,,3
!delete line 3
LDELE, 3
FLST,5,2,5,ORDE,2
FITEM,5,1
FITEM,5,2
ASEL,S, , ,P51X
AAtt, 1,1,1,
FLST,2,2,5,ORDE,2
FITEM,2,1
FITEM,2,2
AGLUE,P51X
wpcsys,-1,0
WPCSYS,-1,1
WPAVE,,,OffsetX1
ASBW,all
wpcsys,-1,0
WPCSYS,-1,1
WPAVE,,,OffsetX2
ASBW,all

wpcsys,-1,0
WPCSYS,-1,1

```

Appendix III Selected ANSYS INPUT FILES

```

WPOFFS,0,0,0.5
WPROTA,0,0,-60
ASBW,all, SEPO, delete
wpcsys,-1,0
WPCSYS,-1,1

FLST,5,12,4,ORDE,10
FITEM,5,1
FITEM,5,3
FITEM,5,-4
FITEM,5,8
FITEM,5,-10
FITEM,5,13
FITEM,5,16
FITEM,5,-18
FITEM,5,21
FITEM,5,-22
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,60,,,,,1
!*
FLST,5,4,4,ORDE,3
FITEM,5,2
FITEM,5,5
FITEM,5,-7
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,120,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,19
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,160,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,11
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,80,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,12
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,80,,,,,1
!*
FLST,5,1,4,ORDE,1
FITEM,5,20
CM,_Y,LINE
LSEL,,,P51X
CM,_Y1,LINE
CMSEL,,_Y
!*
LESIZE,_Y1,,,160,,,,,1
!*
MSHAPE,0,2D

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

MSHKEY,0
!*
FLST,5,4,5,ORDE,4
FITEM,5,1
FITEM,5,-2
FITEM,5,4
FITEM,5,8
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
CM,_Y,AREA
ASEL, , , , 9
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
CM,_Y,AREA
ASEL, , , , 10
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
FLST,5,2,5,ORDE,2
FITEM,5,5
FITEM,5,-6
CM,_Y,AREA
ASEL, , , ,P51X
CM,_Y1,AREA
CHKMSH,'AREA'
CMSEL,S,_Y
!*
AMESH,_Y1
!*
CMDELE,_Y
CMDELE,_Y1
CMDELE,_Y2
!*
allsel,all
csys,1
*AFUN,DEG
NSSEL,S,LOC,Y,-266,86
Nummrg,all

allsel,all

csys,1
Nrotat,all
EQLV,SPARSE      !Use Sparse matrix solver
DMPRAT,0.00      !Define 2% damping ratio

```

Appendix III Selected ANSYS INPUT FILES

```

ANTYPE,TRANS      !Perform Transient Analysis
!*
TRNOPT,FULL
LUMPM,0
!*
NSUBST,300,0,0
OUTRES,ERASE
OUTRES,NSOL,1
TIME,0.0003
FINISH
/SOLU
*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'moment'
*SET,_FNCCSYS,0
! /INPUT,100K moment.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation:  $1.5*0.5*(1-\cos(2*\{PI\}*\{TIME\}/5/10^5))*\sin(2*\{PI\}*10^5*\{TIME\})$ 
!*
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1.5, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0

```


HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1
*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1.5*0.5*(1-cos(2*{PI}*{TIME}/5/10^-5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0.99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!-->

```

Appendix III Selected ANSYS INPUT FILES

```

*DEL,_FNCNAME
*DEL,_FNCMTID
*DEL,_FNCCSYS
*SET,_FNCNAME,'force'
*SET,_FNCCSYS,0
! /INPUT,100KHz.func,,,1
*DIM,%_FNCNAME%,TABLE,6,32,3,,,,,%_FNCCSYS%
!
! Begin of equation: {TIME}
*SET,%_FNCNAME%(0,0,1), 0.0, -999
*SET,%_FNCNAME%(2,0,1), 0.0
*SET,%_FNCNAME%(3,0,1), 0.0
*SET,%_FNCNAME%(4,0,1), 0.0
*SET,%_FNCNAME%(5,0,1), 0.0
*SET,%_FNCNAME%(6,0,1), 0.0
*SET,%_FNCNAME%(0,1,1), 1.0, 99, 0, 1, 1, 0, 0
*SET,%_FNCNAME%(0,2,1), 0
*SET,%_FNCNAME%(0,3,1), 0
*SET,%_FNCNAME%(0,4,1), 0
*SET,%_FNCNAME%(0,5,1), 0
*SET,%_FNCNAME%(0,6,1), 0
*SET,%_FNCNAME%(0,7,1), 0
*SET,%_FNCNAME%(0,8,1), 0
*SET,%_FNCNAME%(0,9,1), 0
*SET,%_FNCNAME%(0,10,1), 0
*SET,%_FNCNAME%(0,11,1), 0
*SET,%_FNCNAME%(0,12,1), 0
*SET,%_FNCNAME%(0,13,1), 0
*SET,%_FNCNAME%(0,14,1), 0
*SET,%_FNCNAME%(0,15,1), 0
*SET,%_FNCNAME%(0,16,1), 0
*SET,%_FNCNAME%(0,17,1), 0
*SET,%_FNCNAME%(0,18,1), 0
*SET,%_FNCNAME%(0,19,1), 0
*SET,%_FNCNAME%(0,20,1), 0
*SET,%_FNCNAME%(0,21,1), 0
*SET,%_FNCNAME%(0,22,1), 0
*SET,%_FNCNAME%(0,23,1), 0
*SET,%_FNCNAME%(0,24,1), 0
*SET,%_FNCNAME%(0,25,1), 0
*SET,%_FNCNAME%(0,26,1), 0
*SET,%_FNCNAME%(0,27,1), 0
*SET,%_FNCNAME%(0,28,1), 0
*SET,%_FNCNAME%(0,29,1), 0
*SET,%_FNCNAME%(0,30,1), 0
*SET,%_FNCNAME%(0,31,1), 0
*SET,%_FNCNAME%(0,32,1), 0
! End of equation: {TIME}
!
! Begin of equation:  $1000*0.5*(1-\cos(2*\{PI\}*\{TIME\}/5/10^5))*\sin(2*\{PI\}*10^5*\{TIME\})$ 
*SET,%_FNCNAME%(0,0,2), 0.00005, -999
*SET,%_FNCNAME%(2,0,2), 0.0
*SET,%_FNCNAME%(3,0,2), 0.0
*SET,%_FNCNAME%(4,0,2), 0.0
*SET,%_FNCNAME%(5,0,2), 0.0
*SET,%_FNCNAME%(6,0,2), 0.0
*SET,%_FNCNAME%(0,1,2), 1.0, -1, 0, 1000, 0, 0, 0
*SET,%_FNCNAME%(0,2,2), 0.0, -2, 0, 0.5, 0, 0, -1
*SET,%_FNCNAME%(0,3,2), 0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,4,2), 0.0, -1, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,5,2), 0.0, -2, 0, 3.14159265358979310, 0, 0, -1
*SET,%_FNCNAME%(0,6,2), 0.0, -4, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,7,2), 0.0, -1, 0, 1, -4, 3, 1
*SET,%_FNCNAME%(0,8,2), 0.0, -2, 0, 5, 0, 0, -1
*SET,%_FNCNAME%(0,9,2), 0.0, -4, 0, 1, -1, 4, -2
*SET,%_FNCNAME%(0,10,2), 0.0, -1, 0, 0, 0, 0, 0
*SET,%_FNCNAME%(0,11,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,12,2), 0.0, -5, 0, 1, -1, 2, -2
*SET,%_FNCNAME%(0,13,2), 0.0, -1, 0, 5, 0, 0, -5
*SET,%_FNCNAME%(0,14,2), 0.0, -2, 0, 1, -5, 3, -1

```

HEALTH MONITORING OF CYLINDRICAL STRUCTURES USING MFC TRANSDUCERS

```

*SET,%_FNCNAME%(0,15,2), 0.0, -1, 0, 10, 0, 0, -2
*SET,%_FNCNAME%(0,16,2), 0.0, -5, 0, 1, -1, 17, -2
*SET,%_FNCNAME%(0,17,2), 0.0, -1, 0, 1, -4, 4, -5
*SET,%_FNCNAME%(0,18,2), 0.0, -1, 10, 1, -1, 0, 0
*SET,%_FNCNAME%(0,19,2), 0.0, -2, 0, 1, 0, 0, -1
*SET,%_FNCNAME%(0,20,2), 0.0, -4, 0, 1, -2, 2, -1
*SET,%_FNCNAME%(0,21,2), 0.0, -1, 0, 1, -3, 3, -4
*SET,%_FNCNAME%(0,22,2), 0.0, -2, 0, 2, 0, 0, 0
*SET,%_FNCNAME%(0,23,2), 0.0, -3, 0, 3.14159265358979310, 0, 0, -2
*SET,%_FNCNAME%(0,24,2), 0.0, -4, 0, 1, -2, 3, -3
*SET,%_FNCNAME%(0,25,2), 0.0, -2, 0, 10, 0, 0, 0
*SET,%_FNCNAME%(0,26,2), 0.0, -3, 0, 5, 0, 0, -2
*SET,%_FNCNAME%(0,27,2), 0.0, -5, 0, 1, -2, 17, -3
*SET,%_FNCNAME%(0,28,2), 0.0, -2, 0, 1, -4, 3, -5
*SET,%_FNCNAME%(0,29,2), 0.0, -3, 0, 1, -2, 3, 1
*SET,%_FNCNAME%(0,30,2), 0.0, -2, 9, 1, -3, 0, 0
*SET,%_FNCNAME%(0,31,2), 0.0, -3, 0, 1, -1, 3, -2
*SET,%_FNCNAME%(0,32,2), 0.0, 99, 0, 1, -3, 0, 0
! End of equation: 1000*0.5*(1-cos(2*{PI}*{TIME}/5/10^-5))*sin(2*{PI}*10^5*
! {TIME})
!
! Begin of equation: 0*{TIME}
*SET,%_FNCNAME%(0,0,3), 0.001, -999
*SET,%_FNCNAME%(2,0,3), 0.0
*SET,%_FNCNAME%(3,0,3), 0.0
*SET,%_FNCNAME%(4,0,3), 0.0
*SET,%_FNCNAME%(5,0,3), 0.0
*SET,%_FNCNAME%(6,0,3), 0.0
*SET,%_FNCNAME%(0,1,3), 1.0, -1, 0, 0, 0, 0, 1
*SET,%_FNCNAME%(0,2,3), 0.0, -2, 0, 1, -1, 3, 1
*SET,%_FNCNAME%(0,3,3), 0, 99, 0, 1, -2, 0, 0
*SET,%_FNCNAME%(0,4,3), 0
*SET,%_FNCNAME%(0,5,3), 0
*SET,%_FNCNAME%(0,6,3), 0
*SET,%_FNCNAME%(0,7,3), 0
*SET,%_FNCNAME%(0,8,3), 0
*SET,%_FNCNAME%(0,9,3), 0
*SET,%_FNCNAME%(0,10,3), 0
*SET,%_FNCNAME%(0,11,3), 0
*SET,%_FNCNAME%(0,12,3), 0
*SET,%_FNCNAME%(0,13,3), 0
*SET,%_FNCNAME%(0,14,3), 0
*SET,%_FNCNAME%(0,15,3), 0
*SET,%_FNCNAME%(0,16,3), 0
*SET,%_FNCNAME%(0,17,3), 0
*SET,%_FNCNAME%(0,18,3), 0
*SET,%_FNCNAME%(0,19,3), 0
*SET,%_FNCNAME%(0,20,3), 0
*SET,%_FNCNAME%(0,21,3), 0
*SET,%_FNCNAME%(0,22,3), 0
*SET,%_FNCNAME%(0,23,3), 0
*SET,%_FNCNAME%(0,24,3), 0
*SET,%_FNCNAME%(0,25,3), 0
*SET,%_FNCNAME%(0,26,3), 0
*SET,%_FNCNAME%(0,27,3), 0
*SET,%_FNCNAME%(0,28,3), 0
*SET,%_FNCNAME%(0,29,3), 0
*SET,%_FNCNAME%(0,30,3), 0
*SET,%_FNCNAME%(0,31,3), 0
*SET,%_FNCNAME%(0,32,3), 0
! End of equation: 0*{TIME}
!-->

nset,s,loc,z,0.3-0.0001,0.3+0.0001
f,all,MY,%moment%
f,all,MZ,%moment%
f,all,FY,%force%
f,all,FZ,%force%
nset,s,loc,z,1.2
d,all,all,0

```

Appendix III Selected ANSYS INPUT FILES

```
allsel,all
finish
/solu
solve

SAVE, 20121003-3,db
finish

/POST26
FILE,'20121003-3','rst',''
/UI,COLL,1
NUMVAR,200
SOLU,191,NCMIT
STORE,MERGE
FILLDATA,191,,,1,1
REALVAR,191,191
!*
NSOL,2,331,U,Y,UY_331
STORE,MERGE
!*
NSOL,3,331,U,Z,UZ_331
STORE,MERGE

! XVAR,1
! PLVAR,2,3,

! Save time history variables to file 20121003-3-90.csv
*CREATE,scratch,gui
*DEL,_P26_EXPORT
*DIM,_P26_EXPORT,TABLE,300,2
VGET,_P26_EXPORT(1,0),1
VGET,_P26_EXPORT(1,1),2
VGET,_P26_EXPORT(1,2),3

/OUTPUT,'20121003-3-90','csv',''
*VWRITE,'TIME','UY_331','UZ_331'
%C, %C, %C
*VWRITE,_P26_EXPORT(1,0),_P26_EXPORT(1,1),_P26_EXPORT(1,2)
%G, %G, %G
/OUTPUT,TERM
*END
/INPUT,scratch,gui
```