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INFLUENCE OF DYNAMIC LOAD AND TEMPERATURE ON
GUIDED WAVE ULTRASONIC DAMAGE DETECTION IN THIN
PLATES

SCHOOL OF AEROSPACE TRANSPORTATION AND
MANUFACTURING
(Manufacturing)

PhD

Academic Year: 2020 - 2023

Supervisor: Dr Muhammad Ali Khan
Associate Supervisor: Professor Andrew Starr
August 2023



School of Aerospace Transportation and Manufacturing

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Manufacturing Engineering
(NB. Remove if the degree award is based solely on examination of the thesis)

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ABSTRACT

Long-thin metallic materials are essentially used in constructing structures of high economic importance, but their service life is shortened by damage such as cracks, corrosion, cavities, notches, and dents. Damage is an inevitable condition of metallic structures over time and, when not detected, could result in a catastrophic breakdown. In the past decades, high interest has been developed in using the guided wave ultrasonic technique (GWUT) to monitor the health of structures and detect damage due to its long-distance coverage potential with little attenuation and cost-effectiveness. Most guided wave ultrasonic studies have focused on detecting and characterising empty cracks or notches. Limited literature is available to explain the behaviour of guided waves while travelling in thin plates exposed to damage filled with debris, which is more likely possible in long-thin structures such as pipelines for oil, water or gas transportation. Debris-filled damage leads to corrosion processes, particularly inducing pitting corrosion. This form of corrosion is localised and difficult to detect. It has contributed to many structural failures, particularly in oil and gas pipelines. Hence, early detection and characterisation of this form of damage is vital to avert catastrophic failure. This study explored the detection of damage filled with different proportions of debris in thin plates using guided wave ultrasonic techniques. The captured response signals underwent analysis through various signal-processing methods in MATLAB. Additionally, the research examined how temperature variations and low-frequency vibrations impact the guided wave responses, aiming to simulate the effect of environmental operation conditions. Through the analysis, an empirical model was developed to predict debris-filled damage and differentiate it from empty damage and the health state of the structure. The predictive model has an average error of about 1.34. Also, the analysis revealed that cross-correlation of the detrended response and reference signals could demonstrate a quick way to visualise and spot debris-filled damage in the structure. Additionally, a model called Olisa-Khan low-vibration mitigation architecture (Olisa-Khan LMA) was created to counteract the severe effects of varying low-frequency vibrations and improve the performance of the damage detection technique. The average percentage deviation of the model response signal and

static response signal was about 1.64 %, suggesting the two signals are very close. The slight deviation could be attributed to the signal loss due to clipping and imperfection in the system. In characterising debris that filled the damage, an excitation signal with a central frequency of 80KHz was found optimal because the deviation of each state of damage differs from the other and decreases from an empty case to a debris-filled case and continues as fluid-filled viscosity increases. The study's merit cannot be overemphasised as it establishes models, especially for predicting novel damage of debris-filled and characterising different debris that filled the damage even in severe environmental operation conditions. Hence, the study would be useful for continuously monitoring long-thin structures of high economic values for possible damage detection and characterisation.

ACKNOWLEDGEMENTS

First and foremost, I extend my deepest gratitude to the Almighty God for bestowing me with strength, patience, and wisdom throughout this challenging yet rewarding academic journey. It is in His grace that all things are made possible.

To my mother, Mrs Regina Olisa, whose unwavering belief in my capabilities was the foundation upon which I built my aspirations. I am forever indebted to your love and relentless support. You have been my guiding star and the embodiment of strength.

My loving wife, Lady Juliet Olisa, and my cherished children, Wisdom Olisa, Starr Olisa and Sunshine Olisa, have been my constant inspiration and joy. Your patience, understanding, and unconditional love provided the warmth and solace I needed during my most trying moments. I am profoundly grateful for the joy you bring into my life. Each page of this thesis contains fragments of the sacrifices you have made and the love you have given. I love you guys forever.

I sincerely appreciate my supervisor, Muhammad Khan, whose mentorship, guidance, and expertise have been invaluable throughout this academic voyage. Your insights, patience, and unwavering support have significantly shaped this research and my scholarly growth. I will remain grateful.

Lastly, I would like to express my heartfelt gratitude to the Petroleum Technology Development Funding (PTDF) for the generous sponsorship and unwavering faith in my potential. Studying at Cranfield University, United Kingdom, has been a transformative experience, and I am eternally grateful for that.

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1 CHAPTER ONE: MOTIVATION AND BACKGROUND STUDY

1.1 Introduction and Motivation

According to American philosopher, Ralph Waldo Emerson in 1960, “First wealth is Health”[1]. This popular saying emphasises the paramount importance of being healthy in our lives. It implies that being healthy is not just desirable; it holds value like wealth, upon which everything in life is achieved. This could be likened to structures. Most civil engineering structures are constructed using metallic parts to perform a task or more. The task would be continually executed at nearly optimum capacity if the structure is healthy. Hence, a healthy state allows structures to perform their tasks diligently as designed and likely increases process productivity with good efficiency. However, it is inevitable for structures in operation to evade damage. Damage is a state of structure that differs from its pristine state[2]. In the context of damage monitoring and detection, the pristine state is considered the healthy state or the original health condition of the structure that is mostly devoid of any form of damage. It could also be referred to as the original or reference state of the structure before damage occurrence. Damage is an indispensable factor affecting the structure's service life cycle and its reliability for intended operational services. It could be initiated in the structural material at the micro-level during the manufacturing process and progresses into macro-level during the service time of the structure[3].

The most studied structural material damage is corrosion, notch, cracks, delamination, impact damage, and weld defects [4]–[6]. Each of the damage has a phenomenal way of affecting the structural material and deteriorating its load-carrying capacity. Corrosion is the major localized damage that affects metallic structures as they experience some form of interaction with several diverse environments, especially in the oil and gas industry. For instance, corrosion activities on structural materials result in thickness thinning with a detrimental effect of localised stress concentration that could initiate cracks or cause early failure of the structure. Formed cracks in structures act as stress risers and reduce its load-carrying capacity. Under applied loads, cracks propagate, leading

to catastrophic failure when they are not detected and repaired. Hence, the prime effects of corrosion and cracks on metallic structures are thickness thinning, rigidity and load-carrying capacity reduction[7]. Therefore, it could be said that damage jeopardizes the structural integrity and leads to its sudden failure, which could claim lives and destroy the environment, assets, and the economy.

The cost of structural damage is enormous. For the past three decades, pipelines have cost over \$7 billion in property damage [8]. According to a National Association of Corrosion Engineers (NACE) study, the annual cost of corrosion in the oil and gas production industry is estimated to be \$1.372 billion [9]. According to Victor Giurgiutu (2014), maintaining structural facilities in the United States costs over \$200 billion yearly [10]. Similarly, in Nigeria, corrosion damage has cost a huge sum of money in dollars and caused environmental degradation through oil spillage [11]. It is estimated that the Nigerian oil and gas industry loses up to \$765 million annually due to the corrosion of oil pipelines [12]. The detrimental effects of corrosion-related damage in oil and gas are pipeline leakages, pipeline bursting of pipelines, fire outbreaks, water and air pollution, and loss of agricultural land. All these affect the quality of human lives, which should not be the case.

Maintenance and safety measures are to be prioritised to checkmate damage in structures and assure their integrity. Different nondestructive techniques (NDT) have been used to monitor, detect, and evaluate structural damage. NDTs, unlike destructive techniques (DT), assess structural integrity and detect damage without causing any form of harm to the host structure. This implies that NDTs are sustainable means of structural evaluation as they do not harm the structure. Some of the NDTs are Ultrasonic-based Nondestructive Testing, Radiographic Testing (RT), Magnetic Particle Testing (MT), Liquid Penetrant Testing (PT), Thermography Testing (TT), Acoustic Emission Testing (AE), Eddy Current Testing (ECT). Each of these techniques differs from the other based on the principle of operation [13]. These methods have advantages and disadvantages that determine whether they are appropriate for a given damage evaluation or not.

1.2 Research Problem and Significance

Metallic parts are primarily used in constructing civil structures. These structures are bound to age and deteriorate due to changes in their mechanical properties when exposed to varying conditions. The long cumulative effect of property variations on the structures results in a catastrophic failure that is detrimental to the economy, environment, and human lives. In the oil and gas industry, pipelines are considered the fastest means to transport crude and refined oils starting from exploration sites [14]. Pipelines are mostly constructed from thin mild carbon steel due to its properties of durability and strength[15]. Due to the high risk of hazardous chemicals and the outburst of pipelines because of degradation, safety is highly prioritised. However, corrosion is prevalent in this sector, accounting for huge industry maintenance costs and safety issues [12]. As a metallic structure's age and service time increase, its strength deteriorates and hastens through damage such as corrosion attack that causes thickness reduction[16]. Corrosion activities are stochastic and threaten structural integrity through thickness and strength reduction, leading to stress concentration at the localised damage [17]. Corrosion activities can occur internally or externally. Internal corruptions are initiated through an erosion attack on the inner surfaces of the structure, while external corrosion is initiated through an accidental event that could cause a dent, a cut, a notch or a crack in the structure. The processes of any of this damage leading to pitting corrosion are elucidated in Chapter 4.

There are different forms of corrosion, but pitting corrosion has been considered to be the most prevalent and serious form of corrosion in the oil and gas sector [18]. According to Abdel-Ghany et al., pitting corrosion is classified as one of the most fatal forms of corrosion[19]. This is due to its localized attack form that is hard to detect. The difficulties of detection arise when the pit, once nucleated, is usually covered with corrosion products or other foreign particles, which is described as debris-filled damage (DFD) in this study[19][20]. Also, a sustained dent or crack in the structure could behave as a covered pit if when trapped and accumulated debris or foreign particles that would initiate corrosion activities in an adverse environment. Hence, early detection of DFD damage is paramount to avoid catastrophic failure of the structure and assure the safety and reliability of

the structure for optimal performance. Although DFD is an active damage, it cannot emit acoustic signals sufficient to detect it. Different nondestructive techniques are used to detect and evaluate damage in structure as mentioned in subsection 1.1 however, guided waves ultrasonic testing (GWUT) is the most preferable of all. This could be attributed to its suitability for online and offline structural health monitoring (SHM), potential for long-range inspection from a single point of structural interrogation and estimation of damage severity [21] using variation in the sensitive characteristics of the propagating wave such as amplitude, velocity, phase, Time-of-Flight(ToF) or Time-of-Arrival (ToA)[22]–[25]. Unlike conventional ultrasonic testing, guided waves propagate through the structure's thickness [26]. They are referred to as "guided" because they follow specific paths or modes within the material, which allows them to travel for longer distances and interact with larger volumes of the material. Guided waves interact with structures and pick information about them, resulting in characteristic variations in response signals. Through signal processing, the picked information of the structure is revealed and correlated with the structure's state of health. However, environmental operation conditions, especially temperature, affect the structural materials and influence the propagating elastic wave.

1.3 Research Aim and Objectives

The study aims to detect a novel type of damage, debris-filled damage (DFD) in a thin structure using guided wave ultrasonic response signals and evaluate the influence of environmental operation conditions in the process. To achieve the aim, the following objectives were set out.

Objective 1: Review scholarly articles on guided wave propagation in thin material structures and damage detection approaches to identify a suitable technique for debris fill damage detection.

Objective 2: Develop an empirical predictive model for debris deposition percentage detection in thin structures.

Objective 3: Evaluate the combined effect of temperature and debris deposition percentage in damage to propagating elastic wave.

Objective-4: Evaluate the effect of external low-frequency vibration on elastic wave propagating in a thin structure.

Objective-5: Differentiate healthy state responses from different fluid-filled damage responses of the structure.

1.4 Research Methodology

The study commenced with a literature review of related articles on structural health monitoring and to find a research gap. The review covered literature on UGWs, damage inspection, severity, temperature influence on the guided wave and parametric characteristics of the inspecting wave. It was noted that more research was needed to comprehend how debris fill-in damage affects ultrasonic response signals. Research plans were created to address the problem through the outlined objectives. Different experimental schemes were performed, starting with baseline signal acquisition to current signal acquisition under different damage situations. Analysis and signal processing were performed on the captured response signals. Through the schemes, empirical models were developed to enhance diagnosis that would promote the safety and efficient operation of structures through fast detection of damage, especially debris-filled damage and to evade the eventuality of catastrophic failure. The models were validated using extra observed data.

1.5 Organization of the work

The thesis is organised as follows. A review of related studies was discussed in **Chapter 2**, through which the study problem and methodology were identified. **Chapter 3** explained the study methodology, emphasizing the model and different experiments conducted. In **Chapter 4**, an empirical predictive model for detecting debris-filled damage in thin structure damage was established. In **Chapter 5**, the confluence effect of temperature and debris-filled damage on guided wave response was discussed, while the effect of external low-frequency vibration on elastic wave propagating in thin structures was evaluated in **Chapter 6** to encompass the influence of external conditions on damage detection. **Chapter 7** discussed differentiating healthy state responses of thin structures

from fluid-filled damage responses, and the conclusion of the study with recommendations for further studies are discussed in **Chapter 8**.

2 CHAPTER TWO: REVIEW OF LITERATURES AND RELATED WORKS

2.1 Overview

This chapter reviewed the literature on ultrasonic guided waves (UGWs), damage inspection approaches, damage severity estimation, temperature influence on the guided wave and parametric characteristics of the inspecting wave. The review is limited to the piezoelectric transduction unit.

2.2 Introduction

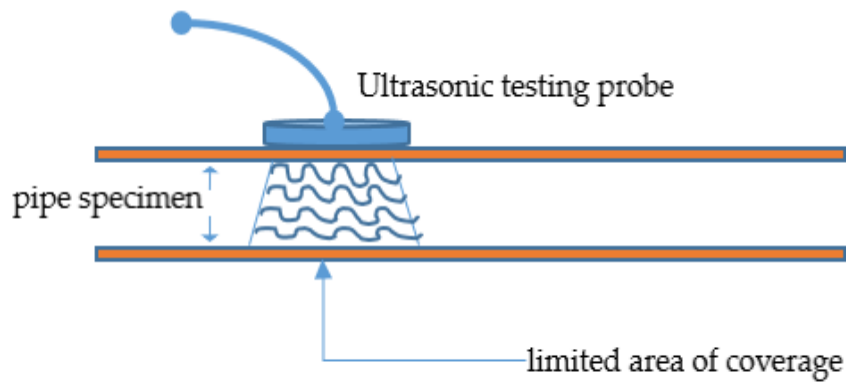
Metallic structures are essential in our society as they are used to perform crucial functions of economic importance. Some structures—such as oil pipelines, railways, aircraft, bridges, etc.—support or convey products prone to hazards. Structures are abounded to age and deteriorate due to changes in their material properties [27][28]. The properties could be mechanical—such as elastic Young's modulus E , Poisson ratio ν , density ρ —or geometrical properties—such as length, thickness, or shape [28]. Load stress and environmental operational conditions affect the structures and contribute to its property variation [29]–[33]. The accumulation of these changes over time results in a catastrophic structural failure that may be detrimental to the economy, environment and human lives [34]. Hence, appraising the structure's healthy state is imperative and necessitates approaches and techniques that could offer the needed information quickly, accurately, and reliably.

Conventionally, inspection for damage on a structure can be appraised visually and manually but principally limited to its surface access. There is a need for damage inspection beyond the surface, hence the non-destructive testing, NDT [35], [36]. Researchers and industries adopt non-destructive testing to inspect structures' internal and external health conditions without destroying it [34]. NDT provides the capability to monitor the structures' health state and detect flaws, thereby impeding and averting possible hazardous failures.

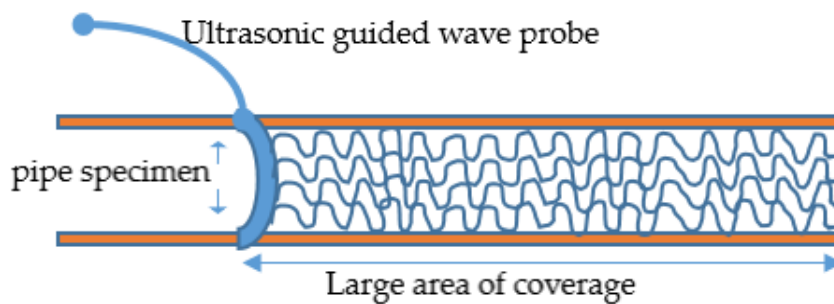
The guided wave ultrasonic testing (GWUT) method is prominent among these techniques. It is an effective method for long-distance inspection of inaccessible

and coated structures from a single testing point. It propagates inspection waves through the structure without point-to-point scanning, minimising inspection drudgery and enhancing work throughput daily.

Conventional ultrasonic testing (UT), whose frequency is dependent on the thickness of the inspecting structure, is different from GWUT of frequency range 40 kHz through 15 MHz or more in rare cases [37], [38]. The UT is a high-frequency pulse-echo inspection technique for deep penetration into structural thickness [39]. It covers a limited area of the structure, unlike the GWUT that propagates a long-distance structure, as shown in **Figure 2-1a** and **Figure 2-1b**.



(a)



(b)

Figure 2-1 Difference between (a) ultrasonic testing, UT; and (b) guided wave ultrasonic testing, GWUT.

In GWUT or long-range ultrasonic testing, LRUT, transducer probes are networked in an effective array manner to emit wave signals of predefined frequency [39]. The signal's low-frequency nature allows the elastic wave to be guided and propagated a long distance at the expense of sensitivity. At the same time, inspection at high frequency is detrimental to distance coverage and power. The high-frequency wave signals are mostly used to study microscale changes in the material structure, like corrosion. In contrast, low-frequency signals are majorly used to inspect and detect macroscale defects in the material structures. Most studies on the application of GWUT have focused on individual damage inspection under varying conditions. However, the coexistence of combined damage on structures and its effect on GWUT parametric features under varying conditions is yet to be studied. Hence, the review on GWUT damage inspection, severity, and temperature influence on the guided waves and parametric features of the inspecting wave.

In nature, dolphins and bats use echolocation techniques to survive in their immediate habitats by processing emitted and sensed signals [40]–[42]. They use the signal's time of flight, ToF, to infer the object's location ahead, thereby manipulating their travelling intention [43], [44]. Their call echo signal's parametric features have been extensively studied as a tool through which they differentiate fishes and detect hidden prey in sediments [45]–[48]. This approach is similarly adopted and extensively researched to inspect and monitor the health state of structures using parametric features of ultrasonic waves and guided wave geometry [49]–[51]. As sound wave propagation is stratified in different frequency ranges, an ultrasonic wave of about 40 kHz–25 MHz is widely used for monitoring and screening structural assets [13], [52]–[56]. The screening and monitoring at less than 100KHz are regarded as low frequency [54][57], which is predominantly used in the long-range screening of about 80–100 km, while above 100 kHz is considered high-frequency screening [58][59]. The propagating ultrasonic wave interaction with the material boundaries and surrounding media affects its parametric features and wave modes, especially when encountering discontinuity, flaws, notch, and corrosion [58]. The interaction of the propagating wave with structural damage results in different effects, such as wave absorption,

scattering, attenuation, and reflection [60][35]. These effects are often proportional to the severity of the encountered defect in the structures [30]. The increase in the number of sensors increases the chances of receiving all damaged scattered response signals for accurate location and quantification of the damage, but this is not cost-effective [39].

A defect in structure is indispensable as it could occur at the manufacturing stage or during service life through dynamic loading, ageing, environmental effects, and corrosion activities [3][61]. All these factors affect the strength of the structure through variation in its flexural rigidity or mass that manifests in vibrational frequency [62]–[65] of the structure as in equation (2-1).

$$f_i = \frac{\lambda_i^2}{2\pi L^2} \left(\frac{EI}{m} \right)^{1/2} \quad (2-1)$$

where f_i is the linear natural frequency, λ_i is modal constant, L is the beam length, EI is the flexural rigidity of the beam while m is the mass. The deterioration of assets if not detected, quantified, localized, and an appropriate maintenance measure administered on time could result in catastrophic failure that might claim lives, harm the environment, and cripple the economy. Hence, predicting the inception of the damage existence early before it becomes severe is eminent. However, at the initial stage of the flaw, its size could be microscale and hard to detect, especially in a coated scenario.

In asset integrity assessment, damage identification is of four spectrums [63] : (i) damage detection, (ii) damage localization, (iii) damage quantification, and (iv) damage prognosis. Some studies emphasized one or any of the combinations. However, the limitation could be attributed to the assessment technique employed, as some could only provide information for the awareness and location of the defect.

Integrity assessment techniques used in determining the health of structures could be passive or active when referenced to the actuation nature of the structure [43], [66]–[74]. The essence of actuation is to set the structure particles into mechanical vibration, thereby propagating wave energy from one point of the

structure to another. In the passive actuation method, ultrasonic sensors are sparsely deployed to sense the structure's health status under dynamic stress, resulting in modal shape deformation and vibrations, emitting a sound of different frequencies. Instances of this technique are the strategic placement of acoustic emission (AE) [43] sensor and fibre Bragg grating (FBG)[75] for sensing the variations in the structure sound frequency and strain caused by the existence of a defect, respectively. FBG fundamentally operates on the principle of reflection and filtering light signature wavelength, the variation of which is proportional to the structural strain [75] as in Equation (2-2).

$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{ 1 - \frac{\eta_e^2}{2} [p_{12} - \nu(p_{12} + p_{12})] \right\} \quad (2-2)$$

where λ_B is Bragg wavelength, η_e is the Bragg effective refractive index, p_{ij} are the silica-photo-elastic tensor components, ν is the Poisson's ratio, and ε is the strain.

Although passive actuation method overcame some of the challenges of the conventional ultrasonic sensor in terms of increased sensitivity, shield to electrical noise and durability, the sparse placement of transducers on structure creates the possibility of flaw detection miss. This challenge could be adequately handled by increasing the number of sensors per area but at the expense of cost.

On the other hand, the active actuation method works with at least two transducers (lead zirconate titanate, PZT) to act as an actuator and as a sensor synchronously without recourse load-induced sound wave occurring in the structure [43][19]. Hence, unlike the passive actuation method, they are nonresonant sensors and could be networked in a phased array or distributed network that offers full coverage of the inspecting structure with a possible wireless data communication interface [43]. The lightweight nature, small size, easy integration of PZT on host structure, and cost-effectiveness made it an excellent choice for structural health monitoring [51][76], especially for thin plate structures and composite materials predominantly used in aircraft constructions. Prominent industries of NDT have used it to develop PZT arrays of various

inspection specifications of 15–100 KHz frequency range and 60–150 m inspection distance [77]–[80].

Lamb waves are prominent for damage detection in thin plates and other flat composite structures because they influence structure properties and propagate useful signal information regarding the structure's integrity. It is sensitive to sundry defects and discontinuity manifesting in its in-plane S_0 and out-plane A_0 modes [81]–[85]. These are fundamental modes of symmetric and antisymmetric Lamb waves that are dispersive. The propagation speed of symmetric S_i modes is faster than antisymmetric A_i modes [85]. The frequency of the guided wave and thickness of the inspecting structure collectively define the lamb wave features' varying nature. Hence, the product of the frequency, f and the structural thickness, d ($f-d$), relate proportionally to the Lamb wave modes [86]. It is pertinent to note that fundamental lamb wave modes exist at a smaller product value of $f-d$. The antisymmetric modes are more sensitive to defects at a higher frequency than the symmetric mode in detecting microcracks [86]–[88]. It was revealed in the study done by Alleyne and Cawley in [87] that the sensitivity of the fundamental modes of the lamb waves are functions of damage depth, h to guided wave thickness, d ratio ($\frac{h}{2d}$).

In a plate–water interface, the in-plane wave mode, S_0 remains the same while partly energy of the out-plane wave mode, A_0 leaks into the water. This is an attribute to differentiate media acoustic properties [89]. Contrary to this, both modes attribute to leaky wave in the case of plate–soil interface. Although lamb waves propagate at high velocity, they are susceptible to the effects of ambient noise, low structural vibration, and temperature, which harden the ease of damage identification and interpretations [90]. In pipe diagnosis and at low frequency, the longitudinal, L ; torsional, T ; and flexural waves, F , are dominant [49], [53], [91], [92]. Aside from the fundamental mechanical waves, other wave formation is feasible, but derivate of them [13], [37], [93] and occurs in different structural conditions. To appreciably differentiate one wave mode from the other, a naming nomenclature was devised by Meitzler in [94] as in equation (2-3).

$$\text{Wave modes} = X(h, g) \quad (2-3)$$

The **X** represents the wave mode type (Longitudinal, **L**; Torsional, **T**, or flexural, **F**) while the **h** and **g** are circumferential order and mode order, respectively. The circumferential order and wave mode order of the longitudinal and torsional waves are similar in convention and differ from the flexural mode. This often occurs due to wave mode conversion of either the longitudinal or torsional modes [95].

2.3 Wave Propagation and Dispersion

Since wave propagation brings about vibration and displacement of structural particles in the temporal and spatial directions, the fusion of the Hooke's law and Newton's law results in a 1D governing wave equation [94] Equation (2-4).

$$\frac{\partial^2 u}{\partial x^2} = \frac{\rho_0}{c} \frac{\partial^2 u}{\partial t^2} \quad (2-4)$$

where u is the particle displacement, x is the propagation direction, ρ_0 is the density of the unstressed structure, c is the elastic constant of the structure, and t is the time. Furthermore, the resolution of the harmonic propagating waves of different frequency, but equal amplitude results in two-term frequencies as in equation (2-5).

$$u = 2A \cos \left(\frac{1}{2} \Delta k x - \frac{1}{2} \Delta \omega t \right) * \cos (kx - \omega t) \quad (2-5)$$

The first term of equation (2-5) is of low frequency with limit group velocity as in Equation (2-6).

$$C_g = \frac{\partial \omega}{\partial k} \quad (2-6)$$

While the second term is of high frequency with phase velocity as in equation (2-7).

$$C_p = \frac{\omega}{k} \quad (2-7)$$

By comparing equations (2-6) and (2-7), it implies that group velocity and phase velocity are related as in equation (2-8).

$$C_g = \frac{d(kC_p)}{dk} = C_p + k \frac{dC_p}{dk} \quad (2-8)$$

where $C_p = C_p(k)$.

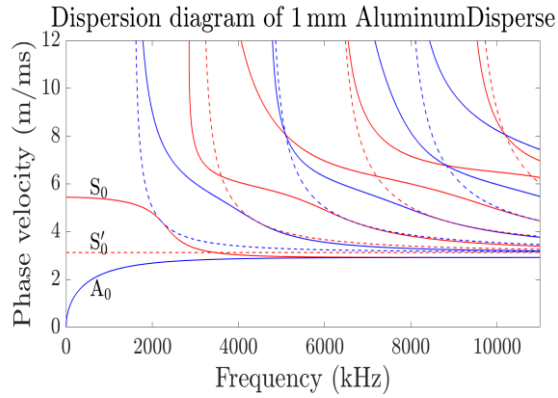
It is pertinent to note that this wave propagation in lossless elastic structure is characterized by group velocity, C_g and phase velocity, C_p . The group velocity is a function of the central frequency, f , and the thickness, d of the guided wave as in equation (2-9).

$$C_g(f, d) = \frac{C_p^2}{\left[C_p - (f \cdot d) \frac{dC_p}{d(f \cdot d)} \right]} \quad (2-9)$$

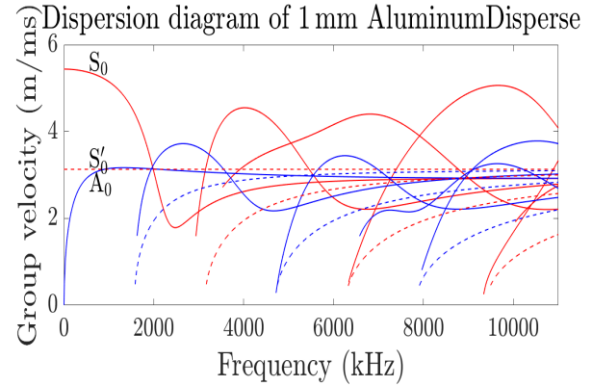
Equally, selecting the distinct wave mode for inspection is substantial for accurate quantitative and qualitative damage detection [96]. However, it is a challenge to achieve this due to the lamb wave's multi-mode nature at different frequencies when the inspection wave mode is supposed to be nondispersive [50]. Hence, in 1990, Mike Lowe and Brian Pavlakovic of Imperial college London developed structure mode evaluation software called 'Disperse' [97]. It predicts possible modes and characteristics of a wave propagating in a structure [98], [99]. This software is prominent and extensively used in NDE and NDT of structures.

Similarly, in 2016 Armin Huber of the Lightweight Production Technology of the German Aerospace Center developed 'Dispersion Calculator' (DC) [98], [100]. DC is more intuitive and interactive than the famous disperse software [99], [100]. The calculator uses the stiffness matrix method that S. I. Rokhlin and L formulated. Wang [101]–[103] to compute the dispersion curve of longitudinal and shear waves in an anisotropic plate and multilayered transversely isotropic

composites. **Figure 2-2** is the guided wave phase velocity and group velocity dispersive curves of 1 mm aluminium plate thickness generated using the DC. It could be deduced from the dispersive curve of phase velocity that S_0 mode is relatively nondispersive up to 200 kHz with C_p of about 5430 m/s when compared with other modes. Therefore, it is suitable to monitor the health condition of the plate using S_0 mode as the generated excitation signal. However, excitability and sensitivity of the modes, especially with regards to thickness reduction due to corrosion was not accounted for. In [96], an optimized dispersion curve that relies on the excitability and sensitivity in addition to the group velocity of the mode was developed. This was named goodness dispersion curve, and it offers an informed mode suitable for damage detection but limited to material thickness reduction due to general corrosion. It was revealed that sensitivity of guided wave varies with wave frequency and at low frequency, the wave is insensitive to small thickness variation of the metal. Interestingly, the fundamental symmetric, S_0 , and asymmetric, A_0 , modes were recorded as insensitive.



(a)



(b)

Figure 2-2 Dispersive curve of 1 mm thickness of Al obtained using DC [100].

2.4 Transducer Arrangement and Configuration for Inspection of Structure.

Structure inspection involves the use of transducers as an actuator (exciter or emitter of pressure waves) and a sensor (receivers or catchers of pressure waves) to generate and receive waves through a waveguide at a predefined distance. The transducer's major component is the piezoelectric material that can transform electrical signals into mechanical vibrations and vice versa [104], [105]. The relationship between the material's electrical and mechanical effects is in Equations (2-10) and (2-11). The parameters of the equations are defined in **Table 2-1**.

$$T_j = C_{ji}^E S_i - e_{jj} E_j \quad (2-10)$$

$$D_i = \epsilon_{ij}^S E_j + e_{ii} S_i \quad (2-11)$$

Table 2-1 Parameter definition.

Electrical Parameters	Mechanical Parameters	Constants and Couplants
(i) E_j applied electric potential	(i) T_j , material tensor stress	(i) e_{jj} , third-rank tensor
(ii) D_i , particle displacements	(ii) S_i , material tensor strain	(ii) ϵ_{ij}^S , permittivity for constant strain
		(iii) C_{ji}^E , elastic stiffness tensor for constant electric field

The transducer pressure wave is of two-zone formation [83]: the near zone and far zone, as shown in **Figure 2-3**. At the near zone, the wave pressure amplitude varies spuriously with many high and low echoes. However, the wave gradually attenuates amplitude beyond the near zone distance N . The multiple echoes at the near zone make it challenging to detect structural damage between the near

zone and the transducer. This is a blind spot of the transducer where damage detection through signal amplitude analysis is ineffective. Hence, damage detection is effective beyond the near zone distance and within the far zone. The near zone distance is defined as in equation (2-12). D is the transducer diameter, f is the pressure wave frequency, λ is the wavelength, v is the velocity.

$$N = \frac{D^2 f}{4v} \quad (2-12)$$

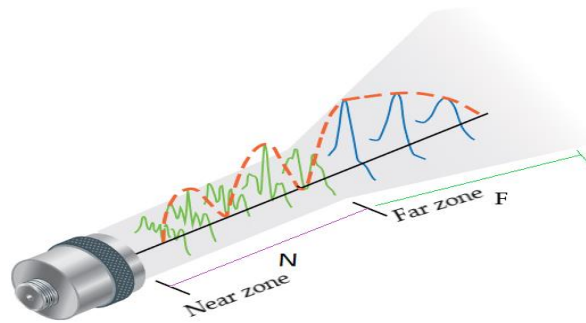


Figure 2-3 Transducer wave zones [106].

The effectiveness of structural inspection, on the one hand, relies on the damping nature and its spectral response to the targeted damage. On this account, transducers are grouped into three and summarized in **Table 2-2**.

Table 2-2 Transducer categories concerning spectrum response.

S/N	Transducer Series	Remarks of Merit
1	High resolution (HR) Series	• Heavily damped • Most broadband • Effective for structure thickness gaging
2	General purpose (GP) Series	• Less damped • Bandwidth is between the narrow banded and broadband series. • Effective in detecting the majority of a structural flaw
3	High gain (HG) series	• Less damped and tuned. • Most narrow banded • Effective in detecting flaws on highly attenuated rough surfaces or relatively thick materials.

The configuration topology of the transducer is majorly either pulse-echo (P–E) or pitch-catch (P–C) depending on the geometry of the inspecting structure, the targeted defect of interest and the needed data [58]. The typical examples of the methods are shown in **Figure 2-4**. In P–E, a single or two transducer(s) is used, and the reflected echo signal, time-of-flight (ToF) alongside the propagation velocity are used to determine defect, deterioration, discontinuity, or thickness of the material structure [93], [107]. A minimum of two transducers is required in P–C and spaced sufficiently to generate a defect interrogating wave and receive it after interrogation with the structural defect. This configuration is often applied to detect damage that is not large enough to cause reflection, somewhat furthering the transmission of the wave though attenuated. Unlike the P–E method, the P–C measurement is the amplitude of the damage signal or the shape of the received damage signal. P–C is an excellent choice to make when the intention is to cover a long-range structure [108].

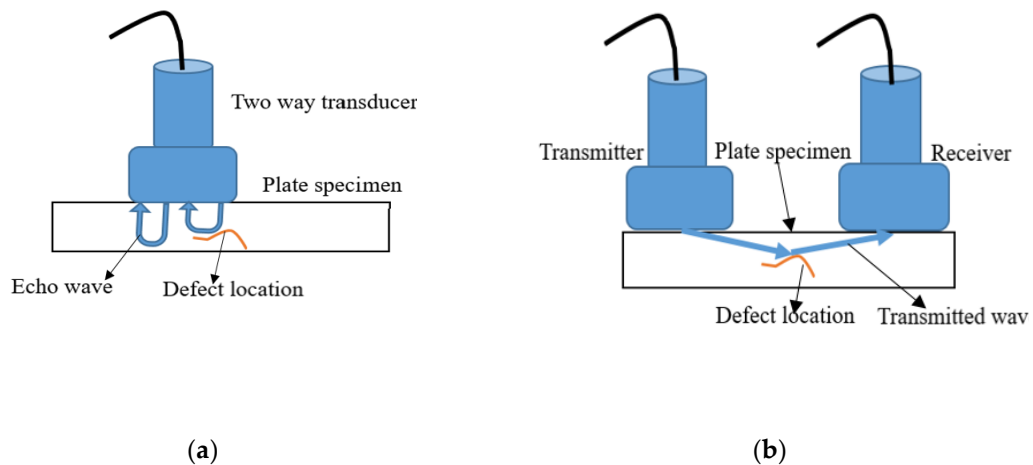


Figure 2-4 (a) Pulse—echo method with a transducer; (b) Pitch—catch method with two transducers(R) [108].

In pipeline inspection, piezoelectric transducers are distributed and interconnected in parallel to form a ring of an array around the pipeline's circumference [67]–[69]. This technique of inspecting the pipeline is devoid of surface preparation, unlike other types of inspecting techniques; hence, it saves time and encourages more length inspection in a day. However, hopping the device from one point to another is laborious, coupled with its weight, installation, and uninstallation time at distances of interest. Some of the available collar ring transducers in the market for a specific inspection challenge are shown in **Figure 2-5**. The compact ring is designed for a wide range of inspection with a 30–35% weight reduction. The solid ring transducer type is for standard inspection of 2–8 inches pipes, while the claw transducer type is designed to inspect a closely spaced pipeline that cannot allow the fitting of the conventional ring [109]. A typical transducer ring array contains 2–24 transducers depending on the diameter of the pipe [53], [110], [111].



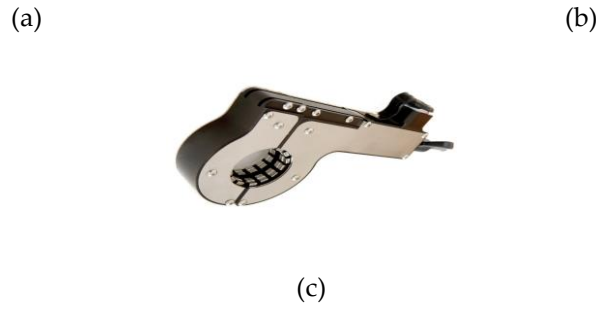


Figure 2-5 (a) Compact ring transducer; (b) Solid ring transducer; (c) Claw transducer [109].

Therefore, about 48 transducers must form two rings of circumferential inspection array of a sizeable, guided wave. The high number of transducers per ring adds to the high cost of inspecting structures. The networking together of such many transducers could pose a challenge in determining when a transducer has failed. Although it offers merit in full inspection coverage of the structure, it increases the system inspection power [94]. Also, the large size of the collar transducers does not encourage in-service inspection of the structure, which demands permanent installation of the device [112]. In **Figure 2-6**, two 24-transducer collars were configured in pitch-catch topology and used to inspect internal corrosion activities in a pipeline [111]. In [53], multiple ring arrays of 24 transducers were used to study the guided wave's unidirectional excitation function. Fundamental Torsional (0,1) wave mode was generated and conditioned to propagate only in a forward direction. This approach reduces complexity in the signal collection and interpretation, and it saves computational costs.

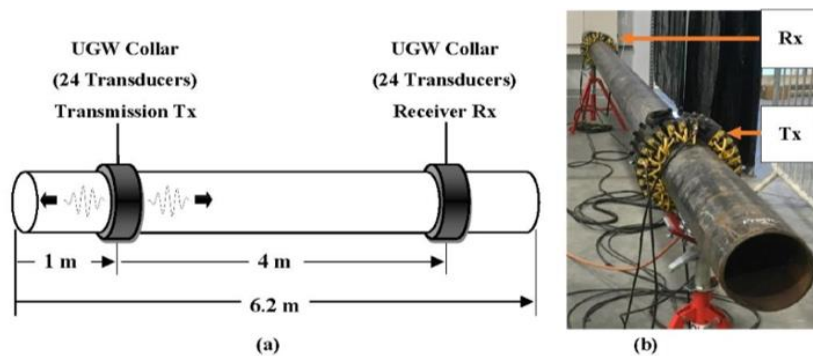


Figure 2-6 (a) Schematic and (b) setting-up of the UGW collar arrangement for pitch-catch configuration topology [111].

2.5 Attenuation of Propagating Wave.

Attenuation reduces signal level in amplitude or energy as it propagates through a medium [104]. **Figure 2-7** is a typical demonstration of wave attenuation in a medium. The diminishing of the propagating signal amplitude often follows an exponential decay pattern expressed in Equation (2-13), while variation in the signal intensity is described in equation (2.14).

$$A = A_0 e^{-\sigma x} \quad (2-13)$$

where A = Attenuated signal amplitude

A_0 = unattenuated signal amplitude

σ = coefficient of attenuation

x = signal travelled distance

$$\Delta I(dB) = 10 \log \frac{P_2^2}{P_1^2} = 20 \log \frac{V_2}{V_1} \quad (2-14)$$

where ΔI = variation in sound intensity between two successive measurements, p_1 and p_2 are successive sound pressure, V_1 and V_2 are successive output voltage of the transducer. In [113], ultrasonic wave attenuation was statistically correlated with the strength of low-carbon steel. The study showed that as wave attenuation increases from 0.24 dB/mm to 0.36 dB/mm, the steel strength decreases from 290MPa to 460 MPa. This linear relationship suggests that a structure's strength can be monitored through a propagating wave's attenuation level. The wave attenuation α and material thickness, X are related as in equation (2-15). ΔA is the change in wave amplitude between successive reflections.

$$\alpha = \frac{20}{2X} \log (\Delta A) \quad (2-15)$$

Aside from reflection, wave dispersion and waveform alteration, the combined effects of wave signal scattering and absorption result in signal attenuation.

Hence, attenuation is a significant effect that happens to wave propagating in structures.

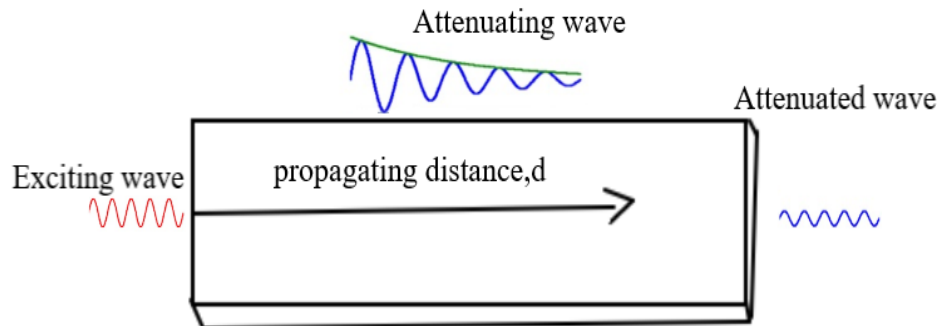


Figure 2-7 Signal attenuation in a medium.

As expected in reality, the propagating wave will attenuate over a distance of the guided medium. This could be due to losses resulting from leaking wave energy from the monitoring structure, interaction with the corroded area, defect, flange, welded area, and cracking. In NDT, attenuation is a linear effect that is commensurate with the degree of defect in the material structure [55]. Accordingly, signal-to-noise ratio, SNR, is used to determine the level of attenuation undergone by a signal using input and output energies or amplitudes of the input and output wave strengths [114]. The GWUT is primarily an inspection/screening tool; hence SNR is suitable for determining the activities of an internal and external defect in the monitored structure. Environmental operating conditions also contribute to the attenuation and distortion of damage signal information [115], thereby leading to false alarms, masking damage signal, and difficulty in defect localization. Temperature is a major environmental factor that causes damage signal distortion and diminishing, although scholarly works have been done to resolve its influence. It is pertinent to note that GWUT serves only the role of inspection and its capability to determine the size, shape, and orientation of crack has not been extensively studied [116]–[118]. In fluid-filled pipe inspection, the wave attenuation is affected by similarity and dissimilarity between the filled-fluid and the surrounding fluid [112]. It was revealed that, irrespective of the position of fixed structure features (weld, flange, etc.), attenuation rate in dissimilarity scenario is twice that of similarity. In a pipeline,

attenuation is considered intrinsic when caused by absorption and extrinsic when caused by pipeline features like corrosion, cracks, and other defects that could decrease signal strength [112].

2.6 Damage Severity Indicator, DSI.

Crucial in structural health monitoring is being aware of the damage present, especially at an early stage. This allows for an appropriate maintenance scheme to be applied on time and avoids unscheduled system shutdown due to structural damage. Several works have used lamb wave features extracted before and after the occurrence of damage or between two state's conditions of the structure to achieve this purpose [68][119][120]. The lamb wave feature extraction could be processed through an already established model or deterministic approach. The quantification of the lamb wave feature's extracted damage information in any of the methods is the damage index (DI). The DI defines the severity of the damage in the structure and its health status. It could be classified as time-domain (root mean square (RMS), time of flight (ToF), wave energy attenuation, peak signal amplitude variation, and beat length), frequency-domain (figure of merit (FoM), spectral density, peak of FFT) or time-frequency domain as in **Table 2-3**. In [121], ToF was successfully used in the two comparable techniques to locate the crack and its propagation in an aluminium plate. The continuous wavelet transform coefficient was used in [122] to detect thickness reduction in a thin aluminium plate.

In contrast, the amplitude coefficient peak was used in [81] to assess fatigue crack in an aluminium pipe. In [66], the beat wavelength was used to monitor thickness reduction due to generalized corrosion activities in the steel structure. In [68], [123], different statistical damage indices (i.e., RMSD (Root-Mean-Square Deviation), MAPD (Mean-Absolute-Percentage Deviation), Cov (Covariance), TMAC (Transmissibility Modal Assurance Criterion), and CC (Correlation Coefficient.)) were compared using PZT impedance measured under the uniformly corroded pipeline.

Table 2-3 Classification of DI according to domain.

Reference	DI Time-Based	DI Frequency-Based	Remark
[122]	Coefficient of CWT, $Z = \frac{\left(\frac{A}{B} + \frac{A}{C}\right)}{2}$ Where A = Fraction of the total energy of the CWT that lies at the centred frequency B = Fraction of the total energy of the CWT that lies at the higher frequency C = Fraction of the total energy of the CWT that lies at the lower frequency		Thickness reduction in a thin plate
[81]	Peak amplitude coefficient, $\beta = \frac{A_2}{A_1^2}$ Where A_1 = amplitude of the fundamental wave and A_2 = amplitude of the second harmonic		Fatigue crack propagation in aluminium pipe
[66]	The beat wavelength, $L =$ $\frac{2\pi}{K_{A0} - K_{S0}}$ K_{A0} and K_{S0} are the wavenumbers of the fundamental symmetric and antisymmetric modes		Monitored thickness reduction due to general corrosion activity

[112]	$R_{ref} = \frac{A_{wel}}{A_{dir}}$ Awel =Peak amplitude at the weld Awel = Peak amplitude from a direct source		The severity of damage in the fluid-filled pipe
[124]		$DI = \left 1 - \frac{fd^T fd}{fbL^T fbL} \right $ fd = the spectral signal frequency response at damage state fbL = the spectral signal frequency response at the undamaged state	Corrosion severity detection in pipeline
[125]		$DI_{ij}(f_{ex}) = \sum_t V_{ij}^B(t, f_{ex}) - V_{ij}^D(t, f_{ex}) $ for i,j = 1~6 where: $DI_{ij}(f_{ex})$ = Damage signal differential $V_{ij}^B(f_{ex})$ = Baseline signal when pairing the i-th PZT actuator and the j-th PZT sensor at a given excitation frequency (fex).	Corrosion detection and severity in the plate Aluminium

		$V_{ij}^D(f_{ex}) = \text{damage}$ signals when the corrosion damage was present at the targeted position of the plate.	
[84]		Spectral density, $DI_2 = \frac{ A(2\omega) }{ A(\omega) }$ Where $ A(2\omega) $ = spectral magnitude of the fundamental frequency $ A(\omega) $ = Spectral magnitude of the second harmonic frequency	Microscale crack detection in a plate structure

2.7 Corrosion And Sensitivity.

Corrosion activity is an inevitable effect on metallic structures. It is one of the significant safety issues in industries and results in corrosion failure of structures. It is instigated mostly through metal interaction with immediate environmental variables (oxygen in the air, hydrogen, chlorine, ambient temperature, humidity, and presence of microbes) or stress on the metallic structure, as in the case of stress corrosion cracking [126]–[128]. The result of corrosion activity would be reddish rust if it happened in the presence of oxygen or greenish rust in the chlorine-dominated environment [129], [130]. Some corrosion forms are pitting, crevice, and stress corrosion cracking with their peculiarities [131], [132], as shown in **Figure 2-8**.

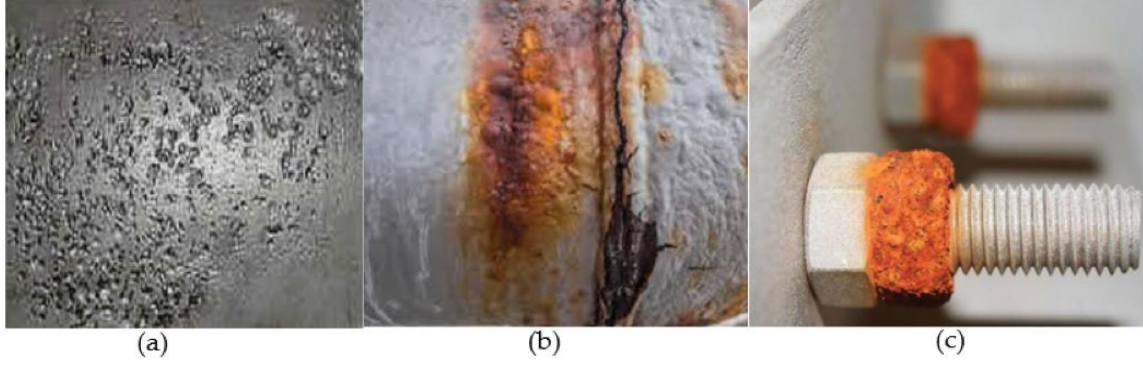


Figure 2-8 (a) Pitting corrosion in carbon steel [133]; (b) stress crack corrosion on carbon steel [134]; (c) crevice corrosion on a bolt [135].

The pitting corrosion is caused by unevenness in the metal structure or the metal surface's protective coating breakdown, thereby exposing it to electron loss. It is not easy to predict and detect. Hence, it has the capability of causing corrosion failure and remaining undetected. Crevice corrosion occurs due to an imbalance in ion concentration between the activity areas of the metal structure. It could happen in an oxygen-limited area, such as under washers or bolts [135]. The growth of cracks on ductile metal due to corrosive surroundings and applied cyclic stress is referred to as stress corrosion cracking (SCC) [136]. The corrosion rate of the material is estimated using Faraday's law [15] of metal's electrochemical reaction as in Equation (2-16).

$$\text{Corrosion rate} \left(\frac{\text{mm}}{\text{year}} \right) = \frac{3.16 \times 10^8 \times i_{\text{corr}} \times M}{z \times F \times \rho} \quad (2-16)$$

where i_{corr} is corrosion current, M is the molar mass of the metal, z is the number of electrons transferred per metal atom, F is Faraday's constant, and ρ is the metal density.

Corrosion can occur on plates and pipes but with different quantification approaches. Unlike plates, the defect size of pipes is quantified by the loss of wall area or thinning of pipe thickness [137]. This loss of wall area is termed percentage reduction in cross-sectional area, CSA, of pipe. This is because propagating incident waves do not extend across the entire plate. Monitoring the corrosion activities and where it happen on the structure under different situations

is of utmost importance to industries. Detecting corrosion activity of the least percentage of CSAL is a step in the early prevention of asset failure. This is plausible using a highly sensitive tool whose parameters can respond quickly to changes in the structure. The aftermath effect of corrosion activity is the deterioration of structural integrity through rust. The formation of rust involves loose surface properties of the structure, contamination of fluid in pipes, decreased service time, and a sudden failure of the structure that could cause loss of lives and highly valued properties.

High-frequency GWUT has been extensively used in monitoring corrosion activity in structures [5][138][52], although low-frequency monitoring was demonstrated in [139] using 64 PZT sensors. In [140], Victor Giurgiutiu et al. leveraged the cheap cost of piezoelectric wafer active sensors (PWAS) and networked multiples of them for corrosion detection and localization in plates and pipelines. Fundamental lamb wave modes S_0 and A_0 at high frequency (120KHz) were generated and used. It was revealed that A_0 is more sensitive than S_0 in detecting corrosion in plates and pipes, although S_0 travels faster but is less sensitive to metal thickness changes. This is depicted in **Figure 2-9**.

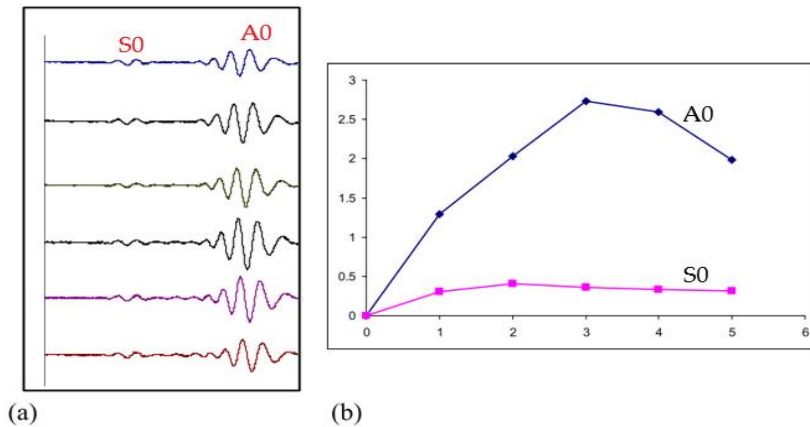


Figure 2-9 DI analysis on pitch-catch signals for corrosion detection. (a) Received signal at PWAS 4 when PWAS 0 sent signal at 120 kHz (b) DI curves of both A_0 and S_0 wave packets at 120 kHz of path 0–4 [140].

In [95], scattering and attenuation of propagating torsional waves in the pipeline with general corrosion was numerically and experimentally investigated using pulse-echo transducer configuration. The study unified rough surface mean depth

and surface roughness as corrosion activity. It was revealed that wave scattering is proportional to the unified corrosion activity. It implies wave scattering increases as the pipe wall thickness reduces and the rough surface area increases. This interaction effect significantly contributes to the wave attenuation and mode conversion from a torsional T (0,1) wave mode to a higher flexural wave mode. Hence, corrosion development on structures impinges on the propagating wave's strength and promotes wave mode conversion that introduces background noise into the monitoring system.

In [141], accelerated corrosion activity on a steel bar in concrete was successfully monitored using a high frequency (200KHz) lamb wave. The study revealed that corrosion of this nature could be detected using the FFT signal's amplitude response. In [82], corrosion activity was experimentally monitored and quantified using a sensor signal's damage index profile map and A0 phase shift. The A0 group velocity was observed to vary accordingly with the material loss from 0–50% of the thickness. The obtained result suggested that the phase shift of the fundamental antisymmetric lamb wave A0 mode can be used to quantify early corrosion activity in structures, as shown in **Figure 2-10**.

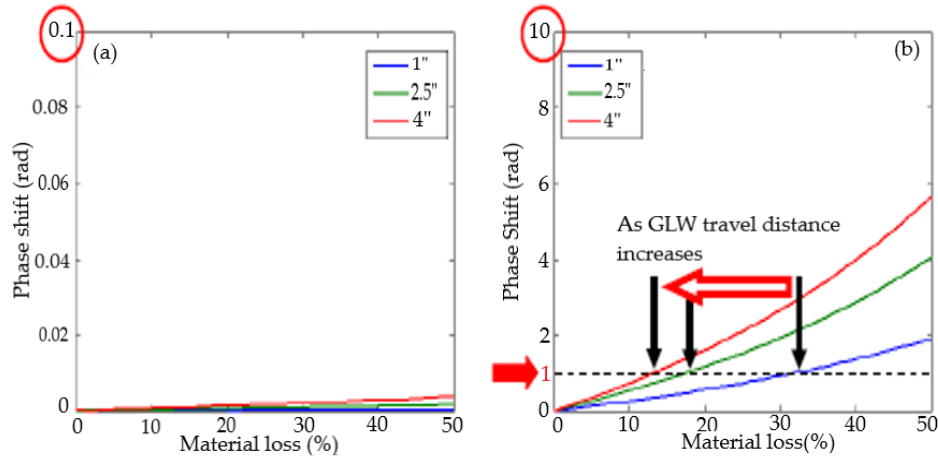


Figure 2-10 Phase shift estimation according to three-wave propagation distance (60 kHz excitation) (a) S0 mode (b) A0 mode of GLW Adopted with permission from [125]. Copyright 2012, ASME.

In [139], real-time low-frequency (30–90 KHz) monitoring of corrosion on mild steel was studied. The fundamental antisymmetric wave mode, A0 was generated

using 64 PZTs. It was revealed that the scattering waves' influence on the accuracy of the thickness reconstruction is minimal. However, the thermal stability of the design on guided wave techniques was not considered.

In [124], PWAS configured in the pitch-catch mode were installed permanently on a SMART layer to perform in-service monitoring of the pipeline integrity. The severity of corrosion activity is determined via the damage index defined in equation (2-17).

$$DI = \left| 1 - \frac{fd^T fd}{fbL^T fbL} \right| \quad (2-17)$$

where

DI = the damage index for each affected path

fd = the spectral signal frequency response at the damage state

fbL = the spectral signal frequency response at the undamaged state

In [66], thickness reduction of material through uniform milling and corrosion activity were studied and compared using the high-frequency Rayleigh waves. Beat length effect due to continua slight shift difference between the two fundamental lamb wave modes, S_0 and A_0 , were used to quantify thickness reduction. The technique was able to determine thickness reduction of about 0.1 mm; hence, it could quantify general corrosion impact or detect early corrosion activity, as a result implying the high sensitivity of the technique. In [142], thickness reduction of a thin copper plate was experimentally studied, compared with actual thickness reduction through milling. The variation of the plate thickness was monitored using group velocity. It was revealed that the two situations showed an agreeable result to the tune of 64% when the reduction was relatively small but deviated when it became more extensive. The study achieved a minimum detectable thickness reduction of 0.37% thickness. In [143], corrosion–erosion activity in plate and pipeline was studied using constant group velocity. The velocity of A_0 mode was adopted in the study. The minimum detectable wall thickness reduction in the study is 1% of the general wall. This result showed an improvement in the sensitivity of the transducer. In [96], Lamb

wave group velocity responsiveness to corrosion activity on the aluminum plate was studied. This study was numerically studied alongside the finite element solutions to determine the most sensitive frequency to thickness variation. It was revealed that sensitivity of guided waves varies with wave frequency and at low frequency, the wave is insensitive to small thickness variation of the metal. Interestingly, the fundamental symmetric, S_0 and asymmetric A_0 modes were recorded as insensitive. Mode conversion of the shear horizontal lamb wave (SH_0 and SH_1) after interaction with corrosion activity is studied in [144]. It was revealed that the group velocity of SH_1 mode varies proportionately with variation in the structural thickness while SH_0 mode remains nearly constant and insensitive to the thickness variation.

2.8 Effect of Environmental Conditions on Guided Wave and Ultrasonic Parametric Features.

Environmental factors vary uncontrollably and interact with installed asset structures. This interaction results in guided wave parameter variation, especially during thermal expansivity [145]. Since metallic structures are an excellent medium for propagating the inspecting wave and serve as hosts for the sensors, the effect of environmental variation on the metal could be transferred to the sensor directly or indirectly, hence causing variation in the parametric features of the sensor signals. These variations mostly result in masking damage signals, thereby allowing failure to occur. Studies have been carried out to investigate the ambient temperature variation on the ultrasonic-guided wave (host) and the transducers (actuator and sensor). In [146], Cawley compared the effect of crack formation on the resonant frequency and the impact of the beam's length on the resonant frequency. The result showed that the change caused by 2% depth cut of the crack was 40 times smaller than that caused by a 2% increase in the beam's length. The effect of temperature on UGW has been widely studied. In [147], Lui Zenghua et al. investigated the effect of temperature ($-4\text{ }^{\circ}\text{C}$ to $34\text{ }^{\circ}\text{C}$) on lamb wave, $L(0,1)$ propagating on steel. The wave velocity was reported to vary inversely to increase in temperature, as shown in **Figure 2-11**. The

retardation rate of the velocity was recorded to be 0.9m/s for every degree of increase in temperature.

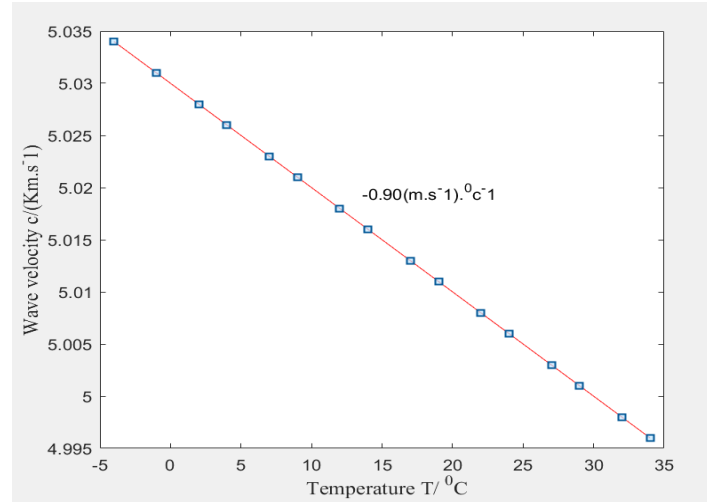


Figure 2-11 Temperature effect on Lamb wave velocity (R) [147].

The study on anisotropic plate material carried out by Lanza et al. witnessed similar behaviour but on the wave signal amplitude [29]. It was observed that the wave amplitude increases at a temperature below 20 °C and decreases at a temperature above 20 °C. This effect is suggested to be attributed to the competing roles of the PZT coefficients and the dielectric permittivity. When the parameters were isolated, the amplitude response to temperature variation was observed to be proportional. A similar proportionality response was observed when the high-temperature transducer array coupled in an empty pipeline was subjected to a temperature of 7–150 °C [148]. In the pitch-catch study of varying temperature (20–150 °C) effect on guided wave performed by Raghavan and Cesnik in [149], the response was observed to be nonmonotonic in the measured amplitude, as shown in **Figure 2-12**. The amplitude response signal increases when the temperature is 20–90 °C but decreases when it is 90–150 °C. This behaviour was subjected to further theoretical and experimental studies. Its behaviour was attributed to the assumption of perfect bonding and constant adhesive layer properties through the temperature range.

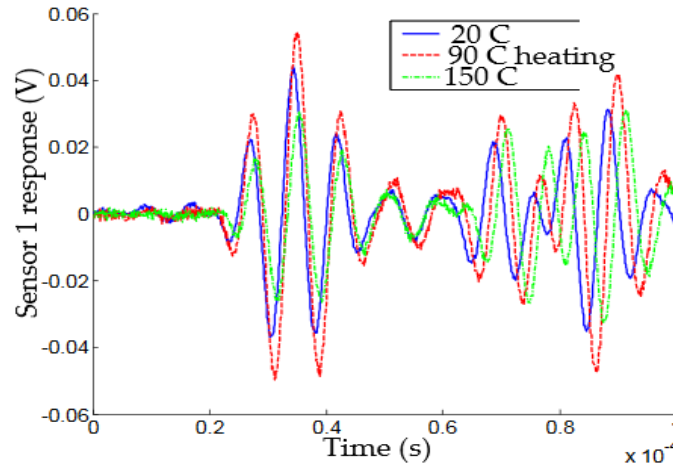


Figure 2-12 Temperature effect on PZT amplitude [149].

Temperature influence on the propagating wave time shift $\left[\frac{\partial t}{\partial \sigma}\right]_T$ and group velocity, $v_g(T, f)$ were modelled in Equations (2-18) and (2-19) respectively [150].

$$\left[\frac{\partial t}{\partial \sigma}\right]_T = \frac{d}{v} \left[\frac{1}{E} + \frac{K}{v} \right] \quad (2-18)$$

$$v_g(T, f) = \left[23 \times \frac{1}{T} + 4.37 \right] - \left[\frac{f}{175} - 0.29 \right] \quad (2-19)$$

where v_g is the group velocity, T is the varying temperature, f is the frequency of the wave, E is the material young modulus and k is the coefficient of change in phase velocity with stress, and v is the propagation velocity. Since $\frac{K}{v} > \frac{1}{E}$ It could be inferred from Equation (2-18) that thermal influence on the wave velocity is more responsible for signalling time shift than the material's mechanical property at peak temperature. Equation (2.19) was proposed in [150] to represent the group wave velocity function of varying ambient temperature and the propagating wave's excitation frequency. The study on the influence of temperature variation on a diffused ultrasonic wave in a plate revealed waveform shift is an attribute of temperature. In contrast, distortion in waveform shape is proportional to the size of the flaw and perhaps its orientation [151]. In [152], the experimental study on

steel thickness measurement at varying temperatures ($>21^{\circ}\text{C}$) revealed an inverse relationship between temperature and the velocity of the ultrasonic wave. Based on the analysis, it was suggested that material young modulus E is the only property that could significantly contribute to variation in ultrasonic velocity under varying temperature and stress conditions as in equation (2-20).

$$C_l = \left[\frac{E \cdot g}{\rho} \cdot \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)} \right]^{\frac{1}{2}} \quad (2-20)$$

Where E is the material young modulus, ν is the Poisson ratio of the material, g is the acceleration due to gravity, and ρ is the density of the material.

Some other research studies on temperature influence on a guided wave and wave inspection parameters can be read in [30], [32]–[35], [153]–[156]. **Figure 2-13** showed the significant effect of temperature variation that resulted in amplitude distortion and signal phase shift [30].

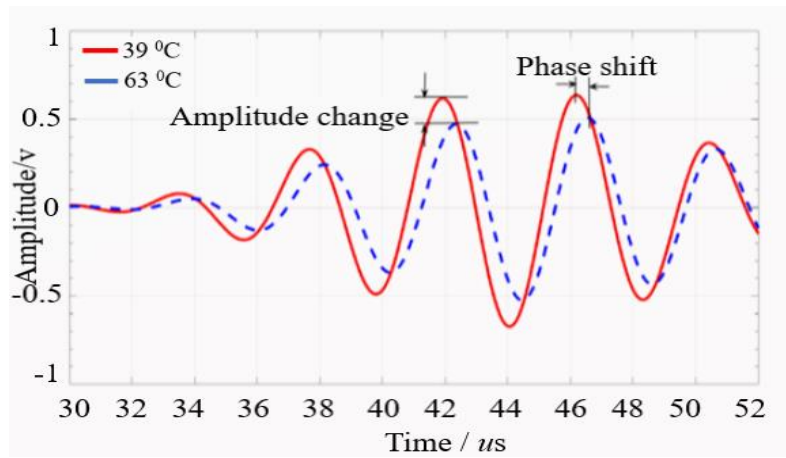


Figure 2-13 Typical signal differences under different temperatures [30].

In [157], the influence of temperature variation ($0\text{--}50^{\circ}\text{C}$) on the ultrasonic feature of pulse-echo between motor oil and 1018 low carbon steel was studied. The attenuation of oil was concluded to affect the wave absorption coefficient significantly. This implies that motor oil is not a suitable interface coupling medium for GWUT under an elevated temperature, although it could limit corrosion development at the interface.

Aluminum metals are predominantly used as a thin plate to construct more extensive parts of an aircraft. Its exposure to harsh and varying environmental conditions are suggested to contribute to its deterioration and possible failures. In [90], the effect of temperature variation (-20 – 60 °C) on the PZT propagating wave on an aluminum plate was experimentally studied. The wave amplitude and velocity were revealed to be inversely proportional to temperature variation. Towards 60 °C, the amplitude variation was about 30%, while it was 2.5% on the velocity. This observation suggested that the tendency of missing damage signal at an elevated temperature of the structure is high.

Although it has been shown that temperature variation significantly affects the guided wave mechanical properties and ultrasonic wave parametric features, most of the studies were performed on pristine materials under controllable temperatures with a marked range [90], [113], [152], [157]–[159].

The unified effect of temperature con other environmental factors on sensor parametric features has not been given sincere attention than the investigative study done on the temperature effect alone.

Conversely, the temperature effect on the PZT ultrasonic sensor's parametric feature has been applied innovatively to monitor an elevated temperature in a heated spiral spring [160]. The ToF of the pulse-echo signal after interaction with the structural predefined embodiment reflectors formed the basis for distributed temperature measurement. The comparable results showed that the ultrasonic waveguide and temperature measurements are acceptable, with a maximum mean error of about 1 – 3 °C. The novel techniques could be deployed to measure assets' temperature in an economical approach since a sensor could monitor the asset's distributed temperature.

Compensating for the environmental effects on wave information signal is an approach to mitigate temperature and improve the positive probability of flaw detection in the structure. Different techniques have been applied to this effect, such as optimal baseline selection, baseline signal stretch technique, linear discriminant analysis [51], [161], [162]. As mentioned earlier, variation in temperature results in ultrasonic phase shift or delay in the signal arrival, reducing

the sensitivity and probability of damage detection. In the absence of temperature, determining the damage and its location would be a simple statistical evaluation between the baseline waveform signal and the current monitored signal. In [51], combined optimal baseline selection (OBS) and baseline signal stretch (BSS) techniques were used to suppress and compensate for the distorted information signal due to temperature variation. The results revealed that a combination of OBS and BSS performed better than simple subtraction method and OBS method. The compensation techniques have temperature range as in **Table 2-4** beyond which they are unreliable. Also, the size of the temperature reference signal interval attributes the ease of calculation process and the reference data set's size.

Table 2-4 Temperature range and interval of some existing compensation technique.

Compensation Method	Temperature Range	Maximum Compensation Interval	Reference Signal Interval
BSS	5–40 °C	5 °C	0.1 °C
OBS	22–32 °C	10 °C	0.1 °C
BSS + OBS	21.5–31.5 °C	10 °C	0.5 °C

In [161], the effect of temperature and flow rate of fluid in working pipeline acquired using principal component analysis techniques and Fourier transform, (FT) were used to classify the damage situation of the pipeline through linear discriminant analysis (LDA). The approach achieved an average of 98% damage detection accuracy. In [162], a modified baseline signal stretch (MBSS) method was used to enhance the damage detection of complex signals due to large temperature variation effect with fewer baseline data set. The improvement was on selecting and applying a range of stretch factors instead of using all at a given time, thereby retaining a minimum value of the residual envelope. It was validated experimentally on a plate structure. The study revealed that MBSS could detect

damage in a structure at a higher temperature variation, hence it has more comprehensive application than BSS, as shown in **Table 2-5**.

Table 2-5 Summary of result indicating the largest temperature change for which the damage could be accurately localized by applying temperature correction methods.

Name	Aluminum Small Artificial Damage	Aluminum Crack	CFRP BVID
BSS	Up to $\Delta T = 3\text{ }^{\circ}\text{C}$	Up to $\Delta T = 15\text{ }^{\circ}\text{C}$	Up to $\Delta T = 8\text{ }^{\circ}\text{C}$
MBSS	Up to $\Delta T = 13\text{ }^{\circ}\text{C}$	Up to $\Delta T = 23\text{ }^{\circ}\text{C}$	Up to $\Delta T = 28\text{ }^{\circ}\text{C}$

In [163], dynamic time-warping temperature compensation was studied to map the monitored data set with the baseline data set. The technique performed better than the stretch-based method at high-temperature variation. The obtained correlation coefficients at different study scenarios were steadily above 0.75, unlike 0.35–0.45 obtained in the stretch-based method. To ensure that the weak damage signature is not hidden in the noise, a statistical step detector approach was used to quantify the damage as correlation coefficients reduce over time. However, the technique's computational cost is high, requiring any other method to reduce the cost while ensuring accuracy in damage detection. The flexibility of the dynamic warping technique is suspected to be unreliable as it has not been subjected to many case scenarios.

In [164], the structural health of the material was studied by monitoring the variation of the propagating frequencies of the exciting wave using PZT transducers. The Gaussian kernel was used in the support vector machine (SVM) to determine the damage state similarities at each measured frequency. The method showed a 90% performance score, although environmental factors were not included in the study or considered. Hence, factoring in the effect of environmental conditions on the approach may improve its performance score to above 90%.

2.9 Impedance-Based Model Damage Detection.

It is an acknowledged fact that temperature variation brings about changes in the PZT constant properties, adhesive layer properties between the PZT and the target structure, and mechanical properties of the target structure such as young modulus [151], [165], [166]. Principally, the PZT is bonded to the target structure using an adhesive agent. When an appropriate excitation voltage is applied to the PZT, it would exert acoustic pressure via an adhesive layer on the target structure and causes its particles to vibrate in their mean positions. The interaction of the PZT sensor with the target structure in SHM has been modelled in different ways. The essence is to understand their behaviour when there is damage in the target structure. Among these models are the static and dynamic finite element models that used the static properties of PZT and structural stiffness to determine the output characteristics of the PZT sensor. The impedance-based model coupled electro-mechanical system has been more interesting and advantageous than the other two models [167], [168]. However, these models are of one degree of freedom (1-DOF) because they considered only the interface between the PZT and the host structure. The physical model of the system is shown in **Figure 2-14**, and its simplified model equation for impedance coupling, $Z(\omega)$ the PZT and the target structure are given in equation (2-21) while Equation's structural impedance is equation (2-22). For brevity, the equation terms are defined in **Table 2-6**.

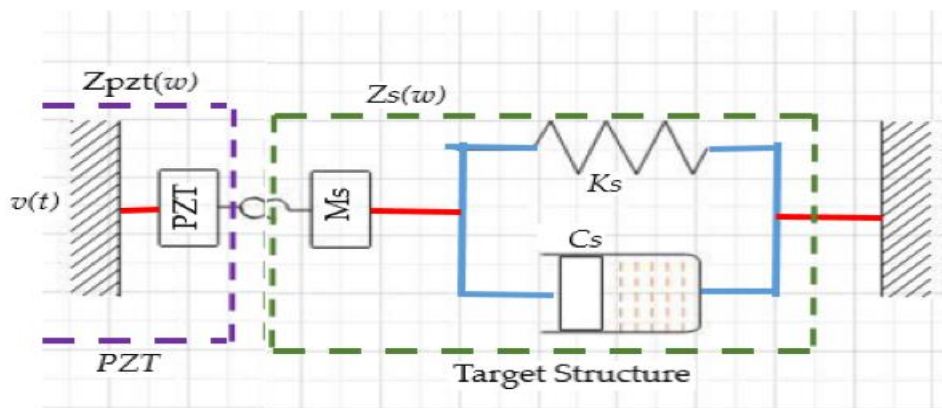


Figure 2-14 1-D PZT–target structure interface [168].

$$Z(\omega) = \left\{ i\omega \frac{w_{pzt} l_{pzt}}{t_{pzt}} \left[\hat{\epsilon}_{33}^T - \frac{1}{Z_{pzt}(\omega)/Z_s(\omega) + 1} d_{31}^2 \hat{Y}_{31}^E \right] \right\}^{-1} \quad (2-21)$$

$$Z_s(\omega) = m \frac{\omega^2 - \omega_n^2}{\omega} + C_s \quad (2-22)$$

Table 2-6 Equation terms definition.

Terms	Definition
$\hat{Y}_{31}^E$	Complex young modulus of the PZT at zero electric field
d_{31}^2	PZT coupling constant in 1-direction
$\hat{\epsilon}_{33}^T$	Complex dielectric at zero electric field
$Z_{pzt}(\omega)$	Electrical impedance of the PZT
$Z_s(\omega)$	Structural mechanical impedance of the target structure
w_{pzt}	Width of the PZT
l_{pzt}	Length of the PZT
t_{pzt}	Thickness of the PZT
C_s	Damping coefficient of the structure
ω	Angular frequency of the excitation voltage applied on the PZT
m	Mass of the target structure
ω_n	The angular natural frequency of the target structure
K_{ij}	Dynamic stiffness of the 2-DOF
$\hat{Z}(\omega)$	Structural mechanical impedance of the interface-target structure

Equations (2-21) and (2-22) showed that impedance-based monitoring of structural damage is a function of the frequency band that must be selected appropriately to detect damage change in a structure effectively. In the case of excitation frequency of the PZT matches the natural frequency of the target structure, the structural, mechanical impedance could be compared with the

mechanical impedance of the PZT thereby resulting in an electro-mechanical impedance given in equation (2-23).

$$Z(\omega) = \left\{ i\omega \frac{w_{pzt} l_{pzt}}{t_{pzt}} \left[\hat{\varepsilon}_{33}^T - \frac{1}{Z_{pzt}(\omega)/C_s + 1} d_{31}^2 \hat{V}_{31}^E \right] \right\}^{-1} \quad (2-23)$$

Hence, damage detection in a structure could be detected through the quantification of the measured impedance variation. However, when PZT is coupled on the target structure without an adhesive agent, it results in a high impedance mismatch due to air that serves the adhesive agent's intended function. Over time, the adhesive layer becomes weak and debonds from the interface, allowing air to exist in between the PZT and the target structure interface. Exposure to high environmental temperatures promotes this effect. This effect degrades the SHM system's sensitivity and makes damage detection difficulty. Hence, there is a need to factor in the impedance-based model the adhesive layer's influence. In furtherance of EMI based 1-D model, an improvement was made on the model to accommodate the adhesive layer [167]. The modified model of the system is in **Figure 2-15**. The resulting 2-DOF EM impedance between PZT-interface-host structure is given in equation (2-24).

$$Z(\omega) = \left\{ i\omega \frac{w_{pzt} l_{pzt}}{t_{pzt}} \left[\hat{\varepsilon}_{33}^T - \frac{1}{Z_{pzt}(\omega)/\hat{Z}(\omega) + 1} d_{31}^2 \hat{V}_{31}^E \right] \right\}^{-1} \quad (2-24)$$

Where

$$\hat{Z}(\omega) = \frac{K_{11}K_{22} - (K_{12})^2}{i\omega K_{22}} \quad (2-25)$$

In this model, the output characteristics of PZT is determined via its dynamic properties and structural impedance. By varying the stiffness of the model depicts changes in the target structure.

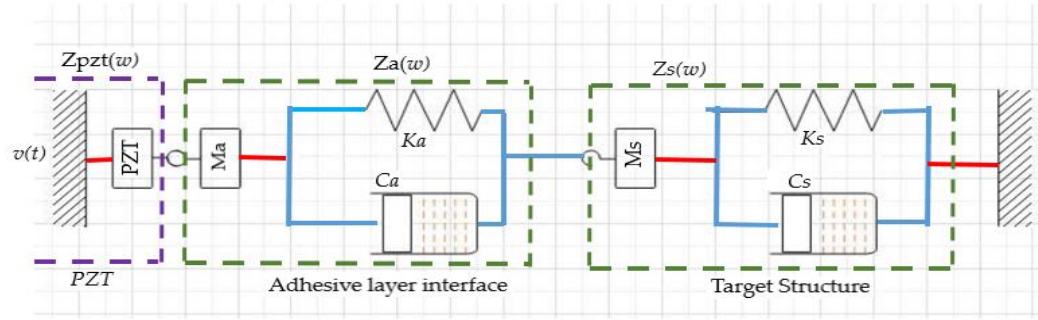


Figure 2-15 Modified PZT–host structure interface [167].

The impedance-based model was used by Bin Lin et al., in [169] to study the durability and survivability of PWAS. The impedance of one free bond PWAS and one bonded PWAS on metal were measured after being subjected to different situations of harsh and mild temperatures for a shorter time. The situations were captured as cryogenic and high temperature, temperature cycling, freeze–thaw, outdoor environment, operational fluids, large strains, and fatigue load cycling [169]. It was concluded that PWAS could function well in cryogenic temperature but not in high temperature. It could be said that the durability and survivability of PZT are subject to the nature of the working environment and the condition of the system operation. In [170], the durability of PZT actuators under the influence of electro-thermo-mechanical condition was studied.

Although PZT could be perfectly bonded to the target structure's surface, the adhesive agent could weaken after a prolonged time in service. At this point, the performance of the PZT will start degrading, and integrity of the SHM compromised. PZT actuator unfortunate damage could occur before or during structural health monitoring. Its failure during operation could impair structural damage detection by generating signals that interfere with structural damage signal [169], [171]. This effect brings complexity in damage signal interpretation. It is vital to determine when a sensor has failed and isolate it from the network of others. Since a failed sensor signal can interfere with the structural damage signal, using the real admittance to discriminate the failed sensor damage signal from that of the host structure, electro-mechanical impedance (EMI) technique has shown strength in this regard [169], [171], [172]. Sensor self-diagnosing was studied in [171] using electrical impedance and in [172] using real admittance of

the EMI-based model. In [172], the authors used the resonant frequency shift of the real admittance caused by structural impedance and root mean square deviation (RMSD) index to achieve this discrimination. However, the study did not consider the effect of temperature variation.

2.10 Summary.

This chapter presents a review of damage inspection, severity, and temperature influence on the inspecting guided wave and its parametric features. The sensor's choice for asset integrity monitoring depends primarily on the structure's nature and the targeted flaw. Different ultrasonic parametric features are used to determine the existence of flaws or damage in the structure. However, it is pertinent that it must be highly responsive to the intended flaw, otherwise a high-rate of false detection alarms is bound to occur, and the reliability of the structure would be jeopardized.

In contrast with the conventional ultrasonic inspection technique, an inspection of a large structure area from a test point is possible with GWUT. This improvement brings about a reduction in the cost of structural assessment and the amount of time required to inspect its health state. Although at the expense of ease of interpretation, the ability of the guided wave ultrasonic technique to generate multi-mode waves is a good characteristic that aids in monitoring and detecting sundry damage in the structure.

From the DI reviewed works, it was observed that damage indices in the time-domain are mostly used to monitor the existence of macroscale damage in structures. These cracks and other damage have developed and could significantly reflect or scatter the propagating wave. The microscale damage under the breathing crack mechanism results in higher harmonics formation, making signal interpretation difficult in time domains. In such a situation, frequency-domain DI is mostly adopted to diagnose and interpret its existence.

Additionally, DI's effectiveness is a function of its responsiveness to the presence and variation of damage while being robust to unwanted interfering signals.

However, most of the IDs depend mainly on pristine structure values to be reasonably accurate, which is difficult to obtain from existing assets that are many years old. All the DIs are mono damage identifiers or mono severity indicators and are unfit to define much damage at a time.

The influence of temperature in damage detection and localization is still a challenge. However, different temperature compensation techniques exist but at the expense of high computational cost and reference to pristine values which are not readily available. The effect of varying temperature on waveforms results in a time shift of the inspecting signal with a high probability of missing flaw detection at an elevated temperature. The influence could worsen at high temperature and large defect size leading to system unreliability. Thermal conductivity is perceived as a key factor in ultrasonic attenuation under temperature variation and the ultrasonic velocity's proportionality behaviour with temperature. Temperature variation is the only environmental factor considered in most studies, whereas other environmental factors could affect the monitoring system when deployed to the field.

Study on the effect of crack or breathing crack in a corroded area on GWUT parameters under varying temperature influences is yet to be studied. Situations abound where corrosion activities may cover cracks, and structural diagnosis would reveal the existence of corrosion. This could cause misinformed asset reliability and unscheduled system failure. Also, damage detection in the dynamically stressed thin plate under the influence of thermomechanical conditions has not been explored using GWUT. In service, most metallic structures are subjected to dynamic stress and environmental conditions. These two conditions are detrimental to damage detection in structures using GWUT. Leveraging the potentialities of GWUT for structure health inspection, determining the effect of these combined conditions is significant in deciding damage severity, location, and orientation in a structure. Understanding the dynamics of these challenges with respect to ultrasonic-guided waves will open a new research discussion. The solution will increase the effectiveness of GWUT in achieving informed and reliable damage detection in metallic assets.

3 CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Overview.

From the description of debris-filled damage (DFD) in Chapter 1 and the review of literature on damage detection and evaluation techniques, the methodology for achieving the remaining objectives of the study is laid out in Chapter 3. Firstly, the conceptualized approach is established then, followed by elastic wave propagation in solid media and the inspection method adopted before discussing different experimental schemes implemented and signal processing techniques used in the study.

3.2 Conceptualization of wave propagation and damage detection technique selection.

Fundamentally, as elastic waves propagate through a solid medium, they cause the medium particles to vibrate about their mean positions[173]. These elastic waves are characterised by the transfer of energy through the medium without permanent displacement of the medium's particles. As the elastic wave propagates and interacts with the medium particles, it picks information about the medium that could be revealed via a suitable signal processing technique. Hence, for the elastic wave to propagate, it must be generated, and to reveal information about the medium, the response signals must be captured and analysed. This is conceptualized in **Figure 3-1**. The conceptualized diagram suggests that the pulse-echo or pitch-catch method could be adopted. However, one of the critical factors in selecting an inspection method is the nature of the targeted damage, as noted in Chapter 2. For the pulse-echo method to be adopted, the damage size must be significant enough to reflect most of the incident wave else, the pitch-catch method would be a suitable method. As described in Chapter 1, debris-filled damage (DFD) would rather attenuate some of the incident waves and transmit the rest of the incident waves than reflect them. The essence of SHM is capturing sufficient response signals that have had interaction with the damage and could contain integrity information about it. Hence, the presence of DFD in the structure leads to contamination of the propagating wave signal due

to attenuation and scattering at the damage edges. On this note, the pitch-catch elastic wave propagating in the healthy state of the structure is modelled in section 3.3.

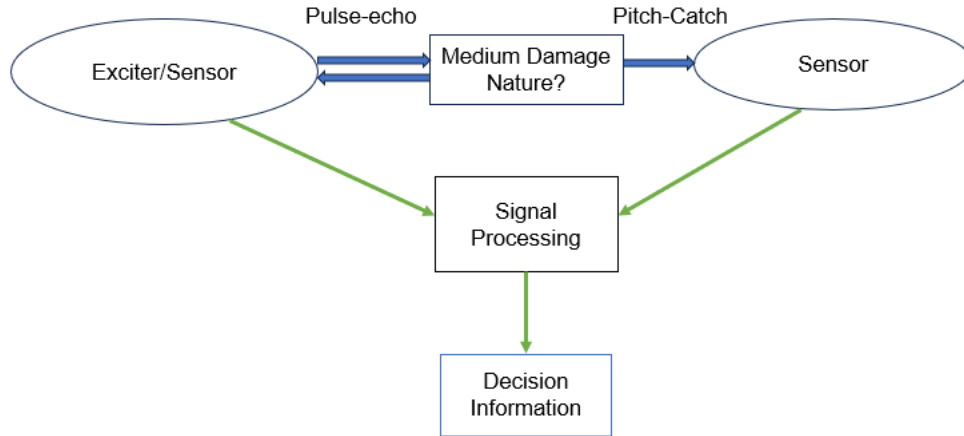


Figure 3-1 The conceptualized mechanical wave-medium interaction and capturing of the response wave.

3.3 Elastic Wave propagation and Active Pitch-Catch Inspection Method.

3.3.1 Governing Wave Motion Equation in free plate

Consider Lamb wave propagating in x_1 and x_2 directions but invariant in x_3 direction of a homogenous thin plate shown in **Figure 3-2**.

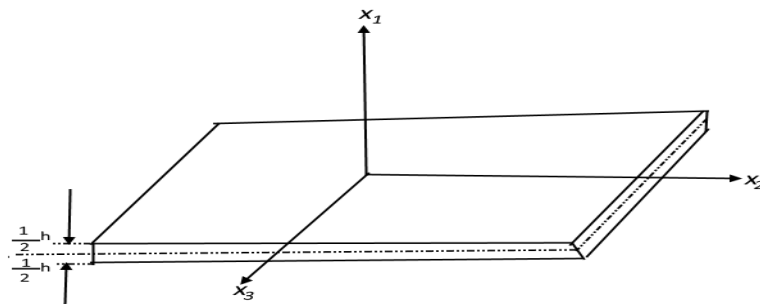


Figure 3-2 An Isotropic thin plate of h thickness.

The propagating waves could be described as particles in motion as given in equation (3-1).

$$\mu. u_{i,jj} + (\lambda + \mu)u_{j,ji} + \rho f_i = \rho. \ddot{u}_i \quad (i, j = 1, 2, 3) \quad (3-1)$$

Where u is the displacement of the plate via the particle motion, λ and μ are Lamé's constants, ρ is the density of the plate particles, $\ddot{u}_i$ acceleration of the vibrating particles, f_i is the force body on the material, t_i is surface tractions at the normal n_j and σ_{ji} is stress on the plate surface. It is considered zero for a traction-free body condition. By considering the effect of strain plane, the displacement U_i of the wave-particle in the direction of wave propagation x_2 and normal to x_1 can be described as

$$U_{i=2} = \frac{\partial \phi}{\partial x_2} + \frac{\partial \Psi}{\partial x_1} \quad (3-2)$$

$$U_{i=1} = \frac{\partial \phi}{\partial x_1} - \frac{\partial \Psi}{\partial x_2} \quad (3-3)$$

$$U_{i=3} = 0 \quad (3-4)$$

Where ϕ and Ψ are Helmholtz decomposition [174] of the wave-particle motion into scalar and vector potentials, respectively, through which the wave-particle displacements are determined. On this account,

$$\sigma_{12} = \mu \left(\frac{\partial U_2}{\partial x_1} + \frac{\partial U_1}{\partial x_2} \right) = \mu \frac{\partial^2 \phi}{\partial x_1 \partial x_2} - \mu \frac{\partial^2 \Psi}{\partial x_2^2} + \mu \frac{\partial^2 \Psi}{\partial x_1^2} \quad (3-5)$$

$$\sigma_{11} = \lambda \left(\frac{\partial U_1}{\partial x_1} + \frac{\partial U_2}{\partial x_2} \right) + 2\mu \frac{\partial U_1}{\partial x_1} = \lambda \frac{\partial^2 \phi}{\partial x_1^2} + \lambda \frac{\partial^2 \phi}{\partial x_2^2} + 2\mu \frac{\partial^2 \phi}{\partial x_1^2} - 2\mu \frac{\partial^2 \Psi}{\partial x_1 \partial x_2} \quad (3-6)$$

By applying traction free at $x_1 = \pm \frac{1}{2}h = \pm b$ (h is the plate thickness) and considering free surface plain traction (Boundary condition)

$$\sigma_{12} = \sigma_{11} = 0 \quad (3-7)$$

Hence, the general equation describing the Lamb wave propagating in a thin isotropic and homogenous plate can be described by equation (3-8).

$$\frac{\tan qb}{\tan pb} = \frac{4k^2 pq \mu}{(\lambda k^2 + \lambda p^2 + 2\mu p^2)(k^2 - q^2)} \quad (3-8)$$

The above lamb wave equation (3-8) can be split into two wave behaviours called symmetric modes and anti-symmetric modes on the account that tangent function is defined with sine and cosine that exhibit symmetry and anti-symmetry modes. Symmetric modes ($S_i, i = 0,1,2,3,4 \dots$)

$$\frac{\tan qb}{\tan pb} = \frac{4k^2 pq}{(p^2 - k^2)^2} \quad (3-9)$$

Anti-symmetric modes ($A_i, i = 0,1,2,3,4 \dots$)

$$\frac{\tan qb}{\tan pb} = -\frac{(p^2 - k^2)^2}{4k^2 pq} \quad (3-10)$$

Where

$$p = \sqrt{\frac{\omega^2 - (c_L \times k)^2}{c_L^2}}; C_L = \sqrt{\frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)}} \frac{E}{\rho} \quad (3-11)$$

$$q = \sqrt{\frac{\omega^2 - (c_T \times k)^2}{c_T^2}}; C_T = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1 + \nu)}} = \sqrt{\frac{\mu}{\rho}} \quad (3-12)$$

$$E = 2\mu + 2\mu\nu \quad (3-13)$$

$$k = \frac{2\pi}{\lambda_w} \quad (3-14)$$

The symmetric and Anti-symmetric wave patterns are shown in **Figure 3-3** and **Figure 3-4**, respectively.

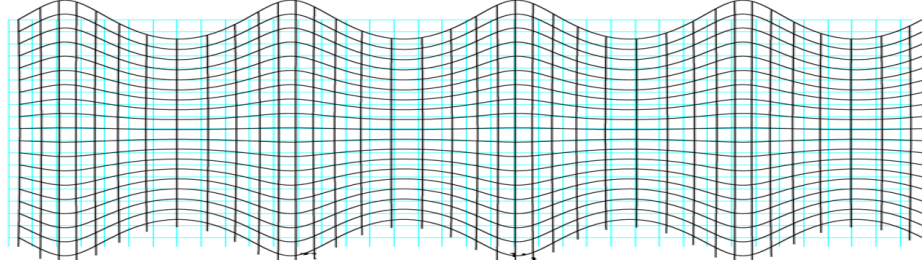


Figure 3-3 Symmetric wave due to radial wave propagation in x_2 direction[175]

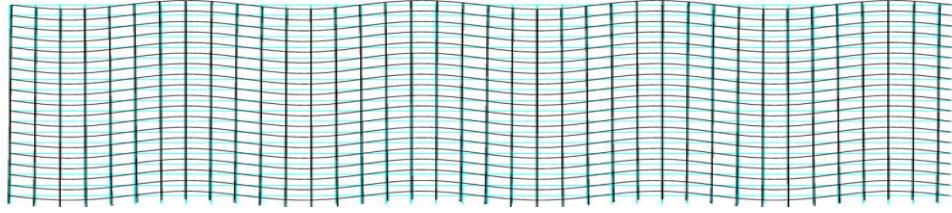


Figure 3-4 Anti-symmetric wave due to transverse wave motion[175]

The propagation of Lamb wave in plate structure could be travelling with either phase velocity c_p or c_g group velocity[176]. The group velocity is the overall velocity with which the wave travels. This represents the speed at which the maximum energy or the main wave packet moves through the plate. On the other hand, the phase velocity of a wave is the velocity at which a particular phase of the wave, such as a peak or a trough, travels through the plate. This represents how fast the wave's phase or shape moves through the plate. Hence, the phase velocity of a wave propagating with a distinct frequency is expressed in equation (3-15).

$$c_p = \frac{\omega}{2\pi} \lambda_\omega \quad (3-15)$$

While the group velocity of the propagating wave is expressed in equation (3-17) as a differential of phase velocity with respect to the product of frequency of the wave and thickness of the plate.

$$c_g(f.h) = d\omega \left[d \left(\frac{\omega}{c_p} \right) \right]^{-1} \quad (3-16)$$

$$c_g = c_p^2 \left[c_p - (f.h) \frac{dc_p}{d(f.h)} \right]^{-1} \quad (3-17)$$

Where

h and f is the material thickness and wave centre frequency, respectively.

To determine the dispersion curve of the phase velocity and group velocity propagation in the $3mm$ thickness plate, equations (3-9) through (3-17) are necessary. However, it could also be determined numerically using disperse software [97] or Dispersion Calculator[177]. The dispersion curve depicts graphical representation of how the phase or group velocity of Lamb waves varies with respect to their frequency and wavelength. In other words, it shows how the speed of propagation changes for different frequencies and modes of Lamb waves in the structure. The dispersion curve for the $3mm$ thick plate used in the study is in the subsequent chapters.

3.3.2 Active Pitch-Catch Model for Healthy Thin Plate

As a corrosion related type of damage that may not reflect much of the incident wave for its detection and quantification, an active pitch-catch inspection method is adopted and modelled in **Figure 3-5**. The model consists of an exciter, a thin plate, and a sensor. The exciter and sensor are of the same type and size. They are coupled to the thin plate using a thin layer adhesive band and separated by a distance x . The thickness of the adhesive layer is smaller than the thickness of the transducers but strong enough to keep bonding the transducers to the thin plate. When a sinusoidal electrical signal is applied to the exciter, it creates a surface shear stress around the exciter, resulting in the propagation of Lamb wave through the thickness of the thin plate. The propagating waves interact with the thin plate and become captured by the sensor at x . Consider an ideal bonding between the transducers and the structure. Also, reflection from boundary edges is considered to be negligible within the duration of lamb wave propagation and wave capturing at the sensor position, x . Also, the transducers are installed at a position sufficiently enough from the plate edges.

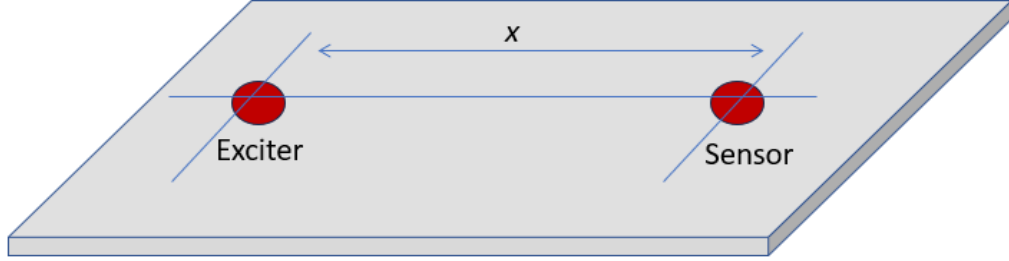


Figure 3-5 An active Pitch-Catch model for health thin plate.

Let the applied electrical signal be,

$$V_e(t) = V_0 e^{i\omega t} \quad (3-18)$$

Taking the FFT of equation (3-18) results in equation (3-19)

$$\hat{V}_e(\omega) = \int_{t_1}^{t_2} f(V_e) e^{-x} dt \quad (3-19)$$

By considering the model in **Figure 3-5** as a system with an input signal, medium and output signal, the relationship between the input signal and the output signal could be related as a transfer function in the frequency domain as expressed in equation (3-20).

$$G(x, \omega) = \frac{\hat{V}_r(x, \omega)}{\hat{V}_e(\omega)} \quad (3-20)$$

$$\Rightarrow \hat{V}_r(x, \omega) = G(x, \omega) \cdot \hat{V}_e(\omega) \quad (3-21)$$

Where $G(x, \omega)$ is the structural transfer function that is responsible for in-plane strain of the plate, $\hat{V}_r$ is the received signal in frequency domain and $\hat{V}_e$ is the excitation signal in frequency domain. Although, waves propagating through the

thickness of the thin plate are dispersive as frequency increases. However, by considering the nondispersive range of the waves' frequency, only the fundamental modes of the Lamb wave will be presented in the captured wave signals. On this account, the transfer function of the thin plate will become as given in equation (3-22).

$$G_0(x, \omega) = S_0(\omega)e^{-ik^{S_0}x} + A_0(\omega)e^{-ik^{A_0}x} \quad (3-22)$$

Hence, the final received response signal at the sensor position for a healthy thin plate is given in equation (3-23)

$$\hat{V}_r(x, \omega) = S_0(\omega)\hat{V}_e(\omega)e^{-ik^{S_0}x} + A_0(\omega)\hat{V}_e(\omega)e^{-ik^{A_0}x} \quad (3-23)$$

Where

$S_0(\omega)$ and $A_0(\omega)$ are modal participation functions that determines the amplitude of the captured fundamental symmetric and antisymmetric wave modes.

By taking the inverse FFT of equation (3-23), we have the captured wave in time-domain form as would captured by the sensor. This is expressed in equation (3-25).

$$V_r(x, t) = \text{IFFT}\{\hat{V}_r(x, \omega)\} \quad (3-24)$$

$$V_r(x, t) = \text{IFFT}\{S_0(\omega)\hat{V}_e(\omega)e^{-ik^{S_0}x} + A_0(\omega)\hat{V}_e(\omega)e^{-ik^{A_0}x}\} \quad (3-25)$$

Hence, equation (3-25) implies the response model of the thin plate when it is in a healthy state and excited.

3.3.3 An Active Pitch-Catch Model for Unhealthy Thin Plate

Figure 3-5 is reconfigured to feature wave-damage interaction as depicted in **Figure 3-6**. Note that all the conditions mentioned in subsection 3.3.2 are still applicable in this model. During the interaction of the propagating Lamb waves with the thin plate, the waves pick up information about the damage and become secondary waves. The continued propagating waves after damage interaction is designated as the secondary waves because it has undergone some

transformation, such as attenuation in the signal amplitude and energy thereby becoming new waves different from the earlier waves although made from it. If a sensor is at the damaged location, x_d , the captured response signal will be as given in equation (3-26).

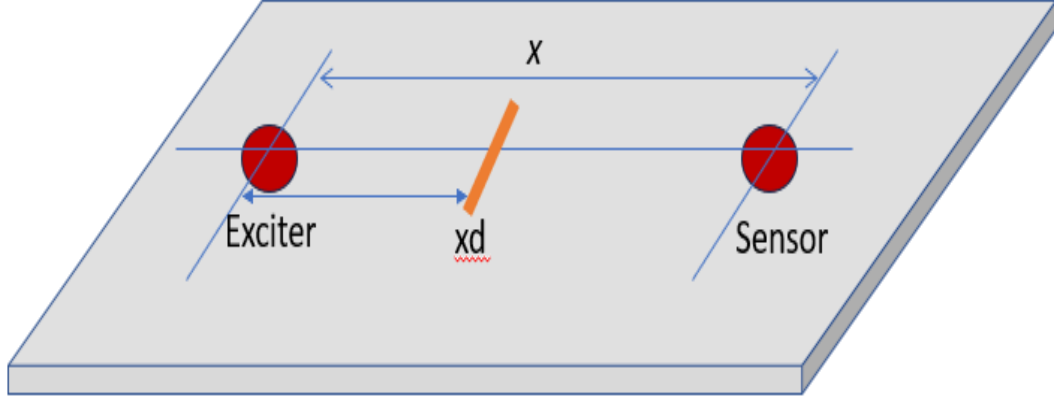


Figure 3-6 Pitch-Catch Inspection Model for damage detection.

$$\dot{V}_{rd}(xd, \omega) = S_0(\omega)\dot{V}_e(\omega)e^{-ik^{S_0}xd} + A_0(\omega)\dot{V}_e(\omega)e^{-ik^{A_0}xd} \quad (3-26)$$

Beyond the damage position, any captured wave is containing the information about the damage. Hence, the response wave captured at the installed sensor position, x is as given in equation (3-27).

$$\dot{V}_{rx}((x - xd), \omega) = S_0(\omega)\dot{V}_e(\omega)e^{-ik^{S_0}(x-xd)} + A_0(\omega)\dot{V}_e(\omega)e^{-ik^{A_0}(x-xd)} \quad (3-27)$$

By applying FFT to equation (3-27), it becomes a time domain wave signal captured by the installed sensor as expressed in equation (3-29).

$$V_{rx}((x - xd), t) = \text{IFFT}\{\dot{V}_{rx}((x - xd), \omega)\} \quad (3-28)$$

$$V_{rx}((x - xd), t) = \text{IFFT}\{S_0(\omega)\dot{V}_e(\omega)e^{-ik^{S_0}(x-xd)} + A_0(\omega)\dot{V}_e(\omega)e^{-ik^{A_0}(x-xd)}\} \quad (3-29)$$

Hence, equation (3-29) implies the response model of the thin plate when it is in unhealthy state and excited.

By comparing equation (3-25) and equation (3-29) through its signatures, the state of health of the thin plate would be determined as shown in the flowchart of **Figure 3-7**.

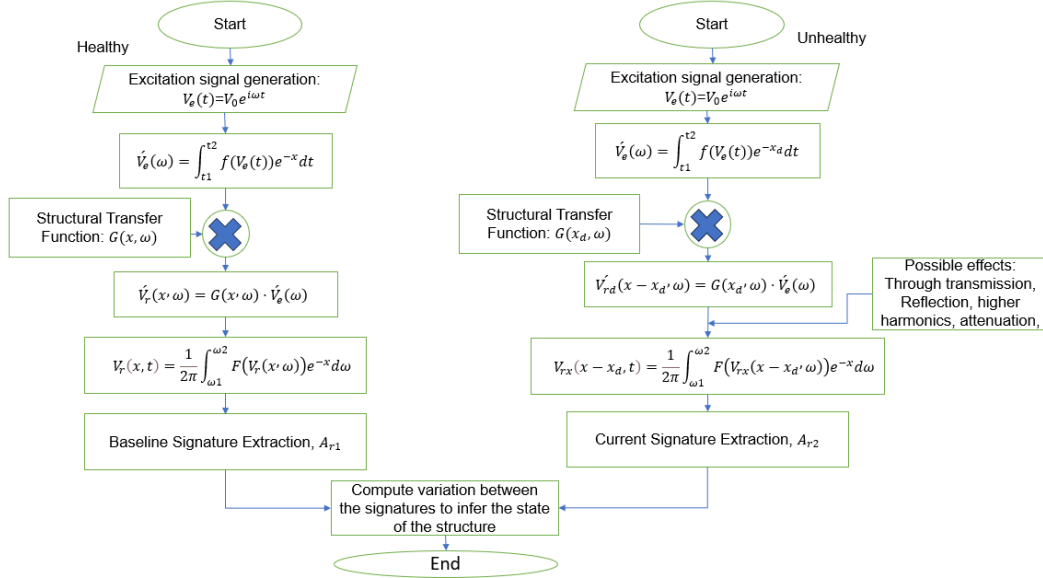


Figure 3-7 The Flow Chart Model for comparing two states of the structure (a) Healthy state (b) Unhealthy state.

The above demonstrated model then formed the basis for different experimental schemes as detailed below with an increase in the number of installed sensors. It is pertinent to mention that the input waveform should be nearly the same with the output waveform shape. After the model expansion, the baseline case and damage case experimental schemes were performed at different conditions.

3.4 Modelling Damage Detection in Thin Plate using Amplitude Modulated Wave.

Due to the unavailability of an arbitrary function generator to create a tone burst excitation signal, the available function generator was used, which changed the earlier scheduled model. The architecture of the active pitch-catch model of **Figure 3-5** and **Figure 3-6** remain the same except for the excitation signal. A modulated signal has a parameter called modulation index that determines the depth of signal modulation. It has another parameter called the coefficient of attenuation, which accounts for the loss of energy as the wave propagates

through the thin plate. Either of these parameters could be used to study damage present in thin plates.

Consider the model where an amplitude of a carrier wave of frequency f_2 is modulated by low-frequency signal of frequency f_1 as expressed in equation (3-30).

$$y(t) = A_c \cdot [1 + m \cdot \cos(2\pi f_1 t)] \cdot \cos[2\pi f_2 t] \quad (3-30)$$

When the wave signal has propagated a distance x through the thickness of the thin plate to where the sensor is installed. The response signal captured by the sensor is as given in equation (3-31).

$$y(x, t) = A_c \cdot [1 + m \cdot \cos(2\pi f_1 t)] \cdot \cos[2\pi f_2 t] \cdot e^{-\alpha x} \quad (3-31)$$

Where

A_c is the amplitude of the carrier signal, m is the modulation index of the wave, f_1 is the modulating frequency or the frequency of the low-frequency signal, f_2 is the carrier frequency signal, t is the duration of the wave propagation and α is the coefficient of attenuation of the wave at the sensor location x .

Also, considering the **Figure 3-6**, when damage has been seeded in the thin plate at distance x_d , the response signal captured by the sensor is as expressed in equation (3-32).

$$y(x - x_d, t) = A_c \cdot [1 + m \cdot \cos(2\pi f_1 t)] \cdot \cos[2\pi f_2 t] \cdot e^{-\alpha(x-x_d)} \quad (3-32)$$

To determine influence of damage on the amplitude modulated wave, some experimental schemes were designed and implemented as follows:

3.4.1 Coefficient of Attenuation

Recall that as wave propagates from its point of source to some distances away, its energy attenuates due to inherent properties of the propagation medium or its interaction with damage existing in the medium. The loss wave energy is absorbed by the medium and converts it into heat. It is pertinent to determine the attenuation coefficient of the material intended to monitor its health state at the

time healthy condition. In the view of this, recall that the propagating wave experiences an exponential decay as the propagation distance increases. This is expressed in equation (3-33).

$$V_2 = V_1 e^{-\alpha x} \quad (3-33)$$

Where

V_2 and V_1 signal amplitudes of the successive peaks.

α = attenuation coefficient of the thin plate.

x is the distance of the sensor from the exciter which implies the distance propagated by the wave.

Four distances were considered during experiment, and they are: 5mm, 10mm, 15mm and 20mm. **Figure 3-8** is the experimental architecture.

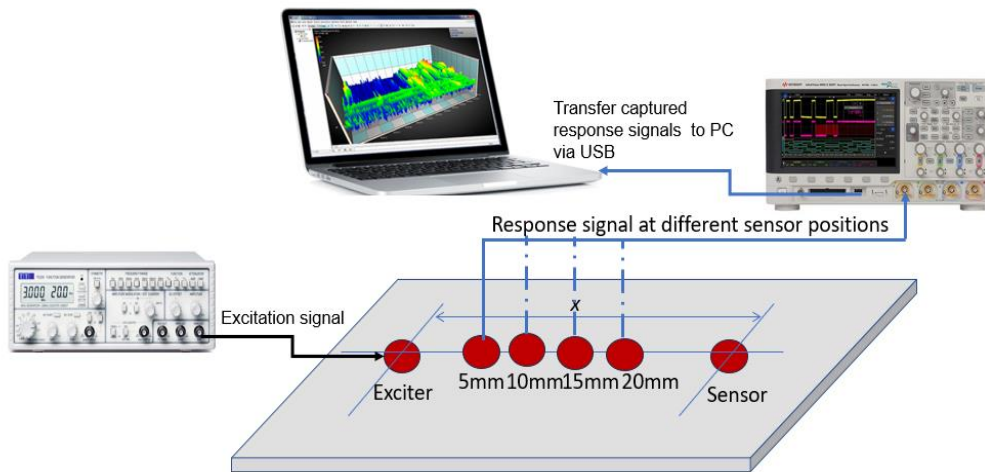


Figure 3-8 Determining the thin plate attenuation.

3.4.2 Baseline Signal Case at no Influence

Figure 3-9 was configured to acquire the baseline case signals of the plate. The dimension of the plate is (500mm × 300mm × 5mm). Four transducers (4) consisting of an exciter and three sensors (PZT₁, PZT₂, PZT₃) were installed on the top surface plain of the plate. The exciter and the middle sensor (PZT₂) were separated by 300mm and 102mm from the edges of the plate to minimize capturing the edge reflected waves. The transducers were configured for pitch-catch method of inspection since the DFD cannot generate signals by itself hence

need to be interrogated with a stress wave to pick up its information signal. The exciter and sensors are of the same property and size. The properties of the transducers as detailed by mouser electronics is in the datasheet[178].

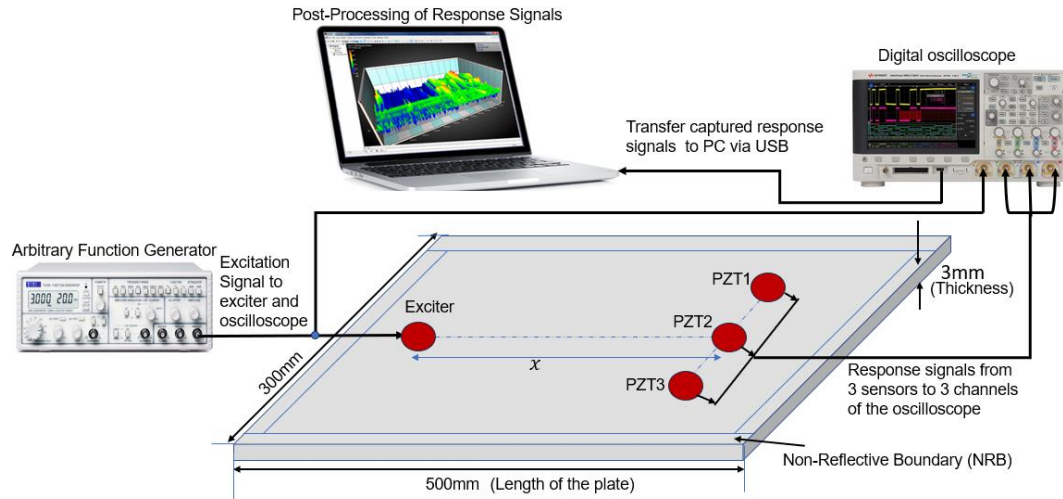


Figure 3-9 Experimental Setup for baseline data collection at no effect condition.

The excitation signal was created using a frequency of 180KHz as the carrier wave frequency while 400Hz internal frequency of the generator is used to modulate the amplitude of the carrier wave signal. The response signals were acquired 5 times and averaged to minimize random error.

3.4.3 Baseline Signal Case with Temperature Influence

Figure 3-9 was expanded to accommodate varying temperature effect using two silicone heater mats of dimension ($200\text{W}, 200\text{mm} \times 150\text{mm}, 240\text{Vac}, +300^\circ\text{C}$) as the source of heat to the plate. This is shown in **Figure 3-10**. They were integrated at the bottom plane of the plate. The silicone heater mat is discussed in subsection 3.7.1. To control the heating and determine the temperature state of the thin plate, a DC controlled AC solid state relay, an Arduino mega 2560 Rev3 and three (3) K-type thermocouples (6.35mm diameter, $+200^\circ\text{C}$ and 0.7s response time) were integrated in the system architecture as shown in **Figure 3-10**. Two (2) of the thermocouples were aligned with the sensors' and actuator's position. The remaining thermocouple was bonded at the middle distance (150mm) between the actuator and middle sensors, PZT_2 . With precautionary

measures, the plate's temperature was varied from 30 °C to 70 °C at an interval of 5 °C. This wide range of temperature aims to accommodate all possible temperature conditions while mindful of the transducers' peak temperature and the adhesive bond layer peak temperature. At each targeted temperature, the actuator is excited and response signals of the plate are captured and saved. Each targeted temperature's response signals were repeated at least 3 times and averaged to ensure repeatability and minimize random error.

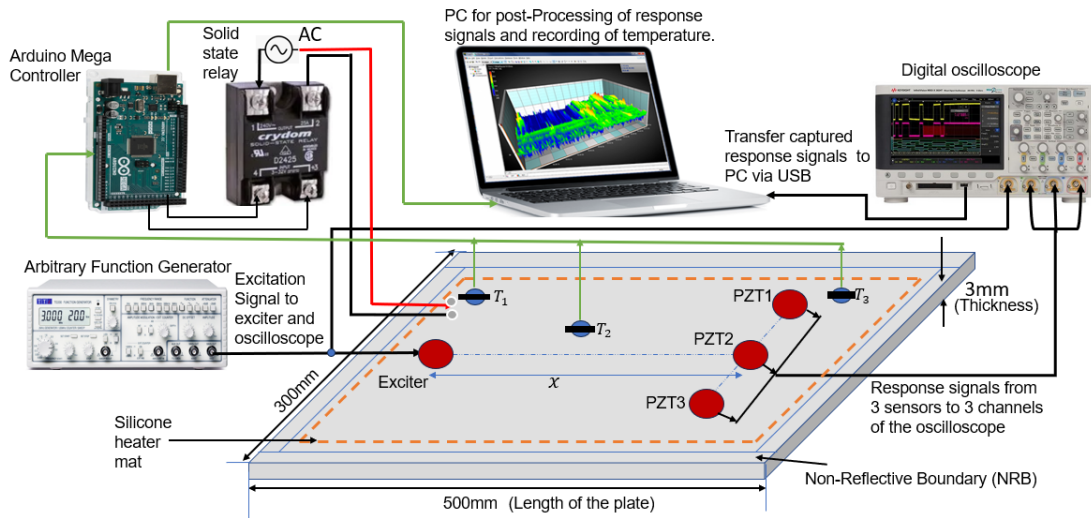


Figure 3-10 Experimental Setup for baseline data collection with varying temperature.

3.4.4 Baseline Signal Case with Vibration Influence

When an excitation signal is applied to the actuator to cause wave propagation through the thickness of the structure, external low-frequency vibration could influence the response signal. To observe the influence, **Figure 3-9** was expanded to include modal shaker as shown in **Figure 3-11**. The modal shaker is mounted at the middle of the plate. The stinger thumb nub is padded and made to have a slight gap with the plate contact. When the sinusoidal input signal is applied to the shaker through the power amplifier, it generates varying responses in the plates. Hence, the amplitude of the input signal was varied from 2v to 5v and the same with the frequency to achieve vibration close reality, the actuator is excited and response signal recorded. Each measurement was repeated at least 3 times and averaged.

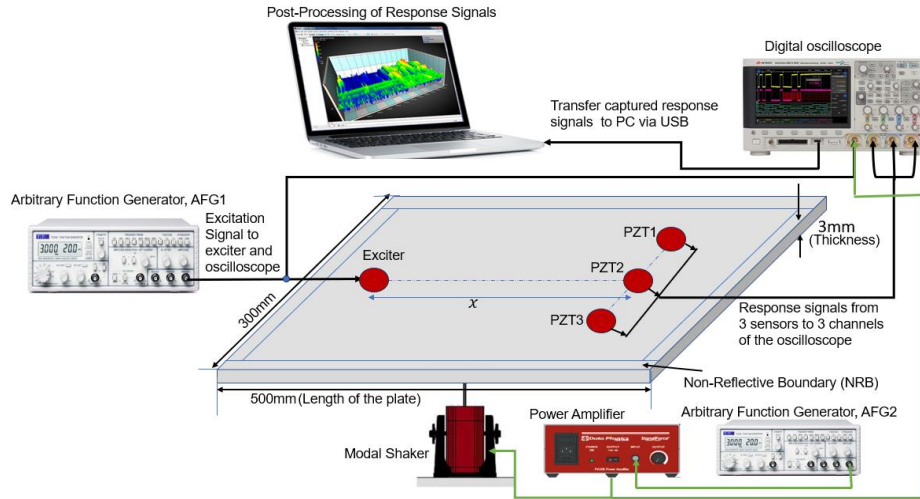


Figure 3-11 Experimental Setup for baseline data collection with vibration effect.

3.5 Unhealthy case of the thin plate.

Figure 3-9 is adapted with seeded damage of varying depth as in **Table 3-1** to form the damage case study of **Figure 3-12**. As waves propagate and interact with the structural damage, it causes some of the incident waves to scatter, reflect and transmit through the damage but attenuated. The influence of damage varying depth as regard thickness reduction by pitting corrosion on the response signal is observed. The procedure used in subsection 3.4.2 is repeated here but response signals for each damage depth is recorded, captured, saved, and later processed.

Table 3-1 Damage dimensions.

S/N	Length(mm)	Width(mm)	Depth(mm)	Actuator/sensor distance, d_{a-s} (mm)
1	40.00	5.00	0.50	300.00
2	40.00	5.00	1.00	300.00
3	40.00	5.00	1.50	300.00
4	40.00	5.00	2.00	300.00
5	40.00	5.00	2.50	300.00

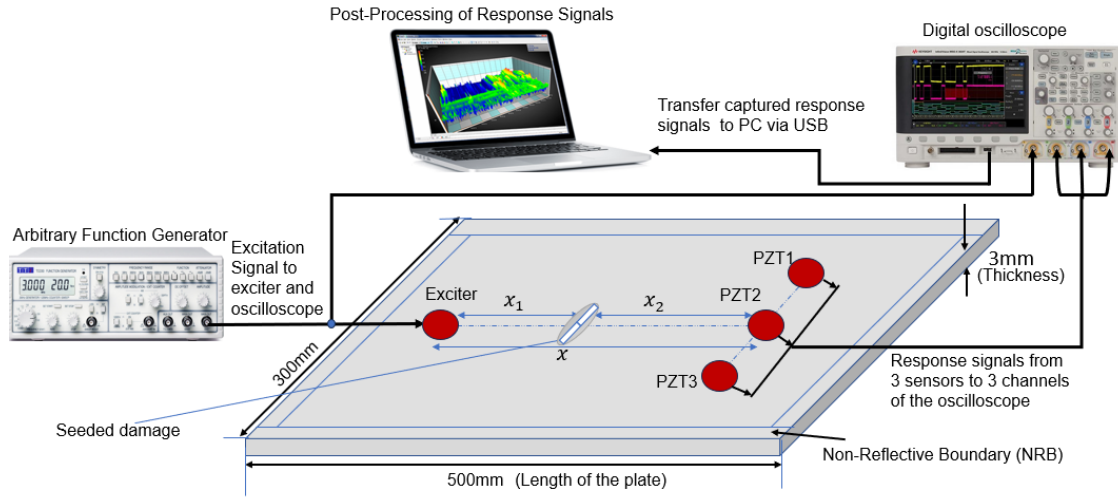


Figure 3-12 The system architecture with varying damage depth.

3.5.1 An unhealthy case of the thin plate with a temperature effect

Figure 3-10 is adapted here but with the inclusion of seeded damage of varying depths. The same procedures of subsection 3.4.2 are repeated but at varying depths of the damage. At each damage depth, the actuator is excited, and the temperature range is applied. The response signals are recorded, repeated three times, and averaged. The experimental architecture of the design is shown in Figure 3-13.

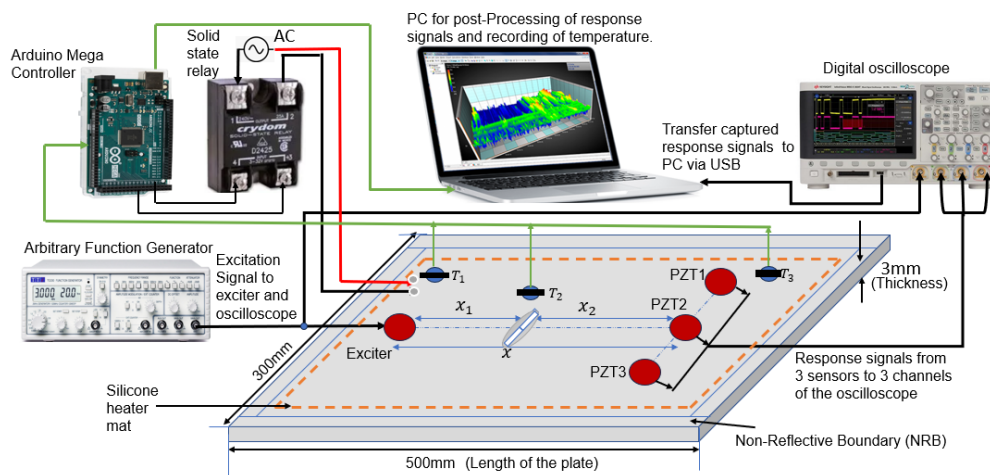


Figure 3-13 Crack and varying temperature effect setup.

3.5.2 Unhealthy case of the thin plate with vibration effect

Figure 3-11 of subsection 3.4.4 is adapted with damage inclusion, as shown in Figure 3-14. For each damage depth, the actuator is excited, and varying impact vibrations of low-frequency shakers are applied. The response signals are captured, recorded, and saved for analysis and comparison.

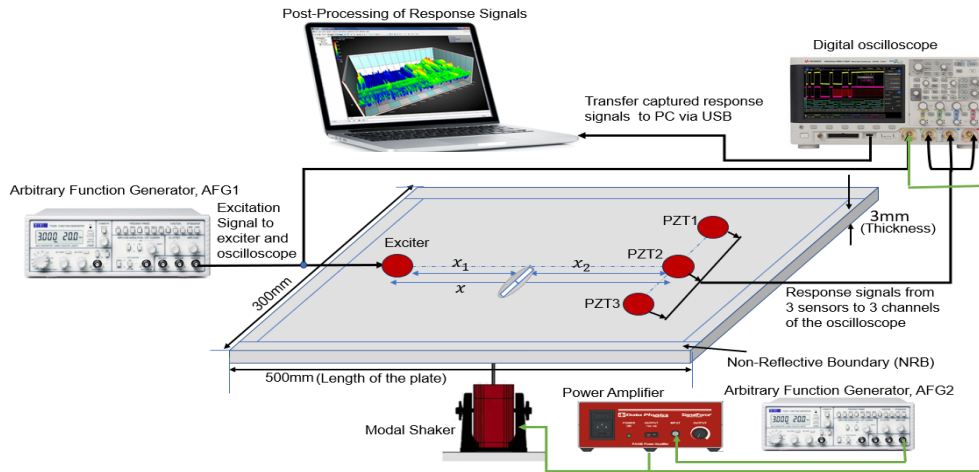


Figure 3-14 The system architecture with damage and low-frequency vibration impact.

3.6 Effect of Debris-filled damage.

The experimental system scheme of Figure 3-12 under section 3.5 is adapted but with a calibrated percentage of debris-filled damage, as shown in Figure 3-15. The debris is the ground of corrosion products used to simulate debris-filled corrosion, as described in the problem statement of Chapter 2. The damage depths considered here are 1.0mm to 2.5mm. The percentage debris used in the study is 20%, 40%, 60%, 80% and 100% of the damage length. At each percentage fill of a given depth of the damage, the actuator is excited and response signals are captured, recorded, and saved. The signals are analysed, and the sensitive parameter of the response wave is correlated with the percentage fill of debris for future prediction.

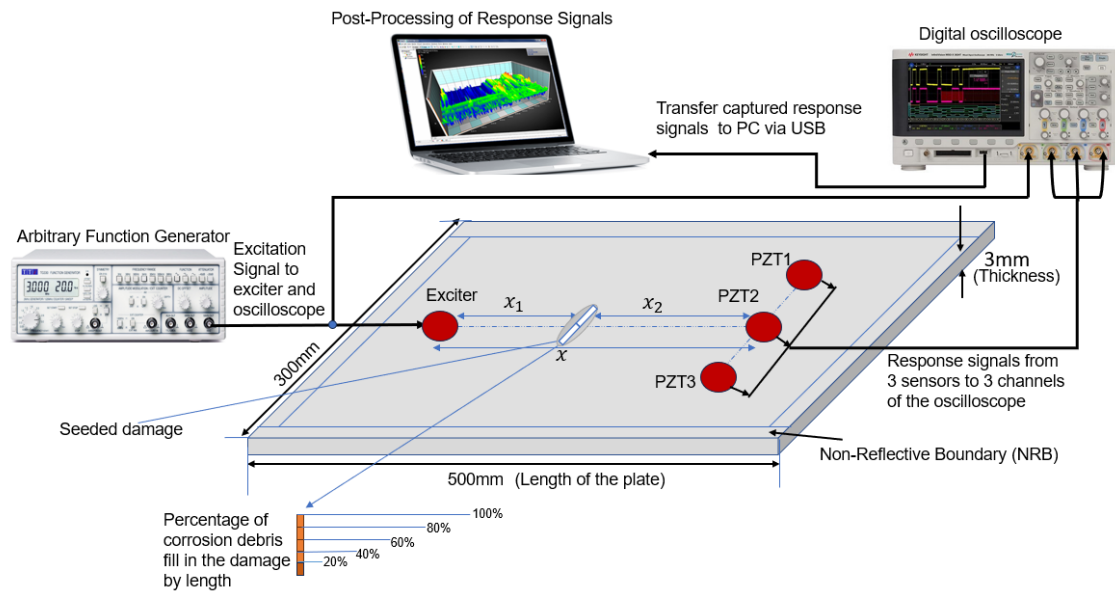


Figure 3-15 The system architecture with debris fill the damage.

3.6.1 Effect of temperature on debris fill damage.

The system architecture of **Figure 3-15** is adapted to the temperature effect as debris fills the damage. **Figure 3-16** shows the new system architecture. The actuator is excited at each damage depth and increasing debris fill percentage while response signals are captured, recorded, and saved at every targeted temperature. By analysing the response signals, the combined influence of the temperature and debris is understood and used for predictive damage monitoring.

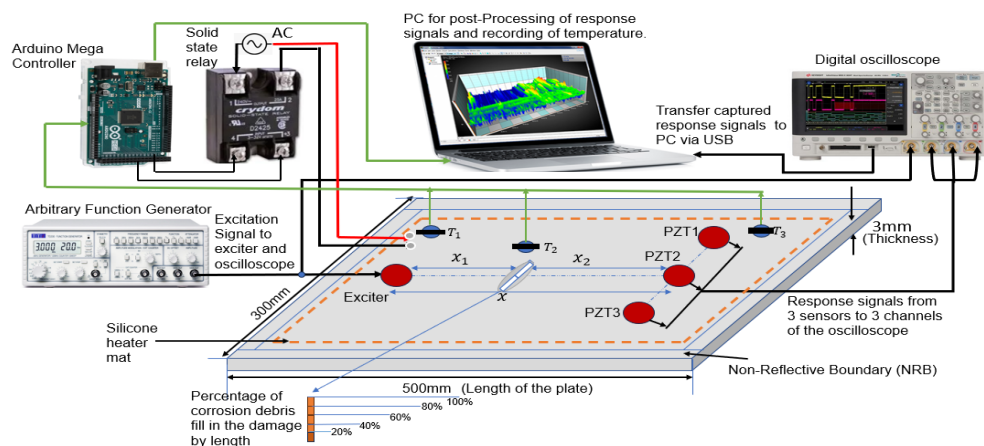


Figure 3-16 The system architecture for debris filled damage and Temperature effect.

3.6.2 Effect of vibration on debris fill damage.

Similarly, the system architecture of **Figure 3-14** is adapted to low-frequency vibration impact effect as debris fills the damage. **Figure 3-17** shows the new system architecture. At each damage depth and increasing debris fill percentage, the actuator is excited while response signals are captured, recorded, and saved at every impact of the low-frequency vibration. By analysing the response signals, the combined influence of the low-frequency vibration impact and debris filled damage is understood and use for predictive monitoring.

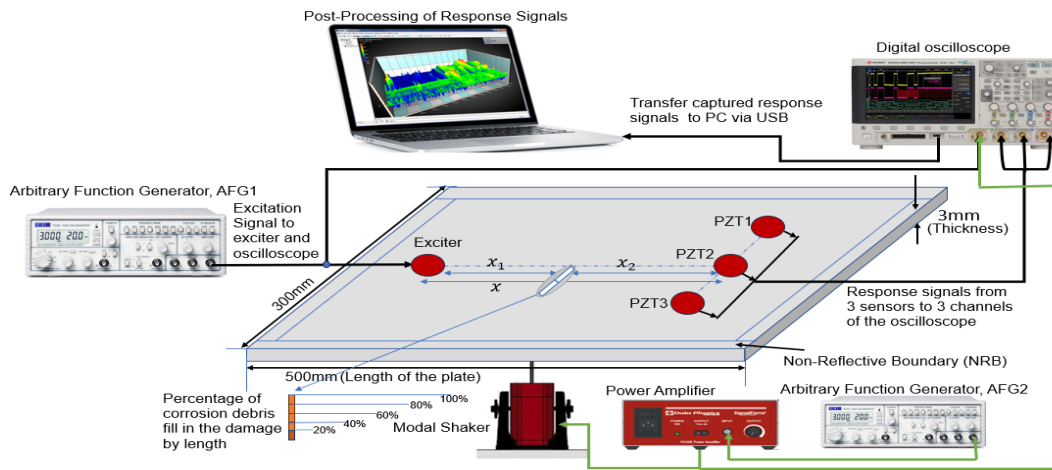


Figure 3-17 The system architecture for debris filled damage and vibration effect.

3.6.3 Combined Effect of Temperature and Vibration on debris-filled damage.

The system architecture of **Figure 3-16** and **Figure 3-17** under subsections 3.6.1 and 3.6.2 respectively are integrated to form a new system architecture shown in **Figure 3-18**. At each selected damage depth, debris-filled percentages and vibration impact, the response signals are recorded, captured, and saved at every temperature.

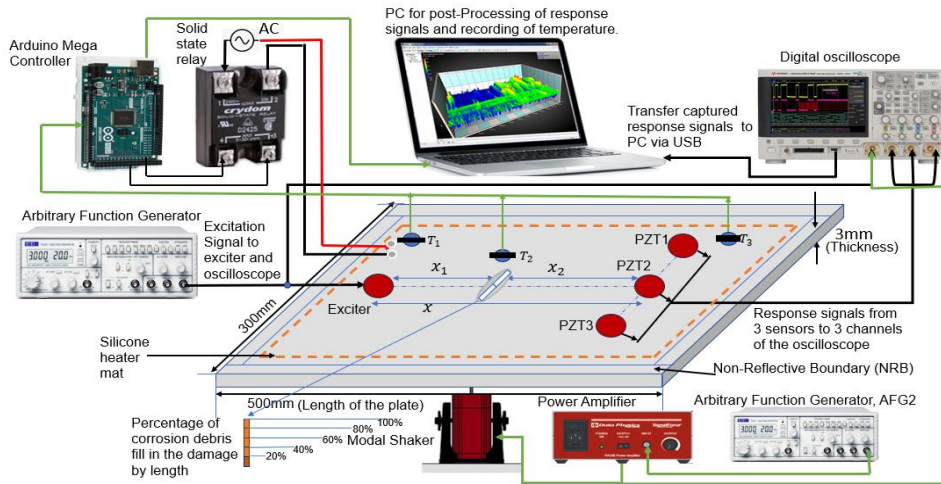


Figure 3-18 The system architecture for Vibration, Temperature and Debris filled Damage.

3.7 Components of the system architectures.

3.7.1 Silicone Heater Mat.

The temperature of the plate was varied using two 50-Watt power rating silicone heater mat of 100mm x 150mm dimensions. The heater mat is flexible, electrically insulated and has strong adhesive surface for bonding and withstanding of high temperature. Each of the silicone heater mats provides a power density of $0.0033W/mm^2$ which is sufficient to offer proper heat distribution across the area of the plate. An A.C type was selected because it heats faster than the D.C type, which depends on unidirectional current (D.C). It was connected through a solid-state relay to the mains to ensure usage safety and achieving targeted temperature, as shown in **Figure 3-19**. Any targeted temperature of the plate T_1 is achieved through a control heating coded in the Arduino mega 2560 Rev3. At every second, the measured temperature of the plate T_2 by the sensor is compared with the targeted temperature, T_1 . If the measured temperature of the plate T_2 is less than the targeted temperature, the solid-state relay remains ON, and heating continued. However, once T_2 is greater than or equal to T_1 , the relay switching will change to a different mode called trickle switching to maintain the

plate temperature at relative constant value of the targeted temperature until some repeated measurements of the response wave are completely captured by PZT1 to PZT3 and recorded by the oscilloscope before a rest request is issued. **Figure 3-20** is the flowchart used to write the control code implemented in the Arduino mega 2560 Rev3. The measured temperature of the plate at every second is visualized in the PC through serial communication port between the Arduino and the PC.

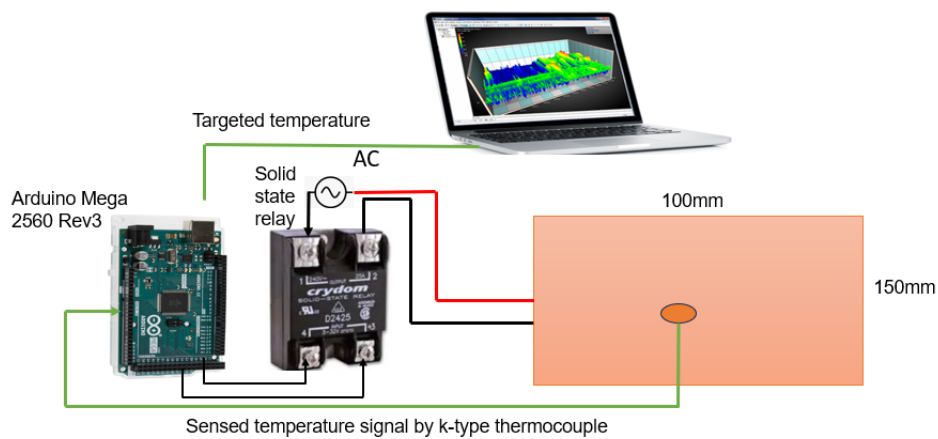


Figure 3-19 Temperature control and sensing architecture.

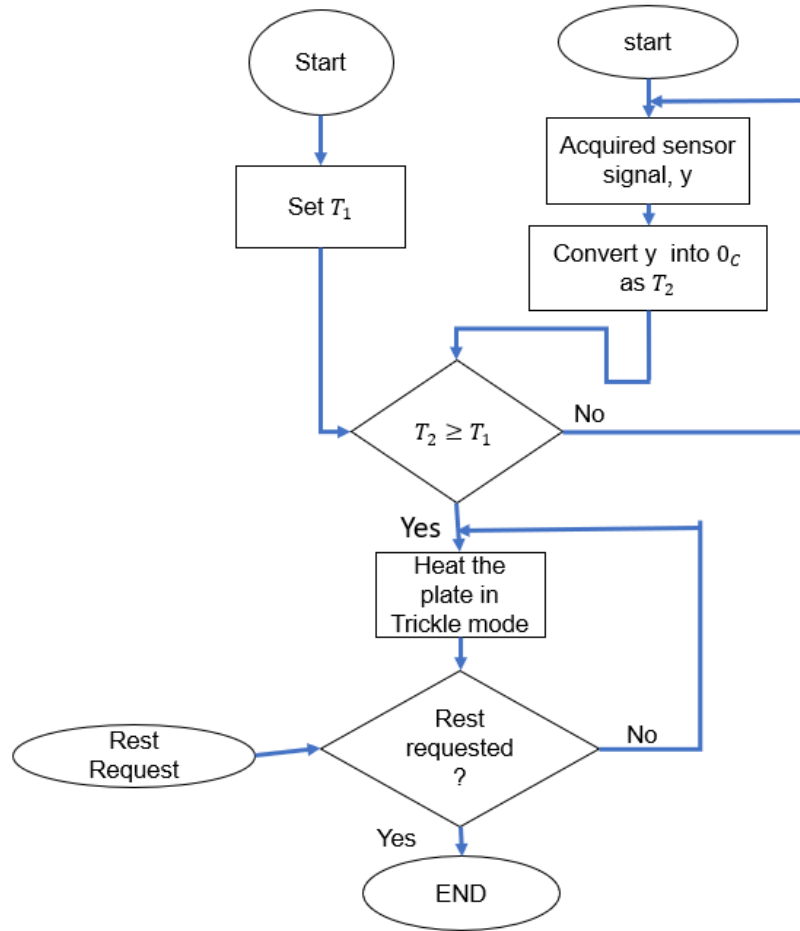


Figure 3-20 The heating control flow chart.

3.7.2 Digital Oscilloscope.

To measure the excitation signal and response signals simultaneously, an infiniivision 3000AX oscilloscope was selected and shown in **Figure 3-21**. It has 4 analog channels of the same impedance of 1 MΩ, ensuring minimal loading effects on the system. The channels are labelled CH1 to CH4 with an ON/OFF button. It has a high sampling rate of 4Gsamples/s and 200MHz bandwidth for nearly accurate capturing of signals. Files are saved as .csv and transferred from the oscilloscope to the PC via the USB using a flash drive. Before signal capturing, the time/division and voltage/division scales are set to be the same for all the channels.

The excitation signal from the function generator is connected to CH1, while the sensors are connected to CH2 and CH4. The CH1 signal, which is the excitation

from the function generator was selected to trigger the capturing of signals across all the channels when the single run control button is engaged. Since excitation of the must occur before response signals are recorded, hence its selection as trigger. This implies that no signal would be recorded by any of the channels if there is no excitation.

By engaging the save button function, an interface for configuring the filename, file type, saving destination and length of samples is launched. For brevity, the files are named using an abbreviation according to the running the experimental case, the selected file type is .csv while length of samples and destination of savings were 10,000 and a created folder in the flash drive respectively. Although there are different acquisition modes but normal acquisition modes were selected and at each excitation, response wave signals are captured 5 times and averaged to ensure repeatability and minimize random error. The following step by steps procedure was created for signal acquisition using the oscilloscope.

1. Insert flash drive in PC and create different destination folders for each experimental case.
2. Turn ON the Oscilloscope after connecting the sensors and function generator output using BNC connector.
3. Switch ON the channels and do all the settings such acquisition mode selection, range of the volt/div and time/div, measurement type.
4. Set CH1 as the acquisition triggering source signal.
5. Insert the USB flash drive and click on save button to launch an interface for file destination, file type and length of samples selections.
6. Engage the Run/Stop button once to allow the signals propagate for about 2-3minutes before engaging the Run/Stop again to capture and displayed the waveforms of the signals on the screen.
7. Engage the save button to register the signals in the connected flash drive.
8. Subsequently, engage the single run control button and save button only to keep capturing and saving the signals of the waveform.



Figure 3-21 The Digital Oscilloscope.

3.7.3 Function generator.

TTi TG550 function generator shown in **Figure 3-22** was used in the study to create amplitude modulated excitation signal for the actuator to start vibrating and create propagating stress waves. Through the digital frequency lock, relative stability was achieved for the created signal. It has a frequency range from 0.005HZ to 5MHz and a peak-to-peak maximum voltage of 20V. It has an internal modulation frequency of 400Hz which was used to modulate the carrier frequency of 180KHz to generate amplitude modulated continuous packet waves used in all the experimental cases.

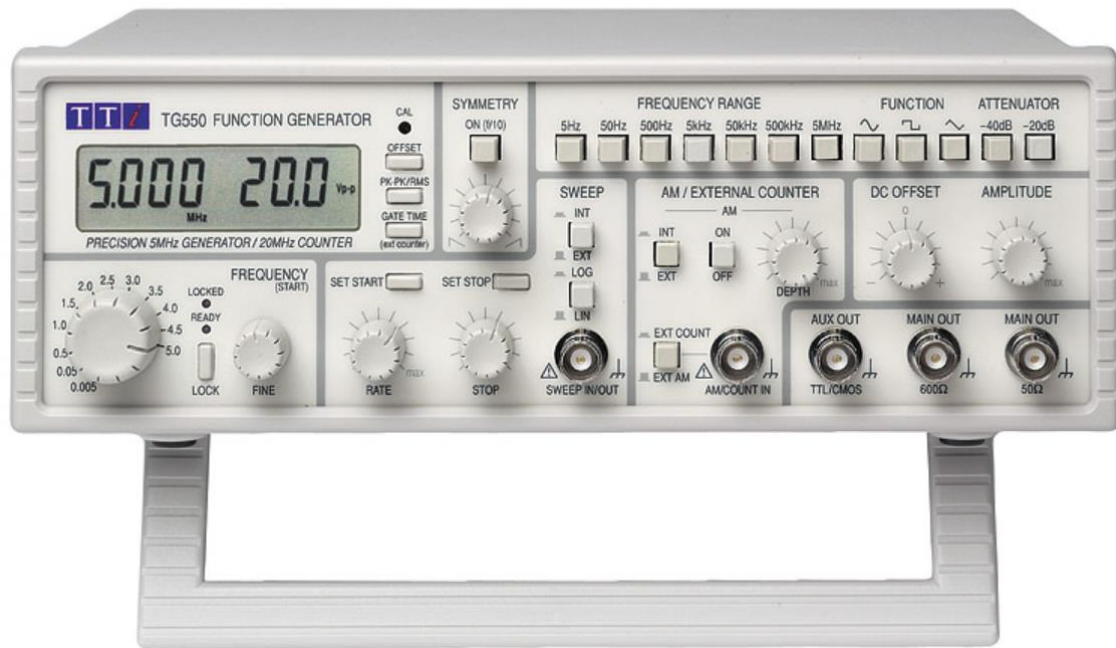


Figure 3-22 The Function generator.

3.7.4 Low-vibration impact effect by Modal Shaker.

To create varying impact of low-frequency vibration effect in the study, a small modal shaker model GW-V4/PA30E from DataPhysics was used. The maximum sine force (pk) and maximum shock of the shaker is the same with a value of 17.8N while the maximum random force (RMS) is 5.9N. By varying the amplitude of the input sinusoidal signal, the output force of the shaker varies. The influence was observed in the response waveform response signal captured by the sensor. **Figure 3-23** depicts the design setup to incorporate varying-low frequency external signals in the damage prediction.

The function generator has two outputs with different resistances of 50Ω and 600Ω but offers the same range of voltage of 2mV to 10V to either of the output ports. This implies that the minimum power is $8 \times 10^{-8}W$ to $2W$ for 50Ω while it is $6.67 \times 10^{-9}W$ to $0.167W$ for 600Ω. This range of power is small to drive the modal shaker, hence the need for the power amplifier. A power amplifier from the same manufacturer with the model number PA100E is suitable for amplifying the input signal. The amplifier has 0.7Vrms as input sensitivity for full output. It can output 10V and 10A, thereby making it a 100W power amplifier. To ensure

the safety of the function generator, the male BNC for output signal was connected to 600 Ω output put and supplies approximately 2mV to the power amplifier. From the amplifier, signals the required input voltages for shaker is first set and visualized in the oscilloscope before integrated into the system.

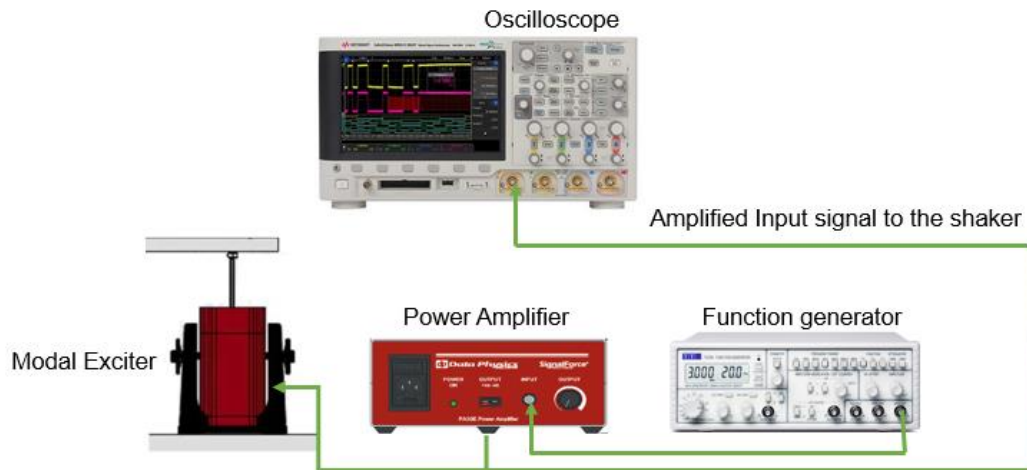


Figure 3-23 The system architecture for modal shaker application.

3.7.5 Damage seeding.

Corrosion is a localized form of damage in structures. It deteriorates the strength and jeopardizes the integrity and availability of the structure. Principally, corrosion activities lead to thinning of the structure thickness. Hence, it could be simulated in structure by milling down its thickness at a certain location. Also, simulating filled damage requires a corrosion product to cover the damage. On this note, damage of increasing depth was created at the mid-distance of the plate. The depth of the damage increases from 0.5 to 2.5 at an interval of 0.5. Corrosion products were grounded and used to fill the damage at each level from 20% to 100% of the damage length. However, other particles could fill the damage if they can be trapped and accumulate in it. Hence, the name debris filled damage, DFD.

3.7.6 Structural material used.

Mild carbon steel from Dore Metals services[179] of dimension ($500\text{mm} \times 300\text{mm} \times 3\text{mm}$) with properties as detailed in **Table 3.2** was used as the structural material. The material has a low carbon content in the range of 0.04-0.3%. It is exceptionally ductile, formable, and mostly used for pipelines, automobile body parts and plates.

Table 3.2

Material	Young modules, E (N/m ²)	Poisson's Ratio, ν	Density, ρ (kg/m ³)	Length, L (mm)	Width, W (mm)	Thickness, T_h (mm)
Carbon steel	2×10^{11}	0.289	7800	500	300	3

3.7.7 Transducers used: Ceramic PZT.

The ultrasonic transducers used in the study are disc ceramic lead zirconate titanate PZT manufactured by Mouser Electronics [180]. The PZT is an active device that can query the structure at any time, unlike passive devices such as resistance gauges [181]. Hence, it is suitable for use as an actuator and sensor of structural vibration and elastic waves to detect and localize damage in the structure through analysis of the recorded signals. The principal operation of the PZT as an actuator and sensor is covered in Chapter 2. The ceramic PZT is fragile and can easily break. Hence, handling it with extreme caution is advisable until installed on the structure. The PZT has two metallic terminals for electrical connections, as shown in **Figure 3-24**. The positive terminal is for positive electrical connection and the top side surface of the PZT, while the negative terminal is for negative electrical connection and the bottom side surface of the PZT. The bottom surface of the PZT is coupled to the structure using an adhesive reagent of **Figure 3-27**. The operating temperature range of the PZT is -40°C up to 160°C [180], which confirms its suitability for the temperature range of 25°C to 75°C used in this study. As an actuator, electrical voltage is applied across it to generate an electric field proportional to its lateral induced displacement.

However, the generated electric charge is inversely proportional to the thickness of the PZT, as expressed in equation (3.26). This implies that more electric charge would be induced on the structure as the thickness of the PZT decreases. With a small thickness PZT and high applied electrical voltage, a more intense stress wave would be generated around the circumferential area of the PZT. However, the decrease in the thickness increases the capacitive impedance of the PZT, thereby increasing the current demand from the function generator. This is expressed in equation (3.27). It is important to emphasize that an increase in the central frequency of the actuation signal increases the current demand for the PZT. This implies that the response signal intensity captured by the sensor will start decreasing after a certain frequency. At this frequency, it implies that the current demand of the PZT is slightly higher than the current supply capacity of the function generator, hence the need for a linear power amplifier. This knowledge is essential while selecting excitation frequency without a linear amplifier.

$$u_{ISA} = S_{ISA}l \quad (3.24)$$

$$S_{ISA} = d_{31}E_3 \quad (3.25)$$

$$E_3 = -\frac{V}{t_a} \quad (3.26)$$

$$I = i\omega C = i\omega \epsilon_{33}^T A/t_a \quad (3.27)$$

Where

A = PZT electrode area, l = *circumferential length*, t_a = *thickness of the PZT*. ω = angular frequency, S_{ISA} = Induced Strain Actuation, E_3 = generated electric field due to applied voltage across the terminals of the PZT. V is the applied dynamic electric voltage. As a sensor, an increase in the thickness increases its sensitivity to stress waves, as in equation 3.28.

$$V(S_1) = t_a D S_1 \quad (3.28)$$

$$\text{Where } D = \frac{k_{31}^2}{(1-k_{31}^2)} \frac{1}{d_{31}}$$

k_{31} and d_{31} are PZT material constant while S_1 is the sensed strain by the circumferential tip of the PZT and t_a is the thickness of the PZT. Hence, a thicker PZT is necessary for acoustic emission detection where the propagating signal

is due to the active damage growth, which is mostly less than the intensity of the response signal in the active pitch-catch method of inspection. Hence, the same dimension of the PZT was selected as an exciter and sensor. The properties of the PZT is in the datasheet provided by the mouser electronics[180]. The diameter and thickness of the transducer is 7.000 x 0.195 mm. To ensure its safety before installation, all the PZT transducers were packed in a plastic tube and padded with small soft foam. Before handling, the electrostatic charge of the fingertips is neutralized by robbing them on an aluminium plate. Disc PZT is selected over rectangular PZT due to its omnidirectional capability for radiating stress waves and sensing strain signals.

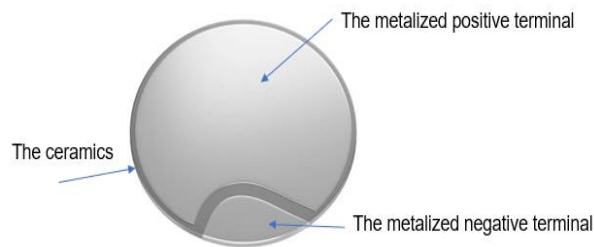


Figure 3-24 Disc Ceramic Lead Zirconate Titanate, PZT.

3.8 Installation of the PZT on the Structure.

Due to the fragile nature of the ceramic PZT, it was kept in the plastic tube until it was time for installation. Proper installation of the PZT is vital for the structural health monitoring process. To ensure this, the following procedures were adhered to.

- i. Each of the transducers was inspected for any physical damage but found none.
- ii. The diameter and thickness of the PZTs were measured using a micrometre screw gauge (0.001mm precision), as shown in **Figure 3-25**. The values obtained were relatively the same as those provided by Mouser Electronics.
- iii. The electrical capacitance of each transducer was measured after installation and before any experiment at least 5 times. The

average value obtained is consistent with the value provided by the manufacturer when compared. **Figure 3-26** showed the measurements.

iv.



Figure 3-25 Measured dimensions of the PZT using a micrometre screw gauge.



Figure 3-26 The measured capacitance of the installed exciter and sensors using a Fluke digital multimeter.

- I. Before installation of the transducers on the top surface of the plate was prepared to ensure appropriate bonding of the PZT with the plate. Hence, the plate surface was cleaned with acetone to degrease and remove any contaminants. It was allowed for about 20 minutes before the PZT layouts and locations were marked without lines.
- II. Two components of adhesive reagent (Epoxy Adhesive Loctite Hysol 9466) shown in **Figure 3-27** were mixed and applied at the marked positions for the PZTs[182]. The adhesive layer causes parasitic capacitance, which

increases with the bonding layer's thickness. Since the thickness of the adhesive layer can influence the transducers from exciting the plate or recording the strain signal, a very thin layer that is less than the thickness of the transducer was applied. The transducers were placed on the marked layouts with the thin-layer adhesive applied. Light pressure was applied on the transducer by placing a lightweight flat head bolt on each to ensure proper bonding and elimination of air between the transducers and the plate.

Although the manufacturer's setting time is 1hr and the cure time is 3 hours, it was allowed 24 hours to cure properly under laboratory temperature. The operating temperature range of the adhesive is -55°C to 120°C while the maximum temperature the plate will be heated is 75°C . Hence, the adhesive is suitable to bond the PZTs to the plate structure. The adhesive ensured that the PZTs were firmly coupled with the plate and that in-between air was eliminated, thereby decreasing air-caused impedance and improving the ease of inducing stress waves on the plate. After curing, acetone was used carefully to remove the overflow layer around the transducer.



Figure 3-27 Two-components Epoxy Adhesive.

After 24 hours of adhesive bond curing and the transducers firmly bonded to the plate, electrical wires were soldered on the transducer's positive and negative metallic silver terminals. Double-sided foam tape was used to hold the wire at a

firm position to avoid unintentional disconnection, which might damage the transducer. All the negative terminals of the transducers were electrically connected to the plate to ensure a complete circuit. A continuity test was conducted using a Fluke digital multimeter to ensure there was no improper electrical connection that would cause short-circuiting.

3.9 Non-Reflective Boundary (NRB).

Considering the geometrical dimensions of the plate, wave reflection from the edges would be inevitable, and it adds to the complexity of analysing the sensor-recorded response signals. A typical wave reflection from the edges of the plate is demonstrated in **Figure 3-28**. To minimize this effect, moulding paper clay was used to cover the edges of the plate. This technique has been used by Victor Giurgiutiu et al. in their recent work on delamination monitoring using NDT and SHM [183].

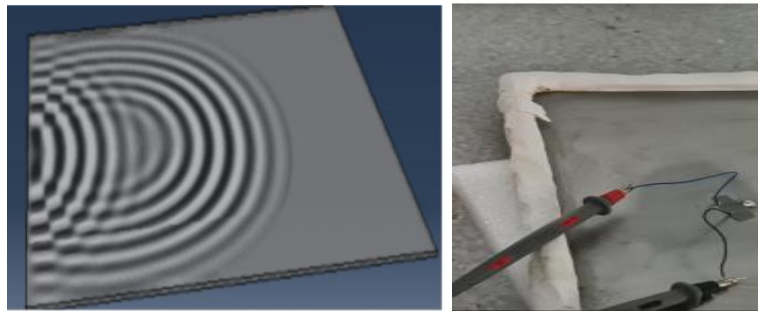


Figure 3-28 Typical wave reflection from the plate edges.

3.10 The Research Methodology

Figure 3-29 depicts the research methodology framework used in the study. The study commenced with a literature review, leading to the selection of materials and methods after problem identification. The analytical model for the healthy and unhealthy cases was established before integrating environmental operation conditions. The response signals for each case were captured at least 3 times and averaged to minimize random error and increase the signal-to-noise ratio. Pre-processing and feature extraction were performed on each response signal before further analysis and correlation with the damage.

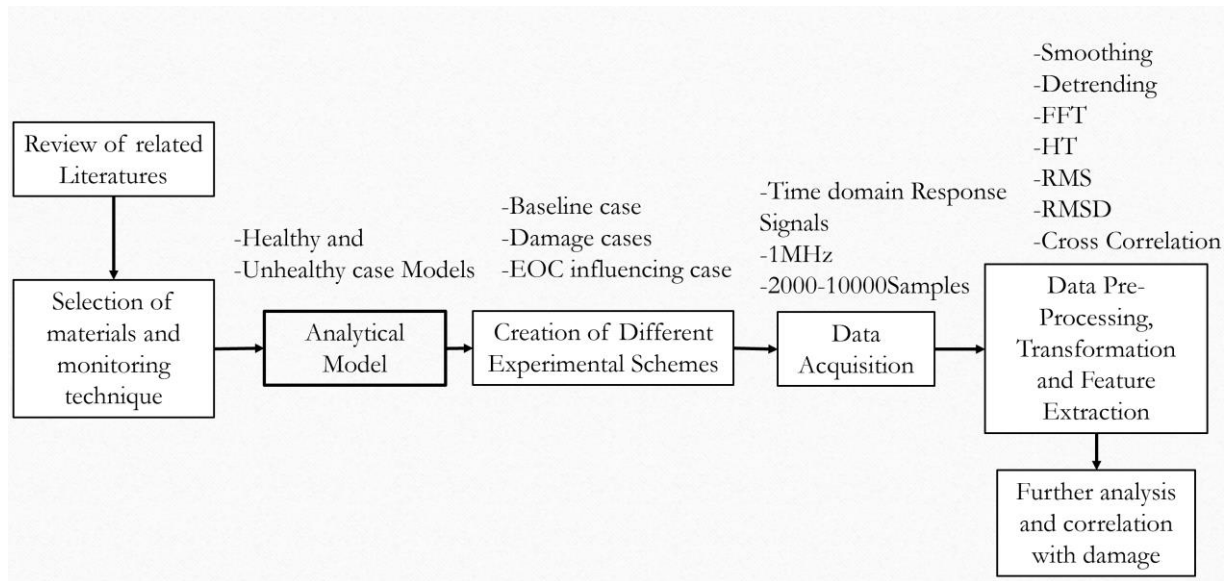


Figure 3-29 The research methodology flow chart.

3.11 Signal Processing and summary.

Signal processing is central to structural health monitoring (SHM), with the core mandate to extract meaningful information from signals captured by the sensors through which damage is detected, localized, and quantified. Hence, different signal processing techniques have been adopted to extract the signature of the captured response wave signals and correlate it with the damage of the study. Different Signal processing techniques such as Fast Fourier Transform FFT, Modulation index, cross-correlation CC, RMS and RMSD have all been used in different stages of the study to accomplish the study objectives. In this chapter, the materials and methods used in this research work were described. The models and different experimental schemes were discussed as well and used in the following chapters.

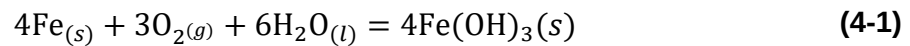
4 CHAPTER FOUR: EFFECT OF DRY DEBRIS FILLED DAMAGE ON PRE-MODULATED GUIDED WAVE

4.1 Overview

In this chapter, monitoring the evolution of debris-filled damage in thin plates is explored. The study employed pre-modulated waves and GWUT pitch-catch. The structural response signals are processed using the Fast-Fourier Transform (FFT), Hilbert Transform (HT), and correlation techniques to detect the damage and quantify the debris filling as the percentage varies.

4.2 Introduction

Damage in a metallic structure entails gradual degradation of structure performance due to the initiation and growth of defects that alter the structure's properties [3]. Fundamentally, defects start from the micro stage and graduate into a macro stage that could cause catastrophic failure of the structure if unrestrained. Some possible damage commonly found in structures are cracks, dents, and corrosion of different forms[184]. Corrosion is an enemy of metallic structures that degrades their strength and elasticity and shortens their useful service life[185]–[188]. Corrosion can form in the existence of other forms of structural damage. Primarily, corrosion happens in the presence of three core components: metal(solid), Oxygen ($O_{2(g)}$) and water ($H_2O_{(l)}$). Equation (4-1) is an oxidation reaction of metallic iron with water in the presence of air[3].



Corrosion occurs in different ways in metallic structures with a singular target of limiting their lifetime of service. Oxygen and water are readily available in the environment where costly metallic structures are deployed. Pitting corrosion is one of the corrosion types that has been seen to be more grievous than others when it existed[66], [137], [189]. It is one of the most localised forms of corrosion that occurs in an aggressive environment, as could be seen in the oil and gas industry[187], marine industry[190] and in an environment that is rich with halides[39], [189]. Its formation is mostly restricted to a small surface area of the host structure to cause stress raiser[17]. The formation of stress riser in structures would result in fast catastrophic failure if not detected early. Also, the activities of pitting corrosion could lead to structural failure via progressive perforation, resulting in stress corrosion cracking. It is particularly difficult to design against pitting corrosion, unlike other forms of corrosion. A small, narrow pit with minimal metal loss can lead to structural failure. In practice, when damage (cavity, dent, notch, or crack) is formed in a metallic structure, it could be covered by trapped debris and substances that speed up corrosion activities and advance the pitting of the structure. The damage could be open or covered with a semi-permeable

membrane of corrosion products or other trapped debris. The covered damage could accelerate the activities of severe pitting corrosion and initiate the weakest point for stress concentration that could lead to structural failure. Localised damage in the protective layer due to chemical or mechanical sources or poor application can initiate pitting corrosion[190]. **Figure 4-1** shows the morphological shapes of pitting corrosion that typically forms in structures:

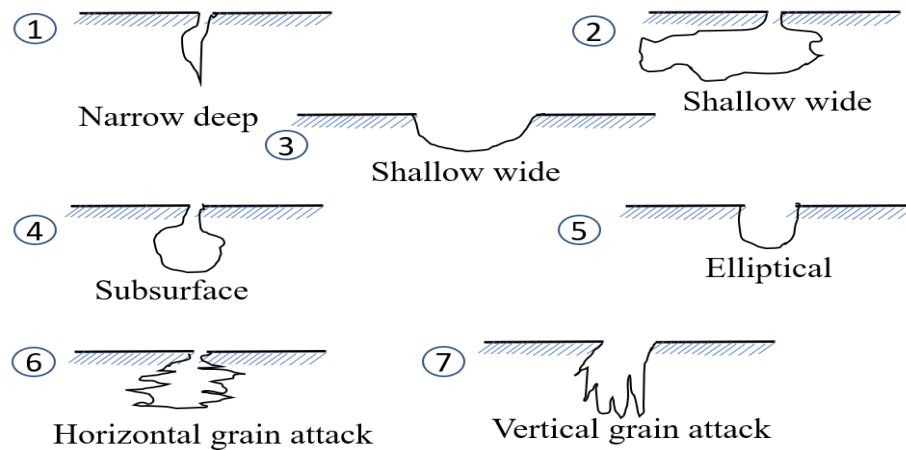


Figure 4-1 Morphology of common shapes of pitting corrosion [189].

Most of the studied surface structural damage were dry and empty types [191]–[194]. Nature does not allow a vacuum; hence, any formed surface structural damage in the field of operation would be filled with debris over time. The debris could be mixed particles trapped and stuck in the damage. The continual accumulation of the debris would close the damage and promote the activities of pitting corrosion[194]. The covered damage creates an illusion of structure continuity but jeopardises its integrity in real life. The stages in pitting corrosion are provided in **Figure 4-2**. These stages led to a damage closure as described below. **Stage 1** depicts a healthy structure without damage, especially cavity, notch, crack, and deep scratch. **Stage 2** represents the scenario when damage is created in the structure without particle accumulation. At this point, the structural loading capacity has been jeopardised. Deterioration of the structure's elasticity property gradually starts as the damaged area transits into the plasticity region. **Stage 3** depicts the environmentally aided particle deposition entrapped in the damaged spot. The trapped heterogeneous particles in a moist atmosphere would lead to observable rust films. The formed corrosion product would

gradually be gelled with time as the particles gain good adhesion to the damaged surfaces, hiding the damage and creating a fake continuity of the structure, as shown in Figure 4.3. The accumulated debris and corrosion-prone particles could be less prevalent in a dry atmosphere than in a humid atmosphere and provide a mechanism for increased crack closure and deepening of the material perforation that would usher in **stage 4**. Pitting corrosion is difficult to detect, especially when covered by debris. Some grievous pitting corrosion has a small pit at the structure's surface but a large size beneath[187]. Hence, to avoid grievous pitting corrosion from forming and advancing through debris-filled damage, there is a need for early detection of debris-filled damage. Most studies focused on detecting and evaluating empty dry damage (such as crack, delamination, debonding, and dent) in isotropic or composite structures using guided waves [66], [195], [196]. This work proposes and implements a novel debris-filled damage detection using long-length pre-modulated excitation wave and a new damage index.

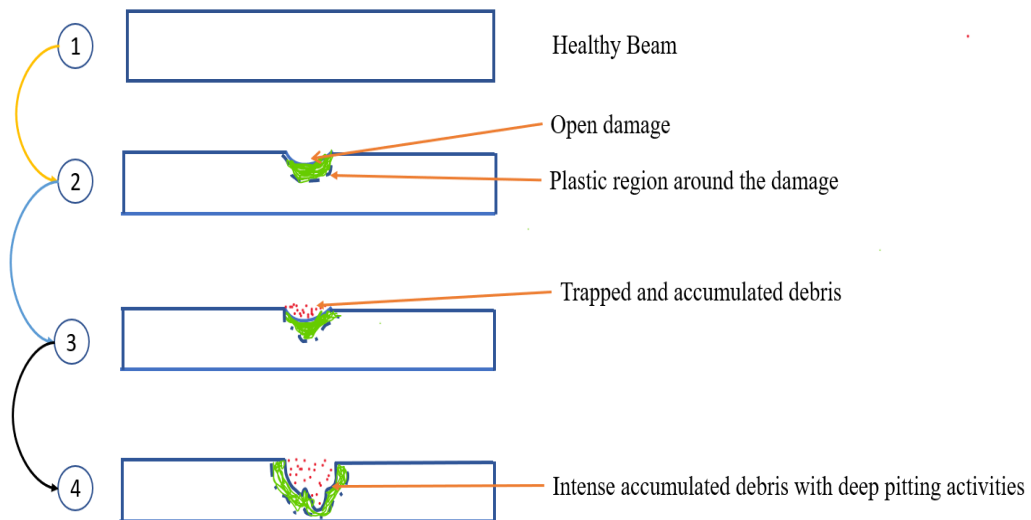


Figure 4-2 The deterioration stages in pitting corrosion.

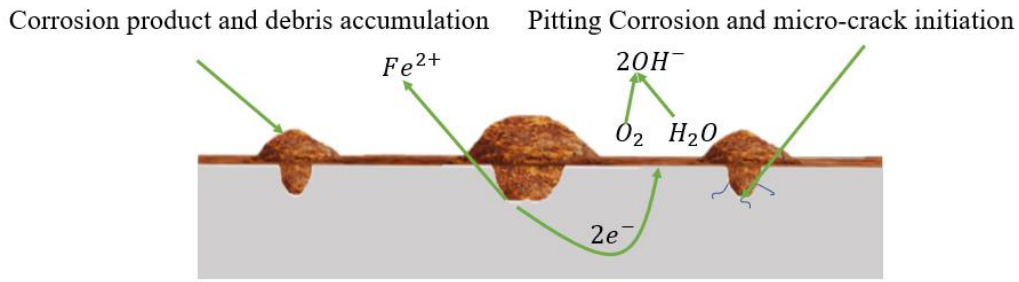


Figure 4-3 The mechanism of corrosion.

This paper provides, in section-2, the relevant theory about the wave-damage interaction, modulation of interacted signals for damage prediction and the methods to process these signals. The theoretical description of section-2 establishes the base for selecting the methods and materials as described in section-3. Section-3 also contains the complete details of an experimental scheme to collect the data for novel debris-filled damage detection with the long-length pre-modulated excitation wave. In section 4, the experimental results are presented and discussed. The conclusions are provided at the end of section 5.

4.3 Theory: Wave-Damage Interaction and Effects

Ultrasonic waves have been extensively used to detect and evaluate damage existence in structures by analysing wave-structure response signals. The waves could be generated through passive or active mode [184], [197]. Passive mode occurs when the received response signals are due to the crack propagation mechanism. The sound wave generated in passive mode is often referred to as acoustics emission (A.E.) [198], which happens only during active crack propagation. In an active mode, the propagating wave is generated through excitation of the actuator or striking the structure with an excitation hammer [199]. The configuration topology of the transducer often used in active mode is Pitch-Catch or Pulse-Echo [76], [184], [200], as in **Figure 4-4**. In Pulse-Echo configuration topology, one or more transducers are used. Using only a transducer in pulse-echo configuration, it would be programmed to actuate an interrogative wave at one time and sense the reflected response wave at another time. This configuration is suitable when inspecting for structural damage that can cause a reflection or an echo of good intensity. In Pitch-Catch configuration

topology, at least two transducers are used. One of the transducers functions as an actuator, and the other functions as a sensor[76].

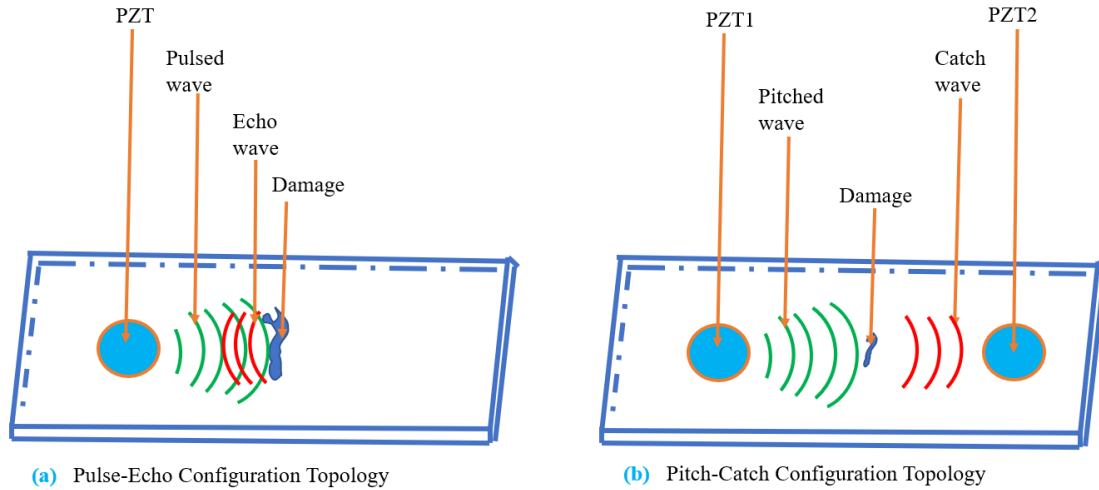


Figure 4-4 Active mode transducers configuration topology.

Various Nondestructive testing (NDT) techniques exist to inspect and evaluate damage presence and structural integrity[36]. These techniques are visual, thermographic, eddy current, radiographic, and guided wave ultrasonic testing (GWUT)[201]. GWUT is advantageous for long-range and full coverage inspection of structures without significant structural modification [21], [184], [202]–[204], which minimises inspection drudgery and enhances daily work output [99], [184], unlike other NDT techniques. GWUT could be used for linear and nonlinear damage-related feature detection[205]–[207]. The linear testing method has been majorly used to detect defects of reasonable sizes. It could be unsuitable for early-stage or corrosion damage activity detection, such as debris-filled damage.

In about 1960s, Zarembo and Krasilnikov conceptualised a method of structural integrity inspection called Nonlinear Wave Modulation Spectroscopy (NWMS)[208]–[210]. It was used in building structures around the 1990s and has been further researched and used in many instances for structural health monitoring(SHM)[210]. The NWMS uses a single high-frequency wave introduced into the structure through the piezoelectric transducer (PZT)[211].

This high-frequency wave is the carrier wave that a low-frequency signal modulates. Impact hammer [212] and material testing system (MTS) [210] have been predominately used to inject a low-frequency signal into the structure, while PZT is used to inject a high-frequency signal. There is often inconsistency in the use of impact hammer and high cost in acquiring MTS for injection of low-frequency signal in the structure. These have limited the adoption of the nonlinear damage detection method in practice. Interpretation of the nonlinearity effect in the response signal and accurately relating them to damage when more than one phenomenon could cause such is challenging [211] [212]. Although in [213], the authors developed a theoretical framework for mixing frequency techniques and used it in [204] to detect impact damage by counting spectral peaks. It is still challenging to credit all the formed spectral peaks to damage existence in the structure. We used a pre-modulated excitation signal to enhance the ease of interpreting the response signal and consistency in signal modulation. This signal is created in the methods and materials section, while its theoretical formulation is discussed in section 3. Unlike the Nonlinear modulation, only two distinct sidebands and the carrier band signals would be formed using the pre-modulated wave. The interaction of the propagating wave with the defined damage would be manifested in the variation of the sideband's magnitude, as noted in the result analysis section. We used the internal low-frequency of the arbitrary function generator to modulate the high-frequency carrier wave. This approach generated modulated packet waves, typically as in **Figure 4-5**.

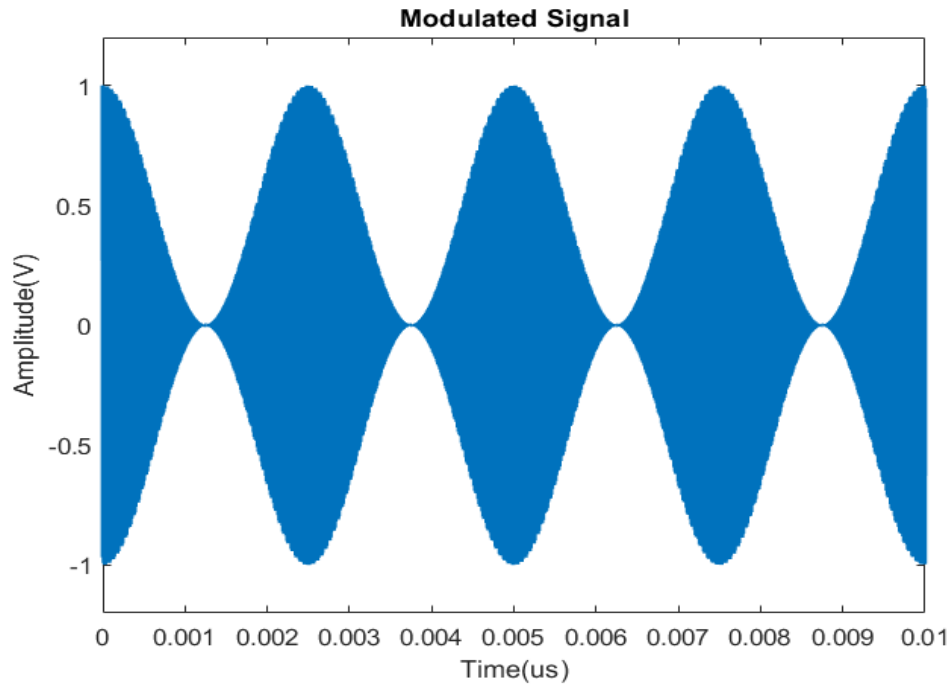


Figure 4-5 The generated modulated excitation signal.

4.4 Amplitude Modulation Theoretical Formulations and Analysis

Modulation is the act of varying any key three parameters (Amplitude, Frequency and Phase) of the carrier wave signal with a low-frequency wave signal that could be referred to as the message signal [209]. If a signal of low value varies the carrier wave's amplitude, frequency, or phase, the process is called amplitude modulation, frequency modulation, or phase modulation, respectively[209]. This study adopted wave amplitude modulation to generate a continuous wave packet that would squeeze and relax the PZT actuator and cause the structural atoms to vibrate about their mean positions. Unlike Nonlinear Wave Modulation Spectroscopy in [208]–[210], the interrogating packet waves would be generated before being introduced into the structure through the PZT actuator. Through this approach, the modulation index of wave signal before injection into the structure with and without damage could be easily estimated, and variations accompanied after that would be an attribute of the damage existence in the structure. The formation of excessive sidebands would be minimised as damage detection would be based on the variation of the upper sideband and lower sideband

strength relative to the carrier signal component. **Figure 4-6** depicts a typical wave amplitude modulation. It could be seen that the low-frequency signal determines the number and duration of the amplitude modulated packet waves.

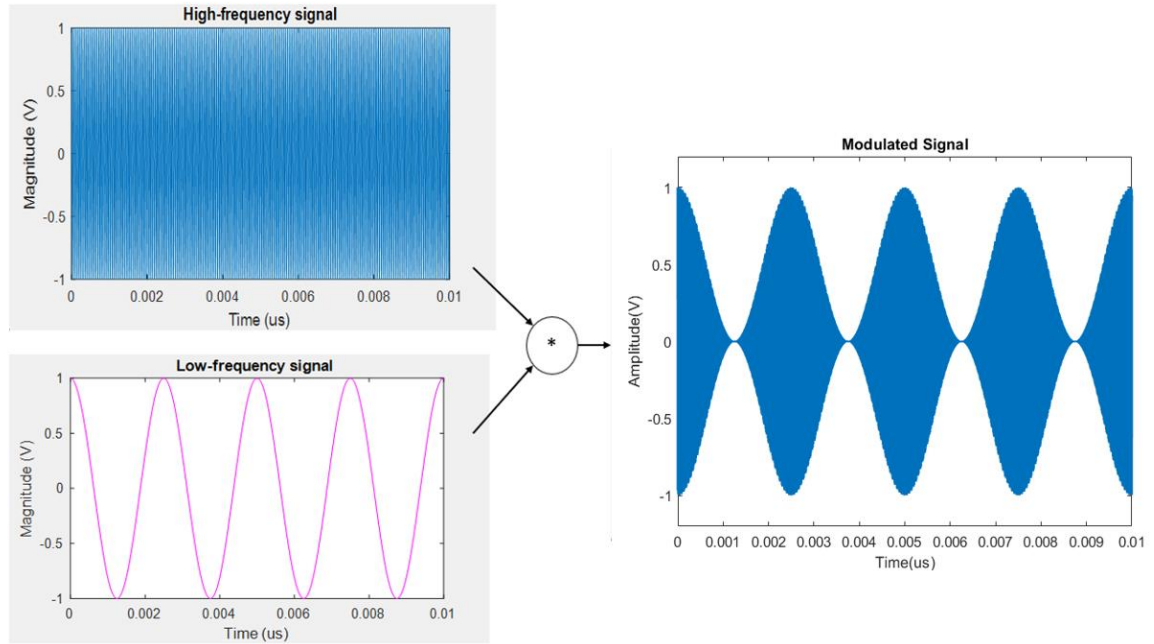


Figure 4-6 Amplitude Modulation of the excitation signal.

Let's assume the high-frequency wave signal shown in **Figure 4-6** is represented in equation (4-2) as the carrier wave signal. And the needed low-frequency signal to modulate the amplitude of the high-frequency wave signal is as in equation (4-3).

$$y_c(t) = \cos(\omega_c t) \quad (4-2)$$

$$y_m(t) = m \cos(\omega_m t) \quad (4-3)$$

Where

ω_c = high angular frequency of the carrier signal component

ω_m = low angular frequency of the message signal component

m = intensity of the message signal component

To achieve modulated wave packets that would excite the transducer actuator, an offset amplitude, A is introduced into the low-frequency signal to form the modulating signal given in equation (4-4)

$$\hat{y}_m(t) = A + m\cos(\omega_m t) \quad (4-4)$$

Using equation (4-4) to modulate equation (4-2) results in equation (4-7) which is called the modulated wave signal. Assuming the structure is a lossless type devoid of attenuation effect, the received response signal by the sensor transducer would be akin to the generated signal. This is analogous to message transmission in radio communication.

$$y(t) = \hat{y}_m(t) * y_c(t) \quad (4-5)$$

$$y(t) = (A + m\cos(\omega_m t)) * \cos(\omega_c t) \quad (4-6)$$

$$y(t) = A\cos(\omega_c t) + m\cos(\omega_m t) * \cos(\omega_c t) \quad (4-7)$$

Taking normalisation of equation (4-7) resulted in equation (4-8).

$$y(t) = \cos(\omega_c t) + \frac{m}{A}\cos(\omega_m t) * \cos(\omega_c t) \quad (4-8)$$

Applying trigonometry identity to equation (4-8) to obtain equation (4-10).

$$y(t) = \cos(\omega_c t) + \frac{1}{2} \frac{m}{A} [\cos((\omega_c - \omega_m)t) + \cos((\omega_c + \omega_m)t)] \quad (4-9)$$

$$y(t) = \underbrace{\cos(\omega_c t)}_1 + \underbrace{\frac{1}{2} \frac{m}{A} \cos((\omega_c - \omega_m)t)}_2 + \underbrace{\frac{1}{2} \frac{m}{A} \cos((\omega_c + \omega_m)t)}_3 \quad (4-10)$$

Where $\omega_c = 2\pi f_c$; f_c = carrier or high frequency; $\omega_m = 2\pi f_m$; f_m = message or low frequency or modulating frequency.

From equation (4-10), it is theoretically evident that the power spectrum of amplitude modulated signal possesses three components signals before being injected into the structure for interaction or integrity query. These components are the carrier or centre frequency and the two sidebands surrounding the carrier component. Expressing this in a typical power spectrum graph would be as in

Figure 4-7. In a situation of no amplitude modulation, there won't be the formation of sidebands.

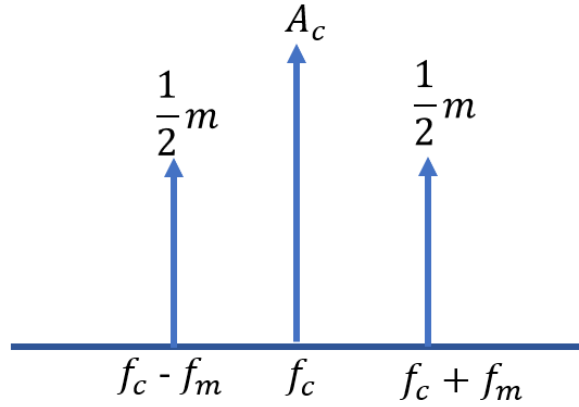


Figure 4-7 Typical frequency domain spectrum of AM signal.

The extent or depth of the carrier wave modulation in the time-domain could be estimated using equation (4-11).

$$\text{Modulation index } M_i = \frac{\tilde{d}}{d} \quad (4-11)$$

where

$$\tilde{d} = V_{max} - V_{min} \quad (4-12)$$

$$d = V_{max} + V_{min} \quad (4-13)$$

V_{max} = the maximum peak of the time-domain signal response

V_{min} = the minimum peak of the time-domain signal response

While in the frequency domain, the modulation index could also be estimated using equation (4-14).

$$\text{Modulation index } M_i = \frac{m}{A_c} \quad (4-14)$$

$$m = (f_c - f_m) + (f_c + f_m) \quad (4-15)$$

m = the sum of the two sidebands amplitudes.

A_c = amplitude of the carrier signal

The modulation index signifies the extent to which the low-frequency signal modulated the amplitude of the high-frequency signal. The modulation index could be 1, implying that the carrier signal amplitude is perfectly modulated. This is quite difficult to realise in most experimental cases as the modulation extent could be affected by wave-structure interaction and wave-damage interaction. The most achieved modulation indices are under-modulation when the modulation index is < 1 and over-modulation when the modulation index is > 1 . If under-modulation occurs, it signifies that the amplitude of the carrier signal is greater or much greater than the message signal amplitude. In the case of under-modulation, the modulation index is below 1 ($\mathfrak{M} < 1$), while over-modulation is greater than 1 ($\mathfrak{M} > 1$). The modulation index categories are expressed in piecewise definition of equation (4-16).

$$\mathfrak{M} \begin{cases} = 1; \text{perfect modulation} \\ < 1; \text{Under – modulation} \\ > 1; \text{Over – modulation} \end{cases} \quad (4-16)$$

4.5 Structural Response Signal Processing Techniques

After interaction of the propagating querying waves with the structure and debris-filled damage, the response signal would be collated and further processed. We employed Fast Fourier Transform (FFT) to ascertain the response signal's frequencies and intensity components. Hilbert Transformation (HT) was used to extract the envelope signal and compute its FFT, while the correlation technique was used to estimate the similarity between the reference signal and various response signals.

4.5.1 Fast Fourier Transform (FFT) of Time-domain Signal

FFT is used extensively in signal processing to transform signals from a time domain into a frequency domain for easy analysis[214]. As the sensor signal is recorded in the time domain, it is tedious to ascertain the different superimposed components that formed it. Hence, the need for frequency-domain transformation. A Fast Fourier Transform (FFT) is a special algorithm that is prominently used to compute the frequency components, $X(\omega)$ of a continuous

time-domain signal, $x(t)$. This is explicitly expressed in equation (4-17). FFT is widely used in NDT to analyse response signals recorded from sensor transducers to determine the signal's constituted components.

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)e^{-j\omega t} dt \quad (4-17)$$

4.5.2 Correlations of Signals

The correlation technique is often used in the signal processing of patterns to determine the similarity of one signal relative to the other signals of interest[215]. If two comparing signals match, their maximum matching peak will occur at the zero-origin. This often happens when a signal matches itself, called autocorrelation, while cross-correlation involves matching two different signals. From a statistical point of view, if the correlation coefficient score of the comparing signals is zero, they are said to be uncorrelated, as in equations (4-18) - (4-20). The nonlinearity effect of damage in ultrasonic signal response could be detected by determining the correlation between the reference signal and response signal before and after damage initiation in the structure. The presence of lag or lead time could signify the existence of a defect in the structure. Equation (4-21) could be used to compute the time delay or lead to a mismatched comparison[216]. It is worthy to note that cross-correlation is less sensitive to background variations or noise interference in signals as it may not affect all of the component peaks and would be attenuated.

$$\text{Uncorrelated, } \rho(x, z) = 0 \quad (4-18)$$

$$\text{Correlated, } \rho(x, z) \neq 0 \quad (4-19)$$

$$\rho(x, y) = \frac{\text{Cov}[x, z]}{\sqrt{\text{Var}[x]\text{Var}[y]}} \quad (4-20)$$

x and z are two comparing signals. Cov denotes the covariance of x and z while Var denotes variance.

$$R(\tau) = \int_{-\infty}^{+\infty} x(t)y(t - \tau)dt \quad (4-21)$$

Where

x and y are functions of time.

τ is the time delay, and it could be negative, zero or positive. R is the cross-correlation with time delay τ .

4.5.3 Hilbert Transformation (HT)

The first prime in nondestructive testing is to detect damage before further analysis of the characteristics of the damage. In radio communication, it is opined that integrity signals are contained in the message signal, which is the modulating signal. Since the response signal is a composite of signals, there is a need for separation and extraction, especially the envelop signal. Hilbert Transformation (HT) is useful in extracting the modulating low-frequency signals that envelop the carrier signal[32], [197]. The HT technique transforms the modulated real response signal into an analytical signal that could be expressed in the complex plane and then makes the computation of instantaneous amplitude and instantaneous phase easier. If the response signal captured by the sensor is, $x(t)$, its transformation into an analytical signal could be computed using equation (4-22)-(4-23).

$$Z(t) = Z_r(t) + jZ_i(t) \quad (4-22)$$

$$Z(t) = x(t) + jHT[x(t)] = A(t)e^{j\phi(t)} \quad (4-23)$$

Where $jHT[x(t)]$ is the real signal but transformed into a complex plane.

The modulation envelope or instantaneous amplitude is computed using equation (4-24).

$$A(t) = \sqrt{Z_r^2(t) + Z_i^2(t)} \quad (4-24)$$

Also, the instantaneous phase of the modulated signal is computed using equation (4-25).

$$\phi(t) = \tan^{-1}\left(\frac{Z_i(t)}{Z_r(t)}\right) \quad (4-25)$$

It is worthy of note that HT is useful for extracting the modulating signal and instantaneous frequency narrowband signals.

4.6 Methods and Materials

The system testing rig was first conceptualised and implemented as in **Figure 4-8**. Mild Carbon Steel is essentially used to construct civil structures, especially oil and gas pipelines. The high use of mild carbon steel is due to its low carbon content and good plastic toughness[187]. In this experimental study, we used a mild carbon plate of dimension: $500mm \times 300mm \times 3mm$. A damage of 40mm length, 5mm width and 2mm depth as shown in **Figure 4-9** was carefully machined at the mid-distance between the transducers to simulate initial damage that would advance into pitting corrosion activities. The mechanical property of the plate is tabulated in **Table 4-1**. The edges of the plate were covered with DAS modelling Air dry clay[217] to achieve a Non-Reflective Boundary structure (NRB). The NRB helped minimise the response signal's complexity by ensuring that signals from the edges of the plate were absorbed and never reflected. The plate is separated from the experimental table surface using a soft foam to avoid vibration transfer from the table. Two ceramic transducers (PZT: $7.000mm \times 0.195mm$) were bonded on the plate using epoxy adhesive[180]. The PZTs are 102mm from the end-edges and 100mm from the side-edges while they are 300mm separated. The transducers have a resonant frequency of 285KHz and curie temperature of 340 °C. One transducer served as an actuator (PZ1), and the other served as a sensor (PZ2). The PZ1 is excited with an amplitude modulated wave signal as derived in equation (4-8). The excitation signal of continuous packet triggering was generated by using the 400Hz internal low-frequency signal of the function generator (TG550 Function Generator) to modulate the carrier frequency of 180KHz. This is called a pre-modulated excitation signal, which differs from the case of using MTS to generate the low-

frequency signal or relying on the damage to generate the low-frequency to modulate the high-frequency signal injected into the structure[218]. The generated excitation signal was visualised and recorded using Agilent Technologies Mixed Signal Oscilloscope (MSO-X 3024A) with a sampling frequency of 1MHz. 10000 samples were recorded and processed using FFT to transform the signal from time-domain to frequency-domain and compute its frequency component's magnitude. The instantaneous magnitude of the response signal was determined using HT. A similarity match was calculated between the reference signal and response signals using cross-correlation, CC. The following scenarios were studied:

- (a) Interaction of the modulated wave signal with the structure when devoid of damage (Healthy state)
- (b) Interaction of the modulated wave signal with the structure when the damage of 40mm length, 5mm width and 2mm depth is machined on it. **Figure 4-9** shows the created damage condition on the plate (Unhealthy State).
- (c) Interaction of the modulated wave with the structure when different percentages of debris filled the damage as it would be in the early start of pit-filled corrosion damage (Debris-filled pitting scenario). **Table 4-2** shows the percentage of debris-filled damage and the percentage of damage not filled with debris. This percentage is calculated based on the length of the machined damage.

Table 4-1 Mechanical properties of the mild Carbon Steel.

Material	Young modulus, E (N/m ²)	Poisson's ratio, ν	Density, ρ (kg/m ³)	Length, L(mm)	Width, W(mm)	Thickness, T _h (mm)
Mild Carbon steel	2x10 ¹¹	0.289	7800	500	300	3

Table 4-2 Percentage corrosion debris coverage of the crack.

S/N	Crack Percentage of fill	Debris-filled length	Debris-unfilled length	Crack depth
1	Empty	0.00mm	40.0mm	2.00mm
2	20%	8.00mm	32.00mm	2.00mm
3	40%	16.00mm	24.00mm	2.00mm
4	60%	24.00mm	16.00mm	2.00mm
5	80%	32.00mm	8.00mm	2.00mm
6	100%	40.00mm	0.00mm	2.00mm

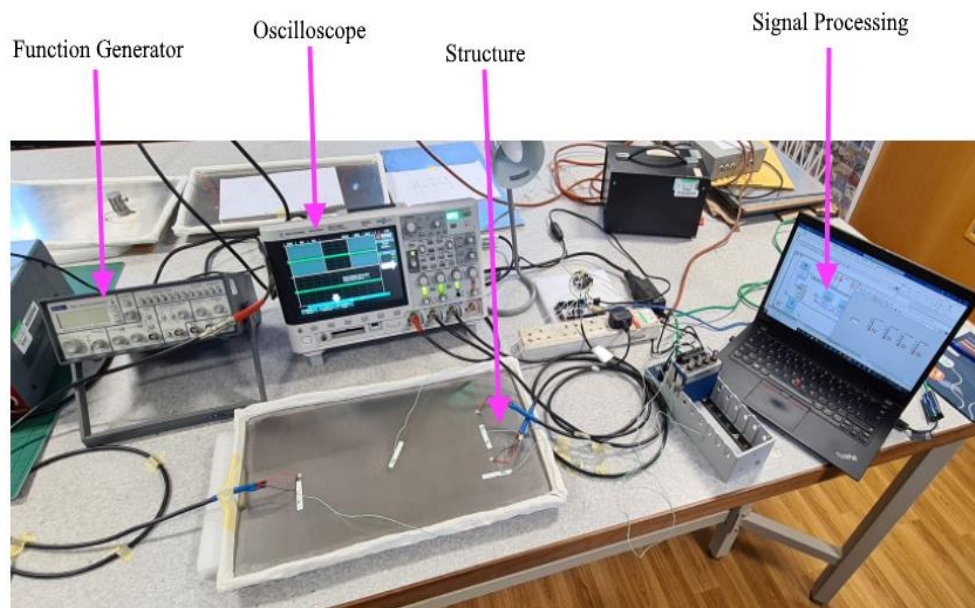


Figure 4-8 The Experimental testing rig.

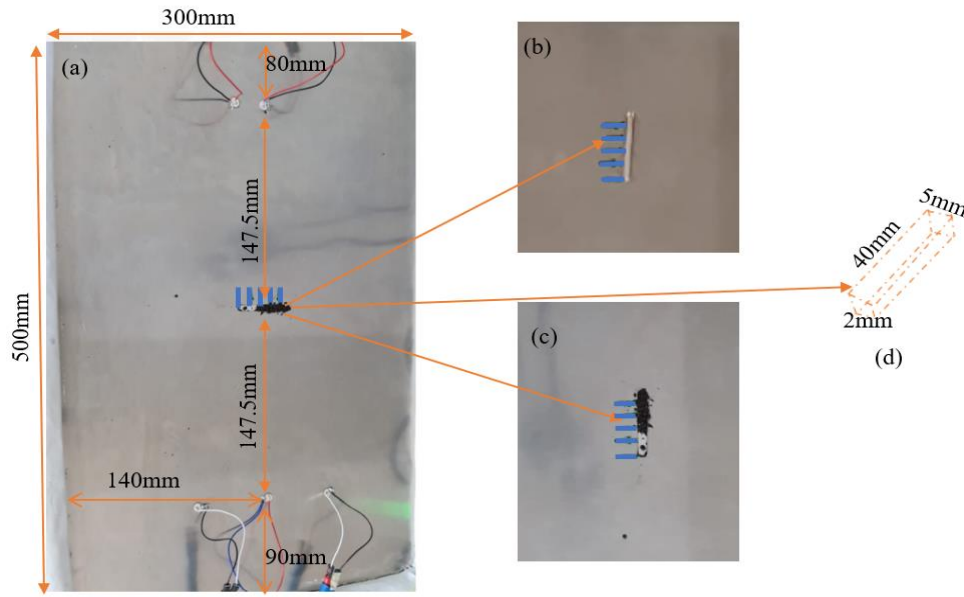


Figure 4-9 (a) The complete structure with sensor and damage (b) the empty machined damage debris-unfilled (c) Debris-filled damage (d) dimension of the damage. **NB:** The marked blue lines indicate the debris filling percentage.

4.7 Results and Discussion

(A). **Figure 4-10** show the recorded excitation signal and its FFT. It is evident from the result that the excitation signal is amplitude modulated as it shows the two sidebands (the Lower sidebands, LSB and the upper Sideband, USB) and the carrier frequency band. The processed signal resulted in a carrier frequency of 180KHz, the lower sideband (LSB) of 179.6KHz (i.e. carrier frequency minus the modulating frequency) and the upper sideband (USB) of 180.4KHz (i.e. carrier frequency plus the modulating frequency). From **Figure 4-10b**, the modulation index of the excitation signal is $\frac{(2.618+2.454)}{5.059} = 1$. Since the modulation index is 1, it implied that a nearly perfectly amplitude modulated wave was injected into the structure through the actuator transducer. The response signal was received using the sensor. When the wave packets in **Figure 4-10a** and **Figure 4-11a** are compared, there is a difference in the arrival time of the wave packets. Due to the high-frequency wave used in the study and continuous injection of the excitation signal, estimating the arrival time with certainty from the time-domain response signal would not be easy. The FFT of the response signal is shown in **Figure 4-11**. The computed FFT result showed that the response's signal frequency of

the carrier band, LSB and USB, is the same as the excitation signal. The modulation index of the response signal is 0.96, and the two sideband signals depict almost the same energy strength. This is a suggestion that there may be no damage to the structure. The cross-correlation between the excitation signal and the response signal was computed and shown in **Figure 4-12**. The cross-correlation showed that the two signals are nearly identical, as their highest matching peak occurred at the zero position. The little lag in the match could be attributed to the inherent inhomogeneity of the plate. The results demonstrated here affirmed that our testing rig works properly and can record integrity signals.

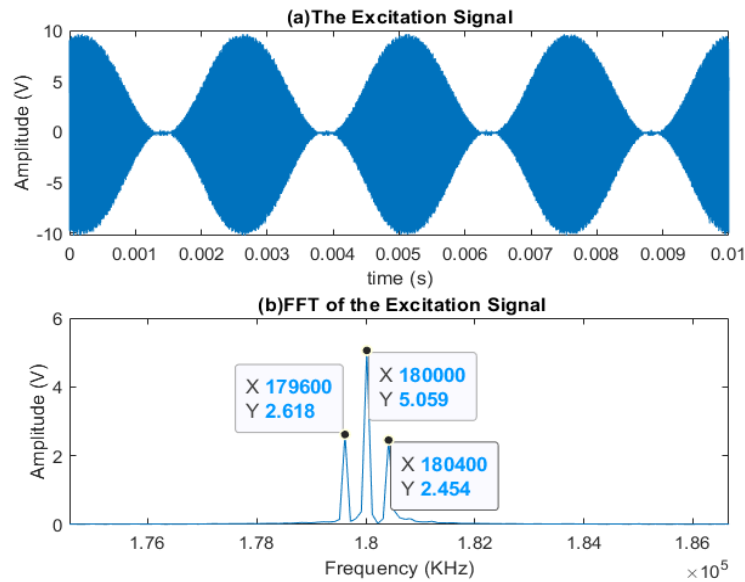


Figure 4-10 (a) The recorded excitation signal (b) The FFT of the recorded excitation signal.

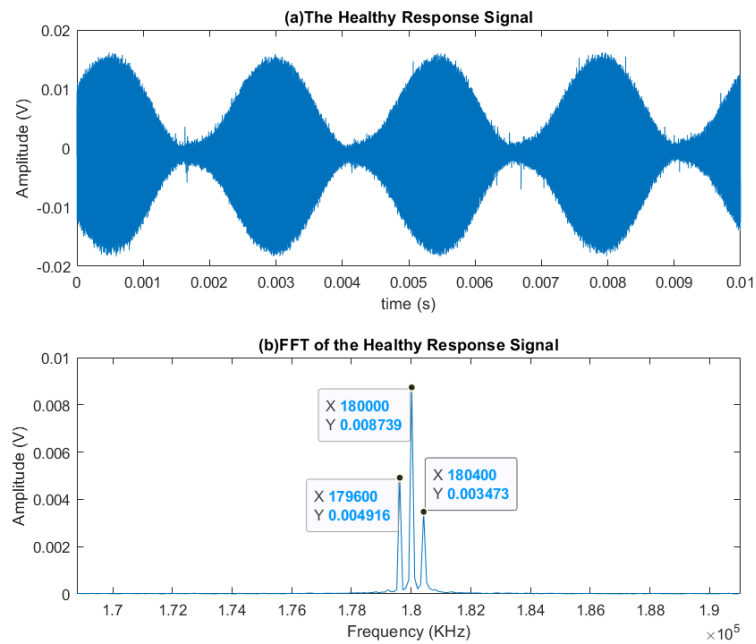


Figure 4-11 (a) The healthy response signal (b) The FFT of the healthy response signal.

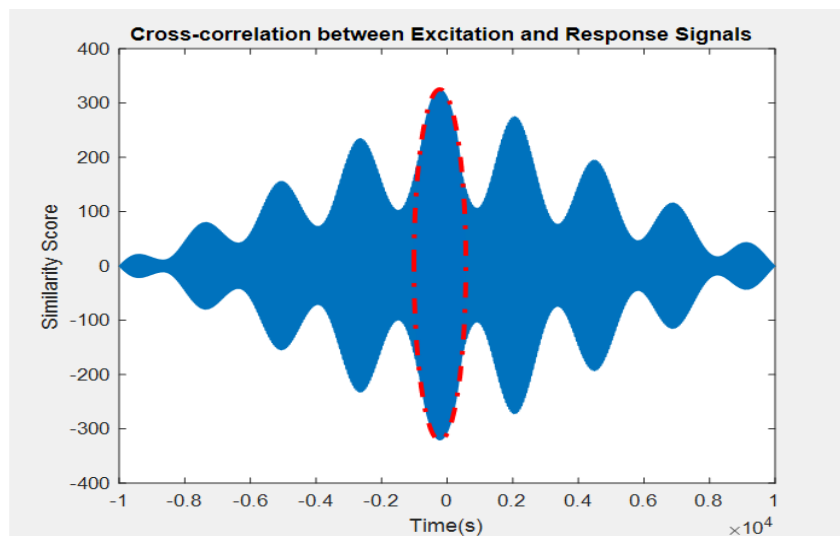


Figure 4-12 The Cross-correlation between the excitation signal and the response signal of healthy structure.

(B). Figure 4-13 is the FFT computational result of the response signal when the defined damage was machined in the plate. We observed that the presence of the damage caused significant variation in the intensity of sideband signals. The

LSB is about eight times greater than the USB. This implies that the LSB is more sensitive to damage than the USB. The upper sideband propagates with the highest frequency. Hence, it possesses the smallest wavelength. It could be that the wavelength of the upper sideband is in the range that it could be easily attenuated or suppressed by the damage, unlike the carrier frequency and the lower sideband components of the propagating wave. The debris-filled damage acts as a high-frequency cut-off filter by suppressing the upper sideband component. We then computed the damage index using the intensity of the carrier and that of the LSB. We obtained DI of 0.92, but the DI of the healthy response is 0.56. Hence, the damage could be detected using LSB and carrier intensity variation. Cross-correlation between the excitation signal and the empty crack response signal was computed to understand the effect further, as shown in **Figure 4-14**. It is evidently from **Figure 5-14** that the existence of a crack in the structure caused a significant delay in the signal, which resulted in a negative uncorrelation between the excitation signal and the empty damage response signal.

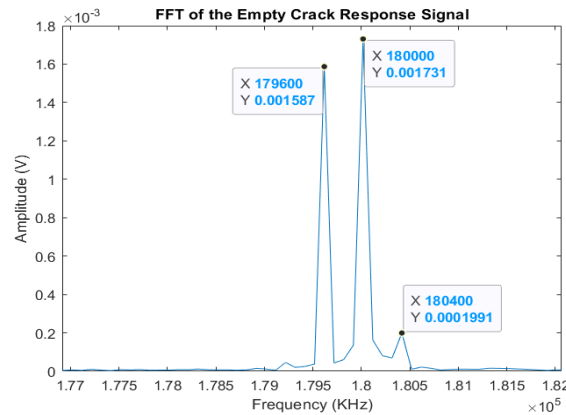


Figure 4-13 The FFT of the response signal when empty damage is initiated in the plate.

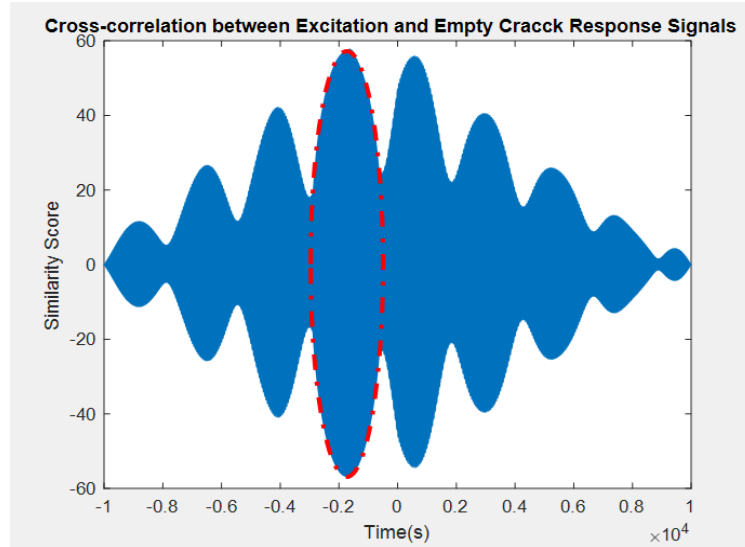


Figure 4-14 The Cross-correlation between the excitation signal and the empty damage response signal.

(C). The FFT of the response signal when the damage is empty and when the damage is filled with dry debris was computed and shown in **Figure 4-15**. The intensity of the LSB, USB and carrier frequencies were computed and tabulated in **Table 4-3**. The modulation index of each response signal was computed and plotted in **Figure 4-16**. The signal modulation index was correlated with the percentage of debris that filled the damage. As the percentage of debris in the damage increases, the response signal becomes more overmodulated. This regression analysis resulted in an empirical predictive model expressed in equation (4-26). The empirical model could predict the health state of the structure, especially in debris-filled damage cases, at an error percentage of 1.34. From the computed modulation index, we observed that the propagating signal is over modulated in a situation of damage existence that is filled with debris. We deduced that the modulation indices of the debris-filled damage are at least 10% greater than the situation of empty damage. The 10% difference could serve as a debris filling inception detection threshold. **Figure 4-17** shows the power signal transmission efficiency. The signal transmission efficiency is the quantitative ratio between the power transmitted by the sidebands and the total transmitted power by the propagating wave. Ordinarily, in AM, the maximum power transmission efficiency of sidebands is about 33.30% which could be observed in the healthy

condition of the structure as a transmission efficiency of 33.45% was achieved, as shown in **Figure 4-17**. However, empty damage (unhealthy) resulted in a sharp decrease in power transmission efficiency with a negative percentage deviation of about -5.7% but gradually increased proportionally as the percentage of debris-filled damage appreciated with a positive deviation in all the debris-filled cases. It could be observed that there is an increase in the power transmission efficiency of the sidebands in the situation of debris-filled damage. This suggests that variations in amplitude modulation sidebands could be useful in classifying stages in debris-filled damage.

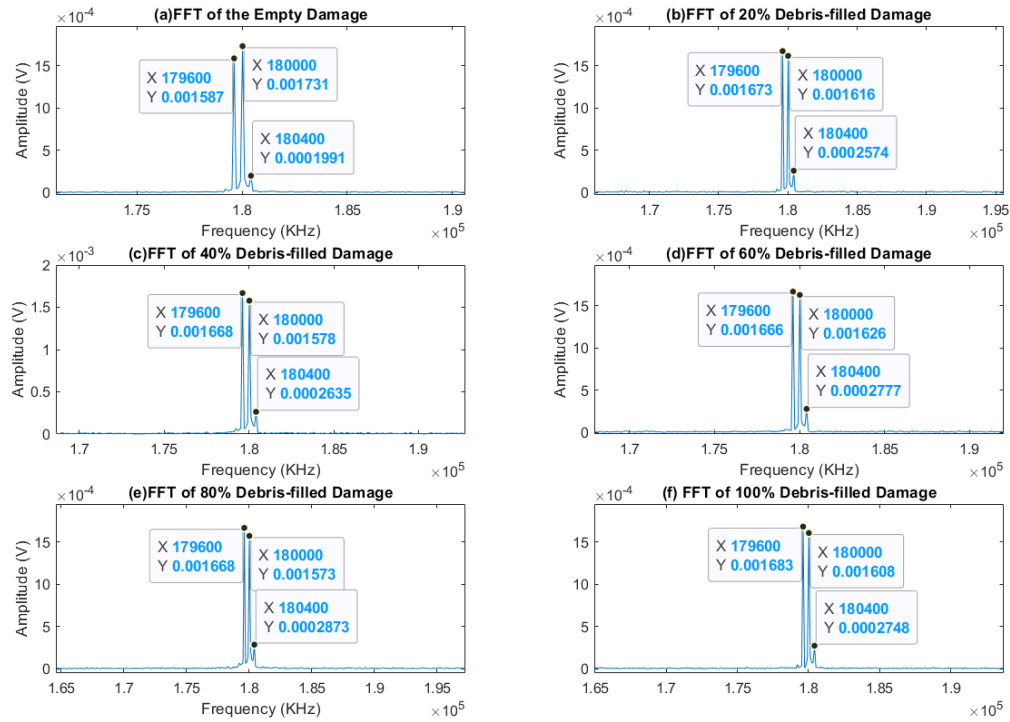


Figure 4-15 The FFT of (a) Empty damage (b) 20% debris-filled damage (c) 40% debris-filled damage (d) 60% debris-filled damage (e) 80% debris-filled damage (f) 100% debris-filled damage.

Table 4-3 Intensities of response signal for debris-filled damage.

Response name	LSB(179600Hz)		CB(180KHz)	USB(180400Hz)	Modulation Index (MI)
Empty Damage	0.001587		0.001731	0.0001991	1.031831311
20% covered	0.001673		0.001616	0.0002574	1.194554455
40% covered	0.001668		0.001578	0.0002635	1.224017744
60% covered	0.001666		0.001626	0.0002777	1.195387454
80% covered	0.001668		0.001573	0.0002873	1.243038779
100% covered	0.001683		0.001608	0.0002748	1.217537313

$$y(x) = 0.8144x^3 - 1.6093x^2 + 0.9833x + 1.0385 \quad (4-26)$$

$$R^2 = 0.9234$$

Where x = percentage of debris that filled the damage.

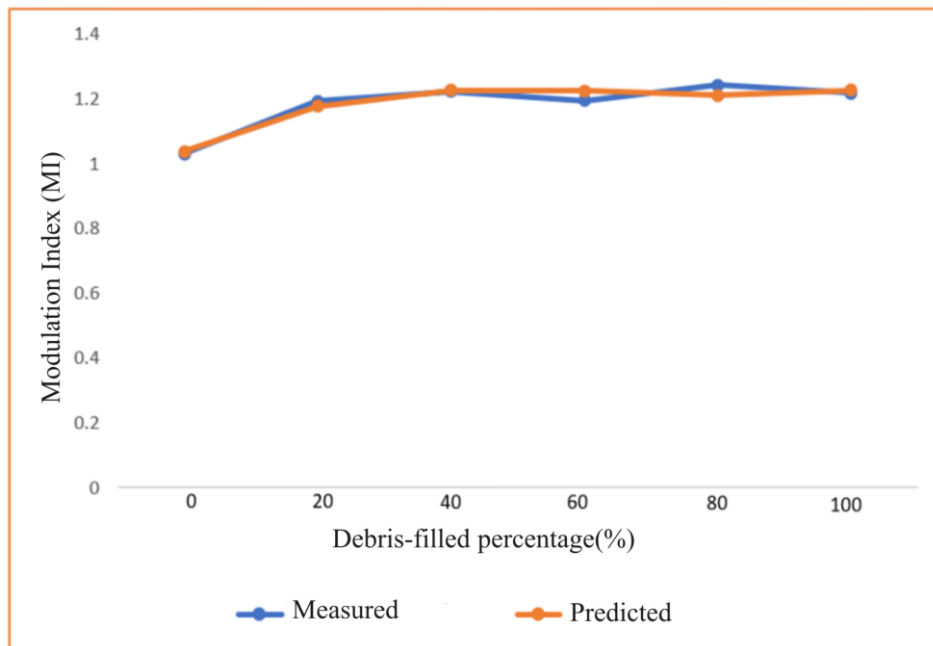


Figure 4-16 The modulation index for different percentages of debris-filled damage.

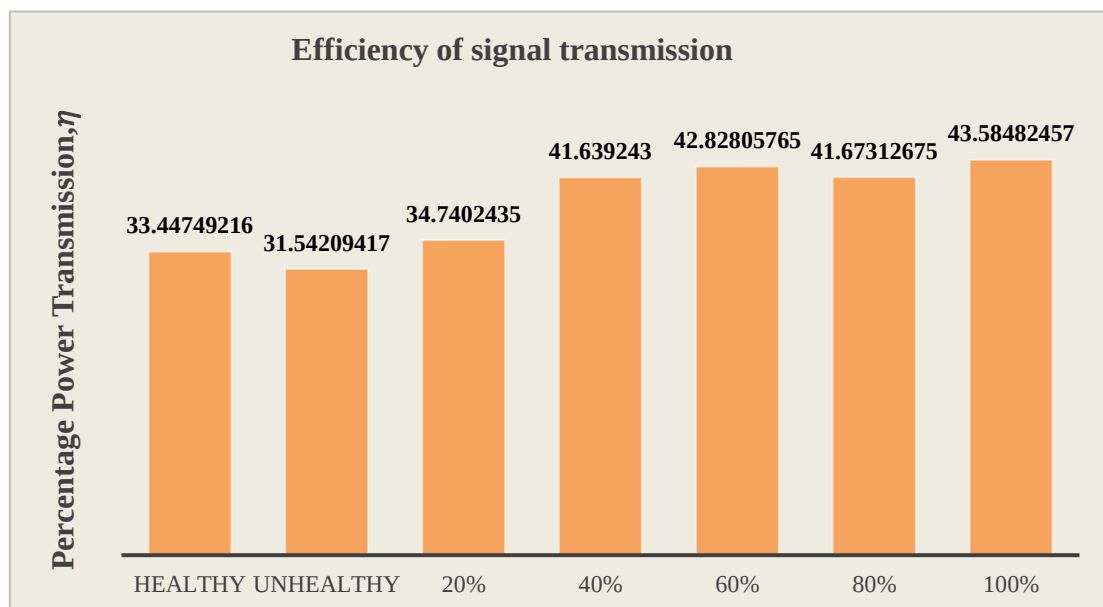


Figure 4-17 The power transmission efficiency in AM (Healthy means good condition; unhealthy means empty damage; different percentages imply the amount of debris that filled the damage).

(D). **Figure 4-18a** is the cross-correlation between the reference signal and the healthy structure's detrended extracted envelope signal. It could be observed that there is a strong positive correlation between the reference signal and the healthy state response signal of the structure. However, the matching peak did not occur exactly at the zero position. This could be due to the inherent inhomogeneity of the structure, as no structure is purely homogenous. **Figure 4-18b** shows the cross-correlation between the reference signal and the detrended extracted envelope response signal of the empty damage. It could be observed from the graph that the response signal from the empty damage is strongly uncorrelated with the reference signal. The uncorrelation situation is due to the existence of damage in the structure.

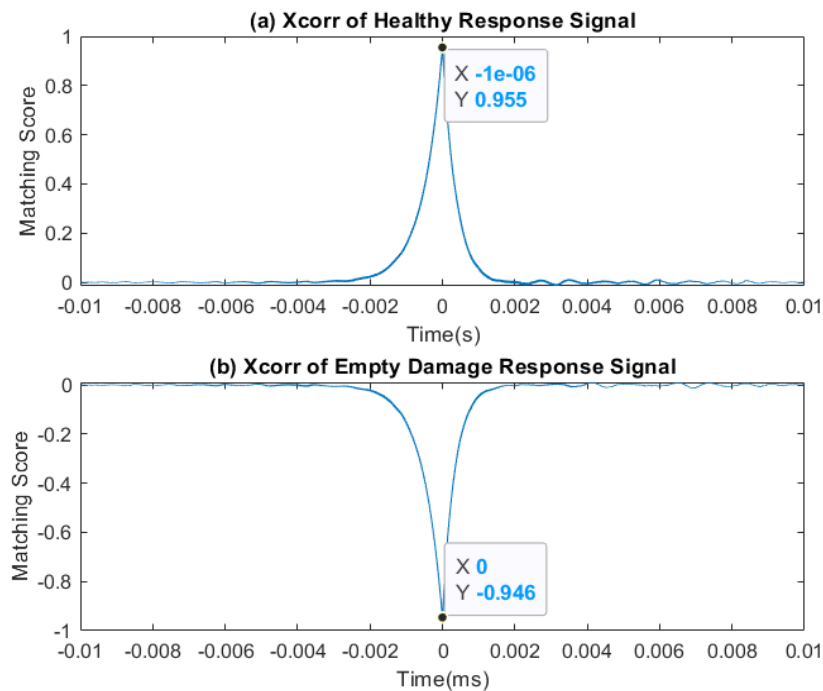


Figure 4-18 (a) Cross-correlation between the reference signal and healthy response signal (b) Cross-correlation between the reference signal and empty damage response signal.

(E). In furtherance, the cross-correlation between the detrended reference signal and the response signal when the damage is gradually filled with debris was computed and plotted in **Figure 4-19**. The similarity matching scores of the compared signals were deduced and plotted in **Figure 4-20**. The results indicate a strong uncorrelation between the reference signal and the response signal from the damaged structure as the debris-filled percentage increases except for 80% and 100%. The uncorrelation could be attributed to the absorption and scattering effect experienced by the response signal at the damaged spot. At 80% debris-filled, the remaining open length of the crack is just 8.00mm, implying that 32mm out of the 40mm length of the damage is filled with debris and would offer less scattering effect to the response signal. As debris fills the damage, it creates false continuity of the structure, allowing easy passage of signals with less distortion and considering that the debris is fine particles. The results suggested that cross-correlation of detrended signal response could be useful in detecting damage and the debris-filling situation at an early stage.

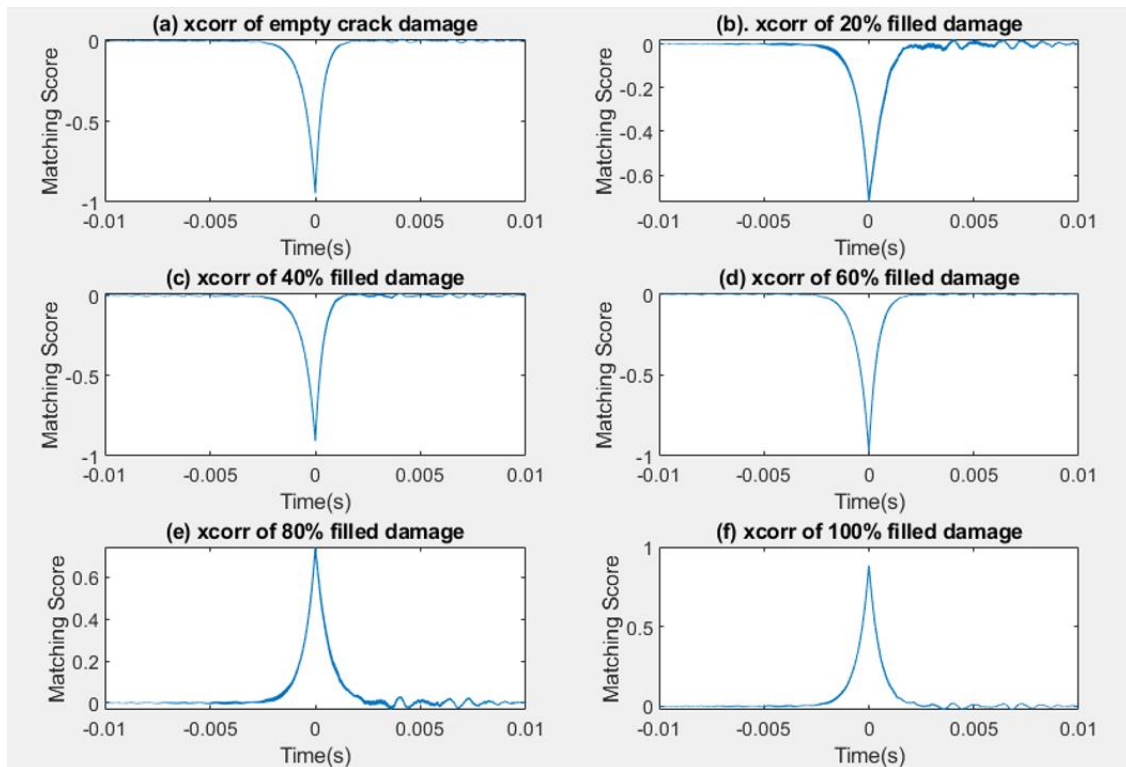


Figure 4-19 The cross correlation between the reference signal and (a) empty crack damage response signal (b) 20% debris filled crack damage response signal (c) 40%

debris filled crack damage response signal(d) 60% debris filled crack damage response signal (e) 80% debris filled crack damage response signal (f) 100% debris filled crack damage response signal.

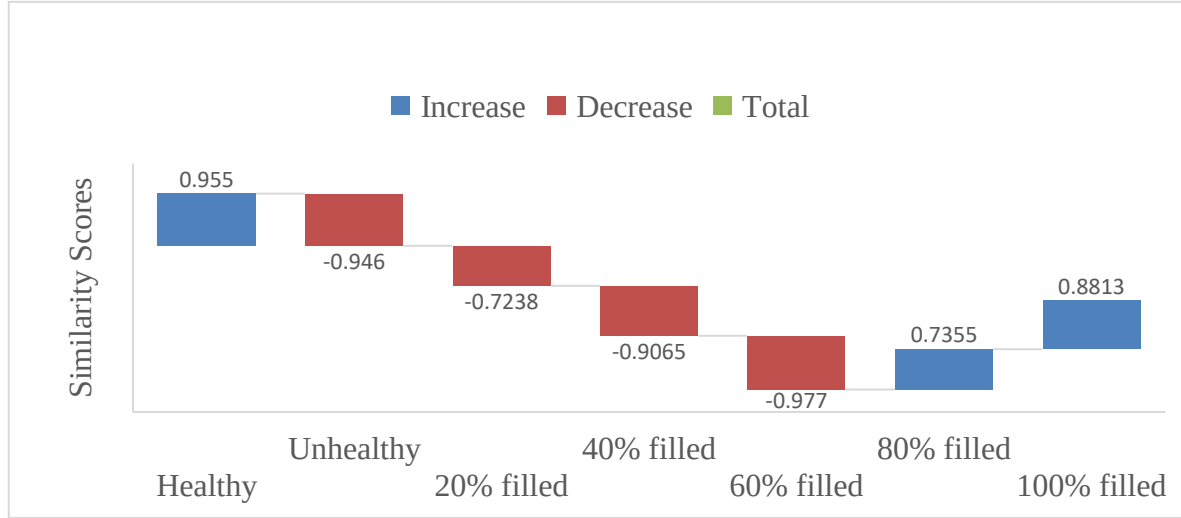


Figure 4-20 The cross-correlation score transition (Healthy means a condition of no damage; unhealthy means a state of empty damage existence; 20% - 100% indicates the size of the damage length filled by debris).

(F). Since we observed that the response signal was further modulated after interaction with the damaged structure, we extracted its envelope and further analysed it. We applied a lowpass filter to cut off any existing high-frequency component, as described in **Figure 4-21**. The spectrum of the reference signal, the healthy state (a state of no damage) response signal, the unhealthy state (a state of empty damage) response signal and the response signal of the structure when debris fills the damage are computed and shown in **Figure 4-22** and **Figure 4-23**. Interestingly, we observed that the damage caused higher harmonics ($2f_m$) of the fundamental low-frequency (f_m) component to occur, as spotted in **Figure 4-23**. The new frequency component is still low and can only be caused by the existing damage and contributes to causing overmodulation of the response signal. The intensity of the higher harmonic varies as the percentage of debris-filled damage increases, as depicted in **Figure 4-23**.

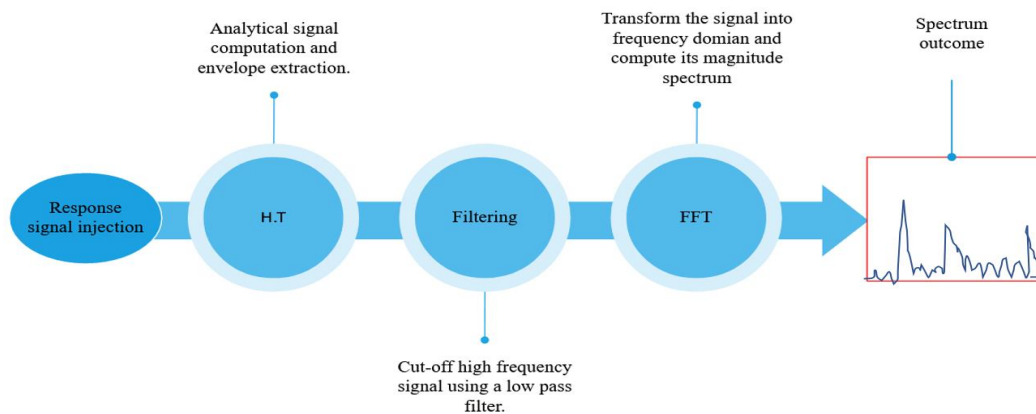


Figure 4-21 The low-frequency components computation flow.

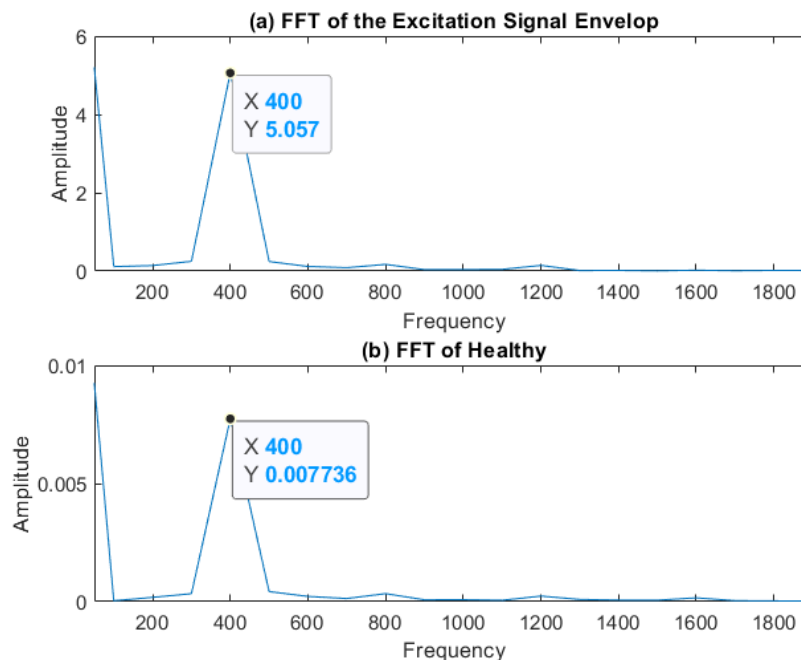


Figure 4-22 The FFT of the extracted (a) Reference signal envelop (b) healthy state response signal envelop.

(G). A regression analysis was performed to describe the relationship between response signal intensity and the debris-filled damage percentage. The damage index was computed and correlated with the percentage of debris-filled damage, as shown in **Figure 4-24**. The correlation resulted in an empirical predictive equation (4-27). The experimental and empirical results were compared, and the mean error was determined. Based on the error result, the practical predictive model could detect an early debris accumulation much better than when it filled

the damage by 100%. The absolute average percentage error of the empirical predictive model is circa 0.21, and its squared correlation coefficient value is about 0.996.

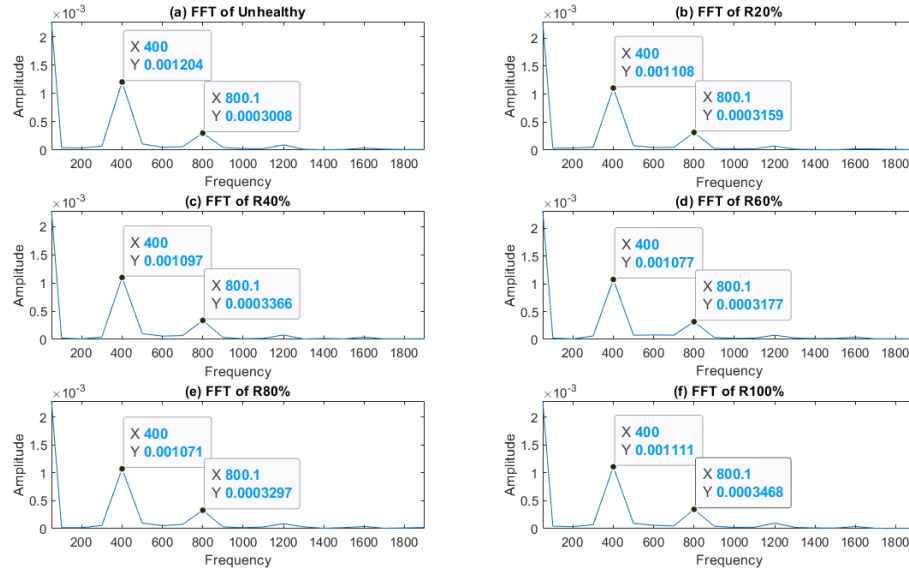


Figure 4-23 The FFT of the processed low-frequency component when the debris coverage is (a) 0% (b) 20% (c) 40% (d) 60% (e) 80% (f) 100%.

$$P(a) = 0.2121a^4 - 0.443a^2 - 0.1102a + 0.1556 \quad (4-27)$$

$$R^2 = 0.996$$

Where a is the percentage of debris-filled damage.

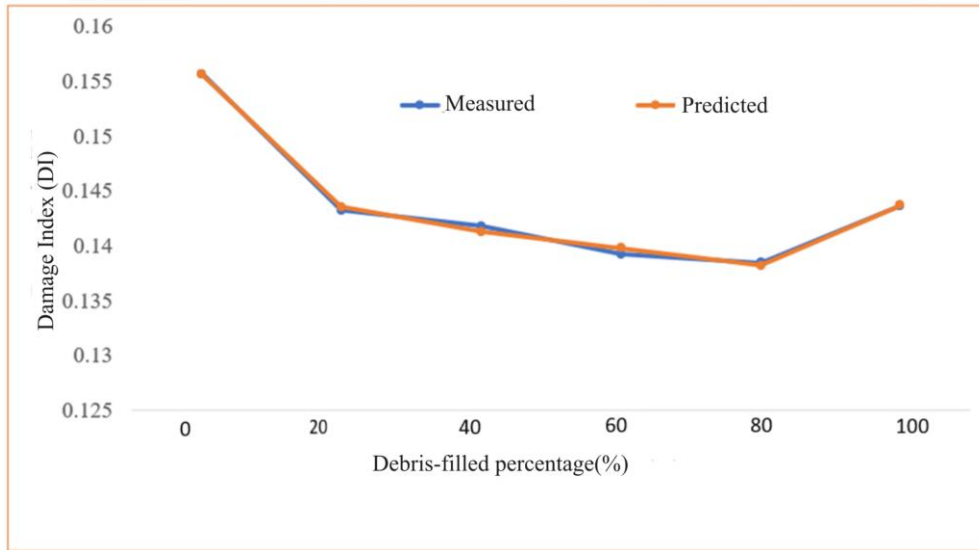


Figure 4-24 Damage index for debris-filled damage of varying percentages.

4.8 Summary

The pre-modulated guided ultrasonic wave interaction with varying percentages of debris-filled damage was investigated. In the study, the high-frequency carrier wave was pre-modulated with a low-frequency wave to form wave packets before being injected into the structure through the actuator transducer PZT. The modulation extent of the wave after interaction with the structure in a healthy state and damage existence conditions were examined. Pitting corrosion filled with varying percentages of debris was discussed and implemented as damage to the structure (mild carbon steel plate). Analysis of the processed response signals showed that pitting corrosion damage and percentages of debris that filled damage could be detected early using a pre-modulated wave and GWUT. The modulation extent of the wave was correlated with the damage existence conditions, resulting in an empirical predictive model equation (4-26) with an average percentage error of 1.34 and squared value of correlation coefficient of 0.9234. Similarly, the response signal of an extracted signal envelope and its analysis revealed that the existence of the damage and its varying percentage of debris-filled could cause a formation of a low-frequency component, 800.1Hz, as in **Figure 4-23**. The formed low-frequency component is a higher harmonic ($\approx$

$2f_m$) of the fundamental low frequency (f_m) wave component. Based on the healthy and unhealthy situation intensity ratio through the processed response signal envelope, another empirical predictive model of equation (4-27) was developed with an absolute average percentage error of 0.21 and squared value of correlation coefficient of 0.996. Cross-correlation of the detrended response signal and reference signal demonstrated to be a quick means to visualise and spot damage existence and its debris-filling conditions. The study approach points out a new possibility for ease of structural health monitoring (SHM) and early detection of debris-filled damage to avert the formation of grievous pitting corrosion attacks in structures of high economic importance. In following Chapters, the influence of environmental operation conditions on the response signals will be evaluated.

5 CHAPTER FIVE: CONFLUENCE EFFECT OF TEMPERATURE AND DEBRIS-FILLED DAMAGE ON GUIDED WAVE RESPONSE

5.1 Overview

As a linkup to damage detection discussed in Chapter 4, this chapter investigates the joint influence of debris-filled damage and temperature variation on Guided Wave Ultrasonic responses. The study employs the pitch-catch technique, Root-Mean-Square (RMS), and Root-Mean-Square-Deviation (RMSD) for signal analysis and establishing a predictive model with good accuracy and reliability.

5.2 Introduction

To further the research, this study examines the collective impact of debris and temperature by utilising the Root Mean Square (RMS) and Root Mean Square Deviation (RMSD) methods. Thin-wall metallic materials are mostly utilised in the aerospace, shipbuilding, and oil and gas sectors for the construction of high-value structural assets. The structural assets convey products prone to environmental hazards that could happen through structural failure [219][220]. Failures in structures are deeply traced to undetected damage. Crack and corrosion are forms of damage that are mainly studied but individually using guided elastic wave ultrasonic[221]. Damage is a state of structure that differs from its pristine state[2]. It is an indispensable factor affecting the structure's service life cycle and its reliability for intended operational services. Damage may be initiated in structural material during the manufacturing process at the micro-level and progresses during the service time of the structure. Formed damage, such as a crack in structures, could accumulate debris over time and accelerate structure deterioration, paving the way for catastrophic failure. The accumulated debris causes crack closure, affects crack propagation and enhances pitting corrosion activities, as explained in[222]. The prime effects of corrosion and crack on metallic structures are thickness thinning, rigidity reduction, integrity and load-carrying-capacity degradation[7], shortening the structure's service lifecycle and making it unreliable. Hence, continuous monitoring of the structural assets with

cost-effective damage-sensitive NDT devices and techniques is a priority to avert catastrophic failure, suggest maintenance on time and save the economy. Most of the previous studies have been on the monitoring and prediction of empty cracks (cracks without debris or dry cracks) in structures using various structural health monitoring techniques [223][43], [224]–[227]. In recent decades, the guided wave ultrasonic technique has received more attention than other NDT techniques for SHM [228]. This is due to GWUT's potential for long-range inspection, non-invasive inspection, the lightweight, small size and cost-effectiveness of ceramic PZT. It has been successfully used for the detection and localization of various damage in structures [43], [228]–[231]. The effect of environmental and operational conditions on the ultrasonic-guided wave, especially temperature, has been well studied [90]. However, the influence of debris-filled damage cum temperature variation on the guided wave has not been studied. In this paper, the influence of debris-filled damage of different percentages under temperature variation is meticulously studied using statistical RMS and RMSD of the captured response signals from pitch-catch ultrasonic guided wave configuration. The suitability of RMS is because guided wave ultrasonic used in SHM is a continuous propagation of energy from one point of the structure to another, and the sensitivity of the signal's energy to damage is significantly higher than amplitude since it is square of amplitude by value [232].

5.3 Theory: Structural Health Monitoring (SHM)

Structural Health Monitoring (SHM) via ultrasonic guided wave (UGW) uses an embedded ceramic piezoelectric (PZT) transducer to transform an oscillating excitation signal into an actuating signal that would cause a stress wave to propagate in the host structure through surface pinching. The propagating wave interacts with the structure and becomes captured as a response signal by another ceramic PZT called a sensor [21]. The PZT operates through a linear transduction mechanism as expressed in the linear constitutive equations (5-1) and (5-2) [43][228].

$$\text{Actuation: } S_{ij} = s_{ijkl}^E T_{kl} + d_{kij} E_k \quad (5-1)$$

$$\text{Sensing: } D_i = d_{ikl}T_{kl} + \varepsilon_{ik}^T E_k \quad (5-2)$$

Where

S_{ij} and T_{kl} are strain and stress mechanical variables, respectively. D_i and E_k are electrical displacement and electrical field variables, respectively. s_{ijkl}^E is the mechanical compliance at zero electric fields, ε_{ik}^T is the dielectric constant at zero mechanical stress, d_{ikl} and d_{kij} denote a coupling between the electrical and mechanical variables. Equations (5-1) and (5-2) are actuation and sensing equations. Hence, the sensor PZT captures the strain effect of the propagating stress wave and transforms it into a signal voltage. The sensor's output voltage is proportional to the amount of the strain effect caused by the propagating wave and the thickness of the sensor.

5.3.1 Wave motion in thin plate

The ultrasonic wave propagates as a distributed stress on a thin plate. The stress causes material particles to vibrate and transfer energy from one point to another as waves. The waves are guided to propagate within the boundaries of the structure. The motion of the vibrating particle in the plate is governed by equation (5-3). The boundary condition of surface traction force is in equation (5-4).

$$\mu \cdot u_{i,jj} + (\lambda + \mu)u_{j,ji} + \rho f_i = \rho \cdot \ddot{u}_i \quad (i, j = 1, 2, 3) \quad (5-3)$$

$$t_i = \sigma_{ji}n_j \quad (5-4)$$

Where u is the displacement of the plate via the particle motion, λ and μ are Lamé's constants, ρ is the density of the plate particles, $\ddot{u}_i$ acceleration of the vibrating particles, f_i is the force body on the material, t_i is surface tractions at the normal n_j and σ_{ji} is stress on the plate surface. It is considered zero for a traction-free body condition. The solution to equation (5-3) by the method of potential separation as in [233] results in characteristics frequency equations of lamb wave grouped into two modes:

$$\text{Symmetric modes: } \frac{\tan(qb)}{\tan pb} = \frac{4k^2 pq}{(p^2 - k^2)^2} \quad (5-5)$$

$$\text{Anti - symmetric modes: } \frac{\tan(qb)}{\tan(pb)} = -\frac{(p^2 - k^2)^2}{4k^2 pq} \quad (5-6)$$

Where

$$k = \frac{2\pi}{\lambda_w} \quad (5-7)$$

$$p = \sqrt{\frac{\omega^2}{c_L^2 - \left(\frac{\omega}{C_p}\right)^2}} \quad (5-8)$$

$$q = \sqrt{\frac{\omega^2}{c_T^2 - \left(\frac{\omega}{C_p}\right)^2}} \quad (5-9)$$

$$C_g = \frac{\partial \omega}{\partial k} = \frac{C_p}{1 - \frac{\omega}{k} \frac{\partial C_p}{\partial \omega}} \quad (5-10)$$

The velocity of the propagating elastic wave is related to the lame's constant and mechanical properties of the material, as expressed in equations (5-11) and (5-12).

$$C_T = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1 + \nu)}} \quad (5-11)$$

$$C_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)}} \frac{E}{\rho} \quad (5-12)$$

Where C_T is the transverse velocity and C_L is the longitudinal or radial velocity of the wave in a solid medium, C_p is the phase velocity of lamb wave, C_L is the longitudinal velocity of lamb wave, ρ , E and ν are the material density, elastic modulus, and Poisson ratio, respectively. It is pertinent to observe that the velocity of the propagating wave depends on the mechanical properties of the waveguide which is the structure. Hence, any consequential effect on the material would affect sensitive parameters of the propagating wave, especially its energy being transferred as the wave propagates.

5.3.2 Wave Dispersion Curve

In an active mode of structural health monitoring (SHM), the actuator pinches the structure to create probing waves when excited with an oscillating electrical voltage. The frequency of the probing signal is often selected from the dispersion curve. The dispersion curves are a set of curves that represent the propagation of wave modes in each waveguide. It describes the relationship between wave velocity (group or phase) and the excitation frequency[231]. The dispersion curve is determined using Disperse software or a Dispersion calculator by providing the necessary properties of the plate material[177]. The dispersion curves of the 3.00mm mild carbon steel plate with properties listed in Table 5.1 are in **Figure 5-1**.

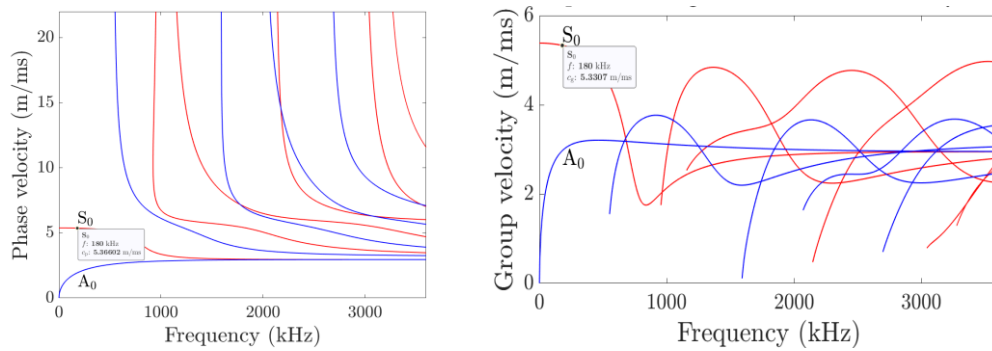


Figure 5-1 (a) Phase dispersion curve (b) Group dispersion curve.

From the dispersion curves, only the fundamental modes exist when the frequency is below 500KHz, but beyond it, multi-modes exist. Also, the fundamental symmetric mode possesses higher velocity, which is relatively constant at the early frequency range than the fundamental asymmetric mode.

The selection of probing frequency is critical for damage detection. There are some criteria used for selecting an appropriate probing. One of the criteria is that the frequency must be sensitive to the targeted damage and possess enough energy to propagate the needed distance. Through experimental frequency sweep, an excitation frequency with the largest RMS is selected on the bases that it possesses more than any other and could travel the longest distance. Recall the rule of thumb for damage detection, which states that damage would stand a higher chance of detection if it is larger than $\frac{1}{2}\lambda$ of the probing wave[234]. Hence, it is necessary to compare the wavelength of the probing wave with the length of the targeted damage. The wavelength of the excitation frequency can be determined using equation (5-13).

$$\lambda = v/f \quad (5-13)$$

Where

v = velocity of a wave mode at given frequency, f .

The wavelength of an ultrasonic wave is the physical limit beyond which two features of structures cannot be distinguished easily. From equation (5-13), it is apparent that as the inspection frequency increases, the wavelength decreases and greater is the ability of the wave to detect damage of smaller sizes but at the expense power source capability as current demand increases with the excitation frequency as shown in equation (5-14).

$$I \approx i2\pi f \varepsilon_{33}^T \frac{A}{t_a} V \quad (5-14)$$

Where I is the current demand of the actuator as the excitation signal frequency increases, A is the area of the actuator, t_a is the thickness of the actuator, and ε_{33} , dielectric constant of the PZT. Hence, it is important to make a choice of the excitation frequency such that the current demand of the PZT is not greater than the current capability of the function generator[235].

5.3.3 Wave-Damage Interaction effects and Inspection Transducer Configuration

Guided wave ultrasonic inspection could be performed using active or passive ultrasonic configuration techniques[184]. The exciter is vital in guided wave inspection, which determines if a configuration is active or passive. If the damage generates the propagating wave, a passive mode is configured [21], and all the embedded transducers would function like human ears and listen to pick up the wave. The active mode is configured when the propagating wave is due to the excitation of the actuator (exciter) with an oscillating electrical voltage of a given frequency [21], [236], [237]. The vibration of the actuator causes particles of the structure around it to start displacing temporary about their mean positions. This mechanism transfers wave energy from one point of the structure to another. The propagating stress wave is constrained by the boundaries of the structure hence the guided wave. The wave interaction with the structure, especially with damage or discontinuity, causes scattering, reflections, mode conversion and some energy absorption at the damaged spot[238] leading to attenuated waves as the captured signal. **Figure 5-2** depicts the effect of wave-damage interaction. **Figure 5-3** shows that the through-transmitted waves are much smaller than the edge-scattered waves by the damage. Hence, capturing the edge-scattered waves would be more valuable than the through-transmitted waves. Also, depending on the nature of the damage, the through transmitted waves are the resultant waves after absorption, reflection, and diffraction of the incident waves, which are usually small in value and called attenuated response waves.

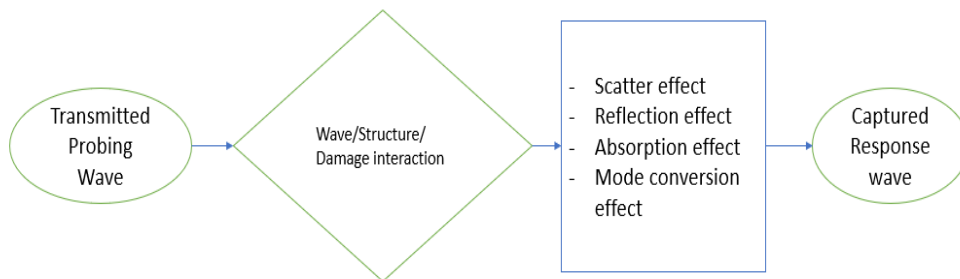


Figure 5-2 Wave-damage interaction effects.

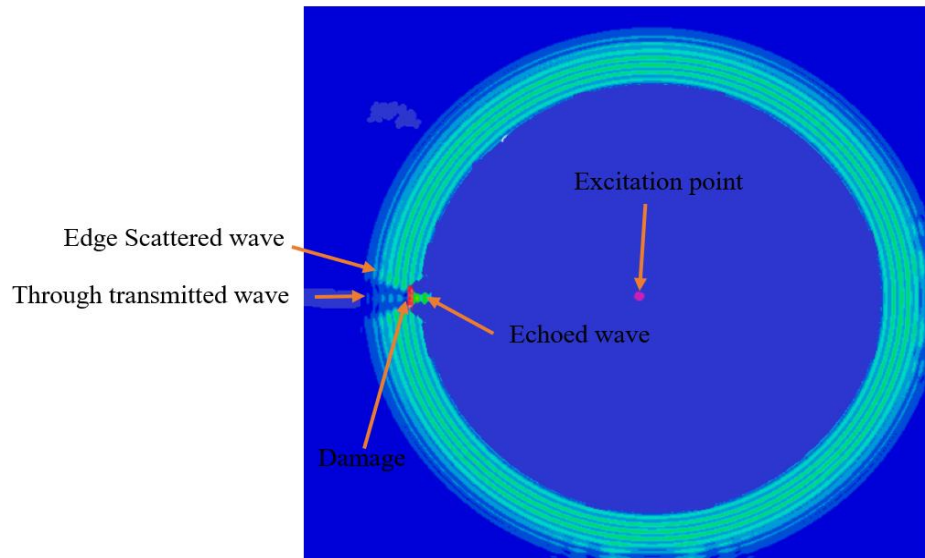


Figure 5-3 Typical Wave-damage interaction effect.

All the effects mentioned above make it possible for damage to be detected and localized using guided wave techniques and a sensitive wave parameter called the signature or feature. The extent of wave reflection or scattering depends on the encountered damage's nature, shape, size, and orientation. Pitch-catch and Pulse-Echo transducer configuration topology are often used in the Active mode inspection technique, as shown in Figure 5-4. The choice of either topology depends on the nature of the damage. This study uses active pitch-catch configuration topology to acquire responses signals that interacted with the structural damage and scattered.

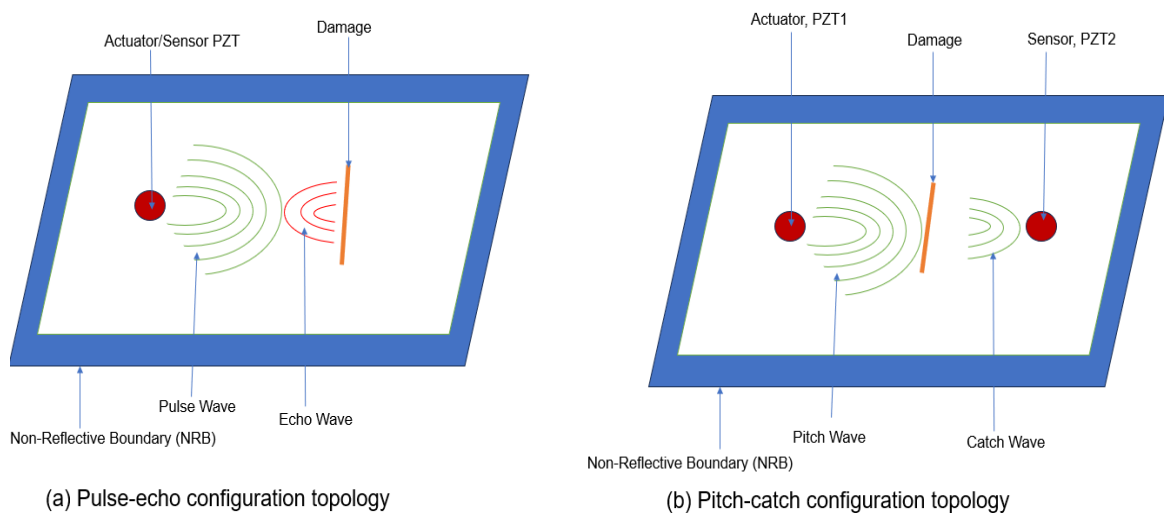


Figure 5-4 Active mode transducers configuration topology.

5.3.4 Temperature Effect on Guided wave

Damage and temperature have different effects on structures but collectively influence structural degradation[239][240]. The core influence of temperature on a mechanical structure is thermal expansion and assisted degradation of the structure's strength and stiffness. An increase in temperature causes a decrease in the elastic modulus of metallic structure but features of propagating elastic wave depend directly on most of the mechanical properties of the structure, especially the elastic modulus, as in equations (5-11) and (5-12). Assuming a linear dependence of the wave characteristics on temperature, the equation (5-15) will be suitable for the study.

$$S(T) = S(T_0) + \frac{\partial S(T)}{\partial T} \Delta T \quad (5-15)$$

Where

$S(T)$ = Any characteristics parameter of the wave at a given current temperature, T.

$S(T_0)$ = The value of the wave characteristics at a reference temperature.

T = Current state temperature of the structure.

T_0 = Reference temperature of the structure.

$\Delta T = (T - T_0)$.

$\frac{\partial S(T)}{\partial T}$ = The parameter sensitivity to temperature which is the slope of the graph.

5.4 Signature/Wave Feature Extraction and Processing

Damage detection and identification largely depend on the approach and signal processing technique adopted for analysis. The captured response signals carry sufficient information about the structure since it has interacted with the damage. Wave amplitude is one of the sensitive parameters of the wave and could be easily extracted from the signal. The damage in the structure could modulate signal's amplitude to either higher or lower values. However, the signal energy is more sensitive to damage and proportional to the square of its amplitude. Hence,

Root-Mean-Square (RMS) and Root-Mean-Square-Deviation (RMSD) were adopted to extract the energy feature of the response wave and determine the damage index. Through the extracted feature of the wave, a model for predicting the debris-filled damage under temperature variation is established. The average RMS of the two sensors used in the design is given in equation (5-16), and the relative RMS is expressed in equation (5-17).

$$X_{ARMS} = \frac{1}{2} \left(\left(\sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \right)_{PZT2} + \left(\sqrt{\frac{1}{N} \sum_{j=1}^N x_j^2} \right)_{PZT4} \right) \quad (5-16)$$

$$R_{rms} = \frac{X_{ARMS}}{E_{rms}} \quad (5-17)$$

where

E_{rms} = the rms of the excitation signal

X_{ARMS} = the average RMS of the signals captured by the two extreme sensors as in equation (5-16).

x_i^2 and x_j^2 are the captured response signals by PZT2 and PZT4 respectively and N is number of samples of the signal. Hence, the R_{rms} is computed for each study case and used to establish the predictive regression model for each damage situation. The damage index is computed by determining the RMSD between the healthy state of the structure and its damage state. Equation (5-18) expresses the damage index.

$$DI_{SC} = \sum_{i=1}^M \sqrt{\frac{\sum (R_{rms_i}^D - R_{rms_i}^H)^2}{\sum (R_{rms_i}^H)^2}} \quad (5-18)$$

Where

$R_{rms_i}^D$ is the relative RMS of the sensors' captured response signals in the damage state of the plate and $R_{rms_i}^H$ is the healthy counterpart of the response.

5.5 Methods and Materials

The Materials used in the study is mild Carbon Steel plate. Mild carbon steel has a low carbon percentage. It is tough and ductile, making it a predominantly used material to construct essential and critical structures of high economic value, such as oil and gas pipelines, rail tracks and bridges. The dimension of the mild Carbon Steel plate used in this study is $500\text{mm} \times 300\text{mm} \times 3.00\text{mm}$. A damage of 40.00mm length, 5.00mm width and varying depth of 1.00mm to 2.50mm at an interval of 0.50mm , as depicted in **Figure 5-5**, was carefully machined at the mid-distance between the actuator, PZT1 and sensor, PZT3. Circular PZTs transducers are used due to its omnidirectional capability of radiating and receiving response signals, unlike rectangular PZTs, which are orientation dependent[241]. The variation in the damage depth is used to simulate the material thickness thinning that corrosion activities would cause. **Table 5-1** reveals the mechanical properties of the used plate material. Wave reflection from the edges of the plate is known to contribute to the complexity of the response wave. In particular, the edge reflected wave would cause mutual interference with the response wave of the actuated signal. Hence, DAS modelling Air dry clay [217] is installed around the edges of the plate to absorb any wave reflection from it. Also, the transition of random vibration between the plate and the table is minimized by placing soft foams in between the two.

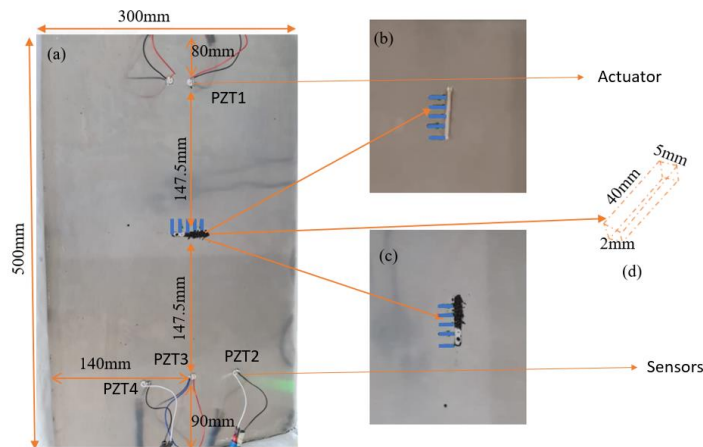


Figure 5-5 The implemented damaged plate with bonded PZTs.

5.6 Experimental Setup Procedure

Pitch-Catch configuration topology was adopted and implemented using four ceramic PZT transducers (PZT: $7.000\text{mm} \times 0.195\text{mm}$). The one of the experimental setups is shown in Figure 5-6. Circular type of PZT transducer is used due to its omnidirectional capability in capturing response signals. Before the transducers were installed, acetone was used to clean the plate's surfaces and allowed to dry up for about 10 minutes. The transducers were embedded on the top surface of the plate using epoxy adhesive. The curing time of the epoxy adhesive is 150 minutes and has an operating temperature range of -55°C and 120°C [242]. However, it was allowed 24 hours to ensure the proper curing of the adhesive since temperature of the will be raised up to 70°C . One transducer, PZT1, was wired as the actuator to generate the elastic wave, while the remaining three transducers were used as sensors to capture the propagated elastic wave. The sensor PZTs were arranged and named as Left sensor (PZT2), Middle sensor (PZT3) and Right sensor (PZT4) when viewed from the actuator's position. The epoxy adhesive was lightly applied to bond the PZTs on the top surface of the plate and to eliminate the high impedance that air would have introduced. The thickness of the epoxy adhesive was ensured to be less than the thickness of the PZT. The properties of the ceramic PZTs are in **Table 5-2**. The PZTs are installed 102.00mm from the end edges of the plate and at least 100.00mm from the side edges. The PZT1 is 300.00mm separated from the PZT3. The distance between the middle sensor, PZT3 and either of the two sensors is 50.00mm which is greater than the wavelength of the elastic wave. The excitation signal is generated using a function generator (TG550 Function Generator), while the response signals are visualized and registered using Agilent Technologies Mixed Signal Oscilloscope (MSO-X 3024A) with a sampling frequency of 1MHz . The experiment was conducted in 3 phases.

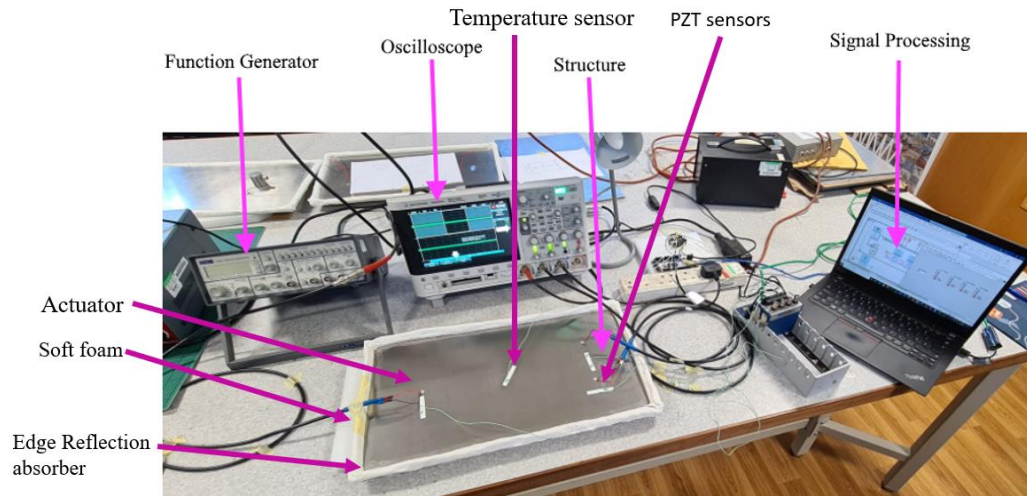


Figure 5-6 The Experimental Setup for data acquisition.

5.7 Study Phases

Phase I: To ensure that the design works, and proper excitation frequency is selected for the study. PZT1 was excited with different centre frequency signal of amplitude modulated waves. The modulating frequency is internal 400Hz of the function generator and different carrier frequencies 100KHz, 180KHz, 280KHz and 360KHz were used to generate an amplitude modulated excitation signal. Each modulated wave excited the actuator 5 times and the captured response wave signals were averaged to ensure repeatability and minimization of random noise effect. The signals captured by PZT2 and PZT4 were processed using equation (5-16) and equation (5-17) to determine which excitation frequency offered the maximum signal energy. The signal captured by PZT3 was processed using the cross-correlation method to determine the Time-of-flight (ToF_E), of the wave packets and compared it with the theoretically determined Time-of-Fight, (ToF_T).

Phase II: The selected excitation frequency from phase I is used to acquire baseline signals by PZT2 and PZT4 under no influence and influence of temperature on the wave signal at the healthy state of the plate. A silicone heater mat and K-type thermocouple temperature sensor were integrated into the testing

rig to generate heat and acquire the temperature of the plate, respectively. A control circuitry was designed using Arduino Mega and solid-state relay (SSL) to regulate the heating rate of the silicone heater mat and ensured that the targeted temperature values were achieved and maintained before baseline response signals were acquired and recorded. The temperature of the plate was varied from 30 °C to 70 °C at an interval of 5 °C.

Phase III: After baseline acquisition, the healthy plate was replaced with unhealthy plates with damaged dimensions as depicted in **Table 5-3**. The PZT2 and PZT4 sensors were used to capture the response signals that had interacted with:

- (a) Empty damage at influence and no influence of temperature.
- (b) Damage filled with different percentages of corrosion debris at influence and no influence of temperature. The testing rig used is as in **Figure 5-5** and **Figure 5-6**.

Table 5-1 Mechanical properties of mild Carbon Steel.

Material	Young modulus, E (N/m ²)	Poisson's ratio, ν	Density, ρ (kg/m ³)	Length, L(mm)	Width, W(mm)	Thickness, T _h (mm)
Carbon steel	2x10 ¹¹	0.289	7800	500	300	3

Table 5-2 The Properties of PZT used in the study are PZT-5A.

	Parameter	unit	Min. Value	Typical value	Max. Value
	Diameter of ceramics	mm	6.80	7.00	7.20
	Thickness of ceramics	μm	175	195	215
	Curie temperature	T _c		340	

	Piezoelectric constant	pC/ N		420	
	Elastic compliance	m ² / N		19.6×10- 12	
	Serial resonance frequency fs	kHz	-5%	285	+5%

Table 5-3 The damage dimensions.

S/N	Damage depth (mm)	Damage (mm)	length	Damage width (mm)
1	1.00	40.00		5.00
2	1.50	40.00		5.00
3	2.00	40.00		5.00
4	2.50	40.00		5.00

5.8 Results and Discussion

5.8.1 Excitation Frequency Selection

In structural health monitoring, SHM, inspection frequency is essential in detecting damage. As stated in **phase I**, two approaches were used to determine the excitation frequency for the studies. In the first approach, the actuator, PZT1, was excited with different centre frequency signals and their corresponding response signals were captured using PZT2 and PZT4 sensors. The used frequencies are: - 100KHz, 180KHz, 280KHz and 360KHz were used to excite the actuator. The response signals captured by the sensors were processed for the relative average RMS value as in equation (5-17). The response signals were

sampled at 1MHz to avoid signal aliasing due to under sampling according to Nyquist's theory of equation (5-19).

$$f_s \geq 2 \times f_{max} \quad (5-19)$$

Where f_{max} and f_s , are the maximum frequency of the signal and the sampling frequency, respectively. **Figure 5-7** is the plot of the computed result. The response signal of excited 180KHz exhibited the maximum relative RMS value compared to others. The RMS value starts decreasing shortly after 180kHz. Also, the result suggests that beyond 180KHz, the function generator will be unable to supply the needed current of the actuator as earlier discussed in subsection 5.2.2 in equation (5-14). The second approach computed the response signal Time-of-Flight (ToF) generated using 180KHz and captured by PZT3. ToF is a crucial feature of guided wave ultrasonic for damage localization. In pitch-catch configuration, it is the time taken for the excited wave to propagate from the actuator to the sensor. Different methods could be used to determine ToF, but cross-correlation ensures a better result because it compares the similarity between two waves of the same length, shape and eliminates spurious reflections caused by the structure boundaries[243][244]. Also, velocity is a needful feature of the wave which depends on and changes with variation in the structure parameter. The knowledge of the propagating wave velocity is essential, especially for damage localization. From the group velocity dispersion curve generated using the mechanical parameters of the plate material and a Dispersion calculator [32], the fundamental symmetric mode was observed to be the fastest and non-dispersive wave up to 500KHz with relatively stable group velocity, as shown in **Figure 5-8**. The group velocity of the wave at 180KHz is 5330.7m/s. The signal's theoretical Time-of-Flight (ToF) is computed using the group velocity and the actuator-sensor distance, 300mm. Experimentally, the excitation signal is cross correlated with the response signal captured by the PZT3 sensor to obtain the ToF of the signal. **Figure 5-9** shows the cross-correlation result between the excitation signal and the captured response signal.

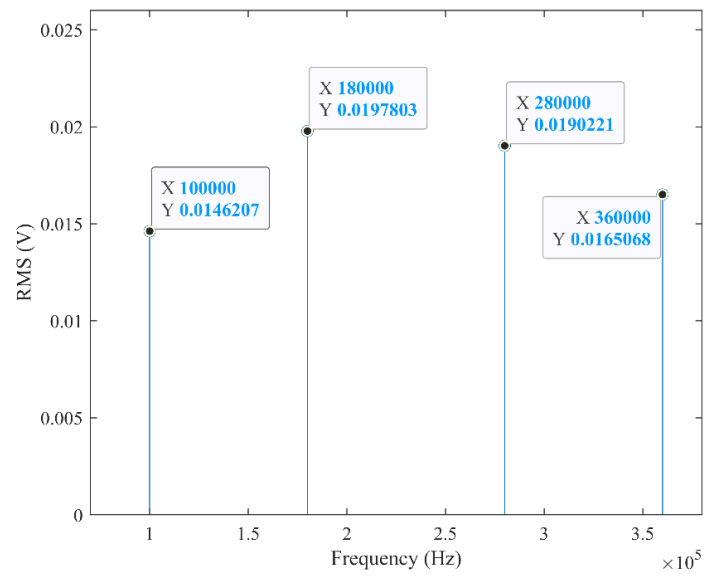


Figure 5-7 The Relative average RMS of response signals captured by PZT2 and PZT4 against the excitation centre frequency.

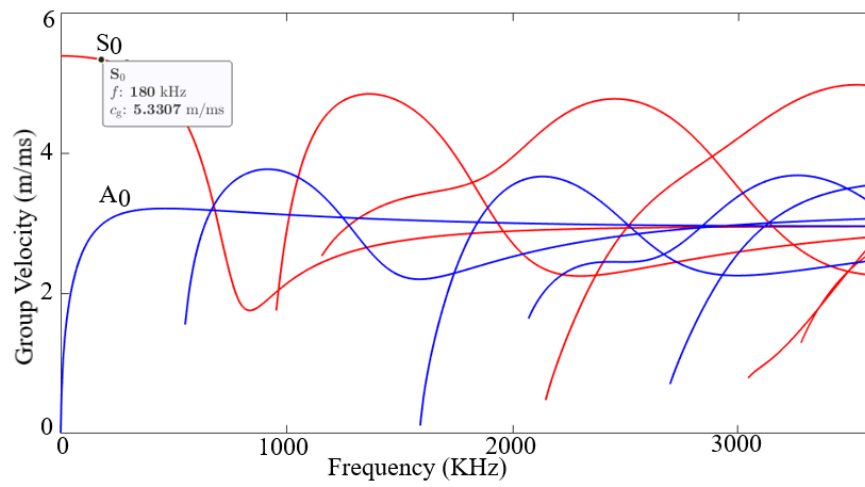


Figure 5-8 The group velocity dispersion curve of 3.0mm carbon steel.

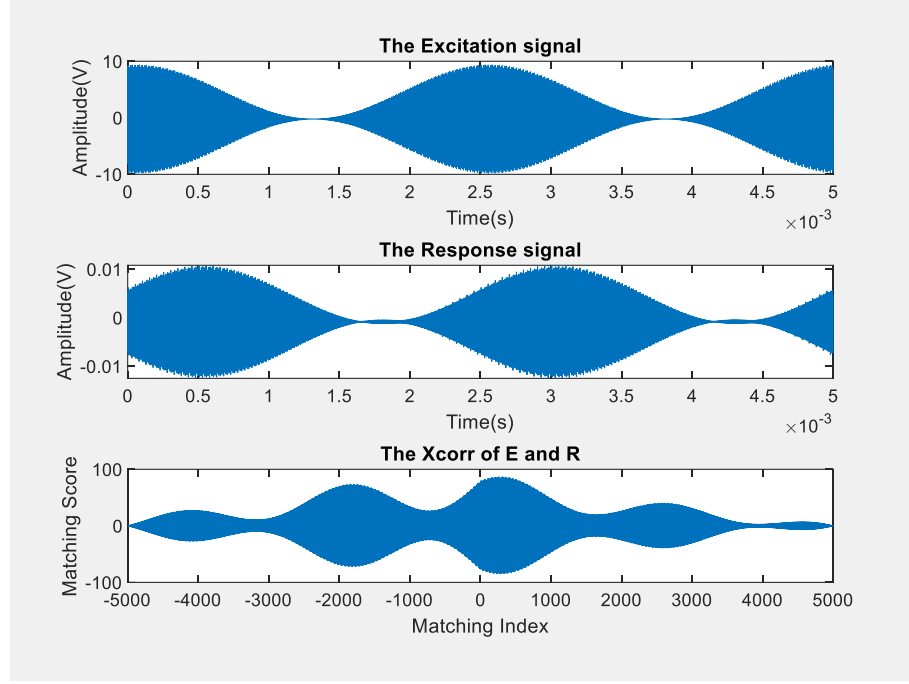


Figure 5-9 cross-correlation of excitation signal with response signal captured by PZT3.

The relationship between the propagating wave velocity, distance covered and ToF is expressed in equation (5-20). The equation defines the theoretical Time-of-Flight, ToF_T as

$$ToF_T = \frac{d_{a-s}}{V} \quad (5-20)$$

Where d_{a-s} is the distance between the actuator, PZT1 and the middle sensor, PZT3 and its value is 300.00mm. The group velocity of the propagating wave packet is V . From the group velocity dispersion curve of **Figure 5-8**, the nearly stable group velocity at 180KHz frequency is 5330.7m/s. Using equation (5-20), the theoretical ToF of the signal is

$$ToF_T = \frac{0.3}{5330.7} = 5.6278 \times 10^{-5} \text{s} \quad (5-21)$$

By cross-correlating the excitation signal with the response signals captured by PZT3 sensor, we observed that the excitation signal lags the response signal by

261 matching index value. The matching index value is then converted into time using equation (5-22).

$$ToF_E = \left| \frac{(I_{maxscore} - 5000)}{5000} \right| * 0.001 \quad (5-22)$$

$$ToF_E = \left| \frac{(261 - 5000)}{5000} \right| * 0.001 = 5.22 \times 10^{-5} s \quad (5-23)$$

$$Relative\ Error, R.E = \left| \frac{ToF_E - ToF_T}{ToF_T} \right| = 0.072 \text{ or } 7.2\% \quad (5-24)$$

Hence, the relative error percentage between the theoretical and experimental ToF is 7.2%. The result signifies that the system setup works well, and the stress wave propagates as designed. Therefore, the probing frequency of 180KHz is selected to further the studies. The velocity of the propagating elastic wave is within the range of nondispersive frequency of the fundamental symmetric mode. The mode encompasses in-plane displacement that contains energy for long coverage inspection, unlike fundamental antisymmetric mode that would leak energy to surroundings through out-of-plane displacement [245].

5.8.2 Baseline Signal Acquisition

Acquisition of baseline signal is vital in structural health monitoring as it helps to quickly detect a deviant behaviour of the structure at an early stage. Baseline signals are captured by the sensors during the healthy state of the structure and used as a reference to compare with a later captured signal of the structure where signals were captured at different damage situations of the structure. The PZT2 and PZT4 captured the response signals that were excited using PZT1. In the absence of temperature variation, 10000 samples were captured and processed for their RMS values. The relative average RMS of the two sensor's response signals at laboratory temperature was 2.236×10^{-3} . The experiment was repeated when the heat source was activated. The temperature of the plate was raised from 30 °C to 70 °C at an interval of 5 °C. At each temperature level, the PZT2 and PZT4 sensors captured and recorded response signals. The relative

average RMS value of the captured response signals was computed and plotted against temperature variation, as shown in **Figure 5-10**.

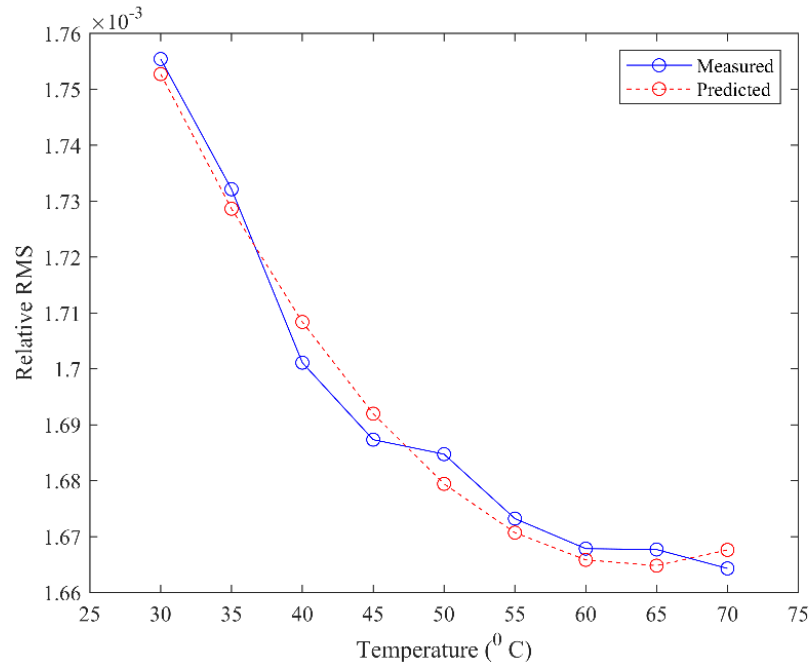


Figure 5-10 The relative RMS response of the plate under varying temperatures.

From **Figure 5-10**, it is observed that as the temperature of the plate increases, the corresponding computed relative average RMS of the sensors decreases. This could be attributed to an expansion effect of heat on the material and variation of the mechanical properties of the plate as its body temperature increases, especially the elastic modulus, which is very sensitive to temperature. The elastic modulus of steel decreases with an increase in temperature, and lamb wave features depend on it for propagation[246]. The thermal differential effect between two response intervals decreases as temperature increases leading to a general polynomial response behaviour as depicted in **Figure 5-10** and **Figure 5-11**. **Figure 5-11** is the Power Spectrum of the PZT2 sensor which shows that the signal power decreases as the plate temperature increases. It could be said that guided wave amplitude is thermally sensitive and decreases due to the superposition of the guided wave with the thermally induced stress wave in the structure. An empirical predictive model for the thermally influenced guided wave is deduced through fitting the measured values. The predictive model is equation

(5-25) with a root-mean-square error of 5.012×10^{-6} and R^2 value of 0.9814 when compared with the measured signal. The R^2 value suggests that the empirical predictive model is good since it could explain substantial amount of variability in the ultrasonic response signal.

Also, the low value of RMSE implies that the predicted values from the model are very close to the measured values of the response signals. Hence, the model provides a near accurate representation of the data within the temperature range of the study (30°C to 70°C). The value of the constant C suggests the response at no temperature influence, which tallies with the response value at the healthy state of the plate as in **Figure 5-6**.

$$g(T) = aT^2 - bT + c \quad (5-25)$$

Where T is the given body temperature of the plate.

$$a = 7.687 \times 10^{-8}; b = 9.815 \times 10^{-8}; c = 0.001978$$

From **Figure 5-10**, as the temperature increases, the sensor response changes rapidly and more linear up until near 55°C and then slows down into quadratic form. The equation (5-25) can be approximated to a linear regression since the linear coefficient is far greater than the quadratic coefficient. It could be observed from Figure 5-10 that the region of linearity is far greater than the quadratic region.

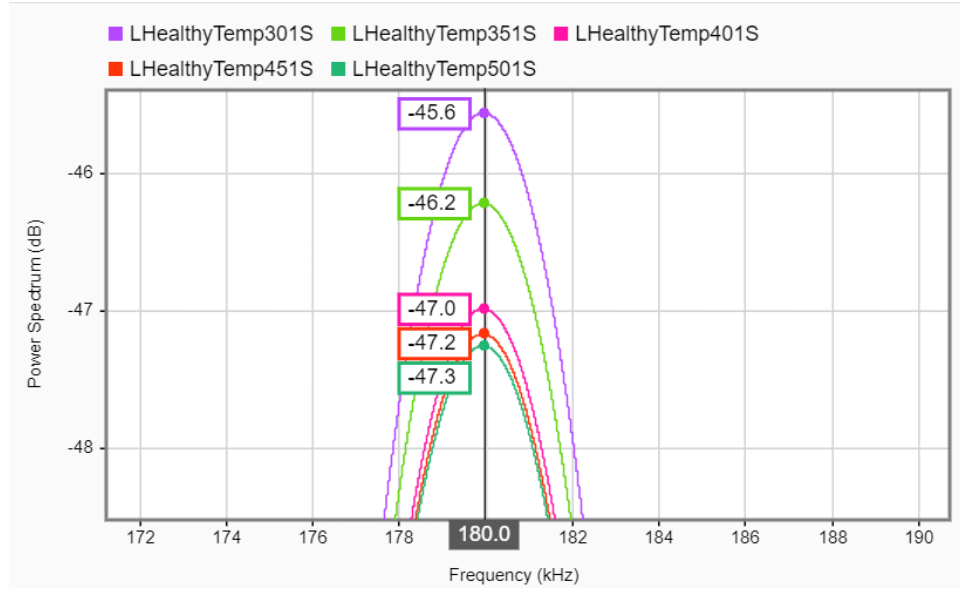


Figure 5-11 Power Spectrum of the captured response signals at different temperatures by PZT2.

5.8.3 Depth Variation Response

The influence of empty damage with varying depths on the propagating elastic wave is first examined before debris fills the damage. Damage of varying depths as in **Table (5.3)** was machined mid-distance between the actuator, PZT1 and the middle sensor, PZT3 positions. The distance between the actuator and the sensors is 300.00mm. The selected inspection frequency is 180KHz with a wavelength of about 29.615mm and propagates with a group velocity of 5330.7m/s. The wavelength of the inspecting wave can detect the damage sufficiently since damage has the possibility of detection if its length is at least greater than $\frac{1}{2}\lambda$ of the inspecting wave[247]. While the damage length is constant, the influence of depth variation on the elastic wave is observed to establish an empirical relationship. At each damage depth, the PZT2 and PZT4 capture the response wave signal and are analysed for relative average RMS values. From **Figure 5-12**, it was observed that the average relative RMS value of the response signals increases as the depth of the damage increases. The increase in RMS values implies that the scattering effect of the response signal increases with damage depth. The captured scattered waves are most probably from the tip of the damage as could be seen from **Figure 5-3**. The result suggests that more

incident waves are diffracted as damage depth increases. Although it is observed that the response value is less than the healthy state value when the damage depth is less than half the thickness of the plate thereby suggesting two groups of damage depth which are shallow depth and deep depth damage. It is remarkably noted that the scattering effect due to the shallowest depth is about 0.26% of the incident wave, while it is about 0.48% for the deepest depth.

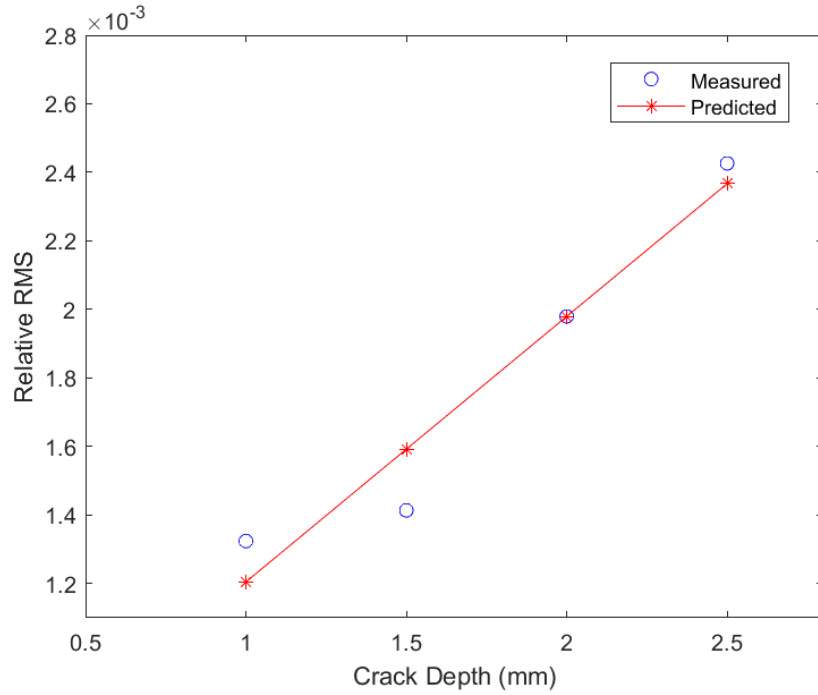


Figure 5-12 The relative RMS response of incident wave at varying crack depth.

The relationship between the damage depth variation and the response signal is linear, as in the deduced empirical predictive model of equation (5-26) with R^2 value of 0.94 and RMSE of 1.574×10^{-4} when compared with the measured data.

$$f(d) = A_1 d + b \quad (5-26)$$

where d is the damage depth value in mm, $A_1 = 7.747 \times 10^{-4}$ is the damage depth variation sensitivity and $b = 4.3 \times 10^{-4}$ is the constant of linearity.

It was observed that when the damage depth is about half the structure's thickness or less, the relative RMS of the response elastic wave signals are less than that of the healthy state of the structure but in the case of the damage depth

greater than half the structure's thickness, the relative RMS of the response elastic wave signals are greater than that of the healthy state of the structure. Hence, the model could predict damage depth greater than half of the structure thickness more accurately than predicting damage depth less than half the structural thickness. Unhealthy responses are noted as the responses captured when damage exists in the plate. The Root-Mean-Squared-Deviation (RMSD) between the healthy and unhealthy state of the plate is computed and plotted in **Figure 5-13**. It was observed that as damage depth increases, the percentage RMSD value decreases. This suggests that as damage depth increases, it becomes more pronounced and easier to differentiate between healthy and unhealthy response of the elastic waves. An empirical predictive model to this effect is expressed in equation (5-27) with an R^2 value of 0.89. From equation (5-27), it implies that beyond the damage depth of 2.748mm the damage response deviation becomes negative. This change in value sign could serve a great deal of alarm for system stoppage to avoid abrupt failure of system as it signifies that the structure is in worst health state when compared with its pristine state of health.

$$f(\dot{d}) = C_1 \dot{d} + C_0 \quad (5-27)$$

Where $\dot{d}$ = damage depth value in mm. $C_1 = -24.44$ and $C_0 = 67.16$

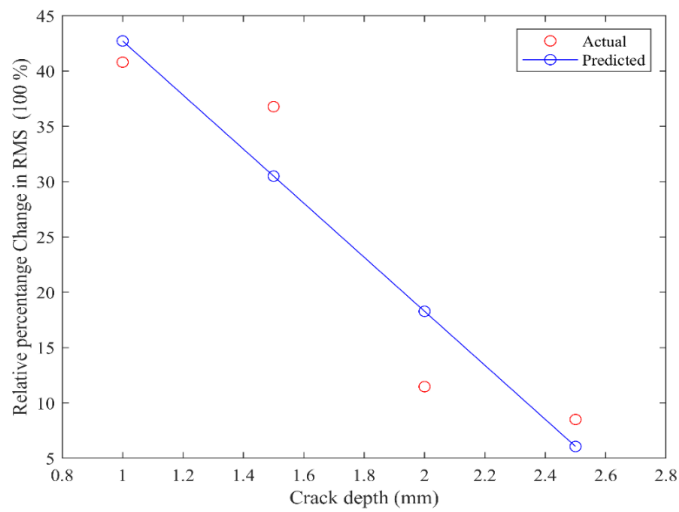


Figure 5-13 The percentage change in the relative RMS as crack depth increases.

5.8.4 Temperature Influence on Empty Damage Response of Guided Wave

Two damage depths, 1.50mm and 2.00mm were selected to observe the influence of temperature. The temperature of the plate was varied from 35 °C to 65 °C at an interval of 10 °C. At each targeted stage of the temperature, the response signals were captured by PZT2 and PZT4 sensors and relative RMS values processed. Comparing the results of **Figure 5-14** and with that of **Figure 5-15**, it showed that there is a variation in the RMS signal value as the temperature increases for different damage depth. The RMS value of the response signal decreases as the temperature increases. This could be attributed to dependences of the elastic wave on the material parameter especially elastic modulus. The percentage of RMSD was computed and plotted against the temperature variation and depth. Through curve fitting of the points as in **Figure 5-16**, a linear predictive model of equation (5-28) was deduced. An R^2 value of 0.8614 and RMSE value of 1.377 were obtained when the model result was compared with the actual RMSD. The R^2 value implies that the model could sufficiently explain more than 86% variation in the response signal caused by variation of temperature and damage depth. Also, the decrease in the RMS value still complies with trend of elastic material modulus variation when temperature of the material is increasing. This still suggests the dependences of guided wave on material parameters and that temperature rising leads to more effect on the response signals than the damage variation of the considered ranges.

$$f(T, d) = 21.96 - p_1 * T + p_2 * d \quad (5-28)$$

Where d is damage depth, T is temperature of the material, p_1 and p_2 are 0.2669 and 12.69 respectively.

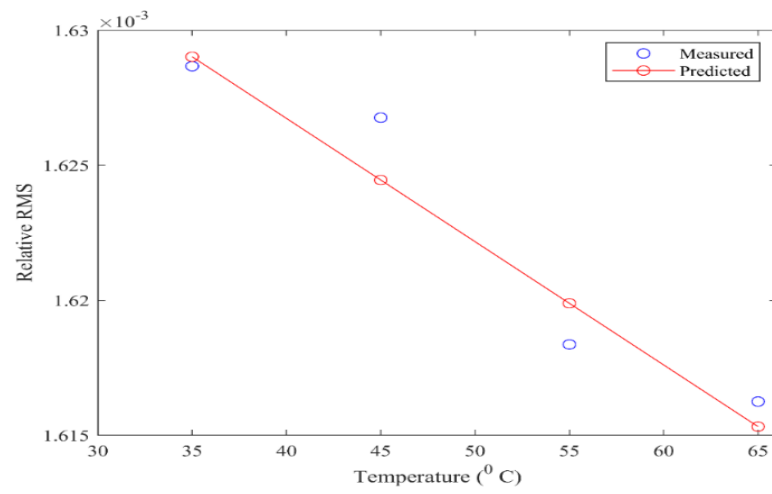


Figure 5-14 The effect of temperature on 1.5mm damage depth.

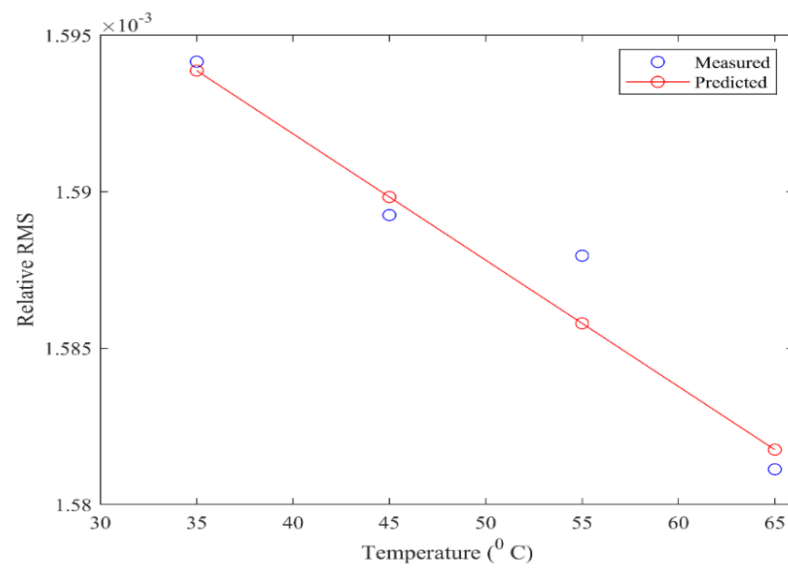


Figure 5-15 Temperature effect on 2mm damage depth.

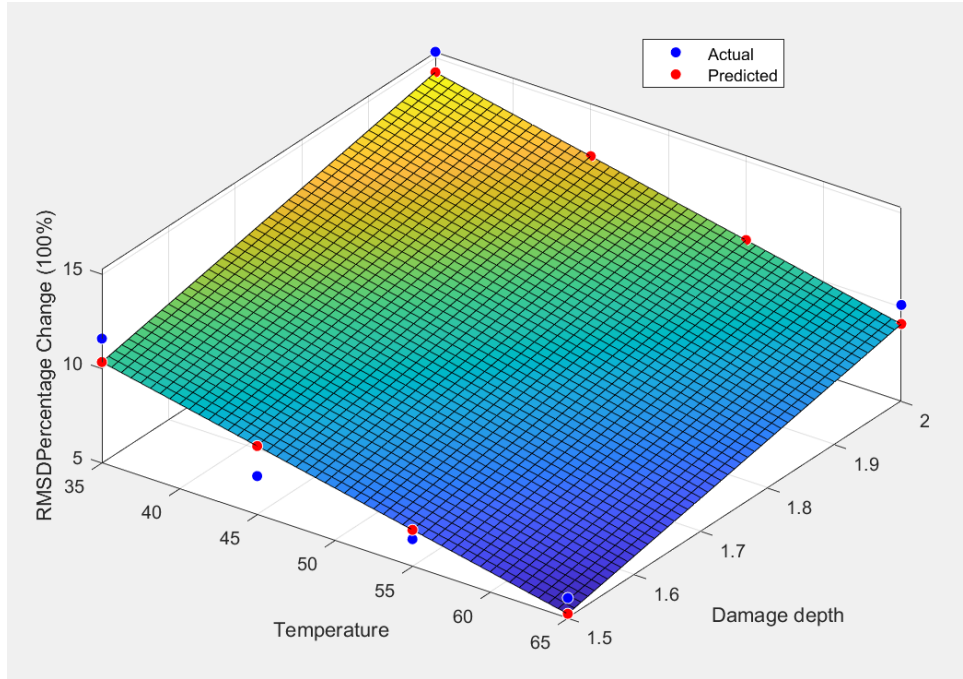


Figure 5-16 Surface plot of the combined influence of damage depth and temperature.

5.8.5 Effect of Debris Filled Damage on the Response Signal

The testing rig remains the same, but the damage is gradually filled with corrosion debris. The debris filled the damage lengthwise at an interval of 20% starting from 20% to 80% of the damage length. At each increased interval of the debris, the response wave is captured and used to compute the relative RMS value and RMSD. **Figure 5-17** shows that debris filled damage could cause the response signal to either increase or decrease with reference to the damage depth. When the damage depth is relatively shallow (less than or equal to half of the plate thickness), the debris-filled damage tends to affect the propagation of waves through the structure. In this case, the debris particles can act as scatterers, causing reflections and attenuations of the incident waves. As the percentage of debris increases, the scatterers become more pronounced, leading to a decrease in the amplitude or energy of the response signals. This could be why the debris damage index decreases with increasing debris percentage.

As the damage depth increases beyond half of the plate thickness, the interaction between the debris and the incident waves changes. Deeper damage allows for

more interaction between the debris and the waves, leading to a more pronounced effect on the response signal. In this scenario, the debris particles might cause constructive interference with the incident waves, resulting in increased amplitudes or energy levels of the response signal. This happening can lead to an increase in the debris damage index as the percentage of debris increases. Hence, the relative influence of debris and damage depth on the elastic wave signal can vary based on the specific scenario. In Table 5-4, the DI of a specified empty damage depth is compared with its debris filled to obtain debris fill factor. This factor depicts the intensity of debris accumulated by a given damage depth. Hence, as the damage depth increases, the debris factor increases which suggests more debris accumulation in the damage. This is depicted in **Figure 5-18**. From the result, existence of debris in the damage tends to amplify the response wave signals suggesting that incident wave scattering increases as debris percentage and damage depth increases simultaneously.

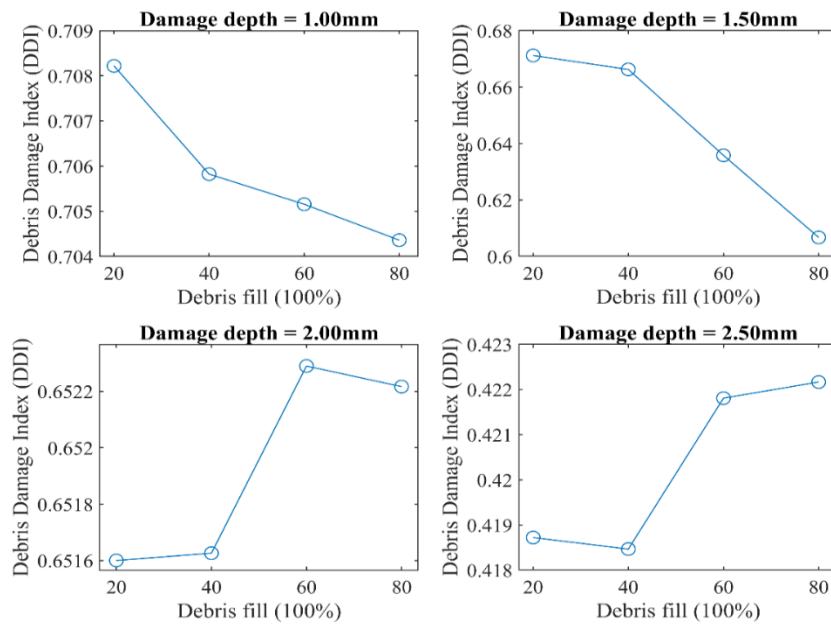


Figure 5-17 The effect of debris filled damage on the guided wave.

Table 5-4 Comparing empty and debris filled DI.

Crack depth(mm)	Empty Damage DI	Debris Filled Damage DI	Debris Factor
1.00	0.408000000	0.7058892961	1.730120824
1.50	0.367800000	0.6449988693	1.753667399
2.00	0.114700000	0.6519333363	5.683812871
2.50	0.085000000	0.5202911002	6.121071767

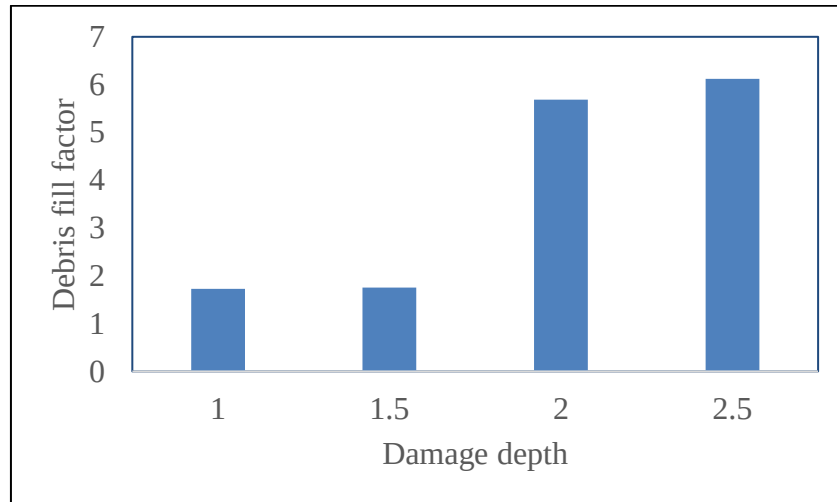


Figure 5-18 Debris filled Damage depth factor.

5.8.6 Influence Effect of Temperature and Debris-filled Damage

To further elucidate the influence of temperature on guided waves interacting with debris-filled damage, a systematic investigation was conducted. A damage depth of 1.5mm was used and different percentages of corrosion debris were introduced within the damage, ranging from 20% to 100% of the damage length. This allowed for understanding of how debris-filled damage reacts under varying temperature conditions. At each temperature stage, response signals were captured using PZT2 and PZT4 sensors, and the relative average RMS was computed. The result was employed to construct a surface plot, as depicted in **Figure 5-19**.

Furthermore, using curve fitting techniques, an empirical predictive model was deduced as in equation (5-29). The efficacy of this model was subsequently assessed against the measured response signals, as illustrated in **Figure 5-20**. The goodness of fit, R^2 value of 0.7879 and RMSE of 7.5×10^{-5} , derived from the predictive model, showed that it could explain sufficiently about 78% variation in the measured responses of the structure caused by temperature and debris filled. Also, the relative error in **Table 5-5** shows that a high error is recorded when the temperature is very high and the ratio of unfilled damage length to the probing wavelength is less than 0.5. This is because, as the debris fills the damage, its length decreases through the closure and consequently decreases the ratio of damage size to probing wavelength. As earlier said, damage stands a high probability of detection if the ratio of its size is greater than or equal to one-half of the probing wavelength[247].

$$f(D, T) = A_1 D + A_2 T + A_3 \quad (5-29)$$

Where T = temperature, D = percentage debris and constants are listed below.

A_3	A_1	A_2
0.001252	4.77E-06	1.17E-06

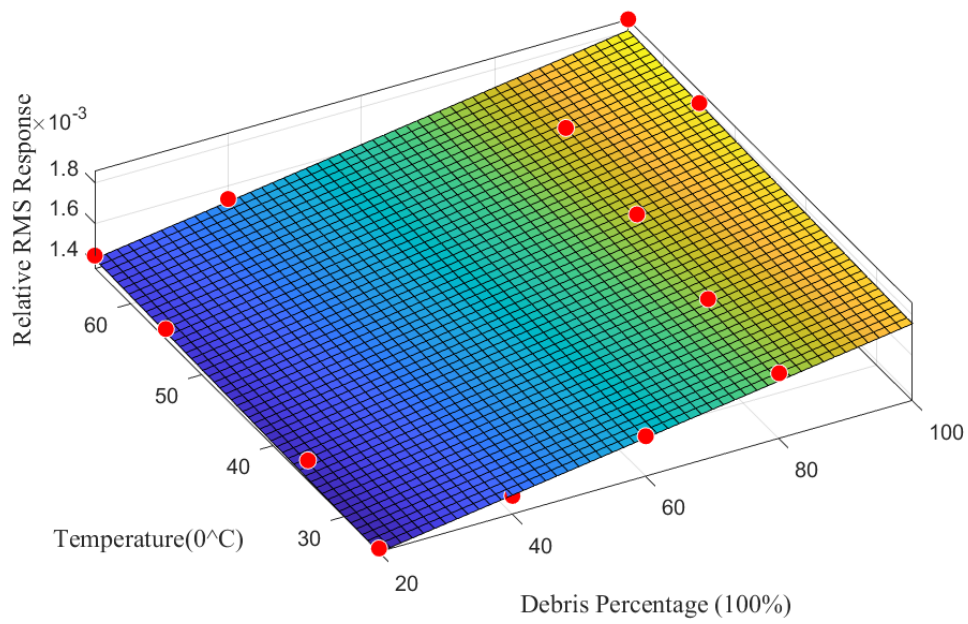


Figure 5-19 Surface plot of the combined influence of debris-filled damage and temperature.

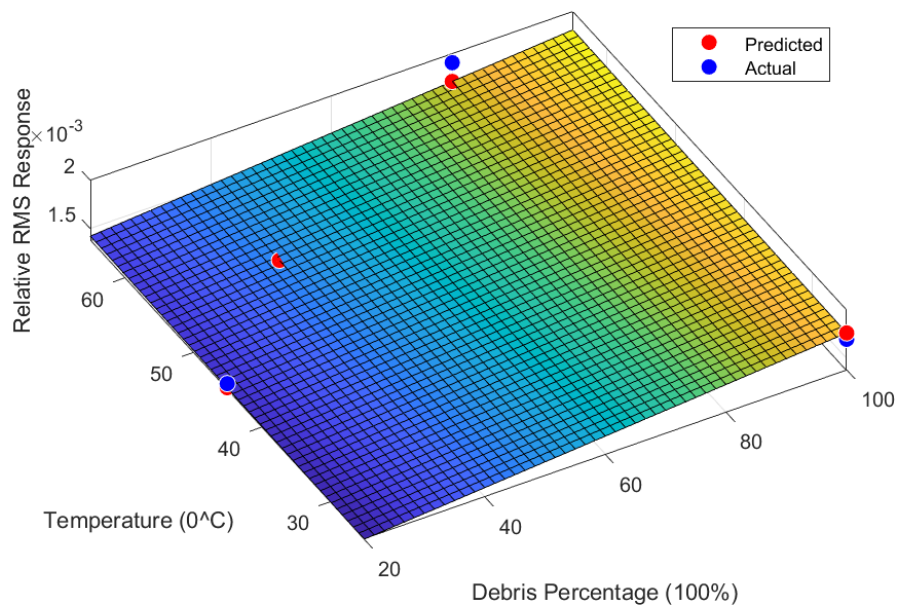


Figure 5-20 Predictive model response and measured test response.

Table 5-5 Comparing the predictive model response with the measured sensor response.

Debris	Temp.	Predicted Response	Measured Response	Relative Percentage Error
20	45	0.001400	0.001442	3.01
40	55	0.001507	0.001495	0.78
80	65	0.001709	0.001903	11.31
100	25	0.001758	0.001692	3.75

5.9 Summary

As damage is an inevitable part of structures, it demands continuous monitoring of structural health status using cost-effective technology and processing algorithm of less computational power to avert catastrophic failure of high-valued structures. This has sparked a high interest in using guided wave ultrasonic testing (GWUT) for SHM. GWUT has been used to inspect many forms of damage, but debris-filled damage, especially under environmental conditions such as temperature. Also, the choice of postprocessing technique for response signal feature extraction captured is a crucial aspect of SHM. In this study, four transducers were used in a pitch-catch configuration topology to study the confluence effect of temperature and debris-filled damage meticulously. By relying on the wave scattering effect from the tip edges of the damage, as in **Figure 5-2**, only two sensors were used to capture and process the damage's impact on the response elastic wave signals. Due to the high sensitivity of propagating wave energy to damage than other features of the response wave, RMS and RMSD were used to analyze the captured response signals. Monitoring the damage depth increase suggests that more incident waves are diffracted as damage depth increases. Also, the influence of shallow depth differs from that of the deepest depth as the latter causes more wave energy diffraction than the former. The relationship between the damage depth and the response signal was found to be linear, leading to the establishment of an empirical predictive model

of equation (5-26) with an R^2 value of 0.9381. The temperature was observed to significantly influence the response elastic wave, especially on the wave that had interacted with the damage. The major influence is a decrease in the intensity of the measured RMS in the cases of 1.5mm and 2.00mm damage depths in **Figure 5-14** and **Figure 5-15**, respectively. The combined influence of debris-filled damage and temperature was studied, and a good predictive model was established. The validation of the model with arbitrary values shows a relative error of less than 10% while its R^2 value is about 78% and RMSE value of about 7.5×10^{-5} . In summary, the results of this study are useful for continuous monitoring of structures for possible damage, especially debris-filled damage with the influence of temperature. The merits of SHM cannot be overemphasised, but less energy computational models and algorithms are needed to enhance fast postprocessing of response signals for on-time detection of damage in structures of high economic values.

6 CHAPTER SIX: INFLUENCE OF EXTERNAL LOW-FREQUENCY VIBRATION ON PROPAGATING ELASTIC WAVE

6.1 Overview

In furtherance to the influence of environmental operation conditions discussed in Chapter 5, this Chapter investigates the impact of low-frequency vibrations on the structural responses of ultrasonic-guided waves (UGW). An architectural model for mitigating the effects of low-frequency vibrations on SHM response signals is established by analysing the captured influenced response signals.

6.2 Introduction

Most economic civil structures in oil and gas, aerospace, automotive, or maritime sectors are constructed using thin metallic plates due to their rigidity, lightweight, load-carrying capacity and easy transportation[248]. A thin plate is a structural element defined by two parallel planes separated by a small distance called thickness. Mathematically, when the ratio of the material thickness to other of its dimensions is far less than one ($\frac{h}{L} \ll 1$, where h is the thickness and L is any other dimension of the plate), the material is considered a thin plate. However, this material is prone to damage of different forms that jeopardize the structure's safety and could lead to catastrophic failure if not detected. Therefore, it is essential to continuously monitor the structure using lightweight devices that is cost-effective for damage detection.

In the recent decade, guided wave ultrasonic has been widely used as a non-destructive structure health assessment technique to detect damage in pipes, plates and composite materials[173], [249], [250]. The technique relies on the ultrasonic wave's sensitive parameters for detecting and localising damage in the structure. This process deeply involves interaction between the waveguide (or structure) and the guided wave under environmental operating conditions (EOC). Many studies on wave-damage interactions have been conducted to understand the influence of EOC, especially temperature, on some damage-sensitive features of the guided wave[251]. In [252], the authors reported that a

temperature value as low as 0.5 °C could cause a change in the amplitude of the guided wave.

Similarly, in [250],[253] and [153], an increase in the temperature value of the waveguide consequentially caused a decrease in the amplitude of the guided wave. Also, an increase in temperature has been observed to cause a decrease in the velocity of the propagating wave [254]. Aside from temperature influence, structures would inevitably be subjected to vibration from various sources during their life cycle [255]. The prime effect of such external vibrations on the structure is an inducement of extra stress, which possibly causes variation in the inspection signal. A few studies have been conducted on the influence of external vibration on guided wave damage detection signals. Time-of-flight (ToF) is an essential parameter of the guided wave for localizing damage in a structure[73], [256]. However, before the damage localisation could occur, damage must be detected. In[255], the influence of external vibration on the ToF of the inspection signal was experimentally studied using two Aluminium plates of different geometrical dimensions and pitch-catch configuration topology. One of the Aluminium was in a static state, and the other was in a dynamic state through variation in frequency. The ToF extracted from the response signals of the two states were compared and observed to have varied slightly.

Although the waveshape of the response signal from the dynamic state was distorted, the authors attributed the slight variation in ToF to measurement error. In [257], the authors investigated the effect of random vibration on the guided wave inspection signal. They suggested that random vibration could cause clipping of the response signals. The influence of wind-induced vibration on the guided wave system has been studied. In[258], the authors experimentally showed that the response signal's waveshape remains intact as the wind speed varies. Also, they observed that the amplitude of the response signal at lower frequencies varied with wind speed while that of high frequencies remained intact. However, the influence of low-frequency vibration on the average energy of the response signals at the sensing position has not been studied. This study is vital as variation in the average energy of structural response at a position is

prominent for damage detection. This technique is demonstrated in Chapters 5 and 7. Under the influence of external low-frequency vibration on structural response signals, an error alarm could be high, and damage detection might be missed. Two case studies are considered to understand the influence of low-frequency vibration on propagating elastic waves. These are the static and dynamic cases of the thin plate. The average energy of the structural signals captured at the sensing positions in the two cases will be analyzed and compared before and after mitigating the effect of external low-frequency vibrations.

6.3 Theory

6.3.1 Elastic wave propagation in thin structure

As shown in the previous chapters (2)-(6), damage detection can be realized through active or passive inspection techniques based on the nature of the damage and the source of the structure excitation signal. Some damage can generate acoustic signals sufficient to cause particles of the structure to propagate energy from the damaged spot to a sensing position, as in the situation of active cracking or fatigue cracking. Therefore, the passive inspection technique is suitable for monitoring such damage, which requires strategic installation and networking of sensors to capture the acoustic signal when occurred readily. However, the active inspection technique is adequate for monitoring and detecting damage that cannot ordinarily emit acoustic signals. This approach has been adopted to study most passive cracks and corrosion-related damage in structures[141]. The active pitch-catch inspection approach consists of at least two transducers and the structure. One of the transducers is configured as an exciter that primarily induces shear stress that causes elastic wave propagation through the structure's thickness when it is excited with an oscillating electrical signal of sufficient voltage. The other transducer is then configured to capture the response signals, which are elastic waves that interact with the structure. As in Chapter 3, the guided wave inspection system could be generally modelled as a linear system[259] with means of input, medium of signal propagation and output. Hence, the structure could be referred to as a transfer system that relates the

output signal to the input signal. Therefore, the response of a guided elastic wave at the receiving sensor position could be expressed as in equation (6-1).

$$u(x, t) = \int_{-\infty}^{\infty} H(x, \omega) F(\omega) e^{-j\omega t} d\omega \quad (6-1)$$

Where

$F(\omega)$ is the Fourier transform of the excitation signal from the time domain to the frequency domain, $H(x, \omega)$ is the system transfer function and $e^{-j\omega t}$ is related to the dispersion of the elastic wave.

6.3.2 Attenuation of propagating elastic wave

As the elastic wave propagates through the structure, it undergoes different forms of attenuation, such as geometrical attenuation and material damping[260]. The geometrical attenuation relates to amplitude loss due to the spreading of the wave from into all directions from the point of excitation. This effect results in signal amplitude reduction that is proportional to the inverse square root of the wave packet distance from the point of generation. This is expressed in equation (6-2).

$$U_2 = U_1 \cdot \sqrt{x_1/x_2} \quad (6-2)$$

Where U_2 and U_1 represent the wave amplitude while x_1 and x_2 represent the respective distances away from the actuator where the wave amplitudes were measured. Similarly, the damping attenuation of the propagation wave due to structural material imperfection is as expressed in equation (6-3).

$$U_2 = U_1 e^{-\alpha(\Delta x)} \quad (6-3)$$

Where α represents the structural material's damping coefficient, which can be determined experimentally. Δx is the distance between the exciter and the sensor. All these attenuations are more prominent in composite materials than in metallic materials, and guided elastic waves experience low attenuation, hence propagating over a long structure distance [228].

6.3.3 Modelling influence of low-frequency vibration

Structures in operation would experience external vibrations which are random in nature. The external low-frequency vibration can be represented in equation (6-4).

$$v(x, t) = B(t) \sin(2\pi f_v t) * e^{-\alpha(\Delta x)t} \quad (6-4)$$

Where

$B(t)$ is the varying amplitude of the low-frequency vibration and f_v is the frequency of the signal. The propagating elastic wave is an amplitude-modulated wave as discussed in Chapter (4) and Chapter (5). The wave is expressed as in equation (6-5).

$$U(x, t) = ((A + m \cos(2\pi f_2 t)) * \cos(2\pi f_1 t)) * e^{-\alpha(\Delta x)t} \quad (6-5)$$

Where A = represents the amplitude of the modulating and carrier signal, f_1 and f_2 represents the carrier and modulating frequencies, respectively.

Without an external low-frequency vibration, the sensors will capture elastic waves that are nearly the same waveform as the excited signals. However, external low-frequency vibration introduced as a superposition wave on the propagating elastic wave will cause distortion in the resultant signal with a high chance of waveform deformation. The resultant response signal is as expressed in equation (6-6).

$$\widetilde{U(x, t)} = U(x, t) + v(x, t) \quad (6-6)$$

$$\widetilde{U(x, t)} = (A \cos(2\pi f_1 t) . A \sin(2\pi f_2 t) + B(t) \sin(2\pi f_v t)) * e^{-\alpha(\Delta x)t} \quad (6-7)$$

The equation (6-7) represents the resultant wave captured by the sensor at x when the thin plate experience external low-frequency vibration of time-varying amplitude. On this account, the influence of the external low-frequency vibration will overshadow the damage's effect on the wave, thereby causing a high-rate error alarm even when damage is not in the structure.

6.3.4 Response Signal Energy Estimation

The signal's energy captured at the sensor position is a vital statical parameter for damage detection [261]. It is more sensitive to changes in the structure than the signal amplitude, and it is estimated using squared amplitudes of the response signal over a given duration, Δt for a periodic signal as expressed in equation (6-8) or for a given sample length, n of the signal as expressed in equation (6-9).

$$RMS(s) = \sqrt{\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} [u(t)^2] dt} \quad (6-8)$$

$$RMS(s) = \sqrt{\frac{1}{n} \sum_{i=1}^n [s_i^2]} \quad (6-9)$$

When more than one sensor is used to increase the chances of damage detection, the average RMS estimates energy at the sensing position as in equation (6-10).

$$Average\ RMS_{av} = \frac{1}{N} \sum RMS(s)_i \quad (6-10)$$

Where N is the total number of the sensor and $RMS(s)_i$ is the energy of the response signal captured by an individual sensor.

6.3.5 Response Signal Decomposition

A multiresolution analysis of the response signal is adopted to mitigate the influence of the varying external low-frequency vibration in the elastic wave response signals. This decomposition technique would provide a framework for analyzing the response signals at various levels of resolution. Each level of resolution represents a component of the response signals at different frequencies. There are different multiresolution techniques, such as Empirical Mode Decomposition (EMD), Continuous Wavelet Transformation (CWT) and Variation Mode Decomposition (VMD). Unlike EMD, which suffers from mixed mode, each component level signal decomposed by VMD has a clear and distinct

frequency[262]. VMD decomposes signals based on a constrained variation problem[263]. Consider equation (6-11) as the captured response signals by the sensor.

$$x(t) = \sum_{z=1}^Z u_z(t) \quad (6-11)$$

Where $u_z(t)$ is the z^{th} decomposed level of the response signal and Z is the total number of component level. The aim of VMD is to determine component levels $u_z(t)$ that minimise the following variational equation (6-12).

$$\min_{\{u_z\}, \{\omega_z\}} \left\{ \sum_{z=1}^Z \int \left| \partial_t \left(\frac{u_z(t)}{1 + j\omega_z t} \right) \right|^2 dt \right\} \quad (6-12)$$

Where ∂_t represents the time derivative, j is the imaginary unit and ω_z represents the central frequency of the z^{th} decomposed level. To ensure the solution to the variational problem corresponds to a decomposition of the signal $x(t)$, two constraints are introduced:

- i. The sum of the $u_z(t)$ modes should reconstruct the original signal $x(t)$.
- ii. The decomposed levels $u_z(t)$ should be orthogonal in the frequency domain, thereby ensuring minimal overlap between the decomposed modes.

Hence, the captured response signal is decomposed into 5 component levels, with the last component level being the external low-frequency vibration. Therefore, expunging the last component level and summing the remaining 4 component levels will result in a reconstruction of the captured response signal without the distortion influence of the external low-frequency vibration, as expressed in equation (6-13).

$$\widetilde{x(t)} = \left(\sum_{z=1}^Z u_z(t) \right) - u_5(t) \quad (6-13)$$

Where $\widehat{x(t)}$ is the reconstructed response signal without distortion and $u_5(t)$ is the low-frequency vibration component of the distorted response signal.

6.3.6 Relative Deviation Percentage

Relative Deviation percentage R.D. is a useful statistical parameter to compare how signals are closely related. If two signals are closely related, the value of R.D. will be very small and tends to zero if they are exact. This is mathematically expressed as in equation (6-14).

$$\text{Relative Deviation, R.D} = \frac{|R_1(t) - R_2(t)|}{R_2(t)} \times 100\% \quad (6-14)$$

Where $R_1(t)$ represents the RMS of either the reconstructed response signals or the expunged low-frequency signal and $R_2(t)$ represents the RMS of the response signals initially captured by the sensors.

6.4 Experiment, Materials and Method

A mild steel carbon plate of dimension $500mm \times 300mm \times 3.00mm$ is used in this study. This thin metallic material is essentially used in constructing critical structural assets of high economic use due to its tough and ductile properties and low carbon content percentage. The property of the used plate is as in Chapter (5). Damage of 40.00mm length, 5.00mm width and depth of 2.50mm is seeded at the mid-distance between the exciter and sensors PZT_1 , PZT_2 and PZT_3 , as depicted in **Figure 6-1**. Before the installation of the transducers, an acetone was used to clean the surface of the plate and allowed about 5 – 10 minutes to dry. This ensured that particles and possible grease that might impede proper transfer of signals between the transducers and the plate were removed. The transducers used in the study are circular PZT types due to its omnidirectional capability of radiating and receiving signal unlike the rectangular PZT transducers that are orientation dependent[241]. The properties of the PZTs are as mentioned in Chapter(5). The reflection of wave from the edges of the plate were avoid via the

installation of DAS modelling Air dry clay round the edges of the plate[217]. The study was grouped into different cases as stated below:

- i. The static case scenario where the plate is excited with the induced stress of the exciter only.
- ii. The dynamic case 1 scenario where the plate is excited with the external low-frequency vibration only.
- iii. The dynamic case 2 scenario where the plate is excited simultaneously with the external low-frequency vibration and the induced stress of the exciter.

In all cases especially the static case scenario, soft foams were used between the plate and the table surface to minimize possible transfer of random vibration from the table to the plate. Two function generators (TG550 Function Generator) were used to in the experiment as shown in **Figure 6-1**. One of the function generators (FG1) creates the amplitude modulated excitation signal with centre frequency,180KHz for the exciter. The second function generator (FG2) was connected through a power amplifier to the shaker. Using the FG2, random low-frequency signals of greater than 30Hz with varying amplitude were generated and fed into the shaker to introduce external vibration on the inspecting plate. As the shaker injects random low-frequency signals into the plate, it vibrates, and response signals were captured by the sensors. The response signals were visualized and registered using Agilent Technologies Mixed Signal Oscilloscope (MSO-X 3024A) with a sampling frequency of 1MHz. Hence, the 3 case scenarios mentioned above were repeatedly performed and analysed to achieve objective 5.

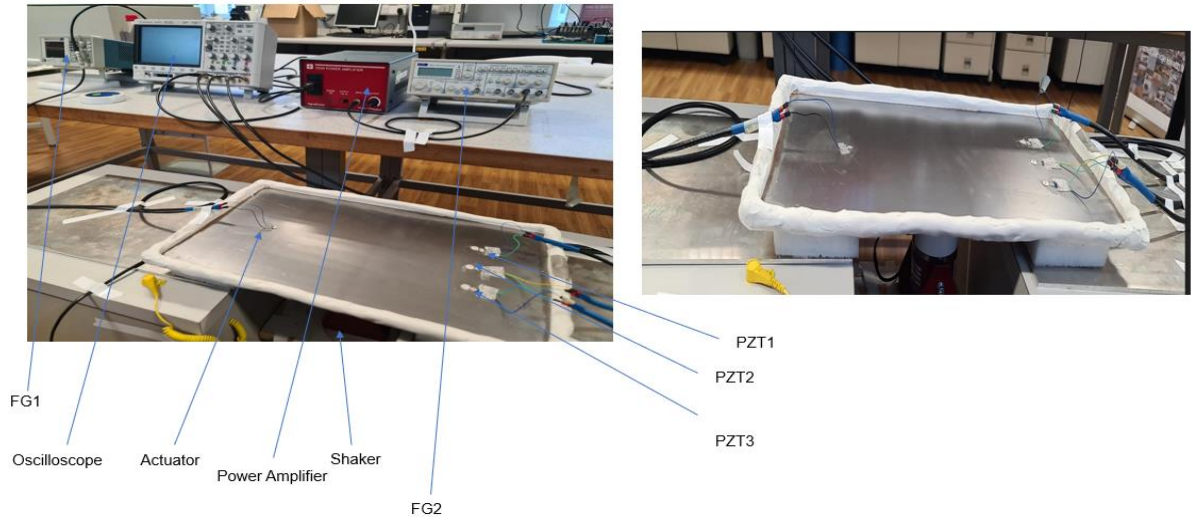


Figure 6-1 The Experimental Setup.

6.5 Results and Discussion

The captured response signals in each case scenario are analysed as follows.

6.5.1 The Static case scenario

Figure 6-2 is a sample of the captured response signals by each sensor when the plate was excited with PZT only. The response signals depicted different variations in modulation due to the extent of interaction with the damage. However, the interest is to determine the average energy of the structural response at the sensing position. The response signals were captured five times by each sensor and averaged to minimize random error using equation (6-15), while the average energy of the response signals at the sensing position is computed using equation (6-10) to be $4.937 \times 10^{-3}V$. This energy is about 2 times the maximum energy recorded by an individual sensor. This signal contained damage information but in the next sections, how external-low frequency affected it will be shown.

$$R_{PZT_i} = \left(\frac{R_1 + \dots + R_5}{5} \right) \quad (6-15)$$

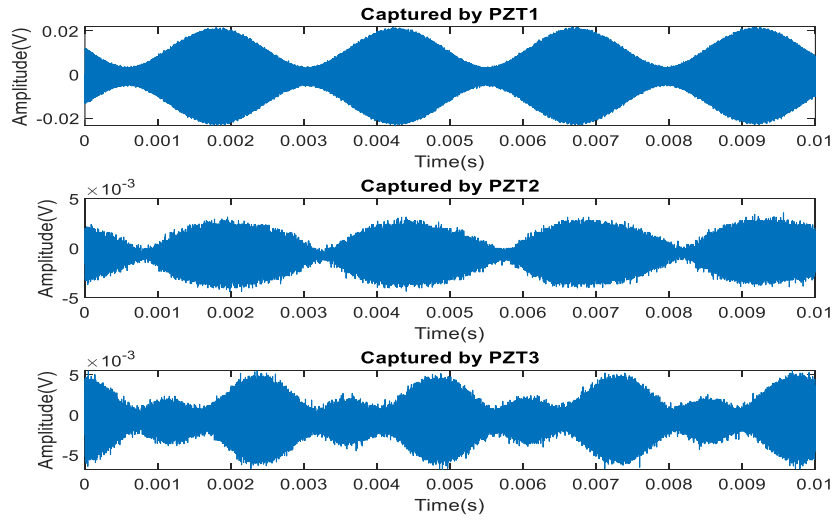


Figure 6-2 The captured response signal when only PZT excited the plate.

6.5.2 The Dynamic Case 1 scenario

In this scenario, the plate was excited with external low-frequency signals. The response signals for the duration of the response signals captured in subsection (6.4.1) were captured, repeated 5 times, and averaged using equation (6-15). **Figure 6-3** is a sample of one of the captured response signals to low-frequency vibration. The computed average energy at the sensing position is $7.59 \times 10^{-3} V$. When compared with the average energy recorded in the static case scenario, the deviation is about 54%. This suggests that the external vibration would potentially influence the response signal and compromise the integrity of the signal in detecting damage in the structure. Therefore, mitigating the influence of external vibration is a necessity. In the next subsection, the real influence on the response signal is discussed.

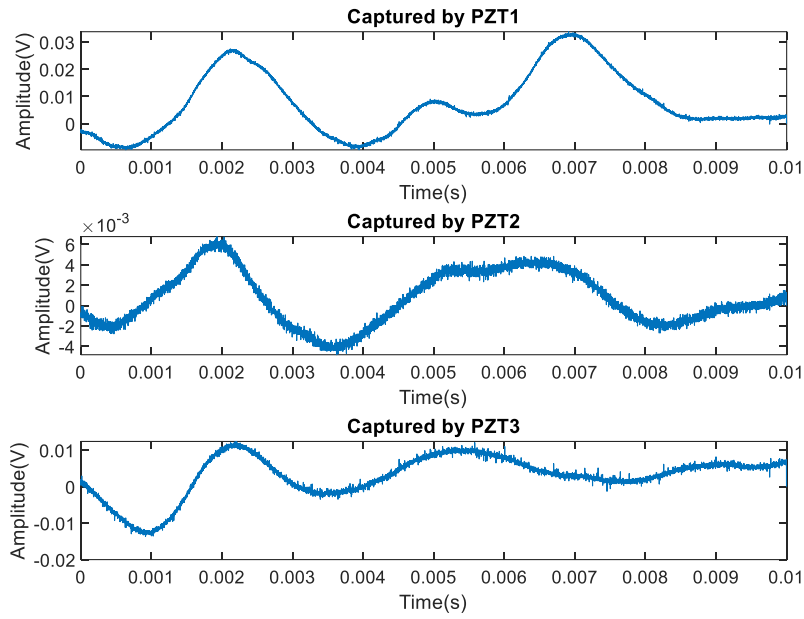


Figure 6-3 The low-frequency waveform due to external influence on the plate.

6.5.3 The Dynamic Case 2 scenario

In this scenario, both the excitation signal and low-frequency vibration from the shaker were simultaneously on the plate. The response signals at the sensing position was captured for the same duration as in the earlier scenarios. **Figure 6-4** is one of the captured response signals of the scenario. It was observed that external vibration influenced the signal highly, and signal clipping occurred in PZT1. The computed average energy at the sensing position is $9.354 \times 10^{-3}V$ which suggests a compromise of the response signal and overshadow of damage influence on the response signal. The computed average energy is about 89.46% deviated from the response signal captured in the static case scenario.

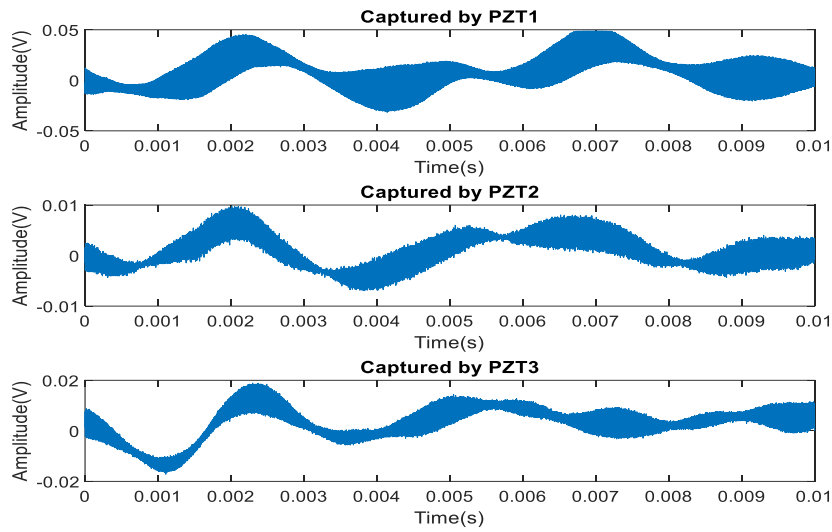


Figure 6-4 The captured response signals under the influence of low-frequency vibration.

6.5.4 Decomposition of the influenced response signal.

The low-frequency vibration highly influences the structural response signals captured in Figure 6-4, thereby overshadowing the damage information. To preserve the response signal integrity, the influence of the external vibration must be expunged, and the main structural response must be retained. Using equation (6-12), the response signals captured by each sensor were decomposed into 5 component levels about their centre frequency, as shown in Figures 6-5 through. The first 5 components (comp1 – Low Freq) are the decomposed signals from the captured response signals by any of the sensors. The last component level, Response Signal, is the influenced response signal. From the figures, it is observed that the waveform of the low-frequency signals is the same as that of the influenced signal. Hence, the waveform of every resultant superposition response signals due external vibration effect is that of the low-frequency signal. The frequency of each of the decomposed level is in **Table 6-1** and it is observed that only one component has low frequency across all the sensors.

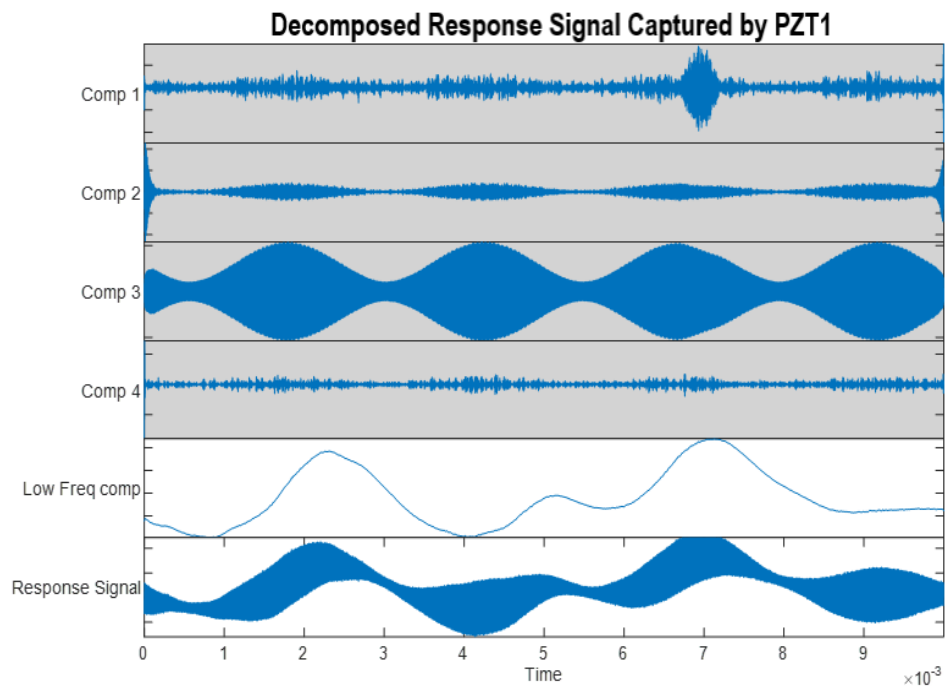


Figure 6-5 The decomposed response signal captured by PZT1.

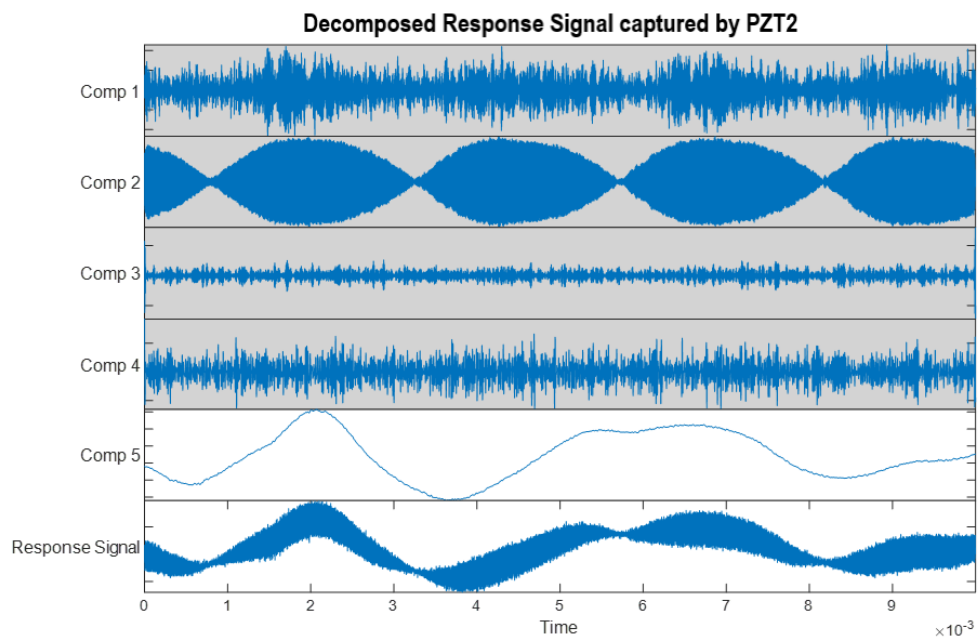


Figure 6-6 The decomposed response signal captured by PZT2.

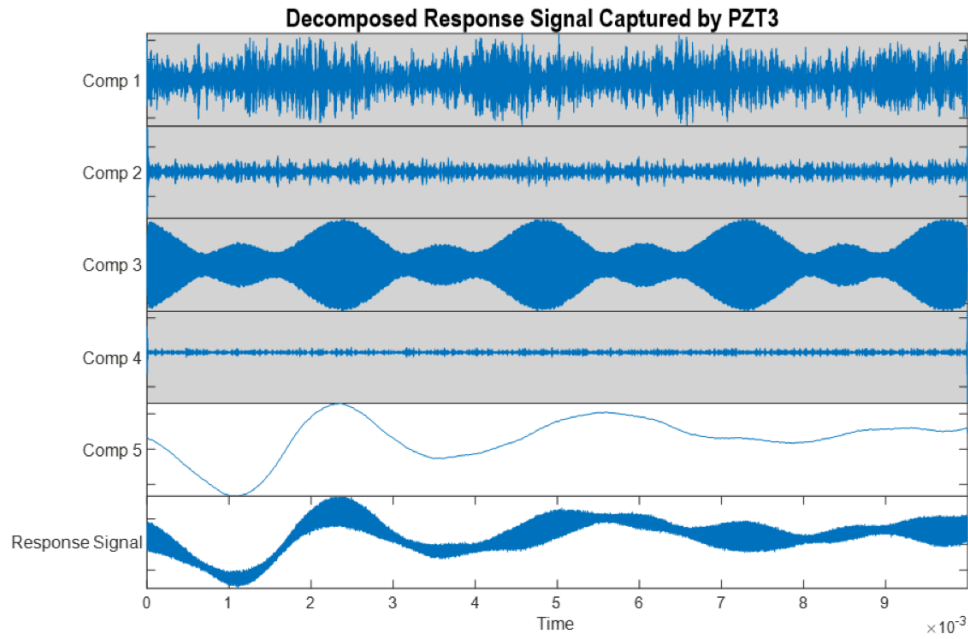


Figure 6-7 The decomposed response signal captured by PZT3.

Table 6-1 The frequency of decomposed levels.

Level Name	PZT1	PZT2	PZT3
Comp 1	360188.20 Hz	360357.75 Hz	362327.54 Hz
Comp 2	180382.76 Hz	179839.92 Hz	247803.15 Hz
Comp 3	180073.96 Hz	132798.20 Hz	180045.71 Hz
Comp 4	96933.47 Hz	69486.54 Hz	117588.61 Hz
Low-freq. Comp	141.18 Hz	225.73 Hz	188.38 Hz

6.5.5 Reconstruction of the Response Signal.

Using equation (6-13), the reconstructed response signals without low-frequency vibration are shown in **Figure 6-8**, while the expunged low-frequency signal is shown in **Figure 6-9**. It is clear that the severe influence of low-frequency vibration is removed from the response signals except for the effect of signal clipping in the response signal captured by PZT1. This is evident when the energy of the signals is computed and plotted in **Figure 6-10**. It was observed

that the relative deviation percentage (R.D.) between the reconstructed and response signals before the influence of low-frequency vibration is about 1.6%. This signifies that almost all the response signals were recovered. Similarly, the relative deviation of the low-frequency signals before the influence and the expunged signals was computed to be 4.4%, which signifies that the expunged signal is nearly the same as the influencing signal.

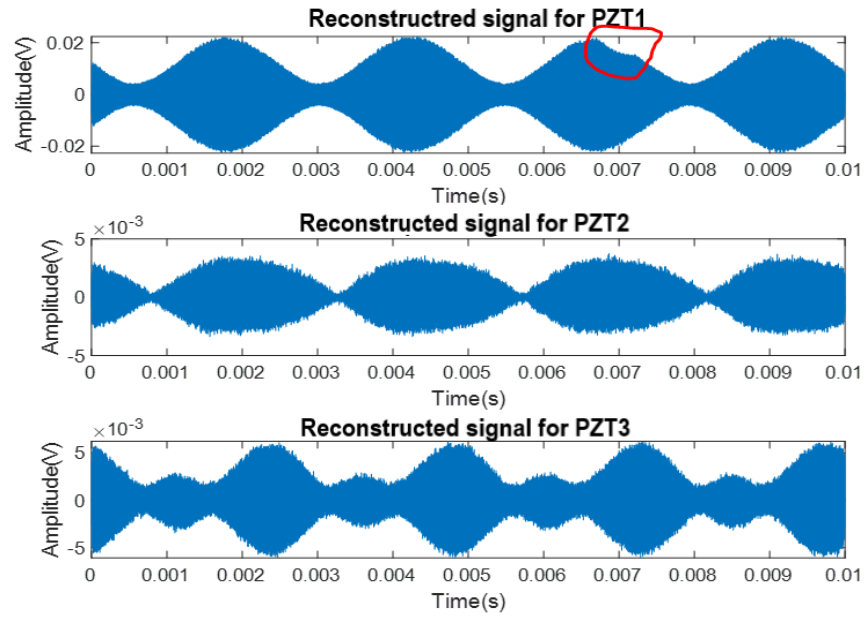


Figure 6-8 The Reconstructed Response Signal.

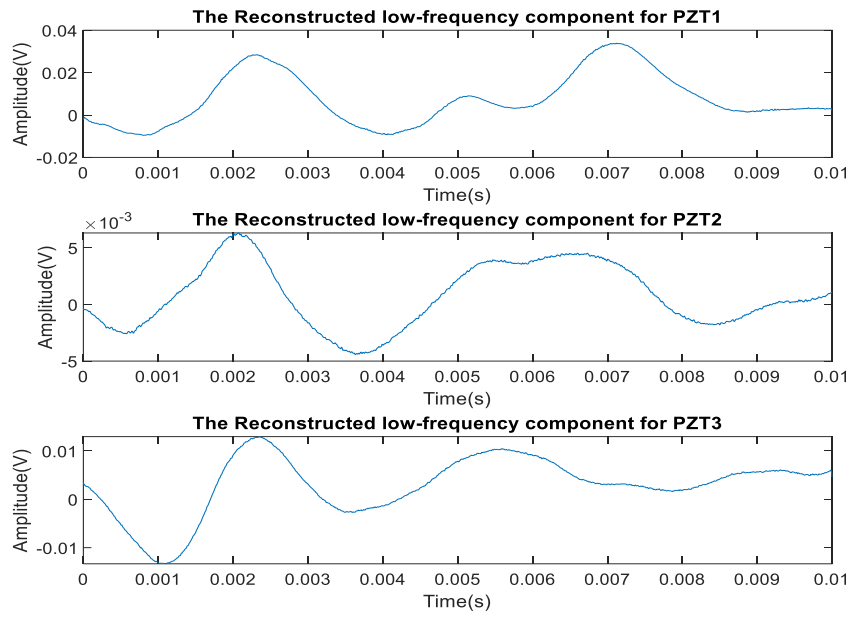
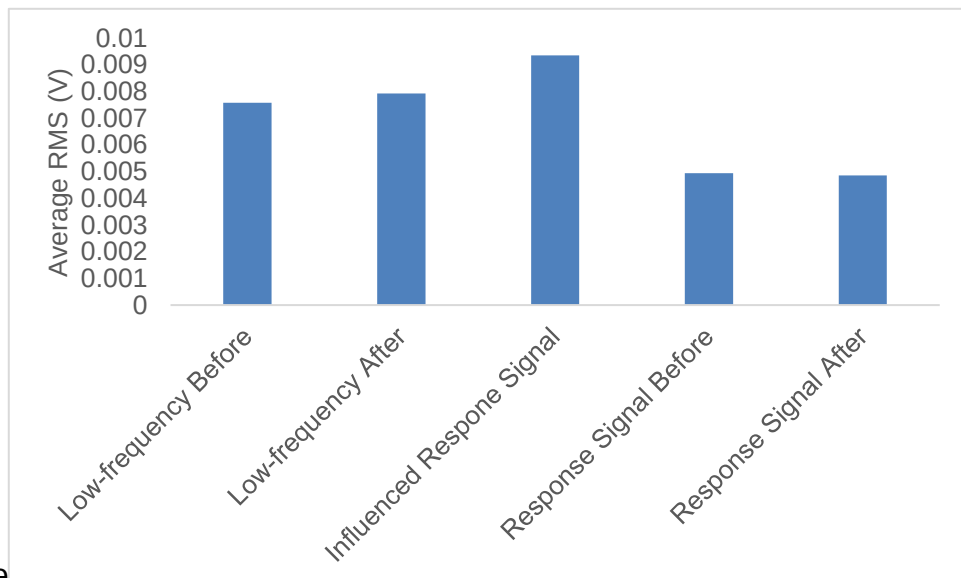


Figure 6-9 The expunged low-frequency signals.

Figure 6-10 Average RMS of different Responses.

6.6 Olisa-Khan Low-frequency Mitigation Architecture (Olisa-Khan LMA)



From the result analysis, an architectural model is designed to mitigate the influence of low-

frequency vibration on structural health monitoring response signals. The architectural model is established to enhance damage detection performance by preserving signal integrity, as shown in **Figure 7-11**. The model can be integrated with an existing or a newly developed SHM system without much adjustment in the design except for establishing points of interface for capturing structural response signals, estimation of minimal relative deviation between healthy, unhealthy, and vibration influenced response signals.

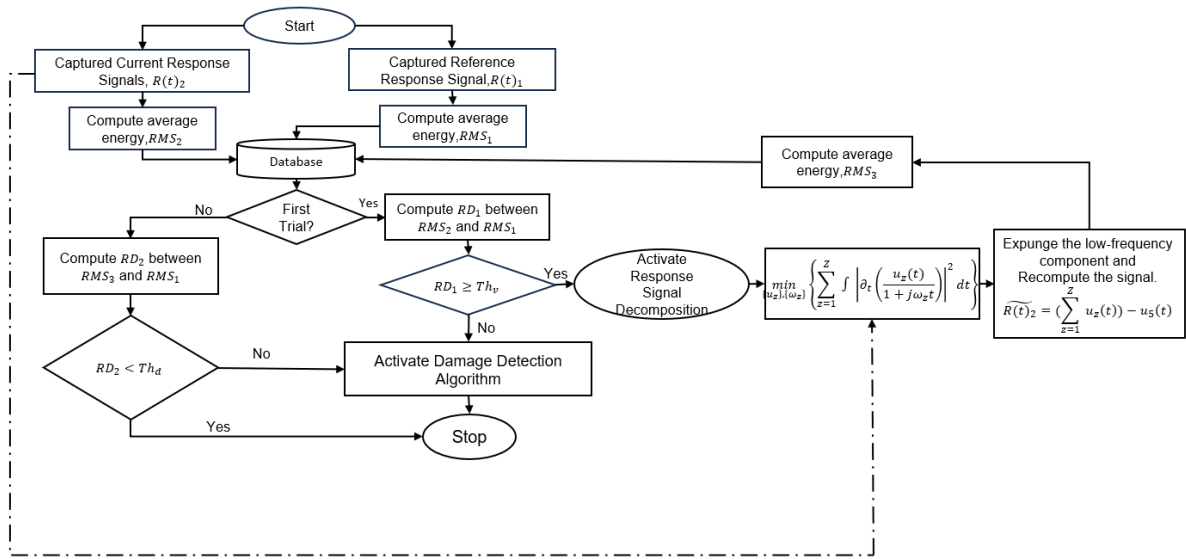


Figure 6-11 Olisa-Khan Low-frequency Mitigation Architecture (Olisa-Khan LMA).

The definition of terms used in the Architecture design are:

- $R(t)_1$: A one-time established reference response signals for the estimation of the average energy RMS_1 , of the healthy response signals acquired at the sensing position.
- $R(t)_2$: The current response signals acquired at the sensing position for estimation of the periodic average energy RMS_2 of the structure at the point.
- $\widetilde{R(t)}_2$: The reconstructed response signals from $R(t)_2$ for estimation of the average energy RMS_3 .
- Database, D.B.: A created memory location with partitioned slots for storage of data

- First Trial: A decision-making and data polling point from the memory location.
- RD_1 : The relative deviation between the average energy of the current acquired and reference response signals.
- RD_2 : The relative deviation between the average energy of the current acquired and reconstructed response signals.

Th_d = the minimal threshold above RD_2 that suggests a damage diagnosis.

Th_v = the minimal threshold below RD_1 that suggests low-frequency mitigation.

Z = is as earlier defined, the level number of decomposition of the influenced response signal

dt = sampling time

Activate damage detection algorithm = These are different damage assessment procedures on $R(t)_2$ or $\widetilde{R(t)}_2$.

U_z = components of the decomposed $R(t)_2$.

ω_z = angular frequency

6.7 Summary

In this chapter, the influence of low-frequency vibration on propagating elastic-guided waves is studied, and a strategy is established to remove this effect and improve the performance of SHM for damage detection and assessment using elastic waves. It was observed that the influencing effect of low-frequency vibration on the elastic-guided wave is waveform distortion, wave signal clipping and increasing energy values at the sensing position. These effects are detrimental to assessing the structure's health state, especially when using average energy at a sensing position. Since the low-frequency vibration and damage existence in structures could vary the energy of sensed structural response signals, mitigating the influence and improving damage detection performance becomes necessary. By using the multiresolution technique, mode

variation decomposition, the influencing signal component on the sensed structural response signal is mitigated, and the supposed structural response signal is reconstructed. The relative deviation (R.D) percentage among the average energies of the reconstructed response signals, the dynamic and static case response signals were computed and compared. Before mitigating the influencing component of the response signal, the R.D between it and the static response case was about 89.46%, as shown in Table 6-1. This high deviation percentage suggests that a factor other than damage influences the response signal. After mitigating the low-frequency vibration, the R.D between the reconstructed response signals and the static response signals case was about 1.64 %, suggesting the two signals are very close. The small deviation could be attributed to the signal loss due to clipping and imperfection in the system. The average energy of the expunged low-frequency vibration signals was compared with that of the response signals captured when the plate was only excited by the low-frequency signal. A small R.D value of 4.4% between the signals suggests a need for an improvement to reduce further the R.D between the reconstructed and the static case signals. Due to the exigency of SHM and the particularly severe effect of low-frequency vibration on structural response signals, an architectural model called Olisa-Khan low-frequency mitigation Architecture (Olisa-Khan LMA) is designed as in **Figure 6-11**. This study improves the performance of the guided wave ultrasonic technique by mitigating the severe influence of low-frequency vibration on the structural response signals.

7 CHAPTER SEVEN: INFLUENCE OF DIFFERENT DEBRIS FILLED DAMAGE ON GUIDED WAVE DAMAGE DETECTION RESPONSES

7.1 Overview

As open damage could trap and accumulate substances other than dry debris, this chapter explores elastic wave mechanics in the damaged metallic plate filled with various substances. The damage trapped and accumulated substances ranging from dry debris to different fluids. Analysis of the structural response to different central frequencies of the ultrasonic-guided waves is explored to detect and classify the damage. This study is crucial for structural health monitoring (SHM) and damage characterization in sectors like oil and gas, where such damage is prevalent.

7.2 Introduction

Engineering structures are often constructed using materials that ensure a long service life for an intended task. The metal plate is the base of most civil engineering structures. Some structures are formed and constructed using either thin or thick plates. One of the ways to classify a plate as thin or thick is to consider its thickness ratio to other geometric dimensions. If plate thickness is greater than one-tenth of its other geometric dimensions, it is called a thin plate; otherwise, it is a thick plate as defined in the piecewise function of equation (7-1).

$$f(D) = \begin{cases} \text{thin}_{plate}, & \text{if } D \ll 0.1 \\ \text{thick}_{plate}, & \text{if } D > 0.1 \end{cases} \quad (7-1)$$

Where D is the ratio between the plate thickness and either the width or length of the plate. The thickness of structures is essential to supporting and carrying intended loads. Variation in the thickness of a structure leads to a hotspot for material degradation and a high chance for catastrophic failure to occur. Structural damage that causes thickness reduction has been associated with corrosion activities [16]. The initiation of corrosion activities in different ways is revealed in [222]. Early damage detection is necessitated due to the severe

implications of damage to structures, especially during service time. Undetected damage could lead to a failure of the structure, which may cost lives and high-valued economic assets. Hence, structural health monitoring (SHM) is devised for continuous monitoring of structures using different techniques to detect and estimate damage[264], [265]. For the past decade, interest in using guided wave ultrasonic technique (GWUT), to monitor structures especially thin structures, has increased tremendously. The increase is due to its cost-effectiveness, long-distance inspection capability, nonintrusive nature and lightweight[21]. The guided wave ultrasonic technique can be configured differently to generate Lamb waves that would propagate in a thin structure, pick information about a concerned area of the structure through interactions and become captured as a response signal of the structure using a sensor[266]. Pulse-echo and pitch-catch configurations are primarily used for this purpose, emphasising the damage's nature and size [266]. Pulse-Echo has been principally used to monitor large damage that could reflect most of the incident wave when encountered. However, pitch-catch is ideal for damage that allows for through transmission of most of the incident wave with little reflection [21]. Unlike pulse-echo, it detects damage that is in the area between the actuator and the sensor.

Formed damage in structures could be empty or filled with substances. Such substances are referred to as debris or fluid[222]. Empty damage is formed when a crack, dent, or notch is devoid of filled substances, while filled damage is formed when a crack, dent, or notch traps and accumulates debris or fluid that could fill it. The filled damage has the potential for pitting corrosion formation over time. Pitting corrosion is a localized damage with various depths and irregular geometry. It has been attributed to the catastrophic failure of structures, especially in the oil and gas industry[187]. In[267], the authors studied the relationship between the scattering of damage signals and different severities of damage using fundamental S_0 lamb wave mode and pitch-catch method of the ultrasonic guided wave. The severities considered were notch length, orientation and notch depth with respect to the plate thickness. In[268], crack severity due to damage depth variation by uniform incremental percentage was studied using guided wave ultrasonic and different damage indices. The RMSD was noted to

be more reliable than other DI metrics. Delamination, corrosion and debonding have been studied as well using ultrasonic-guided waves [125], [269], [270]. Still, there is limited study on the detection of filled-in damage, especially when the damage is filled in with either dry debris or fluids of different viscosities. This study experimentally studied filled-in damage using the pitch-catch guided wave ultrasonic method of three sensors and one actuator. The deviation of each damage state at every excitation frequency was computed using Root Mean Square Deviation, RMSD. Through the dispersion curve, excitation frequencies were selected to ensure the generation of fundamental modes, S_0 and A_0 , of the Lamb wave. The study was performed on 3.00mm thickness plate with a seeded damage of 2.50mm deep. Three case scenarios were studied: (a) a base case using a healthy plate (b) current case of unhealthy plate representing empty damage and (c) and second current case representing damage filled with different fluids. The respective influence of each substance on the guided wave on predicting damage was observed and compared with the healthy state.

7.3 Non-destructive Evaluation and Techniques

The elastic wave is vital for damage detection and severity evaluation in structural health monitoring (SHM). It occurs through restoration forces between particles of the host structure temporarily displaced from their mean positions. The excitation of the elastic wave in structures causes changes in the material properties and thereby influences the characteristics of propagating elastic waves, such as wavelength, wave velocity, phase, Time of wave arrival (ToA), Time of Flight (ToF) and amplitude of the wave. The elastic waves could be bulk waves or guided waves[271]. The two forms of elastic waves differ in some respects, although they obey the same governing equations, especially in mode formation and interactions with the boundaries of the structure[272]. The bulk waves generate finite wave modes while propagating within the structure but away from its boundaries. The boundaries of the structure provide a guide to the guided wave, in contrast to the bulk wave. Due to the dispersive nature of the guided wave through wave velocity dependence on frequency, multiple modes are generated, leading to complexity in wave interpretation.

Prominent forms of guided waves are the Lamb waves and Rayleigh waves[184]. The Lamb wave could be generated from the coupling between longitudinal and vertical shear waves reflected at the structure's free surfaces, especially the plate. The Rayleigh waves are free waves on the surface of a semi-infinite solid. In this form of the guided wave, the traction forces vanish on the structure's surface, and the wave amplitude decays into the depth of the structure. However, the Lamb wave's traction forces vanish on the guided wave's upper and lower surfaces as it propagates through the thickness of the structure. Rayleigh waves are useful in detecting damage in thick structures, while Lamb waves are useful in detecting damage in thin structures. Structures can be monitored in two ways: active or passive technique[184]. In the active monitoring technique, a transducer is used as an actuator to cause the propagation of an elastic wave in the structure. At the same time, the structural response is captured by another transducer functioning as a sensor. Unlike the active monitoring technique, the passive monitoring technique offers only listening and capturing the responses of the structure [273]. This approach is mainly used to infer the state of the structure when the damage cannot emit elastic waves in the frequency range of an ultrasound[21]. Since the damage of interest in the study cannot generate an elastic wave, an active monitoring technique is adopted and used.

7.4 Elastic Lamb Wave and Dispersion Curve

Figure 7-1 depicts the propagation of elastic waves on thin plates. Since an elastic wave is a plane strain that occurs in a free plate, the displacement of the particles via the plate thickness x_2 and in the direction of the wave propagation x_1 are considered. It is important to note that particles are not the atoms of the structure but localised, discrete objects of the material. The particles are set into motion and propagate energy from one point of the material to another as a wave. The wave-particle displacement in the x_1 direction corresponds to longitudinal waves, while in x_2 direction, it corresponds to vertical shear waves [272].

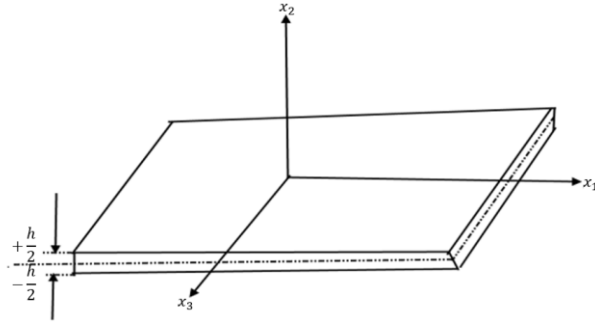


Figure 7-1 Elastic wave propagation in a thin plate.

The plate particles' propagating wave depends on the material's mechanical properties. These properties are the density ρ , elastic modulus, E and shear modulus, G . Hence, the velocity of the wave particles is influenced when the mechanical properties vary. In equation (7-2), the longitudinal wave velocity is influenced directly by the variation of the young elastic modulus E and indirectly by the density of the material structure. Similarly, the transverse wave velocity is influenced directly by the shear modulus and indirectly by the material density, as in equation (7-3).

$$C_L = \sqrt{\frac{E}{\rho}} \quad (7-2)$$

$$C_T = \sqrt{\frac{G}{\rho}} \quad (7-3)$$

The equations imply that the material's elastic modulus and shear modulus, respectively, describe the longitudinal and shear velocities of the wave particles. However, damage, such as a crack, would decrease the material density, while corrosion and the inclusion of corrosion byproducts would increase the material density, particularly at the damaged spot. The modulus values are constant in all directions for isotropic and homogenous materials. Hence, the elastic modulus in

the equations could be substituted with Lamé's constants as in equations (7-4) and (7-5).

$$C_L = \sqrt{\frac{\lambda + 2\mu}{\rho}} \quad (7-4)$$

$$C_T = \sqrt{\frac{\mu}{\rho}} \quad (7-5)$$

Lamb waves are dispersive because the velocity of the wave particles depends on the wave frequency signal. However, equations (7-4) and (7-5) depict a nondispersive elastic wave that depends on material properties and not frequency.

The general wave equation of motion governs the motion of wave particles in the free plate and is expressed in equation (66.) [89][184]

$$\mu \cdot u_{i,jj} + (\lambda + \mu) u_{j,ji} + \rho f_i = \rho \cdot \ddot{u}_i \quad (i, j = 1, 2, 3) \quad (7-6)$$

Where λ and μ are Lamé's constants, u is the displacement of the wave particles, ρ is wave-particle density, and f is the applied force that causes wave propagation. The subscripts 1, 2, and 3 denote wave propagation directions in the free plate. Since this is a free plate problem, it requires a traction boundary condition as in equation (7-7).

$$t_i = \sigma_{ji} n_j \quad (7-7)$$

Where t_i is the three traction components specified on the boundary with a unit normal n . However, a free plate surface is considered traction free. Therefore, equation (7-7) becomes zero. The equation (7-6) of the particle motion can be solved using Helmholtz decomposition vector form as expressed in equation (7-8) [272].

$$u = \nabla \phi + \nabla \times \psi \quad (7-8)$$

Where $\phi = \text{Scalar potential}$ and $\psi = \text{Vector potential}$

By considering the effect of strain on the plane, the components of displacement U_i of the wave-particle in the direction of wave propagation x_1 and normal to x_2 can be described in equations (7-9) and (7-10) on the condition that there is no motion in the x_3 direction as expressed in equation (7-11)

$$u_1 = \frac{\partial \phi}{\partial x_1} + \frac{\partial \psi}{\partial x_2} \quad (7-9)$$

$$u_2 = \frac{\partial \phi}{\partial x_2} - \frac{\partial \psi}{\partial x_1} \quad (7-10)$$

$$u_3 = 0 \quad (7-11)$$

The above equations resolved the displacement of the particles in horizontal and vertical directions. A further derivative of the equation would describe the motion and velocity of the wave particles as in equations (7-12) and (7-13).

$$\frac{\partial^2 \phi}{\partial x_1^2} + \frac{\partial^2 \phi}{\partial x_2^2} = \frac{1}{C_L^2} \frac{\partial^2 \phi}{\partial t^2} \quad (7-12)$$

$$\frac{\partial^2 \psi}{\partial x_1^2} + \frac{\partial^2 \psi}{\partial x_2^2} = \frac{1}{C_T^2} \frac{\partial^2 \psi}{\partial t^2} \quad (7-13)$$

The time-dependent solutions to the equations above are harmonic and can be expressed as in equations (7-14) and (7-15)

$$\Phi = [A \sin(px_2) + B \cos(px_2)] \times e^{i(kx_1 - \omega t)} \quad (7-14)$$

$$\psi = [C \sin(qx_2) + D \cos(qx_2)] \times e^{i(kx_1 - \omega t)} \quad (7-15)$$

Where

$$p = \sqrt{\frac{\omega^2 - (c_L \times k)^2}{c_L^2}} \quad (7-16)$$

$$C_L = \sqrt{\frac{(1-\nu)}{(1+\nu)(1-2\nu)} \frac{E}{\rho}} \quad (7-17)$$

$$q = \sqrt{\frac{\omega^2 - (c_T \times k)^2}{c_T^2}} \quad (7-18)$$

$$C_T = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{\mu}{\rho}} \quad (7-19)$$

$$k = \frac{2\pi}{\lambda_w} \quad (7-20)$$

$$E = 2\mu + 2\mu\nu \quad (7-21)$$

ω is the angular frequency of the excitation signals applied to the structure surface, k is the wavenumber of the signal, x_1 is the distance of wave propagation, and other parameters had been defined earlier. The above solutions represent the travelling waves in the x_1 direction and the standing wave in x_2 direction while invariant in x_3 . Where A, B, C and D are unknown amplitude of the wave, which could be determined from the boundary conditions of the problem. The subscripts 1 and 2 depict the propagation direction implying inward and outward directions to the plate's surface, respectively, as in **Figure 7-1**. The above field variable solutions involve odd and even trigonometry functions (sines and cosines) at about the midplane of the plate, $x_2 = 0$. Hence, the solution could be split into two behavioural modes of the wave, which are symmetric S_i , and asymmetric A_i , about the midplane. For displacement of the wave particle in x_1 direction, the wave-particle behaviour will be symmetric with respect to the midplane of the plate on the condition that it contains even functions. Also, for the displacement of wave particles in the x_2 direction it has asymmetric mode of behavior with an odd function. Hence, the equations of the wave particles could be grouped into the two behavioural modes, which are symmetric and asymmetric modes and are depicted in **Figure 7-2**.

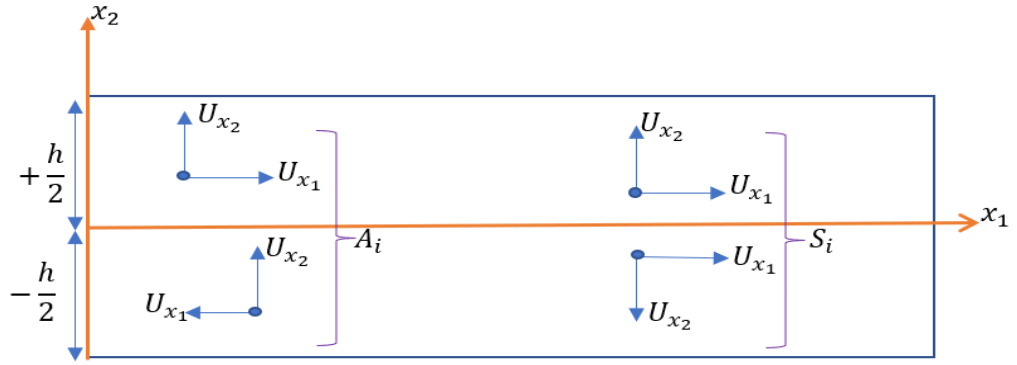


Figure 7-2 Asymmetric and Symmetric modes of particle motion across the plate thickness.

Symmetric mode:

$$\Phi = B \cos (px_2) \quad (7-22)$$

$$\psi = C \sin (qx_2) \quad (7-23)$$

$$u_{x_1} = ikB \cos (px_2) + qC \cos (qx_2) \quad (7-24)$$

$$u_{x_2} = -pB \sin (px_2) - ikC \sin (qx_2) \quad (7-25)$$

$$\sigma_{x_2x_1} = \mu [-2ikpB \sin (px_2) + (k^2 - q^2)C \sin (qx_2)] \quad (7-26)$$

$$\sigma_{x_2x_2} = -\lambda(k^2 + p^2)B \cos (px_2) - 2\mu[p^2B \cos (px_2) + ikqC \cos (qx_2)] \quad (7-27)$$

Considering boundary conditions, $\sigma_{x_2x_1} = \sigma_{x_2x_2} \equiv 0$ at $x_2 = \pm \frac{h}{2}$.

Therefore, equations (7-26) and (7-27) are expressed as

$$\mu [-2ikpB \sin (px_2) + (k^2 - q^2)C \sin (qx_2)] = 0 \quad (7-28)$$

$$-\lambda(k^2 + p^2)B \cos (px_2) - 2\mu[p^2B \cos (px_2) + ikqC \cos (qx_2)] = 0 \quad (7-29)$$

By simplifying equations (7-28) and (7-29) and making substitutions, the symmetric mode behaviour for the wave-particle is equation (7-30). All the parameters have been defined before.

$$\frac{\tan(qx_2)}{\tan(px_2)} = -\frac{(4k^2qp)}{(q^2-k^2)^2} \quad (7-30)$$

For asymmetric mode:

$$\Phi = A \sin (px_2) \quad (7-31)$$

$$\Psi = D \cos (qx_2) \quad (7-32)$$

$$u_{x_1} = ikA \sin (px_2) - qD \sin (qx_2) \quad (7-33)$$

$$u_{x_2} = pA \cos (px_2) - ikD \cos (qx_2) \quad (7-34)$$

$$\sigma_{x_2x_1} = \mu[2ikpA \cos (px_2) + (k^2 - q^2)D \cos (qx_2)] \quad (7-35)$$

$$\sigma_{x_2x_2} = -\lambda(k^2 + p^2)A \sin (px_2) - 2\mu[p^2A \sin (px_2) - ikqD \sin (qx_2)] \quad (7-36)$$

Applying boundary conditions, $\sigma_{x_2x_1} = \sigma_{x_2x_2} \equiv 0$ at $x_2 = \pm \frac{h}{2}$, equation (7-35) and (7-36) becomes

$$\mu[2ikpA \cos (px_2) + (k^2 - q^2)D \cos (qx_2)] = 0 \quad (7-37)$$

$$-\lambda(k^2 + p^2)A \sin (px_2) - 2\mu[p^2A \sin (px_2) - ikqD \sin (qx_2)] = 0 \quad (7-38)$$

Further simplification and substitution result in the asymmetric mode of the lamb wave as in equation (7-39).

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2 - k^2)^2}{4k^2pq} \quad (7-39)$$

Equations (7.30) and (7.39) are called Rayleigh-Lamb frequency relations. They are dispersive elastic waves due to the dependence of velocity on frequency[274]. Hence, the velocity of the wave is a function of the excitation frequency. The wave-particle velocity could be a phase or group velocity[272]. The velocity at which an individual wave of a frequency propagates through the plate. However, the interactions of the individual wave with others result in a

superposition of the wave that propagates with group velocity[275]. Due to complexity, the roots of equations (7-30) and (7-39) cannot be solved simultaneously but numerically. The roots of the equations give the dispersion curve, which is the wave velocity (phase and group velocities) against the wave signal frequency. Hence, disperse software[98] or dispersion calculator (DC)[175] is used to calculate the dispersion curve of the material. **Figure 7-3** is the dispersion curve for 3.00mm mild carbon steel calculated using the Dispersion Calculator.

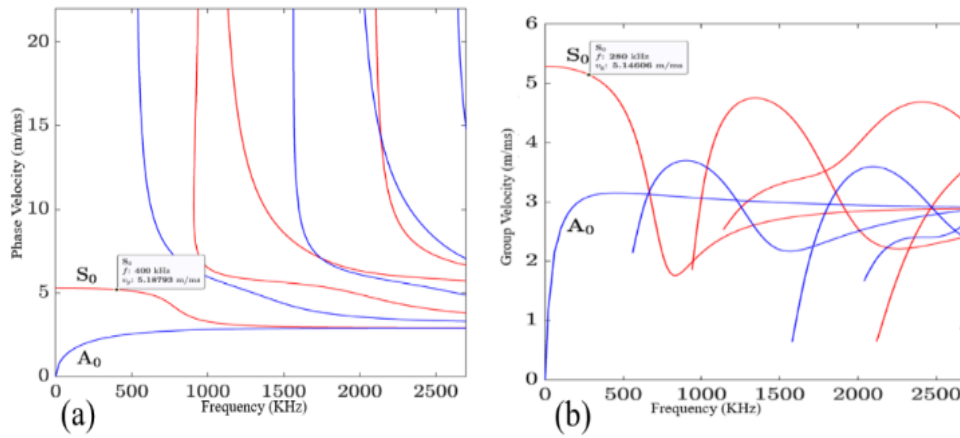


Figure 7-3 Dispersion curve for 3mm Carbon Steel (a) Phase Velocity vs. frequency (b) Group velocity vs. frequency.

7.5 Lamb Wave Modes

The success of structural health monitoring (SHM) largely depends on the selected excitation frequency and its sensitivity to the damage of interest[276]. Ultrasonic Lamb wave propagation in a free plate is initiated using a ceramic Lead Zirconate Titanate (PZT) actuator excited with an electrical signal of appropriate frequency[277]. Since the angular frequency is not directly proportional to the wavenumber, dispersion occurs, and the wave becomes distorted as it propagates. Hence, as shown in **Figure 7-3**, the lamb wave depicts different behaviours called multimode, and its complexity increases as the frequency of the wave increases. In some frequency ranges, the symmetric and asymmetric modes mix up, making it difficult to confidently determine which mode is propagating in the structure and being received by the sensors. To manage the

complexity of the multimode, the fundamental symmetric S_0 and fundamental asymmetric A_0 modes are isolated and used to assess the structure's health state or predict the damage's severity. From **Figure 7-3**, it is evident that the velocity of S_0 is higher than that of A_0 from the least frequency of the curve to about 600KHz frequency in both phase and group dispersion curves. The implication is that the fundamental symmetric mode would arrive at the sensor point earlier than the A_0 . However, the sensitivity of the two modes to damage differs. This study limits the excitation frequency between 60KHz and 180KHz to ensure that higher modes are not formed and captured in the response signal. Also, within the frequency range, the velocity of the wave is relatively nondispersive, and the two modes are well separated.

7.6 Directivity and Attenuation of the Lamb Wave

Excited Lamb waves in structures exhibit differentials in some of its parameters before and after interactions with structural damage. Propagating Lamb waves are captured as a response signal of structure to the exerted stress wave by the actuator. In the healthy state of the structure and devoid of environmental effects, the intensity of the response signal would be approximately consistent in magnitude. Still, it would vary with the path and location of the sensor[278]. Without damage, a sensor in a direct path with the wave excitation source would receive much of the propagating signals, especially when their distance is small compared to sensors installed in other paths of the structure, but at the expense of the crosstalk effect. However, structures under operation have a high chance of sustaining various forms and severity damage. **Figure 7-4** is a typical instance of the fundamental Lamb wave modes propagating in healthy and unhealthy states of the structure. It shows S_0 propagates faster than A_0 but A_0 is the dominant mode.

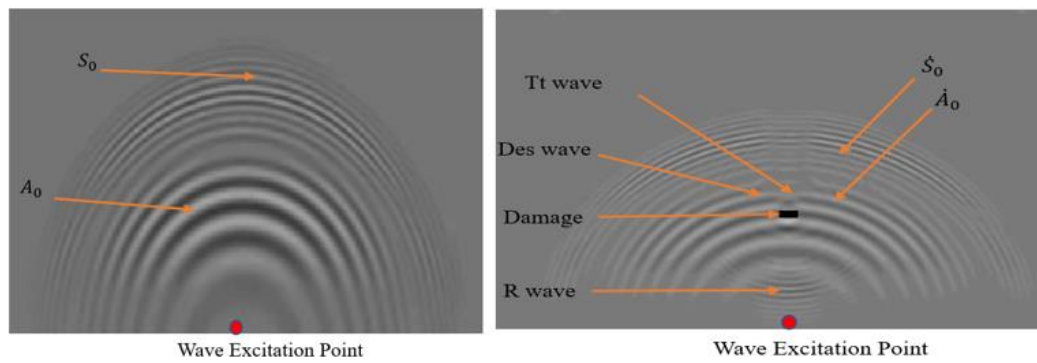


Figure 7-4 A typical fundamental Lamb wave modes propagating in (a) a healthy and (b) damaged plate.

In **Figure 7-4**, the interaction of the propagating wave with the damage resulted in different phenomenal effects in the two wave modes. Some effects are reflected waves, denoted as an R wave; scattered or deflected waves by the damage tips, denoted by a Des wave; and attenuated through-transmitted waves, denoted by a Tt wave. In pulse-echo inspection configuration, the reflected wave would form a new packet while in Pitch-Catch inspection configuration, attenuation effect of the wave is more pronounced[163]. Although the edge of the structure could cause similar reflections, its arrival time would be different from the new packet wave created by the reflection from the damage, and the same with the intensity of both effects. The edge reflection wave is minimized by installing a wave absorber at the structure's edges, which was used in the study. The intensity of the new packets due to wave-damage interaction suggests the severity of the damage encountered. Depending on the size of the damage, some of the incident waves would be transmitted through, and the damage would reflect some. The edge of the damage is equally attributed to the edge scattering of the signal. This study assesses the influence of debris-filled damage and damage filled with different fluids. Three sensors are installed to capture through-transmitted waves and edge-reflected waves. The captured responses are processed and analyzed to predict the state of the structure.

7.7 Guided Wave Excitation Signal Generation

As shown in the experimental setup, **Figure 7-11**, the circular PZT transducers are configured in pitch-catch mode, in which one of the PZTs acts as the actuator and the remaining PZTs act as the sensors. Since creating a desired tone burst signal of modulated amplitudes in the arbitrary function generator is difficult, the signal is created first in MATLAB using equation (7-40) and later transferred into the arbitrary function generator.

$$q(t) = f(t) \times g(t) \times h(a) \quad (7-40)$$

From equation (7-40), three signals are needed to create a tone burst signal. One of the signals is a continuous signal of high frequency, $f(t)$ created using the probing frequency and expressed in equation (7-41).

$$f(t) = A \sin(2\pi ft) \quad (7-41)$$

The second signal is the modulating signal created using the same probing frequency but with a duration bound by the N number of cycles, as expressed in equation (7-42).

$$g(t) = (1 - \cos(2\pi ft/N)) \quad (7-42)$$

The products of equations (7-41) and (7-42) generate a signal of multiple bursts. Due to the formation of multiple bursts, a third signal function $h(a)$ was introduced to extract just a burst. The signal function is as defined in equation (7-43). The third signal is a step function with two possible outputs: a zero or a positive one. In the study, $h(a)$ multiply the two products of the first two signals with the two possible outputs. It is designed to multiply only the first tone burst with a positive one and the rest with a zero. The procedure shown in Figure 7-5 achieved the tone burst excitation signal depicted in Figure 7-6.

$$h(a) = \begin{cases} 1 & \text{if } a \leq t' \\ 0 & \text{if } a > t' \end{cases} \quad (7-43)$$

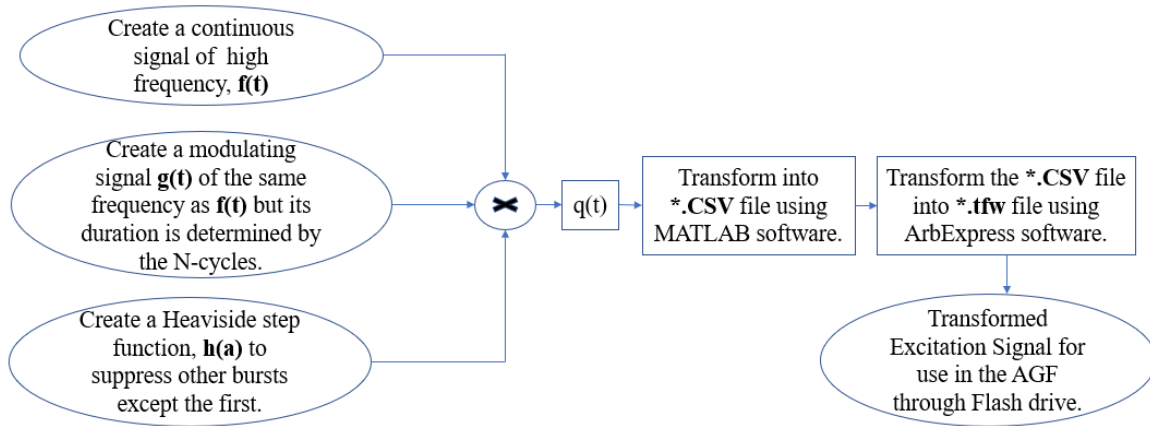


Figure 7-5 Procedure for creating and transferring an excitation signal to an arbitrary function generator, AFG.

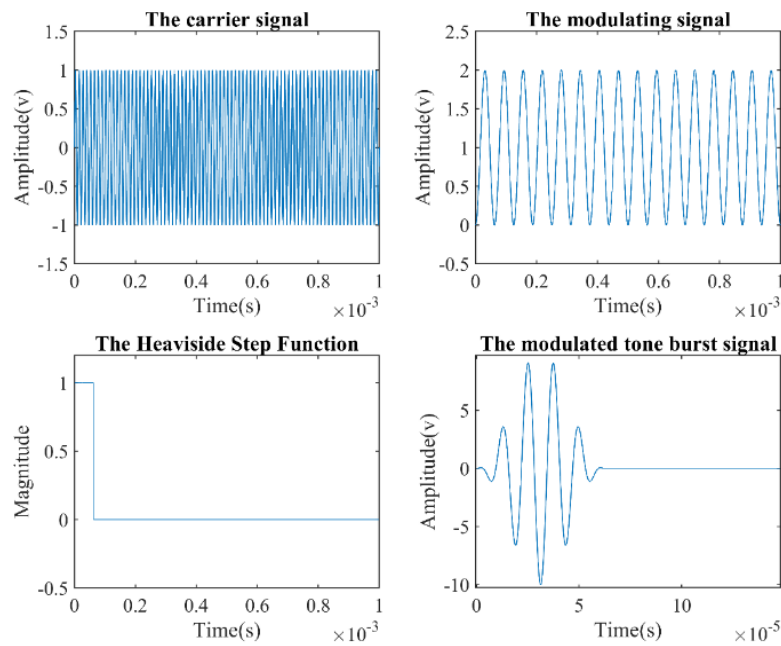


Figure 7-6 Formation of an amplitude modulated tone burst signal.

An excitation signals were created using the four central frequencies, as shown in **Figure 7-7**. The amplitude of the signals is normalized, and about 1.00 ms of duration is allowed before a repeat of another burst. At a relative constant velocity

of the wave, the wavelength and frequency of the signal are proportionally related, as in equation (7-44).

$$\lambda \propto \frac{1}{f} \quad (7-44)$$

Also, from the plotted excitation signals, the signal packet duration decreases as the central excitation frequency increases. This implies a decrease in the signal's wavelength as the frequency increases. The decrease in wavelength increases the sensitivity of the signal to detect small defects. The wavelength of the excitation signal is vital for damage detection, and the probability of detecting small-sized damage increases as inspection frequency increases. Damage stands a reasonable chance of being detected when its size is larger than one-half the wavelength of the probing wave[247]. About 5 cycles were used to create the excitation signal, allowing for high signal resolution in the time domain. As shown in the frequency domain of **Figure 7-8**, the tone burst signal possesses a wide range of low and high frequencies with low harmonic content. This allows for the detection of damage with minimal noise interference.

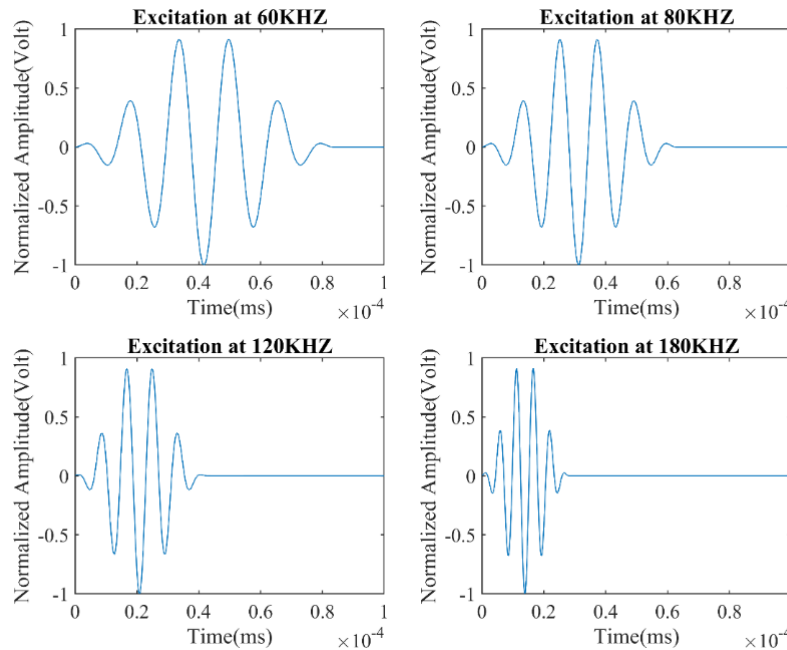


Figure 7-7 Excitation signal with different centre frequencies (a) 60 KHz (b) 80KHz (c) 120 KHz (d) 180 KHz.

Hence, a tone burst of a few cycles offers a mix of a wide frequency range, a short duration, and minimal interference. **Figure 7-8** depicts the frequency spectrum of the excitation signals. The result implies that low-frequency excitation signals possess more power for propagation and penetration into structures than high-frequency excitation signals[173]. This suggests a compromise on propagation distance and sensitivity to small damage as guides to selecting a suitable excitation frequency. Hence, in **Figure 7-8**, the strength of the excitation signal is modelled and expressed in Equation (7-44). As earlier emphasized, the actuation strength of the excitation signal decreases exponentially with increasing frequency. This suggests that high power is required to propagate high-frequency Lamb waves. The consequences would be limitations to the propagation distance and penetration extent that could be achieved because the signal would attenuate faster than the low-frequency signal. Hence, in some studies, this would necessitate preamplification of the excitation signal before use on the actuator. However, this study is not applicable because we could capture a useful strength of the response signal.

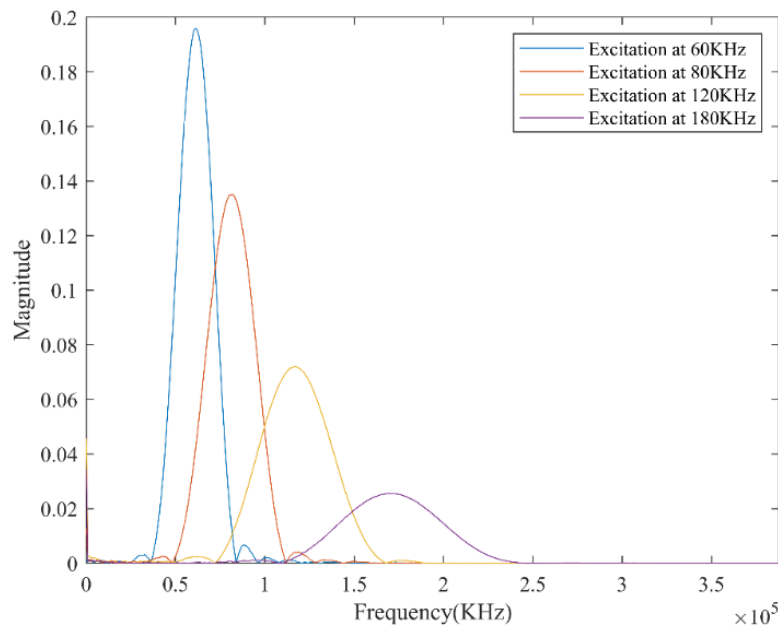


Figure 7-8 The frequency spectrum of the excitation signal.

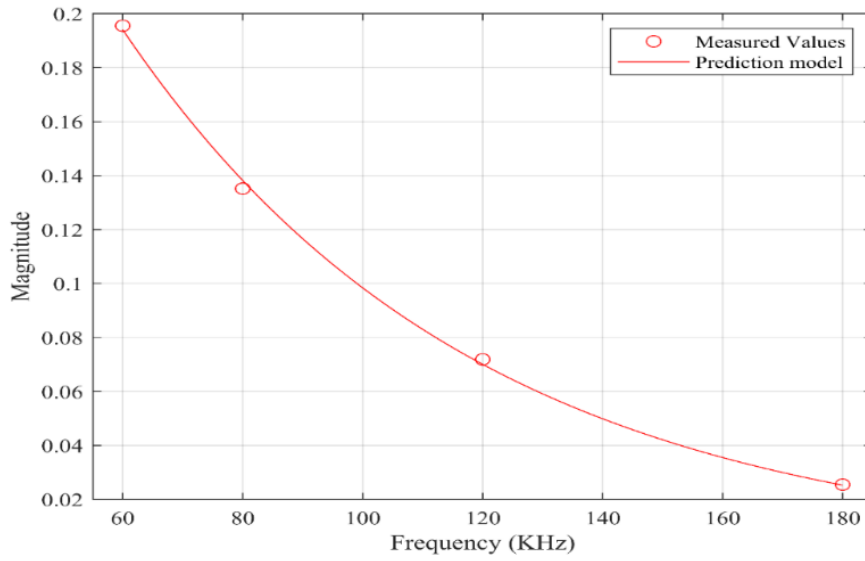


Figure 7-9 Excitation signal strength at varying frequencies.

From the fitted plot of **Figure 7-9**, the excitation signal's magnitude decreases exponentially as the excitation frequency increases. This behaviour is empirically expressed in equation (7-45).

$$g(f) = Ae^{(b*f)} \quad (7-45)$$

Where A and b are constants with values 0.5377 and -0.01698, respectively and f is the frequency of the actuating signal. This suggests a harmonic voltage applied uniformly between the top and bottom surface electrodes of the PZT transducers.

7.8 Materials and Methods

Two mild steel carbon plates of the same dimensions $500mm \times 300mm \times 3.00mm$ were used in the study. One plate was considered a reference structure and used as the pristine plate for baseline signal acquisition, while the second plate was used to create the different damage case scenarios. The properties of the plate are listed in **Table 7-1**. Damage of $40.00mm \times 5.00mm \times 2.50mm$ was seeded at the mid-distance between the actuator, A and the direct path sensor, S_2 . Prior to the installation of the transducers, acetone was used to clean the surface of the plates, which took about 5–10 minutes to dry[279]. The cleaning

ensured the removal of unnecessary particles and oils that might hinder the proper transfer of signals between the transducers and the plate. Four ceramic transducers (PZT: $7.000\text{mm} \times 0.195\text{mm}$) of circular type[180] with the omnidirectional capability of radiating and receiving signals, unlike the rectangular counterpart that is orientation dependent [241] were bonded on the top surface of the plate using two components of epoxy adhesive[242]. The adhesive ensures the elimination of air gaps between the plate and the transducers that would ordinarily cause high impedance and significantly limit energy transfer between the two. Additionally, the applied adhesive thickness was ensured to be very small since it could contribute to energy signal transfer limitations[280]. An active pitch-catch inspection method configuration was used in the study since the damage is not an active crack that could emit stress waves. Hence, one of the transducers served as the actuator, and the remaining three (S_1, S_2, S_3) served as the sensors, as in **Figure 7-10**. The transducers are arranged in triangular form. The two base-end sensors (S_1, S_3) are installed to capture the signals scattered by the damage tips, while the centre base sensor (S_2) captures the through-transmitted signals. The installation paths and distance of the transducers are listed in **Table 7-2** while the properties of the PZTs are listed in **Table 7-3**.

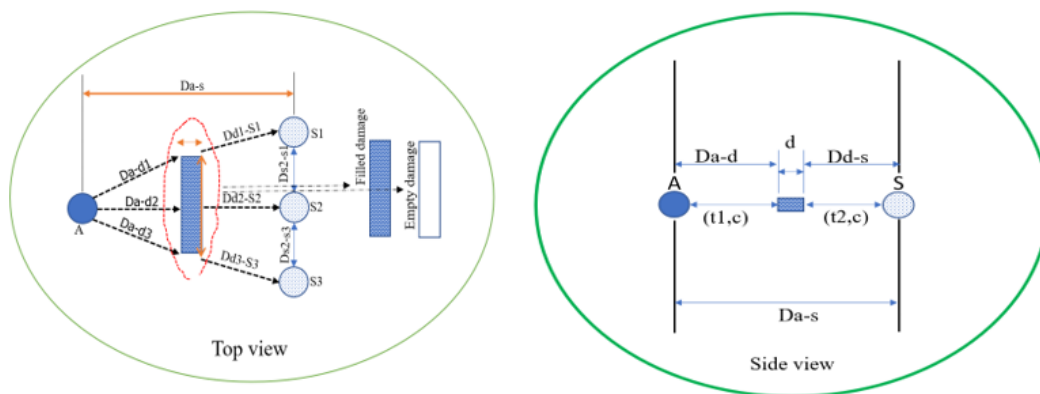


Figure 7-10 Damage model and transducer configuration (a) Unhealthy Plate Top View; (b) Side View of an unhealthy plate.

Table 7-1 Mechanical properties of mild Carbon Steel.

Material	Young modulus, E (N/m ²)	Poisson's ratio, ν	Density, ρ (kg/m ³)	Length, L(mm)	Width, W(mm)	Thickness, T_h (mm)
Carbon steel	2×10^{11}	0.289	7800	500	300	3

Table 7-2 Path definitions and values.

Terms	Meaning	Value	Terms	Meaning	Value
D_{a-d1}	Distance between actuator and damage in path1	14.60cm	D_{a-s}	Distance between actuator and sensor without damage existence.	30.00cm
D_{a-d2}	Distance between actuator and damage in path2	14.75cm	d	Width of the damage	5.00cm
D_{a-d3}	Distance between actuator and damage in path3	14.60cm	A	actuator	-
D_{d1-s1}	Distance between damage in path1 and sensor1 in path 1	15.40cm	S	Sensor	-
D_{d2-s2}	Distance between damage in path2 and sensor1 in path 2	14.75cm	D_{s2-s1}	Distance between sensor2 and sensor1	5.00cm

D_{d3-s3}	Distance between damage in path3 and sensor1 in path 3	15.40cm	D_{s2-s3}	Distance between sensor2 and sensor3	5.00cm
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Table 7-3 The Properties of PZT used in the study are PZT-5A.

Parameter	unit	Min. Value	Typical value	Max. Value
Diameter of ceramics	mm	6.80	7.00	7.20
Thickness of ceramics	μm	175	195	215
Curie temperature	Tc		340	
Piezoelectric constant	pC/ N		420	
Elastic compliance	m ² / N		19.6×10 ⁻¹²	
Serial resonance frequency fs	kHz	-5%	285	+5%

Plate edge reflection waves contribute to the complexity of the response signal [281]. Therefore, minimizing it is necessary, and DAS modelling Air dry clays were installed around the edges of the plate to this effect [217]. An arbitrary function generator, AGF (Tektronix AFG1062 function generator), is used to generate the tone burst signal for the actuator to excite the particles of the plate with stress waves. Four central frequencies (60KHz, 80KHz, 120KHz, and 180KHz) were used to create the excitation signal of 10 V peak-peak. An Agilent Technologies oscilloscope (MSO-x 3024A, 200MHz, 4Gsa/s) was used to acquire the excitation and response signals simultaneously. The function generator's output signal and the three sensors were connected to different

oscilloscope channels. The function generator was connected to channel 1 (CH1), while S_1, S_2 and S_3 were connected to channels CH4, CH3, and CH2, respectively and they were set on same input impedance. Since the actuation would occur before response signals were captured, the excitation signal of CH1 was used to trigger signal data acquisition. Random noise was minimized by using 32 averaging acquisition modes, which improved the SNR of the registered response signals. The experiments were performed under laboratory temperature. The oscilloscope recorded all the captured response signals and transferred to the PC for processing using MATLAB version 2022a. For each state of the plate and specific excitation frequency, 10,000 samples of the response signals were captured and registered for preprocessing and analysis. The state of the plate was classified into two cases as follows.

Case A: The base scenario: The baseline signals were acquired in this case. The healthy plate was used, and the four excitation frequency signals were injected into the plate to interact with it. The sensors recorded the responses, and the oscilloscope registered them. This was performed under a controlled laboratory temperature of less than 26 °C.

Case B: The current scenario: In this case, damage of dimension ($40.00mm \times 5.00mm \times 2.50mm$.) was seeded on the second plate to become an unhealthy plate. Afterwards, the damage was filled with debris and different fluids, as given below. The response signals were captured and analysed.

- a. Empty damage
- b. Debris-filled damage
- c. Water-filled damage
- d. Oil-filled damage
- e. Grease-filled damage

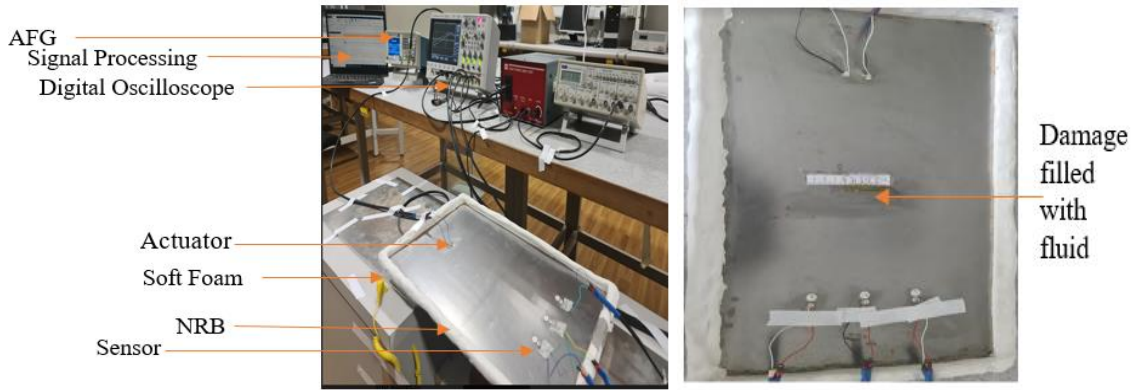


Figure 7-11 The Experimental setup (a): The base case scenario (b) Various situational case scenarios of closed damage.

7.9 Results and Discussion

(a) S_0 and A_0 of the responses in pristine condition.

The responses of the plate to each of the excitation frequencies were captured using 32 mean averaging and further smoothed. This preprocessing was used to minimize random error, increase the signal-to-noise ratio (SNR) of the response signal and enhance signal quality. Also, most of the captured signals were either shifted above or below the time axis. This effect necessitated a response signal origin point check using a correction function defined in equation (7-46). The signal is repositioned to the origin by executing a function in **Figure 7-12**. This is to enhance reliable comparison of any two case scenarios.

$$\text{function } G = \text{CheckandShift}(x) \quad (7-46)$$

```

if x(i) < 0 % Condition 1: check if the first sample point is shifted below origin 0.
    G = x + abs(x(i)); % If True, reposition the signal to the origin point.
elseif x(i) > 0 % Condition 2: check if the first sample point is shifted above the origin 0.
    G = x - abs(x(i)); % If True, reposition the signal to the origin point.
elseif x(i) == 0; % the default

G = x

end

```

Figure 7-12 is a response signal captured by sensor S_1 , but it is shifted at the origin.

Hence the correction function was applied, and it repositioned it as shown in **Figure 7-13**.

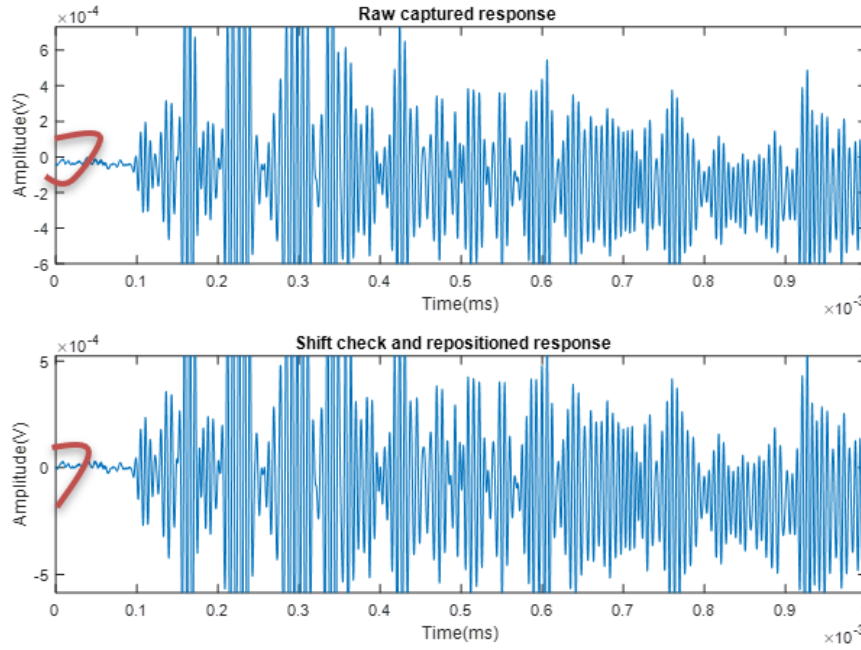


Figure 7-13 Shifted and repositioned response signal captured by sensor1.

Figure 7-14 through **Figure 7-17** are the time-domain plots of the response signals captured by the sensors (S_1, S_2, S_3) at various excitation frequencies. From the figures, the fundamental symmetric S_0 , mode and fundamental asymmetric A_0 mode were observed to be present in the first two main packets of the response signal. The resolution of the captured response signals decreases as the frequency of excitation increases, making it challenging to separate the two fundamental modes with ease. The response signal captured by each of the sensors differs but contains the fundamental modes, which are the dominant modes. Also, it is keenly observed that as the excitation increases, the influence of the electromagnetic interference (EMI) effect starts appearing and becomes well pronounced at 120KHz and 180KHz. The presence of the EMI effect is observed as the first packet of waves in the response signal but with a reduced

amplitude. The EMI could be due to noise from the instrument used or an RFI device in the laboratory. However, it does not change the signal modes of interest in the captured response signals and needs not be misinterpreted as a structural response signal. It can be removed using a filter but not applicable in here because it did not corrupt the needed modes of the signal.

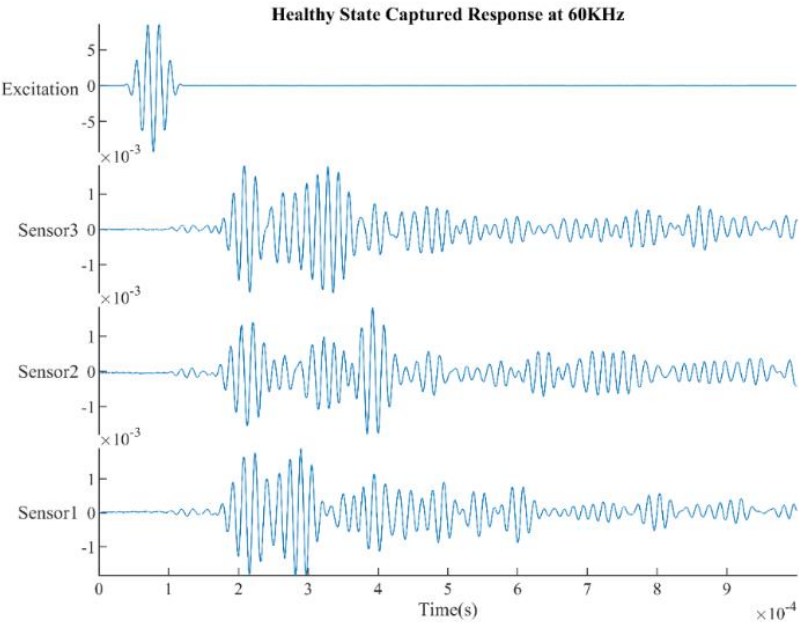


Figure 7-14 The excitation signal of 60KHZ and captured response by the sensors

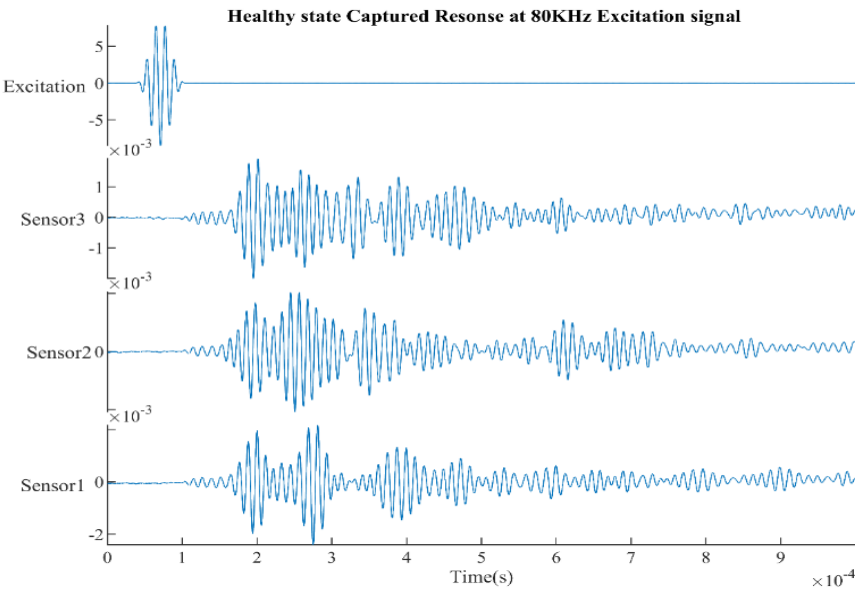


Figure 7-15 The excitation signal of 80KHZ and captured response by the sensors.

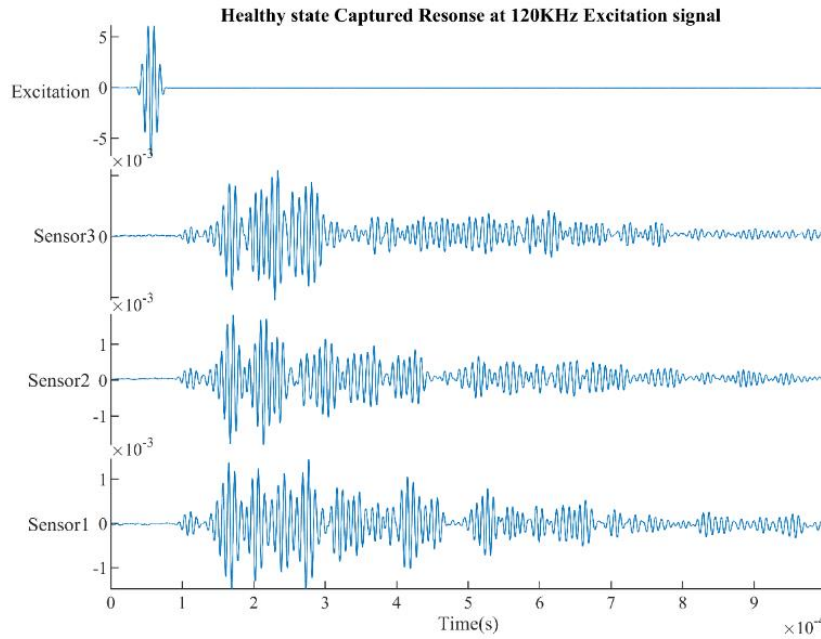


Figure 7-16 The excitation signal of 120KHZ and captured response by the sensors.

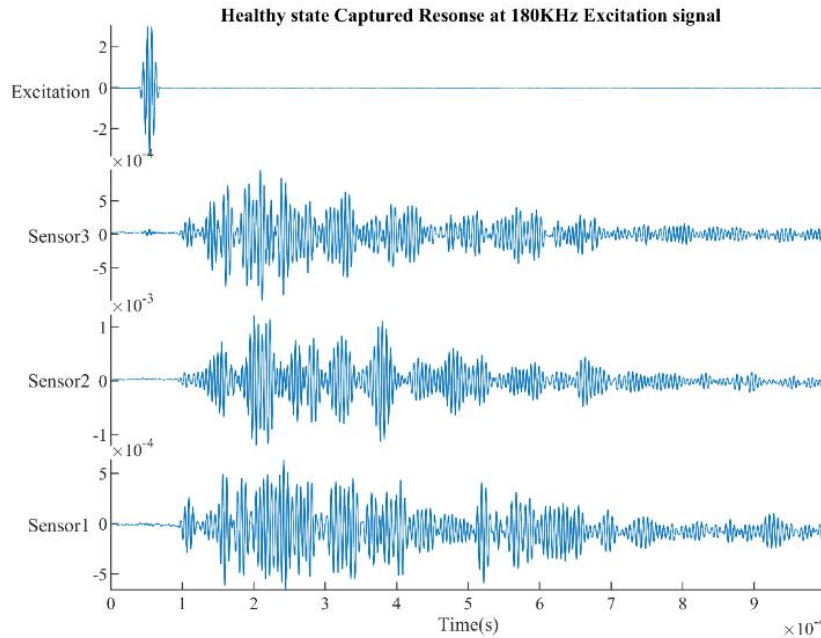


Figure 7-17 The excitation signal of 180KHZ and captured response by the sensors.

The fundamental modes are dominant in the response signals' time domain. This is explicitly shown in **Figure 7-18**, which depicts the captured healthy plate

response signal by S_2 when an excitation signal of 80 kHz was injected into the plate. The fundamental symmetric mode S_0 was registered before the fundamental anti-symmetric mode A_0 , suggesting it to be the fastest mode, although the anti-symmetric mode is the more dominant mode. The maximum peak of the modes is extracted from the response signals for every excitation frequency using equation (7-47). An effective amplitude of the response signal is determined by averaging the amplitude of the fundamental modes captured by all the sensors at a given excitation frequency using equation (7.48)

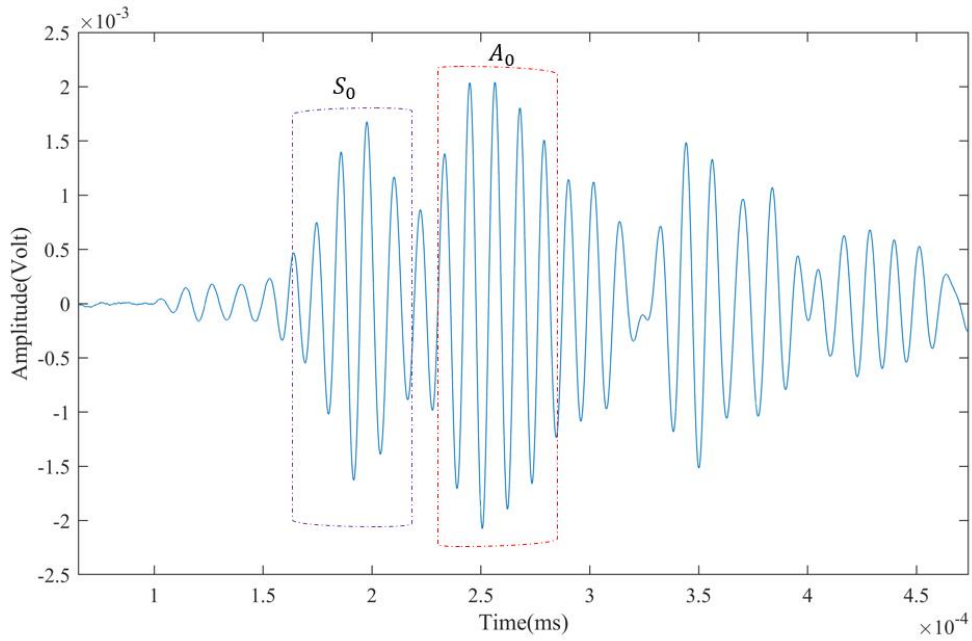


Figure 7-18 Zoomed time-domain response captured by sensor2 for 80KHz excitation.

$$max_peak_{S_i S_0 | S_i A_0} = \max_{t_1 \leq T \leq t_2} (u(t)) \quad (7-47)$$

Where

$S_i S_0$ denotes fundamental symmetric mode of any sensor where $i = 1, 2 \text{ or } 3$.

$S_i A_0$ denotes fundamental asymmetric mode of any sensor where $i = 1, 2 \text{ or } 3$.

$$AVA_{S_0 | A_0} = \frac{1}{N} \sum_{f_j} max_peak_{S_i S_0 | S_i A_0} \quad (7-48)$$

Where $AVA_{S_0|A_0}$ is the average amplitude for either S_0 or A_0 , N is the number of sensors and f_j denotes a given frequency of the excitation signal.

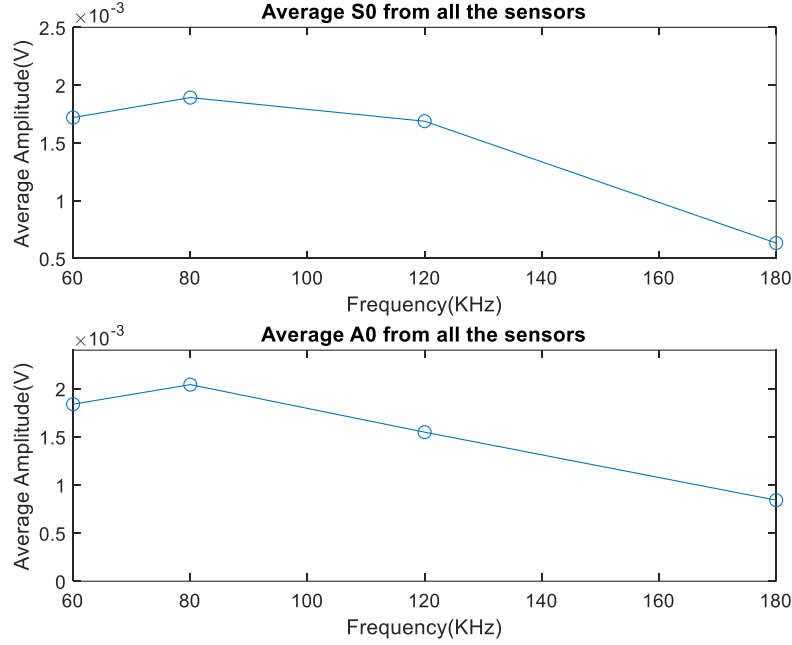


Figure 7-19 The average amplitude of fundamental modes from all the sensors vs frequency.

Figure 7-19 shows that the average intensity of the response signal decreases as the frequency increases. The increase in attenuation as frequency increases could be attributed to more molecular interactions since the wavelength is becoming sizeable to the molecular constituent of the plate, and that results in energy loss due to more scattering. Also, higher-frequency ultrasonic waves tend to be more strongly absorbed by the material through which they propagate. The absorption of ultrasonic energy by a medium is frequency-dependent, and certain materials exhibit increased absorption at higher frequencies. This absorption decreases the intensity of the ultrasonic guided wave as it travels through the material. However, the intensity of the asymmetric fundamental mode is greater than that of the fundamental symmetric modes by an average of about 10%, making it a dominant mode. On the consideration of dominance, the fundamental anti-symmetric mode A_0 , is selected and used to assess the health of the plate. Also, in both fundamental symmetric and fundamental Anti-symmetric modes, it

is observed that the voltage started decreasing after 80KHz. This suggests that 80KHz is the optimum frequency for the study as it possesses the highest response energy, although crack detection is better with higher frequency but at the expense of additional power.

(b) Comparing empty damage and pristine condition

The pristine condition of the plate is compared with the open-damage condition of the plate. An RMSD of the conditions was computed using equation (7-49) for every given frequency. Figure 7-20 shows the RMSD deviation between the pristine condition and empty damage using the average amplitude of the fundamental asymmetric mode. It has been observed that deviation increases linearly with frequency. The increase in the RMSD value suggests better damage detection at higher frequencies because damage detection is wavelength-dependent. It is worth noting that damage has a higher chance of detection if its size is larger than the probing wavelength [14]. From the linear fitting of the observation data, an empirical regression model with a R^2 of about 0.97 was deduced and expressed in equation (7-50). The model is good since it could account for about 97% of the variation in the response.

$$RMSD = \sqrt{\frac{\sum_{i=1}^n \left(AVA_{A_0D} - AVA_{A_0P} \right)^2}{\sum_{i=1}^n \left(AVA_{A_0P} \right)^2}} \quad (7-49)$$

$$y_{ED}(\omega) = 0.0036 * \omega - 0.1386 \quad (7-50)$$

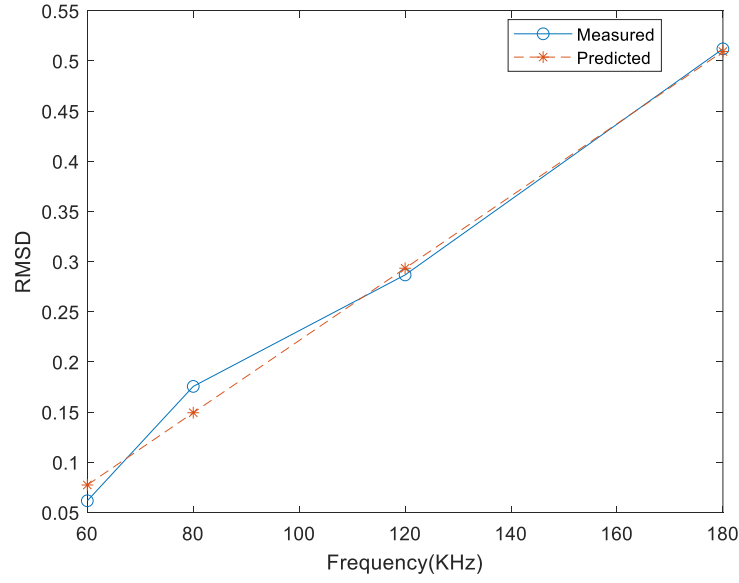


Figure 7-20 RMSD vs Frequency between pristine conditions and empty damage.

(c) Comparing damage filled with dry debris and pristine conditions.

Figure 7-21 shows the variation between the plate's pristine condition and debris-filled damage condition. It is observed that there is a linear relationship between the health state variation of the plate and the frequency of inspection. The variation between the two conditions increases as frequency increases due to a decrease in the signal's wavelength, which would enhance more wave-damage interactions. Particularly, the wave scattering effect would increase as corrosion debris fills the damage and introduces rough surfaces and edges to the damage. The increase in wave-damage interaction results in wave scattering and energy loss that would manifest as a reduction in the signal amplitude. An empirical model for the filled damage response is given in equation (7-51) with an R^2 value of about 0.73 and RMSE of about 0.15. The predictive model is good and can account for about 73% variation in the response due to frequency changes.

$$y_{DFD}(\omega) = 0.0038 * \omega - 0.1101 \quad (7-51)$$

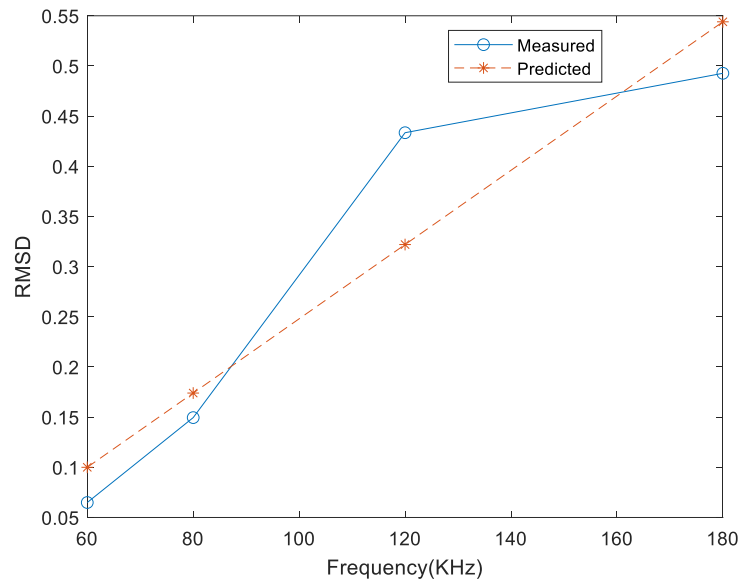


Figure 7-21 RMSD vs Frequency between pristine conditions and debris filled damage.

(d) Comparing different fluid-filled damage and pristine conditions.

Figure 7-22 shows the deviation between the pristine condition of the plate and the filled damage condition of the plate. The three fluids (Water, oil, and grease) that filled the damage have different viscosities. The viscosity is the resistance of fluid to deformation. Hence, water is less viscous than oil and grease, while oil is less viscous than grease. The Lamb waves propagated through the damage and interacted with the fluid. During the interaction, partial reflection, attenuation, and transmission of the wave at the boundaries of the damage occurred. It was observed that there is variation in the response signal when compared across the filled fluid. The interaction resulted in signal amplitude variations as the frequency of the inspecting wave increases. Also, it was observed that deviation changes with viscosity which is more distinct at 80KHz. The relationship between the frequency and the damage index is linear until after 120KHz. The predictive model based on the region of linearity is expressed in equation (7-52) through (7-54). The validated model is plotted in **Figure 7-23**.

For water filled case:

$$y_{WFD}(\omega) = 0.004693 * \omega - 0.2367 \quad (7-52)$$

For oil filled case:

$$y_{OFD}(\omega) = 0.004737 * \omega - 0.2402 \quad (7-53)$$

For grease filled case:

$$y_{GFD}(\omega) = 0.005129 * \omega - 0.3017 \quad (7-54)$$

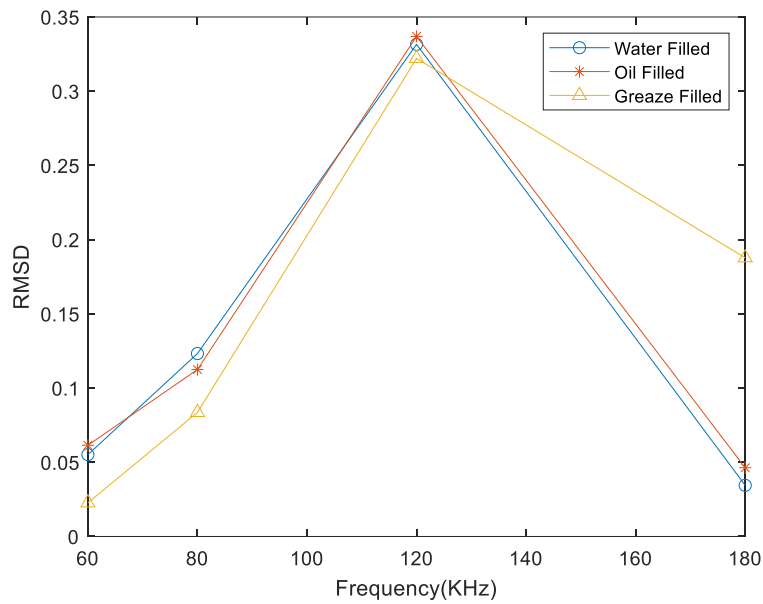


Figure 7-22 RMSD vs Frequency between pristine condition and different fluid filled damage.

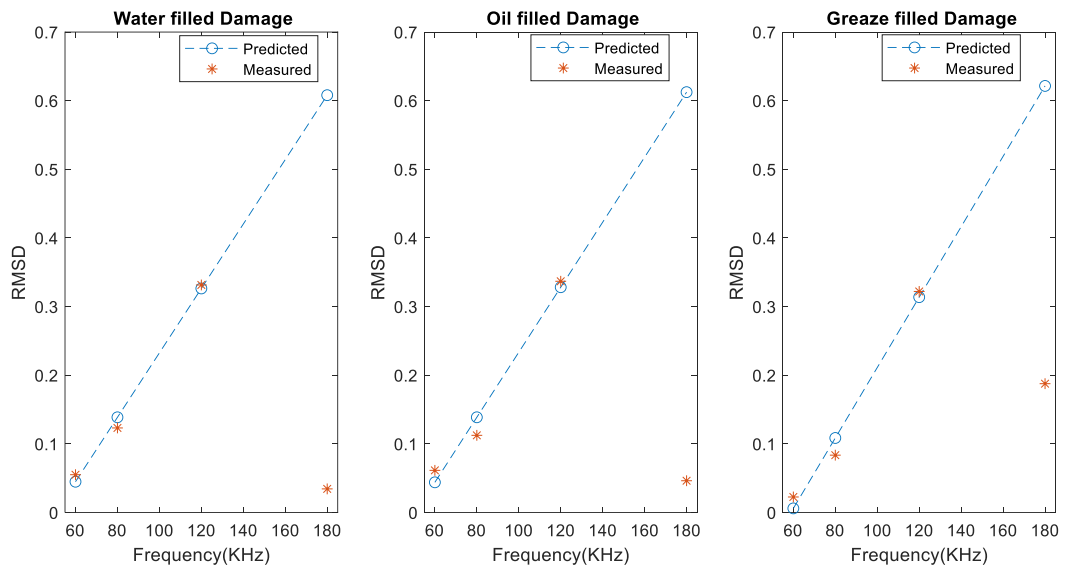


Figure 7-23 The predicted value and measured value plot.

(a) Comparing empty damage, fluid-filled damage, debris-filled damage and pristine conditions.

Figure 7-24 shows the deviation of fluid-filled damage from the pristine condition as the excitation frequency increases.

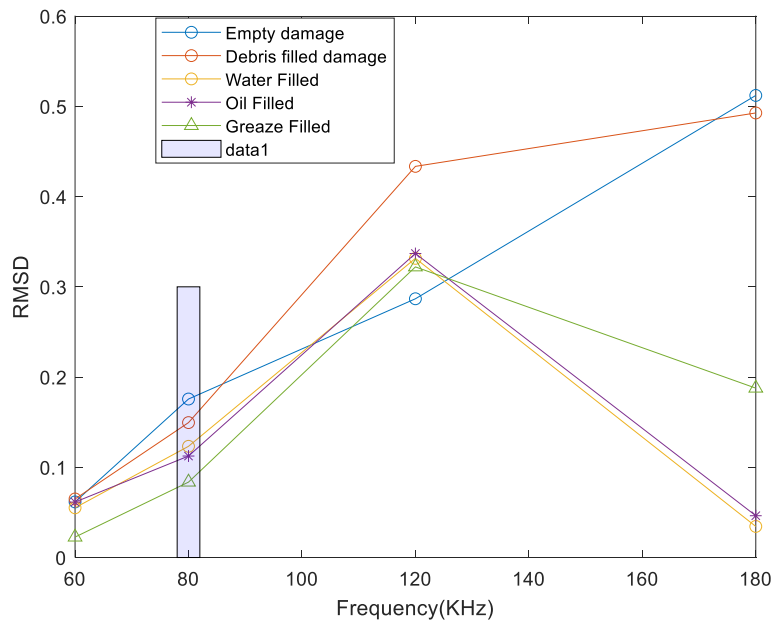


Figure 7-24 RMSD of different states of damage vs frequency.

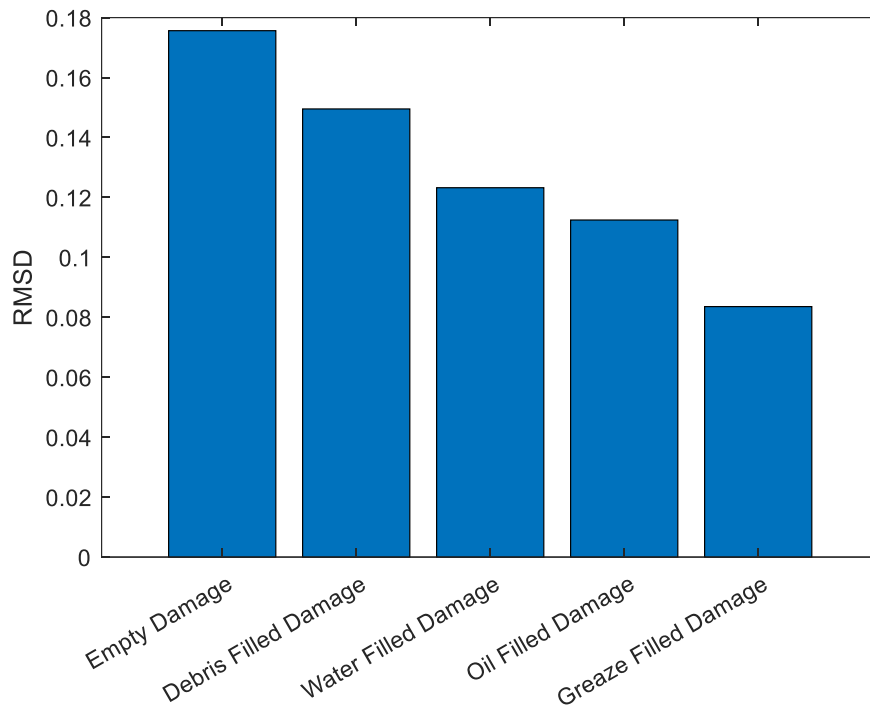


Figure 7-25 Different conditions separated at 80KHz.

At an excitation frequency of 80KHz, the responses are separated from various filled damage scenarios, unlike any other frequency, as shown in **Figure 7-24**. The high deviation with empty damage is due to the combinatory effect of wave scattering from the damage tips edges and attenuation of through transmitted wave. From **Figure 7-25**, the deviation of debris-filled damage from empty damage is much greater than deviations obtained when fluid-filled damage. Also, the deviation of the fluid-filled damage decreases as the viscosity level of the fluid increases. This suggests that fluid inhibits the edges of the damage from scattering the incident wave, and that increases as the fluid becomes more viscous and allows much wave propagation, unlike debris-filled damage with unsmooth damaged edges that would enhance wave scattering.

7.10 Summary

Structures are designed to function at optimal efficiency but are limited by the occurrence of damage. Hence, it is vital to continually monitor structures for early

damage detection and assessment to avoid catastrophic failure. Based on the good properties of guided wave ultrasonics, it is extensively used for structural damage detection and health monitoring. A pitch-catch method of three sensors and an actuator was configured to monitor variations in the response signals of the ultrasonic-guided wave due to changes in the state of the substance that filled the damage. As illustrated in **Figure 7-5** and **Figure 7-6**, an amplitude-modulated 5-cycle tone burst excitation signal was systematically created and used in the study for lamb wave generation. The selected frequencies are such that only fundamental modes were majorly present and distinct in the response signals. The fundamental asymmetric mode was found to be dominant and more sensitive than the fundamental symmetric mode for variation of filled-in damage. It was observed that variations in the nature of damage are directly proportional to an increase in frequency. Although linearity exists, an increase in frequency entails a decrease in wavelength and an increase in interactions with more particles in the medium, leading to fast energy loss. Hence, a sharp drop in deviation was observed immediately after 120KHz across all the media that filled in the damage. This is attributed to significant energy loss due to the decrease in wavelength, which allowed for more wave-particle interactions. It was observed that at 80KHz, the deviation of each state of damage differs from the other, decreases from an empty case to a debris-filled case, and continues as fluid-filled viscosity increases. This deviation is shown in **Figure 7-24** and **Figure 7-25**. It suggests that 80KHz frequency is an optimal frequency to differentiate the state of damage in structures. Empirical predictive models were deduced and would be needed to improve the algorithm of structural health monitoring schemes, especially in the oil and gas sector.

8 CHAPTER EIGHT: CONCLUSION AND FUTURE WORK

8.1 Conclusion

The occurrence of damage in metallic structures is inevitable and detrimental to the operational safety of the economic asset. When damage is undetected, it leads to a range of events, from unscheduled shutdown to catastrophic failure, resulting in loss of economic assets, environmental pollution, and loss of life. Different metallic damages, especially corrosion-related damage, are prevalent in the oil and gas sector. It has accounted for huge annual industry maintenance costs and safety issues. This work is motivated by the desire to detect novel debris-filled damage at varying fill percentages, potentially resulting in pitting corrosion. Pitting Corrosion has been considered a severe form of corrosion affecting the sector. In the study, guided ultrasonic wave response of pitch-catch configuration was used to detect debris-filled damage and evaluated the attributed influence of the environmental conditions to the detection approach. The study established an empirical predictive model correlating the percentage variation of debris-filled damage (DFD) to the modulation index of the response wave signal. Also, an architectural model called Olisa-Khan LMA model was achieved to mitigate external low-frequency vibration influence on propagating elastic waves, thereby enhancing the possibility of GWUT to detect debris-filled damage in a severe environmental condition. Different experiments were conducted as enumerated in Chapter 3 to achieve objectives laid out in Section 1.3 of Chapter 1. The summary of the study achievements is detailed below.

8.2 Summary of the objectives and achievements.

Objective 1: *Literature Review on damage detection using propagating elastic waves.*

In Chapter 2, damage inspection in thin structures via guided wave ultrasonic techniques and the environmental impact on the propagating waves were reviewed and discussed. In the past decades, high interest has been developed in using guided wave ultrasonic techniques (GWUT) to monitor the health of structures and detect damage due to their long-distance coverage potential with

little attenuation and cost-effectiveness. Most guided wave ultrasonic studies have focused on detecting and characterising empty cracks. Limited literature is available to explain guided waves' behaviour when propagating in thin plates exposed to damage filled with varying percentages of debris that could result in pitting corrosion. This form of corrosion is grievous and more likely in long-thin structures used to construct pipelines for oil, water, or gas transportation. Also, unlike the pulse-echo configuration, the pitch-catch transducer configuration was effective for covering a large area of the structure to detect distributed and isolated damage. Hence, the configuration was adopted and devised into methodologies for DFD detection.

Objective 2: Develop an empirical predictive model for debris deposition percentage detection in thin structures.

This objective was attained by investigating the interaction effect between pre-modulated guided ultrasonic waves and varying percentages of debris-filled damage. Analysing the captured response signals for different percentages of debris that filled the damage revealed that varying percentages of debris deposition in damage are sensitive to the modulation index. An increase in the debris percentage resulted in overmodulation of the response signals. Also, the lower sideband (LSB) of the interacted response signals was found to be more sensitive to the debris variation than the upper sideband (USB). Using the modulation extent of the wave and the damage conditions, a validated empirical predictive model was developed in **equation (4-26)** with an average percentage error of 1.34. The empirical model could predict the health state of the structure, especially in debris-filled damage cases. Also, it was deduced that the modulation indices of the debris-filled damage are at least 10% greater than the situation of empty damage. The 10% difference could serve as a debris-filling inception detection threshold. The model and observations relating to this objective allowed for easy SHM and early damage detection that will minimise the probability of the catastrophic failure of thin structures due to pitting corrosion that could occur via DFD.

Objective 3: *Evaluate the combined effect of temperature and debris deposition percentage in damage to propagating elastic waves.*

Temperature is an indispensable factor that affects structures and influences their properties. In Chapter 5, the combined influence of temperature, variation in damage parameters and debris-filled damage on the guided wave response signals was evaluated. It was observed that increased damage depth results in increased RMS values, thereby suggesting more diffraction of the response signals as the damage depth increases. The detected depths of the structure were grouped into shallow and deep damage. Remarkably, the scattering effect due to the shallowest depth is about 0.26% of the incident wave, while it is about 0.48% for the deepest depth. From the experimental study, it showed that waves that had interacted with damage are significantly influenced by temperature. The influence leads to a decrease in the RMS intensity of the waves in the cases of 1.5mm and 2.00mm damage depths, as shown in **Figure 5-14** and **Figure 5-15**, respectively. Subsequently, a validated predictive model with less than 10% error value was established to describe the combined influence of debris-filled damage and temperature. The efficacy of this model was subsequently assessed against the measured response signals, as illustrated in **Figure 5-20**. It was shown that a high error would be recorded when the temperature is very high, and the ratio of unfilled damage length to the probing wavelength is less than 0.5. This is because, as the debris fills the damage, its length decreases through the closure and consequently decreases the ratio of damage size to probing wavelength.

Objective-4: *Evaluate the effect of external low-frequency vibration on elastic wave propagating in a thin structure.*

The objective to evaluate the effect of external low-frequency vibration on elastic waves was attained in Chapter 6. From the study, it was understood that the main effects of low-frequency vibration on the elastic-guided wave were waveform distortion, wave signal clipping and increasing energy values at the sensing position. These effects are detrimental to assessing the structure's healthy state, especially when using average energy at a sensing position. We further proposed

a strategy to minimise the impact of these effects, thereby improving the performance of SHM for damage detection and assessment using elastic waves. The proposed strategy is called Olisa-Khan Low-frequency Mitigation Architecture (Olisa-Khan LMA).

Objective-5: Differentiate healthy state responses from different fluid-filled damage responses of the structure.

In Chapter 7, a study was conducted to differentiate the health state response from different fluid-filled damage. A pitch-catch method of three sensors and an actuator were configured to monitor variations in the response signals of the ultrasonic-guided wave due to changes in the state of the substance that filled the damage. Two modes – asymmetric and symmetric were considered in the damaged filling. Observations showed that the fundamental asymmetric mode was more dominant and sensitive than the fundamental symmetric mode for variation of filled-in damage. Furthermore, the variations in the nature of the damage were directly proportional to an increase in frequency. Following the evaluations, empirical predictive models were deduced which can improve the algorithm of structural health monitoring schemes, especially in the oil and gas sector where damages are easily fluid-filled.

8.3 Recommendations for future work.

This thesis studies the detection of a novel type of damage, debris-filled damage (DFD), in thin structures using elastic waves. However, while it is noted that the results and observations of the experiments and models are useful for continuous monitoring of thin structures for possible damage, especially debris-filled damage, some recommendations are made to improve the study further. The recommendation encompasses a physical model, experimental setup, and signal processing.

- i. Physical Model

The studied novel damage, debris-filled damage, is recommended to be further explored by considering various shapes, sizes and orientations of the damage. This would make the model more realistic

and applicable to a broader range of industrial scenarios, especially in the oil and gas sector. Incorporation of more environmental conditions, such as humidity, and ascertaining the combined influence of the factors on the response wave and damage detection is equally recommended.

ii. Experimental Setup

The data acquisition method used in the study was not automated. This caused challenges in managing simultaneous data acquisition of combined influencing scenarios. Therefore, future work is recommended to explore an automated data acquisition approach. Expanding the number of sensors and optimizing their placement would enhance the detection and characterization of the damage. However, the number of data acquisition ports in the oscilloscope is limited. Therefore, integrating a multiplexing switch between the sensors and the oscilloscope to use the limited ports for many sensors is recommended. A properly designed and integrated multiplexing switch would minimize cross-talk between switching from one sensor to another, thereby improving the integrity of the captured response signals.

iii. Signal Processing

Signal Processing techniques are crucial aspects of SHM as they reveal the structure's damage presence and its localization. Signal processing techniques adopted in the study focused mostly on detecting and quantifying damage in the structure. It is then recommended that machine learning be utilized for automated signal analysis and pattern recognition, which could improve damage detection, classification and characterisation accuracy and efficiency. Also, it is recommended to explore signal fusion to enhance the robustness and reliability of the damage detection process. Exploring machine learning and artificial intelligence would require large

datasets, thereby necessitating data compression and storage methods to manage large datasets during the testing. Also, in further work, it is recommended to integrate decision and action costs in the model. This accounts for false and missing damage detection by the model.

These improvements would significantly enhance the realism and applicability of the physical model, the experimental setup's robustness and the relevance of signal processing in damage detection, classification and characterization.

Journal Publications and Conference

- 1.1 S. C. Olisa, M.A. Khan, and A. Starr,” Review of Current Guided Wave Ultrasonic Testing (GWUT) Limitations and Future Directions,” *Sensors* (Switzerland), vol. 21, no 3, 2021, Doi: 10.1057/9781137353238_7. (Published).
- 1.2 S.C. Olisa, A. Starr, and M.A. Khan,” Monitoring Evolution of debris-filled damage using pre-modulated wave and guided wave ultrasonic testing (GWUT),” *Measurement*, Vol. 199, P. 111558, Aug. 2022, doi: 10.1016/J.MEASUREMENT.2022.111558. (Published).
- 1.3 S. C. Olisa, M.A. Khan, and A. Starr,”Confounding factors effect on Guided Wave Ultrasonic Testing(GWUT),” in 17th International Conference on Condition Monitoring and Asset Management, CM 2021, no. 1. (Published). Available: <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85114203175&partnerID=40&md5=44a288ed2a5c6bbc848511aa4e198e>
- 1.4 S.C. Olisa, M. A. Khan, and A. Starr, “Elastic Wave Mechanics in Damaged Metallic Plates,” *Symmetry* (Basel)., vol. 15, n0. 11, 2023, Doi: 10.3390/sym15111989. (Published).

- 1.5 S.C. Olisa, M.A. Khan, and Z. Yifan,” Confluence Effect of Debris Filled Damage and Temperature on Guided Wave,” (Under Revision).
- 1.6 S.C. Olisa and M. A. Khan,” Low-frequency Vibration Influence and Mitigation on Guided Wave Response Signals,” (Under Revision).

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