Application of Guided Waves for Damage Monitoring in Multi-wire Cable Structures

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BEng (Honours)

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Abstract

Multi-wire cable structures are widely used in civil engineering applications such as stay cables in suspension bridges, elevators and overhead electric transmission lines. The loss of cable load and presence of cable breakage can be catastrophic for the entire structure. Various techniques have been applied to the non-destructive monitoring of structural health of multi-wire cable structures. However, few of them could fully characterize the early structural degradation or reliably determine the damage mechanism due to the limited access to structural components and other environmental factors.

In this thesis, a guided wave-based structural health monitoring system that is capable of monitoring the cable load levels and detecting defect simultaneously is developed for multi-wire cable structures. A series of finite element analysis were conducted using Abaqus/Explicit to explore the feasibility of using ultrasonic guided waves to detect the notch in multi-wire cable structures, followed by the experimental verification on a seven wire strand. Both numerical studies and experimental works presented in this research have revealed that guided waves could be a promising technique for defect detection in multi-wire cable structures. On the other hand, finite element analyses were conducted in this study to investigate the nonlinear characteristics of ultrasonic guided waves in a multi-wire cable under different preloaded levels. The wave signals after a fast Fourier transform indicate that second harmonic peak together with the calculated nonlinear parameters decreased as the preload level increased. The corresponding wave energy was integrated to minimise the adverse influence caused by dispersion and multimodality during wave propagation. The results revealed a similar trend, which demonstrated the feasibility of ultrasonic guided waves to monitor the load level in multi-wire cable structures.
Declaration
I thereby declare that material contained in this thesis has not been published in any other
degree or diploma in any other institution. To the best of my knowledge no material presented
within has been previously published or written by other except where references are made in
the text.

Feng Lin
April 2016
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Chapter 1 - Introduction

1.1 Problem Statement

Multi-wire cable structures are widely used in civil engineering applications such as stay cables in suspension bridges, elevators and overhead electric transmission lines. In such structures, the multi-wire cables are important load-carrying components. The loss of cable load and the presence of cable breakage can be catastrophic for the entire structure. According to the investigation report provided by TCK-W company (http://www.tck-cn.com), since the turn of the twenty-first century, the failures of cable applications have caused over 240 deaths and incalculable economic losses worldwide. In 2002, in particular, the partial collapse of the suspension bridge in south gate of Yichang, China caused the casualties of 12 and more than 5.6 million dollars loss. After the investigation, as can be seen from Figure 1.1, the main cause is the failure of one load-bearing cable that has been corroded.

![Figure 1.1](image_url)

**Figure 1.1** (a) Partial Collapse of Yichang south gate bridge (b) cable corrosion (c) damaged cables

Therefore, structural integrity monitoring of multi-wire cable structures is crucial to ensure the
proper structural performance of cable structures. Basically, the health inspection includes load level assessment and structure defect detection. For decades, various techniques such as visual inspection, radiography, vibration and fibre optic strain sensing system have been applied to the non-destructive health monitoring of multi-wire cable structures. Most of them have shown the potential to flag significant events that affect the integrity of structure. However, few of them could fully characterize the early structural degradation or reliably determine the damage mechanism due to the limited access to structural components and other environmental factors.

As one of the most popular structural health monitoring methods, ultrasonic inspection using guided waves is a promising non-destructive health monitoring method for single wire and multi-wire cables. This provides a promising technique that can provide simultaneous detection of defects and monitoring of load levels in cable structures. In contrast with the typically used bulk waves which are impractical for inspecting large structural components due to its limited propagation distance, guided waves can propagate over a long distance, and could possibly be used to inspect large regions of a structure at once. Ultrasonic guided wave based technique has shown promises for the simultaneous detection of defects and monitoring of the load levels in multi-wire cables. However, there are some limitation on its application, including the dispersive nature of waves and multi-modes that generated during the wave propagation. Therefore, prior to the establishment of a comprehensive structure health monitoring system based on ultrasonic guided waves, it is necessary to fully understand the propagation of guided waves in multi-wire cable structures subjected to different load levels and its interaction with defects.
1.2 Aim and Objectives

The aim of this research program is to investigate guided wave propagation in multi-wire cable structures and advance the understanding of the interaction between the guided waves and cable defects in both linear and nonlinear aspects by using both finite element simulation and experimental study.

The specific objectives need to be addressed include:

- To provide a basic knowledge about the multi-wire cable monitoring and guided wave propagation.
- To build a conceptual framework upon which the research program is based.
- To develop numerical simulation procedures on ultrasonic guided wave propagation in multi-wire cable structures with flaw at different severity. The feasibility and sensitivity of using guided waves to detect the macro defects would be investigated.
- To establish an appropriate laboratory testing approach to investigate the interactions between guided waves and macro cable defects.
- To examine ultrasonic guided wave-based load monitoring method applied on cable structures by numerical simulations.
1.3 Outline of the Thesis

In order to address the abovementioned objectives, this thesis is divided into 6 chapters with a list of references. The chapters are summarised below.

Chapter 2 provides a comprehensive literature review, which gives the research backgrounds and useful information about the proposed study in this thesis. A basic overview of structural health monitoring is firstly introduced. A review on the current progress of monitoring preloaded cables is also presented, followed by an introduction on the properties of ultrasonic guided waves in multi-wire cable structures. Finally, a detailed review on the application of ultrasonic guided waves to monitor both linear and nonlinear defects existing in cable structures is presented.

Chapter 3 presents the numerical modelling work of wave propagation in multi-wire cables. A series of finite element analysis were conducted using ABAQUS/Explicit code to investigate the linear characteristics of ultrasonic guided waves as well as its sensitivity to macro flaws such as breaks and notches.

In chapter 4, the experimental study is aimed to verify the numerical results in chapter 3 is presented. The first part is focused on the description of experimental setup used in the study. The second part demonstrated the detailed experiment processes and the analysis of results obtained from experiments is presented in the last part.

The work presented in chapter 5 focuses on the examination of ultrasonic guided wave-based load monitoring method applied on cable structures. A series of finite element analysis were performed to explore the inter-wire contact that appears responsible for the nonlinearity of guided waves in multi-wire cable structures, which can be used to estimate the load levels.

In chapter 6, the thesis is concluded with a summary of the major findings in this study, followed by the recommendations for the future work.
Chapter 2 - Literature Review

A comprehensive literature review was conducted to build a firm basis based on which the research program was proposed. First, a basic overview of structural health monitoring is introduced. A review on current progress of monitoring of the preloaded cables is also presented. The basic introduction of ultrasonic guided waves is conducted to provide a general background information, followed by an introduction on the properties of ultrasonic guided waves in multi-wire cable structures. Finally, a detailed review regarding the ultrasonic guided waves is presented to explore both their linear and nonlinear characteristics in cable structures.

2.1 Overview on Structural Health Monitoring

Civil structures including bridges, buildings, pipelines, and many others play fundamental roles in modern society. However, due to the factors such as improper design and construction, or environmental corrosion and long term fatigue, many structures in-service could be defective and damages could occur and accumulate over long periods. In most cases, damage can be defined as changes introduced into a system that adversely affects its current or future performance (Farrar and Worden, 2007). Safety and serviceability of the civil structures therefore are essential elements in civil engineering design for years, great efforts have been made to develop practical and effective methods for monitoring, evaluation and maintenance of civil structures.

As a process of implementing a damage identification strategy, structural health monitoring (SHM) technology is based on a comprehensive sensory system and a sophisticated data processing system implemented with advanced information technology and structural analysis algorithms (Xu and Xia, 2011). Fundamentally, the SHM problem could be considered as a statistical pattern recognition which consists of four-part process: 1) Operational evaluation, 2) Data acquisition, fusion and cleansing, 3) Feature extraction and information condensation,
and 4) Statistical model development for feature discrimination (Farrar and Worden, 2007). It can monitor a structural or mechanical systems and analyse features over time, thereby determining the in-situ state of system health (Sohn et al., 2004). The main objectives of the SHM are to assess structural performance under various service environments, to detect its damage or deterioration, to guide its inspection and maintenance, and to verify or update the rules used in its design stage (Xu and Giurgiutiu, 2007).

Economic impacts and life-safety concerns caused by civil structural damages are the primary stimulus for the development of SHM. Decades of research has indicated that in most cases, by applying the SHM system, cost of unnecessary maintenance and structure components removal could be saved greatly. For instance, Bartelds (1997) states that for the aircraft, a SHM system could not only reduce the direct costs related to damage detection that are required frequently, but also save about 40% of the current inspection time. Besides, effective SHM could extend the life-time of structures and therefore reduce the cost associated with repair or rehabilitation while providing higher levels of safety for users during assessment. This is because the SHM could help engineers and decision makers determine when and where to spend funds so that structural safety is enhanced, meanwhile the existing infrastructure can be preserved to satisfy the needs of commerce and the public (Stubbs et al., 2000). There is also an emphasis placed on using SHM to optimize structure designs, where with a well-designed SHM system, engineers would be able to reduce the weight of some structures and yet still provide required strength.

From the excitation perspective, the structural health monitoring system can be categorised as either active or passive. A passive SHM system primarily depends on ambient excitation, in which the structure is generally under its normal operating conditions without embedded actuator, the input excitation is not recorded or unmeasured and its corresponding evolution of the structure is monitored by using embedded sensors to measure various parameters such as
loading, stress and other performance indicators and thereby determining structure’s health state. In an active SHM system, on the other hand, the force excitation would be introduced by embedded actuators to generate perturbations and corresponding response of the structure will be monitored by sensors. Figure 2.1 demonstrates the briefs of both kinds of SHM. Compared with passive SHM system which only acquires information from the structure instead of interacting with it, the active SHM could directly detect the health state of targeted structure, which makes it the better choice for structural health monitoring due to its economic benefits and reliability.

Figure 2.1: Two kinds of SHM system a) passive monitoring; b) active monitoring (Balageas et al., 2006)
2.2 Review on Health Monitoring Techniques of Prestressing Cables

As a general civil structure component, multi-wire cable structures are widely used in civil engineering applications such as stay cables in suspension bridges, elevators and overhead electric transmission lines. In such structures, the multi-wire cables are working as the important load-carrying components. The loss of cable load and the cable breakage, can be catastrophic for the entire structure. Therefore, monitoring health integrity of multi-wire cable structures is crucial to ensure the proper structural performance. For years, various techniques has been applied to the structure health monitoring of multi-wire cables. A general review of some most common methods are demonstrated in this section.

2.2.1 Visual Inspection

As the simplest and oldest form of inspection technique, visual inspection provides information on the health state of structures by examining the structures with naked eyes. Defects and degradation of post-tensioned structure can be detected by human sensory system aided with enhancements, including fiberscopes, Bore scopes, magnifying glasses and mirrors (Spencer, 1996). However, even with above-mentioned aids, human visual inspection still heavily rely on the subjective judgments of inspectors, therefore, this technique require skilful and experienced operators (Phares et al., 2004). Furthermore, generally, the visual method is only efficient when the defects and degradation are visible at the surface of the structure, which may lower the effectiveness of this technique.

2.2.2 Radiography

Radiography is an imaging technique that uses electromagnetic radiation to image the internal structure of the object. Generally, X-rays and Gamma rays are used to create the image. In a radiographic imaging system, a beam of rays are generated by radioactive source, after the radiation passes through the subject and on the detector, usually a photographic film that could
absorb radiation, and difference in thickness of the object under radiation would result in a
density variances of captured image. Therefore, the results are presented pictorially and can
reveal minor fractures and blemishes within it (Willcox and Downes, 2003)

![Radiography Illustration](image)

**Figure 2.2** An illustration of radiography (Willcox and Downes, 2000)

In terms of the inspection of post-tensioned structures, the advantage of this technique is
obvious, including the pictorially presented information, high sensitivity on any material and
ability to accurately locate defects. However, one of the main disadvantages for this technique
is that it can only be applied over short distances, which is unsuitable for a big structure. Other
shortcomings include its inability to be applied to thick sections, and difficulty in imaging
subjects that overlapped each other spatially.

### 2.2.3 Vibration Modal Analysis

The vibration modal analysis has been widely implemented for the assessment of cable
components in cable-stayed structures. The dynamic responses of cables subjected to vibrations
can be monitored by accelerometers to identify the modal characteristics such as natural
frequencies, mode shapes and damping ratios. The structural damages, including losses in
mass, cross sectional area, are generally described as diffused reduction of the cable stiffness,
and defined through its intensity, extent and position (Lepidi et al., 2007). Damages determine the severity of cable defects such as tension losses and sag augmentations. Those acquired measurements are usually correlated with the applied tension forces and sag estimation by employing several analytical formulations based on vibrating chord theory and static equilibrium of cable structure.

![Accelerometers network layout for the vibration monitoring of cables](image)

Figure 2.3 Accelerometers network layout for the vibration monitoring of cables (Enrico Nuti, Giuseppe Quaranta 2015)

However, this technique is only sensitive to the severe structural defects that could change the cable properties dramatically and cannot be applied to assess the small defects such as corrosions and cracks. The accuracy of this technique might also be influenced by environmental conditions changes (for example, temperature and wind) and physical uncertainties like boundary conditions.

### 2.2.4 Acoustic Emission

Acoustic emission (AE) is also a widely used technique that has applications for cables. Not only does this method have the capacity to monitor damage to the specimen, but it can also be used to locate the damages using simple time-of-flight information recorded by sensors (Salamone et al., 2011b). The principle of this technique is that flaws are able to generate elastic waves that can be captured by acoustic receivers. Features of the captured AE signals, including
wave amplitude, arrival time and energy, are analysed and related to the presence of the flaws. The location of damage in the cable structure could be identified by using simple time-of-flight information collected at multiple sensors. Study of (Li and Ou, 2010) indicates that even the process of cable fracture could be monitored by using AE test. Further advanced analysis techniques such as spectral and frequency-domain analysis, have also been proposed to detect the type and model of structure damages.

![Figure 2.4: Typical AE experiment setup (Li et al., 2012)](image)

Because huge amount of research have proven the effectiveness of AE test for real-time damages detection in cable structures, AE has been successfully used in both steel and composite cables for damage monitoring such as cable corrosions and cracks (Li et al., 2012). This technique has also been introduced to detect the wire failure in grouted tendons in a recent study (Cullington et al., 2001). However, as a passive test method, acoustic emission testing can be only used to capture the signals produced by sudden internal structure failures in materials and cannot be accounted as the source of signal and wave propagation (Huang et al., 1998) AE test is therefore not able to detect “inactive” flaws such as pre-existing conditions of the structure. Besides, AE is also ineffective in monitoring load level in cables.

### 2.2.5 Magnetic Flux Leakage

Magnetic flux leakage (MFL) has been successfully performed on the defects detection in both
cables and prestressed tendons. The principle of MFL is shown in Figure 2.5, where the test cable is firstly magnetized by applying a magnetic field with a yoke magnet, the magnetized state in steel cable is comparable to the magnetic field of a bar magnet. A defect in form of metal loss in such a system would create a magnetic dipole-distribution and therefore produce a magnetic leakage flux which could be captured by sensor embedded in the system. Except for the magnetic flux leakage measurement during magnetization by the excited field, the capture of flux leakage could also be conducted in residual magnetic field in which the initial magnetic state has been switched off while the magnetization still exists (Scheel and Hillemeier, 2003). In order to generate decent magnetic flux density for accurate detection, it is important to erase the unknown magnetic history and ensure the magnetization saturation by multiple passes along the test cable, which makes the magnetization processes complex and time-consuming.

![Figure 2.5: Principle of MFL (Kim et al., 2012)](image)

Although the MFL techniques demonstrates great promise for detecting flaws in prestressed strands, in comparison with other methods where sensors can be left on the structure, MFL cannot continuously monitor and does not give an indication of the level of stress in a strand (Salamone et al., 2011). Also, the presence of steel reinforcement in pre-stressed cables has been shown to cause problems in detecting damage on steel strands.
2.3 General Aspects of Ultrasonic Guided Waves

2.3.1 Ultrasonic Guided Waves

Ultrasonic waves refer to high frequency elastic stress waves, which vibrate at a frequency above 20k Hertz (Hz). In NDE applications, ultrasonic frequencies could range from tens of kilohertz to a few Megahertz. Elastic stress waves can propagate in solids at high velocity with low attenuation (loss of energy) (Shui and Solodov, 1988). These features of ultrasonic waves (velocity, attenuation) can be used to characterize a material’s composition, elastic properties, density and geometry. Also, by employing scattering effect caused by defects, it is possible to use ultrasonic waves to detect and describe flaws in materials and structures.

Basically, ultrasonic waves can be classified into two groups shown in Figure 2.6: bulk waves which propagate through a bulk material, and guided waves, where the boundary of the structure guides the propagation of waves. Guided waves can travel in thin plates (Lamb waves), on the surface of semi-infinite solids (Rayleigh waves), or on the interface between two different media (Stonely waves), which are described as waveguide. Guided waves are generated when the bulk waves interact with the boundaries of the waveguide. Compared with the typical bulk waves which are impractical for inspecting large structural components because of their limited propagation distance, guided waves can propagate over a long distance along with the surface of waveguide, and could possibly be used to inspect a large region of a structure at one time.
Compared with previously mentioned non-destructive monitoring techniques, the advantages of ultrasonic guided wave based technique include: (1) the possibility of using transducers permanently attached to the strand for continuous structural monitoring, (2) the potential for providing simultaneous defect detection and stress monitoring capabilities for the strand with the same sensing system, and (3) the possibility for detecting both potential defects and pre-existing defects toggling between the modes of ‘passive’ acoustic emission testing and ‘active’ ultrasonic testing within the same sensing system (Salamone et al., 2011a). However, as demonstrated in Figure 2.7, guided waves propagate in structure components with plenty of wave modes and multiple reflections and dispersion (Biwa et al., 2010), which make the analysis difficult. In addition, it is understood that linear guided waves are insensitive to minor damage. For the purpose of utilizing guided waves as an effective non-destructive evaluation tool for cable health monitoring, particular characteristics of wave propagation in the complex cable structure must be explored.
2.3.2 Nonlinearity of Guided Waves

Nonlinearity is a frequent visitor to engineering structures which can modify the design behaviour of systems. For an imperfect interface between two solids, the contact load between each other is supported by surface asperities. As the load increases, more asperities come into contact with each asperity undergoes flattening deformation Figure 2.8. The change in the contact asperity configuration due to varying contact pressure leads to certain nonlinear behaviour as the mechanical response of the contact interfaces. As a result, as demonstrated in Figure 2.9, new waves at frequencies which are multiples of the initial wave frequency would be generated when a wave interacts with the contact interface (Biwa et al., 2004). After its first discovery by L. Rayleigh (Rayleigh, 1896), acoustic harmonic generation was first verified experimentally in air by Thuras et al (Thuras et al., 1935). The nonlinear third-order elastic constants of the solids were first measure in the early 1960’s (Parker Jr et al., 1964) and since then, many researchers have studied this ultrasonic character for decades.
Early work on the ideally bonded interface (Mayer, 1995) indicates that the second-harmonic surface waves have a field structure different from the fundamental ones and vary with the propagation distances. The first theoretical predictions on the higher harmonics caused by “clapping” of the contact surfaces were proposed by Richardson (1979) during his research about one-dimensional nonlinear wave propagation through a unilateral contact interface. However, in his analysis, realistic features of finite and nonlinear interface stiffness, which may vary with contact condition, are not considered. As a supplemental investigation, the case of a longitudinal plane wave incidence on an interface with nonlinear stiffness was studied by Biwa (2004). In his research, a nonlinear interface model was established and the linear stiffness of the contact interface $K_1$ is expressed by a power-law function of the contact pressure $P_0$. Also, by yielding the relation between the contact pressure and the interface gap distance, this model gives the second-order stiffness of interface as a function of the contact pressure, which revealed the existence of second harmonic component in the waves reflected as well as transmitted through the contact interface. One conclusion was that when the reflected and transmitted fundamental waves increase, the strength of the second harmonic due to nonlinearity will decrease.
Chapter 2 Literature Review

Figure 2.9: Distortion in waveform during propagation by the nonlinear elasticity and higher harmonic generation (Jhang, 2009)

2.4 Review of Ultrasonic Inspection in Multi-Wire Cable Structures

The basic principle of ultrasonic based technique is demonstrated in Figure 2.10. Elastic waves are excited in the waveguide structures and parts of the wave are reflected by the defect and measured by sensors. Afterwards, the damage detection could be determined by signal analysis.

Figure 2.10: Principle of ultrasonic guided waves (Schaal et al., 2015)

However, due to the multimodality and dispersion of guided waves, many propagation modes
can propagate simultaneously with different velocities depending on frequency, which complicated the relevant study. Theoretical and experimental studies of wave propagation in rods and wires have been conducted, in which early work on the wave generation and model coupling in solid cylinder with traction free boundary conditions has set the fundamental basis and are used as an approximation to investigate the more complex phenomena of wave propagation on a multi-wire cable (Baltazar et al., 2010). It is well acknowledged that that generally there are three wave modes existing in rod as: longitudinal axially symmetric modes; torsional axially symmetric modes; flexural axially symmetric modes. As flexural and torsional modes are prone to suffer high attenuation during propagation, longitudinal modes are most commonly used in multi-wire cable structure monitoring (Farhidzadeh and Salamone, 2015). An approximate solution for the L (0, 1) mode was found by Zemanek Jr (1972). Based on above-motioned results, many experimental studies have been proposed to explore the possibility of practical implantation of guided waves to monitor the cable defects. Although different actuator-sensors were used, similar results indicated that analysis of transmitted and received selected ultrasonic signal could be correlated to linear defects such as discontinuities and notches, showing the feasibility of using guided waves-for in situ damage monitoring.

The dispersive nature of waves propagating in multi-wire cable structure has also been investigated for the purpose of cable health monitoring. Farhidzadeh (2015) proposed a new velocity based method to use ultrasonic guided waves to determine loss of cross-sectional area of a steel strand. It was found that a 3% mass loss resulting from corrosion caused significant attenuation such that only the first order longitudinal mode was left (Farhidzadeh and Salamone, 2015). The diameter was then estimated and compared to the measured value at different time points, where the diameter was calculated using the dispersion function for the first longitudinal mode, which relates diameter with velocity and frequency. It was shown that this new approach was able to estimate the diameter with good accuracy, with all measurements
being within one standard deviation of the actual diameter.

Dispersive behaviour of guided waves has also been proven to be able to measure stress levels in seven-wire prestressing steel stands (Kwun et al., 1998). The research indicated that the presence of stress in the strands causes high attenuation of a portion of the guided waves and thus the absence in frequency spectrum of the wave. The centre frequency in this missing portion, called notch frequency was found to be linearly related to the logarithm of the stress levels. However, the principle of the tensile loading effects is not still clear presently.

Despite of the progress that has been made, the theoretical understanding of guided ultrasonic waves in multi-wire strands is far away from fully understood due to the other phenomena such as helical geometry of peripheral wires, the inter-wire coupling, contact effects and acousto-elasticity.

Helical effect in waveguide has been studied in a single helical cable wire by using finite element analysis and semi-analytic finite element analysis (Treyssé, 2007). Numerical results of simulation on wave propagation indicated that though wave numbers of longitudinal modes for both cylinder and helical wire are identical, flexural modes do not occur in pairs of equal wave numbers due to the lack of symmetry of the helical geometry, which gets stronger as the lay angle of helical wire increase. In addition, it was also found that at specific low-frequency range (“band cut” zone) waves of both longitudinal modes and torsional modes become non-propagating while the bands of frequencies also grow with the lay angle.

Friction and energy transfer between cable wires has also been studied using analysis on two single wires. Energy leakage due to inter-wire coupling caused by radial displacements is considered to have an important role in the excitation not only of longitudinal modes, but also of flexural modes.

The research conducted by (Chen and Wissawapaisal, 2001) correlated the effect of acousto-
elastic with axial stress levels of multi-wire strand. The experimental and analytical results indicated that the travelling time of the stress wave propagating inside the centre of a seven-wire prestressing strand could be related to the stress level of the strand, which is mainly due to the elongation of the strand together with the changes in the wave velocities caused by acousto-elasticity of waveguide. However, this proposed evaluation technique was shown only to work well within the prestress forces range from 18% to 70% of the ultimate strength of the strands.

![Graph showing primary excitation and higher harmonic amplitudes for different stress levels.](image)

**Figure 2.11** Results of numerical study conducted by Nucera Claudio

The phenomenon of inter-wires contact existing in multi-wire cable structures could cause the "contact acoustic nonlinearity", which is well known in the ultrasonic testing community. By combining concepts of higher harmonic generation mentioned in section 2.3.2, Nucera and di Scalea (2011) has developed a method to determine the prestress level in strands and railroad tracks. With the discovery of proportional relationship between applied axial force in the strand and inter-wire contact stress, an inverse proportion was reflected between axial load and non-linear ultrasonic behaviour of the strand, i.e. The higher harmonic amplitudes of an ultrasonic guided wave excited into a seven-wire strand decrease with the increasing axial load applied to the strand.
2.5 Study of Ultrasonic Guided Waves in Multi-Wire Cable Structures

2.5.1 Guided Wave Dispersion in Rod-like Structures

Due to the structural complexity of cable structures, even for the simplest cable, an analytical solution which describes the wave propagation in the multi-wire cable does not exist (Rose, 2002). In order to understand the wave propagation, a basic theoretical study for wave propagation in rod and governing equation for different wave modes are presented.

The study started from the investigation of the elastic harmonic waves propagate in an isotropic and homogenous infinite rod, in which guided waves appear in a medium which constrains internal disturbances to move between the lateral bounding.

![Cylindrical coordinates for a solid cylindrical](image)

Figure 2.12 Cylindrical coordinates for a solid cylindrical

Naturally, cylindrical coordinates should be used to solve the problem, as demonstrated in Figure 2.12, where the z-axis is set as the axis along the rod. A solution to the wave equation for an isotropic elastic solid can be obtained in terms of a scalar and vector potential by the method of separation of variables (Zemanek Jr, 1972). For the general case of vibration, the following displacements can be obtained.

\[
    u_r = U(r) \cos n\theta e^{i(kz-\omega t)} \tag{2.1}
\]

\[
    u_\theta = V(r) \sin n\theta e^{i(kz-\omega t)} \tag{2.2}
\]
\[ u_z = W(r) \cos n \theta e^{i(kz - \omega t)} \]  

(2.3)

Where \( t \) is the time, \( \omega \) is angular frequency, \( k \) is the wavenumber \( (r = \frac{\omega}{v} = \frac{2\pi}{\lambda}, v \) is the phase velocity, \( \lambda \) is the wavelength), \( n \) determines the order of the antisymmetric mode. Three types of vibration in a cylindrical rod, i.e. longitudinal, torsional, and flexural are examined in the following study.

In a solid circular cylindrical rod, longitudinal waves are axially symmetric, with displacement components in the radial and axial directions. Longitudinal waves correspond to the case \( n=0 \) in Eqs. (2.1)- (2.3).

The governing equation for longitudinal vibration modes at the surface of rod is known as the Pochhammer frequency equation:

\[
\frac{2\alpha}{a} (\beta^2 + k^2) J_1(\alpha a) J_1(\beta a) - (\beta^2 - k^2) J_0(\alpha a) J_1(\beta a) - 4k^2 \alpha \beta J_1(\alpha a) J_0(\beta a) = 0
\]

(2.4)

Where \( a = \text{rod radius}, J_0 \) and \( J_1 \) are Bessel function of order 0 and 1 respectively; \( \alpha \) and \( \beta \) are given by

\[
\alpha^2 = \frac{\omega^2}{c_L^2} - k^2
\]

(2.5)

and

\[
\beta^2 = \frac{\omega^2}{c_T^2} - k^2
\]

(2.6)

In these equations, \( c_L \) is the longitudinal wave velocity and \( c_T \) is the shear wave velocity.
Similar analysis could yield frequency equations for torsional waves as

\[(\beta a)J_0(\beta a) - 2J_1(\beta a) = 0 \tag{2.7}\]

As for the flexural waves, which depend on the circumferential angle \(\vartheta\) through the trigonometric functions shown in Eqs. 2.1-2.3. For ordinary flexural mode, the case of \(n = 1\) corresponds to the lowest-order family of flexural modes. The displacements are given in following equations:

\[u_z = U(r) \cos \vartheta e^{i(kz - \omega t)} \tag{2.8}\]

\[u_z = V(r) \cos \vartheta e^{i(kz - \omega t)} \tag{2.9}\]

\[u_z = W(r) \cos \vartheta e^{i(kz - \omega t)} \tag{2.10}\]

Therefore, the frequency equations for flexural modes are more complicated than those for the longitudinal and torsional modes. Hudson Graff (1975) has carried out calculations for some of the lowest branches of flexural modes and the resulting Pochhammer frequency equation is:

\[J_1(\bar{\alpha})J_1^2(\bar{\beta})(f_1T_\beta^2 + f_2T_\beta T_a + f_3T_\beta + f_4T_a + f_5) = 0 \tag{2.11}\]

where

\[f_1 = 2(\bar{\beta}^2 - \bar{k}^2)^2 \tag{2.12}\]

\[f_2 = 2\bar{\beta}^2(5\bar{k}^2 + \bar{\beta}^2) \tag{2.13}\]

\[f_3 = \bar{\beta}^6 - 10\bar{\beta}^4 - 2\bar{\beta}^4\bar{k}^2 + 2\bar{\beta}^2\bar{k}^2 + \bar{\beta}^2\bar{k}^4 - 4\bar{k}^4 \tag{2.14}\]
\[ f_4 = 2\bar{\beta}^2(2\beta^2\bar{k}^2 - \bar{\beta}^2 - 9\bar{k}^2) \] \hspace{1cm} (2.15)

\[ f_5 = \bar{\beta}^2(-\bar{\beta}^4 - 8\beta^2 + 2\beta^2\bar{k}^2 + 8\bar{k}^2 - \bar{k}^4) \] \hspace{1cm} (2.16)

and where

\[ \bar{\alpha} = \alpha a \] \hspace{1cm} (2.17)

\[ \bar{\beta} = \beta a \] \hspace{1cm} (2.18)

\[ \bar{k} = ka \] \hspace{1cm} (2.19)

\[ T_x = xJ_0(x)/J_1(x) \] \hspace{1cm} (2.20)

Since the phase velocity and group velocity are

\[ c_p = \frac{\omega}{2\pi} \] \hspace{1cm} (2.21)

\[ c_g = c_p + k\left( \frac{dc_p}{dk} \right), \] \hspace{1cm} (2.22)

By solving the equation for different wave modes with known frequencies, the dispersion curves which relate the phase velocity and group velocity of the guided waves can be established in terms of the frequency of the wave and the diameter of the cylinder.

Figures 2.12-2.13 depict guided waves that propagate in a steel rod with 5.08mm in diameter at a frequency range from 0-1.2MHz. This particular diameter is considered based on the geometry of a 7-wire cable proposed in this study. The dispersion characteristic was calculated by using Disperse software (Disperse Specification). It is observed that the velocity of a particular mode can change with frequency, which leads to the distortion of wave packet when
traveling along the rod. Each wave mode should therefore be analysed to select a suitable one for damage detection in this research.

**Figure 2.13** Phase velocity dispersion curves for 5.08 mm diameter steel rod

**Figure 2.14** Group velocity dispersion curves for 5.08 mm diameter steel rod
2.5.2 Cable Load Level Monitoring with Nonlinear Guided Waves

2.5.2.1 Nonlinear Parameter

This section gives a theoretical background of one dimensional nonlinear wave propagation with a parameter known as nonlinearity parameter $\beta$ which is related to high-order harmonics. When waves propagate in nonlinear medium, the fundamental wave will distort as it propagates, therefore the second and higher harmonics will be generated. Particularly the lattice anharmonicity and dislocation structures contribute to the nonlinearity parameter (Wallace, 1970).

A longitudinal stress perturbation $\sigma$ associated with propagating ultrasonic wave produces a longitudinal strain (Hull and Bacon, 1984).

\[
\varepsilon = \varepsilon_e + \varepsilon_{pl}
\]  

(2.23)

Where $\varepsilon_e$, the elastic is strain; $\varepsilon_{pl}$ is the plastic strain component associated with the motion of dislocation in the dipole configuration. The relation between the stress perturbation and elastic strain can be written in the nonlinear form of Hooke’s law:

\[
\varepsilon_e = \frac{1}{A_2^e} \sigma + \frac{1}{2} \frac{A_3^e}{(A_2^e)^3} \sigma^2 + \ldots
\]  

(2.24)

Where $A_2^e$ and $A_3^e$ are the Hung coefficients.

According to the study conducted by Antonopoulos et al. (1976) the relation between the stress perturbation and the plastic strain $\varepsilon_{pl}$ can be obtained by considering dipolar forces, relative dislocation displacement:

\[
\varepsilon_{pl} = \frac{1}{A_2^{dp}} \sigma - \frac{1}{2} \frac{A_3^{dp}}{(A_2^{dp})^3} \sigma^2 + \ldots
\]  

(2.25)
Where $A_{2}^{dp}$ and $A_{3}^{dp}$ are the dipole coefficients.

Substituting Equation (2.24) and Equation (2.25) into Equation 2.23 as

$$
\varepsilon = \left( \frac{1}{A_{2}^{e}} - \frac{1}{A_{2}^{e}} \right) \sigma + \frac{1}{2} \left[ \frac{A_{3}^{e}}{(A_{2}^{e})^2} + \frac{A_{3}^{dp}}{(A_{2}^{dp})^2} \right] \sigma^2 + \ldots
$$

(2.26)

The wave equation with respect to the Lagrangian coordinate $X$ is given as:

$$
\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial^2 \sigma}{\partial X^2}
$$

(2.27)

Substituting Equation (2.26) and Equation (2.27) results in the displacement based nonlinear wave equation:

$$
\frac{\partial^2 u}{\partial t^2} = c^2 \left[ 1 - \beta \frac{\partial u}{\partial X} \right] \frac{\partial^2 u}{\partial X^2}
$$

(2.28)

Assuming an input wave of the form: $u_0 \cos(kX - wt)$, a solution to Equation (2.28) is:

$$
u = \frac{1}{8} \beta k^2 u_0^2 x + u_0 \cos(kX - wt) - \frac{1}{8} \beta k^2 u_0^2 x \cos[2(kX - wt)] + \ldots
$$

(2.29)

$\beta$ can be expressed by the amplitudes $A_1$ and $A_2$ of the fundamental frequency and the second harmonic frequency respectively which leads to the following expression (Na et al., 1996):

$$
\beta = 8 \frac{c^2}{\omega^2 X A_1^2}
$$

(2.30)

Where,

$\omega$: Frequency

$c$: Wave velocity
As shown in the equation above, the nonlinearity parameter depends on the fundamental wave, the second harmonic, the wave speed, the propagation distance and frequency.

### 2.5.2.2 Contact Force between Wires

This study mainly focused on the cable consisting in a straight core wire wrapped around by a layer of six helical wires, shown in Figure 2.15. In order to simplify the study, several assumptions have been made: 1) each helical wire has a circular cross section in a plane normal to its axis; 2) each helical wire is in contact with its two adjacent wires, including both core and helical wires; 3) both helical wires and core wire have the same diameter.

Following the above-mentioned geometric considerations, it is reasonable to presume that under tension loading there is no relative motion between helical wires and the core along the line of contact. However, between adjacent helical wires, motion is possible. Frictional force can be neglected because the axial force employed in this study would be huge. Thus, the resultant force due to contact is a force directed outward normally to the axial line of the helical wire as shown in Figure 2.16.

The resultant contact force per unit length, $P$ is

$$ P = 2P_h \cos 60^\circ + P_c = P_h + P_c $$

Where,

$P_h$: Contact force (per unit length) due to contact between two adjacent helical wires;

$P_c$: Contact force (per unit length) due to contact between helical wire and core.
Figure 2.15: (a) Cable Sectional View (b) Cable 3D view

Figure 2.16: Contact forces in the transverse cross section of cable

Figure 2.17: Equilibrium of force in an element of a helical wire (Nucera and di Scalea 2011)
Considering a short segment of helical wire in Figure 2.17, an equilibrium can be established.

The following relation can be obtained with regard to contact force (Nucera, 2010):

\[ P = \frac{N_h}{\rho} \]  \hspace{1cm} (2.32)

Where,

- \( N_h \): Axial force acting on the cross section of helical wires;
- \( \rho \): Radius of curvature of helical wires

By using the equation developed in this section, it is possible to determine the inter-wire force in the cable to an axially applied load as a linear function of that load.

According to former study by Biwa (2010), an increase in contact pressure would result in decrease of nonlinearity. Therefore, by assuming that in a multi-wire cable structure, a growing axial load upon cable would lead to the decline of nonlinear parameter, an inverse proportion relation could be established.
2.6 Summary

Structure health monitoring is an essential element in both civil engineering design and construction. For years, many SHM technologies have been developed and applied on cable structures. Compared with other techniques such as vibration modal analysis, radiography and magnetic flux leakage, ultrasonic guided wave based technique was selected particularly in this study because of its possibility of establishing permanent monitoring system and simultaneous defect detection and stress monitoring capabilities. Some detailed characteristics of ultrasonic guided wave propagation on multi-wire cable are presented, aiming at developing a system to monitor the performance of cables structures in both defect detection and load measurement. Current researches using ultrasonic guided waves to monitor the multi-wire cable structure are also summarized in this chapter. It could be concluded that though some progress have been made on using ultrasonic guided waves to detect cable defects, few of them could fully characterize the early structural degradation or reliably determine the damage parameters. Also, although the nonlinear effects in multi-wire cable structures has been investigated through theoretical analysis and experimental studies, there still lack a well-established numerical model to effectively capture the nonlinear characteristics of guided waves.
Chapter 3 - Numerical Simulation on Linear Guided Waves for Defects Detection

3.1 Introduction

Prior to the experiment study, the numerical modelling work is presented in this chapter to fully explore the details of guided wave propagation in multi-wire cables and its interaction with defects. A series of finite element analysis were conducted using Abqus/Explicit code. The main purpose of the FEA study was to investigate the linear characteristics of ultrasonic guided wave as well as its sensitivity to linear flaws such as breaks and notches. In terms of result analysis, the general characteristics of wave propagation in cable structures is explored in the first part, two ways of signal excitation are compared through a case study. After the preliminary simulation, the relationship between the defects and guided wave propagation in structure is also determined.

3.2 Introduction of Abaqus

Abaqus is a suite of powerful engineering simulation programme based on the finite element method and it is capable of solving a wide range of problems from simple linear analysis to complicated nonlinear behaviours. Finite element analyses conducted in this section were extremely complex due to the dynamic phenomenon such as transient dynamic effects, boundary reflections. Besides, densely meshed model and huge amount of element number also increase the computation cost. Therefore, Abaqus/Explicit, an incremental procedure based on the central-difference and diagonal element mass matrices (Abaqus Manual) were used because of its high efficiency and suitability for transient dynamic simulation.

3.3 Input Signal

Due to their multimodality and dispersion, guided waves in different propagation modes can travel simultaneously with different velocities depending on frequency, the wave packets of different frequencies could interfere with each other and distort the signal. Therefore, it is
important to select a proper signal frequency to optimize the guided waves.

In most previous researches, the structural defect detection in multi-wire cable structures is conducted by using ultrasonic guided waves with relatively low frequencies ($f \leq 300\text{kHz}$). This is because that guided wave energy became concentrated near the surface at high frequencies (Baltazar et al), which could complicates the signal interpretation. However, the experimental study on multi-wire cables conducted by Nucera (2011) indicated that the nonlinear effects of guided waves in form of higher harmonics generation are most obvious within the frequency range of 300 kHz-600 kHz.

In addition, based on the dispersion curve obtained in chapter 2 as shown in Figure 3.1, though the guided waves at 500 kHz fall in a dispersive region, the difference in group velocity between wave modes L (0, 2) and other modes are distinct, which means that this wave modes may not be interfered by others in this simulation. It is therefore decided that 500 kHz was used for wave excitation in this study.

After the frequency is determined, the sinusoidal signal was multiplied with Hanning windows in order to get the energy more concentrated at the central frequency. A fifteen cycle Hanning window is defined as:

$$g(t) = \frac{1}{2} + \cos\left(2\pi \frac{t - 1.5 \times 10^{-5}}{3 \times 10^{-5}}\right)$$

(3.1)

While the excited signal can be achieved by using Eq. 3.2,

$$F(t) = h(t) \times g(t)$$

(3.2)

where $h(t)$ is
\[ h(t) = \sin(2\pi ft) \]  \hfill (3.3)

The sinusoidal signals, Hanning window and the final waveform of the excited signal is demonstrated in Figure 3.2.

**Figure 3.1:** Group velocity dispersion curves for wave frequency selection

**Figure 3.2:** Demonstration of Hanning window modulation.
3.4 Finite Element Model

The model used in this chapter is illustrated in Figures 3.3a~d, which consists of seven wires assembled together in ABAQUS/CAE. The geometry of the model was selected based on the real multi-wire cable samples, which includes seven 5.08mm individual wires with the length of 260mm, each peripheral wire is set to have a circular cross section in normal plane, and in contact with other two neighbour wires and core wire in the centre location. The particular sample length representing one cycle of helical wires was selected to simulate the dynamic mechanics of the wave propagation without enormous computational cost.

![Figure 3.3 a) 3D Finite Element Model; b) the model of core wire; c) the model of peripheral wire d) Cross section of overall model](image)

3.4.1 Material Model

Table 4.1 summarises the material properties in the cable model that was applied in this simulation. The material properties of the cable are based on the parameters provided by cable suppliers.
### Table 3.1 Material Property

<table>
<thead>
<tr>
<th>Material</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>7.8e-9</td>
</tr>
<tr>
<td>(tone/mm³)</td>
<td></td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>200000</td>
</tr>
<tr>
<td>(MPa)</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.3</td>
</tr>
</tbody>
</table>

#### 3.4.2 Interaction Properties

In this section, in order to fully explore the wave propagation in multi-wire cable structures, the surface-based tie constraint formulation was used to assign the interaction properties. In ABAQUS/Explicit environment, the tie constraint could provide a simple way to bond surfaces together and obtain both accuracy and simplicity by enforcing contact constraints using a master-slave formulation, which prevents slave nodes from separating or sliding relative to the master surface (ABAQUS Manual 29.3.4).

#### 3.4.3 Mesh

After the model geometry and property assignment, the next step is mesh definition, which is particularly important because the accuracy of the simulation highly depends on the mesh quality. The multi-wire cable is meshed using C3D8R solid elements to effectively describe the ultrasonic guided wave propagation phenomenon. According to the spatial sampling criteria, the maximal element size should be small enough to allow the smallest wavelength of wave can exist in the computation domain as

\[ L_e = \frac{\lambda}{7} \]  

(3.4)

Where \( \lambda \) is the shortest wavelength of waves which may travel in the structure, and \( L_e \) is the
element size in the simulation.

By applying the velocity value extracted from previous experiment data, the wavelength can be calculated as

\[
\lambda = \frac{v}{f} = \frac{5000m/s}{500kHz} = 10mm
\]

Then, the element size of the model can be calculated as

\[
L_e = \frac{10}{7} = 1.43mm
\]

Therefore, the element size used for longitudinal direction was selected as 1.0 mm to simplify the mesh procedure while the element size for transversal section was set as 0.3 mm to improve the computational accuracy.

Though the appropriate element sizes has been selected, due to the complex geometry of the multi-wire cable structure itself, it was extremely difficult to create an ideal, uniform mesh for the established model. Therefore, the geometry of cross-section at each wire was partitioned to improve mesh quality, the process of partitioning is demonstrated in Figure 3.4.

\[\text{Figure 3.4 The details of partition}\]

Finally, with the geometry already partitioned into simpler shapes, the finite element model was meshed with 578952 nodes and 72369 elements totally. Figures 3.5a–c show an overview of the meshed model and other details.
Chapter 3 Numerical Simulation on Linear guided waves for Defects Detection

3.4.4 Analysis Steps
As mentioned before, Abaqus/Explicit module was selected to conduct dynamic analysis because this particular code is technically appropriate for dynamic simulation such as impact and wave propagation.

3.4.4.1 Determining Time Step ($\Delta t$)
All the calculations in this code are conducted based on an explicit central-difference integration rule, which is also known as explicit dynamic integration method, a mathematical technique for integrating the equation of the motion through time. This algorithm obtains the unknown values from information already known. In terms of wave propagation, specifically, the explicit dynamic operator satisfies the dynamic equilibrium at the beginning of the any given increment $t$, the movement of the waves is caused by the applied force on each node,
which can lead to disruption on the initial equilibrium, the accelerations calculated at any given
time $t$ are used to advance the velocity solution to time $t + \Delta t/2$ and the displacement solution
to time $t + \Delta t$. According to the explicit central-difference integration rule, the time step $\Delta t$ is
a vital factor and should be selected carefully. In order to avoid the numerical instability of
solution, the time increment used in an analysis must be smaller than the stability limit of
central-difference operator. Thus, in this particular study, the distance travelled by a wave with
the time step $\Delta t$ should smaller than the ratio of length of the smallest element to the velocity
of the fastest wave mode propagating in structure. Therefore $\Delta t$ should be defined as:

$$
\Delta t \leq \frac{L_{min}}{V}
$$

(3.6)

Where $V$ is the velocity of the fastest wave in the medium.

Since the size of elements has been determined as 1mm, $\Delta t$ could be calculated as:

$$
\Delta t \leq \frac{1 \times 10^{-3}}{5000} = 1 \times 10^{-6}
$$

However, because nonlinearity in multi-wire cable structure could cause the continually change
of the highest frequency of the model, which could subsequently change the highest velocity
of wave in the system and ultimately change numerical stability limit, a conservative time of
$1 \times 10^{-7}$ second was chosen as the limit for the integration time step to ensure the accuracy of
solutions.

### 3.4.4.2 Step Duration

The total calculation time was initially set as 5E-5 seconds, where first 2E-5 seconds was
planned for wave excitation and 3E-5 seconds was designed for wave propagation. However,
due to the wave dispersion phenomenon, the propagation time was generally lengthened. After
preliminary analyses, the most appropriate step duration was found as 2E-4 seconds.
3.5 Finite Element Modelling Setup

There are two main purposes in the numerical simulation. One is to obtain the overview of ultrasonic guided wave propagation in multi-wire cables. The other one is to investigate the feasibility of using guided waves to detect the flaw in cable structures. To investigate the effect of different wave excitations, two types of forces representing different wave excitations were applied. As demonstrated in Figure 3.6b the first type of waves was generated as concentrated force applied to the centre of one end of a particular helical wire along the axial direction of cable with an amplitude of 0.1 N, whereas the waveform in another scenario was achieved by the equivalent element contraction and expansion introduced by symmetric force applied along the short edge of selected area on the peripheral wire surface as shown in Figure 3.6a. All the forces’ amplitude varied with time following the signal designed from -1 to 1 during the wave excitation duration.

![Figure 3.6 a) Force group on the surface on wire; b) Concentrated load in the centre of wire terminal](image)

Based on the established cable model, notches were introduced as flaws at the middle of selected peripheral wire where guided wave was excited, the details are demonstrated in Figure 3.7. In this study, specifically, two notches were created and differentiated by their depths, 1.5mm and 3mm, respectively. The width of the notches were selected as 2mm, which is greater than the wavelength of the waves, so reflections from the back edge of the broken-wire flaws
could be detected, otherwise, the reflection from the back edge of the break will be ignored (Xu et al., 2013).

![Diagram showing selected peripheral wire, schematic demonstration of FE modelling setup, notch with 1.5mm in depth, and notch with 3mm in depth.]

**Figure 3.7:** a) Selected peripheral wire; b) schematic demonstration of FE modelling setup; c) the notch with 1.5mm in depth; d) the notch with 3mm in depth

In addition, a sensor network was designed to collect guided waves. The sensors located at specific locations were designed to collect the wave signals from the wire denoted as wire 1 where the guided waves were excited, the wire next to wire 1 and the wire opposite to wire 1. With such a configuration, the feasibility of guided waves for flaw detection would be fully explored in every wire of the cable.

As can be seen in Figure 3.8a, 7 groups of sensor elements were used to acquire the signals. Groups 1, 4 and 6 were used to collect reflection wave signals while groups 2, 5 and 7 were designed to receive transmitted signals. Sensor 3, in particular, was employed for general analysis in both wave excitation cases.
3.6 Results and Discussion

At the beginning of the result analysis, general features of the wave propagation in the established multi-wire cable model are explored. The wave signals generated in both excitation ways were analysed and compared, and their velocities were also calculated to verify the correction of the simulation and to provide basic parameters for further study. In the second part, to investigate the relationship between the guided wave propagation and defects, the simulation on the models with and without different macro defects were conducted.

3.6.1 General Features of Wave Propagation in Multi-Wire Cable Structures

The simulations on intact cable model with different wave excitation were conducted. Figures 3.9 and 3.10 indicate Von Mises equivalent stress contour during the wave propagation step for the cable model excited by centre-load and surface-forces, respectively. It can been seen
that for both cases, the excited wave from original wire gradually propagate from the loaded wire into the wires in the proximity and propagate through the cable, indicating that there are stable diffusion of energy during the propagation.

The stress output signals of wave propagation from sensor 3 in both modelling results are plotted in Figure 3.11. It can be seen that there are two main differences between these two signals. Firstly, the peripheral surface excitation waves generally have higher amplitudes value. Secondly, the waves excited by peripheral surface forces reached the sensor position faster, which means that the waves generated in this case have a higher velocity. The velocities of first arrival waves were both calculated below:

For the waves of centre-loaded excitation

\[ V_t = \frac{L}{\Delta t} = \frac{260mm}{5.41 \times 10^{-5}s} = 4805m/s \]  \hspace{1cm} (3.7)

For the waves excited by peripheral surface forces

\[ V_s = \frac{L_s}{\Delta t} = \frac{250 mm}{4.98 \times 10^{-5}s} = 5020m/s \]  \hspace{1cm} (3.8)

These velocity values were verified by the later experimental results as 4793m/s and 5093m/s, respectively, which demonstrates that the results from the simulation are reasonable.
Figure 3.9 Wave propagation in a multi-wire cable along the longitudinal direction in centre-load excitation
Figure 3.10 Wave propagation in a multi-wire cable along the longitudinal direction in peripheral surface excitation case
3.6.2 Defect Detection

To investigate the relationship between the guided waves and defects, wave reflection and transmission by the flaws are collected to evaluate the feasibility of using guided waves to monitor the integrity of multi-wire cable structure. The peripheral surface excitation was selected to conduct further study due to its higher amplitude of stress signal in time domain.

3.6.2.1 Flawed Wire (wire 1)

In the first of this section, the reflection and transmission waves in the broken wire itself are collected and plotted. Figure 3.12 indicates the wave reflections on wire 1 with and without a notch 1.5mm in depth. The identical wave shapes for both simulation cases can be observed at the beginning but after a certain time, some differences occur. The wave amplitude for model with the notch after about 3e-5 seconds becomes greater than the intact one, indicating that more energy are reflected by the flaw introduced on the cable. Similar results could be observed in Figure 3.12 b for the signals with and without a notch 3mm in depth.

By subtracting original signal from other signals, the waveform differences of separate cases could be obtained. As can be seen in Figure 3.13, the differences occur around 3e-5 seconds.
between sensor 1 and notches could be calculated as:

\[
D = \frac{\Delta t \times V_s - L_{\text{sensor}}}{2} = \frac{0.000032 \times 5020 - 0.1}{2} = 30.3\text{mm}
\]  

(3.9)

Then, by comparing the distance between the notch and sensor with the calculated value, the accuracy of the experiment results can be obtained as:

\[
P = 1 - \frac{L - L_c}{L} = \frac{30.3 - 30}{30} = 99\%
\]

(3.10)

In addition, it is easy to conclude that the amplitude difference of “intact-1.5mm notch” comparison before 5e-5 seconds could reach as great as 2e -3 MPa while the difference of “intact-3 mm notch” comparison has a peak value of 7.5e-3 MPa, which indicates that the deeper the notch is, the higher amplitude differences between intact and flawed signals in time domain could be. Therefore, the severity of the cable flaws can also be evaluated by using reflection signals.

Transmitted wave signals collected from sensor elements group 2 in wire 1 were also analysed and compared in same way. Though there is no chance to use transmitted signals to determine the location of cable flaw, the obtained results still can be used to examine the existence of cable defect by observing the amplitude changes of first arriving waves. It can be seen from the results in Figure 3.14 that the transmitted waves in cable without flaw general has higher amplitudes due to the fact that some of the energy were reflected because of the notch. The cable severity also could be detected by using the amplitude comparison as well. As can be seen in Figure 3.15, the amplitude differences of transmitted waves between intact model and flawed model would rise when the notch depth increases.
Figure 3.12 a) Reflections of intact model and model with defect 1.5mm in depth; b) Reflections of intact model and model with defect 3mm in depth; c) zoomed a; d) zoomed b.

Figure 3.13 a) Subtracted signal of intact model and model with defect 1.5mm in depth; b) Zoomed a; c) Subtracted signal of intact model and model with defect 3mm in depth; d) Zoomed c.
Figure 3.14. a) Wave transmission signal of intact model, model with notch 1.5mm in depth and model with notch 3mm in depth; b) Zoomed a

Figure 3.15. a) Subtracted transmitted signal of intact model and model with notch 1.5mm in depth; b) Subtracted transmitted signal of intact model and model with notch 3mm in depth
3.6.2.2 Other Wires

Stress signal obtained from sensors located on neighbour wire and opposite wire were similarly analysed following the same process. The reflection wave signals were shown in Figs. 3.16~17. It can be seen that the signals collected in wires other than wire 1 also show the sensitivity of inter-wire propagating guided wave to the macro flaw. The increased energy in flawed model simulation indicates that the reflections generated from the notch in selected wire also propagated into the neighbour wires and eventually reached into opposite wire. By using the velocity for surface loaded excitation case obtained from last section, the distance between sensors 4 and 6 and notches could be calculated as:

\[
D = \frac{\Delta t \times V_s - L_{\text{sensor}}}{2} = \frac{0.000032 \times 5020 - 0.1}{2} = 30.8\,mm \tag{3.11}
\]

\[
D = \frac{\Delta t \times V_s - L_{\text{sensor}}}{2} = \frac{0.0000321 \times 5020 - 0.1}{2} = 30.5\,mm \tag{3.12}
\]

The precisions of the calculation could be obtained as:

\[
P = 1 - \frac{L - L_c}{L} = \frac{30.8 - 30}{30} = 97.33\% \tag{3.13}
\]

And

\[
P = 1 - \frac{L - L_c}{L} = \frac{-(30.5 - 30)}{30} = 98.33\% \tag{3.14}
\]

Regardless the minor differences between three results, the accuracy of the proposed method for strand flaw detection is within a range of 94.6\% \sim 98.33\%. It could be concluded that it is feasible to use guided waves to locate the flaw in multi-wire cable structures.
Figure 3.16 Results obtained from neighbour wire a) Reflections of intact model, model with notch 1.5mm in depth and model with notch 3mm in depth; b) zoomed a; c) Subtracted signal of intact model and model with notch 1.5mm in depth; b) Zoomed c; e) Subtracted signal of intact model and model with defect 3mm in depth; f) zoomed e.
Figure 3.17 Results obtained from opposite wire a) Reflections of intact model, model with defect 1.5mm in depth and model with notch 3mm in depth; b) zoomed a; c) Subtracted signal of intact model and model with notch 1.5mm in depth; b) zoomed c; e) Subtracted signal of intact model and model with notch 3mm in depth; f) zoomed e.
The amplitude differences of stress signals between intact and defected wire grow as the notch depth increase, illustrating that the severer the flaw is, the greater energy would be reflected from it. However, it is noteworthy that though for the intact-1.5mm notch comparison, the stress signals obtained from all three wire demonstrate almost same amplitude differences, 2e-3 MPa, for intact – 3mm notch comparison, flawed wire (wire 1) shows the largest amplitude differences, 7.5e-3MPa, followed by its neighbour wire, 5e-3MPa, and its opposite wire, 3e-3MPa. This comparison means that when the flaw is severe to certain extent, the wave reflections on the flawed wire would be greater than those on neighbour wires, which could be used in practice to identify the flawed wires in multi-wire cable structures.

Transmitted wave signals collected from sensor element groups on other cable wire were also analysed and compared in the same way, according to analysis in Figure 3.18 and 3.19, the obtained results can still be used to examine the existence of cable defect by observing the amplitude changes of first arriving waves, where the transmitted waves in cable without flaw generally has higher amplitudes due to the fact that some of the energy were reflected because of the notch.

As can be seen in the Figs 3.18 and 3.19, for both neighbour and opposite wires, the amplitude differences of transmitted waves between intact and flawed models would rise when the notch depth increase. Therefore, the cable severity could also be detected by using the amplitude comparison.

Besides, by comparing the amplitude differences of intact and notched model results, it can be concluded that the amplitude change of stress signals due to the cable defects on flawed wire are most significant, which could also be used as a characteristic to identify the exact location of the cable defects.
Chapter 3 - Numerical Simulation on Linear guided waves for Defects Detection

Figure 3.18: Results obtained from neighbour wire a) Wave transmission signal of intact model, model with defect 1.5mm in depth and model with notch 3mm in depth; b) Zoomed c). Subtracted transmitted signal of intact model and model with notch 1.5mm in depth d) Subtracted transmitted signal of intact model and model with notch 3mm in depth;

Figure 3.19: a) Wave transmission signal of intact model, model with defect 1.5mm in depth and model with notch 3mm in depth; b) Zoomed c). Subtracted transmitted signal of intact model and model with notch 1.5mm in depth d) Subtracted transmitted signal of intact model and model with notch 3mm in depth;
3.7 Summary
Guided wave propagation in multi-wire cables and its feasibility to identify defects have been evaluated using finite element simulation in this chapter. Different wave excitation methods have been applied in the FE Model and results show their differences for generating guided waves, on the basis of which, waves excited in wire surface were used to detect the existence and severity of flaw in multi-wire cable structures. The numerical results demonstrate that the guided wave reflections and transmissions obtained from all 3 selected wires could be used to determine the location of flaws and their severity while the different characteristics between wires could also be used to identify the exact flawed wire, which reveals that guided wave could be used as a promising technique for defect detection in multi-wire cable structur
Chapter 4 – Experiment Study on Linear Guided Waves for Defect Detection

4.1 Introduction
In this chapter, the experimental verification of using ultrasonic guided waves to detect the presence of defects in multi-wire cables is presented. The experiment tests in this study were conducted on the free multi-wire cable and aimed to analyse the general characteristics of wave propagation in such a structure and its correlation to the defect. The first part of this section is focused on the description of the experiment setup whereas the second part demonstrated the detailed experiment processes, and the analysis of results obtained from experiment is presented in the last part of this chapter.

4.2 Experiment Materials and Measurement Equipment
Experiment specimen and devices used in this experimental study is presented in this section.

4.2.1 Test Specimens
The test in this phase conducted on a grade 270, seven-wire twisted strand with a diameter of 15.24mm, consisting of one core straight wire and 6 helical wires surrounding around the centre one. This strand matches the Australia standard of AS1311 and has been used as auxiliary reinforcement in many civil engineering applications such as long spanned bridges on railway, overhead crane construction, multi-floor industrial building. Figure 4.1 shows an overview of this particular strand and its properties are summarized in Table 4.1
Figure 4.1: Demonstration of the multi-wire cable specimen

Table 4.1 Properties of the seven-wires tested strand
(http://www.constructalia.com/repository/Products/CivilEngineering/Wire_Strands_EN.pdf)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength (MPa)</td>
<td>1860</td>
</tr>
<tr>
<td>Nom. diameter (mm)</td>
<td>15.24</td>
</tr>
<tr>
<td>Cross sectional area (mm$^2$)</td>
<td>139.0</td>
</tr>
<tr>
<td>Weight (kg/km)</td>
<td>1102</td>
</tr>
<tr>
<td>Min yield strength (KN)</td>
<td>234.6</td>
</tr>
<tr>
<td>Modulus of Elasticity (MPa)</td>
<td>195,000</td>
</tr>
<tr>
<td>Specimen Length (mm)</td>
<td>1500</td>
</tr>
</tbody>
</table>
4.2.2 Test Apparatus

The key hardware of the experiment measurement consists of four main parts: the ultrasonic guided wave generator, ultrasonic transducers, ultrasonic preamplifier and digital phosphor oscilloscope.

TEKTRONIX arbitrary/function wave generator AFG 3102 shown in Figure 4.2 was used to excite ultrasonic guided waves in this study. This device features 2 sample input channels with 14-bit resolution, 100MHz bandwidth, and 128 K (1K=1024 points) in memory depth. It includes all the features of sweep generators and function generators and arbitrary waveform can be generated with a maximum sample rate of 1 GS/s. With ArbExpress software waveforms can be seamlessly imported from any Tektronix oscilloscopes while external signals obtained can also be connected and added as the output signal. All these features make this wave generator a proper selection for this experimental study.

![Figure 4.2 TEKTRONIX Arbitrary/Function Wave Generator AFG 3102](image)

Electronic amplifier was used to increase the signal wave energy. The model employed in the present test is US-TXP-4 linear power amplifiers produced by Cipian Company. This amplifier could amplify signals without any distortion within a wide bandwidth form 10 kHz to 10 MHz, and therefore, deliver an enhanced transmitted wave signals and improve the sensitivity of ultrasonic guided waves to defects.
Piezoelectric transducers are used to convert mechanical energy into electrical energy and vice-versa. In this study, due to the strand’s geometry, two kinds of piezoelectric transducers were used to generate and acquire ultrasonic waves in different parts of the strand. The first type of ultrasonic transducer used is demonstrated in Figure 4.4, this particular transducer is produced by PI Ltd, both its particular flat shape and sensibility and efficiency in measurement of in-plane displacements make this sensor a suitable selection for wave generation and detection on peripheral surface. The high frequency ultrasonic wafer with 5mm in diameter used for transversal sectional signal acquisition is illustrated in Figure 4.5, making it possible to be attached as the sensor to the end of any wires in strand. All piezoelectric transducers were glued to the specimen and connected to the acquisition system by using adhesive.

Figure 4.3 Cipian US-TXP-4 linear power amplifiers

Figure 4.4 PZT transducer installed to the specimen
Finally, a digital oscilloscope (TDS 3000) was installed to monitor and record all data acquired by the array of sensors. The oscilloscope was connected to both the high-power amplifier and wave generator in order to monitor the output and amplified input signals simultaneously.

With abovementioned instruments, a data acquisition system was developed to control, execute and manage signal generation and acquisition process. A schematic representation of this data acquisition system is demonstrated in Figure 4.8.
4.3 Experimental Setup and Signal Processing

4.3.2 Experimental Setup

After the establishment of the data acquisition system, a signal generating and receiving network was designed to collect the ultrasonic guided wave signals from the tested specimen. Totally three wires in strand specimen were used for experimental study, i.e. wire 1, where the guided waves were excited at, the wire next to wire 1 and the wire opposite to wire 1. With such a configuration, the feasibility of guided waves for defect detection would be fully explored in every wire of the strand.

The piezoelectric transducers were installed on the strand, as demonstrated in Figure 4.9. One circular transducer was attached to the end of strand wire 1, one rectangular transducer was attached to the surface of wire 1, and both of these transducers were used as actuators to excite the guided wave signals on selected strand wire. Additional 6 rectangular piezoelectric transducers were used as surface sensors, sensor 1, 2 and 3 were used to collect reflection wave signals while sensor 4, 5, 6 were used to receive transmitted signals. Particularly, one circular
transducer was used as Sensor 7 for general analysis.

Once the experimental setup was configured and optimized, the test started by generating and collecting of wave signals on intact strand as benchmark data. The input signal used in former numerical study, a narrowband modulated sinusoids centered at 500 kHz using a Hanning window function was chosen as input signal in this experimental investigation as shown in Figure 4.10.

The output signal created from the wave generator was sent into the test specimen by the actuator, while the output signals were collected from sensors, the information were conveyed into the digital oscilloscope for the signal monitoring. The recorded data were later imported in Origin Pro for further analysis. Afterwards, artificial damage in the form of a transverse notch was made using a handsaw. The notch was created as 1.5mm in width and 2 mm in depth and the experiment was repeated on specimen with defects.

![Figure 4.8 Schematic demonstration of the sensor network](image-url)
4.3.3 Data Processing

The original signal was extremely complex due to the existence of broadband noise, superposition of scattered signals and other features. To solve these problems, discrete wavelet transform (DWT) method was applied to extract the signal within the targeted frequency range. Compared with other time-frequency approaches such as Digital Signal Filter, WT features conservation of energy during the transform, providing full signal information, localisation in both the time and frequency domains, and deployment of the signal with multiresolution. The DWT uses a series of low-pass and high-pass filters to decompose the original time-domain signals into several “frequency levels”, while at each level, high-frequency components and
low-frequency components are separated into details ($d_n$) and approximations ($a_n$). The lower and upper frequency limits of a specific sub-band are determined by both the sampling rate and the level number. In this study, the sampling rate was selected as 250 MKz, and the Dubechies wavelet of order 12 (DB12) was used for original signal decomposition. Finally, the time signal from the level 3 details ($d_3$) was extracted because the targeted wave frequency (500 kHz) is located within its corresponding frequency range (337.5 kHz~675 kHz), as illustrated in Figure 4.12.

Figure 4.11 Principle of DWT-based signal decomposition

Figure 4.13 compares the signals before and after the denosing process. It can be seen that,
after the reconstruction of extracted signals, the signals has been de-noised and any waveform changes of the obtained signals could be easily distinguished and recognised as caused by a defect.

![Figure 4.12 Comparison of signals before and after the denosing process: a) Original signal; b) Zoomed original signal; c) Processed signal; d) Zoomed processed signal.](image)

### 4.4 Results and Discussion

Alike the numerical simulation analysis in chapter 3, general features of the wave propagation in the specimen are first explored. The wave signals generated in both excitation ways were analysed and compared, and their velocities were also calculated to verify the simulation results.
and to provide basic parameters for further study. In the second part, to investigate the relationship between the guided wave features and defects, the wave signals collected on different wires of the specimen with and without defects were analysed.

4.4.1 General Features of Wave Propagation in Multi-Wire Cable Structures

Corresponding to the simulation study, for benchmark test, ultrasonic guided wave signals excited on both strand end and strand surface were investigated. The collected signals of wave propagation from sensor 7 in both excitation methods are plotted in Figure 4.14. It can be seen that the waves excited by peripheral surface actuator reached the sensor position faster, which means that the waves generated in this case have a higher velocity. The velocities of first arrival waves were both calculated below:

For the waves signal generated by actuator 1

\[
V_c = \frac{L}{\Delta t} = \frac{1500 \text{mm}}{3.125 \times 10^{-4} \text{s}} = 4793 \text{m/s} \quad (4.1)
\]

For the waves signal generated by actuator 2

\[
V_s = \frac{L}{\Delta t} = \frac{1400 \text{mm}}{2.75 \times 10^{-4} \text{s}} = 5091 \text{m/s} \quad (4.2)
\]

It can be seen that the velocity values calculated in experimental study are generally consistent with the results obtained from numerical simulation, which are 4805 m/s and 5020 m/s respectively, indicating good agreement in results from numerical simulation and experiment work.
Figure 4.13 Stress output signals from the “Sensor 7” in flawed wire
4.4.2 Defect Detection

To investigate the relationship between the guided waves and defect, after the notch was introduced, wave reflection and transmission by the flaw are collected and compared with benchmark signals to evaluate the feasibility of using guided waves to monitor the health of multi-wire cable structures. Due to the fact that in practice, although same experimental conditions such as actuators and sensors network could remain same, the experimental environment may be influenced by ambient factors such as outside vibrations and temperatures, it is impossible to use subtracted output signals obtained from different experiments. Therefore, in experimental study, minor differences between benchmark results and defect strand test results were neglected and the waveforms are compared by observing the significant differences.

4.4.2.1 Flawed Wire (wire 1)

In this section, the reflection waves in the broken wire itself are collected and compared with benchmark signals in Figure 4.15. Despite some minor differences, a discernible difference between the waveforms is seen around 2.6e-5 seconds due to the reflection of the guided wave from the defect, indicating that more energy are reflected by the flaw introduced on the cable.

![Figure 4.14 Output signals from the “Sensor 1” in flawed wire](image)

By using the velocity for surface excitation case obtained from last section, the distance
between sensor group 1 and notch could be calculated as:

\[ D = \frac{\Delta t \times V_s - L_{\text{sensor}1}}{2} = \frac{0.0002615 \times 5091 - 300}{2} = 51.56 \text{mm} \]  

Then, by comparing the distance between the defect and sensor with the calculated value, the accuracy of the experiment results can be obtained as:

\[ P = 1 - \frac{L - L_c}{L} = \frac{51.56 - 50}{50} = 96.88\% \]  

Transmitted wave signals collected from sensor 4 on flawed wire were also analysed and compared with its benchmark counterpart. Though it is impossible to use transmitted signals to determine the location of the flaw, the obtained results can still be used to examine the existence of cable defect by observing the amplitude changes of first arriving waves. It can be seen from the results in Figure 4.16 that the transmitted waves in the cable without flaw generally have higher amplitudes due to the fact that some of the energy were reflected because of the notch.

![Output signals from the “Sensor 4” in flawed wire](image-url)

**Figure 4.15** Output signals from the “Sensor 4” in flawed wire
4.4.2.2 Other Wires

Output signals collected from sensors installed on the neighbour wire and opposite wire were analysed following the same process. The reflection wave signals were shown in Figures 4.17 and 4.18. It can be seen that the signals collected in wires other than wire 1 also show the sensitivity of to the defect. The increased energy in flawed case indicates that the reflections generated from the notch in selected wire also propagated into the neighbour wires and eventually reached into opposite wire. By using the velocity for surface loaded excitation case obtained from last section, the distance between sensors 2 and 3 and notch could be calculated as:

\[
D = \frac{\Delta t \times V_s - L_{sensor2}}{2} = \frac{0.00027 \times 5091 - 300}{2} = 52.7\text{mm} \tag{4.5}
\]

\[
D = \frac{\Delta t \times V_s - L_{sensor3}}{2} = \frac{0.000235 \times 5091 - 300}{2} = 43.9\text{mm} \tag{4.6}
\]

The precisions of the calculation could be obtained as:

\[
P = 1 - \frac{L - L_c}{L} = \frac{52.7 - 50}{50} = 94.6\% \tag{4.7}
\]

And

\[
P = 1 - \frac{L - L_c}{L} = \frac{-43.9 - 50}{50} = 87.8\% \tag{4.8}
\]

Regardless the minor differences between three results, the accuracy of the proposed method for strand flaw detection is within a range of 87.8\% ~ 96.88\%. It could therefore be concluded that it is feasible to use guided waves to locate the flaw in multi-wire cable structures.
Transmitted wave signals collected from sensors on other cable wires were also analysed and compared in the same way, as shown in Figures 4.19 and 4.20, which can still be used to examine the existence of cable defect by observing the amplitude decrease of first arriving waves because of wave reflection by the notch.
Chapter 4 - Experiment study on linear guided waves for defect detection

Figure 4.18 Output signals from the “Sensor 5” in flawed wire

Figure 4.19 Output signals from the “Sensor 6” in flawed wire
4.5 Summary

In this chapter, experimental work has been conducted to verify the numerical simulation results. Based on the proposed finite element simulation, a data acquisition system was established, followed by an optimized experiment setup.

The general features of wave propagation in the test specimen were extracted and investigated. It is proved that the velocities of wave propagation in the tested strand are generally consistent with the numerical simulation results. After the notch was introduced, the follow-up study demonstrated that the guided wave reflections and transmissions obtained from selected wires could be employed to determine the location of flaw, demonstrating the suitability of using ultrasonic guided waves to detect the flaw in multi-wire cable structures. However, due to the ambient adverse influence in experiments, the severity and the exact flawed wire cannot be determined in current study, further experimental study is required to fully explore the feasibility of this defect detection technique.
Chapter 5 – The Application of Guided Waves in Load Monitoring with Non-linear Characteristics

5.1 Introduction

In this chapter, the technique to monitor the load levels in multi-wire cables was developed and verified using numerical simulation. Former research conducted by Nucera (2011) has verified the potential of using guided waves to monitor load level in multi-wire cable structures in experiment work. However, as demonstrated in Figure 2.11, their FEA results are quite complex to interpret.

In this study, the numerical analysis was carried out to simulate the nonlinear phenomenon of guided wave propagation in multi-wire cable structure. The main purposes of FEA study were to explore the inter-wire contact that appears responsible for the nonlinearity and other detailed contact and friction phenomena of guided wave propagation in such structures.

5.2 Finite Element Analysis

5.2.1 Basic Model

The Model used in this chapter is illustrated in Figures 5.1. Alike the previous finite element analysis, the model is constituted by seven wires assembled together in ABAQUS/CAE. The geometry of the model was selected based on the real multi-wire cable samples used in chapter 4 but the length of the cable was set as 260mm for the simulation of nonlinearity without enormous computational cost. The material properties used in chapter 3 was reused in this stage of study.
5.2.3 Interaction Properties
In order to model the contact interaction between the wires of the cable, the general contact condition as listed in Table 5.1 was selected as the contact interaction in preload (Standard) and wave propagation (Explicit) stages separately. In Abaqus/Explicit environment, the general contact formulation could obtain both accuracy and simplicity by enforcing contact constraints using a penalty contact method. As for Abaqus/Standard step, though there are some changes in the algorithms, general contact could still use finite-sliding, surface-to-surface contact formulation to define the proper contact conditions and ensure the results precision (Abaqus Manual 34.2.1).

Table 5.1 General contact

<table>
<thead>
<tr>
<th>Tangential Behaviour</th>
<th>Fraction Formulation = Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fraction Coefficient = 0.62</td>
</tr>
</tbody>
</table>

| Normal Behaviour     | Pressure-Over closure = “Hard” Contact |

Figure 5.1 Finite element model for load monitoring study
5.2.4 Boundary Conditions
Due to the fact that the model in this simulation would be under load during the first stage, boundary conditions were introduced to restrain the displacements to stimulate the anchorage system. Mechanical restraints applied to both cable’s ends include all displacements perpendicular to the longitudinal direction of the cable and twisting rotation around longitudinal axis. The longitudinal displacement of cable’s unloaded end was also constrained in order to apply the force at the other end. The details are listed in Table 5.2

<table>
<thead>
<tr>
<th></th>
<th>End 1</th>
<th>End 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>U3</td>
<td>Free</td>
<td>0</td>
</tr>
<tr>
<td>UR1</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>UR2</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>UR3</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.2.5 Mesh
Alike previous FEA for linear defect detection, the multi-wire cable is meshed with C3D8R solid elements to effectively describe the ultrasonic guided wave propagation phenomenon. Other vital parameters such as element size limit were also reintroduced in this simulation study. In order to boost the precision of the computational efficiency, the mesh density was progressively increased near the contact zones. Several meshes were performed with a decreasing level of element sizes in the contact area to find the most suitable mesh configuration. Finally, the element size along longitudinal axis was set as 1mm. In terms of
the element on transversal section, the size in inter-wire contact zone was set as 0.15mm while the size near outer surfaces was selected as 0.3mm. The model was therefore meshed with 960072 elements and 1044152 nodes. Figure 5.2 shows an overall view of the meshed model and other details.

![Meshed Model](image)

**Figure 5.2** a) Overview of meshed model; b) Cross section of meshed view; c) Zoomed view of one of cable’s end

### 5.2.6 Analysis Steps and Loads

Different to the simulation in the previous chapter, the numerical analysis of load monitoring includes two separate analysis steps to simulate the cable loading conditions. In detail, the FEA was split into two steps with different types of analysis methods: Standard static analysis and
explicit dynamic analysis. Because that the linear perturbation (preload phrase) cannot be followed by the nonlinear procedures (wave propagation), ABAQUS Explicit-Standard interface has been used to transfer the deformed model from the first standard static step to explicit dynamic analysis.

5.2.6.1 Abaqus/Standard
Abaqus/Standard is a general-purpose, finite element module employed to simulate static and low-speed dynamic events. By using static equilibrium, this ABAQUS code can be used to conduct linear perturbation analyses include eigenvalue buckling load prediction and linear static stress analysis, which are basically the case in this study. Besides, the results within an ABAQUS/Standard can be used as the starting conditions for the following ABAQUS/Explicit.

5.2.6.2 Preload Stage
At this preload stage, as demonstrated in Figure 5.3, a uniform pressure (negative as tension) was applied directly to the ends of all wires to simulate the tension force existing in practical condition. The static load is broken into smaller increments and the iteration is applied within the increment to attempt to find the equilibrium solution. Convergence (equilibrium state based on predefined criteria) need to be achieved and the time incrementation during the step is based on number of iteration required to converge. However, after the preliminary analysis, it has been found that due to the complex geometry and numerous element numbers, convergence is difficult to achieve under the default incrementation settings, therefore, several groups of incrementation data were tested and final parameters were listed in Table 5.3. Six different magnitudes of pressure were applied respectively on the cable as listed in Table 5.4 with their proportion to the ultra-tensile strength. Both stresses and strains were selected as output during this step to obtain the associated stress and strain state, which will be used as initial conditions for the following Explicit analysis after the model importation.
Table 5.3 Incrementation parameters during Stage 1

<table>
<thead>
<tr>
<th>Time period</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2s</td>
<td></td>
</tr>
</tbody>
</table>

**Incrementation Type:**

- Automatic

**Maximum number of increments**

- 100

**Increment size**

- Initial: 1e-3s
- Minimum: 1e-8s
- Maximum: 1s

Table 5.4 Applied tensile forces during step 1

<table>
<thead>
<tr>
<th>Pressure Level</th>
<th>ultra-tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>465 MPa</td>
<td>25% UTS</td>
</tr>
<tr>
<td>744 MPa</td>
<td>40% UTS</td>
</tr>
<tr>
<td>960 MPa</td>
<td>50% UTS</td>
</tr>
<tr>
<td>1116 MPa</td>
<td>60% UTS</td>
</tr>
<tr>
<td>1395 MPa</td>
<td>75% UTS</td>
</tr>
<tr>
<td>1860 MPa</td>
<td>100% UTS</td>
</tr>
</tbody>
</table>
5.2.6.3 Import Modelling Process

ABAQUS provides a capacity to transfer a deformed mesh and associated state between ABAQUS/Standard and ABAQUS/Explicit. In this study, as demonstrated in Figure 5.4, the cable model was transferred from ABAQUS/standard to ABAQUS/Explicit to simulate guided wave propagation after the preloading phase. As discussed in chapter 2, in multi-wire cable structures, nonlinearity is mainly caused by the inter-wire contact force between wires, which will vary with the change of the forces and it is obvious that the rise of longitudinal strain would increase the inter-wire contact forces.
Prior to the importing process, in ABAQUS/Standard, the restart data during simulation process was requested and its restart frequency was set as 500 kHz, which is the excitation frequency of guided waves during stage 2. Besides, the geometric nonlinearity was changed from default setting “NO” to “YES” to enable the reference configuration update during next stage.

After the preload phase, the meshed model with new strain was extracted as output database file and imported to the part section of ABAQUS/CAE with the basics of setup for the importing process as Reference configuration (updated) and material state (no state). In such a configuration, the deformed model could be imported into the simulation of next stage without the effect of out-balance state in the first place.

5.2.6.4 Wave Propagation Stage

During this stage, basic parameters, such as material properties, mesh details and contact conditions are identical with those in preloading phase due to the fact that the model was imported from the first stage. After redefining the boundary conditions, the increment step is selected as 1e-7 seconds for the reason mentioned in chapter 4 to obtain a stable solution. The duration of this stage was set as 2e-4 seconds.

The load applied during second step was a concentrated force with a frequency of 500 kHz and amplitude of 0.1 N, which was applied to the end of one particular helical wire in Figure 5.5. The sinusoidal signal was multiplied with a Hanning window in order to get the energy more concentrated at the central frequency, therefore, the signal modulated in chapter 3 was employed in current study.
5.2.7 Results and Discussion

5.2.7.1 Scope of the Analyses
For the purpose of analysing higher-order harmonics generation in the conditions of different preload forces, the results for every load levels were examined separately in both preload stage and wave propagation stage, focusing on the load evaluation in stage 1 the higher-order harmonics generation in stage 2. The results were then examined to correlate the wave nonlinearities with load levels.

5.2.7.2 Preload Stage
Prior to the importing process, the results obtained from preload stage simulation were analysed to ensure that the deformed models are appropriate for the further research in the next step.

Figure 5.6 illustrates Von Mises equivalent stress contour at the preload step with a tension force of 50% UTS. It can be seen that inter-wire contact stress arises with the growing tension force, indicating that there is stable diffusion of energy during the preload duration.

By selecting elements in both the core wire and peripheral wire, typical stress and strain in terms of time can be drawn as shown in Figure 5.7, which indicates that a well-balanced and
consistent force has been applied on the cable structure.

Same process was repeated to obtain results from the rest cases, and their averaged pressures by simulation are calculated and listed in Table 5.4, compared with their designed counterparts. It can be seen that despite of some minor variances, the preload levels in this simulation are basically in line with original applied pressures.

![Figure 5.6 von Mises Stress Contour Plot – Preload step – 50% U.T.S.](image)

![Figure 5.7 50% U.T.S a) stain vs time curve; b) stress vs time curve](image)
Table 5.4 Comparison of applied pressures and simulated results

<table>
<thead>
<tr>
<th>Ultra-tensile strength</th>
<th>Applied pressure</th>
<th>Averaged pressure by</th>
</tr>
</thead>
<tbody>
<tr>
<td>25% UTS</td>
<td>465 MPa</td>
<td>455 MPa</td>
</tr>
<tr>
<td>40% UTS</td>
<td>744 MPa</td>
<td>743 MPa</td>
</tr>
<tr>
<td>50% UTS</td>
<td>930 MPa</td>
<td>926 MPa</td>
</tr>
<tr>
<td>60% UTS</td>
<td>1116 MPa</td>
<td>1110 MPa</td>
</tr>
<tr>
<td>75% UTS</td>
<td>1395 MPa</td>
<td>1383 MPa</td>
</tr>
<tr>
<td>100% UTS</td>
<td>1860 MPa</td>
<td>1856 MPa</td>
</tr>
</tbody>
</table>

5.2.7.3 Wave Propagation Stage

Figures 5.8 ~ 5.10 show the von Mises stresses for the wave propagation step at different stages. Wave propagation phenomenon is clearly outlined in loaded peripheral wire. Complex stress distribution during the step which was caused by nonlinear dynamic effects was also been observed. In this case, considering a generic element in the core wire around the centre axis in Figure 5.11, stress signals at longitudinal direction (S33 in this study) were extracted.

Figure 5.8 von Mises Stress Contour Plot for the whole cable – Step 2 Time = 5e-5s
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Figure 5.9 von Mises Stress Contour Plot– XY-pane Section View Step 2 Time=8e-5s

Figure 5.10 von Mises Stress Contour Plot–Interwire nonlinear dynamic effect during Step 2
Then the signals processed by a fast Fourier transform (FFT). Nonlinear character was clearly observed with a peak corresponding to fundamental harmonic (in this case at $f=500$ kHz) and other peaks that reflect the second harmonics at 1000 kHz ($2f$) and third harmonics at 1500 kHz ($3f$).

Figure 5.12 Time domain representation of signal for cable preloaded with 50% U.T.S.
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5.2.7.4 Nonlinear Amplitude Analysis

By repeating the processes for the models under other tensile pressures, the energy distribution in terms of frequency for the cases of preload forces from 25% U.T.S to 100% U.T.S were plotted in Figures 5.14-5.19. It is observed that the second harmonic peak amplitude decreases as the preload level increase, which is consistent with the expectation concluded in previous chapter.

Because all the data collected in the same element and the same frequency was selected for each modelling, the nonlinear parameter can be simplified as:

$$\beta = \frac{A_2}{A_1^2}$$

The amplitudes of second harmonic and primary harmonic of FFT spectra for all the preload cases were extracted to quantify the influence of preload level applied to the structure on the inter-wire nonlinearity. As shown in Figure 5.20, $\beta$ value decreases with increasing load level form 25% U.T.S to 100% U.T.S. Therefore, an inverse relationship was built between nonlinearity and preload levels, which could be used to monitor the load level of multi-wire cables.
Figure 5.14: FFT Spectrum of S33 field output at selected element for the preload level of 25%.

Figure 5.15: FFT Spectrum of S33 field output at selected element for the preload level of 40%.
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Figure 5.16: FFT Spectrum of S33 field output at selected element for the preload level of 50%.

Figure 5.17: FFT Spectrum of S33 field output at selected element for the preload level of 60%.
Figure 5.18: FFT Spectrum of S33 field output at selected element for the preload level of 75%.

Figure 5.19: FFT Spectrum of S33 field output at selected element for the preload level of 100%
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**Figure 5.20**: Nonlinear parameter vs. Preload level
5.2.7.5 Nonlinearity Analysis Based on Energy Integration

Despite the fact that the nonlinearity analysis based on the signal amplitudes at targeted frequencies show a consistent inverse relationship, there are still some concerns arising on the accuracy of analysis due to the disturbance of dispersion and multimodality during wave propagation. For instance, the difference between the amplitudes of primary frequency for different preloaded cases and the energy envelopes vary form case to case. Therefore, a more conservative computational method to analyse the frequency domain signals is employed to calculate the total energy between different frequency bands in this section to provide a more precise analysis.

As demonstrated in Figure 5.21, the energy was calculated as the area by using an integration algorithm. The selected frequency band for primary frequency was 400 kHz~600 kHz, while the band for second harmonic frequency was ranging from 950 kHz~1050 kHz. The frequency bandwidths were selected as 200 kHz for primary frequency and 100 kHz for second harmonic frequency in FFT spectra, since only in this way, selected bandwidth could contain most of peak values and sidebands, which stand for the nonlinear energy of signal that disturbed by the dispersion and multimodality during wave propagation.

Figures 5.22~ 5.27 show the calculated values of the area extracted from the frequency domain signals during the wave propagation for the model with preloaded pressures. As can be seen from these figures, the integrated values of the second harmonic decrease as the preload level increase as well. The nonlinear parameter in this section is also simplified as:

\[ \beta = \sqrt{\frac{S_2}{S_1}} \]

Where \( S_1 \) the area value of primary frequency is band and \( S_2 \) is the area value of second harmonic frequency band.
Figure 5.21: A demonstration of Integration method
Figure 5.22: Values integrated from FFT Spectrum of S33 field output preload level 25%.

Figure 5.23: Values integrated from FFT Spectrum of S33 field output preload level 40%.
Figure 5.24: Values integrated from FFT Spectrum of S33 field output preload level 50%.

Figure 5.25: Values integrated from FFT Spectrum of S33 field output preload level 60%.
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Figure 5.26: Values integrated from FFT Spectrum of S33 field output preload level 75%.

Figure 5.27: Values integrated from FFT Spectrum of S33 field output preload level 100%.

The nonlinear parameter for the second harmonic as a function of load level is shown in Figure
5.28, it can be seen that, though there exist some minor differences, β values still share a similar trend with its counterparts extracted from the amplitude.

**Figure 5.28:** Nonlinear parameter obtained from integrating results vs. Preload level
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5.3 Summary
Finite element analyses were conducted in this study to capture the behaviour of ultrasonic guided waves in a multi-wire cable that under different preloaded levels. The well-established model created in former chapter was used with several setup changes. The whole process was divided into two stages in ABAQUS using different algorithms. The preloading phase simulated the loading conditions and after the model importation process, the simulation restarted with waveform excitation to explore the nonlinear properties of waves in the multi-wire cable structure. The wave signals after a fast Fourier transform indicate that second harmonic peak decreased as the preload level increased. Though there are some small variances on peak value of fundamental frequency, the calculated nonlinear parameters shared a same decreasing trend. In order to get rid of disturbance caused by dispersion and multimodality during wave propagation, the corresponding energy was integrated and reanalysed, and the results revealed a similar trend, which demonstrated the feasibility of using ultrasonic guided waves to monitor the load level in multi-wire cable structures.
Chapter 6 - Conclusion and Recommendations

This thesis presents the results of study on ultrasonic guided wave propagation in multi-wire cable structures to explore the feasibility of guided waves to detect macro defects as well as to monitor the load levels in cable system. Both experimental and numerical studies were undertaken for cable flaw detection while for load monitoring the study focuses on the FE simulation. This chapter summarises the major findings from this study, and provides recommendation for future research.

6.1 Conclusions

In this thesis, ultrasonic guided wave technique was studied to evaluate its feasibility of monitoring the structural integrity of multi-wire cable structures.

In the first place, a brief literature review was conducted to build a firm basis based on which the research program was proposed. After the introduction of basic overview of structural health monitoring, a review on current progress of monitoring the preloaded cables is presented. The basic of ultrasonic guided waves is also addressed to provide a general background, followed by a description on the properties of ultrasonic guided waves in multi-wire cable structures. A detailed review regarding the ultrasonic guided waves is also presented to explore both their linear and nonlinear characteristics in cable structures.

On the basis of literature review, a series of finite element analysis were conducted using Abaqus/Explicit to explore the feasibility of using ultrasonic guided waves to detect the macro defects in multi-wire cable structures. The numerical results demonstrate that the guided wave reflections and transmissions obtained from all selected wires could be used to determine the location of flaws and their severity while the different characteristics between wires could also be used to identify the exact flawed wire, which reveals that guided waves could be used potentially for defect detection in multi-wire cable structures.
In order to verify the simulation results, experimental tests were developed and conducted. The investigation on the general feature of wave propagation in the tests proved the results from numerical study. The detection of a notch on a multi-wire cable also illustrated the feasibility of ultrasonic guided waves to detect the flaw in multi-wire cable structure.

Finite element analyses were also conducted in this study to investigate the nonlinear characteristics of ultrasonic guided waves propagating in multi-wire cables under different preloaded levels. Different from previous studies, which basically use one step to model both static and dynamic simulation, the whole process of the numerical simulation in this study was divided into two stages in ABAQUS using different algorithms. The preloading phase simulated the loading conditions and after the model importation process, the simulation restarted with waveform excitation to explore the nonlinear properties of waves in the multi-wire cable structure, which significantly improve the simulation precision. The wave signals after a fast Fourier transform indicate that second harmonic peak decreased as the preload level increased. Its corresponding wave energy was integrated to minimise the adverse influence by dispersion and multimodality during wave propagation. The results revealed a similar trend, demonstrating the feasibility of ultrasonic guided waves to monitor load levels in multi-wire cable structures.

**6.2 Recommendations on future work**

Based on the current study, further experimental and numerical studies are needed to fully understand the ultrasonic wave propagation in multi-wire cable structure. Firstly, since the results presented in chapter 3 were simulated on the small-size cable, there may exist some problem that could happen when ultrasonic guided waves are propagating over a long distance. It is better to establish a large model that could simulate the cable structures used in practice to further investigate the attenuation of guided waves.
As for experimental work related to the macro defect detection in cable, due to limitations of laboratorial conditions, the results presented in chapter 4 are incapable of quantifying the relationship between defects and wave features. Hence, parametric studies on wave propagation in structures with different defect severities and locations are also recommended in the future work.

Secondly, the experimental work about load monitoring in cables need to be conducted to verify the proposed load monitoring method that has been proved by finite element work in chapter 6. In terms of the numerical simulation, as the results presented in this study is based on the single 7 wire cable, more finite element simulations with different physical conditions and various experimental tests should be conducted to determine the feasibility of the proposed method on cables with different geometric properties, configurations and materials. Guided wave propagation in multi-wire cable structures with various excitation modes should be investigated as well to further optimise the wave propagation and possible mode conversions when interacting with defects.
References


References


References


References


