

MODELLING OF GUIDED ULTRASONIC WAVE IN AIRCRAFT WIRING

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ABSTRACT

Degradation and failure of aircraft wiring insulation results in potential flight safety critical system failure or in smoke and fire due to arcing. Therefore, there is a need to detect any defect within the physical structure of the aged wire before any malfunction takes a place. There are different types of non-destructive testing techniques available for aircraft wiring inspection and one of them is the ultrasonic guided waves technique. Using guided ultrasonic wave, inspection can be carried for a long distance from a single location. In order to understand the behaviour of guided waves in aircraft wiring, 2D and 3D modelling was carried out using COMSOL Multiphysics. The modelling tool was used to simulate and predict the behaviour of guided wave characteristics in wires with respect to the stiffness property of the insulation. Artificial anomalies were introduced into the wire and the change in physical characteristics was again modelled. Finally, numerical and experimental results establishing the validity of these models are discussed.

1. Introduction

Economic growth in the aerospace industry has led to a continuous increase in air-traffic for the past decades. This increase is expected to continue at even higher rate for the next two decades. Economists expect that the aerospace industry will be worth €1.6 trillion in the coming few decades [1]. A significant percentage of this figure is planned to be spend on maintenance. One of the greatest concerns the aerospace industry has is ageing wiring inspection. Aircraft wires operate under constant change of operational conditions i.e. aircraft wires might operate under a cold, hot or humid environment with variations in the atmospheric pressure. Operating in such conditions might create chafes, cracks, cuts, delamination or embrittlement in the insulation flow of the aircraft wires. In addition, aircraft wires operate under mechanical vibrations, mechanical stress, moisture and elevated temperatures. The poor conditions the aircraft wires operate in will bring it to a failure status as it is easy to become brittle or cracked. This status of the aircraft wire is a potential of a fire hazard. Therefore, there is a need for an inspection technique to improve the reliability of the aircraft. This consequently will reduce the number of air-traffic accidents, loss of life and associated compensation costs resulting from failure of critical aircraft structure components [1]. Non-destructive testing (NDT) technology can be used to inspect aircraft wires. NDT is promising the aerospace industry to reduce its maintenance cost up to 70%. NDT will increase the system lifetime operation. This will consequently reduce the need for new products, which gives financial gain to the aerospace industry. There are several NDT techniques used to inspect aircraft wires. Low Power Laser-Diode is one technique used to inspect wires; it uses a low power laser diode to generate ultrasound. Low power laser diodes can generate flexural and longitudinal wave mode. These wave modes can be detected by either a conventional ultrasonic transducer or a laser diode. Laser diode with its low power signal has been used to detect heat damaged wires but not for assessing the condition of aging wires. Furthermore, the size of the laser diode makes it practically difficult to use it in this application.

On the other hand, PASD (Pulse Arrested Spark Discharge) technique is also used to inspect aging aircraft wires. PASD operates by discharging electrical sparks in the wire. The sparks have a high voltage with short duration and low energy (few mJ). This technique is used in coaxial cables, twisted shielded pairs and single wire bundles. However, in this technique, the insulated materials need to be removed in order to detect defects in the conductive material of the wire. Time Domain Reflectometry (TDR) is also another NDT technique used to inspect aircraft wires. It operates by generating a short pulse into the wire. The pulse will reflect when there is a flow of discontinuity or the signal hits the wire end. TDR has the ability to detect small anomalies such as frays and chafes [7, 8]. On the other hand, Frequency Domain Reflectometry (FDR) is an alternative technique used for inspection. It works on the basis of transmitting low voltage high frequency signal in a wire. The signal will reflect from any anomaly along the length of the wire. However, this technique requires disconnecting one end of the cable to enable the test fixture to be connected to transmit its signal. The connection and reconnection mechanisms increase the risk of induced maintenance failure. This technique is useful for open and short circuits but not for detecting small anomalies. Furthermore, FDR lacks the ability to detect defects in the insulation where most of the fire hazards occur in addition to the inability to detect small anomalies [2, 3].

This paper is looking at potential of utilising ultrasonic guided waves as an NDT technique to inspect ageing aircraft wires. Guided wave uses the cylindrical geometry of the wire as a wave guide to propagate through its structure [4]. Under the assumption that there is a perfect contact condition between the two materials [5, 6], guided waves propagate in both the conductors and insulators of the insulated aircraft wires. There are two types of wave modes existing in cylindrical geometry axi-symmetrical and flexural wave modes [1, 4, 5]. The axi-symmetric wave mode is non-dispersive at the low frequency. The axi-symmetric wave mode is in the order of a zero circumferential wave mode and can be divided into two types; the axi-radial and torsional. The axi-symmetric wave mode decreases slightly below the Rayleigh velocity as the frequency increases. On the other hand, the circumferential wave mode order one is the flexural wave mode. This wave mode is highly dispersive at the low frequency range. However, the velocity of this wave mode tends to approach just below the Rayleigh wave mode velocity as the frequency increases [5, 4, 6]. Furthermore, the velocity of both wave modes is a function of the material stiffness; this includes the type of conductor and insulated materials, geometry, frequency, wave mode order. A number of authors have reported that the flexural wave mode has a higher energy than the axi-symmetric wave modes [3, 4]. This is due to the way of excitation. As the transmitting transducer excites one side of the wire, this results in pushing the whole section of wire is pushed to the side and produces the flexural wave mode [4]. Furthermore, the authors have reported that the insulation in wires has an impact on the behaviour of the propagated wave modes because as the insulation decreases the magnitude velocity of the travelling wave mode and gives a higher rate of attenuation [4,6]. In addition, insulation has an effect on the dispersion curves, where it decreases the frequency range of the non-dispersive region. However, in order to understand the behaviour of guided wave in such a structure, dispersion curves are constructed.

2. Dispersion Curves

Dispersion curves are used to describe the nature of the existing wave modes at a particular frequency with respect to its travelling velocity. Dispersion curves have been constructed for an insulated wire. The material property data are obtained from the literature [4], with the following parameters:

Material	Brass	Heat Shrinking Tubing
Young's Modulus (GPa)	108.94	0.72
Density (kg/m^3)	8500	958
Poisson's Ratio	0.35	0.46
Rayleigh Velocity, (m/s)	2036	484
Radius, (mm)	1.59	2.175

Table 1: material property and dimensions for the Brass and Heat Shrink Tubing [5]

The radial displacement in this figure shows very little amplitude vibration taking place. On the other hand, operating at the high frequency non-dispersive region (see fig 1.b), the longitudinal wave mode L (0,1) turns its axial displacement to radial displacement. Here, where most of the propagation takes place in the insulation with no displacement in the conductor's material. Furthermore, figure 1.e&f shows that operating at the dispersive region, all the axial and the radial displacement will be taking place in the insulators with no propagation in the conductor's material. Therefore, in order to propagate L (0, 1) in both insulator and conductor materials, exciting longitudinal wave-mode at low frequency will be the convenient way to propagate guided waves.

3. Numerical Modelling

3.1 1-D Analytical Model

Both dispersion curves in figure (1) and literature confirm the findings for the insulator wires. Flexural wave-mode does not appear to exist in such a structure in the low frequency region. Therefore, in this paper longitudinal wave mode will be the focus of this work, to investigate its ability to inspect insulated wires. A 1-D analytical model is developed to understand the effect of the mechanical vibration of the wire when a longitudinal effect occurs. The wave equation for a 1-D problem (or sometimes called uni-directional wave equation) is:

$$\frac{d^2u}{dx^2} = \frac{1}{c^2} \frac{d^2u}{dt^2} \quad (1)$$

$$c = \sqrt{\frac{E}{\rho}} \quad (2)$$

Where c is the wave velocity
 E: young modules
 p: material density

This equation is derived under the assumption that the displacement is taking place in one direction (In this case it is the longitudinal direction), while the displacement in other directions is neglectable with a rate of change equal to zero. Based on the dispersion curves, this model is valid at the low frequency range of the longitudinal direction. A 2-D axi-symmetric model is designed to investigate the effect of the stiffness of the insulator material on the longitudinal wave mode.

3. 2-D Axi-Symmetric Model

Since the investigation is focusing on the longitudinal wave mode which is an axi-symmetric mode in nature, a 2-D axi-symmetric model is used to model the behaviour of longitudinal wave mode by changing the stiffness property of the insulation. An axi-symmetric model assumes that the excitations and the structure are axi-symmetric in form. This type of model does not support any flexural effect; therefore there will be no flexural modes existing in the model. The model is done at a fixed frequency of 200 kHz. This type of model will enable a better understanding of propagating longitudinal wave modes in such a structure.

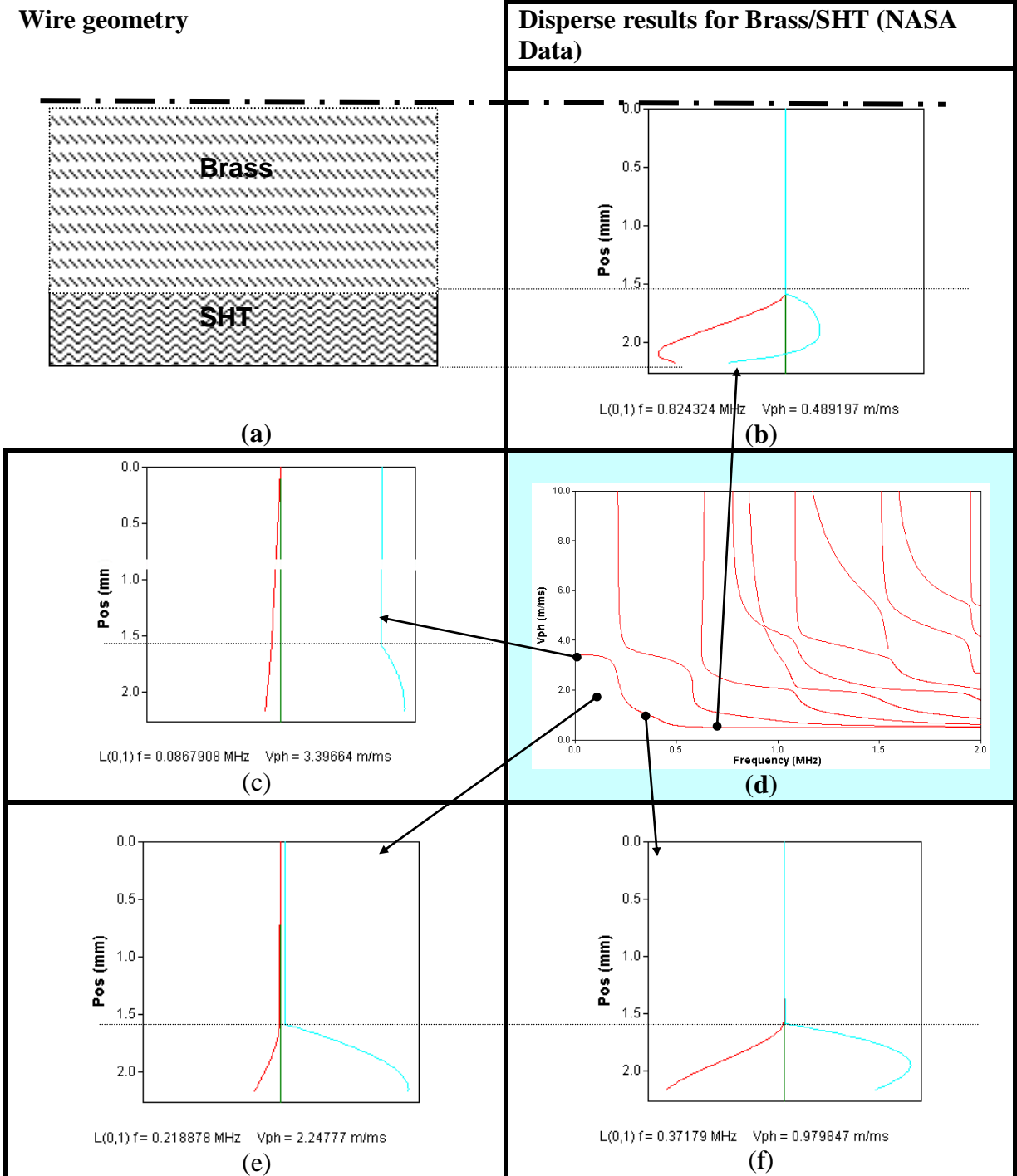


Figure (1): shows different graphs for describing the displacement at different regions in the dispersion curves for the insulated wire: (a) representation insulated wire structure, (b) displacement of guided wave at high frequency in the non-dispersive region, (c) displacement of guided wave at low frequency in the non-dispersive region, (d) dispersion curves for insulated wires, (e) displacement of guided wave at the dispersive region at the low frequency region, (f) displacement of guided wave at the dispersive region at the high frequency region.

Figure (2) shows the effect of changing the stiffness material of the insulation in an insulated wire. The models look at the nature displacement in the conductive material, interface, insulation material when the insulation material is the same as:

- **Conductive material:** Most of the displacement in this model is focused on the longitudinal direction on both materials with very little propagation in the radial direction. See figure (2.a).

- **Density is one quarter of the conductive material ($\rho = \frac{\rho}{4}$):** The displacement is taking place in both shapes, the radial and the longitudinal. However, the displacement is elongated. See figure (2.b)
- **Young modules is one tenth of the conductive material ($E = \frac{E_b}{10}$):** This model shows the effect of dispersion when the young modules has changed. The excited longitudinal mode is more closer to compression than Rayleigh as the energy is propagating in both wire and insulation as shown in figure(2.c). Also this model shows that the propagating wave mode is dispersive.
- **Shrinking Heat Tubing (SHT) as coupled material:** The radial displacement of the conductive material was little; however, the displacement of insulation is significant for the radial. The longitudinal displacement is more significant with relatively higher amplitude in the insulation, which means that the excited longitudinal wavemode is diverted to surface wave at this frequency. See figure (2.d).

3.1 2-D Axi-Symmetric Model

To study the effect of exciting different frequencies for insulated wires with respect to an artificial defect, a model has been created. The stiffness property in table 1 is used to model an insulated wire. The wire has the following geometrical description. After the first 20cm the bare brass wire become insulated with the same stiffness material as the conductive. The defect has been created at 60cm. This description is represented in figure 3. The model has been excited with several frequencies 40 kHz, 120 kHz and 200 kHz.

Figure (4.a&4.b) shows the displacement at position 45cm at the wire surface. At 40 kHz and 120 kHz the arrived signal with its reflection from the flow of discontinuity can be identified. The travelling signal in these two frequencies is a compression wave where the displacement in the insulation and the conductors are continues. This correlates with the findings in the dispersion curves in figure (1); at low frequency there is L(0,1) wave mode with a non-dispersive compression type. However, at 200 kHz the longitudinal wave becomes a Rayleigh wave where most of the energy is focused at the surface of the wire. The Rayleigh wave mode at this frequency is dispersive. This is due to operating at high frequency and also due to the existence of a softer material in the insulation.

The 2-D axi-symmetric model has the limitation of only presenting the longitudinal effect with no flexural existence. Therefore, there is a need to improve the model to count for any possibilities of any occurrence for a flexural effect. The 3-D model provides a higher level description for any occurrence of other wave modes including longitudinal, flexural and torsional.

3.2 3-D Model

In a 3D model, all the modes can be excited, non axi-symmetric geometry can be carried out and any flexural effect is considered. However, the aim of this model in figure (5) is to excite L(0,1) at a frequency of 150kHz. If there are any existing modes generated by this excitation, the model will present it.

The axial displacement is considered at different location points along the length of the wire (z-direction). Figure (6) shows the propagation of longitudinal wave-mode through different points at the core centre of the wire. This clearly shows that there is only one wave mode travelling in the wire structure; this is the L(0,1). Furthermore, it is important to note that with respect to this excitation there are no interface modes between the rigid and the soft material in the wire. This is shown in figure (7) which agrees with figure (6). The 3-D model and the 2-D axi-symmetric models have confirmed that there is only one wave-mode propagated below the cut-off frequency. This wave mode is the longitudinal wave mode. The longitudinal wave mode is a compression wave mode below the cut-off frequency. The longitudinal wave mode converges to Rayleigh

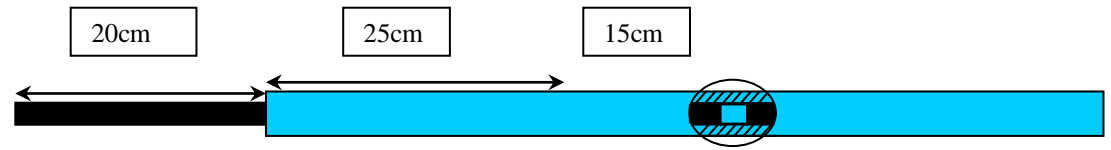


Figure (3): shows the insulated wire with an artificial defect

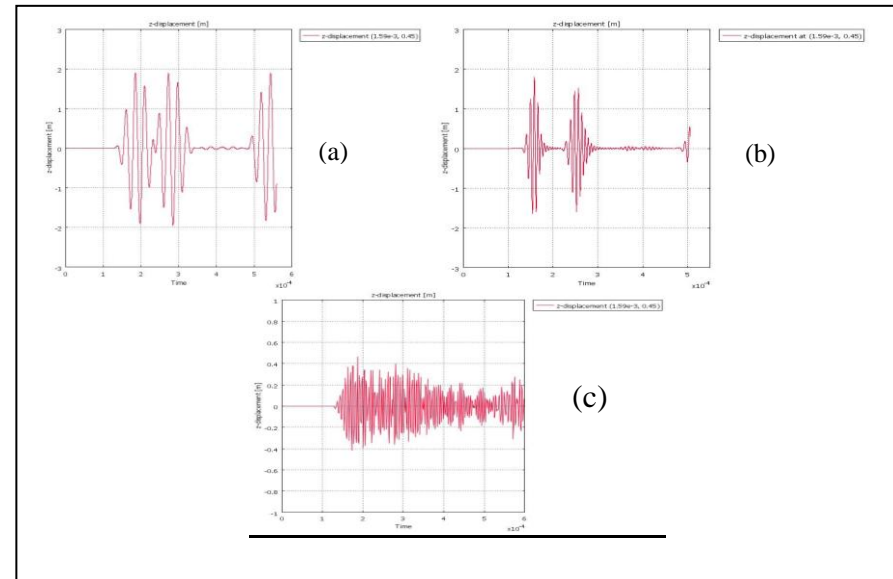


Figure (4): shows the displacement at position 45cm from the excitation surface at the wire surface at (a) 40 kHz (b) 120 kHz (c) 200 kHz

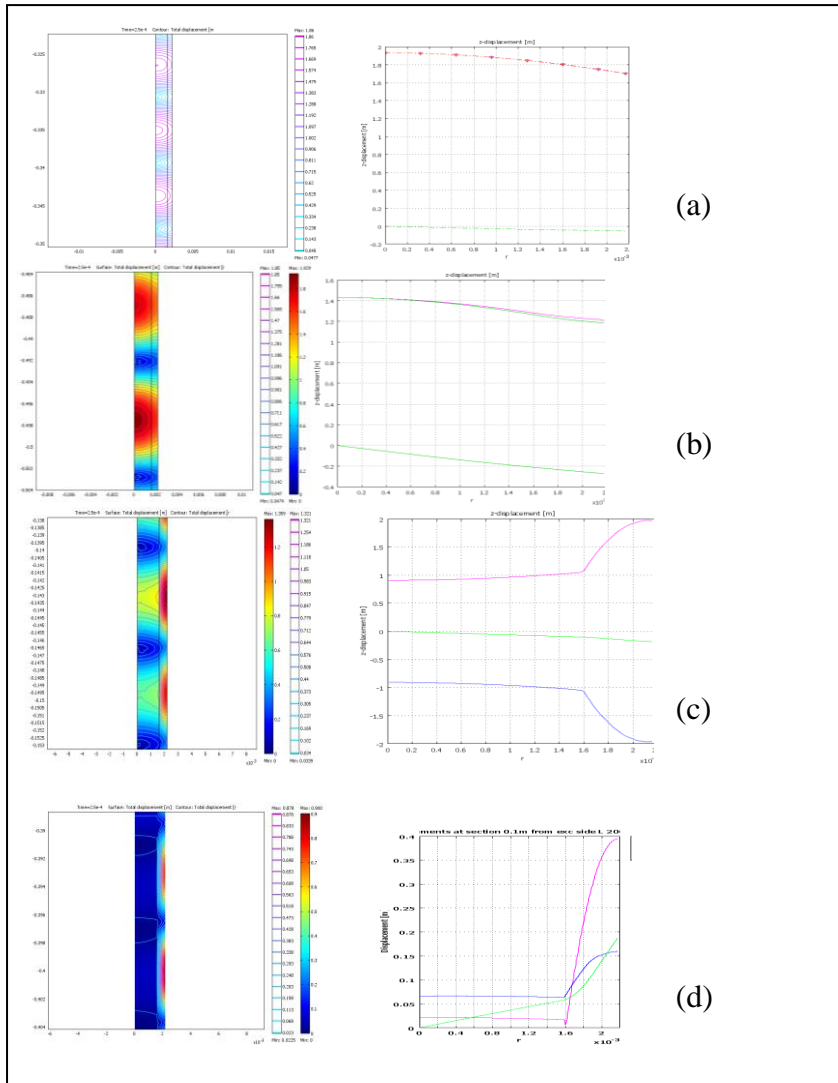


Figure (2): 2-D axis-symmetric model. Total displacement, radial displacement (green), axial displacement (red)

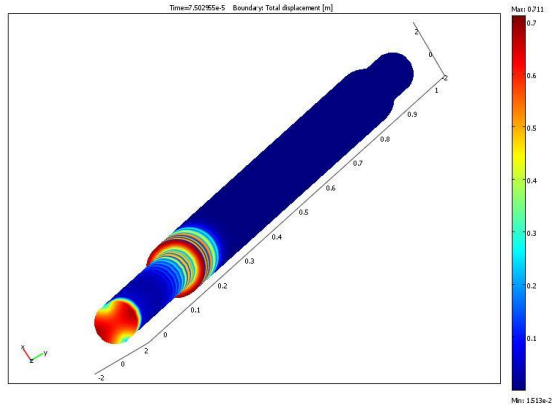


Figure 5: shows guided wave propagated in a coated wire at excitation frequency of 150kHz.

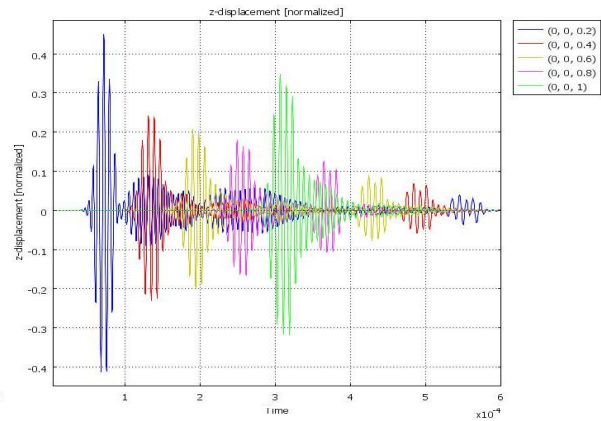


Figure (6): shows the longitudinal propagation of guided wave through different points across the length of the wire

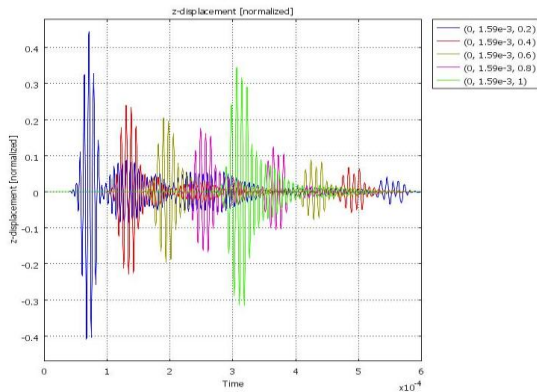


Figure (7): shows the longitudinal propagation of guided wave through different points across the length of the wire at the interface layer

wave mode as it approaches the cut-off frequency. This wave mode is dispersive in nature. However, insulation material will increase the rate of dispersion. A dispersive wave usually elongates and loses its amplitude as it propagates through the wire structure. Finally, there are no interface wave modes between the two different materials in the wire.

4. Experimental Work

In order to validate the findings of the numerical modelling carried out, it is important to carry out real physical experimentation trials. This section of the paper will look at the effect of exciting longitudinal wave mode in bare wire and insulated wire as well as looking at the optimum parameters with respect to the frequency and the number of cycles for the excited signal.

4.1 Initial Experimentation

In this section of the paper, the work is carried out to look at the effect of propagating longitudinal wave-modes in bare and insulated wire. The bare wire is made from copper, and it has been excited longitudinally with a frequency of 150 kHz. Figure (8) shows the propagation of the longitudinal wave at 150 kHz. A pulse echo technique is used to detect the reflected signals from the excited wave mode. The longitudinal wave is decaying as it propagates. This decay is the resultant of the dispersion effect. According to this

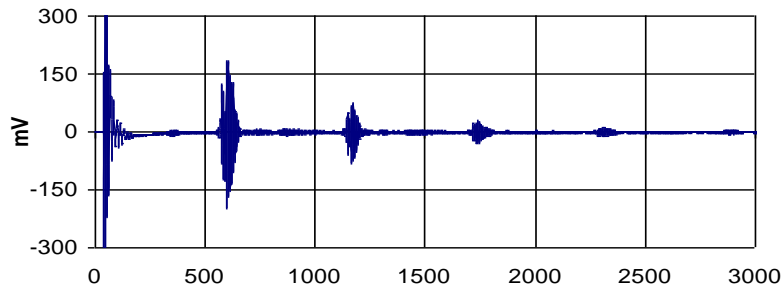


Figure (8): The propagation of longitudinal wave mode in a bare copper wire at 150 kHz

experimental condition, longitudinal wave can travel up to 8m in bare wire. A second test has been carried out for an insulated wire at an exciting frequency of 20kHz. The reason to choose this frequency is due to its high energy. As can be seen from figure (9), the wave in the insulated wire is highly attenuative and dispersive. According to this experimental condition, the longitudinal wave has travelled 4m in insulated wire.

Longitudinal wave travels in bare wire further than in insulated wire. This is due to the presence of the softer material in the insulation, which results in a signal to attenuate and disperse. These findings agree with the modelling and the literature. However, there is a need to find the optimum experimentation parameters with respect to the excited frequency and number of cycles.

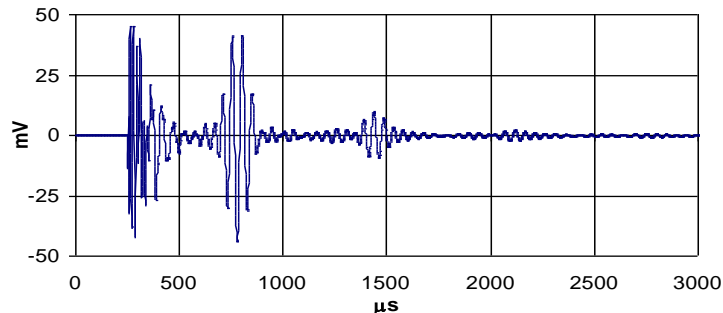


Figure (9): The propagation of longitudinal wave mode in an insulated wire at 20 kHz

4.2 Optimum Excitation Parameters

There is a need to find the optimum frequency range and number of cycles as this will have a significant effect on the nature of the excited wave, propagation distance, attenuation and dispersion. Therefore, a full study and analysis is needed to have compromise parameters which satisfy all these factors. An initial experimental trial is carried out to look into the effect of parameter. This shown in figure (10). Figure (10) shows the number of cycles (vertical axis) versus time (horizontal axis) at different fixed frequencies. From the figure, it shows that 5 cycles are a compromised number for the number of cycles of the tone-burst signal to be constructed and propagated. Furthermore, the frequency range is also significant to propagate guided waves. The lower the frequency, the higher energy the wave mode has, while high frequency has high attenuations. This attenuation is due to the insulation presence. 60 kHz was selected for insulated wires. At this frequency, the effect of dispersion of the output signal dispersion is not shown.

4.3 Correlation between Experimental and Modelling Results

In order to validate the numerical modelling and the experimental results, the received signal in both the modelling and the experimental were correlated against each other. The correlation is done on 20 kHz and 100 kHz on an insulated wire with a presence of a defect. The amplitude of the reflected signals was normalised. Figure (11) shows the correlation between the two signals.

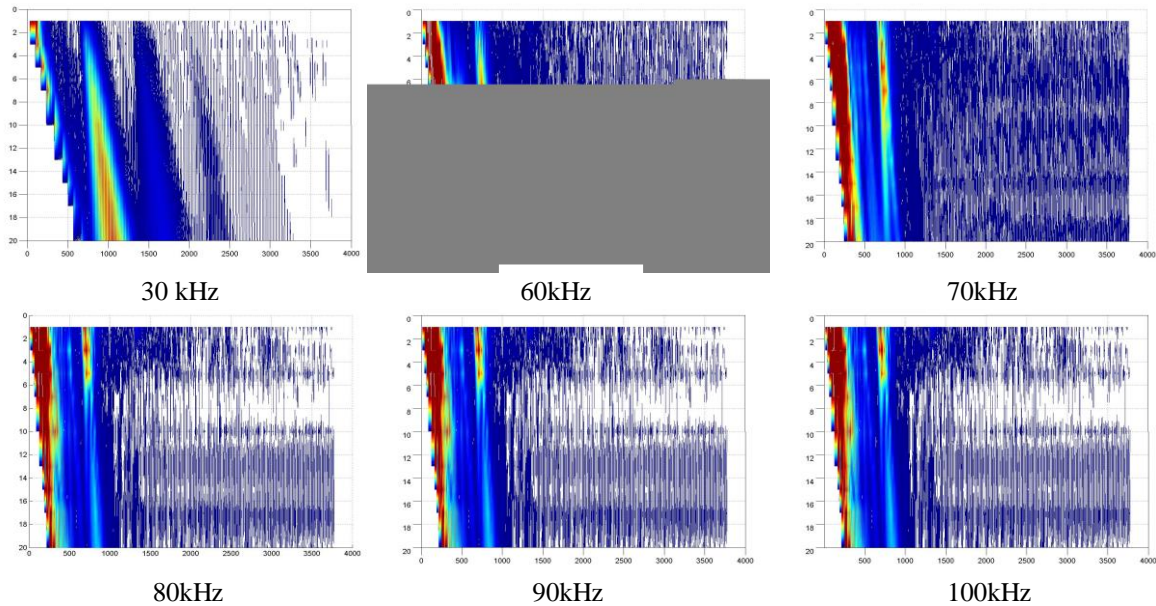


Figure (10): Experimental results for insulated wire at different number of cycles (x-axis) versus at different frequencies

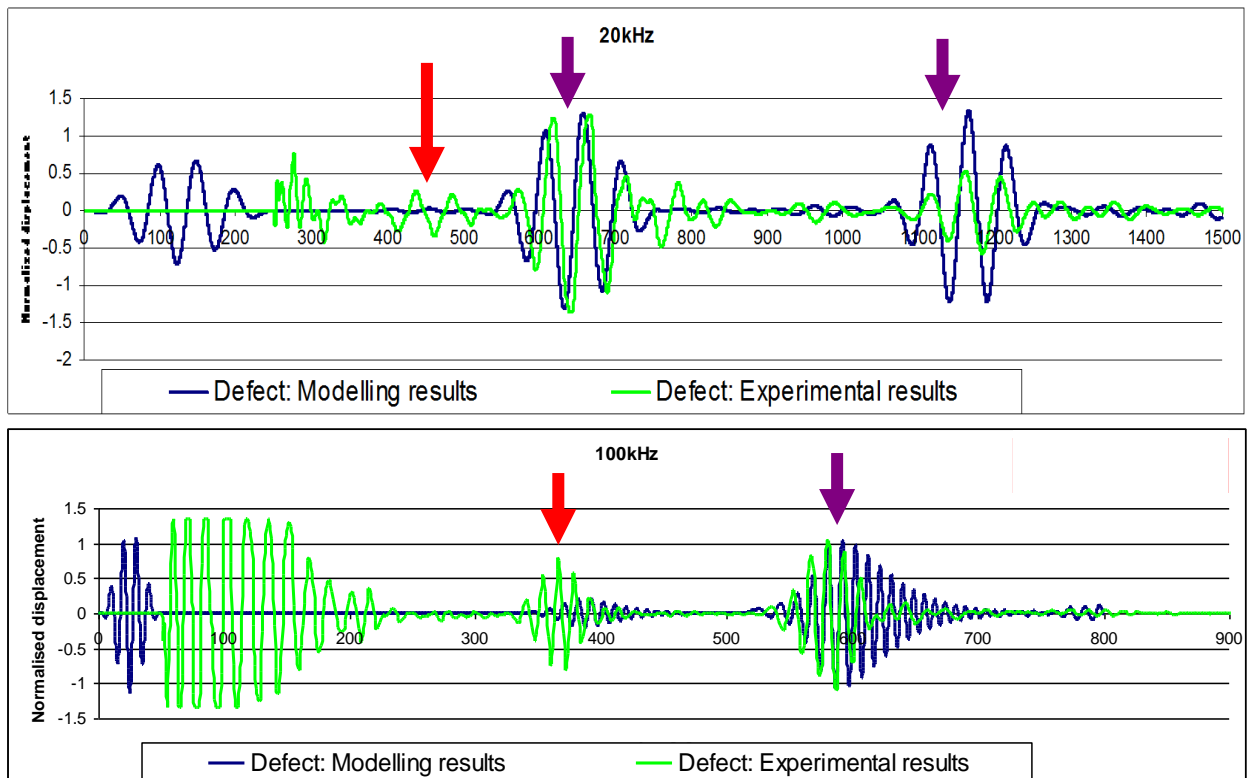


Figure (11): correlation between experimental and modelling results at two different frequencies 20kHz and 100kHz respectively.

Figure (11) shows that there is a large degree of correlation between the modelling and the experimental results. However, there is amplitude difference between the modelling and the experimental results. This difference is due to the attenuation existence in the experimental conditions which is not counted in the modelling. Furthermore, the dispersion effect in the model is higher than in the experiment with a slight shift in the model signal at 100kHz. The model can be improved by counting attenuation and damping.

5. Discussion and Conclusion

Guided wave has the capability of propagating in insulated wire structures. This paper has shown the ability of guided wave to travel in wire structures from a single point of access. However, this propagation depends on different parameters, which include: the number of cycles of the tone burst signal, the excited frequency of the tone burst signal, the stiffness of the conductor material and the insulation and the form of excitation. This paper has focused on exciting insulated wires at low frequency with an axi-symmetric excitation. This excitation imposed the occurrence of longitudinal wave mode type L (0, 1). This is a compression wave mode where the propagation takes place in both materials. The compression wave mode becomes a Rayleigh wave mode in which most of the displacement takes place in the insulation as the frequency increases. L (0, 1) has proved its ability to detect defects within the insulated wire structure. This wave mode has the limitation of being dispersive in nature and attenuative when an insulated material (soft material) is present. Finally, the experimentation and modelling results have shown a large degree of agreement with few variations. These variations are due to the electronic noise generated by the equipment used in the experimentation. In addition, attenuation and damping have not been taken into account in the model. Result improvements can be carried out by conducting further work and integrating those factors into the model.

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