The Effect of Different Materials on the Propagation of Guided Waves in Multi-Wire Cables

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Abstract
This work presents the effect of different materials on the generation and detection of axis symmetric and non axis symmetric guided waves in multiple-wire cables. In order to reflect the mechanism of longitudinal, L(0,1), and flexural, F(1,1), wave motion originated from longitudinal excitation at 500 kHz. Various 3-D FEM analyses were performed using a simplified model comprised of two straight rods that are in contact: the former is made of two rods of aluminium and the latter is made of a rod of aluminium and a rod of steel. The model considers an energy-transfer analysis to describe the guided wave propagation. In this model, due to inter-wire coupling, energy transference caused by radial displacements is considered to have an important role on guided waves propagation. The attained simulation results that visualize the mechanism of flexural and longitudinal motion are compared with experimental measurements using an Aluminium Conductor Steel Reinforced (ACSR) cable, dispersion curves and the wavelet transform. These results are discussed as potential means of damage monitoring of these cables.

Keywords: Guided waves, longitudinal waves, flexural waves, wavelet transform, finite element modelling.

1. Introduction

Multi-wire cables are commonly found in many engineering applications. For instance, they are used in pre-stressing strands and stay cables in suspension bridges; they are encountered on elevators; oil and geothermal industries use them to transport measurement tools in down-hole wells and they are widely used in power transmission lines by electricity companies. These structures are generally exposed to environmental degradation such as corrosion, static loads, wind-induced vibrations and temperature changes. As a consequence, their reliability is a major concern in each application and monitoring their structural integrity becomes progressively more important as the cables age.

Guided waves in rods, single wires and multiple wires have been anticipated as an attractive and effective tool of materials, since they can interrogate large structures and propagate over long distances compared with traditional body waves [1]. However, guided wave propagation in rods possesses an infinite number of vibration modes. These vibration modes depend on material properties and characteristic geometrical parameters of the waveguide, e.g. diameter of the rod, and are dispersive in nature, which complicate its analysis. Wave propagation characteristics in multi-wire cables are even more difficult to investigate due to the load-dependency of inter-wire contact and the twisted geometry of the peripheral wires. Hence, the use of guided waves in these complex structures as a non-destructive testing (NDT) technique is very challenging and requires a firm understanding of the wave propagation.

Propagation of waves in rods and cable structures has been investigated theoretically and experimentally by many researchers for over fifty years. Even though the cables in civil structures do not consist of single cylindrical wires, initial numerical and experimental investigations of guided wave propagation have been performed on single cylindrical
structures. This course of work has been used as an approximation to study the wave propagation in multi-wire cables and has established its fundamental basis [2-6]. In general, the multimodal behavior and the dispersion nature of guided waves in solid cylinders indicate the simultaneous propagation of various types of waves, stated as modes, and the superposition of different modes with distinct velocities [7]. Furthermore, mode conversion has been reported to occur when waves encounter discontinuities or bended structures [8, 9]. The twisted geometry and the contact between adjacent wires make the modeling of the multi-wire cables difficult [12, 14]. Finite element modeling (FEM) techniques have been used to gain insight into ultrasonic wave propagation; nevertheless, as reported by some investigators, modeling of an entire multiple-wire cable is computationally highly demanding [15]. The approach taken with efficacy is to model a two-rod system based on frictional contact between wires to approximate the time average elastic wave power in both rods as a function of propagation distance [16]. Moreover, guided wave propagation in long range inter-wired cylindrical structures is complicated, and many aspects have to be considered in order to develop a pragmatic implementation for damage monitoring.

Experimentally, in this work, the propagation phenomena of individual longitudinal and flexural guided waves modes at 500 kHz in a 0.9m Aluminium Conductor Steel Reinforced Cable (ACSR) were studied. A two piezoelectric transducers system, in a pitch and catch configuration, together with time-frequency analysis based on the wavelet transform was used for identifying guided wave modes. Moreover, a series of 3-D FEM analysis was performed using a simplified model comprised of two straight rods made of aluminium and steel. The simulation results obtained depict the effect of different materials on the propagation of guided waves in a multi-wire ACSR cable. Conclusions complete this article.

2. Experiments and modes identification

2.1 Experiments

This paper focuses on guided waves excited at 500 kHz in a multi-wire ACSR cable commonly found in several realms of engineering for either transmitting energy or as holding element of structures. This cable is a concentric conductor configured in strands consisting of a core of seven straight steel wires and twenty six stranded aluminium wires in two layers as illustrated in a photograph and a cross-sectional view in figure 1a. The diameter of each aluminium and steel wire is 3.5 mm and 2.7 mm, respectively; therefore, the total diameter of the cable is approximately 22.1 mm. The length of the cable used is 0.9 m. The experiment setup is depicted in figure 1b. A pitch and catch arrangement was applied. Two piezoelectric broadband transducers with a central frequency of 1 MHz and 12.7 mm in diameter were attached to the ends of the ACSR cable using a liquid coupling gel. The function generator drives a transmitter piezoelectric transducer with five cycles of 500 kHz sinusoidal waves. Excited guided waves propagate through the cable and are sensed by the receiver transducer that converts them to electric signals via the inverse piezoelectric effect. The electric signals are amplified and acquired by a digital oscilloscope that sends the data to the computer for further analysis.
2.2 Modes identification

Due to the complicated characteristics of inter-wire coupling, an analytical solution that can describe the wave propagation in these multi-wire cables does not exist. A formulation based on a Pochhammer-Chree frequency equation of a cylindrical rod has been presented [17]. Considering an isotropic homogeneous cylindrical rod, the solutions of the elastic equation of motion are known, and correspond to three types of modes: longitudinal L(0,m), torsional T (0,m) and flexural F(n,m). By solving the equations, via the commercial package Disperse© [18], for these vibration modes with known frequencies, the dispersion curves can be obtained. The dispersion curves relate the velocity of the guided wave propagation, to the frequency of the wave and the diameter of the cylinder. The approach taken employed individual dispersion curves of rods of aluminium and steel 3.5mm and 2.7mm of diameter, respectively. Figure 2 shows the group velocity (V_{gr}) dispersion curves of these rods, where it can be observed that the only guided wave modes that could be excited below 500 kHz are the longitudinal L(0,1) and the flexural F(1,1) modes. The group velocities yielded at this frequency for L(0,1) in steel and aluminium are 4957.84 m/s and 4397.28 m/s, respectively, and for F(1,1) are 3313.50 m/s and 3223.61 m/s, correspondently.
However, multi-wire cables make the interaction of the guided wave modes complicated to distinguish. Figure 3a shows the guided wave received signals obtained during the experiments. The approach taken in this study, for signal identification in the trials, was to use the wavelet transform (WT). The WT addresses the general problem of time-frequency analysis and provides the means to analyse non-stationary signals [19]. In this work, the Gabor wavelet was used to identify the guided wave modes generated in the experiments. Figure 3b shows the 2D representation of the wavelet coefficients that allow identification of the guided wave modes found in the disperse simulation. The WT depicts the modes that carry significant energy and the areas where this energy is present within a mode. A depiction in the colour red indicates a larger wavelet coefficient.

Figure 3b shows the frequency-time signals with fundamental group velocity dispersion curves for steel and aluminium rods superimposed. The group velocities have been changed to a time axis using the propagation distance of the guided wave signals. The wavelet contour plot of figure 4b shows that most of the guided wave energy is located in two main areas centered at 500 kHz. The former corresponds to generated L(01,) longitudinal modes, first the L(0,1) mode for steel that is irradiated with the highest energy, and secondly the L(0,1) mode is irradiated for aluminium. The latter corresponds to the two F(1,1) flexural modes; First, the F(1,1) mode for steel that is irradiated with the lowest energy, and afterwards the irradiated F(1,1) mode for aluminium. The WT results follow with good agreement the theoretical dispersion curves of individual wires, indicating that the L(0,1) mode exhibits more energy for the steel rod, while the F(1,1) reveals more energy for the aluminium rod.
2.2.1 Guided wave propagation in rods

All guided wave modes, axisymmetric and non-axisymmetric, propagate in the axial direction of a cylindrical waveguide. The axisymmetric modes comprise both the longitudinal modes, \( L(0, n) \), and the torsional modes, \( T(0, n) \); the non-axisymmetric modes are represented by the flexural modes, \( F(n,m) \). The acoustic fields, i.e. displacement, stress, etc., of non-axisymmetric modes have fields which do vary with the angular coordinate \( \theta \) and comprise the radial, \( u_r \), the axial, \( u_z \), and the circumferential, \( u_\theta \), displacements. On the other hand, the axisymmetric modes are independent of the angular coordinate \( \theta \); therefore, they are composed only for the radial, \( u_r \), and axial, \( u_z \), displacements. Generally, an ultrasonic transducer source can excite all the modes which exist within its frequency spectrum; normally, the spectrum becomes narrower for larger transducers [20]. This is of particular interest considering that an ultrasound procedure with normal beam loading and reception has been used in this work. Hence, surface pressure loading will excite longitudinal modes and/or flexural modes depending on the applied pressure distributions on the rods surface [21]. Since longitudinal, piston-like, ultrasound transducers with ideal uniform pressure distribution are employed in the experiment, fundamental longitudinal \( L(0,1) \) modes in aluminium and steel rods are expected to be excited. According to the software Disperse, the axial \( (u_z) \) and radial \( (u_r) \) displacements for the \( L(0, 1) \) mode in aluminium and steel rods at 503 kHz and 504 KHz, respectively, are shown in figure 4.

![Figure 4](image)

Figure 4. Radial and axial displacements for the fundamental longitudinal mode \( L(0,1) \) as a function of frequency; a) aluminium rod 3.5mm diameter at 503 kHz; b) steel rod 2.7mm diameter at 504 kHz.

Curves of figure 4 show that both rods present axially symmetric radial motion as a function of frequency from the centre to the surface, and consequently they are capable of leaking energy through contact; although, radial motion for steel is smaller than radial motion for aluminium, the interaction between rods suggests that radial components are important in guided wave propagation in real multiple-wire cables.

3. FE Modelling

3.1 Energy-transfer analysis

In this section an energy-transfer analysis has been used to model wave propagation in two rods that are in contact. Figure 5 depicts two rods that are assumed to be portions out of the rods shown in the experiment setup (see Fig. 1).
Since finite pulses of elastic energy are applied to the base of the rods, there is a loss of energy in each rod due to material damping, and also there is a loss and an exchange of energy due to friction coupling caused by radial motion. Radial energy transfer flows, $P$, are indicated by the vertical arrows in figure 5. The energy loss due to material damping in a rod is proportional to the input energy and the distance which the elastic wave propagates, however, for simplification, it is considered that there are no energy losses in the rod due to material damping. Thereby, the energy coupling mechanism is modelled using distributed arrows as energy radial forces for aluminium, $P_A^C$, and for steel, $P_S^C$, which connect the differential rods elements. Figure 5a shows the energy coupling mechanism for a two aluminium rods system, and figure 5b for a system made of an aluminium rod and a steel rod. Using the former system, longitudinal modes are expected to be excited because the radial coupling components possess the same distance in the rods; the latter system, nevertheless, depicts that the energy radial components, having different locations since their velocities, and thereby their wavelengths, are slightly different; therefore, the latter system is expected to excite not only longitudinal modes but also flexural modes. In order to gain understanding of the mechanism of flexural modes generation originated from longitudinal modes due to inter-wire coupling in ACSR cables, various runs of 3-D FEM analysis using the software ALGOR [22] y COMSOL [23] were performed.

### 3.2 FEM simulation results

Transient analysis of guided waves propagation in real multi-wire cables using finite elements 3-D models is computationally very demanding [7]. The approach considered in this study consists of structural modal analyses of a simplified 3-D model. The model consists only of two straight rods of 70mm lengths made of aluminium and steel, which possess the diameters of the ACSR cable under test, and a friction contact line between them was specified. In this model energy transference, due to contact in between rods, caused by radial displacements is considered to have a significant role in guided waves propagation. Several simulations were performed using the model, and the results yielded were compared with experimental measurements.

By means of the software ALGOR© the first simulation was performed using two aluminium rods allowing for the coupling mechanism of figure 5a. The FE model is comprised of 9,838 nodes and 9538 elements. Nodal forces of 10 N were applied at the base of the rods. The contact between rods is specified as bonded, which the nodes on the two edges are matched.
and are in perfect contact during the analysis. The coefficient of friction for the coincident edges was specified as $1 \times 10^{-5}$. The main variable is the displacement magnitude field and three degrees of freedom for the elements are the displacement components at the nodes. When a node on one edge deflects, the node on the adjacent edge will deflect the same amount in the same direction. Figure 6a depicts the attained simulation results using two aluminium rods at a modal frequency of 499 kHz. Axisymmetric longitudinal guided wave propagation and mode shapes, very likely L(0,1), can be observed, which agrees the model depicted in figure 5a. Since two layers of twenty six stranded aluminium wires constitute the bulk of the ACSR cable, this observed mode is associated to the majority of the energy identified during the trials.

The second simulation, employing the software ALGOR®, was performed using an aluminium rod and a steel rod considering the coupling mechanism of the model depicted in figure 5b. The FE model is comprised of 15,358 nodes and 15,498 elements. Nodal forces of 10 N were applied at the base of the rods and the contact between rods and the coefficient of friction was set as previous model. Figure 6b depicts the attained simulation results using an aluminium rod and a steel rod at a modal frequency of 499 kHz. In this simulation, however, the observed guided wave propagation and mode shapes is non-axisymmetric, and could correspond not only to the longitudinal mode L(0,1), but also to the flexural mode F(1,1).

A series of FEM simulations using the software COMSOL Multiphysics®, considering the characteristics of previous models at 500 kHz, were performed to gain insight into the effect of different materials and the contact between them on the propagation of guided waves. In this instance, separating gradually first two aluminium rods and later an aluminium rod and a steel rod, and posteriorly approaching them as far as they are in contact. Separating two aluminium rods and afterwards approaching them until they are in contact depicted only axisymmetric motions as shown in figure 7.

However, using an aluminium rod and a steel rod, flexural motion can also be excited. Figure 8 shows that with a separation of 0.5 mm between rods, there is no evidence of flexural motion; nonetheless, as close as 200 nm distance between the rods, as shown in upper right simulation, flexural displacements start generating in the aluminium rod. If the distance separation between rods is reduced, flexural motion can be distinguished in both rods. Lower
simulations in figure 8 show these displacements at 50 nm separation and without separation, respectively, which concur with the results obtained with the software ALGORE (figure 6b).

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**Figure 7.** FEM simulation results using a system made of an aluminium rod and a steel rod separated various distances: separated 500 µm, 200 nm, 50 nm and without separation.

**Figure 8.** FEM simulation results using a system made of an aluminium rod and a steel rod separated various distances: separated 500 µm, 200 nm, 50 nm and without separation.
4. Conclusions

This study analyzes the effect of different materials, particularly aluminium and steel rods, on the generation and detection of axis symmetric and non-axis symmetric guided waves in multiple-wire cables. Experimentally, using an ACSR cable fundamental longitudinal L(0,1) and flexural F(1,1) modes were identified via dispersion curves and the wavelet transform. An energy-transference analysis, using a two straight rods system, was developed to approximate the coupling mechanism between adjoining rods through friction. Energy transference 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. A series of 3-D FEM analyses were performed using this approach. The obtained simulation results depicted longitudinal excitation, very likely L(0,1) modes, using two aluminium rods, whereas longitudinal and flexural excitation, very likely L(0,1) and F(1,1) modes, were observed using an aluminium rod and a steel rod. These results are adequately related to experimental measurements. The energy-transference analysis approach serves as basis for future studies of multi-wire ACSR cables with damage.

References

23. COMSOL Multiphysics® instructor manual.