Experiments and modelling of guided wave propagation in a multiple-wire cable
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Abstract
The generation and detection of guided waves in multiple-wire cables have been investigated experimentally using two piezoelectric transducers in a pitch and catch configuration. Longitudinal and flexural modes identification was achieved using dispersion curves and the wavelet transform. In order to reflect the mechanism of flexural wave motion originated from longitudinal excitation, a 3-D FEM analysis was performed using a simplified model comprised of two rods, made of aluminium and steel, which are in contact. The model considers an energy-leakage method to describe the guided wave propagation. In this model, due to inter-wire coupling, energy leakage caused by radial displacements is considered to have an important role in guided waves propagation. The attained simulation results that visualize the mechanism of flexural and longitudinal modes are compared with experimental measurements.

Keywords: Finite element modelling (FEM), longitudinal waves, flexural waves, wavelet transform.

1. Introduction

Guided waves in rods, single wires and multiple wires have been anticipated as an attractive and effective tool for structural health monitoring of materials, since they can interrogate large structures and propagate for long distances compared with the traditional body waves [1]. The theory of wave propagation of waves in solids was developed in the 19th century; however, only just for over fifty years, the subject of wave propagation in rod and cable structures has been addressed by many investigators. Related to multi-wire problem, various experimental and theoretical techniques have been reported [2-4]. Chen et al. [2] used the Wigner-Ville transform to analyze the stress wave in order to identify the arrival time in a seven-wire steel strand. In a later study, Rizzo et al. [5] generated and detected ultrasonic waves in single wire and seven-wire cable using magnetostrictive sensors. Their research looked into the acoustoelastic effect in the cables. In another study, Rizzo et al. [5, 6] studied the wave propagation problem in seven-wire cables at the level of the individual wires. They used broadband ultrasonic transducers and time-frequency analysis based on the wavelet transform; in their research, they were capable of identifying vibration modes which propagate with minimal losses. Hagg et al. [7] presented a two-rod system in which the wave energy from an excited rod is transmitted to a neighbouring rod through friction contact. An energy-based model, to approximate the time average elastic wave power, in the two rods as a function of propagation distance was used. The model predictions were corroborated with experimental measurements and FEM simulations.

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 3-D FEM analysis was performed using a simplified model comprised of two rods made of aluminium and steel. The attained simulation results that visualize the mechanism of flexural and longitudinal modes generation are compared with the measurements obtained during the experiments.

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 elements 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 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.

![ACSRR cable cross section view](image1.png)

Figure 1. a) Cross sectional view of the ACSR cable used; b) experiment setup using a real ACSR cable

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 [8]. 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©
[9], 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 (Vgr) 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, correspondingly.

The software Disperse™ was used to simulate the multiple modes generated from a transmitting point of 0.9m in a pitch and catch configuration in relation to the experiment setup. The excitation was five sine cycles of 500 kHz. Considering that only the of L(0,1) and F(1,1) modes were exited at 500 kHz in the aluminium and steel rods, correspondingly, the expected guided waves signals are shown in figure 3.

Figure 2. a) Group velocity dispersion curve of a steel rod 2.7 mm diameter and an aluminium rod 3.5 mm diameter

Figure 3. a) Simulation of the fundamental guided waves L(0,1) and F(1,1) propagation in an aluminium rod and a steel rod, independently.
Group velocities for L(0,1) and F(1,1) modes are clearly separated, thereby the identification of their signals can be identified easily for individual rods. However, multiple-wire cables make the interaction of the guided wave modes complicated to distinguish. 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 [10]. In this work, the Gabor wavelet was used to identify the guided wave modes generated in the experiments. Figure 4 shows the results produced by applying the WT to the guided wave received signals that allowed the signals time of arrival (TOA) estimation.

Figure 4. Discrete wavelet transform used to estimate the TOA of the guided wave received modes in the ACSR cable

Considering the 0.9m length of the ACSR cable and estimating the TOA, it was possible to recognize the excited guided wave modes. Table 1 shows the group velocities attained using the estimated TOA.

<table>
<thead>
<tr>
<th>Identified mode</th>
<th>TOA (s)</th>
<th>Length (m)</th>
<th>Calculated Vgr (m/s)</th>
<th>Disperse Vgr (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L(0,1) steel</td>
<td>0.00018</td>
<td>0.9</td>
<td>5000</td>
<td>4957.84</td>
</tr>
<tr>
<td>L(0,1) aluminium</td>
<td>0.00021</td>
<td>0.9</td>
<td>4285.71</td>
<td>4397.28</td>
</tr>
<tr>
<td>F(1,1) steel</td>
<td>0.00028</td>
<td>0.9</td>
<td>3214.28</td>
<td>3313.5</td>
</tr>
<tr>
<td>F(1,1) aluminium</td>
<td>0.000295</td>
<td>0.9</td>
<td>3050.84</td>
<td>3223.61</td>
</tr>
</tbody>
</table>

The identified received modes were predominantly L(0,1), however, some energy was discerned with lower group velocities as very likely F(1,1). It can be observed that L(0,1)
aluminium signals show more dispersion than the L(0,1) signals of steel, which agrees with its dispersion curves. On the other hand, the F(1,1) modes exhibit more energy in the aluminium. The mechanism of flexural modes generation originated from longitudinal modes relies upon the wave propagation in rods and its interconnection.

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 θ 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 θ; 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 [11]. 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 [12]. 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 5.

![Figure 5](image)

Curves of figure 5 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-leakage method

In this section an energy-leakage method has been used to model wave propagation in two rods that are in contact. Figure 6 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 flows are indicated by the vertical arrows in figure 6. 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, the energy coupling mechanism is modelled using distributed arrows as energy radial forces for aluminium, $E_A^C$, and steel, $E_S^C$, which connect the differential rods elements. Figure 6a shows the energy coupling mechanism for a two aluminium rods system, and figure 6b 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 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, a 3-D FEM analysis using the commercial software ALGOR [13] was 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 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 leakage, 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.

The first simulation was performed using two aluminium rods allowing for the coupling mechanism of figure 6a. 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 $1e^{-0.05}$. The main variable is the displacement magnitude field and the 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 8 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 6a. 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 was performed using an aluminium rod and a steel rod considering the coupling mechanism of the model depicted in figure 6b. 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 9 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). Since the ACSR cable under test consists
only of seven steel wires, the non asymmetric mode observed in this simulation is associated
to the minority of the energy identified in the experiments.

![Figure 9. FEM simulation results for a system made of an aluminium rod and a steel rod](image)

### 4. Conclusions

This study analyses how guided wave energy is propagated in a multiple wire ACSR cable. Experimentally, fundamental longitudinal, L(0,1) and flexural F(1,1) modes were identified using dispersion curves and the wavelet transform. An energy-leakage model, using a two rod system, was developed to approximate the coupling mechanism between adjoining rods through friction. 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. A 3-D FEM analysis was performed using this model. The attained simulation results that visualize the mechanism of flexural and longitudinal modes generation are adequately related to experimental measurements. The energy-leakage model approach serves as basis for future studies of multiple-wire ACSR cables with damage.

### References