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Detection of damage in multiwire cables based on wavelet entropy evolution

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Abstract
Multiwire cables are widely used in important engineering structures. Since they are exposed to several dynamic and static loads as well as detrimental environmental conditions, their structural health can be compromised. Due to the critical role played by multiwire cables, it is necessary to develop a non-destructive health monitoring method to maintain their structure and proper performance. Ultrasonic inspection using guided waves is a promising non-destructive damage monitoring technique for rods, single and multiwire cables. However, the propagated guided waves are composed of an infinite number of dispersive vibrational modes making their analysis difficult. In this work, an entropy-based method to identify small changes in non-stationary signals is proposed. An experimental system to capture and post-process acoustic signals is implemented. The discrete wavelet transform is computed in order to obtain the reconstructed wavelet coefficients of the signals and to analyze the energy at different scales. The use of the concept of entropy evolution of non-stationary signals to detect damage in multiwire cables is evaluated. The results show that there is a correlation between the entropy value and level of damage of the cable including breaking of single wires and change in the mechanical contact conditions among the wires. It is found that the studied method has low sensitivity to signal noise and can reduce the computational complexity encountered in a typical time–frequency analysis.

Keywords: ultrasonic, guided waves, discrete wavelets, multiwire cables

(Some figures may appear in colour only in the online journal)

1. Introduction
Multiwire cables play a very important role in various engineering structures such as bridges, cranes, power lines, etc. These structures are frequently exposed to environmental degradation such as corrosion, temperature and aging, among others. The integrity of such structure relies, very highly, on the health of the multiwire cables (Azevedo and Cescon 2002, Siegert and Brevet 2005).

Guided ultrasonic waves are a promising non-destructive health evaluation technique which have the advantage of being able to propagate far along the structures; so they can potentially be used to monitor large structures at once.

Unfortunately their practical use is compromised due to dispersion phenomena. The propagated guided wave is composed of an infinite number of vibrational modes (longitudinal, flexural and torsional), resulting in non-stationary signals with different groups of waves within the signal, making its analysis in time domain difficult (Rose 2004).

There are, however, other phenomena present in a multiwire cable that make the analysis even more complex, such as mechanical contact among the wires, helical effect and energy transmission. An attempt to develop an exact model of the wave propagation through a multiwire cable problem requires enormous computational cost. Experimental results of wave propagation in a multiwire cable using piezoelectric transducers, EMAT, and laser (Laguerre et al 2002, Rizzo and Di-Scalea 2002, 2004, Rizzo 2006, Xu et al 2013,
Raištis et al (2014) have been reported. Wilson and Hurlebaus (2007), Haag et al (2009) and Schaal et al (2015) have published numerical and experimental results of wave propagation and its correlation to damage detection on multiwire high power overhead cable using contact transducers and laser interferometers. In the said studies, wave propagation has been performed on single wires and whole cable structures; for single wires, laser vibrometer or small piezoelectric elements attached to a single wire were used; to excite the whole cable, piezoelectric elements with ring shape and EMAT transducers have been used. Analysis of transmitted and received ultrasonic signals was correlated to discontinuities and it showed the possibility of practical implementation of guided waves for in situ damage monitoring. There are, however, other phenomena such as mode coupling phenomena with neighbor wires, mechanical contact among the wires, helical effect and acousto-elastic phenomena which are not fully understood. The effect of axial stress has been correlated with acoustoelastic properties of wave propagation (Kwun et al 1998, Chen and Wissawapaisal 2001, 2002, Washer et al 2002, Rizzo 2006, Chaki and Bourse 2009).

Friction and energy transfer between cable wires has been studied using analysis on single wires (Haag et al 2009). Recently, the helical effect in a single cable has been studied using finite element analysis; small differences in wave propagation between helical wires and solid straight ones were found (Treyssède 2007, Laguerre and Treyssede 2009). Thus, there is still a need to further investigate energy transfer affected by mechanical contact conditions, geometry and defects which in most cases are very complex and elusive to analyze with typical time domain techniques. Baltazar et al (2010), (Mijarez et al 2014) performed a set of tests on an aluminum conductor steel reinforced (ACSR) cable with an artificial notch-like damage of up to 9 mm of depth. They found an increase in the amplitude of the transmitted longitudinal modes at certain frequencies and attributed it to mode conversion due to contact between the wires of the cable. Nevertheless, they found a correlation between the change in the amplitude of flexural modes and level of damage by measuring the amplitude change of certain areas of the time-frequency representation maps of the signals.

In general, most windowed techniques of signal analysis allow observations at only a small section of the signal at a time to measure the changes of a variable in the entire signal. The short time Fourier transform (STFT) looks for a frequency \( f \) at a time \( t \) by shifting a window fixed in time through the analyzed signal. Unfortunately, the fixed nature of the time window in STFT implies a single-scale resolution of the spectrograms (Stark 2005). The continuous wavelet transform-based (CWT) algorithms can be used to obtain a multi-scale time–frequency representation of signals for damage detection. Tsai et al (2006) characterized damaged wind turbines from healthy ones by a threshold of energy variance ratio of the scalograms; however, they were not able to locate the damage in the structure. Rucka and Wilde (2006), used 1D and 2D CWT to visually locate damage in beams and plates. The continuous analysis could lead to a redundant result which may not always be desirable. The discrete wavelet transform (DWT) is a fast algorithm which allows a complete reconstruction of a signal without the redundancy encountered in CWT and provides approximations of the signal at different scales (multi-scale). Rizzo et al (2007) use DWT to eliminate noise and compute a damage index with the features from the original reflected signal and features of the reflected noiseless signal.

The concept of entropy was introduced by Shannon (1948) as a quantitative criterion for analyzing probability and the amount of information of a random variable distribution. Thus, entropy can be assumed to be indicative of the degree of order of a complex signal. Typical non-stationary signals have high degrees of entropy because the energy distribution varies through time as well as frequency and the change of energy distribution will lead to a disorder of the signal. Time-evolving entropy can be measured using a windowed technique into the wavelet coefficients provided by the DWT to search for sudden changes of energy within the signal.

Wavelet entropy was used to detect and identify the transmission line fault (El Safty and El-Zonkoly 2009). Rosso et al (2001) proposed a time evolution wavelet entropy method in electro-encephalographic signals to find key points to identify a signal that indicates if an individual has his eyes closed or open. The concept wavelet entropy was also used in Passoni et al (2005) to evaluate dynamic biospeckle images and characterize transient processes such as the drying of paint.

In this work we extend, the concept of wavelet entropy to the field of structural health monitoring (SHM) with the purpose of developing a method capable of detecting small changes in non-stationary guided wave signals. The objectives of this work are: first, to combine the advantages of the DWT and the concept of entropy in order to detect damages in multiwire cables using guided waves; second, to develop an experimental setup to excite piezoelectric transducers on a multiwire cable using ultrasonic waves where various levels of artificial damage are induced; and third, to measure the evolution of the entropy of the energy of the reconstructed wavelet coefficients of the received signals and correlate it to the level of damage in the cable.

2. Theoretical background

2.1. Short time wavelet entropy (STWE)

Wavelet analysis is a technique of signal processing that, in contrast with STFT, characterizes a signal at a certain time window \( \Delta t \) by performing a multi-scale algorithm (Stark 2005). The signal is simultaneously analyzed in time and frequency to transform it into a representation which either makes certain features of the original signal easier to study or enables the original data set to be described more efficiently (Addison 2002).

Mathematically, the wavelet transform is a convolution of a signal with the mother wavelet \( \Psi(t) \). Because of its continuous shifting, CWT requires an infinite number of operations to obtain a complete reconstruction of the signal,
making its results highly redundant. To overcome the redundancy problem, the discretization of the mother wavelet is performed for discrete steps in scales and translations through DWT. The DWT representation can be expressed as:

$$T_{j,k} = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} x(t) \psi(2^{-j}t - k) dt,$$

where $T_{j,k}$ are known as wavelet coefficients, $j$ is the resolution level and $k$ is each of the elements in the time series. The DWT results in discrete blocks of wavelet coefficients with a number of elements that reduces as $j$ increases (Torrence and Compo 1998). To determine the feasibility of the wavelet coefficients to represent the full signal, the concept of wavelet frames can be used. Daubechies (1992) proved that the family of wavelet functions that constitute a frame are such that the energy of the resulting wavelet coefficients lies within a certain bounded range of the energy of the original signal, i.e.:

$$AE \leq \sum_{j,k} |T_{j,k}|^2 \leq BE,$$

where $E$ is the energy of the original signal, $A$ and $B$ are the frame bounds and $T_{j,k}$ the wavelet coefficients. If $A=B$, then, the original signal can be completely reconstructed by:

$$x(t) = \frac{1}{A} \sum_{j,k} T_{j,k} \psi_{j,k}(t).$$

Orthonormal wavelets have frame bounds $A=B=1$. In this work, we use discrete orthonormal wavelets of the type $\psi(2^{-j}t-k)$.

There are a number of basic functions that can be used as the mother wavelet. Through translation and scaling, the mother wavelet produces all wavelet coefficients. This operation requires some tuning since there is no mother wavelet $\psi_{j,k}(t)$ that is optimal for any signal; that is, its proper selection plays a crucial part in achieving an effective coding performance. Qualitative methods of selection are often based on the properties of the mother wavelet (Mojisilović et al 2000, Fu et al 2003); in some cases, a shape matching process by visual inspection can be applied to select the most proper mother wavelet (Ahadi and Bakhtiar 2010, Tang et al 2010). To justify this method of similarity selection between the analyzed signal and the selected wavelet, the use of quantitative methods has been proposed (Ngui et al 2013). The choice of the optimal wavelets includes several criteria: orthonormality, symmetry, vanishing moments, decomposition level (order) and regularity (Cohen 1992, Daubechies 1992 and Teolis 1998). The choice of a mother wavelet is based on these criteria should not affect, with loss of information, the inverse process of reassembling a decomposed signal into its original form.

To select an appropriate mother wavelet we tested several approaches considering a typical signal found in experiments performed on an ACSR cable (figure 1(a)). The orthonormal wavelets Coiflet 1 (coif1), Daubechies 1 (db1 or Haar), Symlet 2 (sym2), Symlet 4 (sym4) and Daubechies 4 (db4) were compared. Based on the relative wavelet entropy (RWE) between the probability distribution $p$ of the original signal with the probability distribution of the wavelet (Quiroga et al 2000) the db1 is the most proper mother wavelet to analyze the original signal, since it gives the lowest relative entropy (figure 1(b)). Nevertheless, in recent research Kumari and Vijay (2012), and Jaspreet and Rajneet (2013) choose the symlet as the most suitable mother wavelet for decomposing an image using DWT. To prove the effectiveness of this wavelet, the maximum cross correlation criteria was performed comparing the original signal with its approximation coefficients (Singh and Tiwari 2006). As can be seen in figure 1(c), the approximation obtained with the sym4 has a slightly better correlation with the original signal. In this work, the results using the db1 were compared with those obtained using the sym4 wavelet.

Once the mother wavelet has been selected and the signal has been decomposed in wavelet coefficients, a continuous approximation of the signal at each resolution level $j$ can be obtained as:

$$d_{j,k}(t) = \sum_{k=-\infty}^{\infty} T_{j,k}\psi_{j,k}(t).$$

Thus, by using equation (4), it is possible to observe the approximation of the signal for each of the $j$ resolution levels. Given a signal of length $M$, the decomposition consists of a maximum of $N$ stages ($j=1,2,\ldots,N$; with $N=\log_{2} M$).

Since both orthonormal wavelets and the signals have finite energy, it is possible to measure the energy of each resolution level $j$ by (Addison 2002):

$$E_{j} = \sum_{k} |d_{j,k}(t)|^2 .$$

Thus, for an entire signal, the total energy is:

$$E_{tot} = \sum_{j} E_{j}. $$

Using equations (5) and (6) it is possible to assign a degree of occurrence equal to the normalized value of the energy to obtain the probability distribution of the wavelet energy for the resolution level as:

$$p_{j} = \frac{E_{j}}{E_{tot}} .$$

Since $p_{j}$ represents the probability distribution of energy at each resolution level $j$, then $\Sigma p_{j} = 1$. The distribution $p_{j}$ offers a suitable tool for detecting and characterizing specific phenomena in time and frequency planes. It is also useful to compute the concept of entropy introduced by, and named after, Shannon (1948).

Entropy is a quantitative criterion for analyzing probability and the amount of disorder of any distribution (Cover and Thomas 2006). It can provide information about the dynamics of the variable involved in the probability
distribution. Entropy is defined as:

\[ H = - \sum_j p_j \ln(p_j). \]  

This can be considered as a measurement of the average uncertainty of a random variable (Shannon 1948). Thus, the wavelet energy entropy is used to detect events that modify the energy distribution of the signal.

In a non-stationary signal, changes in frequency are expected as a function of time. In most cases this involves changes in energy distribution. To study temporal evolution of entropy, as proposed by Rosso et al (2001), the studied signal with a size of \( M \) points is divided into temporal windows of length \( L \), there are \( N_t \) intervals \( i = 1, 2, \ldots, N_t \), with \( N_t = M/L \).

In figure 2, the signal described in figure 1(a) is decomposed into wavelet coefficients. The squared gray area represents the time window \( i \) of length \( L \) where energy is computed using equation (9). Such window will be shifted in order to obtain the energy of the wavelet coefficient \( j \) as a function of time:

\[ E_j^i = \sum_{k=0}^{L} |d_{j,k}|^2. \]  

The total energy of all resolution levels within the window is computed as:

\[ E_{tot}^i = \sum_j E_j^i. \]  

Thus, the time evolution of wavelet energy probability distribution in the window \( i \) is:

\[ p_j^i = \frac{E_j^i}{E_{tot}^i}. \]  

And finally, the entropy of the window \( i \) is:

\[ H^i = - \sum_j p_j^i \ln(p_j^i). \]
Equation (12) gives the STWE of the signal (somehow similar to the well-known STFT). This provides a powerful technique to characterize patterns in a signal, which, since it only reflects changes of the energy distribution, is independent of the amplitude of the signal and has low sensitivity to white noise.

Using STWE, sudden changes in frequency in a data series can be detected with minimal computational costs. This is particularly relevant in SHM using guided waves to identify and quantify damages in a tested structure. According with experimental results in multiwire cables described in the literature (Lanza di Scalea et al. 2003, Baltazar et al. 2010 and Gaul et al. 2012), the signals obtained are highly non-stationary with changes in amplitudes and frequency where small and sudden changes in the frequency–time maps indicate the presence of damage.

For the purpose of illustrating the performance of the STWE and to show the potential application of the proposed time-windowed entropy technique to detect sudden changes in frequency of a dispersive signal, a Gaussian modulated sine wave signal with a fundamental frequency of 0.8 MHz was generated and propagated at a distance \( x \) using the following expression (Puri and Birdman 1983):

\[
A(x, t) = \frac{\sigma}{\sqrt{2(\sigma^2 + i\Gamma)}} \exp \left[ -\frac{1}{2} \frac{x - x_0 - V_g t}{\sqrt{(\sigma^2 + i\Gamma)}} \right] \exp \left[ ik_0 (x - V_p t) \right]
\]

where \( x \) is the spatial location of the wave, \( x_0 \) is the spatial reference (center of the modulated Gaussian function), \( k_0 \) is the wave number estimated at the carrier frequency \( \omega_0 \), \( c_g \) and \( c_p \) are the group velocity and the phase velocity respectively at \( \omega_0 \), \( \sigma^2 \) is the width of the wave packet at \( t=0 \). In this expression, the \( \Gamma \) parameter controls the degree of dispersion by increasing the width of the packet of waves with the time. The signal was then modified by adding white noise and a small disturbance: a tone burst of 3 \( \mu \)s of duration at \( t_i = 35 \mu s \) with a frequency of 0.7 MHz (figure 3(a)).

As shown in figure 3(a), the tone burst cannot be easily identified in time domain neither using fast Fourier transform nor in time–frequency with STFT (figures 3(b) and (c)). In addition, the STFT’s main limitation is that it provides a fixed resolution time–frequency representation of the input signal. On the contrary, time evolution of wavelet entropy computed using equation (9) through (12) allows an easy identification of the signal’s changes on the one-dimensional time trace. In the example, the time index where the tone burst begins and ends (\( t_i = 35 \mu s \) and \( t_f = 38 \mu s \) respectively, figure 3(d)) can be found. The disturb signal was easily identified, despite the dispersion or white noise in the signal. There is a considerable reduction in computational complexity by the implementation of the DWT. The characterization of the signal’s changes is performed only in the time distribution of entropy instead of the two-dimensional plane as in the case of the STFT.

### 2.2. Wave propagation in cylindrical waveguides

Ultrasonic signals propagating along multiwire cables are known to be highly non-stationary. In this case there is no
complete analytical solution to describe the phenomena of ultrasonic waves propagating through the multiwire cable. The only available model is the Pochhammer–Chree frequency equation for a single isotropic and homogenous solid cylinder. It predicts three types of coupled vibration modes: longitudinal, \( L(0, m) \), torsional, \( T(0, m) \) and flexural, \( F(n, m) \), with order \( n \) and sequential numbering \( m \), as illustrated in figure 4.

The solutions of the Pochhammer–Chree equation are a set of differential equations in the form of equation (14), and they provide the phase velocities, \( c_p \), for a given frequency \( f \) and diameter \( d \) of the wire, at which each of the infinite number of modes will propagate:

\[
\Omega_n \left( d, \mu, \lambda, f, c_p \right) = 0,
\]

where \( \mu \) and \( \lambda \) are the Lamé constants of the material of the wire. The index \( n \) determines how the acoustic fields (i.e. velocity, displacement, stress, etc) generated by the guided wave modes vary with the angular coordinate \( \theta \) in the cylinder cross-section (see figure 4). The index \( n \) can be zero or an integer. Each field component can be considered to vary as:

\[
\begin{align*}
    u_r &= U(r) \cos n\theta e^{ikz-\omega t}, \\
    u_\theta &= V(r) \sin n\theta e^{ikz-\omega t}, \\
    u_z &= W(r) \cos n\theta e^{ikz-\omega t}.
\end{align*}
\] (15)

In equation (15), \( u_r, u_\theta \) and \( u_z \) are the displacement components and \( U(r), V(r) \) and \( W(r) \) are the displacement amplitudes provided by the Bessel functions, with angular frequency \( \omega \) and wavenumber \( k \); for further information, see Rose (2004). Since longitudinal \( (u_r \neq 0, u_\theta = 0, u_z \neq 0) \) and torsional \( (u_r = 0, u_\theta \neq 0, u_z = 0) \) vibration modes are axially symmetric modes, i.e. do not depend on \( \theta, n=0 \). The non-axisymmetric modes are the flexural modes \( (u_r \neq 0, u_\theta \neq 0, u_z \neq 0) \) and \( n \) is a non-zero integer.

By solving the Pochhammer–Chree equation for a known frequency, i.e. using MATLAB® with the open-access code PCdisp (Seco and Jiménez 2012) the dispersion curves for all three vibrational modes can be obtained. The dispersion curves relate the phase \( (C_p) \) and group velocity \( (C_g) \) as a function of the frequency of the guided wave. Dispersion...
Curves for an aluminum wire of 3.4 mm in diameter and for a steel wire of 2.7 mm in diameter are plotted in figure 5.

According with experimental results in multiwire cables described in the literature (Lanza di Scalea et al. 2003, Baltazar et al. 2010, Gaul et al. 2012), the ability of ultrasonic wave propagation to detect structural damage is influenced by the energy exchange among intertwined wires and vibrational mode conversion.

To model the energy transmission of a low frequency pulse without dispersion when two or more wires are attached via dry friction, a simplified model using energy propagation concepts was proposed by Haag et al. (2009). In this simplified model, the energy transfer from one wire to another is controlled via an energy coupling mechanism which is modeled using distributed dashpot elements.

In figure 6, a differential section $dz$ of two wires coupled by a dashpot is presented. $E_g(z)$ stands for the total initial energy traveling through the $g$ rod. This amount of energy is balanced as:

$$E_g(z) = E_g(z + dz) + E_g^d(z) + E_{g,h}(z), \quad (16)$$

where $E_g^d(\cdot)$ is the dissipated energy due to the material damping (attenuation), and $E_{g,h}(\cdot)$ is the energy transferred from an active rod $g$ to the passive rod element $h$. These energy flows have an associated time average power $P$, obtained by dividing the energy by the pulse time width. Hence, performing a balance of energy on the individual rod elements (i.e. the net time average power flowing into an element is equal to the net time average power flowing out of the element) yields:

$$\frac{\partial P_g}{\partial z} = c_m P_g - c_c \sqrt{P_g} \left( \sqrt{P_g} - \sqrt{P_h} \right),$$

$$\frac{\partial P_h}{\partial z} = c_m P_h + c_c \sqrt{P_h} \left( \sqrt{P_g} - \sqrt{P_h} \right), \quad (17)$$

where $c_m$ is the material damping coefficient and $c_c$ is the overall coupling coefficient or dashpot coefficient in figure 6.

The set of equations of (17) can be solved simultaneously using the function ODE45 in MATLAB®. It is expected that the average power ($P_g$) on the active wire decreases while the average power in the passive wire ($P_h$) increases with the distance $z$ and they tend to both converge to the same value as $z \to \infty$ as they arrive to an equilibrium of energy. The farther the distance it travels, the greater attenuation the original signal gets on the active wire due to material damping and energy transfer. Considering a distance $z$, the power change for different dashpot coefficients can be easily obtained. The $c_c$ coefficient controls the amount of damped power and consequently the transmitted power (see figure 7).

When exciting a multiwire cable with an ultrasonic signal, the input signal loses power as it goes through the wire. As already mentioned, this phenomenon of attenuation can be
modeled by material factor $c_m$ and the coefficient $c_c$, which is a function of the mechanical contact between the wires. Now, if we assume that the two coupled aluminum rods (with $c_m = 0.002$ and $c_c = 0.05$ following calculations by Haag et al (2009)) are excited with a dispersive signal obtained with equation (13), it is expected that power flow will change as the pulse travels through the rods. Figure 8(a) shows the calculated changes in the propagated signal, for a 40% and 20% value of $c_c$ at a distance $z = 90$ cm. Thus, the energy distribution of the artificial signal is modified by the dashpot coefficient value.

Then, the proposed entropy based method (STWE) is applied to the synthetic signals to determine the sensitivity of the proposed technique to coupling chances. This is applied relating the energy distribution of the original signal (i.e. the signal at distance $z = 0$ cm) with the energy distribution modified by the dashpot coefficient (similarly to the RWE described in Quiroga et al (2000)) and applying equation (9) through (12). Figure 8(b) shows the entropy evolution for signals in figure 8(a); since the STWE detects changes with respect to the original energy distribution, the entropy amplitude increases while the $c_c$ value decreases. This indicates that the coupling conditions can be interpreted as a relative change in the entropy of the system.

The results of figures 3 and 8 show that when using the STWE method the changes in non-stationary, noisy dispersive signals are easily detected. Also, the energy transfer due to coupling conditions of the wires can be detected.

In the next section, we describe experiments carried out on single wires and on a multiwire test cable (ACSR). First, we performed tests on a set of two, three and four aluminum wires of 6.4 mm in diameter and 64 cm in length (figure 9(a)). Each set of rods were held together with a constant applied force through all the experiments using plastic covered copper wires. The rods were tested in a through-transmission configuration where a transmitter transducer of 1 MHz of central frequency and 12.7 mm of diameter was excited with a tone burst of 0.8 MHz and 6 cycles generated by an Agilent function generator (model 33220A). The carrier frequency of the tone burst was selected based on the frequency response of the transducer and the frequency range on the dispersion curves where flexural and longitudinal vibrational modes were expected to be found. The received signal was picked up by another similar 1 MHz transducer and then amplified with a commercial pulser-receiver (Panametrics, 5800), stored and post-processed with the STWE implemented in MATLAB® (figure 9(b)). The experiments were performed to observe the sensitivity of the proposed STWE to energy transmission and possible mode conversion of the vibrational modes due to the various set of rods used.

After these experiments, several tests on a section of a multiwire ACSR cable (commonly used in power overhead lines) were performed. This cable is a concentric-lay-stranded conductor consisting of a 7 straight steel wire core and 26 intertwined aluminum wires in 2 layers. The diameter of each aluminum wire was 3.4 mm, and the diameter of each steel
wire was 2.7 mm. Thus, the total diameter of the cable used in the tests was 21.8 mm with a length of 90.5 cm.

Using the same experimental system as above (figure 9(b)), the transducers were mechanically fixed at both ends of the cable using industrial ultrasonic couplant (Sonotech INC). The transmitter and receiver transducers were excited with a tone burst of 500 kHz (at this carrier frequency there is enough separation between the lowest vibrational modes of steel and aluminum curves as can be seen in figure 5) and the received signal was saved and stored for further post-processing.

Artificial damage was made to the test cable using a handsaw. The notch (handsaw cut) was made transversal to the wave propagation at a distance of 45 cm of the transducer. Cut depth was increased from 1 to 9 mm (the width of the cut handsaw was 1.7 mm). Before and after each increase of depth of the cut, measurements were made in through-transmission configuration and the signals were saved for further processing.

4. Results and discussion

The results of experiments with the groups of single aluminum rods (sets of 1, 2, 3 and 4 wires) are shown in figure 10. The typical observed signals in the time domain do not exhibit a definite pattern that allow the recognition of the energy interaction or possible guided wave conversion as the number of wires increases. Similar results were found for STFT where it was observed that the main contours of the energy map followed the single wire theoretical calculations (solid and dashed lines). However, only small changes in the time–frequency domain between different tests, if any, were observed.

The proposed STWE technique was implemented. A DWT was applied to each signal obtained from previous experiments. The DWT decomposed the signal in 9 wavelet coefficients \(j=9\) using an orthonormal wavelet db1. The STWE technique was estimated with equation (9) through (12). A time window length \(L=10\ \mu s\) (25 data points) was used in all signals. The analysis using the STWE technique has an apparent sensitivity to changes of the signal in frequency and shape. In order to observe the repeatability of the measurements, the tests were performed five times for each set of rods. For each measurement, the transducers were removed and then re-attached for the next trial. The results for the bounded rods show a clear pattern with only minimum variations among them which were linked to variations of the experimental conditions in the experiments among trials (figure 11(a)). The experimental results of each trial had a correlation coefficient with the average value larger than 0.9.

Figure 11(b) shows the comparison of the average values of each group of rods. The STWE results seem to be sensitive to the configuration of the rods; the first peak, corresponding to the \(L(0,1)\) mode, increases its amplitude as the number of rods increase. This is expected, since the energy travels through a different number of rods, which leads to a disordered signal. The peaks of entropy, possibly related to flexural modes \(F(1,4)\) and \(F(2,3)\), at 250 and 300 \(\mu s\) respectively, present a measurable difference of amplitude for the different number of rods. All these changes of entropy have an apparent relationship with the coupling condition (packing structure) of the set of rods.

For experiments with the multiwire cable using the through-transmission technique, the signal in figure 12(a) corresponding to the undamaged cable was obtained. Three packets of waves are visible. Based on theoretical arrival time, the first two packets are longitudinal modes of aluminum and steel wires, while the third packet corresponds to the flexural
Figure 10. Signals in time domain and spectrograms of set of: (a) one, (b) two, (c) three and (d) four rods.
mode of the propagated pulse in both materials. The STFT of the signals was also computed and compared with theoretical calculations (figure 12(b)).

The cable with the largest value of damage (figure 13(a)) exhibits an increase of amplitude for the longitudinal modes, $L(0, 1)$, but the flexural mode $F(1, 1)$ almost disappears. In figure 13(b) the time domain results are confirmed using the spectrogram’s maps, where it is observed that the area corresponding to the arrival time of the flexural mode has minimum energy.

It is important to point out that there is an energy exchange among the wires of the cable. That is, recalling that the damage (notch) was done with increments of 1 mm, and the notch did not reach wires that were not initially sonified by the transducer until damage exceeded 4 mm of depth (see figure 9(b)). However, the signal exhibited sensitivity to it even when the damage was only 1 mm in depth. This result seems to indicate that the phenomenon of energy transfer between the wires of the cable is occurring and it indicates that damage detection in wires that are not directly coupled to the transducer is possible due to this phenomena.

Previous to the measurement of STWE, the maximum energy on small areas with high amplitude of $L(0, 1)$ mode was estimated directly on the spectrogram determined by STFT (as described in Baltazar et al 2010). A relationship between the average energy of the $L(0, 1)$ modes and the level of damage was found (figure 14). There is an increase in the average energy, which appears to contradict the loss of energy expected in a through-transmission experiment. We speculate that this is a consequence of the loss of mechanical contact of
the inner steel wires with the outer aluminum ones which happens as the cut gets deeper. This prevents radial energy transmission and thus, concentrating the energy at the inner wires of the cable where the sensor is located, increases the energy received by the sensor. Nevertheless, the use of the STFT to identify the vibrational modes is in most cases difficult due to its single-scale, and requires extensive visual inspection in the two-dimensional time–frequency plane as well as extensive computational work. Thus, in order to obtain an optimal spectrogram, the STFT’s parameters will depend on the nature of the signal.

The proposed STWE technique was applied to the signals obtained with the experimental setup described above. A DWT was applied to each signal obtained from previous experiments on the cable. The DWT decomposed the signal in 9 wavelet coefficients ($j = 9$) using the orthonormal wavelets sym4 and db1.

The STWE technique was estimated with equation (9) through (12). Since the amplitude of the energy probability distribution increases as the time window gets larger, to maintain its sum as one, the size of the window has a bias effect on the entropy. Thus, a time window length ($L$) 5 $\mu$s was settled for all signals. The analysis using the STWE technique has an apparent sensitivity to changes in the frequency content and distribution of the signal (figure 15).

By comparing the entropies of the received signals, it is possible to detect a correlation between the entropy amplitude and the level of damage in the cable. In figure 15, the recorded values of entropy at the location of the identified vibrational modes: L(0, 1) and F(1, 1) for aluminum and steel are given. The results of the sym4 wavelet and 1 mm in damage show that the entropy values at the location of the L(0, 1) mode of steel follow an inverse correlation with the values at the location of the L(0, 1) in aluminum. The associated flexural modes of the cable decreases (for the db1 wavelet) its entropy as the damage increases which followed the observed behavior in time domain. In figure 15(c), the entropy of the observed maximum values of entropy were plotted. The trend of longitudinal modes resembles that presented in figure 14; even though entropy is only affected by the distribution of the energy and not by its amplitude. In principle, the results can be correlated to the more time consuming measurements using STFT.

It is important to point out that if the uncertainty value remain constant, the changes in amplitude of the signal will not be reflected in the entropy. Thus, the results indicate that a change of entropy amplitude could be related to a phenomena other that an increment in amplitude due to loss of energy as a consequence of the artificial damage. This should be related to a modification in the energy distribution produced by a variation in the energy exchange as the coupling condition between the wires of the cable are modified or is related to mode conversion (flexural mode converted into longitudinal mode). It is possible that as the notch deepens, the wires loses tightness and the energy flow is modified, resulting in a more disordered signal and a larger entropy.
Note that the STWE obtained with the wavelet sym4 (figure 15(a)) is more sensitive to changes in the longitudinal vibrational modes than the results with the wavelet db1 (figure 15(b)), while the wavelet db1 better reflects changes in the flexural modes. This is due to the step-like nature of the db1 wavelet, which makes it able to determine the time when sudden changes occur in the signal, but lacks efficiency to detect the magnitude of those changes. Having more vanishing moments, the wavelet sym4 allows a better detection of changes present in the signal.

The entropy based technique STWE used in this work can be potentially applied instead of the more computationally demanding STFT. The proposed technique is reasonably sensitive to variation in energy distributions of the spectral components as a results of the damage of the cable or modification in the coupling conditions among the wires. The results for through-transmission presented here could be extended to be used with pulse-echo technique to locate mechanical damage (i.e. notches). The insensitivity to signal noise of the STWE when compared to STFT is also a good point to consider from the practical point of view toward the development of an automatic system of damage identification. However, it is clear that a pre analysis to select a more appropriate mother wavelet could be necessary to obtain optimal results.

5. Conclusion

The present work describes an entropy-based methodology for damage detection in multiwire cables. The method uses DWT to measure the energy distribution of the reconstructed wavelet coefficients. The sensitivity of the wavelet entropy to small changes in frequency and amplitude (change in energy) of guided waves in cables and wires was studied. The STWE was capable of finding specific patterns that can be correlated to mechanical coupling conditions of rods bound together. It was possible to detect structural damage in a multiwire cable using the proposed technique (STWE) by observing change in the entropy evolution. It was found that this technique is significantly faster than other windowed techniques of signal analysis such as STFT since it involves a non-redundant fast-wavelet algorithm. The results indicate that the STWE reduces the dimension complexity found in the analysis of 3D spectrogram representations to a 2D plot of entropy as a function of time.

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