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Damage detection in underground high-voltage cables using guided wave method

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Abstract. This work proposes a non-destructive technique for fault detection in high-voltage power cables, based on the wave propagation patterns throughout their structure. Since they are ubiquitous and have massive impact on daily activities in urban environments, effective methods for detecting faults at these devices are of great practical and economical importance. The majority of methods currently applied to detect these pathologies are based on circuit impedance, depending on high-voltage measurements that are potentially hazardous to the technicians who perform them. Here, we describe an alternative way, by considering the cable as a wave guide and studying how mechanical waves propagate throughout their structure. Dispersion curves that are typical of these systems are calculated by means of finite-element methods, applied to specific intervals of frequency and wave number that are of particular interest in this context. The methodology used to calculate these dispersion curves is based on selective extraction of propagation modes and frequencies in an axisymmetric model. Simulation results are used to illustrate both the proposed methodology and its application to fault detection scenarios that are common to power-cable grids.

Keywords: Dispersion Curves, High-Voltage Power Cables, Guided Waves, SAFE methods.

1 Introduction

Underground high-voltage cables (UHVC) are an important part of the infrastructure in modern life. In the last years, there has been a tendency to migrate to this method to transport energy instead of aerial cables due to aesthetics and safety reasons. In Fig. 1(a) a typical cross-section of these cables is shown, where the aluminum or copper nucleus has a thick polymer cover layer, for insulation purposes. This cover can be damaged by soil perturbations or due to natural polymeric degradation, as illustrated in Fig. 1(b), whereas Fig. 1(c) shows how such cables are usually installed. The methods for detecting pathologies in these systems are mainly based on impedance variation measurements, usually, a non-destructive test. In complex situations, however, if the nature or location of the pathology is difficult to find, this test can become destructive, resulting in considerable economic losses and potential danger for the operators, who must work under rigid safety protocols. Therefore, the development of more extensive non-destructive tests (NDT) is desirable, since it would lead to safer operation with reduced service times and economical losses.

In this work, we study the viability of detecting damage to the cover of a power cable by analysing the propagation of guided waves, which, in this case occurs at a waveguide geometry with one dimension length much larger than the other two. This case is typical of laminated structures, such as rails and cables, and its propagation pattern allows one to know a priori the kinds of waves that can occur from a applying an arbitrary excitation. Thus, any variations between the expected pattern and the one detected in the actual structure can be interpreted as a sign of pathologies or material degradation over time. There is a great volume of technical information about the guided wave propagation and its applications in damage detection, such as the classic work by Rose [1]. In our group, some development was also carried out in the case of the structural armor of risers in off-shore oil exploration, see Groth et al. [2, 3].

(a) (b) (c)

Figure 1. Underground high-voltage cables: (a) cross-section of typical cables; (b) Common pathologies in the cables; (c) Typical installation.

2 Theoretical fundations

2.1 Propagation of elastic waves in solid media

Energy propagation in solid media occurs in two basic forms: compression and rarefaction of the medium, and shear movements between planes that are orthogonal to the propagation direction Auld [4]. These forms of propagation generate two kinds of waves in infinite solid media: the P (dilatational) and S (equivolumial) waves, with propagation velocities $C_p = \sqrt{(\lambda + 2\mu)/\rho}$ and $C_s = \sqrt{\mu/\rho}$, respectively, where λ and μ are both the *Lamé* constants and ρ is medium density $(\mathrm{kg}/\mathrm{m}^3)$ for an isotropic material. When such waves find the solid interface, part of the incident energy is transmitted out of the body, and part is reflected back into the solid, also in the form of P and S waves. The relationship between the amplitudes of the transmitted and reflected waves depend on the elastic properties and density of the interface media as well as the refraction and reflection angles of the reflected waves, which are governed by the *Snell's* law Auld [4], Achenbach [5].

In solid media, there are two basic ways of propagating energy: one associated with the compression and the medium rarefaction, and other related to the shear movements between perpendicular planes of the propagation direction Auld [4]. From these two ways of propagation emerge two kinds of waves in infinite solid media: the P (dilatational) and S (equivolumial) waves. The P and S waves have propagation velocities of $C_p = \sqrt{(\lambda + 2\mu)/\rho}$ and $C_s = \sqrt{\mu/\rho}$, respectively, where λ and μ are both the *Lamé* constants and ρ is the density of the medium $(\mathrm{kg\,m^{-3}})$ for an isotropic material. When the P and S waves find the solid interface, part of the incident wave is transmitted out of the body, and part is reflected back into the solid, both cases as P and S waves. The relationship between the amplitudes of transmitted and reflected waves depend on the elastic properties and density of the interface media as well as the refraction and reflection angles of the reflected waves which are governed by the *Snell's* law Auld [4], Achenbach [5]. The P and S waves propagating in waveguides interact with the guide boundaries and generate patterns of energy propagation known as modes Raghavan [6]. These propagation modes, also called modal waves, depend not only on the material properties but also on the geometry of the wave guide.

2.2 Dispersion curves

Dispersion curves of a waveguide are like a map of propagation modes presented by waves throughout their structure. These curves can be determined analytically for simple structures. For complex ones, however, a simulation-based strategy is required, such as using the finite element method (FEM) combined with analytical expression, in what is called the Semi-Analytical Finite Element (SAFE) methods. This work applies the SAFE method as described in subsection 2.3, but other alternatives are possible. For instance, in Groth [7] three of these alternatives are compared in the analysis of a metallic rectangular rod.

2.3 Axisymetric FEM model

In this methodology originally proposed by Cegla [8] a waveguide is presented as a revolution ring which its tangent is oriented longitudinally, while the cross-section of the waveguide is the same as that of the ring. This results in an axisymmetric model in a finite element system, the vibration modes of which are obtained through modal analysis along its length at the longitudinal direction (symmetry radius). Figure 2 shows a rectangular waveguide example.

In the axisymmetric finite elements model, all modes are extracted in a determined wavelength (λ). On the other side, to ensure that the curvature does not affect the results, the radius considered (R) needs to be much larger than the characteristic dimensions of the cross-section. All vibration frequencies associated to the same wavelength represent the frequencies of vibration modes with wavenumber ($1/\lambda$). More detailed explanations about this subject can be found in Cegla [8], Groth et al. [9]

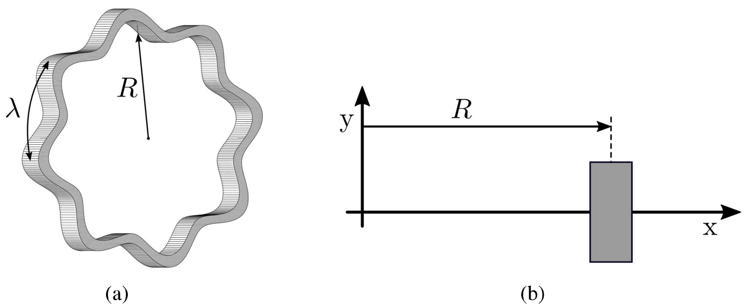


Figure 2. Waveguide represented as a ring for computing its dispersion curve. (a) restriction of the wavelength and radius of the model. (b) transversal section of the waveguide that it is modeled in FEM commercial package.

3 The underground high-voltage cables studied

A typical underground power cable is depicted in Fig. 3(a). The mechanical properties of four regions are given in Table 1. From the center of the cross-section, the conductor core material is made of aluminium, covered by an internal layer of reticulated polyethylene (XLPE) and an external layer of polyethylene with medium density (MDPE).These polymers are separated by a thin copper film of ($t = 0.2\,\mathrm{mm}$) radial thickness, with the purpose of uniforming the electrical field around the circumference. For more information about this cable layout and its applications, refer to Gudmundsdottir et al. [10]. In Figure 3(b) the FEM mesh used at the model is presented. The smallest size of the elements is limited by the copper layer thickness as $0.2\,\mathrm{mm}$. The layers are considered tied each other for this analysis. The simulation was performed in ANSYS® [11] package.

Table 1. Transversal section of the underground high-voltage cables. Mechanical properties of the layers.

Material	Layer	ρ ($\mathrm{kg/m^3}$)	ν	E (GPa)
Aluminum	1	2700	0.360	68.00
XLPE	2	930	0.420	0.95
Copper	3	8960	0.343	110.00
MDPE	4	940	0.460	0.97

3.1 The dispersion curves

In Fig. 4, three dispersion curves are presented, for the aluminium core (Fig. 4(a)), the whole cable (Fig. 4(b)) and the polymeric plus copper layers (Fig. 4(c)). The modes generated in the graph origin are called fundamental

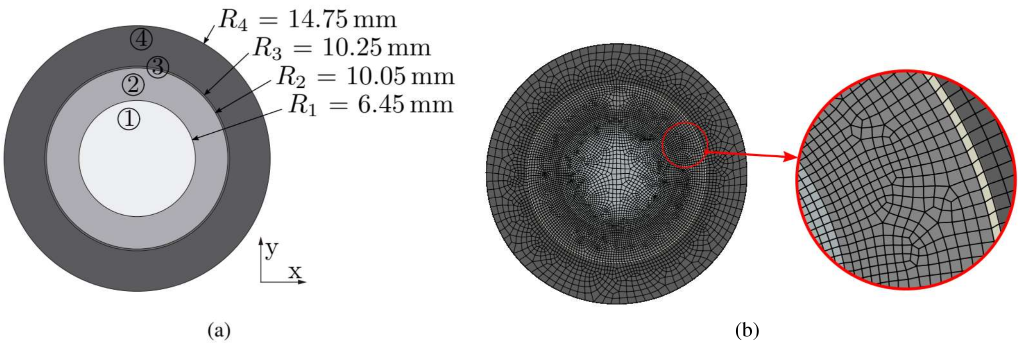


Figure 3. Modeled cable: (a) detailed sketch of the features and (b) detailed FEM mesh applied.

modes or beam modes: the longitudinal (L), torsional (T) and flexural (F). Those beginning with ($f_n \neq 0$) are here considered as *Lamb* modes (denoted by $A(\cdot)$) and do not convey an easy visualization of displacement, as opposed from fundamental modes. For more detail about these patterns, see Groth [7], Cegla [8]. Also in Fig. 4, it can be observed that longitudinal and torsional modes waves propagate with almost constant velocity, which is defined approximately as the angular coefficient (f_0/k) from the curve. Notice also that velocities change for lower values of wave number for the F curves. Finally, it can be viewed in Fig. 4(b) that since the dispersion curves depend on density and stiffness of the structure, even large quantities of polymer tend to exert little influence on the behavior of the curve, as the obtained curves from aluminum are nearer to the curves of the whole model than the polymeric ones.

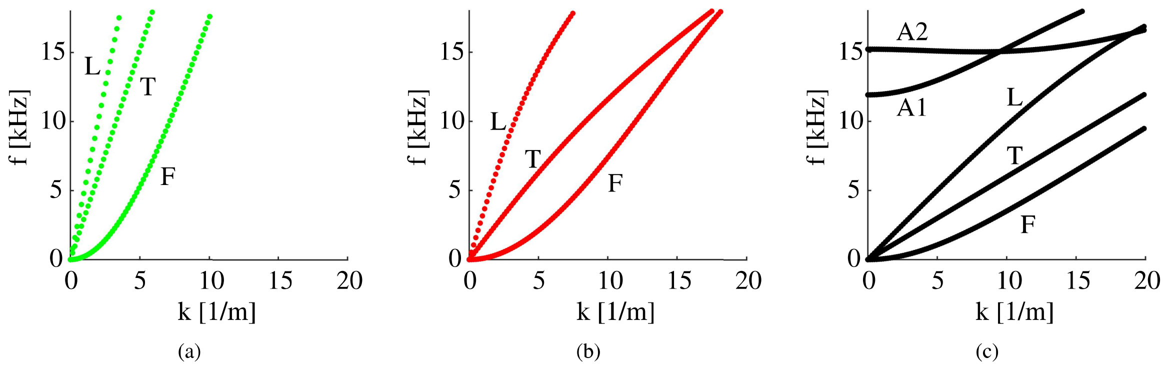


Figure 4. Dispersion curves from cross-sections formed: (a) only by aluminum, (b) by the cable itself as a whole and (c) by polymeric (XLPE and MDPE) layers.

3.2 Validation

To verify the elastodynamic behavior of the structure and the information give by the dispersion curves, a 3D model of a cable 1m-long cable was also developed, as shown in Fig. 5. The analysis was done on the time domain, with an explicit integration scheme using the finite element package Dassault Systèmes Americas Corp® [12]. The discretization around the circumference followed the same procedure applied in the axisymmetric model and the longitudinal edge length of the elements was considered uniformly $\Delta = 1\,\mathrm{mm}$. The adopted boundary conditions are also established in Fig. 5: fixed nodes at plane B, and an axial excitation over plane A. The applied excitation is called *tone burst* (Groth et al. [3]). Its spectrum pulse is well known, and it can be modeled as:

$$f(t) = A_0 \left(1 - \cos\left(\frac{2\pi f_0 t}{n}\right)\right) \sin\left(2\pi f_0 t\right). \tag{1}$$

In all cases cosidered here, this function has frequency $10\,\mathrm{kHz}$ and $A_0 = 0.5$, developing from $t = 0.0\,\mathrm{ms}$ to $0.5\,\mathrm{ms}$.

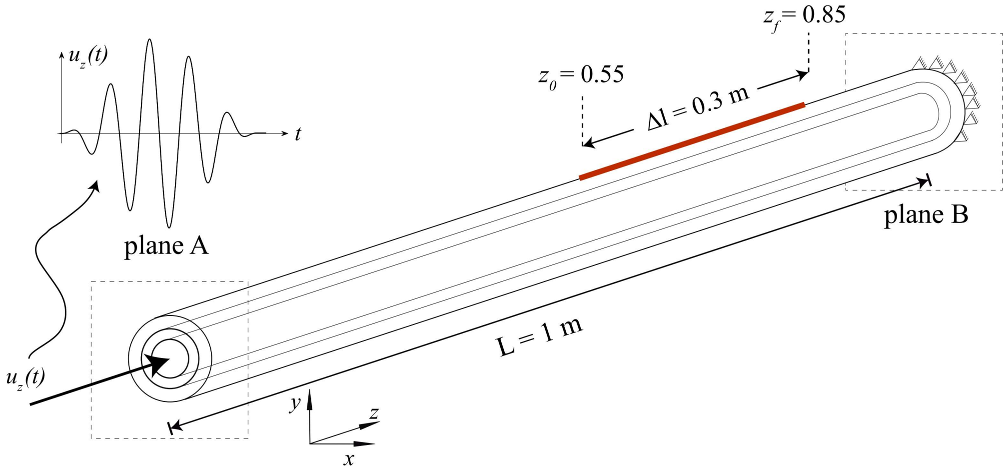


Figure 5. Scheme of the explicit dynamical model accomplished with an excitation along plane A applying displacement oriented over z axis using a tone burst wave. Displacements are collected from the highlighted red line.

To validate the dispersion curves regarding the behavior of a multi-material structure such as the cable ,and also to validate the possibility of detecting defects throughout its structure, many simulations were run with the structure as it was already shown, but considering a circumferential defect at the polymeric external layer, as in Fig. 6.

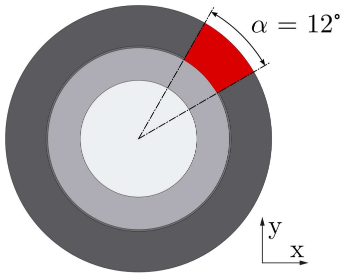
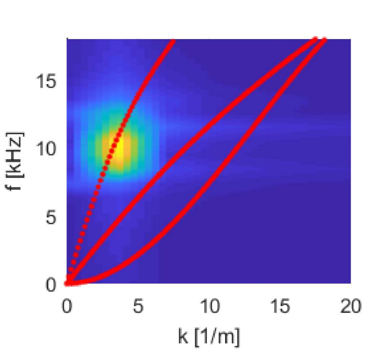


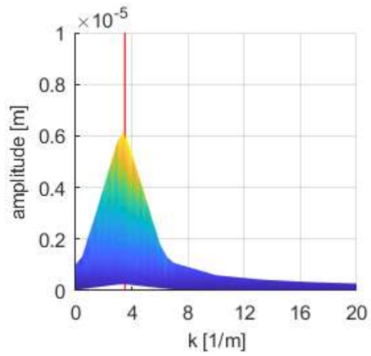
Figure 6. Defect with 12° of circumferential length through layers 3 and 4.

The simulations consist of applying an excitation over the plane A to get the results along the red line of nodes highlighted in Fig. 5. The mechanical response was collected on three hundred equally spaced nodes along this line. The acquisition rate to get the results was $f_s = 1.8\,\mathrm{MHz}$. This way, for each simulation it was created two matrices, one for the internal line (at the interface between aluminum and XLPE layers) and the other for the same line but at the external layer (polymeric layer, denoted in the red line of the figure). These matrices have a number of rows equal to the number of nodes and the number of columns equal to the number of points in time to apply the Fourier Transform along spatial and time domains (Groth et al. [2]).

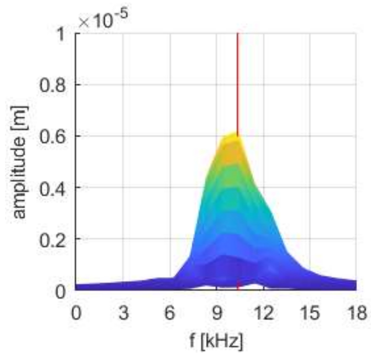
The results found by the Fourier Transform are turned into surfaces in the same domain of the dispersion curves (f, k), where the propagation intensity distribution shows at which modal waves of the dispersion curve the excitation is decomposed as travels throughout the waveguide. In Fig. 7 it is presented a comparison between the dispersion curves of the cable and the energy distribution at the same domain (f, k). It is noted that the excitation energy propagates over the dispersion curves region. As expected due to this kind of excitation, the energy indicated by the Fourier Transform is at the longitudinal mode whether the cable presents defects (Fig. 7(a)) or not (Fig. 7(d)). Figures 7(b) and 7(c) represent cuts in the planes with highest energy levels, illustrating that the energy is concentrated in a unique region. Moreover, it is possible to see that the damage imposed on the model does affect its response: the change in the *tone burst* wave distribution shows that the signal density is divided twice around the original frequency $10\,\mathrm{kHz}$, as pointed in Figs. 7(e) and 7(f). In the same figures it is noted that for $k = cte$ the signal forms two peaks.



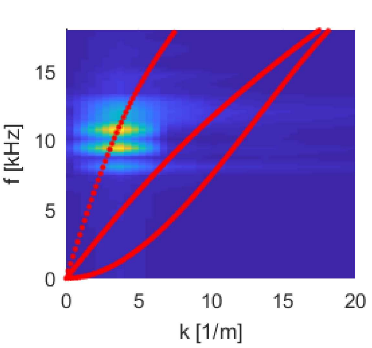
(a) Homogeneous cable, u_y



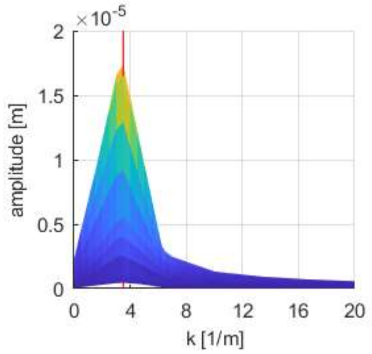
(b) $f = 9.88\,\mathrm{kHz}$



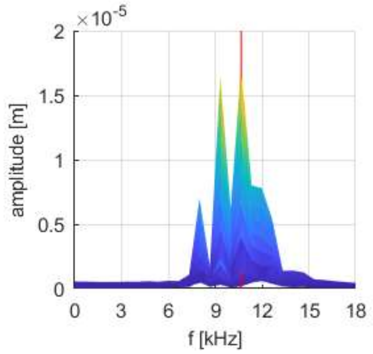
(c) $k = 3.50\,1/\mathrm{m}$



(d) Cable with the defect, u_y



(e) $f = 10.66\,\mathrm{kHz}$



(f) $k = 3.50\,1/\mathrm{m}$

Figure 7. Result in terms of the tone burst excitation applied in plane A shown in the (f, k) domain. From all cases the excitation was applied over all the cross-section.

4 Conclusions

In this work, we exploit the possibilities of applying the guided-wave technique to detect damage at the layers of underground high-voltage cables. Toward this goal the dispersion curves of the cable were obtained from an axisymmetric modal analysis, with a simulation being performed over a 3D model applying explicit integration scheme and a tone burst excitation wave, which confirmed the dispersion curves results. The analysis of the cable with a circumferential defect was also carried out. The main conclusions from there procedures are:

- The dispersion curves from the cable are consistent. As the verification shows when an axial wave with main frequency of $10\,\mathrm{kHz}$ propagates over the structure, the excited domain f, k is on the dispersion curve developed with the associated axial mode.
- When the longitudinal wave interacts with a defect, its behavior change in the frequency domain, but it retains the same kind of excitation from the structure, which can be useful to identify defects.
- For future work, this analysis can be continued by experimental tests and applying parametric analysis, so as to identify how different pathologies can create different perturbations in the waves. Also, other kinds of waves could be used as excitation to exploit this possibility. Finally, the electrical energy itself that is carried through the cable could be used as the excitation for continuously monitoring its structural integrity.

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