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Long Range Guided Wave Propagation Experimental Analysis in Overhead Power Line Cables under Different Axial Load Levels.

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Abstract. Over the past hundred years, overhead power line cables have been widely installed around the world. These cables are commonly exposed to adverse environmental conditions that can affect their structural integrity and over time, could lead to the complete failure of the structure. This research presents the use of guided waves for the inspection of the structural integrity of the overhead power line cables. The proposed system relies on permanently installing on power line cables a multiple transducers collar as well as a pulse receiver. The system is installed on the cable and performs automated regular inspections. One of the key features of this technique is its ability to inspect a long section of the cable from a single inspection point. To achieve this objective, the wave propagation features have been studied in a wide range of frequencies in 50m long cables, where different collar configurations were used. In addition, power line cables, when installed, are subjected to different axial loads depending on the type of cable and the distance between pylons. The effects of the axial load on the wave propagation have been studied. To assess the defect detection capabilities of the system over a wide range of distances without damaging the cable samples, a metallic clamp is used to introduce a cross-section change on the cables, simulating the effect of a fault on the cables (i.e. corrosion). The experimental results show the highly attenuative effect of the axial load on the wave propagation for most of the frequency spectrum. However, it was found that at low frequencies the system performance allowed the inspection of long distances. This was further proven with the experimental results for the clamp detection study.

1. Introduction

Multi-wire cables are used in many industrial applications in different fields. One of them is their use as overhead power line cables. For decades, these cables have been installed globally and currently the grid covers thousands of kilometers. These cables are exposed to adverse weather conditions and many times they are located close to salty or polluted atmospheres. Over time, these conditions can affect the structural integrity of the cables leading to corrosion or broken strands, and eventually this could lead to the complete failure of the structure.

To avoid unpredicted failures and in order to obtain information about the health of the cables, different inspection techniques have been used. The most common approach has been visual inspection, where an operator assesses the status of the cables looking for broken strands or corrosion. This task is normally performed on foot or with the use of a helicopter. This is a time-consuming and costly task that could represent a hazard for the operator due to the difficulty in accessing the location of some of the cables. Due to this limitation, in recent years, different solutions have been investigated for the inspection and monitoring of the cables. The use of UAV has been introduced to substitute the visual inspection by the HD camera or the use of infrared cameras. The defects or corrosion in the cables increase the temperature of the conductor and the infrared cameras are used to find these hot spots. The battery life of the UAV and the possibility of only inspecting the external wires are two of the main limitations of this technique.

As an alternative, the use of ultrasonic guided waves has been investigated as a possible solution for the inspection or monitoring of these structures. Guided waves testing technique is commonly used for the inspection of the pipeline and other plate like structures. The waves have the ability to travel long distances within the boundaries of the structure. This is an advantage over other techniques because a large length of the structure can be investigated from a single point of inspection.

Based on this, the INTEL-LINE project aims to produce a power line cable monitoring solution using guided waves inspection. The INTEL-LINE system (Figure 1) includes a compact electronic design to generate the high voltage pulses with the necessary wireless communication hardware and software to process and send the collected data. The waves are generated by PZT transducers mounted on a collar specially designed to enhance the generation and propagation of the waves. In addition, an energy harvesting system has been specifically designed to use the magnetic field generated by the high current in the cables as a power source for the system. The system has been integrated in a spherical metallic encapsulation to resist the adverse conditions derived from the power line cables operation, as well as the weather conditions. The experimental results presented in this research were performed as part of the INTEL-LINE project.

Figure 1 INTEL-LINE system

2. Guided waves applied to multi-wire cables

Different investigations have been carried out to study the propagation of the guided waves into the multi-wire cables. These studies focused on different types of cables depending on their applications varying from steel strands [1], bridge stand cables [2], or power line cables [3]. The complexity of the cables makes the study of the wave propagation a challenging topic. Two main factors that highly affect the wave propagation have been identified; their multi-element characteristic, with multiple points of contact between the strands, and the complex helical shape of each of these elements [4]. The effect of these two factors in the wave propagation is being studied for different types of cables [5-6]. As a result of these investigations, it was first concluded that the L(0,1) is the optimal wave mode thanks to its lower attenuation and dispersion properties compared to F(1,1).

In addition to the multi-element condition and helical shape of the cables, another parameter that affects the propagation of the waves for the power line case is their operation under external axial load. Once these cables are installed, the axial load is decided according to a safety factor for their maximum operational axial load. Therefore, this value varies depending on the type of cables. Different investigations have been carried out taking into account the axial load effect on the wave propagation in the multi-wire cables [1]. These results show the attenuation suffered by the waves at different frequencies, however these studies were not carried out on long length power line cables [6-7].

3. Experimental setup

The present experimental case shows the effect of the axial load on the wave propagation in a BEAR cable sample of 50 meters length. The cable is formed of 30 aluminum strands in the two external layers and a core of 7 steel strands, all of them with a diameter of 3.35 mm. The experimental test rig was designed in order to allow the axial load applied to the power line cable sample to be controlled, for up to 600 kg force.

Figure 2 50 meters cable test-rig

In order to study the wave propagation in these structures, two different transducers' configuration were used: pitch-catch to study and pulse-echo. For the pitch-catch configuration, two prototypes of the INTEL-LINE system were used, with a distance between the transmitter (Tx) and the receiver (Rx) of 5 and 20 meters.

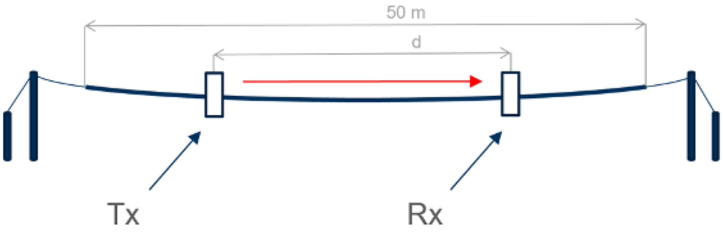

Figure 3 Pitch-catch configuration

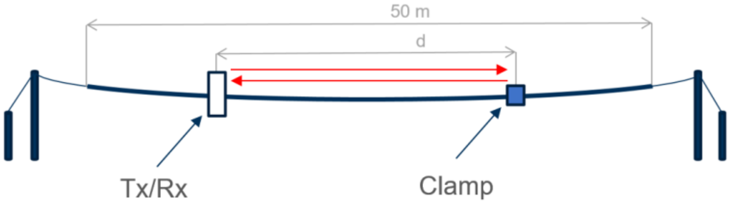

Figure 4 Pulse-echo configuration

In contrast, for the pulse-echo configuration a single unit of the INTEL-LINE system was used (Tx/Rx). To simulate the presence of defects on the cables, without damaging the cables and therefore affecting the structural integrity of the samples, a metallic clamp was used as shown in Figure 5. This clamp also provided flexibility in the experiments due to the fact that it allowed the defects to be located at different positions.

Figure 5 Metallic clamp

4. Results

4.1. Case 1 Wave propagation study under different axial loads with a pitch-catch configuration.

The main objective of this case is to study the amplitude and SNR of the waves travelling throughout the cables. For that a pitch-catch configuration was used, as shown in Figure 3. The initial distance between Tx and Rx was 5 meters. Figure 6 gives the results of the first passing signal for 5 and 10 kHz under different axial loads, [0 – 600 kg force] every 100 kg force. These signals show the high influence of the axial load on the propagation properties of the cables.

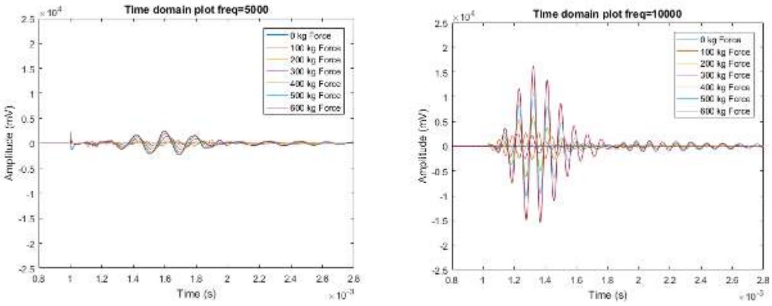

Figure 6 First passing signal at 5 kHz (left) and at 10 kHz (right) for axial loads of [0 – 600 kg force] at 5 meters distance between Tx and Rx.

In order to illustrate this effect, the maximun values of the first passing signals, at 10 and 15 kHz are shown in the following Figure 7. In addition the SNR of the signals is included. Both cases demonstrate how the axial load reduces the amplitude and SNR of the waves up to 200 kg force. For higher values of axial load, the amplitude and SNR increases.

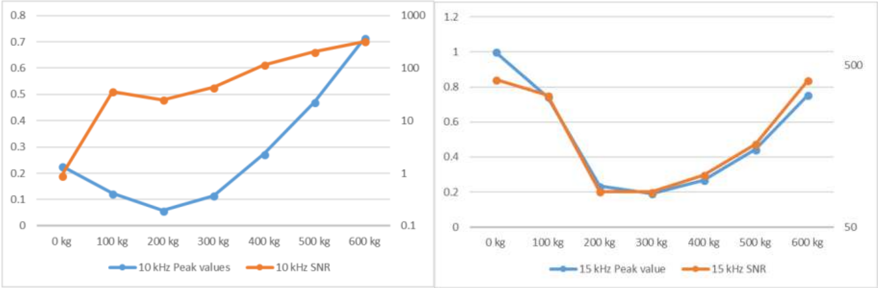

Figure 7 Peak values and SNR of the first passing signals at 10 kHz (left) and 15 kHz (right) at axial load of [0 – 600 kg force]

The following 3D images (Figures 8 and 9) display the effect of the of the different axial load levels on the amplitude and SNR values respectively at axial loads of 0 to 600 kg force with 100 kg force step and a frequency range of 5 to 150 kHz with 5 kHz step.

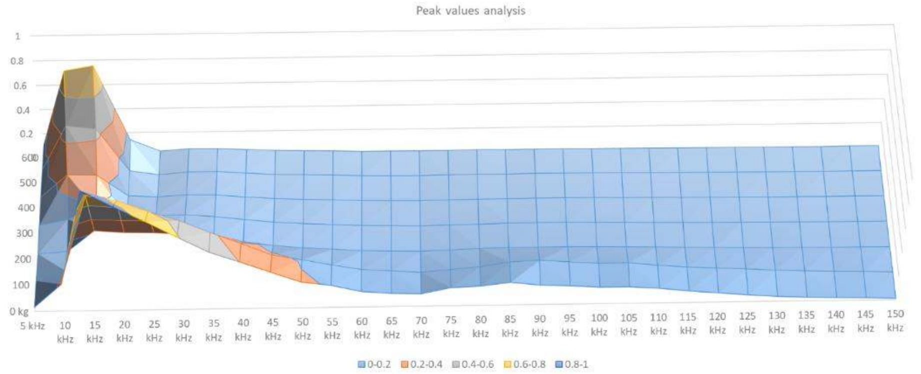

Figure 8 Amplitude values of the first passing signals for axial loads of [0 – 600 kg force] at 5 meters distance between Tx and Rx.

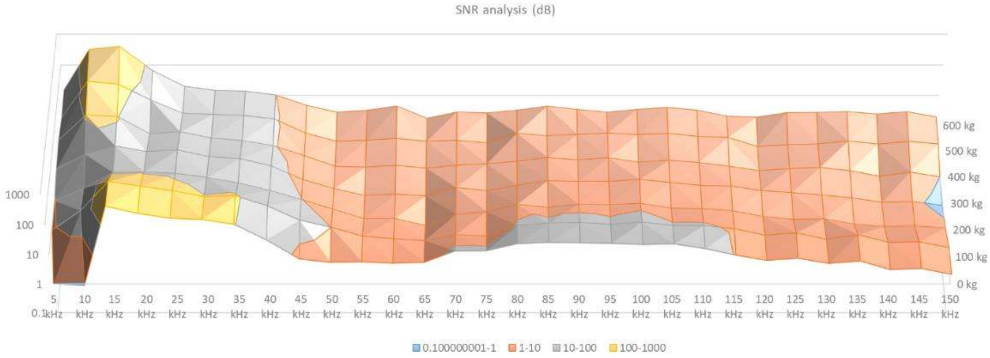

Figure 9 SNR of the first passing signals for axial loads of [0 – 600 kg force] at 5 meters distance between Tx and Rx.

According to Figures 8 and 9 the previous effect shown for 10 and 15 kHz is common for frequencies between 5 to 40 kHz. In addtion, these images also show a shift into the frequency with the highest amplitudes and SNRs to lower frequencies. While under no axial load, the maximum values are obtained between 10 kHz and 35 kHz. Under 600 kg force, this range is concentrated between 5 to 20 kHz. These results compared the first passing signals for a distance of 5 meters, which allowed a wide range of frequencies to be recorded. For a distance of 20 meters it was found that the waves were only visible under an axial load higher than 400 kg force. In order to compare both distances, the peak values and SNR of the first passing signals, under an axial load of 600 kg force, have been included in Figure 10. In this case the analysis focuses on frequencies below 13 kHz, where the maximum amplitudes and SNR levels were found.

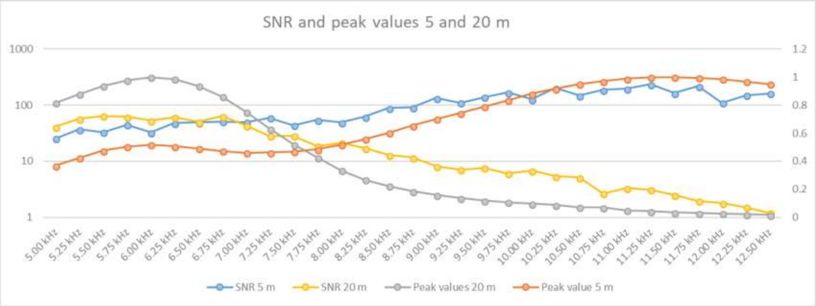

Figure 10 Normalize peak values (left axis) and SNR (right axis) of the first passing signals for axial loads of 600 kg force at 5 and 10 meters distance between Tx and Rx.

Figure 10 shows how, while with a distance of 5 meters the maximum amplitude and SNR levels correspond to the range between 11 to 12 kHz, for 20 meters distance the maximum level is found at 6 kHz.

4.2. Case 2 Wave propagation study for defected cables simulation with a pulse-echo configuration.

After the previous analysis where the most convenient frequency range was found regarding the amplitude and SNR, this second case of study investigates the defect detection capabilities of the technique. To do so, a pulse-echo configuration is used where the waves are reflected by a metallic clamp located at different distances from the INTEL-LINE system. The frequency range used was [6 – 13 kHz] and the axial load was fixed to 600 kg force. One of the limitations of the pulse-echo configuration is that part of the waves generated by the transducers are reflected and collected as part of the received signal. This dead-zone represents a limitation in terms of the study of defects located a short distance from the source of excitation. In order to mitigate the effect of this noise, a baseline subtraction approach was used where the signal from a sample without the clamp attached was used as the baseline. In order to illustrate this method, Figure 11 demonstrates the baseline used and the signal received from the system with the clamp at 8 meters before and after baseline subtraction.

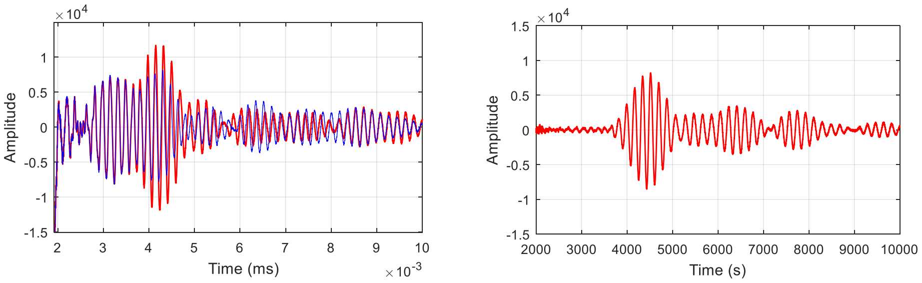

Figure 11 Left: Received signal at 5.75 kHz before (blue) and after (red) attaching the metallic clamp at 8 m. Right: Received signal after baseline subtraction.

This method was used with the clamp attached at different distances for up to 18 m. The results are shown in Figure 12 for a frequency of 10 kHz. This figure demonstrates the attenuation of the reflected waves with the increase in the distance between the excitation source and the clamp.

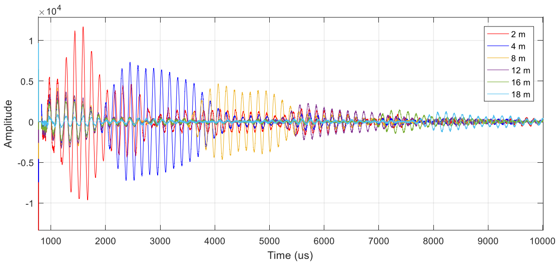

Figure 12 Received signals after baseline subtraction with the clamp at different distances from the Tx at 6.5 kHz

This method was reproduced for the following range of frequencies [6.0 – 13.5 kHz] every 0.5 kHz. The following Figures 13 and 14 show the results of these experiments, the peak value of the reflection, and their SNR respectively.

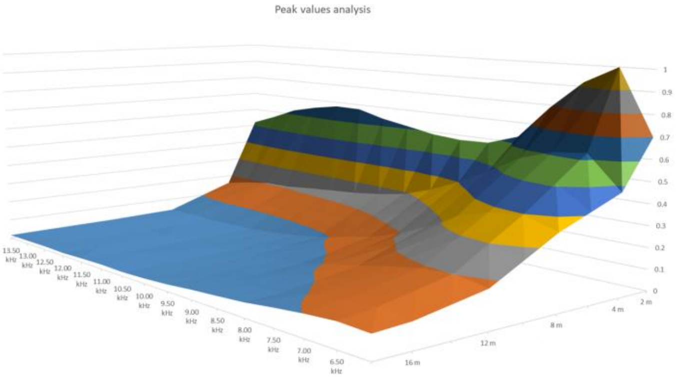

Figure 13 Peak values of the echoes at different distances and frequencies at 600 kg force axial load

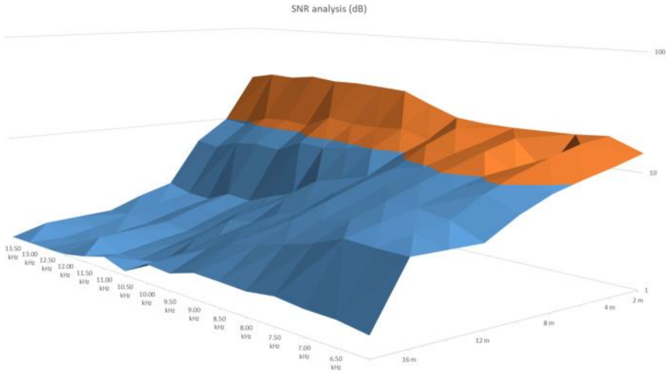

Figure 14 SNR of the echoes at different distances and frequencies at 600 kg force axial load

5. Conclusions and future work

A series of experiments were performed in order to study the wave propagation in power line cables. Two different cases of study were presented. First, we studied the effect of the axial load on the wave propagation. A pitch-catch configuration was used with two different distances between the excitation and reception systems, 5 and 20 meters. For 5 meters distance, the results showed how the axial load have a big influence on the propagation of the waves, heavily attenuating for tensions between 100 – 200 kg forces. For higher tensions of 500 to 600 kg force the opposite effect was demonstrated, where the amplitude values were similar or higher compared to the results without axial load. In addition, with no axial tension, it was found that the maximum amplitudes and SNR corresponded to frequencies between 10 kHz and 35 kHz. However, at 600 kg force these maximum values shifted to lower frequencies [5 - 15 kHz]. Within this range of frequencies, at 5 meters the higher values corresponded to 11 to 12 kHz. In contrast, for a distance of 20 meters, the best frequency was 6 to 7 kHz according to the SNR and amplitude values. These results prove the long range propagation capabilities of the technique.

The second case of investigation's main objective was to study the defect detection capabilities of the technique. In order to study the reflection of the waves at different distances and under axial load without damaging the cables, a metal clamp was used to simulate the defects. Due the use of a pulse-echo configuration and the characteristics of the power line cables with multiple strands, a large dead-zone appeared in the signals. In order to remove this effect, a baseline subtraction approach was used. The results show how the technique was able to increase the SNR of the reflected signals for distances of up to 18 meters. It was demonstrated that the attenuation of the waves varied depending on the frequency. This attenuation is especially severe at higher frequencies [10 – 13 kHz]. In contrast, this frequency range presented higher SNR for distances below 4 meters. This information will be useful when selecting the most convenient frequencies depending on the location of the defects.

The system shows that the waves generated have the ability to travel long distances in cables under axial load and the ability of the technique to detect changes in cross-section characteristic of corrosion. This technique will need to be validated for higher axial loads to reproduce the operation conditions of the cables with the introduction of saw cuts or corrosion into the cables.

Acknowledgments

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