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An ultrasonic guided wave approach for the inspection of overhead transmission line cables

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ABSTRACT

Inspection of overhead transmission line cables is performed using various non-destructive testing techniques, such as visual, temperature, and eddy current-based inspection; yet each of these techniques have their respective shortcomings and safety concerns. The use of ultrasonic guided waves as a non-destructive testing technique is well established for simple geometries such as plates, pipes, and rods. However, its application for multi-wire cables is still in development. In this study, ultrasonic guided waves excited by a shear mode transducer collar are utilised as a defect detection technique for untensioned aluminium conductor steel reinforced cable specimens. The identification and analysis of wave propagation for a broad range of frequencies is performed using a laser scanning vibrometer, and the effect of defect size on wave propagation is studied. Signal processing algorithms, such as wavelet denoising and time scaling, are then deployed for inspection quality enhancement and analysis under noisy conditions. Results yield an extended range of defect detection coverage in pulse echo configuration; with successful detection of defects that correspond to a 4.5% reduction in the cable's cross sectional area; and up to 24% improvement of signal-to-noise ratio.

1. Introduction

Multi-wire cables are extensively used in a broad spectrum of engineering applications to meet various demands; such as load carrying in bridges, cranes, and elevators; post-tensioning in concrete structures; and electricity transfer in power grids. Overhead Transmission Line (OVTL) cables span long distances and form the backbone of the energy distribution grid. Throughout their service life time, OVTL cables are influenced by various effects such as operational factors (applied tensile stress and voltage stress) and environmental factors (wind-induced vibrations, icing, melting, and lightning strikes). Those factors, especially if the specimen has structural imperfections due to faulty manufacturing, can result in structural failures such as broken insulators, loose earth conductors, mechanical failures (twisted/ruptured/broken wires), and corrosion [6,29]. Structural failures have been reported to start emerging in the aluminium layers first [2]. In some cases, however, the steel core is reported to be intact even though the aluminium layers had structural failures [6]. The consequences of a structural failure in OVTL cables is reported in [2], where the failure of Aluminium Conductor Steel Reinforced (ACSR) cables left 67 million people under a power blackout in Brazil. Therefore, a reliable and fast inspection system, preferably an automated one with minimum human involvement, is desirable.

Certain Non-destructive Testing (NDT) techniques have emerged and have been widely used to provide pre-emptive measures against structural failures. Airborne and on-ground visual inspection performed by trained personnel is one of the first methods devised for structural maintenance of OVTL cables. It requires extensive care from personnel [28] and it is subject to regulations [31]. Manual visual inspection, however, is time-consuming, prone to human errors and has associated health hazards; primarily for airborne inspections where helicopter crashes have resulted in loss of lives [12]. In order to avoid human error and reduce health hazards, recent inspection methods have used different techniques to automate inspection systems. Automated visual inspection systems have been developed which apply image processing algorithms on videos/images acquired by either installed camera systems or airborne image acquisition systems. The efficiency of those methods relies heavily on the quality of the acquired images, and thus on the quality of the camera and the stability of the aerial

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vehicle [15]. Temperature inspection methods have been proposed in [30,32], where infrared cameras were used to collect images of the power line components to detect corona effects triggered by structural discontinuities. Eddy current-based systems for the inspection of OVTL cables are reported in [16,34], where eddy currents are utilised for the detection of broken strands and corrosion on an OVTL cable. Kasinathan et al. has described the utilisation of fibre optic cables for temperature monitoring of OVTL cables to extract structural integrity information [14]. Radio and audible noise monitoring to acquire structural health information has also been proposed for OVTL cables [22]. In order to increase inspection range and quality, some studies have also utilised advances in robotics for the inspection of OVTL cables. The use of robotics, however, has its respective disadvantages, such as complexity in design, maintenance of robots, electromagnetic interference to communication systems of remote controlled robots, optimisation of weight and line tracking abilities for unmanned aerial vehicles [15]. In order to tackle design complexity, human errors, and health hazards associated with the abovementioned methods, Ultrasonic Guided Wave (UGW) based NDT methods have been investigated.

UGW based NDT techniques have been utilized for the interrogation of various multi-wire cable structures, and studies related to guided wave characterisation and defect detection in multi-wire cables have emerged. Xu et al. utilised magnetostrictive transducers to generate UGW for defect detection in seven-wire steel prestressing cables [13], and also investigated guided wave-based defect detection of 31 and 37-wire stay cables [35]. Liu et al. studied the optimisation of magnetostrictive transducer configuration to enhance guided wave inspection quality [20]. Studies have also emerged focusing on the possible effects of various factors that affect the wave propagation in multi-wire cables. Rizzo et al. studied ultrasonic wave propagation in seven-wire steel strands and analysed the changes in wave propagation with progressive loads applied on the cable [25]. Liu et al. also analysed the effects of temperature on wave propagation in multi-wire steel strands and related the wave propagation velocity variations to temperature changes [19]. The emphasis was also given to ACSR cables in several UGW based NDT studies. Haag et al. investigated guided wave propagation in ACSR cables with the aim of understanding energy transfer between wires, and formulated a computationally efficient energy-based model to predict the wave propagation in a simplified two-rod system with friction contact [9]. Branham et al. reported the feasibility of defect detection in ACSR cables with two different transducer coupling schemes and an understanding of attenuation and dispersion in ACSR cables [5]. Gaul et al. reported an overall feasibility analysis of the use of guided waves for damage detection in ACSR cables with an emphasis on the reflection of wave packets at structural discontinuities with varying geometry and size [8]. In one of the latest studies, Baltazar et al. investigated the changes in guided wave propagation in ACSR cables in the presence of a defect, and reported that the energy of the flexural modes changes when a defect is introduced and this change can be monitored for defect detection [3]. However, the abovementioned studies have not investigated the inspection efficiency for long OVTL cables under noisy (i.e. measurement noise, random noise, etc.) conditions.

The detection of defects in noisy environments, spatially overlapping echoes coming from closely spaced defects and the effects of dispersion phenomenon on wave propagation in interrogated media have been problematic for UGW applications, and raised the necessity of signal processing methods for inspection quality enhancement. Time-frequency analysis, deconvolution-based approaches, split spectrum processing, pulse compression [11], sparse signal representations, empirical mode decomposition [36], frequency warping [21] and wavelet transforms have been used for ultrasonic NDT applications [37]. Various studies have reported the use of advanced signal processing algorithms for the analysis of wave propagation and defect detection for multi-wire cables. Rizzo et al. utilised Discrete Wavelet Transform (DWT) to extract wavelet domain features for enhanced defect characterisation in multi-wire strand structures [27], and also reported the strength of DWT-based denoising in defect detection [26]. The wavelet transform has also been utilised to achieve good time-frequency representation quality for defect detection in ACSR cables, as reported by Salazar et al. in [10].

The design of a reliable and efficient NDT system requires thorough understanding of the wave propagation in the medium of concern. Evaluation of transducer coupling and respective analysis of wave propagation should be performed to achieve optimal results. In reference [17], the authors presented a study on the use of dispersion compensation for increasing the inspection range for ACSR cables using UGW. To accomplish this, the wave propagation on an untensioned 26.5 meter long Bear 325 ACSR cable was investigated. It was found that the UGW signal consisted of a single wave mode, the longitudinal $L(0,1)$ wave mode, which propagated along individual outer aluminium wires of the cable. While this gave good understanding of the wave propagation over long lengths of cable, it did not investigate wave propagation for short lengths of the cable or across the cable's cross section.

The current paper builds on the work presented in reference [17] by investigating the wave propagation on shorter lengths of untensioned cable and also across the cross section of the cable. In addition to this, the effects on the UGW signal of adding masses and different depth cuts to the cable are investigated. Following this, improved localisation of defects using wavelet de-noising is investigated. Section 2 provides information about the cable and the hardware used in this work. Section 3 presents the experimental set up and necessary theoretical information for wave propagation characterisation. The effect of adding masses and introducing defects is investigated in Section 4. The results of wavelet denoising and time scaling algorithms applied to the experimental results are presented in Section 5. Section 6 provides a discussion on some limitations of this work and areas for future research. Finally, a conclusion is provided in Section 7.

2. Experimental procedure

2.1. Cable information

ACSR cables are among the most widely used power transmission line cables. They are made of twisted aluminium and steel wires. The diameter of the individual wires and number of wires forming the cable vary between different ACSR cables. The cable used in this study, which has the codename Bear 325, has an overall diameter of 23.45 mm and consists of an inner core composed of seven steel wires, which are covered in anti-corrosive grease,

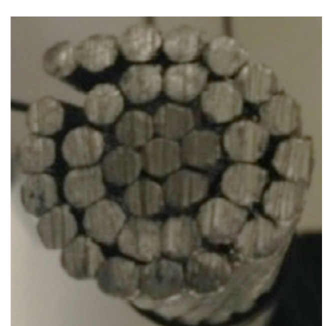

Fig. 1. Photo of cable cross section.