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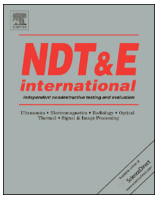

Ultrasonic guided wave-based testing technique for inspection of multi-wire rope structures

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ABSTRACT

The aim of this paper is to investigate the propagation of ultrasonic guided waves (UGW) along multi-wire ropes with polymer cores and to determine whether it is possible to detect defects and to identify a defective strand inside the internal structure of a multi-wire rope. The modes of UGW that propagate along multi-wire ropes have been identified using modelling wherein dispersion curves are calculated using the semi-analytical finite element (SAFE) technique. The optimal excitation regions were estimated using 3D FE modelling. An ultrasonic testing technique to identify particular defective strands inside the internal structure of a multi-wire rope was developed and verified experimentally.

1. Introduction

Multi-wire ropes are widely used in modern engineering structures, for instance, in the structures of cranes, bridges or elevators, and play a critical role when carrying heavy weights. Choosing a wire rope leads to considerations of rope strength; resistance to rotational fatigue; and resistance to crushing, corrosion, wear and abrasion. Multiple defects may develop in a wire rope due to, for example, overloads or a harsh environment [1]. For these reasons, it is important to inspect such wire ropes and determine whether the properties of the elongated structure have changed.

Several techniques can be used to inspect multi-wire ropes. Often, wire ropes are inspected using magnetic flux or acoustic emission testing techniques. The magnetic flux measurement method is widely used for the inspection of pre- and post-stressed steel [2] and for the inspection of wire ropes to determine the number of broken wires [3–5]. This method ensures high accuracy and sensitivity and appears to be the most reliable inspection technique for wire ropes. However, the technique is only applicable to the testing of relatively thin wire ropes (of diameters up to a few centimetres) and is very sensitive to the way in which the wire rope has been magnetised.

The acoustic emission method is used for periodic testing of wire ropes [6]. This method requires a complicated analysis of acoustic signals because various modes of elastic waves may propagate in wire ropes. The acoustic emission method is suitable for the inspection of short sections of wire rope only. The above-mentioned techniques only indicate the presence of defects, and they do not allow accurate identification of a particular defective strand inside the internal structure of the multi-wire rope.

One promising method for wire rope inspection may be the application of ultrasonic guided waves (UGW), as they propagate long distances even in high-attenuation materials and are sensitive to both surface and internal defects [1,3,7–22]. Changes in the properties of wire ropes affect the waveforms of ultrasonic signals captured from the structure. Still, ultrasonic investigation of wire ropes is a challenging non-destructive testing (NDT) task that is quite complicated. Multiple layers and different numbers of wires in different ropes can cause such phenomena as dispersion and the existence of many different wave modes; solving the problem requires an understanding of wave propagation in complicated helical-cylindrical structures and wave interactions with defects. Determining whether just the outer layer or both the outer and deeper layers of the wire rope are being inspected depends on how the waves in a strand are excited (for example, as a whole structure or wire-by-wire) and whether just the outer surface or the end of the strand is accessible.

Studies conducted by Pavlakovic et al., Beard et al., Laguerre and Treyssede show that in the case when only one tip of the strand is accessible, wire-by-wire excitation is possible using

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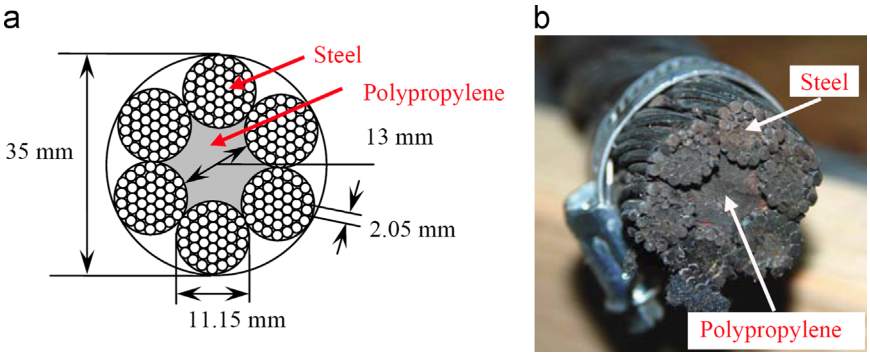

Fig. 1. The object under investigation: schematic view (a) and photo (b) of the cross-section of the multi-bundle and multi-wire twisted rope.

thickness-mode piezoelectric transducers to excite and detect longitudinal modes of UGW. Application of high frequency is recommended to concentrate the energy in the wire [8–10]. Unfortunately, some structures allow no accessible strand tips due to anchoring.

In the case of excitation from the outer surface of the strand, the authors of the above-mentioned studies generally tended to excite the strand as a whole structure using contactless magnetostrictive transducers that encircled the strand [3,11–19]. With this method, it was demonstrated that defects both in peripheral wires (outer defects) [3,11–14,16] and in the central wire (inner defects) may be detected [15].

It should be mentioned that an analysis of a piezoelectric ring that excited the periphery of a strand in an overhead transmission line was conducted by Kulkarni and Hurlabaus [21].

Notwithstanding the fact that non-contact magnetostrictive UGW generation and reception in a multi-wire rope could be very attractive for practical applications in comparison to the contact-type set-up, this method does not provide the ability to identify a particular defective wire or strand in a multi-wire rope [3,11–19].

The longitudinal modes propagate longer distances in comparison to asymmetric modes mainly due to lower leakage losses in deeper layers of the rope. Penetration of the propagating UGW into deeper layers of the rope depends on boundary conditions between the particular wires and has not yet been analysed in detail.

Propagation of the UGW in multi-wire ropes is usually investigated by means of numerical modelling. In the model, solid contact between the wires is usually assumed. Such a contact is transparent for the surface-tangential component of the particle velocity of the propagating wave. Still, in the case of oiled ropes, the boundary conditions are closer to wet coupling between wires. In this case, the contact is transparent only for normal components of the particle velocity. On the other hand, longitudinal modes of GW mainly consist of the tangential particle velocity component oriented along the wire. Stronger normal particle velocity components perpendicular to the wire surface exist in the case of asymmetric modes such as the $F(1,1)$ mode. Thus, it can be assumed that the asymmetric modes of UGW penetrate deeper into the rope. On the other hand, attenuation of the asymmetric modes of UGW is usually higher than that of the longitudinal modes due to leakage losses, which may increase in the presence of non-metallic components in the rope such as a plastic core.

It is necessary to note that generation and propagation of UGW asymmetric modes in wire ropes has not been investigated as deeply as the propagation of longitudinal modes.

Therefore, the main objective of this work is to investigate the propagation of asymmetric modes of UGW along multi-wire ropes with plastic cores. We wish to discover whether it is possible to perform reliable detection of defects inside the rope and to identify defective strands inside the internal structure of multi-wire ropes.

2. The object of investigation

Wire ropes used in modern engineering construction contain a plastic core that acts as a cushion and softens the pressure of the wire contact. A plastic insert works against water ingress and internal corrosion and stabilises the rope. However, a multi-wire steel rope by itself is a complicated structure in terms of ultrasonic non-destructive testing due to dispersion, multiple reflections, scattering of the propagating UGW and the presence of multiple wave modes. In this study, a multi-bundle and multi-wire rope consisting of six twisted steel strands, each with a diameter of 11.15 mm, has been selected as the object of investigation. The core of the multi-wire rope was filled with polypropylene, and each strand consisted of a bundle of 32 wires, each with a diameter of 2.05 mm. The cross-sectional view of the wire rope under investigation is presented in Fig. 1.

2.1. *Dispersion curves of guided waves in multi-wire ropes*

To select the operation frequency and, consequently, the UGW modes suitable for inspection, dispersion curves of the phase and group velocities must be calculated.

There are two main techniques to calculate the guided wave dispersion curves: the semi-analytical finite element (SAFE) technique [23–27] and analytical techniques [9,28]. The SAFE technique is more attractive when applied to the analysis of objects with arbitrary cross-sectional geometry (e.g., rails, bars or other shapes). The SAFE technique was used by Treyssede and Laguerre to analyse UGW propagation along multi-wire ropes [23]. They found that the wave numbers and group velocities of axisymmetric modes, such as $L(0,1)$ and $T(0,1)$, and non-axisymmetric flexural modes, such as $F(1,1)$, are very similar for the cases of a single wire and a bundle of wires (the seven wire strand) in the low-frequency region near the notch frequency for the $L(0,1)$ mode, which appears for the strand structure only. They also observed that the dispersion curves were much more complicated for the strand than a single constitutive wire because of the existence of additional modes in this region [23].

The notations $L(n, m)$, $F(n, m)$ and $T(n, m)$ mentioned above denote the longitudinal axial symmetric, non-axial symmetric and torsional modes in cylindrical structures, respectively. The first index (n) is associated with the circumferential order (0 for longitudinal modes and 1 for flexural modes) and the second index (m) refers to the order of vibration along the wall of the cylinder. Therefore, the notations $L(0, 1)$, $F(1, 1)$ and $T(0, 1)$ describe