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Observation of ultrasonic guided wave propagation behaviours in pre-stressed multi-wire structures

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ABSTRACT

Ultrasonic guided wave (UGW) is a promising technique for nondestructive testing of pre-stressed multi-wire structures, such as steel strand and wire rope. The understanding of the propagation behaviours of UGW in these structures is a priority to applications. In the present study, first the properties of the UGW missing frequency band in the pre-stressed seven-wire steel strand is experimentally examined. The high correlation between the observed results and the previously published findings proves the feasibility of the magnetostrictive sensor (MsS) based testing method. The evolution of missing frequency band of UGW in slightly tensioned steel strand is discussed. Two calibration equations representing the relationship between the missing band parameters and the tensile force are given to derive a new tensile force measurement method, which is capable of measuring an incremental of stress of approximately 3 MPa. Second, the effects of tensile force on the UGW propagation behaviours in three types of complicated steel wire ropes are alternatively investigated based on the short time Fourier transform (STFT) results of the received direct transmission wave (DTW) signals. The observed inherent missing frequency band of the longitudinal mode UGW in the pre-stressed steel wire rope and its shifting to a higher frequency range as the increases of the applied tensile force are reported for the first time. The influence of applied tensile force on the amplitude of the DTW signal and the unique UGW energy jump behaviour observed in a wire rope of 16.0 mm, 6 × Fi(29) + IWRC are also investigated, despite the fact that they cannot yet be explained.

1. Introduction

Multi-wire structures such as steel strand and wire rope are commonly employed as crucial components of cable-stayed bridges and hoist elevators to bear tensile load. The development of advanced nondestructive testing (NDT) methods which are capable of monitoring the stress level and integrity of such structures has attracted much attention in the past two decades [1–3]. Among the developed NDT methods, the ultrasonic guided wave (UGW) technique has been proven to have great potential for both defect detection and stress measurement in pre-stressed multi-wire structures [4,5].

The propagation characteristics of UGW in multi-wire structures should be revealed before applications are put into action. The twisted wires and the complicated contact among them make it quite difficult to theoretically calculate the precise dispersion curves of the pre-stressed multi-wire structures. Washer et al. [6] and Di-Scalea et al. [7] applied a simplified acoustoelastic theory for guided rod waves to predict the variation in the group velocity of the L(0, 1) mode in pre-stressed steel strands. Although the solutions of Pochhammer-Chree equations for cylindrical waveguides [8] can be used to roughly discuss the propagation characteristics of UGW in multi-wire structures [9], they cannot predict the notch frequency phenomenon of L(0, 1) mode in loaded steel strands, which has been experimentally observed by both of Kwun et al. [10] and Laguerre et al. [11].

Researchers have developed numerical simulation models to investigate the properties of the UGW notch frequency in loaded seven-wire steel strands. Bartoli et al. [12] applied the 2D FFT method to extract frequency-wavenumber information of steel strand composed of seven 5.08 mm wires from transient finite element (FE) simulation results. It is founded that new modes appeared in loaded (70% of ultimate tensile stress) strands compared to unloaded (0.7% of ultimate tensile stress) strands, and the main cause of this change is believed to be the energy leakage in adjacent wires due to contact forces. Their obtained dispersion spectra are relatively noisy and cannot be easily converted into precise group velocity dispersion curves, thus the identification and characteristics of notch frequency have not been discussed.

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Treysséede and his research team [13,14] developed the semi-analytical finite (SAFE) method for calculating dispersion curves of unloaded and loaded seven-wire steel strand. In unloaded seven-wire steel strand (with a nominal diameter of 15.7 mm) case, a quick drop of energy velocity occurs around a certain frequency corresponding to notch frequency phenomena. An equation for predicting the notch frequency, f_n, is given as $f_n = 0.33C_s/(2\pi a)$, where C_s and a are the shear wave velocity and radius of the helical wire, respectively. Furthermore, surface contact among the wires is verified to be valid for predicting the variation of notch frequency in loaded strands [15]. For a loaded strand of nominal diameter of 12.7 mm, the notch frequencies predicated by the SAFE method well agree with the experimental results reported by Kwun et al. [10].

So far, the object of both numerical simulation and experimental testing has been restricted to seven-wire steel strand or cables [16] composed of a stack of first-order helical wires around a straight rod. Conclusions regarding the propagation characteristics of the L(0,1) mode UGW in more complex steel wire ropes are extremely limited. From the perspective of developing new NDT methods, the relationship between the UGW notch frequency and tensile load can be employed as a new stress measurement method for steel strands, which is very different from the acoustoelastic theory-based method. However, the criteria for notch frequency identification especially in low tensile force range and the sensitivity of notch frequency to the tensile force variation have not yet been discussed in detail.

In the present study, experimental observations regarding the L(0,1) mode UGW propagation behaviours in the loaded steel strand and wire ropes are presented. In Section 2, first seven-wire steel strands are tested in the developed magnetostrictive sensor-based experimental platform. The identification criteria for notch frequency in the lowest tensile force condition are discussed, after which an accurate tensile force measurement method is derived for seven-wire steel strands. Next, the longitudinal UGW propagation behaviours in three types of tensioned steel wire ropes are alternatively experimentally investigated to determine several unique and interesting phenomena that are reported for the first time. Finally, the conclusions and an outlook are given in Section 3.

2. Observation of UGW propagation in pre-stressed strand/wire rope

2.1. Experimental arrangement

A compact strand/wire rope stretching system is designed to hold tested samples with a length greater than 2 m. As shown in Fig. 1a, the tested strand/wire rope passes through the support frame, load cell and hydraulic cylinder to assemble these components coaxially by mounting anchors at both ends of the tested samples. The hydraulic cylinder is configured to provide axial load to the strand/wire rope, and a pre-calibrated load cell is attached to the support frame to record the value of tensile force.

Various types of sensors can be used to generate and receive UGW in pre-stressed strands/wire rope. Piezoelectric wafers/transducers are mounted onto both ends of the strand/cable to observe the propagation of longitudinal mode UGW in Refs. [17,18]. The direct transmission wave (DTW) between the transmitter and receiver is commonly detected for analyzing the propagation characteristics of UGW in the structures. When the UGW is emitted and received by piezoelectric wafers/transducers at the strand ends, the DTW will be impure, due to its passing through the anchors, which impose confining forces to the strand. Therefore, it is better to employ sensors with non-contact nature for experimental tests. Here, a tailor-made magnetostrictive sensor (MsS), as shown in Fig. 1b, is developed for generating and receiving longitudinal mode UGW in steel strands/wire ropes. The detailed structures of the MsS has been reported by the authors in Refs. [19], and its work principle can be found in Ref. [20].

Permanent magnets, together with the yokes, provide a bias magnetic field to magnetize the strands/wire ropes. An arbitrary function generator outputs a pulse or tone burst signal to the power amplifier, then the amplified signal is fed into the MsS transmitter coil to induce a dynamic magnetic field. Consequently, elastic stress waves can be generated in the ferromagnetic samples, as controlled by principle of magnetostrictive effect. The UGW will first be generated in the peripheral wires due to the skin effect of the electromagnetic field and then transfer to the inner wires through the contact areas during its propagation. According to the inverse magnetostrictive effect, the UGW propagating along the strand/wire rope will interrupt the bias magnetic field to induce voltage in the sensing coil of the MsS receiver. The voltage signal will be acquired and stored by digital oscilloscope for subsequent signal processing. The UGW generated by the MsS will propagate in both sides along the tested sample, and the distance between the transmitter and receiver must be carefully arranged to avoid overlapping of the DTW signal with the signals reflected from the anchors or ends.

2.2. Results and discussion

2.2.1. Seven-wire steel strand case

Approximately 3 m long seven-wire steel strand with a nominal diameter of 17.8 mm is used for testing. The strand has six helical

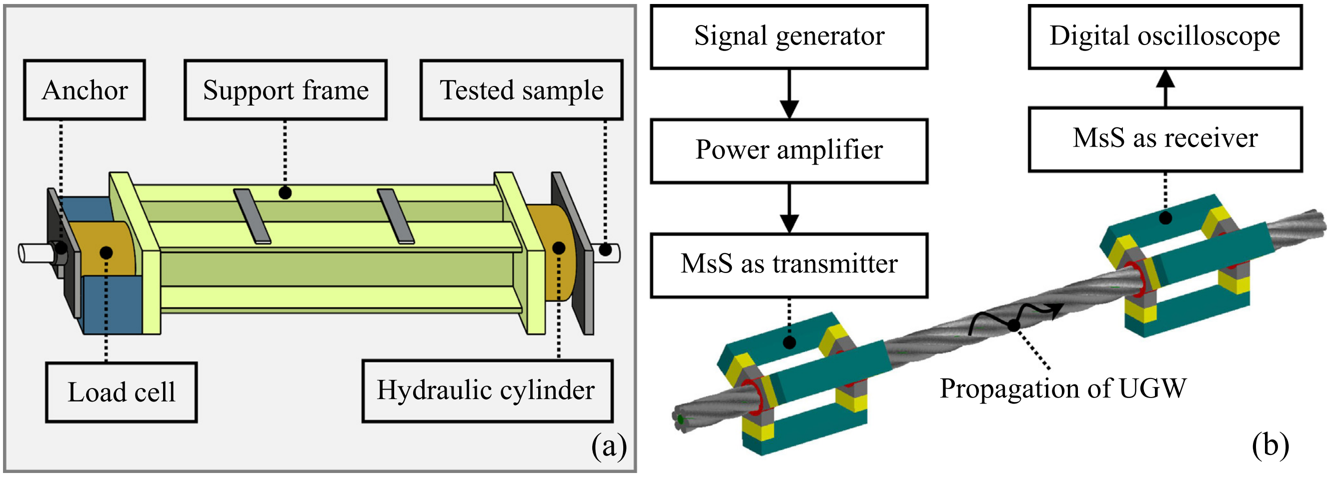

Fig. 1. Schematic diagram of (a) strand/wire rope stretching system and (b) experimental set-up for MsS.