Ultrasonics 53 (2013) 150–156

Contents lists available at SciVerse ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

Detecting broken-wire flaws at multiple locations in the same wire of prestressing strands using guided waves

Jiang Xu *, Xinjun Wu, Pengfei Sun

School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China

A R T I C L E I N F O

Article history:
Received 9 February 2012
Received in revised form 23 April 2012
Accepted 3 May 2012
Available online 17 May 2012

Keywords:
Multiple flaws
Broken wire
Recovery length
Prestressing strand
Guided wave

A B S T R A C T

Broken wires often occur at multiple locations in the same wire of a strand due to the recovery length, which is defined as the length of the wire taking up its full share of the axial load from the break point. The detection of broken-wire flaws at multiple locations along the same wire is investigated using guided waves below 400 kHz. Herein, a sample with three broken-wire flaws in the same wire is analyzed using magnetostrictive guided waves. Our data show that three flaws are found using the low-frequency guided waves (50 kHz) but only one flaw is found using the high-frequency guided waves (320 kHz). By analyzing the reflection and transmission coefficients at the three different flaws, we observe that the energy exchange decreases as the frequency increases along the same propagating distance. Hence, the recovery length for elastic waves, the length of the wire taking up its full share of elastic-wave energy from the break point, is observed. The recovery length for elastic waves in prestressing strands increases with the frequency. To detect prestressing strands using magnetostrictive guided waves, several one-broken-wire flaws at different locations can be distinguished from in different wires or the same wire by employing both low-frequency waves and high-frequency waves. Nevertheless, we cannot identify in which wire the flaws are located because the magnetostrictive sensor analyzes the whole strand.

1. Introduction

Prestressing strands are widely used in prestressed structures, such as power stations, offshore facilities, and bridges. Strands are exposed to a variety of harmful effects, such as fatigue loading and acidic environments [1,2]. As a result, broken-wire flaws often occur in the individual component wire. The broken-wire flaw not only reduces the strand strength, but it also decreases the load-carrying capacity of prestressed structures, possibly leading to collapse. To guarantee the safety of prestressed structures, many nondestructive testing (NDT) methods, such as visual inspection, magnetic flux leakage testing, and radiographic testing method, are employed to detect prestressing strands [3–5]. However, it is difficult to detect a prestressing strand because it is often embedded or covered with a protective layer.

In recent years, guided wave testing technology has gained attention for NDT and structure health monitoring to prestressing strands [6–17]. Guided waves propagate along the axis of a strand for long distances after launch from a single position. The waves are reflected where damages occur, such as notches or breaks. Thus, using guided waves, strands can be detected quickly. There are various ways to generate guided waves in strands, such as the piezoelectric effect, the thermoelasticity effect, the Lorentz force and the magnetostrictive effect [6–10]. Piezoelectric transducers [9,17] and magnetostrictive sensors [6,8,15] are mostly employed. Beard et al. [9] researched the mode shapes based on the dispersion curves of the grouted tendons and bolts. The low-leakage modes, which the relative amount of in-plane stress to shear stress increased and the amount of mode conversion is reduced, were employed. Rizzo and Di-Scalea [10] characterized the dispersive and attenuating behavior of the L(0,1) and F(1,1) modes in the central straight wire and the peripheral helical wire. They concluded that the surface displacements were responsible for the acoustic coupling. An enhance method of monitoring multi-wire strands is proposed [11]. The largest sensitivity to notch depth is the linear dependence on notch depth in logarithmic scale. A method based on outlier analysis and the wavelet transform for structural damage detection based on guided ultrasonic waves were provided [12]. The general framework is applied to the detection of notch-like defects in a seven-wire strand by using built-in magnetostrictive devices. At numerically investigating the propagation of elastic waves in free helical waveguides, Treyssede [18] proposed a numerical procedure based on a periodic FE approach combined with a specific helical mapping in order to reduce the periodic cell length. Then Treyssede [19] developed a semi-analytical finite element (SAFE) method extended to helical waveguides. Recently, a numerical method was given based on a SAFE

* Corresponding author. Tel./fax: +86 27 87559332.
E-mail address: jiangxu@mail.hust.edu.cn (J. Xu).

0041-624X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ultras.2012.05.003

technique that relies on a specific non-orthogonal curvilinear coordinate system [14]. A dispersion analysis for a seven wire strand with simplified contact conditions was then performed. The missing notch-frequency phenomenon in the strand was explained using the FE model.

Only a single notch with varying depths in a strand has been detected using guided waves [11,13,15]. Kwun employed a magnetostrictive sensor to inspect the strands with one broken-wire flaw [6,20,21]. The detection of several broken wires in one location was reported in our previous work [22]. Two notches on both sides of the sensors were detected in Rizzo's work [23]. Because bi-directional waves were generated in the strand, the echoes of two notches were not interference. The strand with one broken-wire flaw and a notch on the same side as the sensors was detected using magnetostrictive technology by Di-Scalea et al. [1]. Mijarez employed piezoelectric transducers to detect one notch in a seven-wire aluminum conductor steel reinforced cable [16]. Most investigations have focused on detecting a single flaw or multiple flaws in different wires.

If a wire is broken at one location, then typically, more break points will not occur along the same wire because the stress has been released. Nevertheless, this view does not apply to strands or wire ropes. The contact and friction force among the flawed wire and unbroken neighbor wires can transfer the axial load to the flawed wire. Thus, the flawed wire can regain its share of the load away from the break point. The length of the wire taking up its full share of the axial load is defined as the recovery length (e.g., development length) [24–26]. Therefore, broken-wire flaws often occur at multiple locations along the same wire of a strand [27]. If a single wire is broken in one location, total reflection will occur in the cross-section. Only the first broken-wire flaw can be detected. We therefore ask: can the guided wave method be used to detect broken-wire flaws at multiple locations along the same wire of prestressing strands?

Several studies have investigated the wave propagation along multi-wire cables. Haag et al. [28] studied the wave energy distribution between two rods through friction contact. They concluded that the subsurface wires could be detected through the spread of elastic energy from the surface wires to the subsurface wires. Although the influence of the frequency was not analyzed thoroughly, it was noted that the elastic energy became concentrated near the surface at high frequencies. Baltazar et al. [17] found that the contact force between wires controlled the mode conversion phenomenon between the longitudinal modes and the flexural modes at high frequencies (i.e., above 500 kHz). The decrease of mechanical contact forces between wires prevents energy exchange. Baltazar mentioned that larger radial displacements caused greater energy transfer. The radial displacements at the surface are small at low frequencies but increases as the frequency gets higher. However, the amplitude increases at low frequencies (below 500 kHz). Moreover, the guided waves used to detect strands were usually less than 400 kHz. There is little information available in literature about detecting broken wires at multiple locations along the same wire of prestressing strands using guided waves.

The objective of this work is to explore the detection of broken-wire flaws at multiple locations in the same wire of prestressing strands using guided waves below 400 kHz. Three broken-wire flaws in the same wire are detected using low frequency (50 kHz) guided waves, and only one broken-wire flaw is detected using high frequency (320 kHz) guided waves. The recovery length of elastic waves, the length of the wire taking up its full share of elastic-wave energy from the break point, is observed. The recovery length of elastic waves increases as the frequency of the guided wave increases. Because the elastic energy exchange among wires with a high frequency guided wave is less than this having a low frequency guided wave along the same propagating distance. A method to determine whether two one-broken-wire flaws at different locations are in the same wire or different wires is discussed herein.

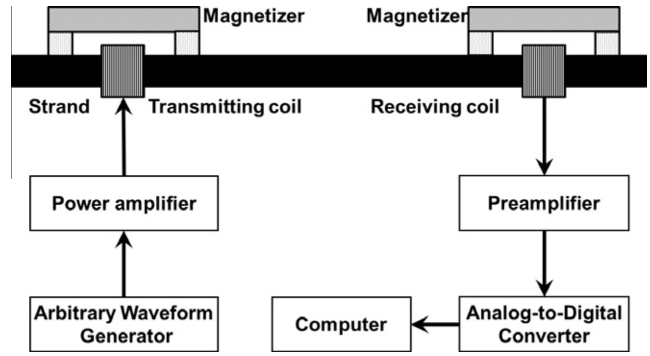

Fig. 2. Schematic of the magnetostrictive guided wave inspection system.

2. Experimental procedure

A prestressing strand sample was composed of seven steel wires where a center wire was enclosed tightly by six helical wires. The specification of the prestressing strand was 15.24 mm diameter, 1 ∗ 7-wire steel prestressing strand (ASTM A416-90a, ISO 6934-4). The diameters of the straight wire and the individual helical wires were 5.08 mm. The length of the strand was 5000 mm. There were three broken-wire flaws along the same wire as shown in Fig. 1. The flaws were cut by a grinder and the three flaws were completely through one wire. The width of the three flaws was about 3 mm.

Piezoelectric transducers need to contact the surface of the strands to generate and receive guided waves, but magnetostrictive sensors can generate and receive guided waves without contacting the strands. Therefore, we employed the magnetostrictive technology to detect strands in this experiment. A magnetostrictive guided wave inspection system was employed as shown in Fig. 2. The transmitter consisted of a transmitting coil and a magnetizer. The coil had 60 turns of American wire gauge 26 enameled wire and 17 mm in diameter. The structure of the coil, which was similar as Rizzo's coil [1], is shown in Fig. 3. The center distance of the three-part coil was adjustable to satisfy the response requirements for different frequencies. The magnetizer was made of permanent magnets with an armature and provided a static axial bias magnetic field to cancel the second-harmonic generation

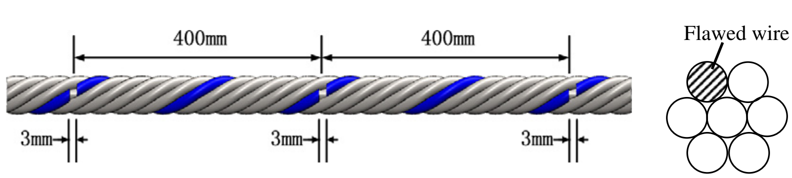

Fig. 1. The distribution of three broken-wire flaws in the prestressing strand.