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Reference-free corrosion damage diagnosis in steel strands using guided ultrasonic waves

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ABSTRACT

This study presents a nondestructive evaluation method based on guided ultrasonic waves (GUW) to quantify corrosion damage of prestressing steel strands. Specifically, a reference-free algorithm is proposed to estimate the strand's cross-section loss by using dispersion curves, continuous wavelet transform, and wave velocity measurements. Accelerated corrosion tests are carried out to validate the proposed approach. Furthermore, the propagation of Heisenberg uncertainty to diameter measurement is also investigated. The method can reasonably estimate the wires' diameter without any baseline as a reference.

1. Introduction

Multiwire steel strands are widely used in civil structures such as cable-stayed bridges, prestressed concrete structures, and re-centering systems. Despite this increase in usage, the corrosion of the multiwire strands has become a concern for designers, owners and regulators. Many of these structures have suffered the failure of strands due to corrosion [1–3]. Extensive inspection and maintenance/repair programs have been established, with attendant direct costs and significant indirect costs due to business interruption [4]. Evaluation of strands is technically challenging. In many structures, inaccessibility of steel strands, eventuate in difficult, expensive and often inconclusive evaluation. Several nondestructive evaluation (NDE) techniques for evaluating the condition of strands have been developed to address these issues in the past few years [5]. Half-Cell potential [6], time domain reflectometry (TDR) [7], linear polarization resistance (LPR) sensors [8], magnetic flux [9], and acoustic emission [10] are some of the most commonly used NDE methods for corrosion diagnosis. Although these techniques have shown promise, very few if any are capable to quantify the cross-sectional loss. A technique that shows potential to quantify the extent of corrosion (e.g., cross-sectional loss) is based on guided ultrasonic waves (GUWs). As opposed to the waves used in traditional impact-echo (IE), that propagate in 3-D within the structure, GUWs propagate along the strand itself by exploiting its waveguide geometry [11]. Most previous researches attempted to use GUWs to detect and assess corrosion damage on reinforcing bars in reinforced concrete (RC) structures [12–15] and steel strands in prestressed concrete structures [4,16–20]. For instance, to diagnose corrosion in reinforcing bars, energy and attenuation characteristics of longitudinal and flexural GUW modes were used [13,14]. Other methods based on time of flight (ToF) of the first packets were also proposed to investigate various levels of corrosion in reinforcing bars [21]. Longitudinal GUWs were also used to monitor pitting and delamination in steel rebars [15]. To monitor the corrosion process in post-tensioned concrete beams, fractal analysis of GUWs was investigated [4].

In this study, a reference-free algorithm is proposed to quantify the extent of corrosion through estimating the cross-section loss using GUW measurements. An experimental setup was designed to carry out an accelerated corrosion test on a loaded strand. The diameter of the strand's wires was estimated using the continuous wavelet transform (CWT) [22] of the GUWs. Furthermore, the uncertainty associated with estimated diameter, which originates from the Heisenberg principle in CWT [23], was quantified. In the next section, the behavior of GUW in rods and the effect of cross-section loss on dispersion curves, followed by a short introduction on CWT are presented. The details of experimental setup are then explained. The results of diameter measurement using GUW are discussed and finally the conclusion is given.

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2. Theory

2.1. Guided ultrasonic waves in rods

A guided ultrasonic wave (GUW) is generated whenever an ultrasound propagates into a bounded medium [24]. GUWs are known to be multimode (many vibrating modes can propagate simultaneously) and dispersive (the propagation velocity depends on the wave frequency f). In cylindrical waveguides, such as rods, three different modes can propagate: longitudinal, flexural, and torsional [24,25]. The dispersive behavior of these modes is represented by the dispersion curves like the ones shown in Fig. 1. These curves describe the relationship between wave velocity and frequency, and can be calculated analytically or they can be computed by approximate solutions derived from numerical methods [24]. In this work a MATLAB open source toolbox, PCdisp (Pochhammer-Chree dispersion) [26,27] was used to generate the dispersion curves (Fig. 1).

The longitudinal modes have received significant interest in the past few years, for the nondestructive evaluation of cylindrical waveguides, mostly because the flexural and torsional modes experience high attenuation during the propagation phenomena [16,18,28–30].

2.2. Effect of corrosion on GUWs

Corrosion is usually an electrochemical oxidation–reduction process that converts the major component of steel, iron (Fe), to ferrous hydroxide ($Fe(OH)_2$). A consequence of this process is the reduction in member cross sectional area, which eventually may affects its structural performance. To simulate the effect of corrosion and investigate how the reduction in a rod's cross sectional area affects the guided wave propagation, the dispersion curves for the first longitudinal mode $L(0,1)$, were generated for various diameters, ranging from 5 mm to 2.5 mm. The results are shown in Fig. 2. It can be observed that in a frequency range between 0 and 600 kHz the group velocity increases as the cross-sectional area decreases. Moreover, certain frequencies (e.g., 500 kHz) provide a larger sensitivity to diameter changes than other frequencies (e.g., 300 kHz). It is worth to mention that guided waves thickness measurement methodologies based on group velocity changes have been studied by some researchers for other applications such as plate-like structures [31–35].

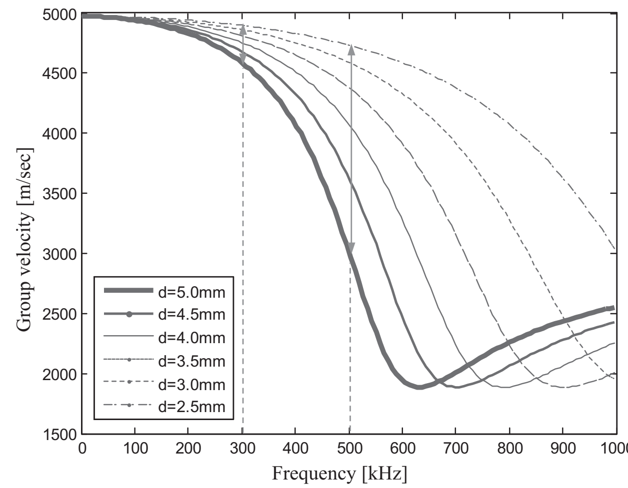

Fig. 2. Dispersion curves for the first longitudinal mode $L(0,1)$ in steel rods with various diameters.

Fig. 3 shows the group velocity of the $L(0,1)$ mode as a function of the frequency-diameter product (i.e., $v = F(fd)$). Therefore, the inverse problem, which is to calculate the diameter given the dispersion curves, can be solved by measuring the velocity of a certain frequency component in the signal. In order to limit the effects of the high order modes the excitation frequency was selected in a frequency range below the first cut-off frequency. In this work, a time–frequency analysis (continuous wavelet transform) was used to measure the group velocity of the $L(0,1)$ mode.

2.3. Continuous wavelet transform

Continuous wavelet transform (CWT) for analyzing non-stationary signals has received significant interest in the last few years, due to its ability to extract signal time and frequency information simultaneously [23]. The CWT of a time domain signal $f(t)$ is given by Ref. [23],

$$WT(s,b) = \frac{1}{\sqrt{|s|}} \int_{-\infty}^{\infty} f(t)\psi * \left(\frac{t-b}{s}\right) dt \qquad (2.1)$$

where $\psi*(t)$ denotes the complex conjugate of the mother wavelet $\psi(t)$, s is the dilation parameter (scale), and b is the translation

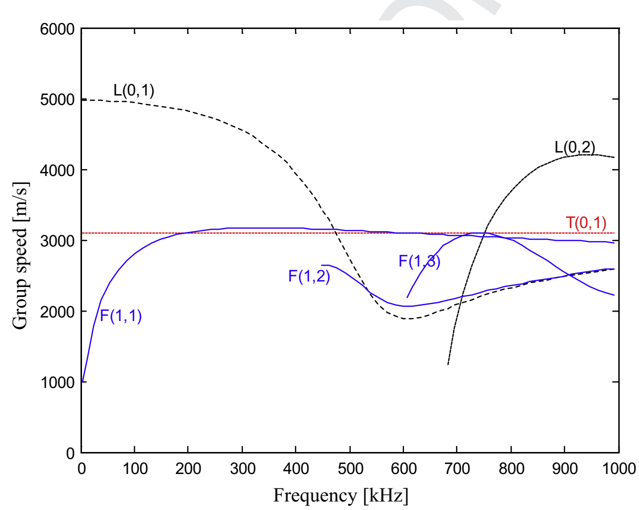

Fig. 1. Group velocity dispersion curves for a 5 mm diameter steel rod.

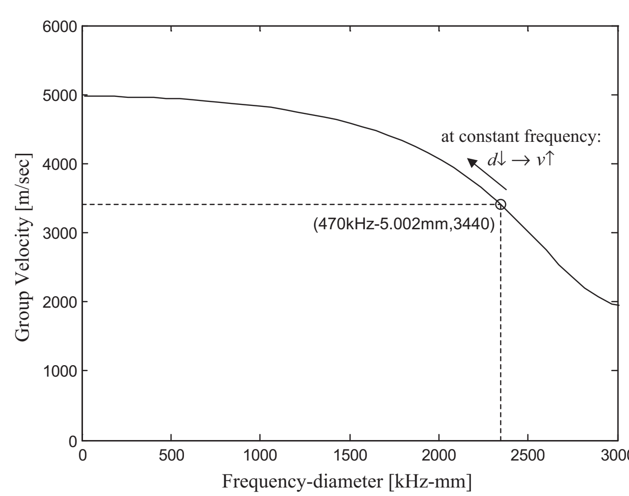

Fig. 3. Dispersion curve for the first longitudinal mode $L(0,1)$ in a steel rod versus product of frequency and diameter.