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Higher order longitudinal guided wave modes in axially stressed seven-wire strands

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ABSTRACT

This paper investigates the effect of axial stress on higher order longitudinal guided modes propagating in individual wires of seven-wire strands. Specifically, an acoustoelastic theory for a rod is used to predict the effect of stress on the phase velocity of guided modes in a strand. To this end, the exact acoustoelastic theory for an axially stressed rod is adapted for small deformations. Aside from the exact theory, approximate phase velocity changes (derived from both theory and experiment) are proposed, without the need to solve for dispersion curves. To validate the use of rod theories for strands, a custom-built prestressing bed was designed to apply axial load (up to 50% of yield) to a strand while conducting guided wave measurements. Higher order modes were excited in individual wires, and their phase velocity change under stress is compared to the exact acoustoelastic theory. Furthermore, it is shown that the proposed approximate phase velocity changes derived from theory and experiment only differ by roughly 2% from their exact counterparts. Higher order modes are shown to have stable stress dependence near their peak group velocity, which is beneficial for stress measurement. Additionally, linear stress dependence is observed, which is predicted by rod theories. Due to the unavailability of third order elastic constants for the steel strand, constants for a steel with similar Carbon content (0.6% C Hecla 17) were used as representative values in the theory. Using the Hecla 17 constants, roughly 15% mismatch in the slope of the linear stress dependence was observed when compared to the measurements on a steel strand.

1. Introduction

Seven-wire strands serve as load bearing elements in civil infrastructure, such as cable-stayed bridges and prestressed/post-tensioned concrete structures. The level of stress in a strand (and within individual wires) is therefore critical to the performance of the structure. As such, the ability to monitor this stress using guided waves may yield valuable structural information. Aside from stress measurement [1–4], guided ultrasonic waves have received attention for damage detection as well [5–9]. A recent study [10] has also addressed the issue of attenuation in strands and identified the potential for large inspection distances (> 100 m). In damage detection applications, however, the effect of stress may need to be compensated for. This is because false indicators of damage (e.g. changes in wave velocity) may be caused by stress as opposed to damage.

The effect of stress on wave propagation is referred to as acoustoelasticity [11]. To date, the effect of stress on guided waves has been studied in a wide range of structures, including plates [4,12], pipes [13–15], and rails [16,17]. For rods in particular, theoretical studies have been carried out on longitudinal [18], flexural [19], and torsional [20] modes, dating back to the early years of acoustoelasticity in the 1960s-70s. Due to the complex interaction of wires in a seven-wire strand, the first studies on the effect of stress in this waveguide were experimental, and did not come until roughly 30 years later. Kwun, et al. [21] experimentally studied guided waves generated by magnetostrictive sensors, which excite all of the wires at once within a strand. In their study, missing frequency content (termed the notch frequency) was linearly correlated with the logarithm of the stress level. Chen and Wissawapaisal [22,23] also performed experimental studies on the fundamental longitudinal mode L(0,1) in stressed strands. In their work, they proposed an approximate acoustoelastic rod theory to predict the stress dependence of waves propagating within individual wires. Washer, et al. [24] performed experiments with magnetostrictive sensors, demonstrating a linear dependence of velocity with respect to large levels of stress (> 50% ultimate tensile strength, or UTS). Rizzo [25] experimentally studied the effect of stress on the transmission energy of the L(0,1) mode in both the

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core wire and entire strand. One of the main conclusions of this study was that the core wire has better potential for stress measurement than the entire strand. Chaki and Bourse [2] studied the L(0,1) mode excited in the core wire of a strand for the purpose of stress measurement. The approximate acoustoelastic theory developed in [22,1] was applied to predict the stress dependence in an individual wire, although there was some disagreement with the experimental results. In particular, a nonlinear stress dependence was found at lower stress levels ($< 35\%$ UTS), which diverged from the theory and has not yet been definitively explained. Nonlinear and divergent results were also found earlier by Lanza di Scalea, et al. [1] using magnetostrictive sensors. More recently, the semi-analytical finite element (SAFE) method has been used to study guided waves propagating within seven-wire strands as a whole. In particular, Treyssède and Laguerre [26] presented the first SAFE study applied to seven-wire strands, which explained the notch frequency discovered by Kwun, et al. [21]. Nucera and Lanza di Scalea [27] studied the effect of stress on higher harmonics, where the generation of a second harmonic from a primary excitation was correlated with stress. Lastly, Schaal, et al. [28] and Treyssède [29] studied the energy leakage between adjacent wires in a stressed strand. The work by Treyssède provided numerical validation for the stress dependence of the notch frequency.

Although studies have been made on the fundamental mode L(0,1) for stress measurement, higher order modes $\mathrm{L}(0,n), n > 1$ have seen little attention for this purpose. In addition to the unexplained nonlinear dependence of the fundamental mode at lower stress, there has also been reasonable disagreement ($> 50\%$) between theory and experiment at higher stress [2]. Aside from the fundamental mode, higher order modes have also been studied for potential damage detection in strands [30–32]. However, the effect of stress on these modes has seen little attention. Furthermore, although the exact guided wave theory for an axially stressed rod was presented in the 1960s, it has seen little applications to strands. Instead, only approximate rod theories have been used [1,2]. One of the attractive characteristics of higher order modes (particularly $n > 5$) is that their mode shapes are concentrated near the core of a rod in certain frequency ranges [33,34]. This translates into minimal energy leakage and attenuation when there is another medium bordering the rod. In this paper, the term higher order modes is used to refer to those with $n > 5$, where their behavior becomes increasingly similar [33].

This paper studies the effect of stress on higher order modes propagating in individual wires of seven-wire strands. The main idea is to use acoustoelastic rod theory to predict the effect of stress on these modes, while idealizing each wire as a rod with free boundaries. To this end, the exact acoustoelastic rod theory developed by Suhubi [18] is adapted for small deformations. Expressions for the mode shapes are then derived, from which the concentration of higher order modes near the core of a stressed rod may be verified. In this paper, an approximate theory for higher order modes is also proposed. This is presented in the form of an explicit function of stress, as opposed to an implicit dispersion equation. In order to validate the application of acoustoelastic rod theories to strands, a custom-built prestressing bed was designed for recording higher order mode measurements on a stressed strand. The stress-induced phase velocity change is used to characterize the influence of stress on these modes. In combination with the approximate theory, another approximation is also proposed for higher order modes. This approximation allows for the phase velocity change to be computed from time change measurements in a simpler manner. Together, the two approximations may be used to compare theoretical and measured velocity changes of higher order modes without solving for dispersion curves.

This paper is organized as follows: First, in Section 2, the adaptation of the exact acoustoelastic theory and the proposed approximate theory are presented. In addition, theoretical results are presented based on these formulations. In Section 3, the higher order mode experiments on a stressed strand are described, as well as the approximate phase velocity change derived from experiment. Experimental results for higher order modes are then presented in Section 4. Finally, concluding remarks and suggestions for future work are outlined in Section 5.

2. Theoretical formulation for an axially stressed rod

This section presents the exact acoustoelastic theory for an axially stressed steel rod, and derives expressions for the mode shapes of the guided wave solutions. The proposed approximate theory for higher order modes is then presented. In addition, theoretical results for the effect of stress on guided waves in a steel rod are demonstrated. Since a tensioned strand generates predominantly axial stresses within individual wires, the waveguide of each wire is idealized as an axially stressed rod [1,2].

2.1. Exact acoustoelastic theory for longitudinal modes

Suhubi [18] has solved for the exact dispersion equation of longitudinal modes in an axially stressed elastic rod of arbitrary strain energy function (and therefore arbitrary stress-strain relation). This theory is adapted here for a strain energy function that is applicable to steels and other stiff materials under small deformations [35].

Let us consider a rod subjected to an axial stress τ, which is illustrated in Fig. 1. The variable τ is used to indicate that the stress is referenced to the deformed configuration (Cauchy stress). It produces the principal extensions λ_r, λ_z in the radial and axial directions, respectively. The deformed diameter of the rod is therefore expressed in terms of the undeformed diameter d as

$$D = \lambda_r d \tag{1}$$

Small amplitude guided wave motion, with wavenumber K and angular frequency ω, is then superimposed on the deformed configuration. The radial and axial displacement components of guided waves are described in terms of the deformed configuration of the rod as [18]

$$\begin{aligned} u_r &= U_r(R)\exp[\mathrm{i}(KZ - \omega t)] \\ u_z &= U_z(R)\exp[\mathrm{i}(KZ - \omega t)] \end{aligned} \tag{2}$$

where R and Z are the radial and axial position in the deformed configuration. From the equation of motion in [18], the displacement mode shapes U_r, U_z can be written as

$$\begin{aligned} U_r &= C_1 J_1(\chi_3 R) + C_2 J_1(\chi_4 R) \\ U_z &= C_1 \frac{\chi_1^2 - \chi_3^2}{\beta_1 \chi_3} J_0(\chi_3 R) + C_2 \frac{\chi_1^2 - \chi_4^2}{\beta_1 \chi_4} J_0(\chi_4 R) \end{aligned} \tag{3}$$

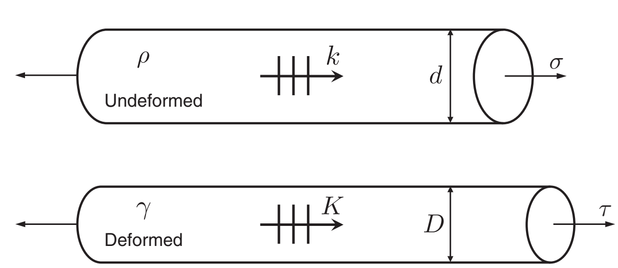

Fig. 1. Undeformed and deformed configurations of stressed rod, showing density (ρ, γ), stress (σ, τ), and wavenumber (k, K) of longitudinal guided wave.