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Energy-based models for guided ultrasonic wave propagation in multi-wire cables

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A B S T R A C T

Wave-based Structural Health Monitoring (SHM) to detect damages in civil and mechanical structures is a growing research field. In order to apply SHM to multi-wire cables, in this work, ultrasonic wave propagation in such coupled waveguides is studied theoretically, numerically and experimentally. In addition to transient finite element simulations, novel energy-based models are presented. With these models, efficient simulations of cables with many wires can be performed. Both finite element and energy-based models are verified with sophisticated experiments.

1. Introduction

Regular monitoring of civil and mechanical structures predicts failure and allows for the estimation of the residual life cycle. New Structural Health Monitoring (SHM) methods target multi-wire cables, such as stay cables of cable-supported bridges and overhead power lines. These cable structures are subject to wind-induced vibrations, temperature changes and corrosion. Failure of these multi-wire cables begins with cracks in individual wires and can eventually lead to a fracture of the entire cable (Siegert and Brevet, 2005). Since regular visual inspection is an expensive and hazardous practices that is limited to the detection of surface flaws, automated monitoring schemes are developed. Vibration-based techniques either monitor external loads or environmental conditions, or the structural response. Algorithms for the first two concepts usually rely on statistical processing whereas changes in eigenfrequencies of the target structure are typically analyzed for monitoring the structural state (Alampalli, 2000).

This work focuses on active wave-based techniques for damage detection. An exemplary scheme for stay cables (Gimsing and Georgakis, 2012) of cable-stayed bridges is depicted in Fig. 1(a): Elastic waves are excited in the waveguide structure and parts of the wave are reflected and measured by a sensor. Damage detection algorithms then determine the structural state.

Waveguides are structures that confine the propagation of waves in one direction. In particular, guided waves qualify for material evaluation since these waves travel long distances with little decay. However, the generally multimodal and dispersive nature of guided wave propagation has to be accounted for (Graff, 1991). Also, mode conversion may occur when waves encounter discontinuities (Bischoff et al., 2014). Subsequently, waves often consist of the superposition of several modes with different velocities, and sophisticated signal processing is required to analyze the measurement signals. Often such analyses are performed using the short time Fourier transform (STFT) (Baltazar et al., 2010) or wavelet transform (Nishino et al., 2006).

Moreover, real cable structures are composed of several twisted wires, as shown in Fig. 1(b) for a typical power line cable. The helical geometry (Treyssède, 2007) and the contact between wires complicate modeling of the multi-wire cables (Rizzo and Lanza di Scalea, 2004). Furthermore, the cables might be composed of wires of different material, resulting in different wave velocities.

Transient finite element (FE) simulations are typically used to investigate wave propagation in waveguides (Moser et al., 1999). Simulations for multi-wire cables require, however, fine meshing, resulting in a very large number of nodes. Typically, strands of multi-wire cables are combined to one solid waveguide to reduce the computational costs (Raiutis et al., 2014). Alternatively, different semi-analytical methods have been developed recently. With the Waveguide Finite Element (WFE) method (Mace et al., 2005) and the spectral finite element (SFE) method (Gavrić, 1995; Finnveden, 1997), two efficient modeling techniques are available for arbitrary waveguides. Treyssède and Laguerre (2010) analyzed

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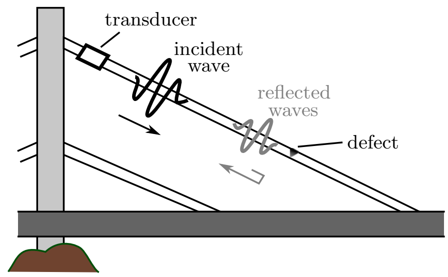


(a) Pulse-echo mode: transducer induces guided waves that are partially reflected at defects and detected at the transducer

(b) Typical overhead power line

Fig. 1. SHM concept for stay cables of cable-stayed bridges and overhead power lines.

the helical seven-wire cables using a modified semi-analytical FE method. While they assumed perfectly bonded wires, Schaal et al. (2013) used the WFE method to investigate coupled waveguides, considering a more realistic frictional contact. In addition, Haag et al. (2009) introduced an energy-based approach to model wave propagation in coupled waveguides.

In the article at hand, first wave propagation in cylindrical waveguides is introduced in Section 2, including an overview over dispersion effects. In Section 3, efficient FE modeling of coupled cylindrical waveguides is shown. In Section 4, a computationally efficient energy-based approach is presented. Two coupling models are derived to represent the frictional contact between twisted wires. Both models are applicable to arbitrary multi-wire cables and can be implemented on low-cost sensor nodes for damage detection (Schaal and Gaul, 2014). The experimental setup for experimental verification of numerical methods is introduced in Section 5. Thereby, also excitation of waves in waveguides and boundary conditions of FE simulations are discussed. In Section 6, previously presented numerical models are then fit to experimental data and a detailed comparison of the results is shown. Finally, the results are discussed in the last section and an outlook is given.

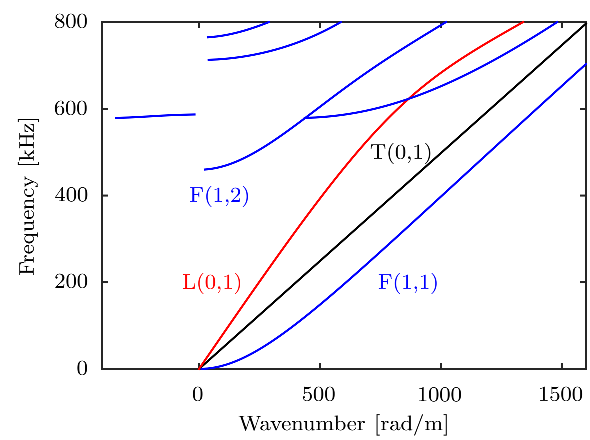
2. Wave propagation in cylindrical waveguides

Guided waves propagate in one direction while having characteristic spatial displacement fields along all three axes. Solid bodies that allow for propagation of guided waves are called waveguides. The displacement field $\boldsymbol{u}$ of a harmonic guided wave in cylindrical structures with the angular frequency ω can be written as

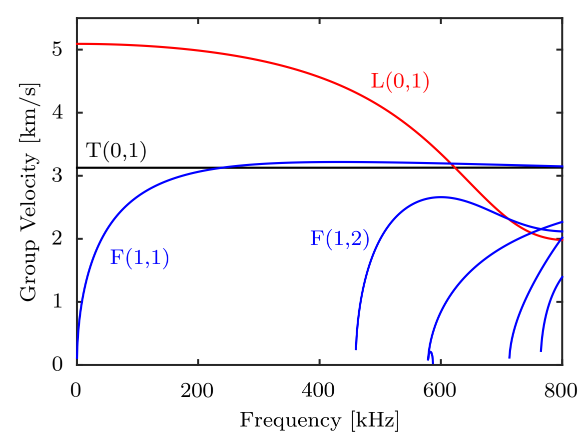
$$\boldsymbol{u}(\boldsymbol{x},t) = \hat{\boldsymbol{u}}(x_1,x_2)\mathrm{e}^{\mathrm{j}(kx_3-\omega t)} = \hat{\boldsymbol{u}}(r,\varphi)\mathrm{e}^{\mathrm{j}(kz-\omega t)} \quad (1)$$

in Cartesian and cylindrical coordinates (see Fig. 3), respectively. The wave modes are characterized by their respective displacement fields $\hat{\boldsymbol{u}}(r,\varphi)$, which are also called mode shapes. For cylindrical waveguides, three types of waves may propagate: longitudinal, flexural and torsional waves (Achenbach, 1987). Using common nomenclature, these waves are abbreviated as L(0,m), F(n,m) and T(0,m) with order n and sequential numbering m. For complex angular wavenumbers k, solutions with no imaginary part correspond to non-decaying propagating waves, while solutions with a nonzero imaginary part are considered as non-propagating waves. Evanescent modes, which decay exponentially with distance, form a subclass of non-propagating waves.

Fig. 2(a) shows the dispersion curves for an aluminum cylinder with radius $R = 2$ mm. Red lines represent longitudinal, blue lines flexural and black lines torsional modes, respectively. The curves are determined using the WFE method (Mace et al., 2005; Schaal et al., 2013) out of convenience. Alternatively, the analytical dispersion equations (Graff, 1991) can be solved numerically. In Fig. 2(b), the group velocity $c_g = \frac{d\omega}{dk}$ is shown, which is also referred to as the energy transport velocity (Lee et al., 2007) and is used in the following derivations. From the diagram it is clear that the longitudinal wave L(0,1) is the fastest wave below ~600 kHz, which is one of the reasons, why the L(0,1) mode is typically used for SHM purposes. Note, frictional coupling of cylindrical waveguides does not affect dispersion properties of the L(0,1) mode (Schaal et al., 2013).



(a) Frequency versus wavenumber



(b) Group velocity versus frequency

Fig. 2. Dispersion curves for aluminum cylinders with radius $R = 2$ mm. Red lines represent longitudinal, blue lines flexural and black lines torsional modes, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1. Energy of propagating waves

In the following, a description of the energy of a propagating wave is derived in order to develop new computationally efficient models for describing wave propagation in multi-wire cables.