Mechanical Systems and Signal Processing 112 (2018) 417–429

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Low-frequency acoustoelastic-based stress state characterization: Theory and experimental validation

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ARTICLE INFO

Article history:
Received 11 July 2017
Received in revised form 16 March 2018
Accepted 6 April 2018

Keywords:
Acoustoelasticity
Reference-free stress measurement
Nondestructive evaluation
Dispersion
Optimization

ABSTRACT

The acoustoelastic theory has been widely utilized for nondestructive stress measurements in structural components. Most of the currently available techniques operate at the high-frequency, weakly-dispersive portions of the dispersion curves and rely on time-of-flight measurements to quantify the effects of stress state on wave speed. High-frequency elastic waves are known to be less sensitive to the state-of-stress of the structure. As a result of such low sensitivity, calibration at a known stress state is required to compensate for material uncertainties, texture effects, and geometry variations of the structure under test.

In this work, a new model-based stress measurement technique is developed. The technique integrates the acoustoelastic theory with numerical optimization and allows the utilization of the highly-stress-sensitive, strongly-dispersive, low-frequency flexural waves for reference-free stress measurements. The technique is experimentally validated on a long, rectangular aluminum beam, where accurate stress measurements have been achieved at low excitation frequencies. For instance, with a 500 Hz excitation signal, the error in the measured state-of-stress is found to be in the order of 1 MPa for the different loading scenarios considered in this study. Experimental results show that the developed technique is capable of measuring the state-of-stress without the need for calibration at a known stress state, which makes it ideal for in-service structures.

1. Introduction

Structural and mechanical components are all designed to bear certain loading patterns. Besides externally applied loads, stresses arise from two main additional sources; environmental conditions, induced by temperature and moisture variations, and manufacturing processes in the form of residual stresses [1,2]. Continuous monitoring of the state-of-stress of structural and mechanical components provides valuable information regarding loading patterns, structural integrity, and material degradation. Such information is vital for damage identification and prognosis. Thus, accurate and reliable nondestructive solutions for stress state measurement have the potential to advance structural health monitoring practices, facilitate damage prognosis, and guide operations planning efforts [3,4].

Several theories and techniques have been developed over the last few decades to tackle the problem of stress state measurement, with many of these being destructive in nature. Nondestructive techniques, on the other hand, exploit the dependence of mechanical, acoustic, electrical, or magnetic characteristics of the material on its state-of-stress [5–7]. Among these

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https://doi.org/10.1016/j.ymssp.2018.04.011

theories, the acoustoelastic theory, which describes the dependence of propagating waves characteristics on the waveguide state-of-stress, has been the focus of numerous studies. Hughes and Kelly were among the first to study the propagation of bulk elastic waves in a pre-stressed solid [8]. They applied the Murnaghan theory of finite deformations along with third order elasticity theory to describe the dependence of longitudinal and shear wave speeds on the wave guide's state-of-stress. The extension of this theory to wave propagation in semi-infinite and bounded media has been thoroughly investigated in the literature [9–11]. Unlike bulk waves, which are non-dispersive in nature, waves propagating along bounded waveguides (the stress-sensitive, anti-symmetric Lamb wave modes for instance) show frequency dependent characteristics. The dispersive nature of such waves is reflected on their corresponding acoustoelastic constants, and these constants are strongly dependent on frequency [9]. As the wavelength decreases, wave speed approaches that of Rayleigh waves [12]. Thus, the dispersive characteristics of such wave modes fade, which allows the utilization of time-of-flight measurements to determine changes in wave speed.

This has laid the foundation for material characterization and stress measurement via ultrasonic waves. These methods involve introducing a low-energy, high-frequency stress wave in the material and analyzing its propagation and reflections to evaluate the state-of-stress of the structure. Despite their success, the fact that these techniques operate at the high-frequency, weakly-dispersive portions of the dispersion curves adversely affect their sensitivity. High-frequency elastic waves are known to be less sensitive to the state-of-stress of the structure, where changes in wave speed are in the order of 10^{-6} per MPa [1]. As a result, calibration at a known stress state is required to compensate for material uncertainties, texture effects, and geometry variations of the structure under test. This limits the applicability of these techniques to such cases where a known reference state-of-stress is attainable.

The effects of excitation frequency on the sensitivity of the acoustoelastic effect have been addressed by a number of researchers. Rizzo and di Scalea studied the acoustoelastic effect in axially loaded steel bars [13]. They reported that the acoustoelastic sensitivity is frequency-dependent and low-frequency excitations enhance sensitivity. Albakri and Tarazaga theoretically showed, based on approximate beam theories, that the sensitivity of stress measurements are enhanced when low-frequency flexural waves are utilized [14]. Due to their highly-dispersive nature, the utilization of low-frequency flexural waves render time-of-flight-based measurements impractical, and thus, a more advanced analysis techniques are required. The larger wavelength at low frequencies further complicates the analysis, as measured waveforms usually consist of incident waves in addition to those reflected from structure's boundaries.

In this work, a model-based stress measurement technique is developed where the acoustoelastic theory is integrated with numerical optimization to calculate the state-of-stress of one-dimensional structures. The highly-stress-sensitive, low-frequency, first anti-symmetric Lamb wave mode is utilized for this purpose. The semi-analytical finite element (SAFE) method is adopted to study the effects of the initial state-of-stress on the low-frequency Lamb wave modes. The performance of the proposed stress measurement algorithm is evaluated through numerical simulations. Experimental validation of the developed technique is also presented, where a long, rectangular beam is interrogated at several excitation frequencies. This work provides the basis for reference-free, acoustoelastic-based stress measurements, where calibration at a known stress state is not required. The developed technique is thus ideal for in-service structures.

This paper is organized as follows, Section 2 briefly presents the SAFE method formulation, and provides a comparison with the predictions of approximate beam theories. The newly developed stress measurement algorithm is presented in Section 3. Experimental results are presented and discussed in Section 4. Concluding remarks are presented in Section 5.

2. Loading effects on dispersion relations

The SAFE method provides a computationally efficient solution to study wave propagation in structures of arbitrary cross sections where exact solution and approximate theories may fail. Considering the propagation of harmonic waves along the waveguide, the x-direction, the displacement field can be expressed as follows [15–18]

$$\boldsymbol{d}(x,y,z,t) = \overline{\boldsymbol{d}}(y,z)e^{-i(kx-\omega t)} \tag{1}$$

where $\boldsymbol{d} = \{u \quad v \quad w\}^T$ and $\overline{\boldsymbol{d}} = \{U \quad V \quad W\}^T$ are the displacement vectors, k is the wavenumber, and ω is the angular frequency. Thus, the three dimensional problem of wave propagation along the structure is reduced to a two dimensional problem. This solution form, given by Eq. (1), has been widely used in the linear regime. It has also been adopted by Gandhi et al. [10], Loveday [16], and Mazzotti et al. [17], for prestressed waveguides where geometric nonlinearities are taken into consideration.

Elastic waves propagating along structures only results in small perturbations of the initial state. Therefore, in the absence of preloading, with a zero initial state-of-stress, the assumption of infinitesimal strains can be adopted. However, in the presence of an initial state of stress, finite strains and deformations can be induced in the waveguide. The Green-Lagrange strain tensor is adopted to describe strain-displacement relations, which is presented in Voigt notation as follows